Coastal region and small island papers 18

Applications of satellite and airborne image data to coastal management

Seventh computer-based learning module
(third edition)
(Revised and expanded for *Bilko 3*)

APPLICATIONS OF SATELLITE AND AIRBORNE IMAGE DATA TO COASTAL MANAGEMENT

SEVENTH COMPUTER-BASED LEARNING MODULE (THIRD EDITION)

(REVISED AND EXPANDED FOR *BILKO 3*)

EDITED BY A. J. EDWARDS

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The 'Coastal region and small island papers' series was launched by the Organization in 1997. Information on CSI activities can be obtained at the following address:

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website: http://www.unesco.org/csi

Front photo: A colour composite IKONOS satellite image of part of the Caicos Bank in the Turks and Caicos Islands. The image is about 7 km across.

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FOREWORD

Nowadays the importance of coastal regions and their resources, particularly for small island developing States, hardly needs argument. The challenge lies in arriving at enduring solutions to the complex problems facing these unique areas, where considerable ecosystem services and high human population pressure coincide.

In publishing *Applications of Satellite and Airborne Image Data to Coastal Management*, the Seventh Computer-based Learning Module for *Bilko* in 1999, UNESCO's intent was to continue making available to the user community, a series of interactive lessons designed to explain how to use satellite and airborne remotely sensed imagery as an aid for coastal and small island management. The original module (published as *Coastal region and small island paper 4*) proved very popular with users worldwide, and had to be reprinted to meet demand. This Third Edition has been completely revised to make full use of the additional functionality and major enhancements of the latest version of the *Bilko* software (*Bilko 3*) and has had two extra lessons added.

The first *Bilko* learning module was published by UNESCO in 1989 as No. 70 in the *Marinf* series, sponsored by the former Division of Marine Sciences as part of an effort involving scientists and others in a number of countries. It provided a unique service to the international community by furnishing institutions and individuals with learning materials, free of charge, on the interpretation of image data from satellite, airborne and *in-situ* sensors. These pedagogical materials have evolved over the past decade and a half for the development of human resources and infrastructure, especially in economically less-favoured countries. The Organization's support has been continued as an activity of the Coastal Regions and Small Islands (CSI) platform. Launched in 1996, CSI facilitates and supports intersectoral actions that assist Member States towards environmentally sustainable, socially equitable and culturally appropriate development in their coastal areas.

The Coastal Region and Small Island Papers series disseminates information to managers and stakeholders to assist in the search for adequate solutions to coastal problems. This volume was prepared in camera-ready form under the supervision and editorship of Dr. Alasdair Edwards of the School of Biology of the University of Newcastle, UK. The editor and his colleagues are congratulated for their excellent and diligent work.

Extra copies of this document, as well as a CD-ROM with the present and previous modules, can be obtained free of charge and within the limit of stocks, by contacting:

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European Way, Southampton SO14 3ZH, United Kingdom
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Website: http://www.unesco.bilko.org/

DIRK G. TROOST,
CHIEF, CSI
UNESCO, PARIS, DECEMBER 2004

EDITOR'S NOTE

The majority of the world's population live in coastal regions. Increasing competition for the diminishing resources in coastal areas and the growing disparity between those who have and those who have not, make coastal belts potential flash points for resource conflict. Often these conflicts may be between, on the one hand the pressures of global tourism, poorly implemented industrialisation, or inappropriate aquaculture developments, and on the other, local communities dependent on coastal resources who find these threatened by such external forces. To manage such coastal areas is a unique and complex challenge. Integrated coastal management (ICM) seeks to rise to this challenge by co-ordinated planning and action involving communities, stakeholder groups and managers at local, regional and national level as well as both natural and social scientists.

As a first step to coastal management and planning, managers need to map existing coastal habitats and resources and determine how these relate spatially to areas of urban, industrial, aquaculture, tourism and other developments. This allows sites of potential conflict, high biodiversity, inappropriate development, high sensitivity to environmental impacts, etc. to be identified and for management initiatives and scarce resources to be targeted accordingly.

The primary tool for mapping coastal habitats and resources is remote sensing using satellite sensors and, increasingly, airborne digital scanners. This remote sensing distance-learning module, the seventh in the *Bilko* series, focuses on these coastal management applications. In ten practical lessons it gives users a thorough grounding in a suite of coastal management related remote sensing tasks, ranging from acquisition of appropriate imagery and interpretation of coastal images, through geometric, radiometric and water column correction, to sun glint removal, mapping of coastal marine habitats and quantitative assessment of seagrasses and mangroves. The module seeks through its training to improve the quality of spatial data available to coastal managers and planners and thus ultimately to improve the management of the coastal resources on which local communities depend.

CONTENTS

Environment and development in coastal regions and in small islands

INTRODUCTION

This is a revised and expanded version of the seventh computer-based learning module prepared in UNESCO's *Bilko* project. This was the first developed to support the Coastal Regions and Small Islands platform (CSI: http://www.unesco.org/csi). It has been revised to make use of the latest version of the *Bilko* software (*Bilko 3*). Like its predecessors, it contains a series of lessons based on the display of data in image form and it demonstrates the processing and interpretation of these images using *Bilko*. Like the first edition of Module 7 published in 1999 it requires that *Excel* (or a spreadsheet package which can read *Excel* files) also be installed.

Coastal management

Module 7 (first published in 1999) was the first thematic module and is strongly orientated towards coastal management applications in tropical countries.

Habitat maps derived using remote sensing technologies are widely and increasingly being used to assess the status of coastal natural resources and as a basis for coastal planning and for the conservation, management, monitoring and valuation of these resources. Digital sensors commonly used for coastal management applications have spatial resolutions ranging from about 1–80 m and spectral resolutions ranging from a single panchromatic band to around 16 precisely defined wavebands which can be programmed for specific applications. Costs of imagery range from about £0.25k for a low-resolution (80 m pixel) satellite image covering 35,000 km² to perhaps £80k for a high-resolution (3 m pixel) airborne multispectral image covering less than half this area. In addition, high-resolution analogue technologies such as colour aerial photography are still in routine use. Coastal managers and other end-users charged with coastal planning and management and the conservation and monitoring of coastal resources require guidance as to which among this plethora of remote sensing technologies are appropriate for achieving particular objectives. To this end the UK Department for International Development (DFID) funded production of a *Remote Sensing Handbook for Tropical Coastal Management,* which was published by UNESCO in 2000. Module 7 complements this *Handbook* by providing training for practitioners on *how* to carry out key image processing steps that are particularly important for coastal management applications. It also guides practitioners in the mapping of coral reef, seagrass and mangrove ecosystems and the quantitative assessment of the status of the latter two resources using airborne and satellite imagery.

The satellite and airborne images used in this module are primarily of the Caicos Bank area of the Turks and Caicos Islands which lie to the south-east of the Bahamas. This area was chosen as a test site to discover what coastal management objectives are realistically achievable using remote sensing technologies and at what cost. This site offered good clear-water conditions, a broad mix of coastal habitat types, a very large area (>10,000 km²) of shallow (<20 m deep) coastal waters that would be amenable to the technologies. Module 7 builds on the experience gained in our investigation for DFID of the capabilities of the range of sensors in wide current use. The objectives of using remote sensing should always be clearly defined so that appropriate imagery is obtained and adequate processing is carried out. The objectives of coastal managers in using remote sensing are listed below.

Uses of remote sensing in the coastal zone

Worldwide, sixty coastal managers and scientists (out of 140 contacted) responded to a questionnaire in which they were asked (a) to identify what they saw as the primary applications of remote sensing and (b) to prioritise the usefulness to them of various levels of information on coastal systems.

The most in-demand applications of remotely-sensed data were to provide background information for management planning and to detect coastal habitat change over time (Figure 1). The term "background information" reflects the vagueness with which habitat maps are often commissioned and indicates a need for objectives of remote sensing surveys to be defined more rigorously. 70% of respondents who were using remote sensing for change detection were concerned with mangrove assessment and/or shrimp farming. The primary uses made of the habitat/resource maps are shown in Figure 1.

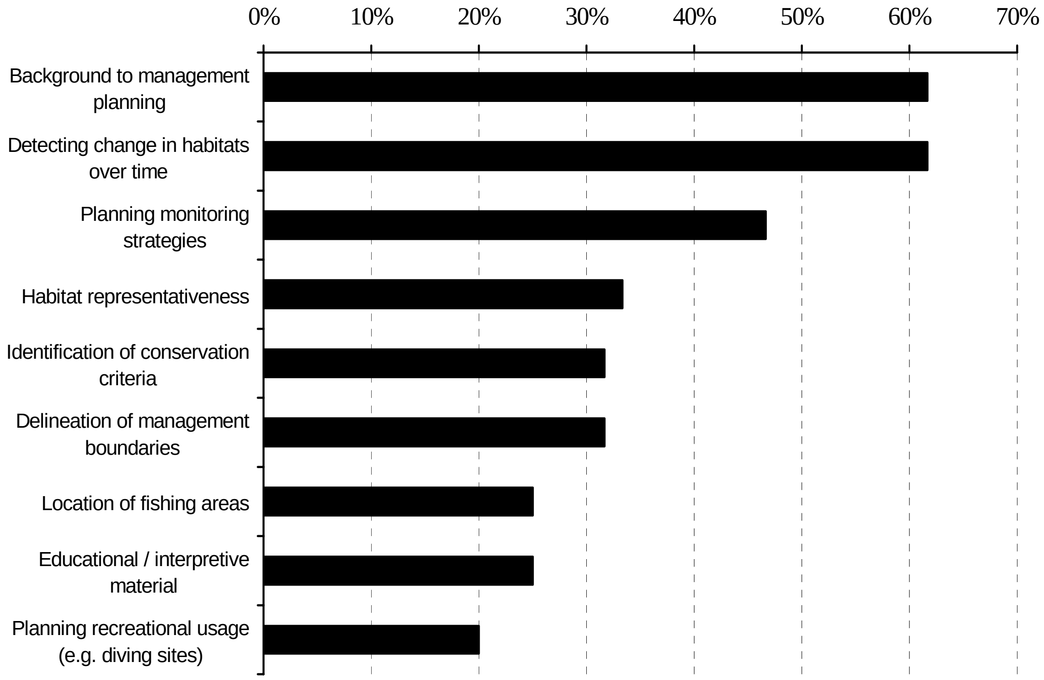


Figure 1. Responses of 60 coastal managers and scientists to a questionnaire asking them to identify what they considered the primary applications of remote sensing for tropical coastal management.

Getting started: The full list of files needed for Module 7 is detailed in Appendix A.

The minimum recommended level of computing hardware is a Personal Computer (PC) with a reasonably fast Pentium processor and 128 Mbytes of memory, which is running under Windows 98 or later. A graphics card that can display 24-bit colour images is recommended although 16-bit (High colour) is adequate to view colour composites. The lessons are available over the World Wide Web (http://www.unesco.bilko.org/) and on CD-ROM.

Lesson texts and other documentation are available as Microsoft Word (.doc) and Adobe Acrobat (.pdf) files, which you can print from disk or edit to suit your specific training and educational needs.

Use of the module: Just one condition and one request are attached to the copying and distribution of the material in this module. The condition is that **the material may not be sold**. The request is that if you make use of this module, either the original or a copy, you fill in the reply sheet and return it to the UNESCO-Bilko, c/o V. Byfield, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, United Kingdom. The return of reply sheets helps us to assess whether our modules are reaching the community for which they are intended, and so serves as a guide in preparing new lesson material for future modules. A reply sheet is attached to the letter accompanying this module and it is reproduced on page 253.

Perspective: It is now over 15 years since the first memoranda on what has become the *Bilko* project were circulated. For those of us who have been involved with the project since its inception, it was a pleasure to experience the warm reception accorded the first module and a relief to see the steady growth of the small community of interested teachers and researchers as subsequent modules were published. We now have lessons from five continents and the present module will be available worldwide over the internet.

With the increasing number of lessons has come an increase in the community that surrounds the *Bilko* project. The first module was written by the founding group and distributed to colleagues known at UNESCO to be interested in the teaching of marine sciences. Recipients were asked to make copies freely available to colleagues and students, and to consider writing a lesson for publication in a future module. The number, quality and variety of the lessons received are evidence that the recipients are not content merely to use the materials provided, but do indeed think it worth while to contribute to this exercise in improving the quality of teaching.

Since its earliest days, the prime objective of this project has been, by example, to promote excellence in teaching. This is a demanding task, but the reports on existing modules are good. We are aware, however, of two shortcomings relative to the original goals: lessons, while extensively reviewed and edited, have not usually been subjected to the extensive student testing that is normally a prominent feature in the development of computer-based lessons, and the range of topics covered remains narrower than it need be given the power of the existing software.

You too can contribute: One purpose in writing this introduction is to ask your help. The project is open to development along three broad lines, which may be described as relating to access, excellence and community. All are asked to take part in this development, but key contributions will come from those who teach their students using the lessons and offer their experience for the benefit of others.

The writing of *Bilko 3* is an important development. We know that their experience in the classroom has led many teachers to add their own questions and refinements to the published lessons. Our objective is to enrich these lessons by pooling the knowledge that already exists in the network of *Bilko* users. For this, we'd like questions, descriptions of student projects, alternative images and alternative presentations. Please do not hesitate to send exercises, modifications or additional explanations that have worked well with your students. It is a simple matter to link optional text to the main lessons, and we hope to add several tens of exercises to the published versions of existing modules.

All types of lessons are welcomed, provided they are based on data that make use of the *Bilko* software. If you would like to contribute a lesson, you will find helpful guidance in two documents, which can be downloaded from the *Bilko* website (www.unesco.bilko.org): *Guidelines for Bilko Authors.pdf* and *Technical Notes for Bilko Authors.pdf.* As with most scientific educational literature, contributed lessons are subject to editorial review before publication. To find out more, a useful first step is to fill in the reply sheet at the end of this module. If you would like to discuss the matter informally, do not hesitate to contact any member of the International *Bilko* Executive Steering Team (IBEST).

Other modules: If you find this module interesting and would like to obtain copies of others in the series, these are downloadable over the internet. See the *Bilko* website at http://www.unesco.bilko.org/ for further details or write to (or e-mail) UNESCO-Bilko, c/o V. Byfield, Southampton Oceanography Centre at the address given on page 253. The contents tables of these earlier modules can be browsed over the internet at the address above and are also reproduced in Appendix B.

International *Bilko* Executive Steering Team (IBEST) – 2005

Section 1

Introduction to using the *Bilko 3* image processing software

BACKGROUND INFORMATION, NOTATIONAL CONVENTIONS AND GETTING STARTED

Aims: To give you some background information on the *Bilko v. 3* image processing software, to introduce the topics covered and notational conventions used in the *Introduction to using Bilko*, and to tell you how to start *Bilko*.

Objectives: You will learn the conventions used to refer to mouse and keyboard actions, menu selections and files, and how to start the *Bilko* program.

Bilko is an image processing system developed for **educational use** and comes with lessons, images and worksheets in ocean and coastal oceanography and in coastal management applications of remote sensing. Its routines may be applied to the analysis of any image in an appropriate format and include a wide range of standard image processing functions.

Bilko v. 3 is designed to run on PCs running Windows 2000 and Windows XP but runs happily under Windows 95, Windows 98 or Windows NT 4.0 or later. It is optimised to help students learn the techniques of remote sensing. It is assumed that potential users of *Bilko* are familiar with the Windows environment and how to use a 'mouse'. The software includes an integrated and detailed context-sensitive Help system.

This introduction has been split up into a series of interactive tutorials, each of which introduce you to one aspect of *Bilko*'s capabilities. If you have the time, you are advised to undertake each tutorial in turn in the order they are listed below. Later tutorials may assume some familiarity with topics covered in tutorials 1–6, which cover the essential basics.

Contents

The following typographic conventions and definitions are used throughout the introduction to using *Bilko*.

Mouse buttons (description for right-handed mouse use)

Your computer may be set up so that you can open a file with a single mouse "click" (i.e. by depressing the left mouse-button once) or it may be set up so that you need to "double-click" to open a file (i.e. by depressing the left mouse-button twice in quick succession). In the text, we will just ask you to "open" the file. "Right-click" means depress the right mouse-button once to bring up a menu associated with the object under the mouse pointer. "Click" means make a single left-button click with the mouse pointer positioned on the menu item indicated. *Bilko* also supports Microsoft IntelliMouse scrolling and zooming features using the mouse wheel.

Keynames

In this document the names of keys are written as follows: <*Esc*> for the Escape key, <*Enter*> for the Enter or Return key (often marked ↵), <*Ctrl*> for the Control key, <*Spacebar*> for the Spacebar, <*Shift*> for the Shift key, <*Alt*> for the Alternate key), *<Tab>* for the Tabulate key. On your own keyboard the key caps may abbreviate the names or represent them a little differently.

Direction keys

The direction keys are the four arrow keys (↑ ↓ → ←) on your computer's keypad. The name of the individual direction key refers to the direction the arrow points: the <*Up arrow*> key, the <*Down arrow*> key, the <*Right arrow*> key, or the <*Left arrow*> key. You use the direction keys to move the selection, the pointer, or the insertion point on your screen. For larger movements the *<Home>*, *<End>*, *<Page up>*, *<Page down>* may be used. These keys may be used in combination with the *<Ctrl>* key. Details of how to move the cursor around each type of *Bilko* document can always be obtained by pressing the F1 (Help) key while the document is active and then selecting the link in the help page to "moving around in a *xxx*" where *xxx* refers to the document type in question.

Combinations of keys and key sequences

A plus sign (+) between key names to press and hold down the first key while you press the second key. For example, "press <*Alt*>+F" means to press and hold down the <*Alt*> key and press the F key, and then release both keys.

A comma (,) between key names means to press and release the keys one after the other. For example, "press <*Alt*>, V" means to press and release the <*Alt*> key, and then press and release the V key.

Filenames and folder names

Names of files and folders (directories) are typed in bold italics. For example, if you are asked to perform some operation on a file called "West_Africa.bmp", what you actually type is shown in an Arial bold italic font: ***West_Africa.bmp***. The three-letter "extension" to filenames, which indicate the filetype, are always shown to indicate what type of file is being referred to. This is useful as *Bilko* uses some 20 different types of file.

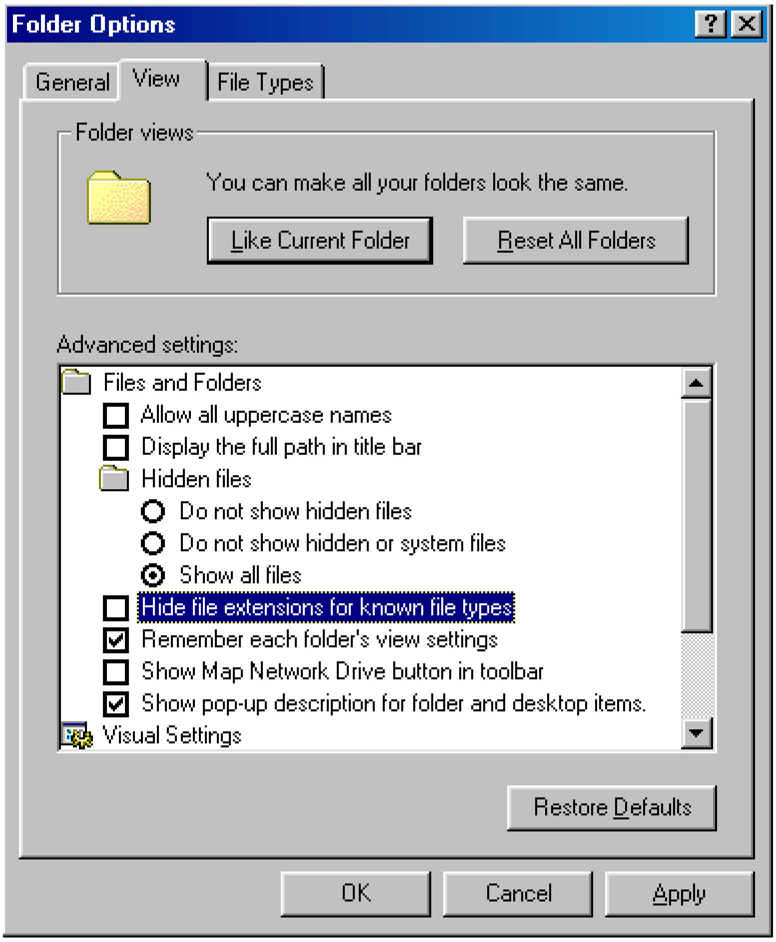
Menu choice

In *Bilko* most entries are made by choosing an item from a menu. The convention adopted here is that menu items are shown in Arial font bold face type as, for example, **File** and **Help.** Some commonly used choices have toolbar buttons assigned to them. They can also be invoked by pressing <*Alt*> + the underlined letter in the menu item. Series of nested menu selections are separated by commas, thus select **View, Reflect, in Both** means go to the **View** menu and select the **Reflect** option and then the **in Both** sub-option.

Screen shots

To augment instructions and descriptions in the text of the tutorials, details from many screen shots are included. The exact way that *Bilko* will look on the screen varies between different *Windows* operating systems (e.g., it looks very different in *Windows 95* and *Windows XP Professional*), thus do NOT expect the dialog boxes to look **exactly** as on your computer.

Getting started



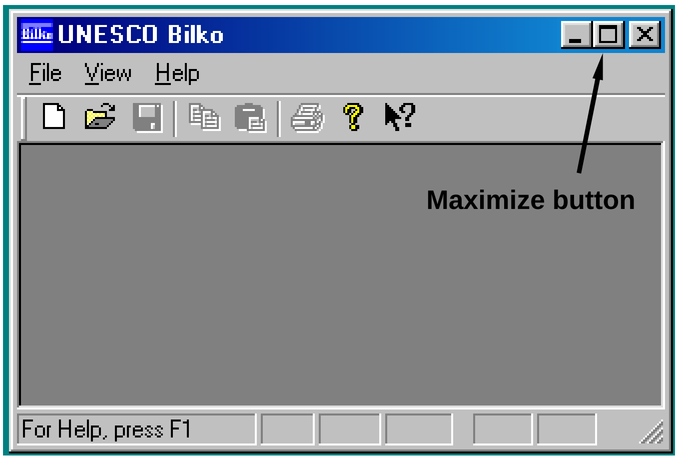
On most Windows systems the default settings for *Windows Explorer* are set such that the Hide file extensions for known file types checkbox is checked. In order that you can easily distinguish the different file types that *Bilko* uses, you should make sure that this checkbox is blank (unchecked) as in the picture to the right.

Activity: To do this you should open *Windows Explorer* and select **Folder Options** which is available from the **View** or **Tools** menu, depending on your version of *Windows Explorer*. Then click on the **View** tab of the **Folder Options** dialog box. If the Hide file extensions for known file types checkbox is checked, uncheck it by clicking on it. You will now be able to see the file extensions within *Bilko*.

Making the file extensions visible can be particularly helpful when you are saving image files in different formats but wish to keep the same filenames.

If you've installed *Bilko* yourself on your own PC, you can start the program either by opening the *Bilko* short-cut on the Windows desktop or the *Bilko* program icon in the *Bilko* directory which by default is installed in your ***Program Files*** folder. If you are working on a network, your instructor will inform you where the *Bilko* icon (see left) can be found so that you can start the program.

Activity: Open the *Bilko* program (i.e. single-click or double-click on the *Bilko* icon – see above) to start *Bilko*. Then make sure the **UNESCO BILKO** application window (see right) fills the screen by clicking on its Maximize button. This gives you plenty of space to view images and other *Bilko* documents.



The Main *Bilko* Menu

You have three options in the menu bar: **File, View** and **Help.** We will discuss **using Help** first as this is particularly useful when you are starting to use *Bilko* and are unfamiliar with its capabilities.

1. USING *BILKO* HELP

Aim: To introduce you to the versatile and integrated *Bilko* Help system.

Objectives: You will learn how the access the in-built Help system of the *Bilko* program which provides information on all the functions of *Bilko*. You will become aware of the several different ways of accessing this useful source of information, which can be used when you are unsure about some aspect of using *Bilko*.

Before you do anything else you ought to familiarise yourself with the powerful *Bilko* on-line Help system. This system works like web pages and provides useful information on the full range of *Bilko* menus, commands, dialog boxes and functionality. Don't spend too long on this section which is primarily intended to alert you to the Help system so that when you do need it; you know how to access it.

Activity: Click on **Help** and the drop-down menu gives you three useful options: **Contents, Index** and **Search.** Initially, select **Contents** and something similar to the following window appears. [*Note:* Alternatively, you could have just pressed the F1 key and clicked on the **Contents** tab.]

If you move the mouse pointer over topics in the right-hand pane of the window (normally in blue but displayed in deep red after use), these become underlined when the pointer is over them and the pointer changes into a hand. If you now click the left-button of the mouse you will get information on the selected topic.

The information in the *Bilko* Help screens gives guidance on all aspects of how to use the image processing software. You should consult Help regularly whilst going through the *Introduction. to using Bilko* tutorials.

Note: The quick key to access help is the F1 function key. The Help offered will depend on what document is the active document; thus if an image document is the active document and you press F1, you will get the Help page related to Image Documents; whereas, if a histogram is the active document, pressing F1 will give you the Help page related to Histogram Documents.

Activity: Select **Basic Concepts** from the right-hand pane, then **Using Help** from the list of links offered. Note that this page offers some advice on how to use Help so that it doesn't take up too much of the screen. Finally, click on the **context-sensitive help** link and scan this page for future reference. Since this is a particularly useful page, we suggest that you click on the **Favorites** tab and use the 

button to add the **Context-Sensitive Help** topic to your Help **Favorites**. Explore very briefly what the **Index, Contents** and **Search** options have to offer by clicking on their tabs and then pursuing one or two inquiries.

Use of the two buttons to the right of the toolbar

Clicking the first of these two buttons on the toolbar brings up a window entitled **About UNESCO BILKO** which contains information on your computer such as the amount of memory and disk space available. The second (*context-sensitive* Help) button may be used to make specific Help queries about menu items, other toolbar buttons or the *Bilko* environment.

Activity: Click on the *context-sensitive* Help button, or press *<Shift>*+F1 whilst the main *Bilko* window (not the *Bilko* Help window) is the active document. In either case, the mouse pointer changes to an arrow and question mark and now looks like the right-most toolbar button. Move the pointer to **File** on the menu bar and press the left mouse button whilst dragging the highlight until it is over **Open**. Now release the mouse button and help information appears on the **Open command.** Note that both the toolbar button and the keyboard shortcut for opening a file is displayed as well as some information on opening files and links to related information.

Click on the context-sensitive Help button  again and move the pointer until it is over the Status bar at the bottom of the *Bilko* main window, then click on it. You will activate a Help page on the Status Bar. If not all the page is visible and you have a wheel mouse, rotate the mouse wheel towards you to scroll down the Status Bar help page. [*Note: Bilko* supports Microsoft IntelliMouse scrolling and zooming features using the mouse wheel.]

Finding out about *Bilko*'s different document types

Bilko uses ten main types of files or 'document types' and you will need to know something about all these different document types to use *Bilko* effectively. Indeed, the majority of the *Introduction to using Bilko* tutorials seeks to help you to learn about how and when to use these different document types. A good starting point for information on each type is the Help folder called **Document Types**.

Activity: Click on the **Search** tab, type in "document types" as the word(s) to be searched for and click on the List Topics button. Near the top of the list of titles generated by the search should be one called **Document Types**. Select this title and click on the Display button. Links to information on the ten main document types (Table 1.1) will be displayed. You may wish to add this help page to your *Bilko* Help **Favorites**. [*Note:* Hierarchical image documents are really just a type of Image document but because of their importance and complexity are dealt with separately, making 11 links in total.]

Note: Images can be opened in a wide variety of formats and saved to disk in several formats; these are discussed in more detail in the next tutorial.

Table 1.1. The main document types used in *Bilko* with their extensions.

IMAGES (***.bin, .gif, .nc, .hdf, .n1, .tif, .bmp,*** etc.)	TRANSECTS (***.tsc***)
FILTERS (***.flt***)	FORMULAS (***.frm***)
HISTOGRAMS (***.hst***)	SCATTERGRAMS (***.sct***)
PALETTES (***.pal***)	TABLES (***.tbl***)
STRETCHES (***.str***)	SETS (***.set***)

Activity: To find out more about the different document types, briefly explore these links. The different document types are central to how *Bilko* operates so it is important that you understand a bit about them. Explore the information on the document types sufficiently to answer the three questions below.

Question 1: Where is the default origin of an Image document without geographical coordinates and what are its (row and column) coordinates?

Question 2: What does the information in a Stretch document relate to?

Question 3: What information do Histogram documents contain and how is this represented?

At this point it is perhaps most important just to know that Help has information on each document type and where to find it. *Note:* the best starting point for information on each type of document is its page in the Document Types help folder.

Some further tips on using *Bilko*'s integrated context-sensitive Help when using dialog boxes and specific document types will be given in later tutorials. Now that you are aware of the in-built guidance which *Bilko*'s **Help** menu can give you, you are ready to start using *Bilko* in earnest. Firstly, you need to learn how to **open, view and save** satellite and airborne images in *Bilko*.

Answers to Questions

Using *Bilko* Help

Question 1

The default origin of an Image document without geographical coordinates is at the top left-hand corner of the image; it is at column and row coordinates (0, 0).

Question 2

The information in a Stretch document relates to the contrast enhancement of image data.

Question 3

Histogram documents contain frequency information relating to image pixel values in the region of the image currently selected. This information is represented as a chart of frequencies of each pixel brightness value (or if more than 1500 possible values, the frequency of pixels in each "binned" pixel value class).

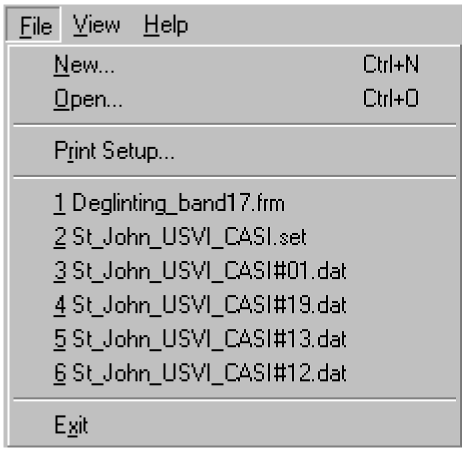
2. OPENING, VIEWING AND SAVING IMAGES

Aim: To introduce you to the details of opening, viewing and saving images in *Bilko*.

Objectives: You will learn (i) how to open a complex binary "flat file" image, (ii) details of the structure of images, (iii) how to save an image in *Bilko* data format, (iv) how to connect related images so that they can be readily compared or made into colour composites, (v) to create a "set" of related images, (vi) how to zoom in and out of an image, and (vii) how to open a hierarchically structured file in a format such as N1, HDF or netCDF.

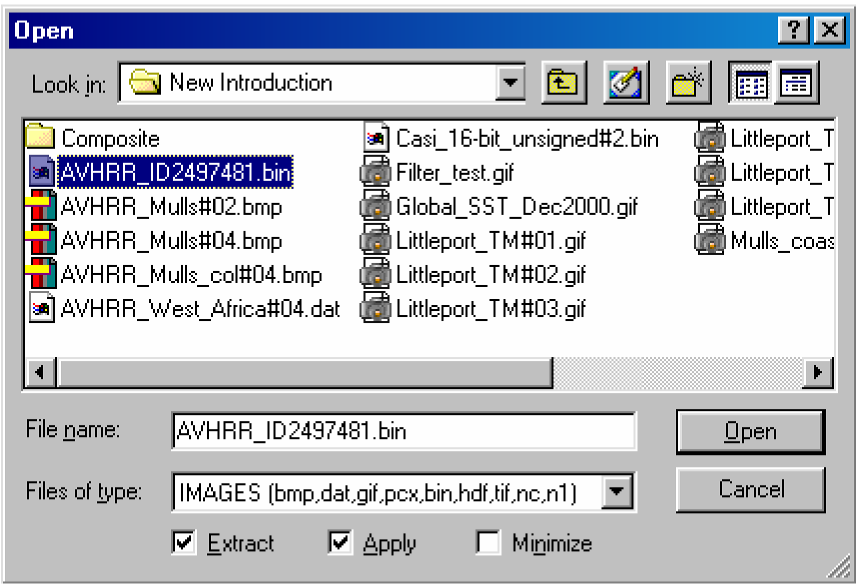
To make use of the *Bilko* software it is necessary to provide an image on which to perform the available operations. *Bilko* works with various types of 'documents' (files), as was noted in the **Using *Bilko* Help** section. If you are on a computer network, find out the drive and folder where images, palettes, stretches and other files used by *Bilko* are stored in case you need to tell the program software where to find them.

Activity: Click on the **File** menu: note that the names of the six most recently used files are indicated on the menu (see example to right). Then click on **Open**. This brings up the **Open** dialog box, which will initially be looking to list files of the IMAGES document type, since nothing useful can be done until an image is opened. [*Note:* **make sure** the **Extract** and **Apply** check boxes are checked, **and** the **Minimize** button is unchecked for this tutorial].



Images may be stored in a number of formats, which are denoted by the various file extensions in parentheses after IMAGES in the **Files of type:** box (see below). In order to introduce you to the range of options available for opening images, you will start with a complex image; as you will see later, opening images is normally much more straightforward. Once you have mastered how to open this complex image you should be able to open any appropriately formatted image in *Bilko*.

Activity: The file you will work with first is called ***AVHRR_ID2497481.bin***. If this is listed in the **File name:** list box, double-click on it to open it.



If necessary: Use the **Look in:** box to tell *Bilko* where the images are stored (normally the ***Introduction*** folder within the ***Module07*** or later module folder) and then click on ***AVHRR_ID2497481.bin*** followed by the Open button.

This will start the process of displaying the image file named ***AVHRR_ID2497481.bin***. This is a so-called binary "flat file" which can be read by most image processing programs if you know its structure.

In this case you need to tell the computer what the structure of the binary file is in some detail as it is very different from the default settings (512 pixels per line, 256 lines, 8-bit unsigned, BSQ, 1 band only, etc.). The details of the ***AVHRR_ID2497481.bin*** image file are as follows:

(i) the image has no header (**Header Length:** is 0),

(ii) it has 737 **Pixels per Line:** (i.e. the image has 737 columns or its DX: = 737),

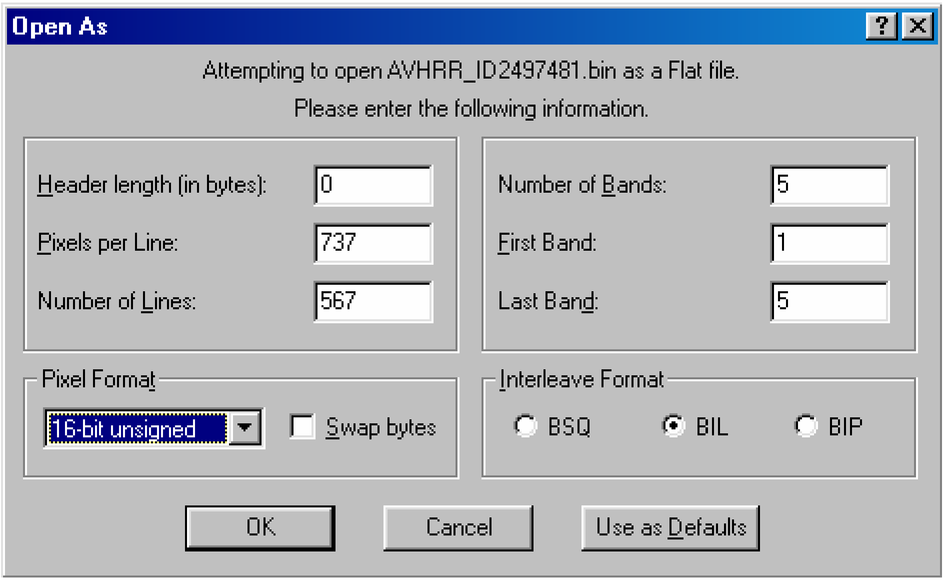
(iii) the **Number of Lines:** per band is 567 (i.e. the image has 567 rows/lines; its DY: = 567),

(iv) the **Pixel Format:** is 16-bit unsigned (i.e. each pixel value is stored as an integer value in 2 bytes = 16-bits, with no negative values); there is no need to "Swap bytes" as the flat binary file was created on another PC. However, if it had been created on an Apple Macintosh or Unix system, then you might have needed to check this box (see *Bilko* **Help** for further details).

(v) the **Number of Bands:** is 5,

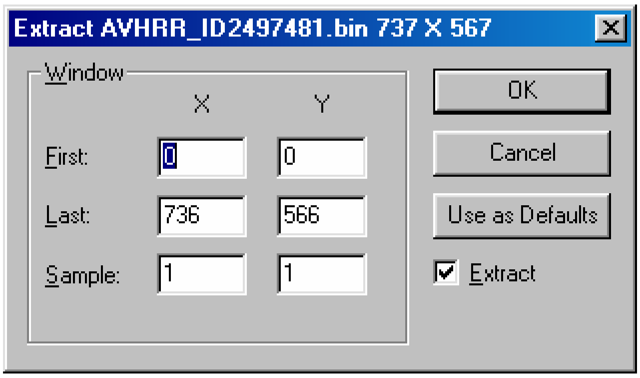
(vi) you want to display all bands, so set **First Band:** to 1 and **Last Band:** to 5.

(vii) the **Interleave Format** is BIL (Band Interleaved by Line). This means that the first 737 pixels [stored as 1474 bytes (= 2 x 737)] record data values in band #1, the next 737 pixels cover the same strip of the Earth's surface but record data values in band #2, the next 737 pixels the same strip in band #3, and so on). Thus line 1 of the image is recorded in each band followed by line 2 in each band, and so on until line 567. Note the other interleave format options, which are Band Sequential (BSQ) and Band Interleaved by Pixel (BIP) – see *Bilko* **Help** if you do not know what these terms mean.

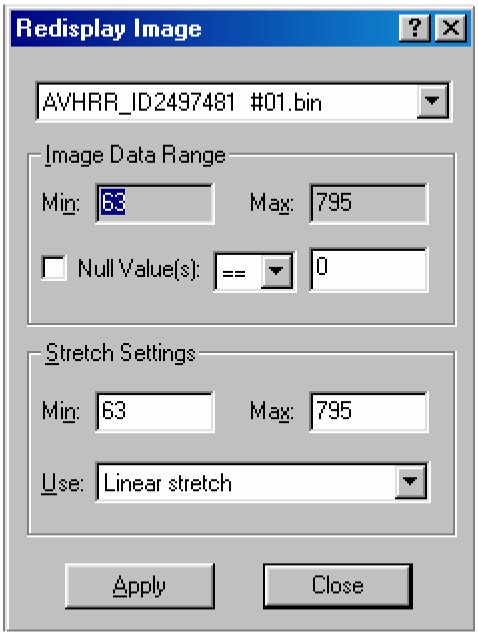


Activity: Click on the Help button **?** at the top right corner of the **Open As** dialog box and note that the context-sensitive help pointer appears. Move this over **Pixels per Line:** data entry box in the dialog and click the left mouse button. A popup with help relating to this part of the dialog box appears. Click on the **?** button again, move the pointer over the **BIL** radio button area and click for help on this interleave format. Then try right-clicking on the **BIP** radio button; you will be offered a **What's This?** dialog (see right). Click on this and help on BIP interleave format appears. Remember that Help is never far away!

Now, use the data in (i) – (vii) above to fill in the **Open As** dialog box so that it looks like the image above. When finished, click on **OK**.



If the **Extract** checkbox is checked, then you have the option at this stage to just display part of an image (i.e. a "Window" within an image). In the **Extract** dialog box (right) the **First: X** and **Y** boxes allow you to set the pixel where the image window begins (top left of rectangle within the image) and the **Last: X** and **Y** boxes allow you to set the pixel where it ends (bottom right of a rectangle within the image). Unless the file you are looking at is very large you will normally wish to display all pixels. In this case **Sample:** will be set to **1** for both *x*-axis (columns) and *y*-axis (rows). If **Sample:** is set to **2** for the *x*-axis (columns), then every other pixel on each line is displayed. If **Sample:** is set to **2** for the *y*-axis (rows) then every other row of pixels will be displayed.



Activity: For now, uncheck the **Extract** checkbox (to the bottom right of the **Extract** dialog box) as this will not be needed for this image, but leave the **Window** settings as they are. Then click on [OK] or press <*Enter*> to open the image. A **Redisplay Image** dialog box will appear for each band. Note that the minimum and maximum values (often referred to as DNs = Digital Numbers) in each waveband of the image are listed. For the AVHRR (Advanced Very High Resolution Radiometer) sensor these DNs are between 0 and 1024. Ignore the **Redisplay Image** dialog box for now and just click on [Apply] for each band until all 5 wavebands of the AVHRR satellite image are displayed. Select the band #2 image (***AVHRR_ID2497481 #02.bin***) and examine it. If it looks recognisable then congratulations, you've opened the image successfully! [*Note:* the image may be a little dark on poorly set up monitors; if so, increase the brightness]. If it looks a mess, then go through the sequence again being very careful to make sure the **Open As** dialog box values are filled in correctly.

Question 1: What are the five main countries in the area covered by the image?

Note: i) that each image is displayed in shades of grey and has a grey scale with 256 brightness levels (ranging from black=0 to white=255) displayed beneath it,

ii) that the menu bar has changed with four new menus (**Edit, Image, Stretch** and **Window**) appearing.

To manage efficiently the 5 different wavebands (all recorded at the same time), which together provide our AVHRR image data, we can "connect" them using the **Image, Connect** menu option.

Activity: Select **Image, Connect** to bring up the **Connect** dialog box. You should see a list of the five constituent image files read from the binary flat file. Select all five images[1], check the **Stacked** option, and then click on OK. The 5 bands are now "stacked" like a series of layers with band #1 on top and band #5 on the bottom. Use the <*Tab*> key to view each band in turn. Note how the relative brightnesses of the bands differ with band #3 being much brighter. You can automatically flip through the bands by clicking on the **Loop** button. To stop the loop, click the button again.

Note: This provides a useful way of comparing images of the same area taken at different times as well as comparing the same scene recorded in different wavebands.

Opening a binary flat file is not very convenient because you need to remember all kinds of information about the file in order to open it. So your next task is to store the file in *Bilko* data format (***.dat*** file format) so that you can open it more easily.

Activity: Make sure band #1 at the top of the stack is the active file. Select **File, Save As** from the menu. In the **Save As** dialog box select the folder where you want to save the images in the **Save in:** box (if necessary) and make sure that Bilko .dat is selected as the file type in the **Save as type:** drop down menu (this should be set as the default file type). The **File name:** should now be set to ***AVHRR_ID2497481 #01.dat***. Click on Save to save band #1. Press the <*Tab*> key to move to band #2 and repeat the save as process to save band 2 in *Bilko* ***.dat*** format. Then repeat for the bands #3 to #5 until all 5 bands are in *Bilko* ***.dat*** format. When finished, use the <*Tab*> key to flip through the images in the stack to check that they all now have ***.dat*** extensions.

Note: If the file pixel format for the images had been 8-bit unsigned (integer) you could have saved the images in CompuServe .gif format or in Windows .bmp format.

Since the 5 images are all likely to be used together, now that they re in *Bilko* ***.dat*** format, you can further simplify opening them by saving them as a "set" of image files which can all be opened together (rather like the original wavebands were combined together in the original binary flat file, but much simpler!).

Activity: Select **File, Save Set** and in the **File name:** box enter ***AVHRR_ID2497481***, then click on the Save button. Once the set is saved, select **Window, Close All** to clear all the files cluttering the *Bilko* workspace.

Now click on **File, Open** and in the **Open** dialog box select SETS (*.set) from the **Files of type:** drop-down menu and then *either* double-click on ***AVHRR_ID2497481.set*** in the file list *or* click on it once and then click Open. This time, in the **Redisplay Image** dialog box, use Auto linear stretch as the stretch setting (this is discussed further in Tutorial 5), and then click on the All button. The stacked set of images is restored and can be tabbed through as before.

To create some colour you can display three of the AVHRR wavebands through the different colour "guns" on your colour monitor. Your monitor has Red, Green and Blue (RGB) colour guns each of which can take any intensity value between 0 and 255. When you "connect" three or more images (using **Image, Connect**) you can assign them to the different colour guns using the **Selector** toolbar. Since you already have a stack of connected images you could just select **Image,**

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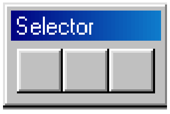
[1] *Hint:* If you click on the top image on the list (***AVHRR_ID2497481 #01.bin***), hold down <*Shift*> and then click on the bottom image (***AVHRR_ID2497481 #05.bin***) you can select all the images at once. If you wanted to select just the band#1, band#2 and band#4 images, you would click on the top one (***AVHRR_ID2497481 #01.bin***), hold down <*Ctrl*> and then click on ***AVHRR_ID2497481 #02.bin*** and then ***AVHRR_ID2497481 #04.bin***.

Composite and the top three images or layers in your stack would be displayed as a colour composite image with waveband #1 displayed in red, waveband #2 in green and waveband #3 in blue (hence the colours associated with the filenames in the **Selector** window of the stack).

Activity: Select **Image, Composite**. You will get a rather hazy blue image.

A more pleasing composite image is created using bands #1, #2 and #4.

Activity: Select **Image, Connect** and select bands #1, #2 and #4 (***AVHRR_ID2497481 #01.dat, AVHRR_ID2497481 #02.dat*** and ***AVHRR_ID2497481 #04.dat***). Do NOT check the **Stacked:** checkbox this time. Then click OK. A tile of the three connected images will appear along with a **Selector** toolbar (see right) near the middle of the screen. The button numbers correspond to the RGB gun order (R=1, G=2, B=3). For this colour composite you should put waveband #1 through the red gun (button 1), waveband #2 through the green gun (button 2), and waveband #4 through the blue gun (button 3). Just click each button in order from left to right to do this. Then select **Image, Composite**. You will get a somewhat better false colour composite image with land of a greenish colour and the sea dark. Before proceeding further, close (i) the hazy blue composite, (ii) the 3 connected images tile, and (iii) the set of 5 stacked images, but leave the nicer colour composite open.



To examine this image more closely you can zoom in and out in various ways.

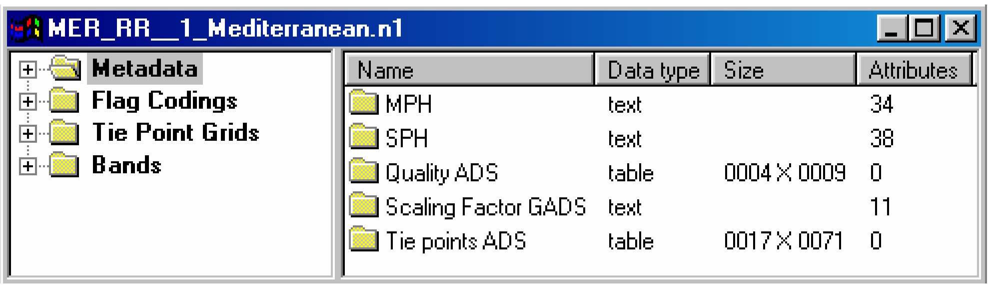
Activity: Right-click on the colour composite image and select **Zoom** from the menu that appears (*or* click on **View, Zoom**). Enter 200 in the **Zoom %:** box to zoom in. Experiment with other zooms set using the menu. Then try double-clicking on the image to zoom in. Try holding down <*Ctrl*> and double-clicking to zoom out. Check how far you've zoomed in or out using the **View, Zoom** menu or by right-clicking on the image and selecting the **Zoom** option. Finish by setting the zoom to 100%.

It can be useful to save an image as a picture to put in a document once processing has been completed. For example, one might wish to include a colour composite image in a report.

Activity: Firstly, note that the colour composite has three colour bars underneath the image to indicate that it is composed of three images, each displayed through a different colour gun on the monitor. With the colour composite as the active image select **File, Save As…** Note that the default file type is Bilko .set (i.e. a set of the three images which make up the composite). In this case you want a picture for a report rather than the three images that make up the composite, so select Windows .bmp (Windows bitmap format). This is a 24-bit colour picture format. The default filename is informative, indicating which bands have been used to make the composite image; however, you can change the name if you wish. Once you are happy with the name click Save. This saves a picture representation of the colour composite with the 16-bit unsigned integer values in each band reduced to 8-bit values (on a 0–255 scale). Close the bitmap file and then reopen it. Note that now it is a Windows bitmap it no longer has three colour intensity bars; close the composite again.

Many satellite images come in hierarchically structured formats, a bit like complex sets of images; these formats usually include considerable additional data apart from the images themselves. Many datasets that are freely available over the internet are stored in these hierarchical formats. Widely used formats include HDF (***.hdf***), the European Space Agency's N1 format (***.n1***) and netCDF (***.nc***). *Bilko* is able to read files in these formats, giving you access to huge amounts of valuable Earth observation and oceanographic data from a range of satellites. Such datasets are complex and exploring any one format in detail could be the subject of a lesson (or even several lessons!) in itself. Here you will just examine one of these images with its associated data. This is an MERIS (Medium Resolution Imaging Spectrometer) image from the European Space Agency's ENVISAT satellite.

Activity: Open the file ***MER_RR__1_Mediterranean.n1,*** which is a MERIS image of the central Mediterranean around Italy. For the purposes of this tutorial we have shortened the filename (originally: ***MER_RR__1PNPDK20030813_094018_000022742019_00022_07591_4499.N1***). A window will open which displays the N1 hierarchical file structure (see below). The images (bands) and associated metadata, flag codings and tie point grids (to do with geolocating the image pixels), are listed as a series of nested folders on the left pane of the window. The **Metadata** folder is open and its five constituent folders are shown in the right pane. Examine the metadata folders by double-clicking on their



folder icons or right-clicking on them and selecting **Open Items**. In the **SPH** (Specific Product Header) folder you can find text indicating when and where the image was taken, the number of bands and their wavelengths and bandwidths, etc. Note that two of the folders contain tables of information. Using the **SPH** folder information answer the following questions.

Question 2: On what date was the MERIS image taken? How many bands were recorded?

Flag Codings are very important and indicate what the different values on a "flag" image included with the bands mean. These "flags" indicate such things as where there is land, water, cloud, coastline, sunglint, invalid data, etc. on the image. How to use these flag images is briefly introduced in the tenth tutorial on **using formula documents**.

Activity: Open the **l1-flag** codings folder and note that land is coded as 16 and coastline as 64. Inspect the **Tie Point Grids** folder and note the fifteen sub-folders of information, which aid geolocation, interpretation and processing of the image data. Finally, open the **Bands** folder and note that there are 15 bands of radiance image data, a flags image and a detector index image. Right-click on the **radiance_1** folder in the right-hand pane and select **Open Properties** from the menu that appears.

The properties of the band #1 image are displayed; these comprise a description, scaling factor and offset, units ($mW.m^{-2}.sr^{-1}.nm^{-1}$), spectral band index, bandwidth (9.93 nm) and mid-wavelength (412.545 nm). To open the band #1 image, you can either double-click on the **radiance_1** folder or right-click on it and choose **Open Items**.

Activity: Experiment with opening the **radiance_1** image. Close the image when you have finished.

Click on the **radiance_2** folder in the right-hand pane, hold down the *<Ctrl>* key and then click on the **radiance_5** and **radiance_7** folders so that all three are highlighted. With the mouse pointer over one of the highlighted image folders, right-click and select **Open Connected** from the menu that appears. In the **Redisplay Image** dialog box, check the **Null Value:(s) == 0** checkbox, select Auto linear stretch and then click on the All button to apply this stretch to all three images. This displays the MERIS band #2 (in the blue part of spectrum), band #5 (a green waveband) and band #7 (a red waveband) images.

A stack of the three connected images will appear along with a **Selector** window. Click on the drop-down list button of the **Selector** window and you will see band #2 in red, band #5 in green and band #7 in blue (see right). You want to create a colour composite with waveband #7 displayed through the red gun, waveband #5 through the green gun, and waveband #2 through the blue gun. To achieve this you need to make the band #2 image the third (@3 = blue) image and the band #7 image the first (@1 = red) image. Make sure that the top (red) band #2 image is selected and press the *<3>* key. The colour of the filename changes to blue (@3) and if you click on the drop-down list you will see that band #7 is now in green. Select band #7 and press the *<1>* key. The colour of the filename changes to red (@1) and you are now ready to create a colour composite with each waveband displayed through the correct colour gun.

Select **Image, Composite**. You should get a nice false colour composite image with land of a brownish colour, the sea blue, and clouds and snow-capped peaks white. Examine the image.

Finally, open the **l1-flags** image, select the whole image (*<Ctrl>+A*) and apply an automatic linear stretch (**Stretch, Auto Linear**). Note how the coastline, land and cloud (“bright”) areas are delineated.

When you have finished close all open images by selecting **Window, Close All**. Do not save any images.

In this section you have learnt how (i) to open complex images, (ii) to “connect” images to make “stacks” of overlaid images so that images can be readily compared, (iii) to connect images to make colour composites, (iv) to save images in various formats, (v) to link related images as “sets” so that it is easy to work on them, (vi) to zoom in and out of images, and (vii) to open a complex hierarchical image and associated data file.

In the next section you will learn how to use the **image toolbar selection buttons and the status bar** to find out more about the image.

Answers to Questions

Opening, viewing and saving images

Question 1

The five main countries in the area covered by the image are Spain, Portugal, Morocco, Algeria, and France.

Question 2

The MERIS image was taken on 13 August 2003. 15 bands were recorded.

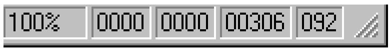
3. USING THE IMAGE TOOLBAR BUTTONS TO EXAMINE IMAGES AND INTERPRETING THE STATUS BAR

Aim: To introduce you to using the image toolbar selection buttons and to interpreting the information provided in the status bar panels.

Objectives: You will learn to interpret the panels of the Status Bar for an image document, the distinction between underlying and display data values, use of point selection, line selection (transect) and box selection buttons, use of **Go To** function from the **Edit** menu, and how to select a sub-area of an image and save this as a new image.

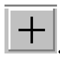
Pre-requisites: To do this tutorial you need to have completed the tutorial on opening, viewing and saving images and in particular have created the image file ***AVHRR_ID2497481 #02.dat***.

Activity: Open the image ***AVHRR_ID2497481 #02.dat*** using the default settings but make a note of the minimum and maximum values of the image data in the **Image Data Range** part of the **Redisplay Image** dialog box.



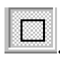
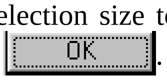
Once the image is open, look at the bottom right hand corner of the **UNESCO BILKO** workspace Status Bar and note the five grey panels. The first panel shows the zoom on the image, which is currently 100%. The next two panels show the column and row coordinates of the cursor, which should be at the top left (coordinates 0, 0) of the image. The last two panels show firstly, the underlying value of the pixel where the cursor is and secondly, the display value (on a scale of 0 [black] to 255 [white]).

In this 16-bit integer image, the actual values of pixels can range from 0 to 66535 but a computer monitor can generally only display 256 grey levels so the *Bilko* program has to map the image data range to the monitor (screen) data range. The default settings map the lowest image pixel value, which you should have noted as 48, to 0 and the highest pixel value, which you should have noted as 762, to 255, with intermediate value pixels taking values in between. This mapping is discussed in more detail in a later section.

Activity: Make the image cursor a "point selection" by clicking on the point selection button . Now move the mouse pointer over the middle of Spain and click the left hand button. The white arrow places a flashing cursor in the form of a cross (+) on the image where it is clicked. The last four grey panels will now contain the *x*-coordinate (column), *y*-coordinate (row) and both underlying and display brightness values of the pixel that the cursor is on. If the cursor was on a pixel 300 from the left and 295 rows down the panels would look as follows,

showing that the pixel has an underlying data value (DN) of 226 and is displayed as a grey level of 64. Being able to find out the value of an individual pixel at a given location using the image cursor can be very useful.

To practice your use of the cursor we will find out typical values of sea and land pixels in the clear part of the AVHRR band #2 image. This is recorded at wavelengths of 0.72-1.10 µm in the near infra-red part of the spectrum. Near infra-red is strongly absorbed by water and strongly reflected by vegetation and thus infra-red images can be useful for determining land-sea boundaries. To focus in on the non-cloudy part of the image you will select a sub-area from the main image and make this into a new image before examining land and sea pixel values using the status bar.

Activity: Make the image cursor a "box selection" by clicking on the box selection button . Select **Edit, Go To** and set the position (top left coordinates) to an **X:** of 185 and **Y:** of 290 and selection size to a **DX:** of 245 [columns] and **DY:** of 230 [rows]. Once this is done click 

. The specified sub-area is now delimited by a box.

Note: You can also delimit boxes interactively by clicking on the top left of the area you want and then, holding the left mouse-button depressed, dragging the bottom right of the box to where you want. Now that you know the area you want, practice doing this. At any time you can click on **Edit, Go To** in order to check precisely what sub-area you have selected and modify this using the position and selection size coordinate boxes.

When happy with this, leave a cloud-free sub-area, similar to that suggested above, selected. Then select **File, New** from the menu and in the **New** dialog box select **IMAGE Document** and click OK. This creates a new image of the clear sub-area you want to focus on.

You can move the cursor around the new image using the arrow keys (↑ ↓ → ←) on the keyboard. By default, each press of an arrow moves the cursor 10 pixels in the direction indicated until it is within 10 pixels of the edge of the image. To move the cursor one pixel at a time hold down the <*Ctrl*> key and then press the appropriate arrow key. You can also use **Edit, Go To** to alter increments moved by the image cursor (with or without the <*Ctrl*> key depressed) or to go to a specific column and row coordinate on the image, e.g. 90, 135. The latter function is particularly useful on images with geographical coordinates.

Activity: Experiment with using the cursor and then use it and the status bar to find answers to the following questions. [*Hint:* zooming in may help in positioning the image cursor around the coastline.]

Question 1: Concentrating on the coastline but trying to avoid "mixels" (i.e. pixels which overlap both land and sea), what are the maximum underlying pixel brightnesses (DN values) in areas that are clearly sea?

Question 2: Concentrating on the coastline but trying to avoid "mixels" (i.e. pixels which overlap both land and sea), what are the minimum underlying pixel brightnesses (DN values) in areas that are clearly land?

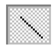
Question 3: Why are the sea pixels much darker (i.e. have lower DN values) than the land pixels?

Activity: When you have finished close the sub-image and close the ***AVHRR_ID2497481 #02.dat*** image. Now open a colour composite image (***AVHRR_ID2497481_composite.set***) that has been saved as a set of three images (bands #1, #2 and #4 of the AVHRR_ID2497481 image). In the **Redisplay Image** dialog box select **Auto linear stretch** for the stretch setting to use and click the All button to apply this stretch to all three bands of the composite (see **tutorial 5** for details of stretches). Click the point selection button and select **Edit, Go To** dialog box from the menu bar. Use this to place the cursor on the pixel at column (**X:**) 258 and row (**Y:**) 329. The fourth and fifth panels of the Status Bar should now each contain three values separated by commas (see right).

In the fourth panel are the image data values (123, 234 and 513) for the pixel at column and row coordinate (258, 329); in the fifth panel are their display brightness values (21, 66, 41 if **Stretch, Options Min %** is 0 and **Max %** is 100; 20, 85, 18 if **Stretch, Options Min %** is 5 and **Max %** is 95). The first number refers to the image displayed through the red gun, the second to that displayed through the green gun, and the third to that displayed through the blue gun (*Hint:* Remember RGB). You can check what these images are by dragging down the top of the image window.

Activity: To do this, click on the grey edge above the image (indicated by the arrow) but below the title bar and holding down the left mouse-button drag the image "window pane" downwards (it works a bit like a roller-blind). [*Note:* When the mouse pointer is positioned correctly over the top of the window pane it will change into a pair of parallel lines with up and down

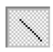
arrows.] Under the composite image you should see: **False Colour Composite AVHRR_ID2497481#01+#02+#04.** This tells you that the top (Red gun) image is band #1, the second (Green gun) image is band #2 and the third (Blue gun) image is band #4 of the AVHRR_ID2497481 image. This type of information on image history is automatically stored by *Bilko* and can be very useful at times. Use **Window, Close All** to close all the images making up the set.

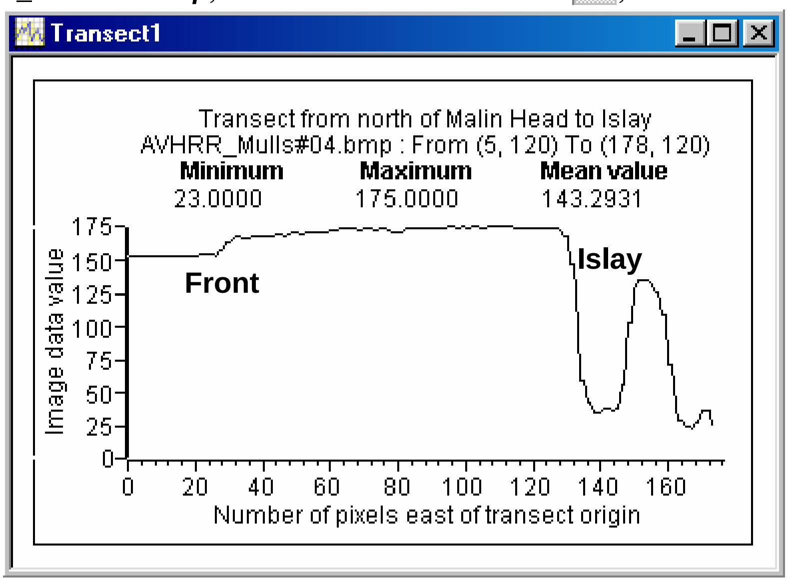


Finally, in this section we will look at the transect button on the menu bar. The Transect option allows you to view a graph of pixel brightness values along a transect drawn between any two points on an image. This is shown as a graph of pixel values on the *y*-axis versus number of pixels along the line between the points. Transects can be used to study how pixel values change between different areas of the image. To find information about the transect button, click on it and while holding the left mouse button down, press the F1 key.

Figure 3.1. Map showing the area covered by the ***AVHRR_Mulls#04.bmp*** image.

For this you will look at an AVHRR image taken in band #4 which senses emitted thermal infra-red electromagnetic radiation in the wavelengths 10.50–11.50 µm. This image has been processed and re-scaled to 8-bits. By convention darker areas are warmer on this type of AVHRR thermal image. Colder parts of the image will thus appear brighter (high pixel values) and warm parts dark (low pixel values).

Activity: Open the image ***AVHRR_Mulls#04.bmp***, click on the Transect button , or select the **Selection, Line** option from the **Edit** menu. Start the transect north of Malin Head (Figure 3.1) near coordinates (5, 120) and drag the mouse pointer to the middle of Islay island (Figure 3.1). This draws a transect which passes through the oceanic front off Northern Ireland and ends on land. Now click on **File, New**



and select a TRANSECT Document (the default) from the **New** dialog box.

The front shows up as a sudden increase in pixel values whilst the warm land (whose pixel values are very low) is where pixel DN values suddenly plummet to around 30.

Activity: Note that if you needed the transect information for reference purposes, you could save the transect document (extension ***.tsc***). You may wish to experiment with this, saving and re-opening the transect document. When you have finished with the transect, close it. If you are **not** going onto the next tutorial, you can also close the ***AVHRR_Mulls#04.bmp*** image.

In this section you have learnt how to use the image cursor and panels of the Status Bar to interpret an image, the distinction between underlying image data and display data values, use of point selection, line selection (transect) and box selection buttons, use of **Go To** function from the **Edit** menu, and how to select a sub-area of an image and save this as a new image. You have also learnt how to find out more about an image by dragging down the top of the image window. These skills are all routinely used in image interpretation and image processing and will come in useful later.

At this point you can either go on to further **examine images using Histograms** or you may wish to take a break.

Answers to Questions

Using the image toolbar buttons to examine images and interpreting the status bar

Question 1

The majority of sea pixels have values between 51 and 70 and close to coast a few seem to reach around 85. Maximum values for sea pixels are around 85-90.

Question 2

The majority of land pixels have values between 145 and 285 and close to coast a few seem to have values into the 130s. Minimum values for land pixels are around 130.

Question 3

The sea pixels are much darker because infra-red radiation is strongly absorbed by water.

4. USING HISTOGRAMS TO INTERPRET IMAGES

Aim: To introduce you to using histograms to interpret images.

Objectives: You will learn how to create histograms (which show the numbers of pixels of each image data value) and how these can be helpful in interpreting images.

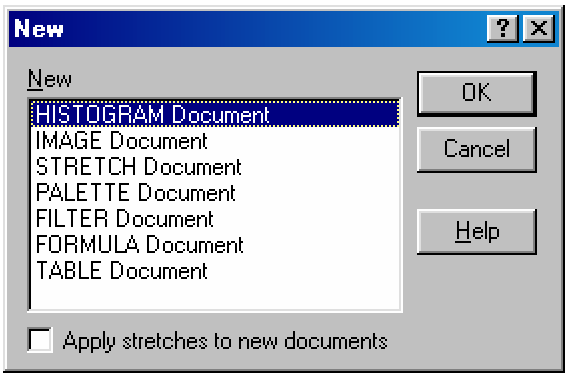
If you completed the previous tutorial (**Using the image cursor and interpreting the status bar**) you will have noted that sea pixels differed markedly from land values in their reflectance. A good way of seeing whether pixels fall into natural groupings on the basis of their reflectance/emittance in a particular waveband is to study a frequency histogram of brightness values. In this section you will be examining an AVHRR image, taken in band #4 which senses emitted thermal infra-red electromagnetic radiation in the wavelengths 10.50–11.50 µm. This image has been processed and re-scaled to 8-bits. By convention darker areas are warmer on AVHRR thermal images. Colder parts of the image will thus appear brighter and warm parts dark.

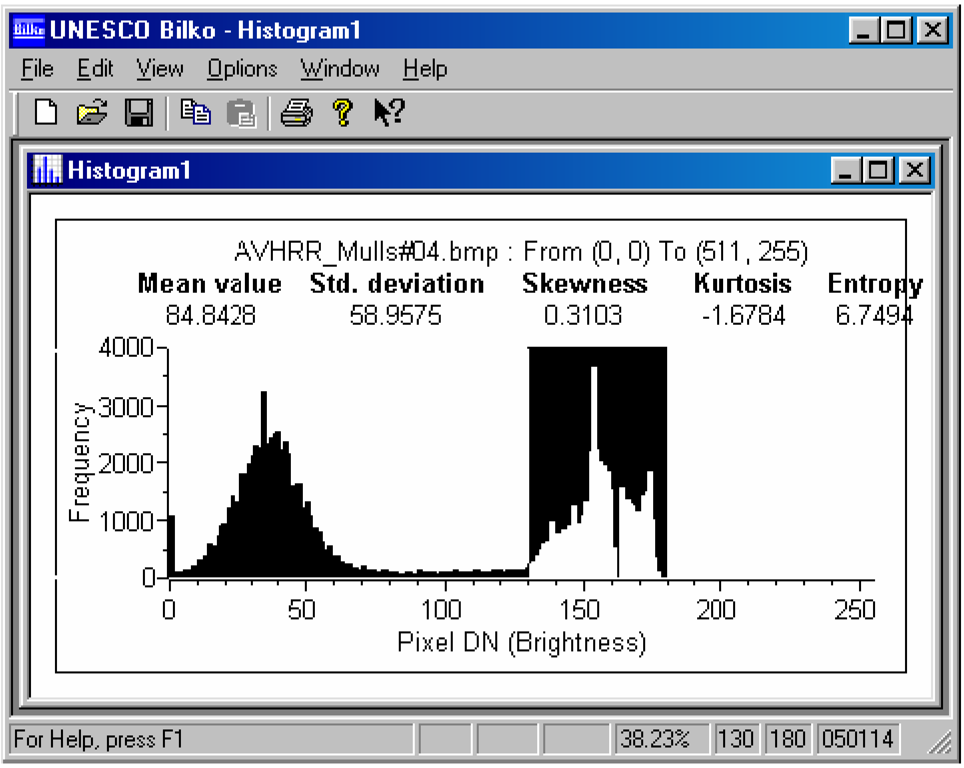
Activity: If it is not open already, open the image ***AVHRR_Mulls#04.bmp***. The image was obtained in the daytime in summer. Note that the warm land is generally dark but the sea is brighter with the coldest (brightest) water lying north-east of Malin Head (Figure 4.1).

Figure 4.1. Map showing the area covered by the ***AVHRR_Mulls#04.bmp*** image.

To create a histogram of all the pixel values in an image you first need to select the whole image file.

Activity: Click on **Edit** and then **Select All** or use the short-cut keys *<Shift>+<Spacebar>* (or *<Ctrl>+A*) to select the whole image. Then click on **File** and **New** to bring up the dialog box to the right. Since you want to create a Histogram and the **HISTOGRAM Document** option is already highlighted you can click on **OK** or press *<Enter>* to generate the histogram.





A histogram window will appear in the workspace resembling the **Histogram1** window displayed to the left. The histogram shows the number of pixels in the selected image having given pixel values (*y*-axis) versus the set of values (DN) that pixels can take (*x*-axis).

Note that the histogram is bimodal (has two peaks). The lower peak (i.e. that covering pixel brightness values with DNs from about 10–70) is composed mainly of land pixels, whilst the upper peak (i.e. that covering pixel brightness values with DNs from about 130–175) is composed mainly of sea pixels.

Activity: Click on the histogram and a vertical line will appear. You can use the mouse or the left and right arrow keys (→ ←) to move this line through the histogram. The arrow keys by themselves move the line 10 brightness values at a time to right or left. To move one brightness value at a time hold down the *<Ctrl>* key and then press the appropriate arrow key. Make sure the Status Bar is in view. In the bottom right hand corner you will see four panels which record firstly, the % of pixels in the image with the brightness value (DN) highlighted; secondly, the start and finish values of the range of DN values highlighted (if only one DN value is highlighted, these will be the same); and lastly the absolute number of pixels in the image with values in the highlighted range.

In the example above the upper (sea) peak between DN values of 130 and 180 has been highlighted and the Status Bar shows that there are 50,114 pixels in the image with values of 130–180 and that these account for 38.23% of the ***AVHRR_Mulls#04.bmp*** image area.

Activity: Move the cursor-line across the histogram and the display will change accordingly. To select a range of DN values, hold the left mouse button depressed and drag the mouse to right or left. Use the vertical line and the Status Bar information to answer the following questions.

Question 1: What is the brightness value (DN) of the brightest pixels?

Question 2: What percentage is this value of the maximum brightness that could be displayed?

Question 3: What is the modal pixel brightness value (DN) of the lower (land) peak and how many pixels in the image have that value?

Question 4: What is the modal pixel brightness value (DN) of the upper (sea) peak and how many pixels in the image have that value?

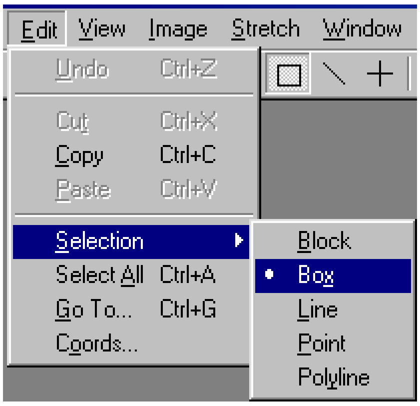
Assume that pixels with DNs between 0 and 62 are land. Now use the mouse to select all these land pixels in the histogram. [Position the vertical line at 0, depress the left mouse button and looking at the Status Bar drag until 62 is reached.]

Question 5: What percentage of the image is land pixels?

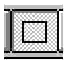
Question 6: If the image is 563 km by 282 km, what is the area of land?

So far you have inspected a histogram of the whole image, however, you can select parts of the image in order to discover what the range of pixel brightness values are of particular areas of the image in which you may be interested.

Minimise the histogram window using the minimize button.



Activity: Click on **Edit**, **Selection**, **Box** or click on the box button (right) on the toolbar. Then click near the top left hand corner of the sea in the ***AVHRR_Mulls#04.bmp*** image and holding down the left mouse button drag the mouse until a rectangular area of sea is outlined with bottom right hand coordinates around pixel (118, 140)†. [Look at Status Bar to see the coordinate you have reached]. Then select **File**, **New** and open a new histogram for the pixels inside the box. You will see a histogram with one peak (unimodal) which shows that the sea pixels in the area you have selected range from a DN of about 129–175 in brightness. Note that the legend above the histogram indicates the top-left and bottom-right pixel coordinates of the box and will look something like the text to the right. Repeat the same exercise with a box of entirely land pixels on the Scottish mainland (see Figure 4.1). You should get a unimodal histogram with pixel brightness values between 0 and about 70.



AVHRR_Mulls#04.bmp : From (2, 5) To (118, 140)

†*Note:* fine positioning of the bottom right hand corner of the box can be achieved using the keyboard. If you need to do this, hold down <*Shift*>+<*Ctrl*> and use the arrow keys to extend your selection.

Activity: When you have done this, close these last two histogram windows of the sea and land pixels (do not save changes) but, if continuing with the next section about using stretches, leave the image open and the histogram of the whole image minimised as you will need this later.

The activities above indicate the kind of information you can find out from studying the histogram (frequency distribution of pixel brightness values) of an image. One of the first things one usually does after loading an image is thus to inspect its histogram to see whether i) all pixels clump together in one peak or whether there are two or more separate peaks which may correspond to different areas of interest on the image, ii) whether pixels are spread over the full range of potential brightnesses or lumped together causing poor contrast.

The histogram of ***AVHRR_Mulls#04.bmp*** confirms that the image is not optimally displayed; that is, it is rather dark and it does not utilise the full range of display DNs available and so is somewhat lacking in **contrast**. To rectify this we can adjust how we display the pixel values by a process known as contrast stretching. As the word "stretching" implies, the process causes the pixels to be displayed over the full range of (at least) 256 display brightness values (DNs) available. The next tutorial deals with **using stretches to optimise image display**.

Answers to Questions

Using histograms to interpret images

Question 1

The DN value of the brightest pixels is 178.

Question 2

The maximum which can be displayed is 255. The brightest pixel in the image has a value of 178. 178/255 is 69.8% of maximum brightness.

Question 3

The modal DN value of the lower (land) peak is 34. There are 3246 pixels with this value in the image.

Question 4

The modal DN value of the upper (sea) peak is 153. There are 3668 pixels with this value in the image.

Question 5

55.28% of the pixels have values between 0 and 62 and can be classed as land pixels.

Question 6

The whole image has an area of 563 km x 282 km = 158,766 km^2. Multiplying this by 0.5528 (55.28% of pixels are land, i.e. have values from 0 to 62) gives a land area of 87,766 km^2 to the nearest square kilometre.

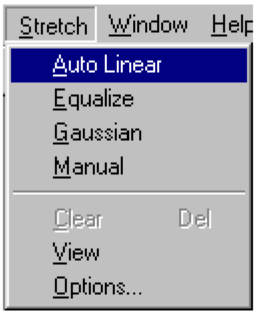
5. USING STRETCHES TO OPTIMISE IMAGE DISPLAY

Aim: To introduce you to using stretches to optimise how images are displayed.

Objectives: By the end of this section you will have explored the *Bilko* **Stretch** menu and learnt how stretches can be used to optimise the display of images on your computer screen and make it easier to see objects or patterns of interest. You will also have learnt how to optimise the display of images with data values greater than 255 (non 8-bit data), using the **Redisplay Image** option.

For this section you will be using ***AVHRR_Mulls#04.bmp***, the same AVHRR image used in the previous two tutorials. This image records emitted thermal infra-red electromagnetic radiation in the wavelengths 10.50–11.50 μm and has been processed and re-scaled to 8-bits. By convention darker areas are warmer on AVHRR thermal images. Colder parts of the image will thus appear brighter and warm parts dark. You should be familiar with **histograms** before attempting this section.

Activity: If the ***AVHRR_Mulls#04.bmp*** image is not already open (from last section), please open it. If a histogram of the unstretched image is not already open (from **previous tutorial**), please open it.



The **Stretch** menu offers seven options:

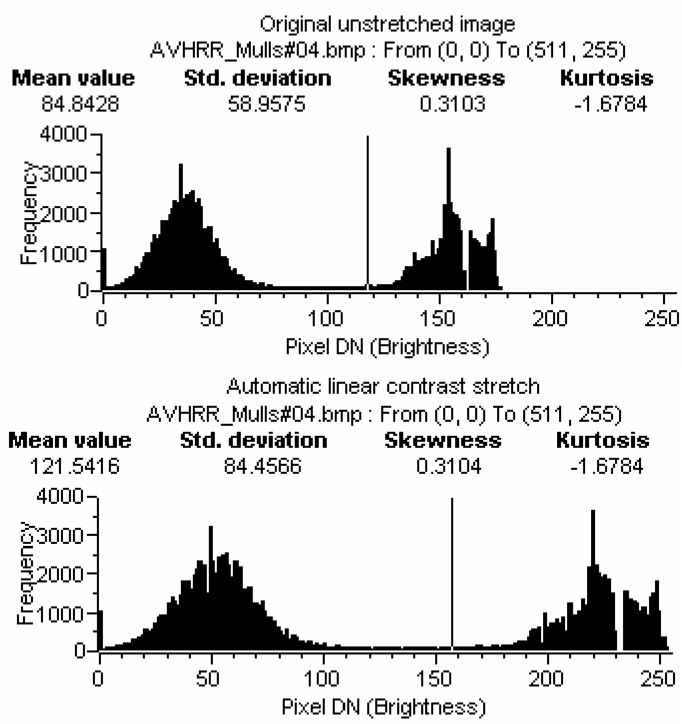
- An Automatic Linear stretch
- A Histogram equalization stretch
- A Gaussian stretch
- A Manual stretch option
- A Clear stretch option (once a stretch has been applied)
- A View option which allows stretches to be viewed graphically
- Options... which control how stretches are applied

For more details of what the different stretches do, see the *Bilko* Help or a remote sensing textbook. In this tutorial, you will look at the results of firstly an **automatic linear stretch** and secondly a **manual stretch** to allow a detailed look at the part of the ***AVHRR_Mulls#04.bmp*** image that is water. Before doing these stretches, note the relatively poor contrast of the sea in the unstretched image.

Activity: If you do not already have a histogram of the unstretched (raw) image open from the previous tutorial, select all of the image file ***AVHRR_Mulls#04.bmp*** by clicking on it and pressing <*Ctrl*>+A, or by selecting **Edit, Select All** from the menu. Then select **File, New** and open a new histogram document for the unstretched image.

Before carrying out a stretch, ensure that the **Stretch, Options...** are set such that **AutoLinear Min%** is **0** and **Max%** is **100**, and that the **Apply stretches to charts, clipboard etc.** checkbox is checked.

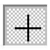
Make sure that you have selected all of the image file ***AVHRR_Mulls#04.bmp*** to stretch (by clicking on it and pressing <*Ctrl*>+A). Now click on **Stretch** and then **Auto Linear**. Note how the image immediately brightens and becomes more contrasty. To see the effect on the histogram, click on **File, New** and open a new histogram document for the stretched image.



The picture to the left compares the histogram of the unstretched image (upper left) where the maximum pixel brightness was 178 with that of the image after an automatic linear stretch where the pixel DNs have been spread out over the full range of display brightness values (lower left). Thus those pixels that had a brightness value of 178 now have a value of 255. In mathematical terms the original pixel values have been multiplied by 255/178, this being the simplest way to make use of the full display scale in the present case.

You can check this by examining the pixel brightness values at which the modes in each peak *now* occur. If you look at the mode in the upper peak (sea pixels) you should find that it now occurs at a pixel brightness value of 219 (= 153 x 255/178). Similarly the lower peak (land pixels) mode has moved from a pixel brightness value of 34 to one of 49 (= 34 x 255/178).

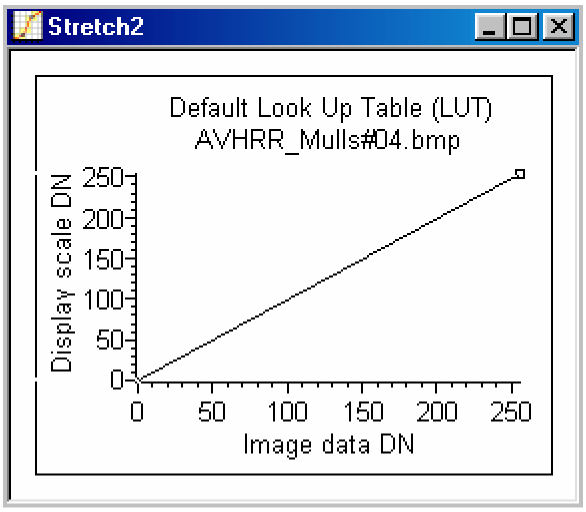
Having stretched the image, you have only changed the display values of the pixels, which will now be different from the underlying data values.

Activity: Click on the  (Point selection) button and select **Edit, Go To** to put the cursor on (*x*, *y*) or (*column*, *row*) coordinates 90, 135. Note that now the last panel on the Status Bar shows that this pixel now has a display value of 249 (= 174 x 255/178). The underlying image data values, however, remain unchanged.

Zoom | column coord | row coord | image value | display value

Close the histogram of the automatic linear stretched image (without saving it). Then select the ***AVHRR_Mulls#04.bmp*** image window and use **Stretch, Clear** (or just press the <*Delete*> key) to remove the stretch before the next exercise.

Often one is interested in just one part of an image, for example, an oceanographer is not interested in the land pixels but only the sea pixels. In such a case the person processing the image may wish to preferentially stretch the pixels of interest and largely ignore those not of interest. This may be achieved using a **manual stretch**.

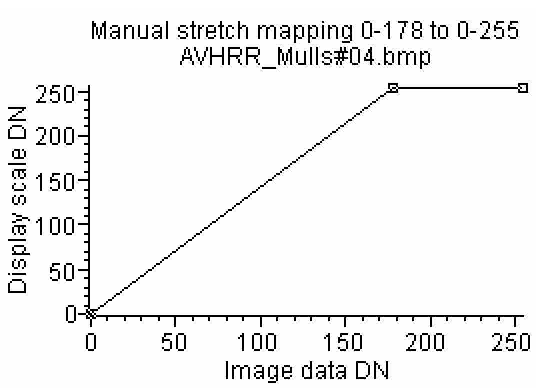


Activity: Make sure the image file ***AVHRR_Mulls#04 .bmp*** is the active window, then from the **Stretch** menu choose **Manual**. The graph that appears (right) is the default Look Up Table (LUT) and shows that the pixel brightness values (grey tones) in the image (*x*-axis) are mapped linearly onto the display scale (*y*-axis) with no change. Thus an image pixel with value 0 is displayed with brightness 0 whilst one with value 178 is displayed with brightness 178.

Stretching involves changing this mapping to take full advantage of the 256 grey levels available on the display.

Activity: Position the mouse pointer on the stretch graph on the $y = x$ line running from (0, 0) to (255, 255) at around coordinates (175, 175) and double-click on the line. A small flashing box should appear on the line. (If it doesn't, try again). This is called a **'knee-point'** and can be used to change how the image data is mapped to the display (computer monitor). As a first try we will mimic the automatic linear stretch you have just performed. This involves increasing the slope of the line so that although pixels with value 0 in the image still map to 0 on the display scale, the maximum image pixel value of 178 maps to 255. To do this the knee-point should be dragged upwards until the Status Bar shows it to be at coordinates (178, 255) and it look like the inset to the right.

Note how the image changes interactively as you move the knee-point. The image immediately brightens and becomes more contrasty as the stretch is applied.

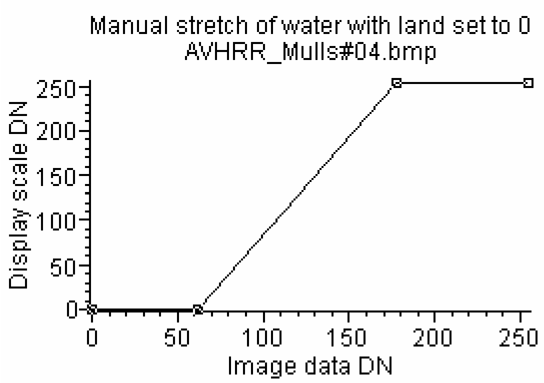


The picture to the left shows how your simple manual stretch should look. It is mapping image pixels with DNs of 0–178 (x-axis) onto a display scale of 0–255 (y-axis). Thus any pixels with DN values of greater than 178 in the image (of which there are none in this case) would map to 255. This is the type of stretch carried out by the automatic linear stretch algorithm. Check this by looking at the histogram of your stretched image.

Once you are satisfied that the stretch has altered the histogram as expected, close the histogram window.

Pixels with brightness values between 0 and about 62 on the ***AVHRR_Mulls#04.bmp*** image are land. If we were not interested in the land, we could map all these pixel values to 0. The remaining pixels in the image with values from 62–178 represent freshwater lakes (loughs in Ireland and lochs in Scotland) and sea. We can stretch these even more if we make a second knee-point.

Activity: Click on your manual stretch document to make it the active window again. When you have done this double-click on line above a value of about 60 on the x-axis to make a second knee-point. Drag this one downwards to the x-axis until the Status Bar shows the mapping (62, 0) (it will read 062 000). The stretch should now look like the one shown to the right.



Note that the land now goes completely black with inland freshwater areas standing out well and the sea showing a lot more detail than the ordinary stretch.

You can further refine this stretch for oceanic water pixels by inserting a third knee-point and reducing the amount of the display scale used by non-oceanic water pixels with DN values between 62 and about 130. This then allows maximal stretching of image pixels in the sea with values from 130–178.

Activity: Experiment with this interactively, seeing at what point the Lough Neagh freshwater pixels become dark on the image as you move the third knee-point on the stretch along the x-axis towards a value of 130. This markedly improves the sea pixel contrast, with sea areas now stretched over the full range of display scale values.

This stretch may be useful and is worth saving.

Activity: Make your manual stretch the active window, if it isn't already. Before you save your stretch you should label it so it is clear what it is, so *either* click on the **Options** menu and select the **Names** option, *or* right-click on the stretch and select the **Names** option. This brings up the **Names** dialog box. This has three boxes to fill in: **Chart Name**, **X Axis Name**, and **Y Axis Name.** You can move between these by clicking in them with the mouse or by using the *<Tab>* key. In the **Chart Name:** box, type [without the quotes] "Stretch of sea with land set to 0", in the **X Axis Name:** box type "Image data DN" as these are the underlying digital numbers in the image, and in the **Y Axis Name:** box type "Display scale DN" as these are the digital numbers which are actually displayed on the screen for pixels with these values in the image. When you have done this click on OK.

Now click on the **File** menu and select **Save**. In the **File, Save As** dialog box type ***AVHRR_Mulls#04.str*** in the **File Name:** box and click 

. Your stretch is now saved for future use. To clear the workspace click on **Window, Close All.**

In Tutorial 2 on **opening, viewing and saving images** you were briefly introduced to the **Redisplay Image** dialog box but asked to "ignore it for now". For images with pixels recorded at more than 8-bits (i.e. those with image data values > 255) this function acts both to map and to stretch the underlying image data to the 8-bit display scale. It offers a basic **Linear** and **Logarithmic** option for how the data are displayed as well as three options, which correspond to the various stretches (Auto linear, Equalize and Gaussian) in the **Stretch** menu. You will now briefly explore how the **Redisplay Image** option works with a 16-bit integer AVHRR image (recorded as 10-bit data (i.e. DNs between 0 and 1024), but stored as 2 bytes = 16-bits per pixel) of West Africa recorded in the thermal infra-red at same wavelengths as the ***AVHRR_Mulls#04.bmp*** image. In this case the actual sea surface temperature (SST) in degrees Kelvin is 273.15 + 0.01 x pixel DN in the image.

Activity: Open the image ***AVHHR_West_Africa#04.dat*** without altering the **Redisplay Image** dialog box. The result is an unrecognisable mess of black (most of the image) and white (actually cloud). Disappointing!

To see why this is, you need to examine a histogram of the image.

Activity: Select the whole of the image (*<Ctrl>+A*), click on **File, New** and select **HISTOGRAM document**. Make sure the **Apply stretches to new documents** checkbox is **not** checked. The histogram shows image data values between 0 and approximately 65550 with frequencies displayed for 50 DN value wide "bins". Inspect the histogram. Then click on the far right of the "Image data DN" axis (*x*-axis). Note that the last four panels in the Status Bar (right) show that 0.08% of the image pixels occur in the last bin, that this bin records the number of pixels with DN values between 65,500 and 65,549 and that there are 372 pixels in the image with these high values. Note that pixels are clustered into two areas of the histogram. Use the histogram to answer the following questions.

Question 1: How many pixels in the image have values between 10,000 and 60,000?

Question 2: What is the highest bin (state lower and upper values) of the lower cluster that contains pixels and how many pixels are in this bin?

The lower cluster (with pixels < a DN value of 5000) represents thermal infra-red emittance from the sea and land; the upper cluster (with pixels > a DN value of 60,000) represents thermal IR emittance from thick clouds. The HUGE difference in brightness between land/sea and cloud pixels means that the former display as black and the latter as white. To see the sea and land properly you need to configure the **Redisplay Image** mapping to the display scale so that the high value cloud pixels are ignored.

Activity: Firstly, ensure that the **Stretch, Options...** are set such that **AutoLinear Min%** is **5** and **Max%** is **95**, and that the **Apply stretches to charts, clipboard etc.** checkbox is checked. Then, right-click on the ***AVHHR_West_Africa#04.dat*** image and select **Redisplay** from the menu. In the **Redisplay Image** dialog box you want to set all pixels >= 4150 (which is the highest value of lower, land/sea cluster) as "null values" so that they are ignored when the image is stretched and redisplayed. Select **>=** from the drop-down list, enter 4150 in the **Null value(s):** box and then check the **Null value(s):** checkbox. In the Stretch Settings' **Use:** box, select **Auto linear stretch**. Once all this is done, click on [Apply] to apply the mapping. Close the **Redisplay Image** dialog box.

You now have a reasonable greyscale image with different SSTs displayed as different shades of grey. If you scroll down the image (use mouse wheel if you have one) you can now see considerable SST structure in the sea south of the Canary Islands (see upper right). Note also that thick cloud is now set to white. To improve the SST discrimination still further you can try a Histogram Equalization stretch.

Activity: Right-click on the ***AVHHR_West_Africa#04.dat*** image again and select **Redisplay** from the menu. This time, in the **Redisplay Image** dialog box you want to set the Stretch Settings' **Use:** box to **Equalize**. Once this is done, click on Apply and then Close. This produces an even better image (see lower right) with sea of different temperatures very clearly delineated. Adjusting the "redisplay" further so that land areas are all mapped to white further improves the contrast in the sea. You can do this by adjusting **Null value(s):** value (try ≥ 2150). [*Note:* You need to uncheck and recheck the **Null value(s):** checkbox to change]. When you have finished close all files.

With images like the 16-bit ***AVHHR_West_Africa#04.dat***, you have seen that optimising display is slightly more complicated than for simple 8-bit images. However, similar results can be achieved using the **Redisplay Image** option and final adjustments can still be made interactively using a manual stretch.

Often you know before opening an image that certain pixel values are Null. For example, land or sea might be "masked" in an image and set to zero. In this case, when the **Redisplay Image** dialog box appears you would set **Null value(s): ==** to **0** and these "background" pixels would be ignored when the image is redisplayed; this would usually improve the display of the image. For some AVHRR images the value -32768 is used as a "fill" value and would upset the display of such images even more. In this case you would want to set **Null value(s): ==** to **–32768** when opening the images.

So far you have displayed the images as a set of grey scales and in this section you have seen how to optimise the display of these to emphasise features of interest. You can also control the display so as to assign colours to pixels with certain brightnesses (display scale values) to create thematic maps. In the next part of the introduction, **using palettes to enhance display and create thematic maps**, you can investigate how to do this.

Answers to Questions

Using Stretches to optimise image display

Question 1

There are zero pixels in the image with values between 10,000 and 60,000.

Question 2

The highest bin of the lower cluster that contains pixels records the frequency of pixels with values from 4,100 to 4,149. There is only one pixel with a value in this range.

6. USING PALETTES TO ENHANCE DISPLAY AND CREATE THEMATIC MAPS

Aim: To introduce you to using and creating palettes to enhance the display of images and make thematic maps.

Objectives: By the end of this tutorial you will have explored how the *Bilko* palette generator works, learnt how palettes can be used to enhance the display of images on your computer screen, and made a thematic map of global sea surface temperature.

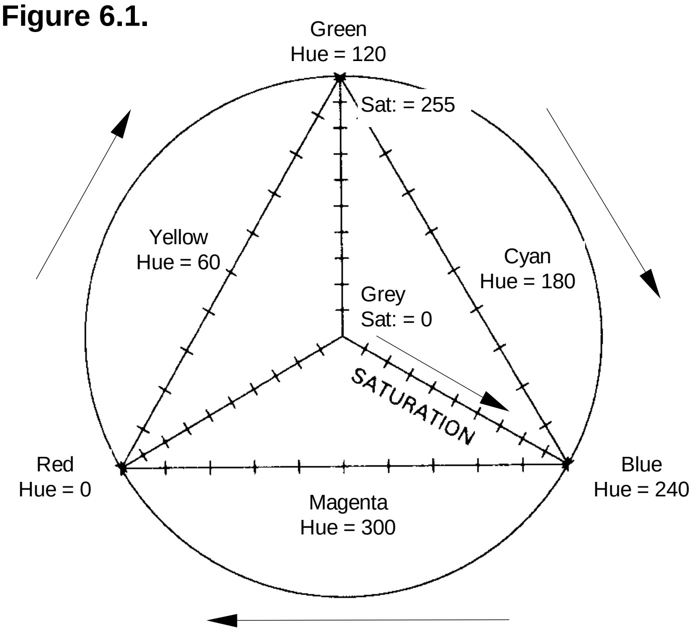
This tutorial investigates the use of colour palettes in image analysis and how they may be used to convey useful information.

About Colour

In order to understand the use of palettes, it may be helpful to give a brief summary of colour and the way in which the human eye discerns colour. Definitions for the terms used in this exercise will also be given. A useful website on colour is: http://www.soc.soton.ac.uk/JRD/SCHOOL/mt/mt001a_2.html

The human eye perceives colour by means of light-sensitive receptors in the retina called cones. There are three types of cones. These contain different photosensitive pigments and thus respond to light of different wavelengths. The three different types of cone are broadly sensitive to wavelengths in the red, green, and blue part of the visible spectrum respectively. This system works because all colours that we can see can be reproduced by adding together red, green and blue (RGB) in different proportions. This is known as Young's tristimulus theory of colour.

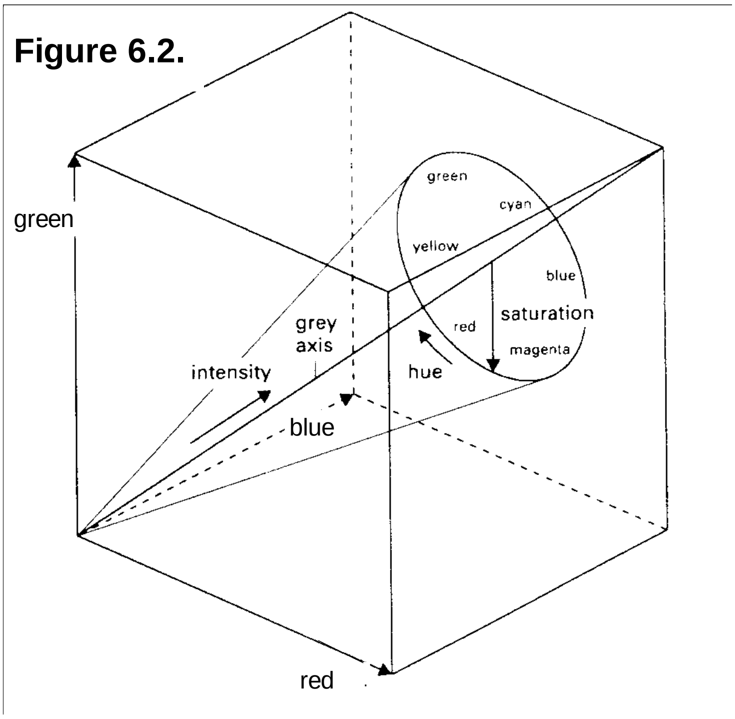
Figure 6.1.



Red, green and blue are known as *primary* colours because none of them can be produced by mixing the other two colours. As well as being used by our eyes, these additive primary colours are used in the screens of colour monitors and televisions, which are coated by regularly spaced dots of red, green and blue phosphors that emit light when bombarded by electrons from the red, green and blue guns respectively.

Figure 6.1 shows the 3 colour theory illustrated diagrammatically as a triangle with the primary colours at each apex. Points along the outlines of the triangle represent mixtures of two primary colours; thus a pure cyan is a 50:50 mixture of blue and green. Points inside the triangle represent mixtures of all three primary colours and include pastel shades such as browns, purples and pinks. Right in the centre of the triangle where you have equal amounts of each primary colour you have the achromatic point where you see a grey. This point is on an axis (the achromatic line) coming out of the page which represents the brightness, or *intensity*, of the colours (and ranges from black to white).

So far when you have been looking at greyscale images you have just been using this achromatic line to display the pixels at 256 different grey levels (i.e. at grey levels ranging in *intensity* from 0 (black) to 255 (white)). The terms *hue* and *saturation* are explained below.



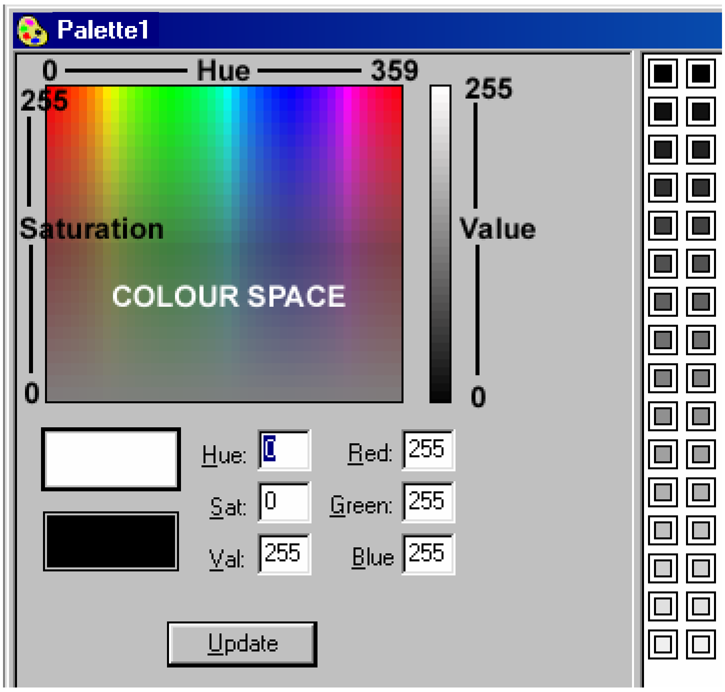
Colours can also be described in terms of three attributes – *intensity, hue* and *saturation* (the IHS system):

Intensity: refers to the brightness of a colour which for 8-bit displays will vary from 0-255.

Hue: refers to the relative amounts of two primary colours making up a colour. In the *Bilko* palette generator hue can take values from 0-359 with primary colours (at full *saturation*) considered to lie along the circumference of a circle (360°). Red, green and blue are thus each 120° (hue units) apart with yellow, cyan and magenta lying half way between them (Figures 6.1 and 6.2).

Saturation: the pureness of a primary colour (expressed as its distance from the central grey point or achromatic line).

Figure 6.2 is a three-dimensional view of the hue-saturation triangle in Figure 6.1 to show the achromatic line (grey axis) and intensity cone. Try to relate the elements of the palette generator box illustrated below to the diagram above and note that colours are expressed both in terms of amounts of red, green and blue (RGB) and in terms of intensity, hue and saturation. You can set up colours using either system. In the palette box below, the colour being set up is white. This is made by mixing red, green and blue in equal amounts at full intensity; thus under the RGB system we see Red: 255, Green: 255 and Blue: 255. Under the IHS system we think of white as a point at full intensity on the achromatic line, that is with a saturation of 0; thus we see Sat: 0 and Val: 255. The hue value does not matter in this case since saturation is 0 and could be any number from 0–359 (in the palette box below it just happens to be 0). If this puzzles you study Figures 6.1 and 6.2 again.



Intensity: In the palette generator intensity is referred to as *Value* (**Val**:).

Hue: Red is arbitrarily assigned a hue of 0; green has a hue of 120, and blue a hue of 240. Moving around the circumference of the hue circle in Figures 6.2 or 6.3 is equivalent to moving along the top of the colour space rectangle in the palette generator box (left).

Saturation: In the palette generator a fully saturated colour has a saturation of 255, whilst greys on the achromatic line have a saturation of 0. Black thus has a saturation of 0 and a value of 0; white has a saturation of 0 and a value of 255; mid-grey has a saturation of 0 and a value of 127.

Table 6.1. For reference, the RGB mixtures required to make the main full intensity (Val:=255), pure (Sat:=255) colours are shown below along with the attendant Hue values obtained. To obtain dark versions of the same colours (Val:=127), you would replace the 255 values in the Red, Green and Blue boxes by 127.

Colour	Hue	Red	Green	Blue
Red	0	255	0	0
Yellow	60	255	255	0
Green	120	0	255	0
Cyan	180	0	255	255
Blue	240	0	0	255
Magenta	300	255	0	255

The file you will be using in this section is a processed National Oceanic and Atmospheric Administration (NOAA) AVHRR Oceans Pathfinder sea surface temperature (SST) image of the whole world, built up from many images collected during December 2000. To save space the image has been cut down from its original size of 4096 x 2048 pixels to a size of 2048 x 950 pixels. SST in degrees Celsius is equal to 0.15 x (pixel DN – 3.0). Thus a pixel value of 188 means a sea surface temperature of 27.75°C.

Activity: Open the image file ***Global_SST_Dec2000.gif*** (using **File, Open**). Use **View, Zoom** (*or* right-click on the image and select **Zoom**) to set the zoom to 45% of full size so that you can see the whole image at once. Study the image, noting that all land is set to black (0) and the sea to varying shades of grey.

Before assigning colours to various pixel brightness values in the image it is useful to view a histogram of the image to see whether some SST values dominate or whether they are fairly evenly distributed throughout the range of pixel values.

Activity: To view a histogram of the ***Global_SST_Dec2000.gif*** image, click on the image window to make it active and use *<Ctrl>+A* to select the whole image. Now click on **File, New** and select **HISTOGRAM Document** in the **New** dialog box. Since all land is displayed with a DN of 0 there are over 830,000 pixels with value 0 in image so the histogram is not very well displayed. To adjust the scales so that you can see the distribution of the water pixels, click on **Options, Scale** (*or* right-click on the histogram and select the **Scale** option). In the **Scale** dialog box you can either set **Maximum:** to 16000, **Major Unit:** to 2000 and **Minor Unit:** to 1000, or just click on the **Ignore zero** box, and click on OK to show the improved display. Size or move the histogram window so that you can see both it and most of the image clearly at the same time.

In the histogram you can clearly see the distribution of the brightness values of water pixels. The pixels are reasonably evenly distributed between pixel values of 1 and about 230, with a bulge of pixels around a value of 200 due the large areas of warm water in the tropics. This suggests that you can assign different colours to a series of equal brightness bands and get a reasonable result. Before continuing, minimise the histogram window.

Activity: Click on the ***Global_SST_Dec2000.gif*** image to make it active and then click on **File, New** and select **PALETTE Document** in the **New** dialog box. A palette generator box like that discussed earlier appears. The grid of 256 cells range from 0 = black to 255 = white with 254 intermediate shades of grey. Click on the cells and note that **Red:**, **Green:** and **Blue:** values are identical and always equal to **Value:** and that saturation (**Sat:**) remains zero since only greys are displayed. The cells can be considered as lying along the central intensity grey axis in Figure 6.2.

Activity: With the last cell (bottom right) selected, position the mouse pointer in the Colour Space area and click. Depending where you have pointed the colour of the upper rectangle beneath the left hand side of the Colour Space area will change to the colour to which you have pointed. At the same time the hue, saturation, and red, green and blue boxes will change their values. However, the **Value:** box will remain set at 255. Explore the Colour Space briefly by clicking in different parts of it and noting how the hue, saturation and RGB mix change.

It is particularly instructive:

i) to click at the top left of Colour Space and holding down the left mouse button to slide the pointer along the top of Colour Space (**Sat:**=255) and see how both the Hue value and colour in the upper rectangle changes; and

ii) to click at the bottom left of Colour Space and holding down the left mouse button to slide the pointer up an down the left hand boundary of Colour Space (**Hue:**=0) and see how Saturation changes.

When you have seen how Colour Space is structured in terms of Hue and Saturation, click on cell 255 again. Now position the mouse pointer over the intensity or value bar to the right of the Colour Space area and click. Note that the numbers displayed in the **Value:**, **Red:**, **Green**:, and **Blue:** boxes change in unison. Holding the left mouse-button depressed, slide the mouse-pointer up and down the intensity bar. This is equivalent to moving up and down the achromatic line or grey axis of Figure 6.2 and the values change from 0 to 255 as the colour in the upper rectangle beneath the Colour Space changes from black to white.

The brief exploration of the palette generator above should give you a reasonable grasp of the concepts behind the palette generator. You will now apply this knowledge to colour the land in ***Global_SST_Dec2000.gif*** green. At present all the land is black with a DN value of 0. Thus all we have to do is make the first cell of the palette dark green.

Activity: Click on the first cell (cell 0) in the top left hand corner. All values (except **Hue:**) should be zero. We want a dark green so click on the Green: box and type in 127 to indicate a half-intensity pure green. Note that as you type in, the other boxes change so that Hue:=120, Sat:=255 and Val:=127. This makes sense because under the HSI system, dark green is a fully saturated colour with a hue of 120 and intensity of 127. Click on 

to effect the colour change and note that cell 0 now shows as dark green.

Congratulations! You have now succeeded in making your first change to the palette. To apply this change to the image you need to copy the changed palette to the image.

Activity: To apply the altered palette to the image, click on the Copy toolbar button , then click on the ***Global_SST_Dec2000.gif*** image and click on the Paste toolbar button . Note that all the land (and some areas which were cloud covered throughout December 2000) is dark green. You can now close the greyscale palette without saving it as you will not need it further.

Now you are ready to do the main exercise. In this you will be assigning a different colour to every 16 cells according to the scheme in Table 6.2. This will create 16 different coloured temperature bands. To save you time a half-finished palette has been created with only six rows of 16 cells still left as grey.

Activity: Open the palette ***SST_Exercise.pal*** after making sure that the **Apply** checkbox in the **Open** dialog box is NOT checked. Note that the palette has two series of grey cells interspersed by coloured cells. If the 256 cells are not arranged as a grid of 16 x 16 cells adjust the size of the palette generator window until they are. This makes it easier to work with them. **The instructions below assume this layout.**

Question 1: What are the Saturation, Value, Red, Green, and Blue values displayed for cell 64 at the beginning of row 5 in the palette?

Each row (except first and last rows which begin with a white cell and end with a black cell respectively) should now be either a single colour or in the case of 6 rows a series of grey shades. You will firstly see the effect of applying the palette and then fill in the missing rows of colour. To apply the half finished palette to the ***Global_SST_Dec2000.gif*** image you need to copy it and paste it to the image.

Activity: Copy the palette and paste it to the image.

Polar and warm temperate seas are now coloured. Cold temperate and tropical oceans remain to be coloured. Note that the land and cloudy areas are now white.

Table 6.2. Scheme for colour palette for SST image. The cells in rows 5-7 and 12-14 need to have their colours assigned. Row numbers assume that cells are arranged in a 16 x 16 matrix.

Cell # = greyscale	Row	Red	Green	Blue	Colour
0	1	255	255	255	White
1-15	1	63	0	63	Very dark purple
16-31	2	127	0	127	Dark magenta
32-47	3	255	0	255	Magenta
48-63	4	175	0	255	Violet
64-79	5	0	0	255	Blue
80-95	6	0	140	255	Blue-cyan
96-111	7	0	255	255	Cyan
112-127	8	0	255	160	Green-cyan
128-143	9	0	255	75	Bluish green
144-159	10	75	255	0	Yellowish green
160-175	11	175	255	0	Lime green
176-191	12	255	255	0	Yellow
192-207	13	255	140	0	Orange
208-223	14	255	0	0	Red
224-239	15	175	0	0	Dark red
240-254	16	120	32	16	Red brown
255	16	0	0	0	Black

Activity: Click on the palette generator. Then click on the cell 64 at the start of row 5 and holding the left mouse-button down drag the mouse across to cell 79 on the right had end of the row, then release the mouse-button. [Note that the Status Bar shows the start and finish cell numbers]. The upper rectangle under the Colour Space will be dark grey and the bottom rectangle mid-grey. Click on the upper large rectangle under the left side of the Colour Space and then type the value 0 in the **Red:** box, 0 in the **Green:** box and 255 in the **Blue:** box (row 5 values from Table 6.2). The upper rectangle turns blue. Now click on the bottom rectangle and do the same. It too turns blue. Click on the 

button and all the highlighted cells turn blue.

Using the same technique, methodically set up the colours for the five remaining rows of cells. Refer to Table 6.2 for the RGB values for the colours and remember that BOTH the upper and lower rectangles have to be set to the colour before the palette is "updated".

When all colours have been updated on the palette, copy the palette and paste it to the image. Note the colour bar beneath the image, which shows how the colours are assigned as a series of bands. When you have done this successfully, save the palette as ***SST.pal***.

Congratulations, you have created a palette similar to the standard temperature palette used by NOAA for AVHRR Oceans Pathfinder SST images! The image is now **thematically** coloured with land white, and water ranging from very dark purple where coldest to red, where warmest. To see what the actual NOAA palette looks like you can apply this.

Activity: Make sure that ***Global_SST_Dec2000.gif*** is the active document by clicking on it. Select **File, Open** and then, after having checked the **Apply** checkbox of the **Open** dialog box, open the palette ***SST_Pathfinder.pal***. This opens and immediately applies the stretch to the image.

To view the palette itself, uncheck the **Apply** checkbox in the **Open** dialog box and re-open it. Click on the cells of the palette to see what their values are.

You will see that the NOAA palette is very similar to the palette you created but that each cell is slightly different in colour to its neighbours (check RGB values to see this). If you look at the colour bar beneath the image you will see that the colours now blend rather than forming distinct bands. Remember that the palette just alters how the image is displayed on the screen but does not alter the image itself. However, if you wanted to save a picture of the coloured image you could save it as a coloured CompuServe gif file.

Activity: Select all (*<Ctrl>+A*) of the ***Global_SST_Dec2000.gif*** image and then select **File, New** and IMAGE Document in the **New** dialog box. This creates a copy of the image, which contains the colour information. You can save this new image and when you re-open it, the image will be coloured. However, if you close and re-open the ***Global_SST_Dec2000.gif*** image it will still be a greyscale image. You may wish to satisfy yourself of this. When finished close all the images.

Many images are not georeferenced when received, that is, they are not linked into any geographical coordinate system such as latitude and longitude or the Universal Transverse Mercator (UTM) grid system. To properly orientate such images and link pixels to geographical coordinates requires that the image be **rectified and resampled.**

Answers to Questions

Using Palettes to enhance display and create thematic maps

Question 1

The Saturation = 0, Value = 64, Red = 64, Green = 64, and Blue = 64 for the 64th cell as it is currently set to a grey value (no colour saturation) equivalent to its position (as in a normal 256 value grey palette).

7. RECTIFICATION (GEOMETRIC CORRECTION) OF IMAGES AND RESAMPLING

Aim: To introduce you to methods of rectifying images and linking them to geographical coordinate systems by resampling.

Objectives: By the end of this tutorial you will have learnt how to use a series of ground control points (GCPs) of known longitude and latitude to rectify an AVHRR image and generate a resampled image with each pixel having latitude and longitude coordinates like a map.

This tutorial investigates the **Image, Rectify** and **Image, Resample** options of the *Bilko* menu using an AVHRR band #2 image of Northern Ireland and SW Scotland (***AVHRR_Mulls#02.bmp***), recorded in the near infra-red (wavelengths 0.72–1.10 µm).

So that you can judge how well the rectification has worked we have downloaded a geometrically corrected United States Geological Survey (USGS) MapGen 1: 250,000 image that shows the coastlines of the area from http://rimmer.ngdc.noaa.gov/coast. This file has been saved as ***Mulls_coastline.gif***. To save you time we have also set up a Table document (***Mulls_coastline.tbl***), which links a series of ground control points (GCPs) in the geometrically corrected coastline image (with known longitude and latitude) with a corresponding series of points in the AVHRR image for which we only know the column and row coordinates. You will need to add five new GCPs to properly rectify the AVHRR image and will learn two different ways of doing this.

Activity: If you have any images open, please close them. Open the image file ***AVHRR_Mulls#02.bmp*** and ***Mulls_coastline.gif.*** Examine the two images. Note that Longitude and Latitude coordinates are displayed in the Status Bar for any point that you click on in the ***Mulls_coastline.gif*** image and that **View, Coords** is checked. By contrast, note that you cannot set **View, Coords** in the ***AVHRR_Mulls#02.bmp*** image.

Note also that because the AVHRR band#2 sensor is recording reflected near infra-red radiation that the land is bright because vegetation reflects near-IR radiation strongly. By contrast, the sea is very dark because water absorbs near-IR radiation. Note that the more richly vegetated lowland areas are noticeably brighter than the sparsely vegetated higher ground.

Note that the ***Mulls_coastline.gif*** image consists of only two values. The coastline is black with pixel values set to 0, the remainder of the image is white with pixel values set to 255.

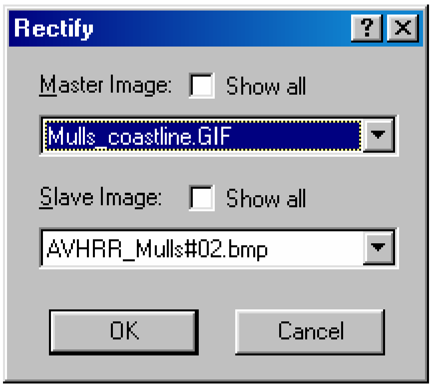
Question 1: How many columns and rows does the ***AVHRR_Mulls#02.bmp*** image have?

Question 2: How many columns and rows does the ***Mulls_coastline.gif*** image have?

Question 3: What is the longitude and latitude of the top left corner of the ***Mulls_coastline.gif*** image?

Question 4: Across how many degrees of longitude (W–E) and latitude (N–S) does the ***Mulls_coastline.gif*** image extend?

Using the ***Mulls_coastline.gif*** as a "master" image we have matched a series of pairs of GCPs of known longitude and latitude on this image to a series of points of known column and row coordinates on ***AVHRR_Mulls#02.bmp*** "slave" image. These GCP pairs are stored in a Table document ***Mulls_coastline.tbl***. However, before you use this we will take you through what you would normally do if starting out to rectify an image.



Activity: With the ***AVHRR_Mulls#02.bmp*** image selected as the active window, select **Image, Rectify** from the menu. This opens the **Rectify** dialog box (see right). Inspect this and note that because you have only one image with and one without geographical coordinates open, the **Master Image:** is already set to ***Mulls_coastline.gif*** and the **Slave Image:** to ***AVHRR_Mulls#02.bmp***. This is what you want, so don't change anything but just click on 

.

Examine the blank table which appears and note that it has four columns: **Description** (this will usually contain place names corresponding to each GCP); **Master:** which is set to ***Mulls_coastline.gif***; **Slave:** which is set to ***AVHRR_Mulls#02.bmp***; and **RMS:** which stands for Root Mean Square error.

At this point you would normally start entering 20–30 GCP pairs from points fairly evenly distributed across the master and slave images. To save you time, you will only enter one (for Malin Head, see Figure 7.1 below) in the blank table and then open the previously prepared table and enter a few more GCPs there.

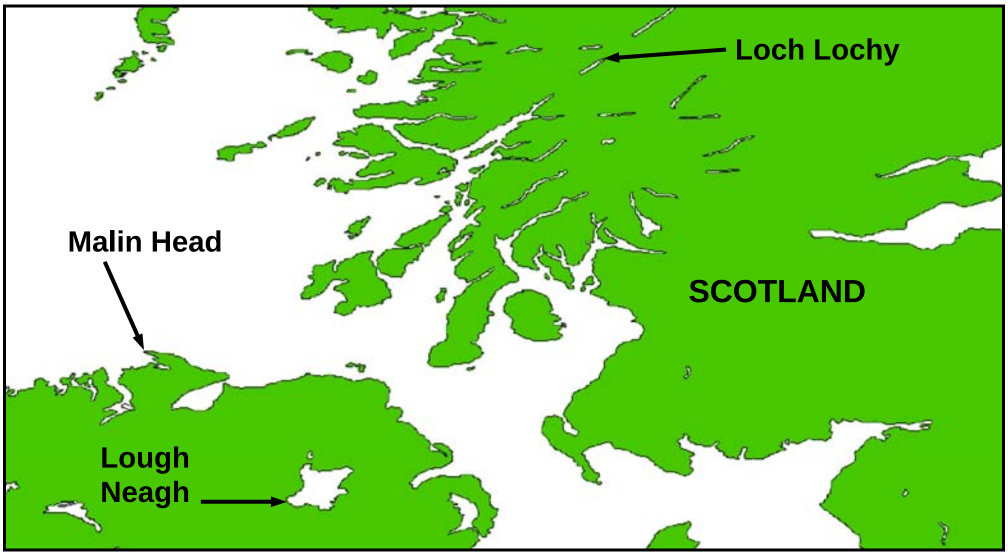


Figure 7.1. Map showing positions of three of the GCPs to be entered.

Activity: Position the mouse pointer over GCP #000: and click on it. It should become a blank box. Type in *Malin Head* as the description for the GCP and press the *<Tab>* key to move to the second column. Now click on the ***AVHRR_Mulls#02.bmp*** image and try to position the image cursor on the NW tip of Malin Head using the Status Bar to guide you as to where the land (bright) : sea (dark) boundary is. When you are satisfied that you've got the image cursor in position, click on the ***Mulls_coastline.gif*** image and position the image cursor on the corresponding point on this image. When you are satisfied that you've got the cursor correctly positioned, press the *<Insert>* key.

A yellow cross with 000 beneath it will appear on both images. The longitude and latitude coordinates of the GCP will appear in the **Master** column of the table. The column and row coordinates of the GCP will appear in the **Slave** column of the table. Congratulations! You've successfully set up your first GCP. The first line of the table should now look something like this:

GCP #000: Malin Head	(007°24'20.32"W, 55°22'24.72"N)	(0008, 0145)

Activity: Before proceeding, note that unchecking the GCP checkbox changes the colour of the GCP to cyan on the two images. Only checked GCPs are included in the rectification process. Also note that if you hover the mouse pointer over the centre of the GCP cross on the images then an information box appears with the Description information for the point.

Close the Table without saving it. Note that the GCPs disappear. Now open the table ***Mulls_coastline.tbl***. Note that many GCPs appear on both images. Inspect the table document and the distribution of GCPs on the images.

20 GCPs are filled in for you (GCP #000 to #019). There is a lack of GCPs in the north-east and south-west of the images and if you are to achieve good rectification you need to enter some here. You will enter three of these from Table 7.1 which is set up as if someone had used a map to find out longitude and latitude of three points on the ***AVHRR_Mulls#02.bmp*** image for which column and row coordinates are known. You will later enter a further two GCPs using the same method that you used for the Malin Head GCP.

Table 7.1. Three GCP pairs showing longitude and latitude of three points on the ***AVHRR_Mulls#02.bmp*** image.

Description	Master	Slave
GCP #020:	3°41'05.00"W, 56°01'34.85"N	452, 123
GCP #021:	3°10'59.51"W, 55°59'20.40"N	499, 132
GCP #022:	6°16'20.32"W, 54°34'54.72"N	100, 237

Activity: Click directly on the master image column for GCP #020. You can enter the first coordinates as: 3 41 5W 56 1 34.85 *or* 3o41’5”W 56o1’34.85”N *or* 3 41 5W, 56 1 34.85N. All will work. Pick a format that suits you. [*Note:* you must specify if coordinates are W or S but do not have to specify if N or E]. When done press the *<Tab>* key to move to the slave image column. The column and row coordinate 466, 125 (or similar) should appear, which is where the program predicts the point will be on the ***AVHRR_Mulls#02.bmp*** image based on other GCP pairs and the current transform. You should enter the correct coordinate (452, 123) and press the *<Tab>* key. The RMS errors for each point and the overall average RMS are recalculated as the new GCP pair is entered.

Repeat the process for GCPs #021 and #022 and check that values are all correct. To see where the new points are, uncheck the three GCPs’ checkboxes so that they appear in cyan on the images. Having seen where they are, recheck them so that all checkboxes are ticked.

To complete the table, two more GCPs – one at the NE end of Loch Lochy and one at the SW end of Lough Neagh (see Figure 7.1) – need to be added. You will use the same method as you used for Malin Head.

Activity: Position the mouse pointer over GCP #023: and click on it. It should become a blank box. Type in *NE end of Loch Lochy* as the description for the GCP and press the *<Tab>* key to move to the second column. Now click on the ***AVHRR_Mulls#02.bmp*** image and try to position the image cursor on the NE end of Loch Lochy (Figure 7.1) using the Status Bar to guide you as to where the land (bright) : water (dark) boundary is. When you are satisfied that you’ve got the image cursor in position, click on the ***Mulls_coastline.gif*** image and position the image cursor on the corresponding point on this image. When you are satisfied that you’ve got the cursor correctly positioned, press the *<Insert>* key. Repeat the process for GCP #024 at the SW end of Lough Neagh (Figure 7.1). Check their positions on the images.

The two new GCPs should look something like this in the rectification table:

GCP #023: NE end of Loch Lochy	(004°50'20.32"W, 57°00'54.72"N)	(0377, 0012)
GCP #024: SW end of Lough Neagh	(006°36'20.32"W, 54°31'24.72"N)	(0057, 0240)

Congratulations, that's enough GCPs to rectify the image. You will now carry out rectification of the ***AVHRR_Mulls#02.bmp*** image using two different transforms so that you can compare their effectiveness.

Activity: Make sure all GCPs are checked. To find out what transform is being used, right-click on the rectification table document and select the **Transform** option. This should be set to **Linear**. [Note that the other two options are Quadratic and Cubic]. Now that all GCPs are entered and the transform is set, click on the Copy button on the toolbar, select the ***AVHRR_Mulls#02.bmp*** image and then click on the Paste button to fix the GCP pairs.

You are now ready to resample the image and map it onto the master image's coordinate system.

Activity: Select **Image, Resample** and a **Resample** dialog box appears with four tabs (Window, Pixel, Image, Interpolation). Inspect this and answer the questions below.

Question 5: What are the three methods of interpolation which are supported?

Question 6: What is the width and height of the pixels in the rectified output image set to?

Activity: Select **Cubic convolution** as the method of interpolation and click on the **Apply** button to make this take effect. Leave all the other settings alone for now and select OK to carry out the resampling. Inspect the output image that has been rectified using a linear transform and note how the geometry has been significantly altered. In particular it is now clear that the image "north" is several degrees different to true north.

You will now compare the rectified image to the master image coastline map to see how good the rectification has been. To do this you will connect the new image and the master image and then use a formula document to draw the coastline as a white line on the new image.

Activity: Use the **Image, Connect** function to connect the rectified (resampled) output image to the ***Mulls_coastline.gif*** image and use the **Selector** toolbar to designate the rectified image as image 1 (@1 in formulas) and designate the ***Mulls_coastline.gif*** image as image 2 (@2 in formulas). Now open the formula document ***Draw_Mulls_coastline.frm***. Copy the formula and Paste it on the connected images window. Inspect the resultant image.

Question 7: How well does the resampled image fit the original master image coastline?

You will see that a linear transform is too simple to give the required result. The curvature of the Earth means that at least a quadratic tranform is needed to warp the AVHRR image and fit it to the master image coastline map.

Activity: Close the connected images window and the resampled image without the coastline added. Click on the rectification table and make a note of the average RMS value (in column header). Change the transform setting to **Quadratic** and note how the value improves dramatically from around 5 pixels to less than 1.5 pixels. Now that the new transform is set, click on the Copy button on the toolbar, select the ***AVHRR_Mulls#02.bmp*** image and then click on the Paste button to fix the transform.

Select **Image, Resample** and in the **Resample** dialog box select **Cubic convolution** as the method of interpolation again (don't forget to click the Apply button!). Carry out the resampling and connect (**Image, Connect**) the rectified (resampled) output image to the ***Mulls_coastline.gif*** image as before. Finally, copy the formula (***Draw_Mulls_coastline.frm***) and paste it on the connected images window. Inspect the resultant image. Compare to the linearly transformed image with the coastline added.

You will see that you now have an almost perfect fit between the two images. Congratulations, you've mastered the basics of rectification and resampling!

To finish this tutorial you will now apply your rectification table to band #4 of the AVHRR image (***AVHRR_Mulls#04.bmp***).

Activity: Firstly save the ***Mulls_coastline.tbl*** with your new GCPs in it. Then close all files EXCEPT ***Mulls_coastline.gif*** and ***Mulls_coastline.tbl*** which are still needed.

Now open ***AVHRR_Mulls#04.bmp*** and right-click on the ***Mulls_coastline.tbl*** table and select the **Change View** option. Click on the **Slave Image:** drop-down list and select ***AVHRR_Mulls#04.bmp*** as the new slave image. Click on OK and the GCPs are transferred to the new image. Using a quadratic transform (and not forgetting to copy and paste the rectification table to the new image), resample ***AVHRR_Mulls#04.bmp*** to the master coastline image. When you have finished close all images.

For further practice at geometric correction using a false colour composite of a large AVHRR image of the Mediterranean, there is a **mini-lesson** available (***Mini-lesson01_Geometric_correction.pdf***).

Quite often you need to exchange rectified images between different software packages or you may be sent binary "flat file" images without any coordinates attached, but which have already been geometrically corrected to a geographical coordinate system such as Universal Transverse Mercator (UTM) or latitude and longitude. In such cases, at least the coordinates of the top left of the image (the image "origin") and pixel dimensions will normally be known. Armed with this information you can apply coordinates to the image. The first part of the next section describes **how to "edit" the coordinates** to do this.

Answers to Questions

Rectification (geometric correction) of images and resampling

Question 1

The ***AVHRR_Mulls#02.bmp*** image has 512 columns (pixels per row or DX:) and has 256 rows (DY:).

Question 2

The ***Mulls_coastline.gif*** image has 670 columns (pixels per row or DX:) and has 365 rows (DY:).

Question 3

The longitude and latitude of the top left corner of the ***Mulls_coastline.gif*** image is 8°10′50.32″W and 57°17′54.72″N.

Question 4

The ***Mulls_coastline.gif*** image extends over 5°35′00.00″ of longitude and 3°02′29.99″ of latitude.

Question 5

The three methods of interpolation which are supported are i) Nearest neighbour, ii) Bilinear interpolation and iii) Cubic convolution. (Look these up if you do not know what they are).

Question 6

The width and height of the pixels in the rectified output image is set to 30″ (30 seconds of longitude and latitude) = 0.5′ (0.5 minutes of longitude and latitude) which is the pixel size in the ***Mulls_coastline.gif*** image.

Question 7

The resampled image generated using a linear transform does not fit the original master image coastline very well although its geometry has been radically altered. Essentially, a linear transform is not adequate due to the curvature of the Earth’s surface.

8. EDITING AND VIEWING COORDINATES, CREATING SCATTERGRAMS AND PRINCIPAL COMPONENTS ANALYSIS

Aim: To introduce you to (i) how you can apply a geographical coordinate system to a rectified image of known geographical origin and pixel size (but stored as rows and columns only), (ii) how to plot pixel values in one band against those in another band to visualise how features separate spectrally, and (iii) how principal components analysis (PCA) can aid image analysis.

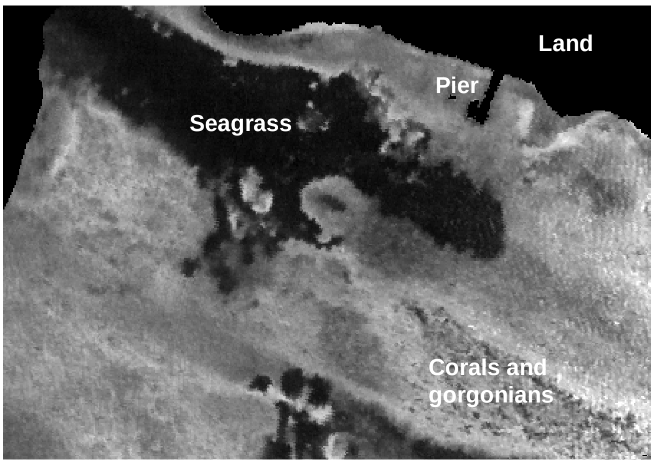
Objectives: By the end of this tutorial you will have learnt how to apply geographical coordinates to a (previously rectified) image imported without coordinates from another software package. You will also have explored the scattergram option, which allows pixel values in two bands to be displayed as a chart, and carried out PCA to enhance separation of different land cover types.

In the previous section on **geometric correction**, methods for rectifying and resampling raw images were studied. Quite often you need to exchange images between different software packages or you may be sent binary "flat file" images without any coordinates attached, but which have already been geometrically corrected to a geographical coordinate system such as Universal Transverse Mercator (UTM) or latitude and longitude. In such cases, at least the coordinates of the top left of the image (the image "origin") and pixel dimensions will normally be known. Armed with this information you can apply coordinates to the image and then save it as a CompuServe .gif or *Bilko* .dat file which will store the coordinate information. You will practice this using one band of a CASI (Compact Airborne Spectrographic Imager) digital image, which has been previously georeferenced to the local UTM grid system.

The single band image has been exported from ERDAS Imagine (a commercial remote sensing package) as a 16-bit unsigned integer binary flat file (.bin) extension (***Casi_16-bit_unsigned#2.bin***). Each pixel in this image is 1 × 1.1 m in size (so the spatial resolution is 1000× better than the AVHRR images you've been studying). The image is 452 pixels wide and made up of 317 scan lines.

Activity: Use **File, Open** to start the process of opening ***Casi_16-bit_unsigned#2.bin***. *Bilko* needs more information from you to open this file and so an **Open As flat file** dialog box appears. There is no header, so leave the **Header length (in bytes):** entry as **0**. Put the correct values (see above) in the **Pixels per Line:** and **Number of Lines:** boxes. Now move to the **Pixel Format** drop-down menu box and select the correct pixel format. Since there is only one band the **Interleave Format** has to be Band Sequential (BSQ), which is the default. The program now has enough information to open the file, so click on [OK].

If the **Extract** dialog box appears, click on [OK]. In the **Redisplay Image** dialog box, check the **Null Values(s):** checkbox so that 0, which is used to denote background areas outside the scanned image and masked land, is set as a null value. Note that the image data values range from a minimum pixel value of 626 to a maximum of 3988. Click on [OK] to display the image with the default Linear stretch. You will now see the image which shows a seagrass bed off South Caicos Island in



the West Indies. See above for a labelled picture to help you orientate yourself.

Activity: Click on dark and bright parts of the image such as the large seagrass bed and the sandy area around the coral and gorgonian (sea-fan) dominated seabed. Note the underlying pixel values displayed in the second to last panel of the Status Bar and the display values in the last panel. The underlying values were recorded on a scale of 0–4095. Click on the **View** menu and note that the **Coords** option is unavailable.

The image just has row and column coordinates at present but you are provided with the information that a GPS (global positioning system) position fix for the top left hand corner of the image gave the Easting 237430 and Northing 2378282 for UTM grid zone 19. You have also been told the pixel size after resampling (1.0 × 1.1 m).

Activity: Whilst the ***Casi_16-bit_unsigned#2.bin*** image is the current window, select **Edit, Coords** to enter the UTM coordinates. This will bring up the **Set Coordinates** dialog box. Enter the appropriate values (see above) in the **Easting (X):** and **Northing (Y):** boxes. The pixel size is 1.0 m wide by 1.1 m along-track. Enter these values in the **Pixel Size (metres)** boxes for **Width (DX):** and **Length (DY):** respectively and then click on OK.

Now that you have entered the UTM coordinates of the top left of the image (which has been previously geometrically corrected) the *Bilko* program can calculate the UTM coordinates of any pixel. If you look at the Status Bar you will now find that rather than columns and rows, UTM eastings and northings are now displayed. If you click on **View, Coords** you can switch back to row and column coordinates. With **View, Coords** checked use **Edit, Go To...** function to put the cursor at UTM position 237760, 2378193.

Question 1: Where on the image is the UTM coordinate 237760, 2378193?

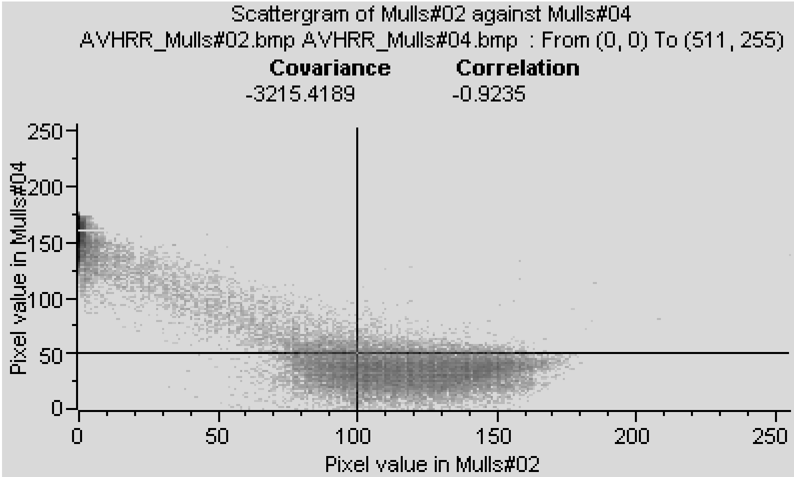
Activity: To save the image with its coordinate information, you can save it in *Bilko* ***.dat*** format. Select **File, Save As** and in the **Save As** dialog box, select the file type as Bilko .dat (if not already automatically selected) and click on Save. Close the file and then re-open it. Note that now *Bilko* knows the file size and type and automatically displays the UTM coordinates. Close the file, which will not be needed again.

Note: All types of file can be stored in *Bilko* .dat format but standard CompuServe .gif format is recommended for 8-bit files. For export to other applications, .bmp (Windows bitmap) or .bin (flat binary) file formats are most likely to be useful.

Scattergram option

When you have two connected images, such as images of the same scene recorded in two different wavebands, it is often useful to be able to view how reflectance or DN values of pixels in one band relate to those of the same pixels in the other band. **SCATTER documents** allow you to do this. You will connect a band#2 and band #4 AVHRR image and see how pixel DNs are correlated between these two bands. Details of these two images are provided in earlier tutorials.

Activity: Open the two AVHRR images ***AVHRR_Mulls#02.bmp*** and ***AVHRR_Mulls#04.bmp***. Use **Image, Connect** to connect the two images and use the **Selector** toolbar to make sure that ***AVHRR_Mulls#02.bmp*** is designated image 1 (which will plotted on *x*-axis) and ***AVHRR_Mulls#04.bmp*** is designated image 2 (which will be plotted on *y*-axis). With the connected tiled images as the active window, click on **Edit, Select All** to select all of the two images. Then select **File, New** from the menu and SCATTER Document and click on OK to display a scatter-gram. This is a plot of the DN values of each pixel in



AVHRR_Mulls#02 (image 1, *x*-axis) against its DN value in ***AVHRR_Mulls#04*** (image 2, *y*-axis). Note that there is an inverse relationship between pixel DN values in the two images. Thus pixels with a high DN in ***AVHRR_Mulls#04*** have a low DN in ***AVHRR_Mulls#02***, whereas those with a low DN in ***AVHRR_Mulls#04*** tend to have a high DN in ***AVHRR_Mulls#02***. Note the cross-hair on the graph (positioned at a pixel value of 100 in Mulls#02 and 50 in Mulls#04 in the example above). The number of pixels with the combination of band #2 and band #4 values indicated by the cross-hair is shown in the third panel from the left of the Status Bar. [The stretched "display" value of this number is also shown in the fourth panel and can be useful when interpreting pixel densities]. Use the mouse to drag the cross-hair to coordinate 100, 50 on the scattergram.

Question 2: How many pixels have value of 100 in band #2 and 50 in band #4 of the ***AVHRR_Mulls*** image?

Question 3: What feature on the image has pixels with a high DN in ***AVHRR_Mulls#04*** but low DN in ***AVHRR_Mulls#02***? What feature on the image has pixels with a low DN in ***AVHRR_Mulls#04*** but high DN in ***AVHRR_Mulls#02***? Why is there this inverse relationship?

Activity: Note that if you right-click on the scattergram, you have the option to **Redisplay** it with different stretches (just as for an image). You can also copy and paste palettes to it so that the density of pixels with different pairs of values is clearer. Open the palette ***SST_Pathfinder.pal*** and copy and paste it to the scattergram. Note that with the default logarithmic stretch, pixel densities around 90–120 on the display scale are light-blue to cyan and those around 25–50 on the display scale are shades of mauve (assuming you have not changed the default logarithmic stretch). Close the scattergram, the connected tiled images, the palette and the ***AVHRR_Mulls#02.bmp*** and ***AVHRR_Mulls#04.bmp*** images.

Principal Components Analysis

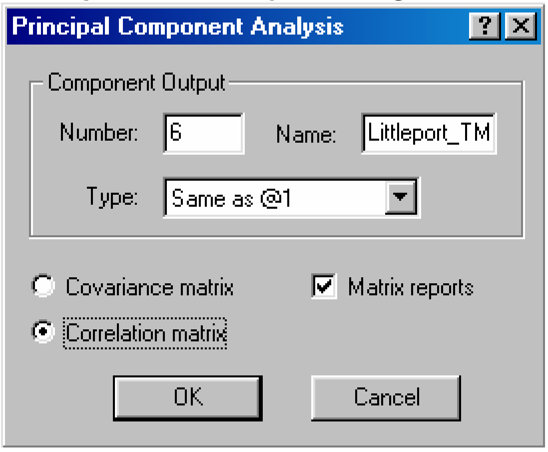
Adjacent bands in multispectral images are often correlated, which implies redundancy in the data as some information is being repeated in different bands. Principal components analysis (PCA) defines the number of dimensions that are present in a data set and the principal axes of variability, and generates principal component images that encompass this variability. Thus in a six band Landsat Thematic Mapper (TM) image (omitting thermal band 6) of land cover you may be able to encompass over 95% of the variability of the data in the first 3 principal component (PC) images. A colour composite image made with these three PC images is thus likely to give you a much clearer picture of different land cover types than any combination of three of the original bands. A useful account of PCA is given in Mather (1999), which refers to the images you will use.

To demonstrate this and how to carry out PCA in *Bilko*, you will take a set of six bands from a Landsat TM image of the countryside around Littleport, near Ely in Cambridgeshire, UK. The main features in the image are the River Ouse running from south to north on the right-hand side of the image and the parallel Old and New Bedford Rivers, running in a north-easterly direction on the left-hand side. The area is low-lying, flat, fertile Fenland where barley, wheat and sugar-beet are grown. A few clouds and their shadows can be seen.

Activity: Open the set ***Littleport_TM.set***, which will open the six bands as a stack. Use the *<Tab>* key or **Image, Animate** option (or button) to scroll through the six bands. Some images are a little poor in contrast, so use *<Ctrl>+A* to select all of the images and apply an automatic linear stretch. Scroll through the bands again and note the improvement. Now make a colour composite (you just need to select **Image, Composite** as the images are already connected). The false colour composite formed from bands #1, #2 and #3 is poor in contrast so apply an automatic linear contrast stretch to this too. This improves it markedly.

Your next task is to perform PCA on the six bands and then construct a false colour composite using the first 3 principal component images. This can be compared to the raw band composite already made or other composites you may care to make using different band combinations.

Activity: Minimize the composite and make sure the stacked set of images is the active window. Select **Image, PCA**. to open the **Principal Components Analysis** dialog box. Leave the number of components set to the default of 6 and the type of output set to Same as @1 but select **Correlation matrix** for the matrix type. You will usually want the **Matrix reports**, which provide important information about the PCA, so leave this box checked. When the dialog box is set up correctly (see right), click on OK. Six principal component images will be produced, each accounting for progressively less of the variability in the data. Also two tables will be produced. The first of these shows the correlation matrix and has the first column headed **Correlation**. It shows the degree of correlation between all combinations of bands. The second table shows the principal component loadings for the six principal components of the Littleport TM image and has its first column headed **PCA**.



The principal component images will be labelled something like ***Littleport_TM pc1***, ***Littleport_TM pc2***, etc. You now want to make a false colour composite of the first 3 principal components.

Activity: Close the unwanted principal component images; that is, the pc4, pc5 and pc6 images. Then connect the pc1, pc2 and pc3 images as a stack. You can now directly make a colour composite (you just need to select **Image, Composite**). The false colour composite formed from principal component images pc1, pc2 and pc3 shows different land cover types clearly but its contrast can be improved. Apply an automatic linear contrast stretch. I hope that you agree that land cover types are now extremely clear! Compare this composite with the original one made from the three visible waveband TM images (and, if you wish, other combinations of raw bands).

This shows how PCA can be a useful method of data compression, concentrating most of the information in the six bands into 3 principal component bands in this example. To find out how much of the variability (variance) in the data has been compressed into the 3 principal component bands, you need to examine the PC loadings table and perform a few calculations on it. This can be done most easily in an *Excel* (or other) spreadsheet and forms part of a mini-lesson (***Mini-lesson04_Principal_Components_Analysis***), which you may wish to look at if you have reasonable spreadsheet skills. This analysis indicates that approximately 97% of the variance in the data is encompassed by the first 3 principal component images.

Activity: When you have finished, close all images and tables.

In earlier sections you have seen how to enhance images using stretches and palettes; the next section introduces you to how to use **filters to enhance features of interest in images**.

Answers to Questions

Editing and viewing coordinates, creating scattergrams and PCA

Question 1

At the seaward end of the pier.

Question 2

19 pixels have value of 100 in band #2 and a value of 50 in band #4 of the AVHRR_Mulls image.

Question 3

Pixels with a high DN in ***AVHRR_Mulls#04*** but low DN in ***AVHRR_Mulls#02*** are sea pixels, which absorb near infra-red wavelengths and are thus very dark on ***AVHRR_Mulls#02*** but are relatively bright (cool) on the processed thermal infra-red ***AVHRR_Mulls#04*** image. Pixels with a low DN in ***AVHRR_Mulls#04*** but high DN in ***AVHRR_Mulls#02*** are lowland land pixels, which are relatively warm and thus dark in the processed thermal infra-red ***AVHRR_Mulls#04*** image but well vegetated and thus relatively reflective and bright in the near infra-red ***AVHRR_Mulls#02*** image. Thus areas that tend to be bright in one image tend to be dark in the other. Highland land areas and lakes provide intermediate values.

Reference

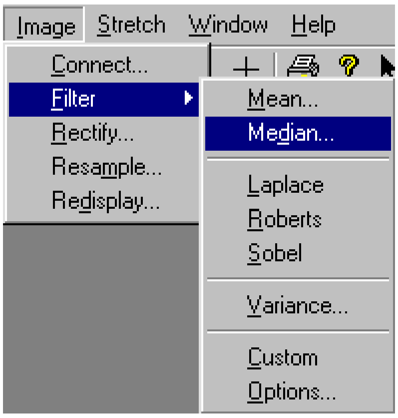
Mather, P.M. (1999). *Computer Processing of Remotely-Sensed Images. An Introduction.* John Wiley & Sons: Chichester. Second Edition. 292 pp. ISBN 0-471-98550-3.

9. USING FILTERS TO ENHANCE IMAGES

Aim: To introduce you to how to use filters to enhance features of interest in images.

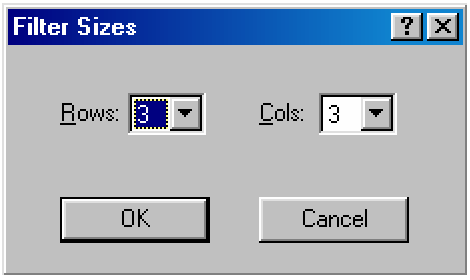
Objectives: By the end of this tutorial you will have learnt what the main types of filters are, what they do, how to apply them and how to construct customised filters.

This tutorial introduces you to the use of "filters" which act on your image (i) to enhance edges (like filters used to sharpen digital photographs), (ii) to smooth thematic or radar images (like filters use for dust and speckle removal or to blur digital photographs) or (iii) to enhance areas that are rough (with variable reflectance or backscatter). Filters perform calculations on the underlying image data and then create a new image transformed according to the type of filter applied.



The **Filter** submenu of the **Image** menu allows the user to apply filtering processes to an image. Six predefined filters (Mean, Median, Laplace, Roberts, Sobel and Variance) are provided and users are also allowed to create their own customised filters. The first two predefined filters act to **smooth** the image and are sometimes called 'low pass' filters. The middle three act to enhance edges or **gradients** (i.e. areas on the image where there are sudden changes in reflectance in a given waveband) and are sometimes called 'high pass' filters. The predefined **Variance** filter is a textural filter which makes areas of variable reflectance appear brighter than relatively uniform areas which appear darker the more uniform they are.

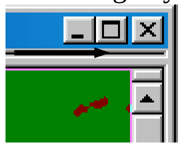
The three predefined high pass filters all act on 3 × 3 groups of pixels whilst the **Mean, Median** and **Variance** filters can have their sizes altered in a **Filter Sizes** dialog box (right). By default these filters act on 3 × 3 groups of pixels (3 rows × 3 columns) and this setting is initially displayed. The maximum size allowed is 15 × 15 pixels.



Activity: Open the image called ***AVHRR_Mulls_col#04.bmp***, a coloured thematic image showing sea surface temperatures in various colours with warmest water deep red and coldest cyan in colour. Before proceeding, check the filter options by selecting **Image, Filter, Options** to display the **Filter Options** dialog box. Make sure that all four checkboxes are checked and that the **Filtered Image Type:** is the Same as unfiltered. Then use **Edit, Select All** or press *<Ctrl>+A* to select the whole of this image for filtering.

The first filter you will experiment with is a simple 3 × 3 Median filter. This replaces the central pixel in each square of nine pixels by the median value of the nine pixels (i.e. the middle value after they have been ranked according to DN). This filter is a smoothing filter and will emphasise the major changes occurring in our thematic colour map of sea surface temperatures at the expense of localised differences. Often as the last cosmetic operation after creating a thematic map one smooths the final image to remove "noise" and emphasise the broad changes in features (in this case, sea surface temperature).

Activity: From the **Image** menu, select **Filter, Median** with the mouse. The **Filter Sizes** dialog box will appear (see above). Since we want a 3 × 3 filter, just click on **OK**. A Status box briefly appears as the filtering is carried out and then a window containing the filtered image appears. Compare the filtered and unfiltered image. Note that the broad changes in water temperature are more clearly displayed in the smoothed image. You can see what you have done to the new smoothed image by clicking on the grey edge [indicated by arrow on picture to right] above the image but below the title bar (when you are in the correct position the mouse pointer changes into black upward and downward arrows emanating from a pair of parallel lines) and dragging this window pane downwards (it works a bit like a roller blind). Underneath the image you should see **3x3 Median Filter over AVHRR_Mulls_col#04.bmp : From (0, 0) To (511, 255)**



Note how the filter emphasises the broadscale distribution of water masses of different temperature. How ever, some detail is inevitably lost.

The larger the array used for filtering the harsher the smoothing will be. To see the effect of a large smoothing filter you should try a 7 × 7 Median filter, which replaces the central pixel in a 7 × 7 pixel array by the median of all 49 pixels in the array. As you can imagine, such a filter, although bringing out large-scale features, can cause considerable loss of detail.

Activity: Click on the ***AVHRR_Mulls_col#04.bmp*** unfiltered image. From the **Image** menu, select **Filter, Median**. In the **Filter Sizes** dialog box click on the down arrows by the **Rows:** and **Cols:** boxes and select 7 for each (or type 7 in each box), then click on . A **Status** box briefly appears as the filtering is carried out and then a window containing the filtered image appears. Compare this image both with your original unfiltered image and the image filtered with a 3 × 3 Median filter. Note how Malin Head and some small islands have almost disappeared and the rather cartoon like quality of the heavily smoothed image. This illustrates the care which one must take using such filters. Close the two filtered images (do not save changes).

The **Mean** filter acts in a similar fashion to the **Median** filter but replaces each pixel value by the **mean** (average) of the group of 3 × 3 pixels of which it is the centre. With the median filter all pixel values in the output filtered image will be represented in the image data but with a mean filter you may be creating pixels which have values which do not exist in the input image. Depending on the type of image you may wish to use one or the other filter.

We will now look at the effects of some custom ‘high pass’, edge-enhancing filters on a test image, which will demonstrate how directional filters work. The **Image, Filter, Custom** option allows you to create your own customised filters in which you define the weights (usually integers) for each cell in the filter array. We will experiment with constructing a few 3 × 3 filters to carry out specific modifications to an image. You will firstly try out a filter which is designed to enhance East–West running edges, then one designed to enhance North–South running edges, and finally one designed to pick up edges running in any direction. In each case after applying the filter you should perform an automatic linear stretch of the resulting image to display the result. Details of precisely how these *convolution* filters work are beyond the scope of this introduction but are covered in standard textbooks.

E-W edge enhancer

1	2	1
0	0	0
-1	-2	-1

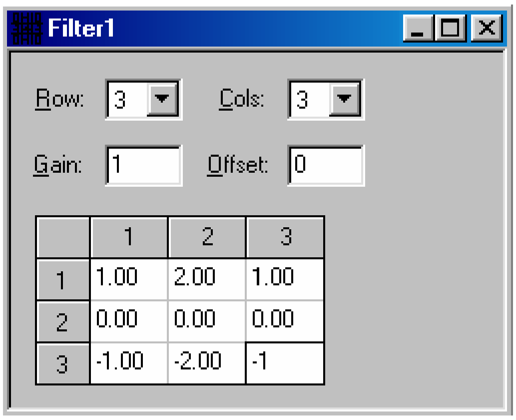
N-S edge enhancer

1	0	-1
2	0	-2
1	0	-1

Non-directional edge enhancer

-1	-1	-1
-1	8	-1
-1	-1	-1

Activity: Close the ***AVHRR_Mulls_col#04.bmp*** image and open the test image, which is called ***Filter_test.gif***. The test image looks remarkably boring with a patch of black in the north-west corner, a patch of white in the south-east corner and a big expanse of dull grey in between. Let’s see what edge-enhancing filters can reveal.



Press *<Ctrl>+A* to select the whole of this image and select **Image, Filter, Custom.** Set up the custom filter as an E–W edge enhancer, typing the numbers into each cell of the array and using the *<Tab>* key to move between cells. When all the cells are correctly filled in, click on the Copy button, then click on the ***Filter_test.gif*** image and click on the Paste button to paste the filter to the image. You will see a faint but distinct pattern of horizontal lines in the grey area. Apply an automatic linear stretch (**Stretch, Auto Linear**) to see the results more clearly.

Note the series of lines running E–W that are now clearly revealed in the grey area.

Activity: Close the filtered image and the filter you created. Then open a new custom filter and set it up as a N–S edge enhancing filter as in the diagram above. When all the cells in the new filter are set up correctly, copy and paste the new filter to the ***Filter_test.gif*** test image. [*Note:* if you find you cannot paste the filter to the image then press *<Ctrl>+A* to select the whole image]. Apply an automatic linear stretch (**Stretch, Auto Linear**) to see the results more clearly.

Question 1: What do you see this time in the grey area?

Activity: Close the filtered image, save the filter you created as ***N-S_edge_enhancer*** (*Bilko* will automatically add the ***.flt*** extension) and then close it. Then select **File, Open**, make sure that the **Apply** checkbox is **not** checked, and open the filter called ***High_pass.flt***, which is the non-directional edge enhancing custom filter in the diagram above. Copy and paste the new filter to the ***Filter_test.gif*** test image. Note the pattern that now appears in the grey area. Apply an automatic linear stretch (**Stretch, Auto Linear**) to see the results more clearly.

Question 2: What do you see this time in the grey area?

Note: if the **Apply** checkbox of the **Open** dialog box had been checked and the ***Filter_test.gif*** image had been the active document, then the filter would have been applied directly to that image (without being opened). You may wish to experiment with this.

The exercises above show how selective filters can be. There is in fact some sort of faint grid within the grey area, which is not visible in the normal image but can be brought out by edge enhancing filters. The directional filters only reveal one part of the grid (e.g., *either* E–W *or* N–S running lines) whereas the non-directional filter reveals the whole grid.

The predefined edge-enhancing filters (**Laplace, Roberts,** and **Sobel**) all produce similar results to the non-directional custom filter. You can quickly check this by applying these three filters to the ***Filter_test.gif*** test image (see next activity). Details of these filters are available from *Bilko*'s **Help**.

Activity: Close the filtered image and the ***High_pass.flt*** filter. Make sure the entire ***Filter_test.gif*** test image is selected and then apply the three predefined edge-enhancing filters in succession, applying automatic linear stretches to see the results clearly.

If you select just part of the image [*Hint:* click on the block or box selection button and then click on the top-left of the area you want to filter and drag box to the bottom-right of the area], you can apply the filter to only the sub-area selected.

When you have finished experimenting, close all the filtered images (without saving them) and close the ***Filter_test.gif*** test image.

The remaining predefined filter, the **Variance** filter replaces each pixel value by the variance of the group of $n \times n$ pixels (default 3×3 pixels) of which it is the centre. Its use is demonstrated in specific lessons but will not be considered further here.

In this tutorial you have learnt how to smooth thematic or noisy images using mean and median filters, how to enhance edges using both custom filters and predefined ones and how to construct your own customised filters. You have also learnt how to save and open custom filters so that you could build up a set of your own specialist filters if required.

The final tutorial in this series of tutorials introduces you to *Bilko*'s powerful **formula documents** facility that allows you to carry out calculations on a single image or using combinations of connected images.

Answers to Questions

Using filters to enhance images

Question 1

This time you will see a pattern of vertical (N-S) running lines in the grey area part of the filtered image.

Question 2

This time you will see a grid pattern in the grey area part of the filtered image. Thus each of the directional filters only enhanced half of the pattern hidden in the grey area.

10. USING FORMULA DOCUMENTS TO PERFORM CALCULATIONS ON IMAGES

Aim: To introduce you to how formula documents work and some applications of formulas to perform calculations on images.

Objectives: By the end of this tutorial you will have learnt how to construct simple formulas, apply them to one or more images to perform useful tasks, and to utilise flag information that comes with some images.

Formula documents provide a powerful tool for modelling and performing sophisticated manipulations and calculations using images. For the non-mathematical they can seem rather daunting. This section thus starts with some background information on Formula documents, which, after reading through, you should use largely for reference. This background explains the syntax used in formulas, gives some advice on best-practice for using formula documents (using comments and constants), and provides reference information on mathematical and logical operators and functions which can be used in formulas. Those of you with some knowledge of using formulas in spreadsheets (e.g. in *Excel*) or of computer programming will find Formula documents fairly straightforward. Those without such a background will probably find them a little difficult! The information here can also be obtained using the *Bilko* on-line Help facility. While going through the background, you will be taken through some routine uses of formulas so that you can see them in action. The tutorial finishes by introducing you to how to use bit-wise operators to interrogate and utilise the “flag” information that comes with various image types (e.g., ENVISAT data).

Background

Each Formula document consists of a series of executable statements, each terminated by a semi-colon ‘**;**’. Images are referred to in formulas by the **@** symbol followed by a number which refers to the tile **Selector** toolbar buttons or stack **Selector** list number and maps to the appropriate image in the connected images window. Unless only part of a referenced image has been selected, the Formula document will operate on every pixel in the images so referenced. Unless only a single image is being operated on, images have to be connected and the Selector mapping set up, before they can be operated on by Formula documents.

This tutorial introduces you to:

1. Use of comments,
2. Operators,
3. Functions,
4. Setting up of constants,
5. Conditional statements, and
6. Bit-wise operators for utilising “flag” information.

1. Comments

Comments make formulae comprehensible both to others and (when you come back to them after some time) to yourself. It is good practice to include copious comments in your formula documents.

Comments are any lines preceded by the hash symbol **#**.

An example of a set of comments at the start of a formula document is given below:

```
# Start of Bilko formula document to radiometrically correct Landsat-5 TM bands
# 1-3 collected over the Turks and Caicos on 22 June 1990.
#     Converting DN to at satellite spectral radiance (L) using formulae of the type:
#             Lmin + (Lmax/254 - Lmin/255) * @n ;
#
#     Input values
#     ==========
#     Lmin: TM1 = -0.116, TM2 = -0.183, TM3 = -0.159
#     Lmax: TM1 = 15.996; TM2 = 31.776; TM3 = 24.394
```

All comment lines are ignored by the program that processes formula documents. They help other people to understand your formulas and help you to understand them when you come back to them after not using them for some time.

2. Operators

Formula documents support a range of arithmetic, relational (comparison), and logical “operators” to manipulate images. The most important ones are listed below.

Arithmetic	Relational	Logical
Exponentiation (^)	Equality (==)	AND
Multiplication (*)	Inequality (<>)	OR
Division (/)	Less than (<)	NOT (can also use the “!” sign)
Addition (+)	Greater than (>)	
Subtraction (–)	Less than or Equal to (<=)	
	Greater than or Equal to (>=)	

Do not confuse the equality operator used in comparisons (==) with the assignment operator (=) used in constant or other statements. The difference between the two is illustrated in the section on conditional statements. When several operations occur in a Formula document statement, each part is evaluated in a predetermined order. That order is known as operator precedence. Parentheses (brackets) can be used to override the order of preference and force some parts of a statement to be evaluated before others. Operations within parentheses are always performed before those outside. Within parentheses, however, normal operator precedence is maintained. When Formula document statements contain operators from more than one category, arithmetic operators are evaluated first, relational operators next, and logical operators are evaluated last. Among the arithmetic operators, exponentiation (^) has preference (is evaluated first) over multiplication/division (*, /), which in turn have preference over addition/subtraction (+, –). When multiplication and division (or addition and subtraction) occur together in a statement, each operation is evaluated as it occurs from left to right (unless parentheses direct otherwise).

Thus the formula statement:

0.15 * (@1 – 3.0) ;

will firstly subtract 3.0 from every pixel in the image referenced by @1 and then multiply the result by 0.15 to generate the output image. In this example the parentheses make sure the lower precedence subtraction operation takes place *before* the higher precedence multiplication. If the formula statement had been written:

0.15 * @1 – 3.0 ;

then each pixel of the image referenced by @1 would have been multiplied by 0.15 and afterwards would have had 3.0 subtracted, giving a totally different and wrong! result.

This simple formula can be used to convert pixel DNs in an 8-bit processed National Oceanic and Atmospheric Administration (NOAA) AVHRR Oceans Pathfinder sea surface temperature (SST) image (freely available on the internet) to values corresponding to SST in degrees Celsius. [*Note:* The output image type needs to be 32-bit floating point to store these numbers]. You will now do this in case you are getting bored.

Activity: Open the image file ***Global_SST_Dec2000.gif***. Right-click on the image and select the **Zoom** option from the menu; set the zoom to 45% of full size so that you can see the whole image at once. Note that all land and areas with no data (clouded during December 2000) are set to black (0) and the sea to varying shades of grey. Use a histogram to confirm that pixel values in the sea have values between 1 and 240. [*Hint:* you will need to check **Ignore zero:** in the **Options, Scale** dialog box for the histogram because of all the black land pixels]. Open the formula document ***Pathfinder_SST.frm***. Study the formula and note that because only one image is open *Bilko* knows that this image must be @1.

The formula is not valid for land and cloud areas (which are set to 0), so the IF statement checks if each pixel is 0 and, if it is, sets the output image to 0. If it isn't (ELSE), the formula converts the DN value of the pixel to a temperature in degrees Celsius. Such "conditional" statements are covered in detail in section 5 of this tutorial. [*Note:* If more than one image were open then a connected images window would need to have been set up using **Image, Connect** so that the program knew which image was designated @1.]

Activity: Use the **Options!** menu (which appears when the formula is the active window) to set the **Output Image Type:** to 32-bit floating point so that decimal degrees Celsius values for temperature can be displayed. [Ignore the other settings for now.] Copy the formula by clicking on the Copy button and then click on the image and paste the formula on it by clicking on the Paste button. A new image will be generated with pixel values equal to the sea surface temperature in °C.

The new image is too dark and needs to be stretched to see it properly. Right-click on it and select **Redisplay** from the menu. In the **Redisplay Image** dialog box select check the **Null Values(s):** box to set null value as zero and select Equalize as the stretch to be used. Check out the new image, noting how all land and cloud areas are represented as a "?" on the Status Bar, whereas sea areas show SSTs in degrees Celsius. To check the range of temperatures, open a histogram of the new SST image.

Question 1: Using the histogram, find out what are the upper and lower values of the "bin" with the highest temperature in the sea (to one decimal place). How many pixels have this temperature?

Question 2: Using the histogram, find out what the modal (most common) temperature (to two decimal places) of tropical oceans was in December 2000. [*Hint:* Find the value of the most frequent "bin" at the warmer end of the SST distribution.] How many pixels are in this temperature "bin"?

Activity: When finished, close all images and the formula document.

3. Functions

The following functions are supported within Formula documents. The “argument” that you wish the function to act on is enclosed in parentheses. For the trigonometric functions (sin, cos, tan and arctan) the argument is in **radians** (not degrees). 180° = π radians so you can convert degrees to radians using the equation: $\text{Radians} = \frac{\text{Degrees} \times \pi}{180}$.

Function	Formula document syntax
Square root	SQRT()
Logarithm to the base 10	LOG()
Logarithm to the base *e* (Natural log)	LN()
Exponential (*e* to the power of)	EXP()
Sine	SIN()
Cosine	COS()
Tangent	TAN()
Arctangent	ATAN()

A few functions which may be of use in remote sensing (e.g. in radiometric correction or bathymetric mapping) and which can be easily derived from these basic functions are listed below.

Function	Formula document syntax
Secant	1 / COS()
Cosecant	1 / SIN()
Cotangent	1 / TAN()

4. Setting up of constants

Constants, like comments, make formulae easier to understand, particularly complex formulae, and can make formulae much easier to alter so that they can be applied to different images. Constant statements should be inserted at the start of formula documents. The form of the statement is:

CONST name = value ;

Where the keyword CONST alerts the program processing the formula document to the fact that this is a constant declaration. The name can be any string of alphanumeric characters (but beginning with a letter), that signifies what the constant refers to; the value is an integer or decimal number that you wish to be assigned to the constant name. The constant statement assigns the value to the name so that in formula you can use the name instead of typing in the value. If the constant is a long string of numbers like -1.0986543 and appears lots of times in the formula document, or you wish to experiment with several different values for a constant, having only to change one constant statement can be very useful. Some examples of constant statements are given below.

```
        CONST Lmin = -0.116 ;              CONST Lmax = 15.996 ;
        CONST pi =3.14152 ;
        CONST d_squared = 1.032829 ;
        CONST SunZenithAngle = 32 ;
        CONST ESUN = 195.7 ;
#
#       Converting L to exoatmospheric reflectance (ER) with formula of the type:
#       pi * L * d² / (ESUN * cos(SunZenithAngle))  ;
        @2 = pi * (Lmin + (Lmax/254 - Lmin/255)*@1) * d_squared / (ESUN *
        COS(SunZenithAngle/180*pi)) ;
```

In the example above, involving radiometric correction, the values of Lmin, Lmax and ESUN vary for different wavebands. Just changing three of the constant values allows the same formula to be used for several different wavebands, minimising the chance of an error. Note also that more than one statement can be typed on one line.

You can also use constant statements to set up labels for images. For example,

```
CONST AVHRR_band4 = @1 ;
CONST AVHRR_band5 = @2 ;
```

This assigns a pair of connected images (@1 and @2) to two constant names which make it clear that the formula is designed to work on thermal infra-red bands #4 and #5 of AVHRR scenes which are used to calculate sea surface temperature. [Note that you cannot use the # symbol for bands in formulae as it is reserved for comments].

Using constants improves the understandability of formula documents. They also allow you to more easily apply a complex formula to a set of images; only having to change the constant statement assignments at the beginning to use with different connected images.

Constant names may be made up of letters (uppercase and lowercase), numbers and the underscore character. However, they may not begin with an underscore.

5. Conditional statements

To illustrate the use of conditional (IF ... ELSE ...) statements you will look at how they could be used to make a "land mask" from ***AVHRR_Mulls#02.bmp***. By land mask we mean an image made up of only zeros and ones (a Boolean image) with zeros lying over land and ones lying over water. If you wanted to process water areas separately in ***AVHRR_Mulls#02.bmp*** or ***AVHRR_Mulls#04.bmp*** you would just have to multiply these images by the land mask to set all land areas to 0 while leaving water pixels as they were.

Sea pixels in ***AVHRR_Mulls#02.bmp*** have values of 45 or less. Land pixels have values in excess of 45. We will set up this threshold value as a constant called "Threshold".

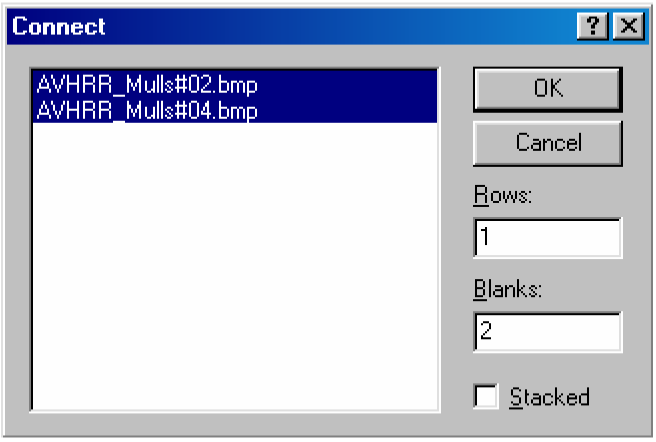
The following conditional statement which has one equality comparison (==), one inequality (<), one logical (OR) and two assignment operations (=) makes a "land mask" from ***AVHRR_Mulls#02.bmp***.

CONST Threshold = 45 ;	assigns the value 45 to the constant name "Threshold"
CONST Mulls2 = @1 ;	assigns the image designated @1 by the Selector toolbar to the constant name "Mulls2" (this should be ***AVHRR_Mulls#02.bmp***)
CONST Landmask = @3 ;	assigns the image designated @3 by the Selector toolbar to the constant name "Landmask" (this will be the output image)

```
IF (Mulls2 == Threshold OR Mulls2 < Threshold) Landmask = 1
ELSE Landmask = 0 ;
```

The statement says: IF the pixel value in @1 image (= ***AVHRR_Mulls#02.bmp***) is equal to the constant **Threshold** (= 45) or is less than the constant **Threshold**, then assign a value of 1 to the corresponding pixel in @3 (the blank image to which the name **Landmask** has been assigned) ELSE assign a value of 0 to the @3 image. Thus all sea pixels (equal to or below the threshold) are set to 1 and land pixels (above the threshold) are set to zero.

Activity: Open the files ***AVHRR_Mulls#02.bmp*** and ***AVHRR_Mulls#04.bmp***. Use **Image, Connect** to bring up the **Connect** dialog box. Connect the two files and set the **Blanks:** box to **2** to add two blank images to the connected images window. Use the **Selector** toolbar to designate ***AVHRR_Mulls#02.bmp*** as image 1 (and thus @1 in formulas), ***AVHRR_Mulls#04.bmp*** as image 2 (and thus @2 in formulas) and the two blanks as images 3 and 4 (@3 and @4 in formulas).



Click on **File, New** and create a new Formula document. Enter the three constant assignment statements and the conditional statement described above into the formula document. Use the **Options!** menu to set the **Output Image Type:** to Same as @1, if need be. Then copy and paste the completed formula to the connected tiled images window and the first blank will turn black as it becomes the land mask. Apply an automatic linear stretch to the connected tiled images (remember to select all *(<Ctrl>+A*) of the @1 image first) to see the mask, which should look like the image above. Check that the land is set to zero and the sea to 1 (underlying image data values, not display values) in the land mask image.

Note: To modify the formula so that the mask is produced as a new image not in the connected images window, the formula would be modified thus:

CONST Threshold = 45 ;
CONST Mulls2 = @1 ;
IF (Mulls2 == Threshold OR Mulls2 < Threshold) 1
ELSE 0 ;

Thus if no image *@n* is assigned for the output of the Formula document then a new image is created to receive it. **Do not do this now**, although please feel free to experiment later!

The next step is to apply this land mask (which is most easily generated from the near infra-red band #2 image due to sharp land:sea boundary) and apply it to the ***AVHRR_Mulls#04.bmp*** image so that the sea surface temperature information can be analysed separately. To do this, two lines (see below) should be added to the formula document:

CONST Mulls4 = @2 ;

and

@4 = Mulls4 * Landmask ;

Activity: Insert the new constant assignment after the "**CONST Mulls2 = @1 ;**" statement and insert the second statement, which multiplies the AVHRR band #4 image by the land mask, at the end of the formula document. Once you've checked the new lines carefully to make sure there are no errors, copy the updated formula and paste it to the connected tiled images window. Check the fourth tiled image, which should now contain a masked band #4 image, to make sure that the land has now indeed been set to 0.

[*Note:* If you wanted to save a copy of the masked band #4 image (@4), you would need firstly to select all (*<Ctrl>+A*) of the fourth tiled image and then select **File, Save**].

Activity: When you have finished, close all the image files. You may wish to save the formula document for reference.

Question 3: How could you simplify the conditional statement in the formula (refer to the table of operators in section 2 above)?

6. Bit-wise operators for utilising "flag" information

Images from many sensors may come with "flag" data, which are usually in the form of an image that contains flag attributes for each pixel. Examples are the AVHRR (Advanced Very High Resolution Radiometer) sensor of the United States' National Oceanographic and Atmospheric Administration (NOAA), and the MERIS (Medium Resolution Imaging Spectrometer) and AATSR (Advanced Along Track Scanning Radiometer) sensors of the European Space Agency's ENVISAT satellite. The flag attributes indicate such things as where there is land, water, cloud, coastline, sun glint, invalid data, etc. on the image.

Activity: Open the file ***MER_RR__1_Mediterranean.n1,*** which is a MERIS image of the central Mediterranean around Italy. Click on the ***Flag Codings*** folder in the left hand pane of the hierarchical file window and then double-click on the ***l1_flags*** text file. This opens and tells you what the 8 flag codes (attributes) are, that can be applied to each pixel in this dataset. In this instance, since there are only 8 flags, the flag information can be stored as an 8-bit unsigned integer image; each flag being represented by one bit (Table 10.1).

Table 10.1. Flag Codings that can be represented by an 8-bit unsigned integer. Each of the 8 bits of each pixel's flag codings can be set to 1 to represent a different attribute.

	Bit 8	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1
Power of 2	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Value	128	64	32	16	8	4	2	1

Activity: Click on the ***Bands*** folder in the left pane. Note that the Data type of the ***l1_flags*** image folder in the right pane is 8-bit unsigned integer and that the flags image is the same size (1121 x 1121 pixels) as the 15 radiance bands of the MERIS image; that is, there is one flag coding for each pixel of the MERIS scene. Right-click on the ***l1_flags*** image folder and select **Open Properties**. The MERIS Level 1b classification and quality flags are listed. These are displayed in Table 10.2 below.

Table 10.2. Level 1b classification and quality flags for MERIS imagery.

Flag descriptors	Value	8-bit unsigned integer (binary)	Binary digit (bit) setting	Result
COSMETIC	= 1	00000001	Bit 1 set	$2^0 = 1$
DUPLICATED	= 2	00000010	Bit 2 set	$2^1 = 2$
GLINT_RISK	= 4	00000100	Bit 3 set	$2^2 = 4$
SUSPECT	= 8	00001000	Bit 4 set	$2^3 = 8$
LAND_OCEAN	= 16	00010000	Bit 5 set	$2^4 = 16$
BRIGHT	= 32	00100000	Bit 6 set	$2^5 = 32$
COASTLINE	= 64	01000000	Bit 7 set	$2^6 = 64$
INVALID	= 128	10000000	Bit 8 set	$2^7 = 128$
Example combinations				
Land and duplicated		00010010	Bits 2 and 5 set	2 + 16 = 18
Bright and land		00110000	Bits 5 and 6 set	16 +32 = 48
Land and coastline		01010000	Bits 5 and 7 set	16 + 64 = 80

Bit-wise operators
And (&)
Or (|)

Bilko provides you with two bit-wise operators that allow you to utilise this flag information. The key one is the bit-wise "And" operator which is represented by an ampersand "&" sign in formula documents. Bit-wise "Or" is also implemented but will not concern us further here. The flags allow one to mask out areas of the image that are unwanted for various reasons (e.g., contain suspect data, bright areas (sensor saturation) due to such features as thick cloud, are land (not ocean) – if one is studying ocean features, are affected by sun glint, etc.). This is best implemented in formula documents by setting up a series of constants for each flag you wish to utilise and then performing a series of bit-wise "and" operations between these constants (flag settings) and the "flags" image to identify areas affected by each flag. This is best explained using an example.

Activity: Double-click on the ***radiance_2*** image folder in the right pane to open the TOA (Top Of Atmosphere) radiance band 2 MERIS image. [If an **Extract** dialog box appears, uncheck the **Extract** checkbox and click OK.] This brings up the **Redisplay Image** dialog box. Check the **Null Value(s): == 0** checkbox and make a note of the maximum pixel value. Select **Equalize** as the stretch and then click the **Apply** button. Note that the image is in 16-bit unsigned integer format. Briefly inspect the image, which shows Italy, the Adriatic and Croatian coast, and the western Mediterranean around Corsica, Sardinia, Sicily and the Balearic Islands. Now right-click on the ***l1_flags*** image folder and select **Open Items** to open the flags image. Inspect this image using the cursor and answer the following question.

Question 4: In the flags image, what values do (1) clear ocean, (2) most land, and (3) most of the bright (cloud) area in the north-east of the image have? Which flags are set to give these values?

Activity: Connect the flags image, the band 2 radiance image and one blank image as a group of three tiled connected images using the **Image, Connect** menu. Using the Selector toolbar designate the flags image as @1 (image 1), the band 2 radiance image as @2, and the blank image as @3. When this is done, open the formula document ***Bitwise.frm***.

Inspect the formula document. Note that (i) it is expecting the flags image to be @1 and the band 2 radiance image to be @2, (ii) constants have been set up for 6 of the flags, and

(iii) that the output image from the formula will appear in the third tile (@3) of the connected images window.

Let us now examine what the formula does. It seeks to mask out (i.e. set to zero) all areas of the image that (i) have glint risk, (ii) are suspect, (iii) are land, (iv) are bright (i.e. have thick cloud or are causing sensor saturation for some other reason), or (v) are invalid. Each bitwise "and" (denoted by a **&**) operation between a flag constant and the flag image creates a Boolean image (that is, one in which all pixels have values of either 0 or 1), with areas where the flag is present having a value of 1 and those where it is absent having the value 0 (Table 10.3).

Since you want to mask out areas where the flag is present, you want the opposite. To achieve this, each bit-wise "and" is preceded by a NOT operation (in this case using the **!** sign, which can be used interchangeably with NOT in *Bilko* formula documents). This creates a series of masks for each flag such that areas where the flag is present are set to 0, and the remainder of the image is set to 1. Multiplying the band 2 radiance image by this series of masks sets all the unwanted areas to zero.

Table 10.3. Results of bitwise "and" operations for three cases. ***Case 1***: the flags image indicates land with thick cloud (bright); a bitwise "and" with a *bright* flag constant indicates true (i.e. Bit 6 is set in the flags image **and** in the constant) and so the result for that pixel is 1. This is switched to 0 by the NOT (!) operation. ***Case 2***: the flags image indicates land with thick cloud (bright); a bitwise "and" with a *land* flag constant indicates true (i.e. Bit 5 is set in the flags image **and** in the constant) and so the result for that pixel is 1.This is switched to 0 by the NOT (!) operation. ***Case 3***: the flags image indicates open ocean with no problems; a bitwise "and" with a *land* flag constant indicates false (i.e. Bit 5 is **not** set in the flags image) and so the result for that pixel is 0. This is switched to 1 by the NOT (!) operation.

Case	Flags image pixel		Flag constant	Flag descriptor	Result in output image	Result after NOT (!) operation
1	00110000	&	00100000	Bright (32)	0000000**1**	0000000**0**
2	00110000	&	00010000	Land (16)	0000000**1**	0000000**0**
3	00000000	&	00010000	Land (16)	0000000**0**	0000000**1**

Activity: The output image needs to be a 16-bit unsigned integer image like the band 2 radiance image. With the formula document as the active window, select **Options!** from the menu. In the **Formula Options** dialog box, uncheck the **Use special handling for Nulls** checkbox, select 16-bit unsigned integer as the **Output Image Type:** and click on OK. You can now apply the formula to the tiled connected image by copying it and pasting it on the connected images window. Inspect the new image in the third tile of the connected images window and note that all areas with land, with risk of sun glint, with thick bright cloud or with suspect pixels are set to zero and you are only left with data values for water areas.

In the formula document two other ways of achieving the same result are shown as "comments". You may wish to comment out the formula you used and delete the **#** signs before each of the alternative formulae in turn to satisfy yourself that these do the same thing. You will find that the second alternative formula, which uses a series of bitwise "or" operations, works the fastest.

To see exactly where the coastline is on the new image one can draw a bright line to coincide with pixels flagged as coastline. The brightest pixel value in the band 2 radiance image, which you should have noted earlier, was 52547. Let us thus set the coastline to have a value of 60000. To do this you need to add two new statements to the formula document after the alternative formulae. One way of doing this is to add the following two lines:

CONST NewCoast = 60000 ;
IF (Flags & Coastline) NewCoast ELSE @3 ;

This will create a new image; this will be the @3 image with the coastline added with a value of 60000.

Activity: Add the two new lines to the end of the formula document and rerun the formula. Inspect the new image. You will find that the sea areas are very lacking in contrast and uniformly grey. To rectify this, right-click on the image and select **Redisplay**. In the **Redisplay Image** dialog box select Equalize as the stretch to use and apply the stretch. This greatly improves the image.

When you have finished, close all the image files. You may wish to save the formula document for reference.

Some images may come with more sophisticated sets of flags. For example, several ENVISAT image products use 16 flags such that 16-bit unsigned integer data types are required for the flag images. Some even have 24 flags and need 32-bit unsigned integer data types to represent them. These flags can be utilised using the same methods.

These three examples have taken you through the basics of using formula documents and how to make formulas as understandable as possible both for your own and other people's use. Formulas can be used to perform elements of radiometric correction, perform band ratios, calculate vegetation indices, utilise flag data, carry out water column correction and a whole host of both simple and sophisticated manipulations of image data. These capabilities are further explored in various lessons. A number of advanced features and functions have not been covered here but will be covered in a mini-lesson on advanced use of formulas.

Answers to Questions

Using Formula documents to perform calculations on images

Question 1

The upper and lower values of the "bin" with the highest temperature in the sea are 35.7°C and 35.7°C (to one decimal place). Only one pixel has this temperature.

Question 2

The modal (most common) temperature of tropical oceans in December 2000 was 29.85°C. 12,810 pixels are in this "bin".

Question 3

The formula could be simplified by replacing the long-winded comparison (equal to OR less than) with a single *less than or equal to* relational operator, thus:

```
CONST Threshold = 45 ;
CONST Mulls2 = @1 ;
CONST Mulls4 = @2 ;
CONST Landmask = @3 ;

IF (Mulls2 <= Threshold) Landmask = 1
ELSE Landmask = 0 ;
@4 = Mulls4 * Landmask ;
```

Note that addition of comments would make the formula more transparent to other users.

Question 4

In the flags image:

(1) clear ocean has a value of zero (no flags set).

(2) most land has a value of 16 (land and not ocean – LAND_OCEAN – flag set), and

(3) most of the bright (cloud) area in the north-east of the image has a value of 48 (land [LAND_OCEAN = 16] and bright [BRIGHT = 32] flags both set). A few pixels are set to 50 because they are also duplicated [DUPLICATED = 2].

Section 2

Practical lessons using coastal image data of the Caicos Bank and Virgin Islands

Applying Remote Sensing to Coastal Management Issues

The lessons in Module 7 are designed to aid the training of remote sensing practitioners in developing countries who are working with coastal images and want to gain the most from their images. The primary aim of the lessons is to promote an understanding of the principles of the various techniques involved and to develop the student's critical faculties in terms of assessing whether remote sensing technologies are likely to be useful in achieving defined objectives. Some of the lessons are fairly straightforward (Lessons 1, 2 and 8), others guide the student through some complex and difficult areas of image processing (e.g. Lessons 4, 6 and 7), and others introduce relatively simple techniques which are nevertheless at the forefront of applied remote sensing and can greatly enhance the usefulness of imagery to coastal managers (e.g. Lessons 5, 9 and 10).

Lessons 1, 2 and 9 were drafted by Dr Peter Mumby and Lessons 3, 4, 5, 6, 7, 8 and 10 were written by Dr Alasdair Edwards who then edited all the lessons for consistency of style. Most lessons drew heavily on chapters from the *Remote Sensing Handbook for Tropical Coastal Management* (Green, E.P., Mumby, P.J., Edwards, A.J. and Clark, C.D., 2000). Specific chapters in the *Handbook* where the skills learnt in each lesson can be followed up are indicated in the lessons. The lessons attempt to follow a logical sequence of image interpretation and processing.

Thus **Lesson 1** allows you to get to know the study area in the Turks and Caicos Islands from where most of the images were acquired and concentrates on visual interpretation of imagery using colour composites. It also seeks to builds your ability to link what is on the images to actual habitats on the ground (or in the sea!) and to indicate how remotely sensed imagery can be used to guide field survey. **Lesson 2** focuses on the importance of acquiring images of an appropriate scale and spatial resolution to meet your objectives. In the lesson you estimate the size of a range of habitats and man-made structures and then discover which image types are suitable for mapping these habitats or structures. **Lesson 3** introduces the important skill of how to rectify (geometrically correct) an image to a local map system. **Lesson 4** is a specialist lesson and is probably the most complex of all. It explores the radiometric correction of imagery, which is necessary if you are trying to monitor change or are just working with more than one image, and seeks to show why radiometric correction (including atmospheric correction) is necessary for certain applications and how to carry it out. **Lesson 5** describes an exciting new technique for removing sun glint from high resolution satellite and airborne images to recover the underlying reflectance. **Lesson 6** is partly included as preparation for Lesson 7, which deals with how one compensates for the effect of water depth on bottom reflectance. It introduces you to the effects of water depth and how its influence on bottom reflectance is such that one can crudely map depth using optical imagery. **Lesson 7** then shows you how to compensate for the effect of water depth so that you can map submerged marine habitats with some degree of confidence. This very important processing step is often not done although, for imagery with more than two wavebands that penetrate the water column, it dramatically improves the accuracy of habitat mapping. **Lesson 8** takes the outputs of depth-invariant processing covered in Lesson 7 and uses these to illustrate the principles of habitat classification using a simple box-classifier. The **Lessons 9 and 10** show how one can quantitatively map seagrass standing crop and mangrove leaf area index (LAI) respectively using satellite and airborne imagery. The relatively simple techniques involved seem under-utilised. They use the same imagery used to map the habitats to provide considerable additional information to coastal managers. This makes much better use of the imagery although some additional field survey work is required.

Hopefully, the lessons will stimulate better use of existing imagery and a better understanding of the processing steps required to achieve habitat maps of useful accuracy. The issue of accuracy of outputs is more fully explored in the *Remote Sensing Handbook for Tropical Coastal Management*.

To carry out the lessons successfully you need to have a good working knowledge of *Bilko 3* (obtainable by working through the *Introduction to using the Bilko 3 image processing software*). Also for many of the lessons, a working knowledge of the spreadsheet such as *Excel* is required. Such knowledge is indispensable for anyone thinking of carrying out remote sensing.

1: VISUAL INTERPRETATION OF IMAGES WITH THE HELP OF COLOUR COMPOSITES: GETTING TO KNOW THE STUDY AREA

Aim of Lesson

To learn how to interpret satellite and airborne digital imagery visually, relate features revealed on images to features on the Earth's surface, and understand how images can help in planning field survey.

Objectives

1. To become proficient in preparing colour composite images of both satellite and airborne imagery for visual interpretation.
2. To learn to use field reconnaissance data to assist in visually interpreting images.
3. To understand how satellite and aerial imagery may be used to aid planning of field surveys.
4. To introduce you to the problem of differential attenuation of light of different wavelengths through the water column.

Overview of Lesson

A simple visual interpretation of remotely-sensed imagery can often reveal considerable detail on the nature and distribution of habitats in the area of interest. Visual interpretation is the identification of features based on their colour, tone, texture and context within the imagery. To visually interpret digital data such as satellite images, individual spectral bands must be displayed simultaneously in the form of a colour composite. For example, Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) and IKONOS-2 bands 1, 2 and 3 (Appendix 1.1 and 1.3) broadly represent the blue, green and red parts of the electro-magnetic spectrum (EMS). When these bands are fed through the corresponding blue, green and red "colour guns" of a computer monitor, the resulting image resembles what our eyes would see from the sensor's vantage point. We thus have an intuitive understanding of the colours presented and can usually make an informed interpretation of the scene (e.g. dark blue probably represents deep water). Such images are called *true colour composites* (TCC).

This lesson begins by describing how to make a colour composite image from the spectral bands of SPOT XS (Appendix 1.2). SPOT XS does not have a spectral band in the blue part of the EMS, so the composite is biased towards longer (red) wavelengths and is known as a *false colour composite* (FCC). However, false colours can still be related to habitats of interest and photographs are provided to relate the FCC to some of the mangrove habitats present in the area represented by the image. The other marine habitats described in this module are introduced by visually interpreting an image of Cockburn Harbour, South Caicos that was acquired using an airborne multispectral digital sensor called the Compact Airborne Spectrographic Imager (CASI: see Appendix 1.4).

Fieldwork is an essential part of any remote sensing study and the lesson ends with a discussion of how visual interpretation can aid the planning of field surveys.

Background Information

Chapters 4 and 10 of the *Remote Sensing Handbook for Tropical Coastal Management* discuss the use of visual interpretation for planning field surveys and habitat mapping respectively, and you are recommended to consult this book or similar texts for further details.

The *Bilko 3* image processing software

Familiarity with *Bilko 3* is required to carry out this lesson. Most of the lesson is confined to locating coordinates on images, interpreting images visually and matching areas of habitat on images to photographs taken during field survey. Tutorials 2 and 3 in the *Introduction to using the Bilko 3 image processing software* are particularly relevant and provide a good grounding for this lesson.

Image data

Most of the images used in this module are of the Turks and Caicos Islands, to the south-east of the Bahamas. The first image was acquired by a multispectral sensor (XS), which was mounted on the first three SPOT satellites. It was acquired on the 27th March 1995 at 15:28 hours Universal Time (i.e. at approximately 10:30 local time in the Turks and Caicos Islands). The full extent of this SPOT image is presented in Figure 1.1 but only a subset of the scene, centred on the South Caicos area, is provided here (see Figure 1.2 for location). SPOT XS has three spectral bands which are represented by the files ***SPOTXS_SCaicos#01.gif*** (green waveband), ***SPOTXS_SCaicos#02.gif*** (red waveband), and ***SPOTXS_SCaicos#03.gif*** (infra-red waveband). Following geometric correction and resampling, each pixel on this image covers 23 m x 23 m on the ground/sea (not 20 m x 20 m as you might expect).

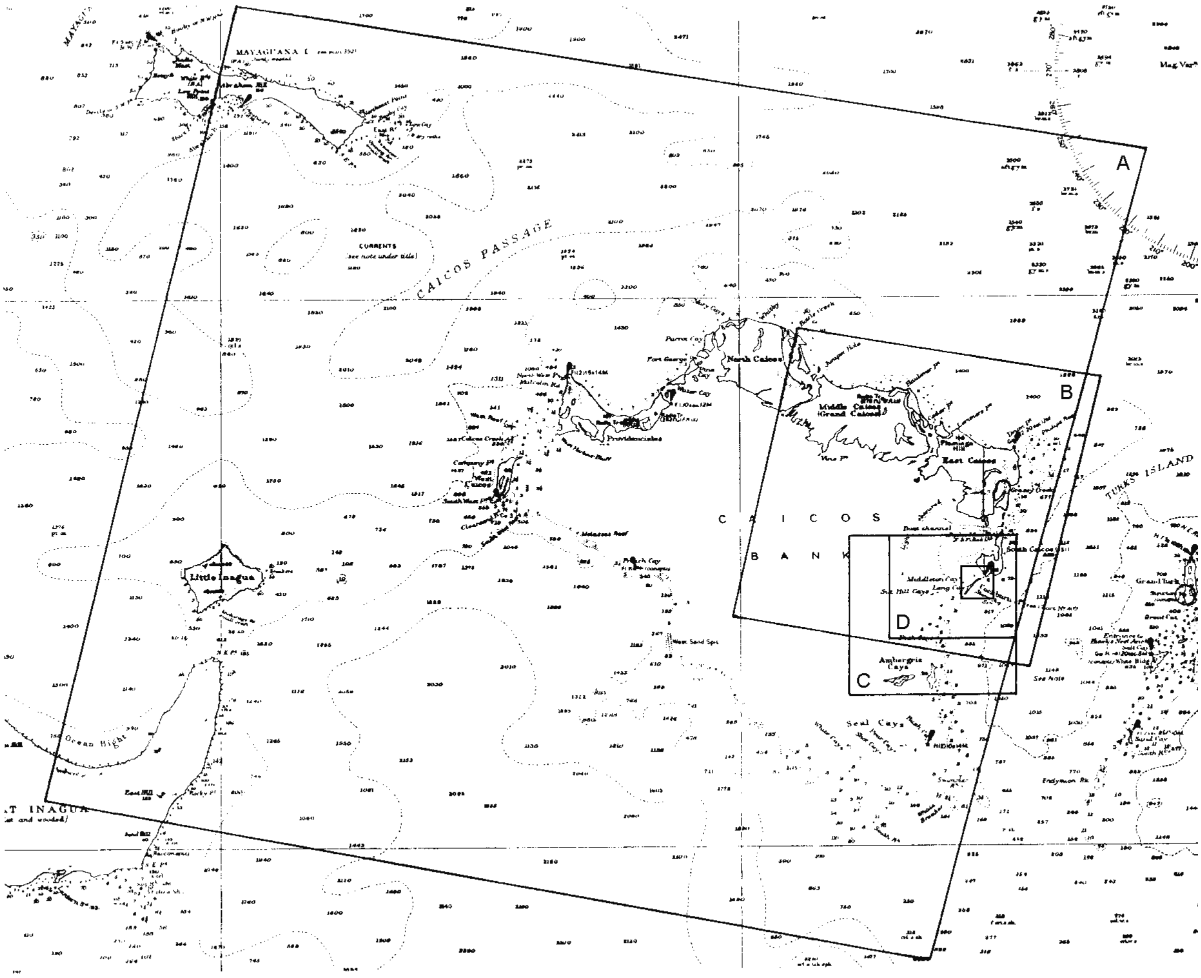
The second image (***CASI_Cockburn_Harbour#05+#03+#01.set***) is a colour composite of CASI data acquired for Cockburn Harbour (see inset of Figure 1.2). The CASI was mounted on a locally-owned Cessna 172N aircraft using a specially designed door with mounting brackets and streamlined cowling. An incident light sensor (ILS) was fixed to the fuselage so that simultaneous measurements of irradiance could be made. A Differential Global Positioning System (DGPS) was mounted to provide a record of the aircraft's flight path. Data were collected at a spatial resolution of 1 m^2 in 8 wavebands (Table 1.1) during flights over the Cockburn Harbour area of South Caicos, Turks and Caicos Islands (21^o 30' N, 71^o 30' W) in July 1995. Further details are given in Clark *et al.* (1997). Images were geometrically corrected using the UTM (zone 19) projection, Clarke 1866 spheroid and NAD27 (Bahamas) datum.

Table 1.1. Band settings used on the CASI.

Band	Part of electromagnetic spectrum	Wavelength (nm)
1	Blue	402.5 - 421.8
2	Blue	453.4 - 469.2
3	Green	531.1 - 543.5
4	Green	571.9 - 584.3
5	Red	630.7 - 643.2
6	Red	666.5 - 673.7
7	Near Infra-red	736.6 - 752.8
8	Near Infra-red	776.3 - 785.4

The CASI image displayed here was acquired at approximately 10 a.m. local time on 16 July 1995. For the purposes of this lesson, a colour composite image has been created and saved as a *Bilko* set comprising bands 1, 3 and 5 (Table 1.1). When the set is opened the 3 constituent bands (***CASI_Cockburn_Harbour#01.dat***, ***CASI_Cockburn_Harbour#03.dat*** and ***CASI_Cockburn_ Harbour#05.dat***) are opened and displayed through the blue, green and red guns respectively.

Figure 1.1. Location of the Landsat and SPOT scenes from which sub-scenes were taken and areas of two of the larger Landsat sub-scenes. Showing position on part of UK Hydrographic Office Admiralty Chart 1266 of the south-eastern Bahama Islands.



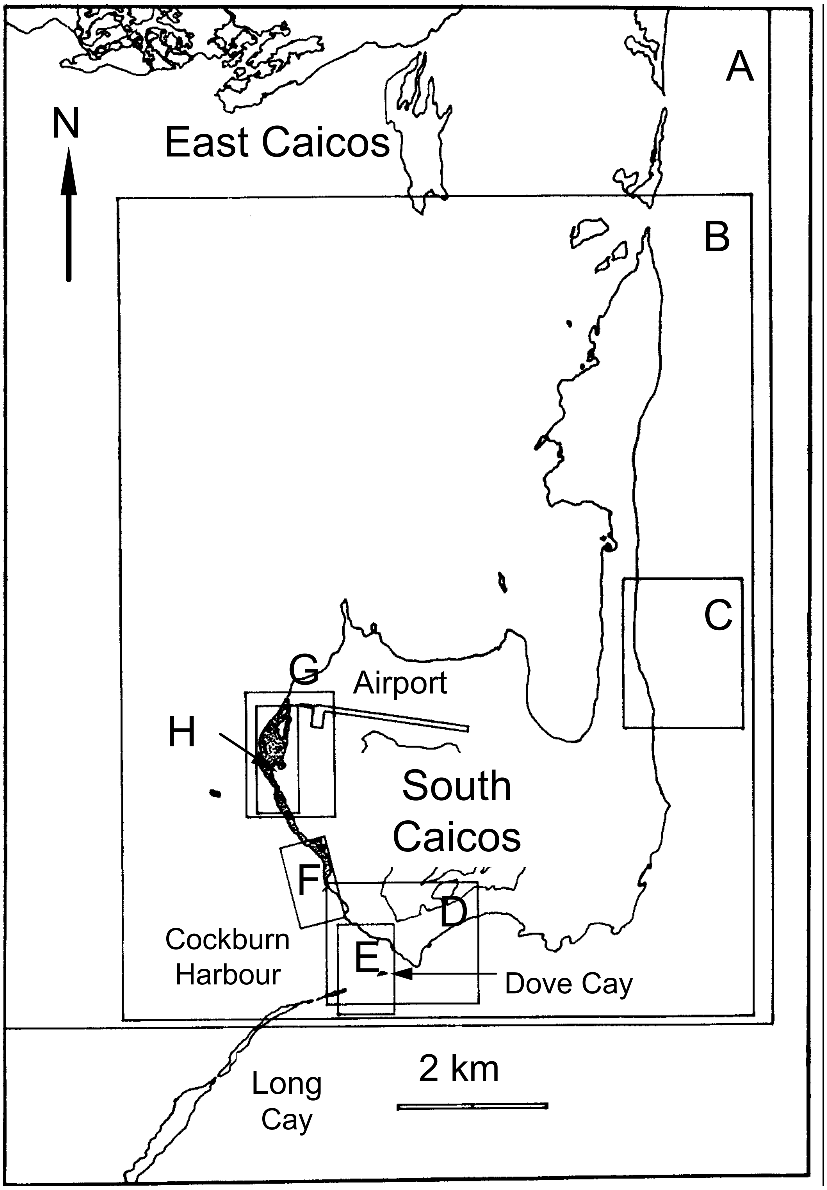
A. Approximate area covered by whole Landsat TM and MSS scenes (roughly 185 km x 185 km) from which sub-scenes were taken.

B. Area covered by whole SPOT XS and Pan scenes (60 km x 60 km) from which sub-scenes (see Figure 1.2) were taken. Note that one Landsat scene contains about 9 SPOT scenes.

C. Approximate area covered by Landsat MSS sub-scenes used in Lesson 2 (***LandsatMSS_Caicos#01.gif*** – ***LandsatMSS_Caicos#03.gif***) and Landsat TM sub-scene used in Lesson 6 on mapping bathymetry (***LandsatTM_bathymetric#01.gif*** – ***LandsatTM_bathymetric #04.gif***).

D. Location of Landsat TM sub-scenes used in Lesson 4 on radiometric correction. The small square within area D shows approximate location of IKONOS sub-scenes used in Lesson 2 to show appearance of 4 m multispectral and 1 m panchromatic satellite imagery.

Figure 1.2. South Caicos area to show locations of principal images used.
Mangrove areas on the west coast of South Caicos are stippled.



A. Boundaries of SPOT XS sub-scenes used in Lessons 1 and 2 (***SPOTXS_SCaicos#01.gif – SPOTXS_SCaicos#03.gif***).

B. Boundaries of SPOT Pan sub-scene used in Lesson 2 (***SPOTXP_SCaicos.gif***).

C. Location of aerial photographic sub-scene ***AP_east_SCaicos.gif*** used in Lesson 2.

D. Location of aerial photographic sub-scene ***AP_south_SCaicos.gif*** used in Lesson 2.

E. Location of CASI (Compact Airborne Spectrographic Imager) images used in Lessons 1 and 2 (***CASI_Cockburn_Harbour#05+#03+#01.set***) and in Lesson 7 on water column correction (***Casi_16-bit_SCaicos#02.dat – Casi_16-bit_SCaicos#05.dat***).

F. Approximate location of the CASI colour composite image of mangroves used in Lesson 2 (***CASI_mangrove#07+#05+#03.set***).

G. Location of aerial photographic subscene ***AP_mangrove_SCaicos.gif*** used in Lesson 2.

H. Location of CASI images used in Lesson 10 on assessing mangrove leaf area index (***Casi_mangrove#06.dat – Casi_mangrove#07.dat***).

Lesson Outline

Creation of a false colour composite from SPOT XS data

Your first task is to make a colour composite image of a geometrically corrected three-band SPOT sub scene of the island of South Caicos.

Activity: Launch *Bilko*. In the **File**, **Open** dialog box deselect **Extract** and **Minimize** (if these are checked). Then select ***SPOTXS_SCaicos#01.gif*** from the list of image files with the mouse pointer and with the <*Ctrl*> key held down select ***SPOTXS_SCaicos#02.gif*** and ***SPOTXS_SCaicos#03.gif*** also, then click on 

. This should open all three SPOT XS images at once.

Question: *1.1.* How many kilometres wide and long is the SPOT sub scene [*Hint:* interrogate the **Edit, Go To** dialog box after selecting the whole of an image in one band]?

Activity: Connect the three images using the **Image, Connect** function (highlight each with the cursor whilst depressing the <*Ctrl*> key, or select first and last images whilst depressing the <*Shift*> key), leaving the **Stacked** checkbox <u>unchecked</u>. Click on the **Selector** toolbar buttons so that the third connected image (***SPOTXS_SCaicos#03.gif*** – XS near-infra-red band) is designated image 1, the ***SPOTXS_SCaicos#02.gif*** (XS red band) as image 2, and ***SPOTXS_SCaicos#01.gif*** (XS green band) as image 3. Now select the **Image**, **Composite** function to make a false colour composite.

Remember that the image you designate 1 (@1) is displayed using the red gun of the computer monitor, image 2 using the green gun, and image 3 using the blue gun – hence the term RGB monitor.

Activity: Select the whole of the colour composite image using **Edit, Select All** or <*Ctrl*>+A and experiment with different stretches (**AutoLinear, Equalize** and **Gaussian**) to display the colour composite to full advantage. Choose the stretch that gives the greatest visual contrast. [We found the automatic linear stretch to be best.] Keep the colour composite image in the viewer but select and close all other images individually. Do not save any changes to image files.

Question: *1.2.* What principal colour is the land in the colour composite? Why is this? Why is the deep sea dark blue and shallow water cyan in colour?

Question: *1.3.* Between which approximate column and row (*x, y*) coordinates does the runway, including cleared areas at either end (see Figure 1.2 for location) on South Caicos Island run? Roughly how many kilometres long (to the nearest 0.1 km) is the runway?

Visual interpretation of SPOT XS Imagery of South Caicos

Part 1: Identification of mangrove habitats of South Caicos

You are now going to follow a transect across the mangrove fringing the coast starting at the water's edge. Mangrove forests often exhibit well-defined patterns of species zonation from the water's edge to the higher and drier land further within the forest. To simplify finding locations on the image we will use column and row coordinates rather than the Universal Transverse Mercator (UTM) Eastings and Northings to which the image is georeferenced.

Activity: If Eastings and Northings are displayed on the Status Bar then switch these off using **View, Coords**. Use the **Edit, Go To** command to place the cursor at *x, y* coordinates 179, 475 (make sure that the **Selection Type:** is set to Point Selection). If you cannot see the winking cursor, scroll down the image [*hint:* use mouse wheel, if present]. Position the mouse pointer over the cross and double-click. The image will zoom in. Double-click again. (*Note*: you can zoom out by depressing <*Ctrl*> whilst double-clicking)[1]. You should note a red coloured (high infra-red reflectance) belt along the west coast of the island, which corresponds to a mangrove stand. A northward-facing colour aerial photograph was taken at the position of the cursor. To view the photograph, use **File**, **Open** and select ***Mangrove_aerial.bmp***. The dark green band of mangrove is clearly visible along the waters edge. Note also the west end of the runway and channel just off the coast (compare positions on aerial photograph and SPOT image). Close the aerial photograph file.

Click on the false colour composite image and use the **Edit, Go To** command to place the cursor at each of the column (X:) and row (Y:) positions in Table 1.2. At each position, open the corresponding photograph which was taken during field work (*Hint*: Close each photograph before moving on to the next).

Table 1.2. Visual interpretation of SPOT XS data to examine mangrove zonation

Coordinates X:	Y:	Photograph file name	Notes
184	472	***Mangrove_red_short.bmp***	Fringing stand of short Red mangrove (*Rhizophora mangle*), which is usually found near the water's edge. This mangrove stand is continually advancing seaward making this a dynamic area of mangrove proliferation.
188	472	***Mangrove_red_tall. bmp***	A forest of tall Red mangrove (*Rhizophora mangle*), which can reach 7 m in height.
190	472	***Mangrove_black.bmp***	An area of tall Black mangrove (*Avicennia germinans*), which is usually found set back from the water's edge in drier environments.
194	472	***Mangrove_white.bmp***	The short, scrubby White mangrove (*Laguncularia racemosa*), which is found on higher ground where it is often interspersed with non-mangrove vegetation.

Part 2: Identification of some marine habitats in Cockburn Harbour

The second part of this section will focus on the main submerged habitats of Cockburn Harbour which lies to the south-east of the area you have just viewed for mangrove habitats (see Figure 1.2).

Activity: Use the **Edit, Go To** command to place the cursor at coordinates 205, 510. A colour aerial photograph was taken in a south-eastward direction at this point. To view the photograph, use **File**, **Open** to select the file ***Cockburn_harbour.bmp***. The coast of Cockburn Harbour is visible and the long island opposite is Long Cay whose northern-most point lies at position 222, 578 in the SPOT image. The foreground of the photograph shows a mosaic of seagrass beds and sand patches. Close the aerial photograph.

Using the **Edit, Go To** command, move the cursor to position 215, 536 in the SPOT composite image. Position the mouse pointer over the cursor and double-click on the image to zoom in further (or depress the <*Ctrl*> key and rotate the mouse-wheel). The image looks very dark in this area because the habitat there is dense seagrass, which has a generally low albedo. To see how this seagrass looks underwater, open the file ***Seagrass_dense.bmp***.

[1] For more controlled zooming in and out of an image, you can hold the <*Ctrl*> key depressed while rotating the mouse-wheel forwards (to zoom in) or backwards (to zoom out).

Close the photograph and move the cursor a few pixels eastwards to coordinate 218, 537. The reflectance is greater at this position due to the presence of bare sand (you may need to zoom in to a 7:1 ratio to see the brighter pixels). The sand habitat is illustrated in file ***Sand_habitat_CCC.bmp***.

Once you have completed this part of the lesson, close all files without saving their contents.

Visual interpretation of CASI imagery of Cockburn Harbour

To save you time the next colour composite has been saved as a *Bilko* "set". A set is just a text file that tells *Bilko* (i) which three images make up the colour composite and (ii) the order in which they should be opened. The order determines which colour gun each will be displayed through, with the first being displayed through the red gun, the second through the green, and third through the blue gun. Background pixels of the CASI image are set to zero and should be treated as null values.

Activity: Use **File**, **Open** to bring up the **Open** dialog box. Select SETS (*.set) from the **Files of type:** drop-down menu and open the set ***CASI_Cockburn_Harbour#05+#03+#01.set***, which is a colour composite of Cockburn Harbour, South Caicos taken with the CASI. In the **Redisplay Image** dialog box check the **Null value(s):** checkbox to set null value == 0 and select Auto linear stretch as the stretch to be used. Click the [All] button to apply the stretch and null value settings to all three bands and open the colour composite (and its constituent bands).

Examine the image [*hint:* a zoom of about 60% allows you to see most of the image at one time]. Note that if you click on a pixel in the image and examine the Status bar of the *Bilko* window, you can see the following information displayed: (i) the zoom %, (ii) the pixel's Universal Transverse Mercator (UTM) Easting and Northing coordinates, (iii) the pixel's underlying data values in the CASI band #5, band #3 and band #1 images respectively, and (iv) the pixel's display values (0–255) in the CASI band #5, band #3 and band #1 images respectively.

Question: *1.4.* Which CASI band is displayed through the red gun, what part of the EMS is this band in and what wavelengths in nanometres does the band stretch between? Which CASI band is displayed through the blue gun, what part of the EMS is this band in and what wavelengths in nanometres does the band stretch between? [See Table 1.1.]

The wiggly edge to the image is caused by the rolling of the aircraft as it flies along. The image represents the far (eastern) side of Cockburn Harbour as viewed in the aerial photograph ***Cockburn_harbour.bmp***. The CASI sensor itself can be viewed by opening the file ***Casi_sensor.bmp*** showing the instrument mounted in a specially designed door (for further details see *Image data* section above and Clark *et al*., 1997).

Many reef habitats can be identified in this image. To familiarise you with these habitats and introduce the skills of visual interpretation, you are provided with a series of column and row coordinates (easier to type in than UTM ones), photographs and interpretation notes (Table 1.3).

Activity: Switch from UTM coordinates to column and row coordinates by selecting **View, Coords** (**Coords** should not be ticked/checked). Now use the **Edit, Go To** command to relate the location (coordinate) of each site to the habitat. The notes should outline the mental decisions taken when identifying each habitat. Close each photograph before moving on to the next and zoom in and out of the CASI colour composite as necessary.

Table 1.3. Visual interpretation of CASI imagery to identify key marine habitats.

Co-ordinates X:	Y:	Habitat photograph file name	Description of habitat	Notes on visual interpretation / recognition of habitat on CASI image
630	182	***Brown_algae.bmp***	brown algae (*Lobophora variegata*) dominated	often located on hard substrata near the shoreline, happens to have brownish orange colour on composite
595	380	***Montastraea_colonies. bmp***	large coral heads (*Montastraea annularis*) on sandy bottom	distinctive heterogeneous texture: dark patches up to ~8 m across surrounded by paler sand
587	616	***Elkhorn_A-palmata_CCC.bmp***	large stands of elkorn coral (*Acropora palmata*)	usually located in shallow areas with high wave energy (e.g. reef crest, seaward side of islands)
490	889	***Montastraea_survey. bmp***	*Montastraea* reef – a mixed community of corals, algae and sponges. Of the hard corals, the genus *Montastraea* dominates	associated with the outer fringing reef (seaward of the reef crest or lagoon) and at depths where the wave exposure is reduced (i.e. 5 m plus)
377	852	***Sand_habitat_CCC. bmp***	sand gully in deep water (15 m depth)	high reflectance yet deep water indicating a strongly-reflecting substratum
356	498	***Gorgonian_plain.bmp***	plain dominated by soft corals (gorgonian plain)	this habitat often has a high percentage cover of bare substratum with a high reflectance. Therefore, its colour lies somewhere between sand and the shallowest areas of *Montastraea* reef
416	176	***Seagrass_dense.bmp***	dense seagrass (*Thalassia testudinum*)	usually distinctive dark patches of considerable extent (ranging from 15 m across in higher energy areas to 50–100s m across in more sheltered areas) which appear black in deeper water. Most obvious features are homogenous consistency (texture) and sharp boundaries
531	264	***Seagrass_sparse.bmp***	sparse seagrass	fairly homogeneous texture but the tone is much lighter than dense seagrass. Other features are relatively large (10–100 m across) patch size and indistinct boundaries
426	230	***Seagrass_blowout.bmp***	seagrass "blowout"	not a habitat but an important feature created by a loss of seagrass within a seagrass bed. Characteristic elliptical shape with high contrast between sand and dense seagrass

Activity: When you have finished studying the photographs and honing your visual identification skills, answer the following questions, giving your reasoning.

Question: *1.5.* What habitat would you expect to find at column and row coordinates 375, 64?

Question: *1.6.* What habitat would you expect to find at coordinates 455, 361?

Question: *1.7.* What habitat would you expect to find at coordinates 522, 412?

Question: *1.8.* What habitat would you expect to find at coordinates 132, 722?

Question: *1.9*. What habitat would you expect to find at coordinates 320, 87?

Activity: When you have answered the questions think about how you might a) define habitats so that other people will know what you mean, and b) how you might use remote sensing to help plan field surveys. Leave the CASI images open as you will need these later.

The habitats you have looked at in this lesson were defined from ecological field data. Bear in mind, however, that one person's understanding of a "habitat type" may vary from the next person's and thus, it is important to make a clear definition of habitats prior to undertaking a study. The objectives of most habitat mapping exercises fall into four groups:

(i) *ad-hoc* definition of habitats without collecting field data,

(ii) application-specific studies focused on only a few habitats,

(iii) geomorphological studies, and

(iv) ecological studies.

An *ad-hoc* approach to defining habitats is relatively cheap but is only recommended in the cases where the accuracy of habitat maps is not important. Habitat-specific studies (e.g. a seagrass study) should include the habitat of interest and those additional habitats that are most likely to be confused with it (e.g. macroalgae is easily confused with seagrass), thus permitting the accuracy of mapping to be evaluated. Geomorphological classifications can be assigned to imagery with little or no field work. The establishment of objective ecological habitat classifications (e.g. assemblages of bottom-dwelling species and substrata) usually requires multivariate analysis of field data, such as hierarchical cluster analysis. These methods simplify the dataset and provide a clearly defined basis to the classification scheme. The characteristic and discriminating features of each habitat can be identified and used to make a clear and unambiguous description of the classification scheme, thus facilitating its use and interpretation, and allowing later surveys in monitoring studies to compare their data. For further information, you are directed to Chapter 9 of the *Remote Sensing Handbook for Tropical Coastal Management*.

Use of visual interpretation when planning field surveys

Field survey is essential to identify the habitats present in a study area, to record the locations of habitats for supervised multispectral image classification (i.e. creation of habitat maps – see Lesson 8 of this module) and to obtain independent reference data to test the accuracy of resulting habitat maps. The efficiency of a field survey campaign can be maximised by making a visual interpretation of imagery during the planning stage.

Visual interpretation of imagery helps plan field survey in the following ways:

1. *Providing the location of known (and often target) habitats.*

2. *Providing the location of unknown habitats* (*i.e. habitats that cannot be identified using visual interpretation skills*). These habitats might become a priority of the field survey.

3. *Identifying the main physical environments of the study area*. The physical environment (e.g. depth, wave exposure, and aspect) will, to a large extent, control the distribution and nature of marine habitats. Relative depths can be inferred from most optical imagery (deeper areas are darker) and if the prevailing direction of winds and waves are known, the area can be stratified according to the major physical environments (e.g. Figure 1.3). If possible, each of these areas should be included in the survey, thus maximising the chances that the full range of marine habitats will be surveyed.

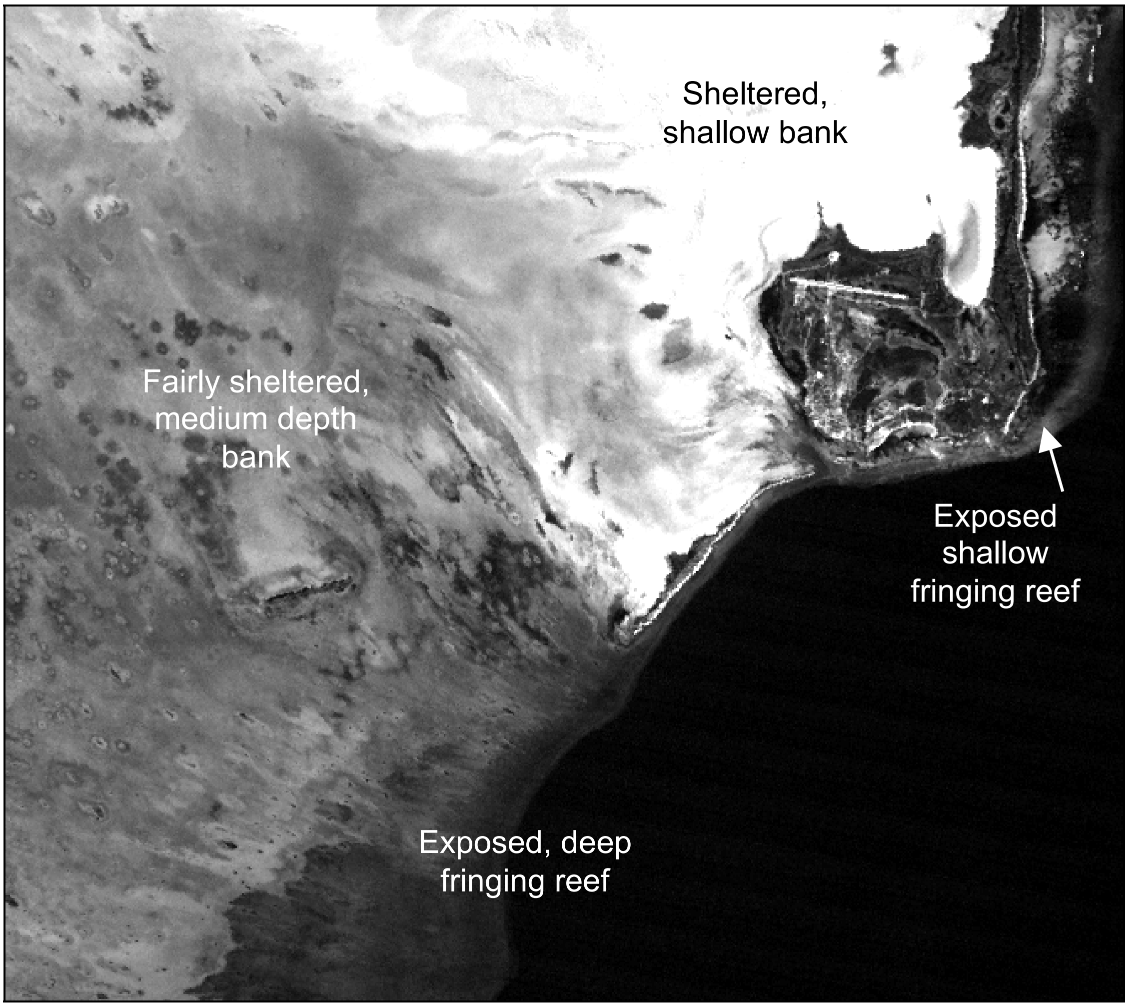


Figure 1.3. Principal physical environments of the Eastern Caicos Bank

4. *Identify the range of environmental conditions for each habitat*. Coastal areas will often possess gradients of water quality and suspended sediment concentration (e.g. plumes of sediment dispersing from an estuary). Changes in water quality across an image will alter the spectral reflectance of habitats measured by the remote sensor. For example, the spectral reflectance recorded for, say, coral sand will be greater in clear water than in turbid water. Field survey should therefore incorporate areas with different water quality so that the variation in spectral reflectance of each habitat is known throughout the image. Failure to do so may increase the degree of spectral confusion during image classification (or visual interpretation) and therefore the mis-assignment of habitat categories. If field surveys represent a full range of physical environments, the survey data can also be used to test the accuracy of the habitat maps and highlight the extent of any inaccuracies.

5. *Stratification of survey effort*. The field survey should attempt to include a reasonable number of samples from each habitat of interest. To achieve this goal efficiently, the distribution and coverage of habitats should be considered carefully. For example, the shallow sheltered bank in Figure 1.3 is visibly homogenous suggesting that the habitat type is fairly uniform throughout the area. It follows that relatively few field surveys should adequately represent this area; thus survey effort can be concentrated in areas with greater heterogeneity (e.g. the complex region of patch reefs in the fairly sheltered area with medium depth, Figure 1.3). For more details on sampling effort and accuracy assessment, readers are referred to the *Remote Sensing Handbook for Tropical Coastal Management* (Chapters 4, 10 and 19) and Congalton (1991).

Differential attenuation of light through the water column

We will now briefly look at the problems created by the fact that longer visible wavelength light (red end of the spectrum) is absorbed more as it passes through the water column than shorter wavelength light (blue end of the spectrum). You will firstly compare the light penetration in the 3 CASI bands and then examine one habitat (sand) at different depths.

Activity: Use **Image, Connect** to connect and stack the three constituent images which make up the CASI colour composite (***CASI_Cockburn_Harbour#01.dat***, ***CASI_Cockburn_Harbour#03.dat*** and ***CASI_Cockburn_Harbour#05.dat***). You should now have a stacked set with the top image (@1) being ***CASI_Cockburn_Harbour#01.dat*** and the bottom image (@3) being ***CASI_Cockburn_Harbour#05.dat***. Use either the *<Tab>* key or the Loop button to compare shallow water areas towards the top of the image for each band in turn. Note the good contrast in CASI bands #1 and #3 and relatively poor contrast and lower radiance in band #5 in the red part of the spectrum.

Repeat your comparison for the middle of the image and note how the red light is failing to return any significant signal from the seabed at depths over about 5 m. Repeat again for the south part of the image where water is deepest (around 18 m).

Your inspection of the three bands highlights two central problems in remote sensing of submerged habitats. Firstly, the same habitat will have very different radiances (pixel values) at different depths. Secondly, the way these values change with depth will be different for different wavebands. If we wish to classify submerged habitats on the basis of their multispectral reflectances (spectral signatures), this clearly presents a major problem. How you can deal with the problem is dealt with in Lesson 7. Meanwhile you can get a rough idea of the difference in the rates of attenuation of the red and blue wavebands by looking at sand pixels at 2 m and 15 m depth.

Activity: Close the stack (without saving anything) and make the colour composite the active image. Place the image cursor on coordinate 319, 860 in the sand gully in about 15 m depth. Note the underlying data values for each of the three composite bands from the Status bar (so that you can answer the questions below). Then place the image cursor on coordinate 653, 509 on the shallow sand patch at about 2 m depth off Dove Cay and note the underlying data values for each of the three composite bands here. In each case the habitat is white coral sand but in the first case it is deep and in the second shallow.

Question: *1.10.* (a) For the red band, what percentage of the 2 m deep pixel value is the 15 m deep pixel value? (b) For the blue band, what percentage of the 2 m deep pixel value is the 15 m deep pixel value? [Give your answer to the nearest whole %.]

Saving colour composites as pictures

If you need to illustrate a report (e.g., a *Word* document), scientific paper, or *Powerpoint* presentation with colour images like the colour composite you have been working with, you should save the composite as a Windows bitmap (***.bmp***) file in *Bilko*. However, if you wanted to continue to work with a colour composite image in *Bilko*, you would save it as a set.

Activity: With the colour composite (***CASI_Cockburn_Harbour#05+#03+#01.set***) as the active image select **File, Save As.** In the **Save As** dialog box, choose Windows .bmp as the **Save as type:** and click on **Save**. This will save the composite as a 24-bit Windows bitmap, giving a true colour image; this file can be inserted into *Word* documents or *Powerpoint* presentations using the **Insert, Picture, From File** menu option in these packages. Windows ***.bmp*** files can also have lettering, scale bars, labels, etc. added in photo editing packages, in *Powerpoint* or in *Word*. You may wish to experiment with this at some time.

Close all files (**Window, Close All**) and then reopen the Windows bitmap you have just created. Note that it faithfully shows the colour composite, with the **Redisplay** options you had applied at the time of saving. However, also note that it no longer has any UTM coordinates and that it lacks the three colour bars underneath, which indicate the stretches applied to each band. It is no longer a set of three 16-bit images, just a picture of how these were displayed at the time you saved the image. Close the bitmap.

References

Clark, C.D., Ripley, H.T., Green, E.P., Edwards, A.J., and Mumby, P.J. (1997). Mapping and measurement of tropical coastal environments with hyperspectral and high spatial resolution data. *International Journal of Remote Sensing* **18**: 237-242.

Congalton, R.G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment* **37**: 35-46.

Green, E.P., Mumby, P.J., Edwards, A.J. and Clark, C.D. (Ed. A.J. Edwards) (2000). *Remote Sensing Handbook for Tropical Coastal Management. Coastal Management Sourcebooks 3.* UNESCO, Paris. ISBN 92-3-103736-6 (paperback).

Answers to Questions

1.1. The easiest way to find out the size of the image is to select the whole SPOT XS subscene (any of the 3 bands will do) with *<Ctrl>*+A (or **Edit, Select All**) and then select **Edit, Go To.** You will see that the **Selection Size:** is 012650.0E (**DX:**) by 0013800.0S (**DY:**). This means that the image is 12650 m (= 12.65 km) wide and 13800 m (= 13.8 km) from north to south. Alternatively if you uncheck the **Coords** checkbox in the **Edit, Go To** dialog box you will see that the SPOT XS subscene is 550 pixels wide (**DX:**) and 600 pixels/lines long (**DY:**). Since each pixel is 23 x 23 m you can calculate that the image is 550 x 23 = 12650 m or 12.65 km across (west to east) and 600 x 23 = 13800 m or 13.8 km long (north to south). Another way is to switch off the display of the geographic coordinates (uncheck **View, Coords**), put the cursor on the last (bottom right) pixel of the image, and note that the status bar indicates you are on pixel 549, 599. You need to remember that the first pixel in the image (top left) is at coordinates 0, 0 so that you need to add one to both numbers to get the size of the image (550 columns by 600 rows). Multiplying by pixel size (23 m) gives you the image dimensions.

1.2. In the SPOT XS colour composite the land appears primarily red. This is because the sea tends to reflect more strongly in the green (displayed on the blue gun) and (where shallow) in the red part of the spectrum (displayed through the green gun) than the land. By contrast, the land (and particularly vegetation on the land) tends to reflect much more strongly in the infra-red (displayed through the red gun) than the sea, which strongly absorbs IR wavelengths. Thus in the false colour composite the land tends to appear dark on the blue and green guns but bright on the red gun. By contrast, deep sea areas are only bright on the blue gun, and shallow sea areas are bright on the blue and green guns (thus appearing cyan on the false colour composite).

1.3. The runway is on the northern side of the main (south) part of South Caicos, running west to east between approximate column and row (*x, y*) coordinates 205, 415 and 300, 430. This can be determined by laying a transect from the western to the eastern end of the runway and then selecting **Edit, Go To** with the **Coords** checkbox unchecked. This shows the column and row coordinates at the start of the transect (around 203, 414) and the number of columns (**DX:**) and rows (**DY:**) difference between the start and end of the transect (around 97 and 17 pixels respectively). Thus the end of the transect is at 203 + 97 = 300 and 414 + 17 = 431, that is at column and row coordinate 300, 431. By Pythagoras one can calculate the number of pixels between the two ends of the transect.

Hypotenuse = $\sqrt{97^2 + 17^2} = \sqrt{9409 + 209} = \sqrt{9698} = 98.5$ pixels. Pixel size is 23 m so length in metres = 98.5 x 23 = 2265 m. Thus the runway is about 2.3 km long.

Alternatively you can select to view geographic coordinates by clicking on the **Coords** checkbox in the **Go To** dialog box. This displays the east-west and north-south distances in metres between the two ends of the transect laid along the runway. This indicates around 2231 m east-west (**DX:**) and 391 m north-south (**DY:**). Using Pythagoras the hypotenuse (transect length) is = $\sqrt{2231^2 + 391^2} = \sqrt{4977361 + 152881} = \sqrt{5130242} = 2265$ metres or 2.3 km to the nearest 0.1 km.

1.4. CASI band #5 (***CASI_Cockburn_Harbour#05.dat***) is displayed through the red gun; this band is recorded in the red part of the EMS at wavelengths of 630.7–643.2 nm. CASI band #1 (***CASI_Cockburn_Harbour#01.dat***) is displayed through the blue gun; this band is recorded in the blue part of the EMS at wavelengths of 402.5–421.8 nm. [Data is presented in Table 1.1.] Note that set filename of the colour composite indicates the RGB (Red, Green, Blue) order of the constituent bands.

1.5. Brown algae; because the area is close to the rocky shoreline and the habitat appears similar to that at coordinate 630, 182.

1.6. Dense seagrass; because it is a very homogeneous very dark patch with distinct boundaries which appears similar to the dense seagrass patch identified at coordinate 416, 176.

1.7. Less dense seagrass; it has a similar texture and boundaries to the dense seagrass but appears less dark.

1.8. An Elkhorn coral (*Acropora palmata*) stand; because it appears similar in tone to the stand identified on Dove Cay at coordinates 587, 616 and is on the high wave-energy seaward end of Long Cay.

1.9. A small blowout in the seagrass bed; it looks similar but smaller than the blowout identified at coordinates 426, 230. The habitat within the blowout will largely be sand.

1.10. (a) The 15 m depth red band pixel has a value 127; the 2 m depth red band pixel has a value of 1979. It thus has 127/1979 = 6% of the value of the shallow water pixel. (b) The 15 m depth blue band pixel has a value of 574; the 2 m depth blue band pixel has a value of 1647. It thus has 574/1647 = 35% of the value of the shallow water pixel. The red wavelengths are clearly attenuating much faster than the blue wavelengths.

APPENDIX 1.1

LANDSAT THEMATIC MAPPER (TM) AND ENHANCED THEMATIC MAPPER (ETM+) SENSORS

The Landsat Thematic Mapper (TM) and its successor the Enhanced Thematic Mapper (ETM+) have been operational since 1984 following the launch of Landsat-4. The spatial resolution for the TM sensor is 30 m except for Band 6 which measures emitted thermal infra-red radiation and has a resolution of 120 m. For the ETM+ sensor the Band 6 spatial resolution was improved to 60 m and a panchromatic band (band 8: spectral range 520–900 nm) with a spatial resolution of 15 m was added. The radiometric resolution is 8 bits (256 grey levels). The swath width for the sensor is 185 km. At the time of this research (1995) the Thematic Mapper was only operational on Landsat-5 having failed on Landsat-4 in August 1993. Currently (2005) Landsat-7, launched in April 1999, is providing ETM+ imagery.

The spectral characteristics of the Landsat TM bands are as follows (ETM+ characteristics are included in parentheses where they differ):-

TM Band	Colour	Wavelengths (nm)	Uses
1	Blue	450–520 (450–515)	Good water penetration; useful for mapping shallow coastal water. Strong vegetation absorbance; good for differentiating soil from vegetation, and deciduous from coniferous vegetation.
2	Green	520–600 (525–605)	Designed to measure visible green reflectance peak of vegetation for vigour assessment. Also useful for sediment concentrations in turbid water.
3	Red	630–690	Strongly absorbed by chlorophyll; an important band for vegetation discrimination. Also good for detecting ferric (red coloured) pollution.
4	Near Infra-red	760–900 (750–900)	Very strong vegetation reflectance; useful for determining biomass. High land/water contrast so good for delineating water bodies/coastlines.
5	Short Wave Infra-red	1550–1750	Moisture sensitive; indicative of vegetation moisture content and soil moisture.
6	Thermal Infra-red	10,400–12,500	Used in vegetation stress analysis, soil moisture discrimination, and thermal mapping.
7	Short Wave Infra-red	2080–2350 (2090–2350)	Good for discriminating rock types.
PAN	Panchromatic	520–900	15 m spatial resolution (ETM+ only)

Images are produced by reflecting the radiance from 30 m wide scan lines on the Earth's surface to detectors on board the satellite using an oscillating mirror. Each scan line is 185 km long (thus the **swath width** or width of ground covered by the sensor in one overpass is 185 km). The Instantaneous Field of View (IFOV) of the TM sensor (roughly equivalent to the **spatial resolution**) is a 30 m x 30 m square on the Earth's surface except for the thermal infra-red Band 6 where it is 120 m x 120 m in TM and 60 m x 60 m in ETM+. A 15 m x 15 m pixel size panchromatic band was also added with

ETM+. Each **pixel** in a TM multispectral digital image is thus a measurement of the brightness of the radiance from a 30 m x 30 m square on the Earth's surface.

Because the satellite is moving so fast over the Earth's surface, the TM sensor had to scan 16 lines at a time or 4 lines at a time for Band 6 (thus covering 480 m along track on each scan). Since the TM sensor measures the radiance in seven different wavebands at the same time, it thus has 6 x 16 + 4 = 100 detectors in total. Each detector converts the recorded irradiance into an electrical signal, which is converted to an 8-bit number (256 grey levels). The **radiometric resolution** of the TM sensor is thus 4 times that of the Landsat Multi-Spectral Scanner.

The image size is 185 km across by 172 km along-track (170 km on ETM+); equivalent to 5760 lines by 6928 pixels. With seven wavebands each TM scene thus consists of about 246 Mbytes of data!

Further information on Landsat can be found at:

http://geo.arc.nasa.gov/esd/esdstaff/landsat/landsat.html

and

http://landsat.gsfc.nasa.gov/

APPENDIX 1.2

SPOT

SPOT (Satellite Pour l'Observation de la Terre) is a remote sensing satellite developed by the French National Space Centre (CNES - Centre National d' Études Spatials) in collaboration with Belgium and Sweden. SPOT-1 was launched in February 1986, SPOT-2 in January 1990, SPOT-3 in September 1993 (failed in November 1997), SPOT-4 in March 1998 and SPOT-5 in May 2002.

The SPOT images for these lessons are from the High Resolution Visible (HRV) sensor carried by SPOT-1 to SPOT-3. Each of these satellites carried two High Resolution Visible (HRV) sensors. The HRV sensor is a "pushbroom scanner" which can operate in either multispectral mode (3 wavebands) at 20 m resolution (XS), or in panchromatic mode (1 waveband) at 10 m resolution (XP or Pan). Radiometric resolution is 8 bits (256 grey levels) in multispectral mode and 6 bits (64 grey levels) in panchromatic mode. The swath width is 60 km per HRV sensor and images are supplied as 60 x 60 km scenes. The two HRV sensors overlap by 3 km giving a swath width of 117 km for the satellite as a whole. SPOT-4 and SPOT-5 sensors have enhanced capabilities with an additional short-wave infrared band on SPOT-4 and enhanced spatial resolution for all bands on SPOT-5 (see http://www.spotimage.fr/ for details).

The mirror which focuses the light reflected from the ground-track onto the detector array can be angled by ground control through ± 27° allowing off-nadir viewing within a strip 475 km to either side of the ground-track. Using the mirror, stereoscopic imagery can be obtained by imaging a target area obliquely from both sides on successive passes. The mirror also allows target areas to be viewed repeatedly (revisited) on successive passes such that at the Equator an area can be imaged on 7 successive days, whilst at latitude 45° eleven revisits are possible.

The detectors are Charge Coupled Devices (CCDs)† which form a solid state linear array about 8 cm long. Each pixel across the scan line is viewed by an individual detector in the array so that in panchromatic mode there are 6000 detectors each viewing a 10 m square pixel, whilst in multispectral mode there are 3000 detectors each viewing a 20 m square pixel on the Earth's surface. The linear array is pushed forward over the Earth's surface by the motion of the satellite, hence the name "pushbroom scanner".

†CCDs are light sensitive capacitors which are charged up in proportion to the incident radiation and discharged very quickly to give an electrical signal proportional to the radiance recorded.

Orbital characteristics

1) Near-polar sun-synchronous orbit.
2) Altitude of 832 km.
3) Equatorial crossing time at 10:30 h.
4) Repeat cycle 26 days.

HRV sensor spectral characteristics (SPOT 1 to 3)

Multispectral (XS)	Pixel size	**Spectral band**
Band 1: Green	20 m	500–590 nm
Band 2: Red	20 m	610–680 nm
Band 3: Near-IR	20 m	780–890 nm
Panchromatic (XP)	10 m	500–730 nm

Images in either multispectral mode (XS) or panchromatic mode (XP) can be purchased.

APPENDIX 1.3

IKONOS

The launch of the IKONOS-2 satellite in September 1999 provided the first commercial high-resolution satellite imagery. The spectral resolution for its 4 multispectral bands are more or less identical to those of Landsat TM (and ETM+) bands 1 to 4, but it spatial resolution is such that for each Landsat TM pixel there are around 50 IKONOS multispectral pixels or 900 panchromatic pixels.

IKONOS sensor spectral characteristics

Multispectral	Pixel size	**Spectral band**
Band 1: Blue	4 m	450–520 nm
Band 2: Green	4 m	510–600 nm
Band 3: Red	4 m	630–700 nm
Band 4: Near-IR	4 m	760–850 nm
Panchromatic	1 m	450–900 nm

Radiometric resolution is 11 bits compared to 8 bits for Landsat TM (ETM+).

Orbital characteristics

1) Near-polar sun-synchronous orbit.
2) Altitude of 680 km.
3) Equatorial crossing time at 10:30 h.

Details of IKONOS can be found at:

http://www.spaceimaging.com/products/ikonos

APPENDIX 1.4

Compact Airborne Spectrographic Imager (CASI)

CASI is a pushbroom imaging spectrograph designed for remote sensing from small aircraft. The instrument used to obtain the images used in these lessons comprises a two-dimensional 578 x 288 array of CCD (Charge Coupled Device) detectors. It is light (55 kg) and can be mounted in an aircraft as small as a Cessna 172 (single-engine, four seats). A modified Cessna door in which the instrument can be mounted is available so that CASI can be mounted without making holes in the aircraft. It requires only 250 Watt of power and can be run off a light aircraft's power circuit in most cases. If not, it can be run off a heavy-duty lead-acid battery. CASI is manufactured by ITRES Research of Calgary, Alberta, Canada. Details of later CASI models (CASI-2 and CASI-3 systems) can be found at:

http://www.itres.com/docs/sensors.html

Details of the CASI sensor used to obtain the images for these lessons follow. The width of the array was 578 detectors, which in imaging mode viewed a strip 512 pixels wide underneath the aircraft (the remaining 64 detectors being used for calibration purposes). The angle of view was 35° and the width of this strip and size of the pixels was determined by the height of the aircraft. At an altitude of 840 m (2750 feet) pixels were 1 m wide, at about 2500 m they were 3 m wide. The speed of the aircraft and scanning rate of the instrument are adjusted to make the pixels square. The instrument could scan at up to 100 lines per second and was designed for spatial resolutions of 1–10 m. The 288 detectors per pixel allowed up to 288 different spectral bands (channels) to be sampled across a spectral range of about 400–900 nm. The minimum bandwidth was 1.8 nm. The radiometric resolution was 12 bits (4096 grey levels).

In **imaging mode** a set of up to 16 spectral bands were chosen and the instrument was programmed to record in these bands. At 1 m resolution it was found feasible to record in only 8 wavebands because of the rate of data acquisition required, whilst at 3 m resolution it was possible to record in 16 wavebands. A 16 band marine band-setting optimised for water penetration was used for flight-lines over water, and a 16 band terrestrial band-setting optimised for mangrove and vegetation mapping was used over land. Band settings could be switched in flight. Locating pixels accurately for ground-truthing at this high spatial resolution requires a good **differential global positioning system** (DGPS).

In **multispectrometer mode** the instrument recorded in 288 different 1.8 nm wide bands for up to 39 look directions (pixels at a time) across the swath width. This allowed detailed spectral signatures of pixels to be built up. The difficulty is in determining precisely where these pixels are and then ground-truthing them so that spectral signatures can be assigned to defined habitats.

CASI-3 offers spatial resolutions as good as 0.5 m and at 1 m spatial resolution has a swath width of 1480 m as opposed to the 512 m offered by the instrument we used in 1995. It also has a radiometric resolution of 14-bits and spectral range of 400 to 1050 nm.

2: THE IMPORTANCE OF ACQUIRING IMAGES OF THE APPROPRIATE SCALE AND SPATIAL RESOLUTION FOR YOUR OBJECTIVES

Aim of Lesson

To demonstrate the effects of image spatial resolution (ranging from 1 m to 80 m) on your ability to discriminate between different coastal habitats.

Objectives

1. To investigate how different major features appear at a range of spatial resolutions.
2. To investigate the effect of image pixel size on habitat identification.
3. To use transects across images to determine the spatial frequency of key habitats.

Overview of Lesson

A wide variety of remotely-sensed imagery is available for coastal habitat mapping and therefore one of the most important questions to consider when planning a remote sensing project is, "Which imagery will allow me to map the habitats of interest?". The answer to the question depends largely on the size of the habitat of interest. Remote-sensing instruments divide the Earth's surface into a grid of sampling units called "pixels" whose spatial dimensions depend on the altitude and design of the sensor. The pixel size roughly equates to the spatial resolution of the sensor. For example, each pixel in a SPOT multispectral image (XS) measures 20 m by 20 m and thus the smallest linear dimension on the Earth's surface that can be resolved in SPOT XS images is roughly 20 m. In order to map the boundaries of a given habitat, the spatial resolution of the imagery should be smaller than the minimum size of the habitat. This means that SPOT XS is poor at detecting habitats whose average patch-size is less than 20 m x 20 m.

The spatial resolutions of a range of widely used remote-sensing sensors are listed in Table 2.1. Although spatial resolution is a key consideration when selecting a remote-sensing method (and we dwell upon it in this lesson), other considerations must also be taken into account. In terms of sensor specifications, the most important of these are the number of useful spectral bands and the area covered by the image. In short, the greater the number of spectral bands, the greater the likelihood that you can identify habitats correctly during image processing. For example, two different habitats might have the same overall colour when viewed in a single band of blue light, but their appearances might differ markedly if viewed in blue, green and red bands simultaneously.

An important aspect of spatial scale is texture. In a remote-sensing context, texture describes the structure or pattern of a feature in the imagery. Texture can be fairly simple and uniform or complex and patchy. Many habitats have a characteristic texture (patchiness), which, if considered, can greatly improve the chances of correctly identifying habitats in image data. To measure the texture of habitats using remote sensing, the spatial resolution of the imagery must be similar in size to the smallest patch that makes up a particular pattern or texture. For example, imagine a sparse seagrass bed comprising small patches with an average width of 5 m. Although the entire bed of sparse seagrass may have a width of, say, 100 m, the imagery would need a spatial resolution of 5 m, or less, to detect its texture. Statistical measures of texture (e.g., inter-pixel variance) are available which measure the local variability in pixel reflectance, but you will make a qualitative assessment of texture in this lesson.

Table 2.1. Principal specifications of satellite (above), and airborne digital and aerial photographic imagery (below) used in lessons.

Specification	Landsat MSS	Landsat TM	SPOT XS	SPOT Pan	IKONOS multispectral	IKONOS panchromatic
Spatial resolution	80 m	30 m	20 m	10 m	4 m	1 m
No. of spectral bands for habitat mapping	4	6	3	1	4	1
Area covered (km)	185 x 185	185 x 170	60 x 60	60 x 60	variable	variable

Specification	CASI (airborne)	Aerial Photography
Spatial resolution	0.5 m to 10 m	variable (>0.2 m)
No. of spectral bands for habitat mapping	8-21 *user defined*	1-3 † *analogue*
Area covered (km)	variable	variable

† One band for monochrome aerial photography, three bands if colour aerial photography is scanned in the red, green and blue.

This lesson will focus on the importance of matching the spatial scale of coastal habitats to the spatial scale of imagery. To begin with, you will measure the spatial frequency (average patch size) of some key habitats. These measurements will be based on airborne imagery, which usually has the highest spatial resolution. With these measures of spatial frequency in mind, you will then predict whether various types of remotely-sensed data are capable of detecting these habitats. You will then see for yourself by comparing images whose spatial resolution varies between 2 m and 30 m.

It is worth noting in passing that the term “descriptive resolution” has been coined to describe the detail to which a sensor can map a given area. For mapping benthic habitats, a coarse descriptive resolution would only separate habitats into broad classes, e.g. coral, algae, sand, and seagrass. A finer descriptive resolution would also distinguish reef zones, variations in seagrass standing crop and so on.

Background Information

The capability of different sensors for mapping coral reef, seagrass and mangrove habitats are discussed in detail in Chapters 11–13 of the *Remote Sensing Handbook for Tropical Coastal Management* and papers by Mumby *et al*. and Green *et al*. (see *References* section for this lesson).

The *Bilko 3* image processing software

Familiarity with *Bilko 3* and Lesson 1 of this module are required to carry out this lesson. Readers who are not familiar with the Turks and Caicos or the appearance of coral reef, seagrass and mangrove habitats should undertake Lesson 1 before continuing further. You will need experience of using the image cursor to examine and interpret images and of making colour composite images. These features are covered in Tutorials 2 and 3 of the *Introduction to using the Bilko 3 image processing software*.

Image data

All images used in this module were acquired around the island of South Caicos, Turks and Caicos Islands (see Figure 1.1, Lesson 1 for a map). Images are supplied at a range of spatial resolutions (Table 2.2), the most detailed of which is CASI and IKONOS panchromatic. *Note:* When geometric correction and other processing are carried out, the pixel size may be changed from the original size (a process called resampling). Spatial resolution and **actual pixel sizes** are shown in Table 2.2.

You are supplied with three spectral bands of sub-scenes of multispectral satellite images at four different spatial resolutions (Landsat MSS [80 m]: Appendix 2.1; Landsat TM [30 m]: Appendix 1.1; SPOT XS [20 m]: Appendix 1.2; IKONOS [4 m]: Appendix 1.3). These can be viewed individually or connected to make false colour composites. You are also supplied with sub-scenes of SPOT (Appendix 1.2) and IKONOS (Appendix 1.3) panchromatic (single-band recorded across the visible spectrum) images at 10 m and 1 m resolution respectively and some subscenes from monochrome aerial photographs scanned so that each pixel is 2 x 2 m on the ground. You are also provided with sets of 3 bands of two airborne multispectral CASI images (Appendix 1.3) taken at 1 m spatial resolution.

Table 2.2. Images used in this lesson and their principal specifications. Monochrome aerial photographs © Ordnance Survey. **† The actual pixel size in the images is included in brackets.**

Image type	Platform	Acquisition date	Spatial resolution (m)†	File Names
CASI	aircraft	16/07/95	1 (1 x 1.1)	***CASI_mangrove#03.dat*** ***CASI_mangrove#05.dat*** ***CASI_mangrove#07.dat*** ***CASI_Cockburn_Harbour#01.dat*** ***CASI_Cockburn_Harbour#03.dat*** ***CASI_Cockburn_Harbour#05.dat***
IKONOS panchromatic	satellite	March 2001	1	***Ikonos_Caicos_pan.dat***
Monochrome aerial photography	aircraft	1981	2	***AP_east_SCaicos.gif*** ***AP_south_SCaicos.gif*** ***AP_mangrove_SCaicos.gif***
IKONOS multispectral	satellite	March 2001	4	***Ikonos_Caicos#01.dat*** ***Ikonos_Caicos#02.dat*** ***Ikonos_Caicos#03.dat*** ***Ikonos_Caicos#04.dat***
SPOT panchromatic	satellite	27/03/95	10 (12)	***SPOTXP_SCaicos.gif***
SPOT XS	satellite	27/03/95	20 (23)	***SPOTXS_SCaicos#01.gif,*** ***SPOTXS_SCaicos#02.gif,*** ***SPOTXS_SCaicos#03.gif***
Landsat TM	satellite	22/11/90	30 (33)	***LandsatTM_SCaicos#01.gif,*** ***LandsatTM_SCaicos#02.gif*** ***LandsatTM_SCaicos#03.gif***
Landsat MSS	satellite	28/06/92	80 (66)	***LandsatMSS_Caicos#01.gif*** ***LandsatMSS_Caicos#02.gif*** ***LandsatMSS_Caicos#03.gif***

The CASI was mounted on a locally-owned Cessna 172N aircraft using a specially designed door with mounting brackets and streamlined cowling. An incident light sensor (ILS) was fixed to the fuselage so that simultaneous measurements of irradiance could be made. A Differential Global Positioning System (DGPS) was mounted to provide a record of the aircraft's flight path. Data were collected at a spatial resolution of 1 m^2 in 8 wavebands (Table 2.3) during flights over the Cockburn Harbour area of South Caicos. Further details are given in Clark *et al.* (1997). The two CASI images have been made into false colour composites and then saved as the *Bilko* sets ***CASI_Cockburn_Harbour#05+#03+#01.set*** and ***CASI_mangrove#07+#05+#03.set*** to save you time.

Table 2.3. Band settings used on the CASI.

Band	Part of electromagnetic spectrum	Wavelength (nm)
1	Blue	402.5–421.8
2	Blue	453.4–469.2
3	Green	531.1–543.5
4	Green	571.9–584.3
5	Red	630.7–643.2
6	Red	666.5–673.7
7	Near Infrared	736.6–752.8
8	Near Infrared	776.3–785.4

Lesson Outline

The activities in this lesson are divided into four parts:

1. Taking spatial measurements from various images with a view to becoming familiar with spatial resolution.
2. Measurement of the spatial frequency of mangrove habitats followed by an examination of imagery to see whether the habitats are visible.
3. Measurement of the spatial frequency of some seagrass and coral features. You will then use this knowledge to predict the spatial scales at which these features can be detected using remote sensing. Your predictions will be tested by viewing imagery of various spatial resolutions.
4. The use of texture when interpreting remotely-sensed imagery. You will be provided with imagery at two spatial scales and asked to compare your ability to identify habitats in each.

Part 1. Taking measurements and comparing spatial resolutions of imagery

For this part of the lesson you will use imagery at three spatial resolutions: aerial photography (2 m), SPOT Pan (10 m), and Landsat MSS (80 m). The aim is to estimate the width of the landing strip at South Caicos international airport using each image type and in so doing, gain a practical feel for various spatial resolutions. Measurements will be made by recording several measurements of the number of pixels or metres (for images with UTM coordinates) across the landing strip and then taking their mean to calculate the width of the landing strip. Since the landing strip is more or less east-west, it is not thought worthwhile using Pythagoras to refine the measurements.

Activity: Launch *Bilko* and use **File**, **Open** to view the monochrome photograph, ***AP_mangrove_SCaicos.gif***.

Question: *2.1.* What is the width of the area covered by the aerial photograph on the ground in km (to the nearest 0.1 km)?

Activity: Using **Edit**, **Go To**, place the cursor at coordinate (519, 64), which marks the northern side of the landing strip. Place the mouse cursor at the cross-hairs and double-click to zoom in[1] to 300–400% (see Status bar for zoom). [Alternatively, hold down *<Ctrl>* and rotate your mouse-wheel forwards to zoom in and backwards to zoom out.] The landing strip should be clearly visible and comprises three zones – two white areas of pavement surrounding a dark area of tarmac runway. For this exercise, the "landing strip" is defined as both the runway and areas of pavement surrounding it.

Click on the transect tool. Place the mouse pointer at the northern side of the landing strip (519, 64) and, keeping the left mouse-button depressed, drag it down to the far side of the landing strip and release. Cursor coordinates should now read approximately (514, 102). (*Note*: Since the landing strip does not run exactly from west to east so your cross-runway transect will be at a slight angle to the vertical.) Click on **Edit**, **Go To** in order to display the **Go To** dialog box. This should have Line selection highlighted under **Selection Type:**. Under **Selection Size**, the value **DX:** should be a small negative number as the runway does not due east-west. The value **DY:** represents the number of pixels across the landing strip. Enter this value into Table 2.4. Take two or more transects to the east of the first and note the widths in pixels in Table 2.4. Once you have three or more measurements, calculate their mean and use this to calculate the width of the landing strip. Enter your width calculated from Aerial photography in Table 2.4 .

[1] *Note:* Using *<Ctrl>*+double-click zooms out.

Table 2.4. Width of landing strip at South Caicos airport

Image type	Measurements across landing strip (pixels or metres)	Pixel size (m)	Width of landing strip (m)
Aerial photography		2	
SPOT Pan (XP)		12	
Landsat MSS		66	

Activity: Close the ***AP_mangrove_SCaicos.gif*** file and open the SPOT Pan image, ***SPOTXP_SCaicos.gif***.

Question: *2.2.* What is the width of the area covered by the SPOT Pan subscene on the ground in km (to the nearest 0.01 km)?

Activity: When you have answered the question, use **Edit**, **Go To** to place the cursor at UTM coordinate (237238E, 2381303N) and zoom in to about 500%. The landing strip should be clearly visible although the boundaries are not as clear as those in the aerial photograph. Using the methods set out above (except that you will be able to read off distance in metres), measure the width of the landing strip at coordinate 237238E, 2381303N and at various other points along the landing strip where the boundary is reasonably clear. Enter your measurements in Table 2.4. [*Note:* If you drag the transect from north to south the **DY:** gives you the distance in metres S of starting coordinate.] If you have a range of values for landing strip width, take the average as your best estimate of the landing strip width.

Question: *2.3.* Is there any difference between the average width estimated using aerial photography and SPOT Pan? If there is a difference, how does it relate to the spatial resolution of SPOT Pan (i.e. 10 m)?

Activity: Close ***SPOTXP_SCaicos.gif*** and open ***LandsatMSS_Caicos#02.gif***, which is band #2 (green) of the Landsat MSS image. Use *<Ctrl>+A* to select all pixels in the image and apply a contrast stretch using **Stretch**, **Auto Linear**.

Question: *2.4.* What is the width of the area covered by the MSS subscene on the ground in km (to the nearest 0.1 km)?

Use **Edit**, **Go To** to move the cursor to coordinate (237303E, 2381329N). Examine the image at its current magnification.

Question: *2.5.* Is the landing strip visible?

Position the mouse pointer at the cursor and zoom in. The landing strip will probably become progressively more difficult to identify as you zoom in. Our eyesight is good at picking out the general linear shape of the landing strip at low magnifications but less so at higher magnifications where less of the feature is visible. At a starting point of (237303E, 2381329N), enter the number of pixels that seem to comprise the width of the landing strip (Table 2.4). [Note: The image cursor sits on the mid-point of the selected pixel.]

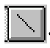
Question: *2.6.* Would you have much confidence in your estimate of landing strip width from the MSS image? Which of the three remote-sensing sensors you have tested, would you recommend for mapping roads of South Caicos (you may list more than one)?

Close the ***LandsatMSS_Caicos#02.gif*** image.

Part 2. Spatial scales and mangrove mapping.

You are provided with a false colour composite of part of a CASI image of Cockburn Harbour and the mangroves on the west coast of South Caicos (***CASI_mangrove#07+#05+#03.set***). Although a variety of habitats exist here (see Lesson 1), we will focus on mangrove at two levels of descriptive resolution. The first is the entire fringe of mangrove forest, which encompasses a variety of sub-habitats, and is simply termed "mangrove". The second is a sub-class of mangrove dominated by the red mangrove, *Rhizophora mangle*. An isolated circular patch of mangrove trees just off the coast of South Caicos is a good example of this habitat.

Activity: Open the composite, which has been saved as the *Bilko* set ***CASI_mangrove #07+#05+#03.set***. In the **Redisplay Image** dialog box, set null value to zero, select an automatic linear stretch and click on the **All** button to apply these settings to all three images making up the composite. The mangrove appears as red because the near infra-red band #7, which vegetation reflects strongly, is displayed through the red gun. At the bottom of the image (scroll down as necessary) you can see part of the Cockburn Harbour settlement and several piers.

Use **Edit**, **Go To** to place the cursor on the circular patch of *Rhizophora* lying just offshore at coordinate (237040E, 2379098N). Zoom in to about 400%. Calculate the diameter of the patch in the horizontal plane starting at coordinates (237022E, 2379099.7N) using the transect tool . [*Hint*: once you have dragged the transect over the patch, use **Edit**, **Go To** to find the number of metres (**DX:**) across.] Enter the distance in Table 2.5. Move the cursor to coordinate (237039E, 2379082.1N) at the north end of the patch and measure the vertical diameter of the patch (this time enter the distance in **DY:** into Table 2.5). Calculate the average diameter of the patch, entering your results in Table 2.5. The area of a circle is calculated using the formula below where the radius is half the diameter and $\pi = 3.142$.

$$\text{area of circle} = \pi \times (\text{radius})^2$$

Question: *2.7.* Using your measurement of patch diameter, what is the area of the circular red mangrove patch (to nearest whole m^2)?

Activity: Zoom out a bit. Using the coordinates in Table 2.5, measure the width of the fringing "mangrove" (estimate the distance from the waters edge to the inland (non-red) edge of the mangrove) perpendicular to the coastline. For example, if you place the cursor at (236817E, 2379531N) and lay a transect across the mangrove you should get a **DX:** of about 38 m and **DY:** of about 45.1 m. Note the **DX:** and **DY:** for each transect in Table 2.5 and then use Pythagoras to calculate distance along the hypotenuse. This is done for you for the first transect to save you time.

$$\text{Length of transect} = \sqrt{\text{DX}^2 + \text{DY}^2}$$

Question: *2.8.* What is the average width of fringing mangrove based on the three transects in Table 2.5.?

Table 2.5. Measuring the dimensions of two mangrove habitats.

Habitat	*Rhizophora mangle* patch		Fringing mangrove		
Starting position of transect (X:, Y:)	237022E, 2379099.7N (DX:)	237039E, 2379082.1N (DY:)	236817E, 2379531N (DX:, DY:)	236897E, 2379460N (DX:, DY:)	236992E, 2379379N (DX:, DY:)
Habitat diameter/DX:, DY: (m)			38.0, 45.1		
Mean diameter/width of fringe (m)			59.0		

To make a rough estimate of the area of this mangrove fringe on the northern part of the image (north of the gap in the mangrove fringe) one can measure its length by using the mouse pointer to lay a transect parallel to the coast along the middle of the mangrove fringe. Such a transect might begin in the extreme NW of the image at around (236726E, 2379655N) and end around (237085E, 2379315N).

Activity: Use the mouse pointer and transect tool to lay a transect along the length of the middle of the northern mangrove fringe parallel to the coast. Select **Edit, Go To** and read off the **DX:** (metres W–E) and **DY:** (metres N–S) of the transect and use Pythagoras's theorem to work out its length as follows:

$$\text{Length of transect} = \sqrt{\text{DX}^2 + \text{DY}^2}$$

Question: *2.9.* a) What is the length of the transect in metres (to nearest m)? b) Using the average width of the mangrove fringe calculated earlier, what is the **approximate** area in hectares (to nearest 0.1 ha) of the fringing mangrove in the northern part of the image? [*Hint:* Treat the area as a rectangle.]

Keeping ***CASI_mangrove#07+#05+#03.set*** composite available for future comparisons, you will now create a false colour composite from the three SPOT XS imagery bands (***SPOTXS_SCaicos#01.gif – SPOTXS_SCaicos#03.gif***).

Activity: Close the three constituent images of the CASI false colour composite and minimize the ***CASI_mangrove#07+#05+#03.set*** image. Open the SPOT XS image files ***SPOTXS_SCaicos#01.gif, SPOTXS_SCaicos#02.gif*** and ***SPOTXS_SCaicos#03.gif***. Connect the three images using the **Image, Connect** command (highlight each with the cursor whilst depressing the <*Ctrl*> key). Set the **Selector** toolbar so that the XS band #3 image is 1, the XS band #2 image is 2, and the XS band #1 image is 3 (thus displaying them on the red, green and blue guns respectively in a colour composite).

Select the **Image**, **Composite** command to make a colour composite. Then use the **Edit**, **Select All** command (or <*Ctrl*>+<*A*>) to select all pixels in the image, and to improve the contrast within the image, apply an automatic linear stretch (click on the **Stretch** menu and apply the stretch, **Auto Linear**). [*Checkpoint:* The land should be bright red and the sea turquoise and blue if the images have been combined properly.] Select **Save As** to save the colour composite as a *Bilko* set, ***SPOTXS_SCaicos#03+#02+#01.set,*** as you will need it in Part 4 of this lesson. Then close the connected tiled image and constituent SPOT images individually, leaving only the composites open. Do not save any changes to these other image files.

Use the **Edit**, **Go To** command to move to coordinates (237045E, 2379095N) on the SPOT composite then zoom in to around 450%. The mangrove area is visible as a red fringe but with much less detail than in the CASI image viewed earlier. The patch of *Rhizophora* red mangrove is just visible at (237043E, 2379094N) but its circular shape is not preserved because it is now represented by one SPOT pixel (though it influences neighbouring pixels to give 'mixels'). (*Remember*: the same patch was represented by about 900 pixels in CASI imagery!).

Question: *2.10.* Why isn't the offshore mangrove patch visible as distinct from the coastal mangrove? [Explain why quantitatively.]

Activity: Inspect the mangrove fringe and note that detail of the larger, fringing mangrove habitat (bright red pixels) is also much reduced as it is now has an average width of 3–4 SPOT pixels (i.e. 60–80 m). Note that it is much harder to determine exactly where the mangrove begins and ends, with many 'mixels' where the mangrove meets the sea.

Minimize the SPOT false colour composite. Then create a new false colour composite from bands #1, #2 and #3 of Landsat MSS. [*Hint*: Follow exactly the same procedure as set out for SPOT XS above but use files ***LandsatMSS_Caicos#01.gif, LandsatMSS_Caicos#02.gif*** and ***LandsatMSS_Caicos#03.gif***.] As before, display the infra-red band through the red-gun so that vegetation (which has a high reflectance in the near-IR) appears bright red. Use **Edit**, **Go To** to place the cursor at coordinates (237040E, 2379150N) and then zoom in as required. Note that at this spatial scale (66 m pixels, 80 m spatial resolution), the patch of *Rhizophora* cannot be distinguished but the fringing mangrove habitat is just visible as a strip 1 or 2 pixels wide.

When you have finished, close the CASI and Landsat MSS images.

To conclude, the spatial resolution of imagery has a significant influence on the detail to which mangrove habitats can be identified. CASI imagery allows us to make fairly precise estimates of the shape and area of even small habitats such as patches of Red mangrove, *Rhizophora mangle*. SPOT XS allows us to make moderately crude estimates of these parameters but detail is drastically reduced. At the broadest scale, however, Landsat MSS does not identify small (< 80 m) patches as distinct entities and even where fringing mangrove is visible, measurements of habitat width are not precise (i.e. the width is estimated as 1–2 pixels wide which in this case equals 66 m or 132 m with no possible intermediate values).

Part 3. Spatial frequency of seagrass and coral features

In this part you will work with a colour composite CASI image (1 m spatial resolution) of Cockburn Harbour (***CASI_Cockburn_Harbour#05+#03+#01.set***) showing seagrass and reef habitats. These habitats were described in some detail in Lesson 1 and photographs may be opened in the *Bilko* viewer for further familiarisation (files ***Seagrass_blowout.bmp, Seagrass_dense.bmp, Montastraea_colonies.bmp***). The first exercise is to measure the width of two important features that have different spatial frequencies: seagrass blowouts (***Seagrass_blowout.bmp***) and colonies of the hard coral, *Montastraea annularis* (***Montastraea_colonies.bmp***).

Activity: Open the *Bilko* set ***CASI_Cockburn_Harbour#05+#03+#01.set***. In the **Redisplay Image** dialog box, set null value to zero, select an automatic linear stretch and click on the **All** button to apply these settings to all three images making up the composite. Select **View, Coords** to switch from UTM coordinates to column and row coordinates (these are shorter and less hassle to enter!). Then use the **Edit**, **Go To** command to place the cursor on the seagrass blowout (coordinate 428, 230). Zoom in so that you can accurately measure width. Using the transect tool and **Edit**, **Go To** to measure the horizontal widths of the remaining unmeasured blowouts listed in Table 2.6. The coordinates are in the middle of the blowouts. [*Hint*: Since the pixel width = 1 m then you can directly read off distance.] Enter your results in Table 2.6.

The next task is to measure horizontal distances across clumps of *Montastraea* colonies on sand. For this exercise 5 clumps have been selected (three of which have been measured for you). The coordinates in Table 2.6 are just to the west of each clump. In each case you should assume that values in band #3 (displayed through green gun) <2200 are coral and those >2200 are sand. You need to position the image cursor at each Table 2.6 coordinate and then use *<Ctrl>+<Right arrow>* keys to move the cursor one pixel at a time to the right, counting the number of pixels <2200 (in band #3) for each coral patch.

Activity: Use the **Edit**, **Go To** command and the coordinates listed in Table 2.6 to place the cursor to the left of each patch of *Montastraea,* which contrast with the pale background. Measure the horizontal width of the two remaining darker coral patches (pixels <2200 in green = band#3) as indicated above and enter your results in the table.

Table 2.6. Estimating the spatial frequency of seagrass and coral features using CASI imagery

Feature	Seagrass blowouts				*Montastraea* colonies				
Coordinates	468, 179	428, 230	320, 87	469, 154	612, 383	574, 393	588, 340	580, 384	594, 397
Width (m)	23			5	10	3			8
Average width (m)									

Question: *2.11.* What are the average widths of seagrass blowouts and *Montastraea* colony clusters in Cockburn Harbour?

You should now use your knowledge of spatial frequency to predict which of these features you would expect to see in various types of imagery. Table 2.7 lists these sources of imagery and their spatial resolutions.

Activity: Place a tick in the predicted presence columns (labelled "pred.") if you expect to see a particular feature and remember to consider the maximum size of each feature as well as its average size because some larger examples of, say, blowouts may be visible. Once you have made your predictions, proceed with the exercise to check your accuracy.

Table 2.7. Predicting the descriptive resolution of aerial photography, SPOT Pan and Landsat TM for key marine features. res. = resolution, pred. = predicted presence, c = column, r = row.

Sensor	Top left of study area (c, r)	DX:, DY: (c, r)	Spatial res. (m)	blowout		coral colonies	
				pred.	test	pred.	test
Aerial photography	210, 305	230, 205	2				
SPOT Pan	255, 800	45, 35	10				
Landsat TM	135, 252	20, 15	30				

To check your predictions entered in Table 2.7, you are provided with monochrome aerial photography (***AP_south_SCaicos.gif***), SPOT Pan imagery (***SPOTXP_SCaicos.gif***), and Landsat TM imagery (***LandsatTM_SCaicos#01.gif – LandsatTM_SCaicos#03.gif***).

Activity: Open the aerial photographic image ***AP_south_SCaicos.gif*** and apply an automatic linear contrast stretch. Then open the SPOT Pan image ***SPOTXP_SCaicos.gif*** which does not need to be stretched. Finally open the three Landsat TM bands and create a colour composite, assigning TM bands #3, #2, and #1 to the red, green, and blue colour guns respectively. Apply an automatic linear stretch.

For each image in turn, use **Edit, Go To** in order to outline the study areas suggested in Table 2.7 and double-click until you are satisfied with the zoom. Visually interpret each image to check for the presence of blowouts, seagrass beds and *Montastraea* heads. Were your predictions correct? Fill in the test boxes in Table 2.7.

Part 4. The advantage of considering habitat texture when interpreting remotely-sensed imagery

Activity: Maximize (or if necessary, open) the SPOT XS false colour composite image ***SPOTXS_SCaicos#03+#02+#01.set*** which you created in Part 2 of this lesson and apply an automatic linear stretch if you've had to open the file. Use **View, Coords** to switch from UTM coordinates to column and row coordinates. Move the cursor to position (419, 387) and zoom in several times. The cursor represents a large area of sand in shallow water just to the east of South Caicos. The sand bed is surrounded by patches of seagrass and coral reef. All of the patches are at least several pixels wide and easily detected using SPOT XS. However, SPOT pixels are 20 m wide and reveal very little of the texture of each habitat. The column and row coordinates of 5 patches are given in Table 2.8. Using the **Edit, Go To** function to locate the patches, can you identify which patches are coral and which are seagrass based on their colour, size and texture? Enter "S" in Table 2.8 for seagrass and "C" for coral reef. [*Note:* You will probably need to scroll up and down the image to find the cursor].

Minimize the false colour composite of SPOT XS and then open the image ***AP_east_SCaicos.gif*** which is a monochrome aerial photograph with a spatial resolution of 2 m. Use **View, Coords** to switch from UTM coordinates to column and row coordinates. Place the cursor near coordinates 400, 497 and zoom in to view the sand area examined earlier in the SPOT scene. The high spatial resolution of the aerial photograph reveals considerable textural detail to help with habitat identification.

Question: *2.12.* What are the principal textural differences between the seagrass beds and coral reef patches?

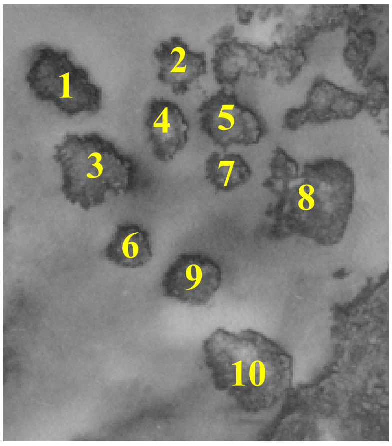
Activity: Examine this image in detail and visit the column and row coordinates provided in Table 2.8 to see whether your identification of habitats differs in light of the greater textural information now available. (*Note*: each position on the image is equivalent to that provided for SPOT.) You can use the **Window** menu to alternate between the SPOT XS image and aerial photograph.

Table 2.8. Identification of seagrass and coral patches based on their texture. Use "S" for seagrass and "C" for coral.

	SPOT XS coordinates	S / C	Aerial photography coordinates	S / C
patch 1	412, 434		260, 899	
patch 2	409, 362		170, 269	
patch 3	421, 410		360, 739	
patch 4	402, 388		135, 490	
patch 5	439, 380		553, 391	

You should have found it very easy to determine coral and seagrass patches on the aerial image but more difficult on the SPOT image. On the aerial image the texture clearly shows what is coral reef and what is seagrass. On the SPOT image one has to use habitat size and shape as a guide and then make an educated guess. A histogram equalization stretch of the SPOT image gives more detail but does not help identification.

Activity: Finally, assess the average width of the 10 coral patches scattered around coordinates 420, 790 on the aerial photographic image (see below for image showing location). [Hint: Use the mouse to drag a horizontal transect across the middle of each patch. When the transect is in position, select **Edit, Go To**. In the **Go To** dialog box click on the **Coords** checkbox and read off the distance (**DX:**) in metres.]



Question: *2.13.* What is the average width of the ten coral reef patches? Which image(s), among all those you have looked at, is/are likely to be ineffectual at resolving these patches?

Activity: Close the two images.

This part of the lesson should have illustrated the significance of texture when mapping habitats. Although the resolution of SPOT XS was fine enough to map the boundaries of these patches, it could not resolve the texture of each habitat. Aerial photography was capable of both because its spatial resolution was an order of magnitude finer than that of SPOT XS. In practice, a habitat map of coral reefs and seagrass beds would probably contain a greater number of errors (mis-identifications) if created from SPOT XS than if derived from aerial photography. However, we mentioned at the beginning of this lesson that spatial resolution is not the only important sensor attribute; spectral resolution is also important. Even if remotely sensed data cannot distinguish two habitats on the basis of their texture, their spectra might be distinguishable, hence, resolving the issue of habitat identification. Therefore, whilst a measure of texture is often useful, it is perhaps most needed where the spectra of two habitats are difficult to distinguish. This has been shown to be the case for IKONOS multispectral imagery (Mumby and Edwards, 2002).

The lesson as a whole should have indicated that while satellite imagery at resolutions of 20–80 m is able to map habitats to a coarse descriptive resolution, for finer discrimination and mapping of patchy habitats airborne imagery with a spatial resolution of <5m is likely to be needed. Mumby and Edwards (2002) show that whilst the 4 m spatial resolution of IKONOS satellite imagery significantly improves classification accuracy at a fine descriptive resolution (13 habitat categories), the overall accuracy is still only 50% compared to around 80% using CASI airborne imagery. Although the high spatial resolution of the IKONOS imagery allows textural information about habitats to be used in classification, the lack of spectral resolution (which is very similar to Landsat TM and ETM+) prevents satisfactory fine-level discrimination (Mumby and Edwards, 2002). The main operational lesson is: make sure that your imagery can achieve your mapping objectives.

Activity: To finish, you should examine IKONOS satellite imagery at a spatial resolution of 4 m (multispectral) and 1 m (panchromatic). Open the *Bilko* set ***Ikonos_Caicos#03+#02+#01.set*** (set null value to zero and use an automatic linear stretch) and the panchromatic image ***Ikonos_Caicos_pan.dat*** (set null value to zero and use a histogram equalization stretch). Examine these images with special regard to discrimination of roads, houses, boats, dense seagrass beds, seagrass blowouts, *Montastraea* colonies and reef and seagrass texture. Note the marked improvement on Landsat TM and SPOT XS and panchromatic imagery.

These images show the amazing detail of the latest generation of satellite images but if compared to the CASI image of the same area show the loss of radiance contrast due to the atmosphere (Mumby and Edwards, 2002).

Activity: When you have finished your examination, close all images.

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Answers to Questions

Part 1.

2.1. The quickest way to determine the width of the ***AP_mangrove_SCaicos.gif*** aerial photograph is to use *<Shift>+<Spacebar>* (or **Edit, Select All,** or *<Ctrl>+A*) to select the whole image and then use **Edit, Go To** dialog box to read off the width of the image (**DX:**) in pixels. It is 600 pixels wide so the width of the image is 600 x 2 m = 1.2 km.

2.2. You can directly read off the width of the ***SPOTXP_SCaicos.gif*** image in metres because it has been geometrically corrected to UTM coordinates. Select the whole image and inspect the **Edit, GoTo** dialog box, which will show the width (**DX:**) in metres as 8640.0E. The width to the nearest 0.01 km is thus 8640 m = 8.64 km.

Table 2.4. Width of landing strip at South Caicos airport

Image type	Measurements across landing strip (pixels or metres)	Pixel size (m)	Width of landing strip (m)
Aerial photography	38, 37, 39, 36, 40 pixels	2	72–80 (mean = 76)
SPOT Pan (XP)	84, 84, 96,72, 84, 96, 84, 72 m	12	72–96 (mean = 84)
Landsat MSS	1	66	approx. 66

2.3. Even on the aerial photography it is not absolutely clear where the edge of the landing strip pavement is. The landing strip appears to be between 36 and 40 pixels across, giving a mean width of 76 m. On the SPOT Pan image it appears to be somewhere between 72 m and 96 m across, with a mean width of 84 m. The difference is about 8 m, which is a bit less than the resolution of the SPOT Pan sensor. “Mixels”, that is pixels that are half vegetation and half landing strip pavement, on either side of the runway make it very difficult to be sure exactly where the landing strip edges are. These create half to one pixel’s worth of uncertainty making it harder to estimate the width with from SPOT Pan imagery.

2.4. You can directly read off the width of the ***LandsatMSS_Caicos#02.gif*** image in metres because it has been geometrically corrected to UTM coordinates. Select the whole image and inspect the **Edit, GoTo** dialog box, which will show the width (**DX:**) in metres as 33066.0E. The width to the nearest 0.1 km is thus 33066 m = 33.1 km.

2.5. The landing strip is visible in the Landsat MSS scene. But would you have recognised it as such if you did not know it was there?

2.6. No, one can see that some linear structure is there but all one can say is that it is similar in width to the spatial resolution of the sensor (80 m). In the Landsat MSS image much of the landing strip appears one pixel wide, in some places it seems to be two pixels wide and in a few places is not visible. Both aerial photography and SPOT Pan appear to be suitable for mapping roads with the aerial images picking out narrower tracks which cannot be seen on the SPOT Pan imagery.

Part 2.

Table 2.5. Measuring the dimensions of two mangrove habitats.

Habitat	*Rhizophora mangle* patch		Fringing mangrove		
Starting position of transect (X:, Y:)	237022E, 2379099.7N (DX:)	237039E, 2379082.1N (DY:)	236817E, 2379531N (DX:, DY:)	236897E, 2379460N (DX:, DY:)	236992E, 2379379N (DX:, DY:)
Habitat diameter/DX:, DY: (m)	34	35.2	38.0, 45.1	47.0, 63.8	38.0, 50.6
Mean diameter/width of fringe (m)	34.6		59.0	79.2	63.3

2.7. The average diameter is about 34.6 m (average of 34.0 m and 35.2 m) giving a radius of 17.3 m. This gives an area of about 940 m² for the mangrove patch.

2.8. Based on the three transects, the average width of the mangrove fringe is 67 m (to the nearest metre).

2.9. a) The transect running through the middle of the fringing mangrove parallel to the coastline has a DX: of about 360 m and DY: of about 340 m; it is thus 495 m long to nearest metre.

$$\text{Length} = \sqrt{360^2 + 340^2} = 495\,\text{m}$$

b) The average width is 67 m so the area is 495 x 67 = 33,165 m², which is equivalent to about 3.3 ha.

2.10. The offshore mangrove patch is not visible as distinct from the coastal mangrove in the SPOT image because it is only about 8–10 m offshore; this is less than a half a SPOT pixel width (spatial resolution 20 m) so that the shallow water area between the mangrove islet and the coast cannot be resolved by the SPOT imagery.

Part 3.

Table 2.6. Estimating the spatial frequency of seagrass and coral features using CASI imagery

Feature	Seagrass blowouts				*Montastraea* colonies				
Coordinates	468, 179	428, 230	320, 87	469, 154	612, 383	574, 393	588, 340	580, 384	594, 397
Width (m)	23	23	9	5	10	3	6	5	8
Average width (m)	15.0				6.4				

2.11. The average width of the blowouts is about 15 m and the average width of the *Montastraea* colony clusters is 6 m.

Table 2.7. Predicting the descriptive resolution of aerial photography, SPOT Pan and Landsat TM for key marine features. A tick indicates that the features are visible.

Sensor	Coordinates of study area (c,r)	Spatial res. (m)	blowout		coral colonies	
			pred.	test	pred.	test
Aerial photography	259,356	2	✓	✓	✓	✓
SPOT Pan	264, 808	10	?	✓†	✗	✗
Landsat TM	141, 257	30	✗	✗	✗	✗

† The largest blowouts can be seen but smaller ones do not appear visible. Blowout size is right on the borderline of the spatial resolution of SPOT Pan.

Part 4.

2.12. Seagrass beds have a fairly uniform texture whereas coral reefs have a complex patchy texture. The seagrass beds tend to be fairly uniformly dark whilst the reef areas tend to be lighter and of varied texture internally but have dark bands around their edges.

Table 2.8. Identification of seagrass and coral patches based on their texture. "S" = seagrass and "C" = coral.

	SPOT XS coordinates	S / C	Aerial photography coordinates	S / C
patch 1	412, 434	S	260, 899	S
patch 2	409, 362	S	170, 269	S
patch 3	421, 410	C	360, 739	C
patch 4	402, 388	S	135, 490	S
patch 5	439, 380	C	553, 391	C

2.13. The patch widths are approx. 68, 54, 76, 44, 68, 50, 48, 80, 64, and 88 m across giving an average width of 64 m. The MSS imagery (80 m) resolution would be ineffectual at resolving most of the patches but they should be visible on all the other images.

APPENDIX 2.1

Landsat Multi-Spectral Scanner (MSS)

The Landsat Multispectral Scanner (MSS) was operational from 1972, following the launch of Landsat-1, until 1993. The spatial resolution for the sensor is 79 m. The radiometric resolution is 6 bits (64 grey levels). The swath width for the sensor is 185 km. Multi-Spectral Scanner data ceased to be collected in 1993.

The spectral characteristics of the Landsat MSS bands are as follows:-

MSS Band #		**Colour**	**Wavelengths (nm)**
Landsat 1–3	Landsat 4–5		
4	1	Green	500–600
5	2	Red	600–700
6	3	Near Infra-red	700–800
7	4	Near Infra-red	800–1100

Images are produced by reflecting the radiance from 79 m wide scan lines on the Earth's surface to detectors on board the satellite using an oscillating mirror. Each scan line is 185 km long (thus the **swath width** or width of ground covered by the sensor in one overpass is 185 km). The Instantaneous Field of View (IFOV) of the sensor is a 79 x 79 m square on the Earth's surface. This area can be regarded as the **spatial resolution** of the sensor, that is the smallest area which can be sampled by the sensor. Each picture element or **pixel** in a MSS digital image is thus a measurement of the brightness of the radiance from a 79 x 79 m square on the Earth's surface.

Because the satellite is moving so fast over the Earth's surface, it has to scan 6 lines at a time (thus covering 474 m along track). Since the MSS sensor measures the radiance in four different wavebands at the same time, it thus has 24 detectors in total. Each detector converts the recorded irradiance into a continuous electrical signal which is then sampled at fixed time intervals (approximately every 10 µs) and converted to a 6 bit number (64 grey levels). During this interval the ground distance covered by the oscillating mirror is only 56 m. Thus the picture elements or pixels making up an MSS image are 56 x 79 m rectangles. The resampled pixel size in this lesson of 66 m x 66 m is approximately

The 6-bit numbers representing reflectances recorded from each point (79 x 79 m on the Earth's surface) are either recorded on magnetic tape on board the satellite (in earlier Landsats) or transmitted to an Earth receiving station where they are recorded on high-density digital tapes (HDDTs).

A full Landsat MSS scene consists of measurements of the radiance from a ground area of 185 x 185 km and thus consists of 2340 scan lines each consisting of 3240 pixels. There are thus about 7.5 million pixels per scene, each of which has radiances recorded in four wavebands, giving a total of 30 million bytes of information. It takes about 25 seconds to record one scene. The digital information for a scene is supplied on Computer Compatible Tapes (CCTs) or on Exabyte tapes to users who then need to process it on computers according to their needs.

3: GEOMETRIC CORRECTION OF AN AERIAL IMAGE OF SOUTH CAICOS ISLAND

Aim of Lesson

To learn how to rectify an image to a Universal Transverse Mercator (UTM) coordinate system and to understand why it is important to carry out geometric correction of remotely sensed images.

Objectives

1. To understand that measurements made from images that have not been geometrically corrected can be misleading and that just because an image looks like a map it does not necessarily have the properties of a map.
2. To learn how to make measurements of distances between points on an image using Pythagoras's theorem so that you can compare distances between known points *before* and *after* rectification and georeferencing of the image.
3. To discover how Ground Control Points (GCPs) are obtained at selected positions, which are carefully chosen to be readily identifiable on the image, using a Global Positioning System (GPS) so that the geographical coordinates of a series of pixels can be linked together in a rectification table.
4. To understand how a rectification table works by linking pixels at know column and row coordinates to GCPs at know geographical (in this case-study, Universal Transverse Mercator) coordinates obtained using a GPS.
5. To use *Bilko* to enter details of three GCPs in the rectification table and learn how to select an appropriate transformation (linear, quadratic or cubic) for rectification.
6. To understand what Root Mean Square (RMS) error means and find out how to deselect problem GCPs that have unacceptably high RMS errors (perhaps due to a GPS error or human error in transcribing coordinates).
7. To carry out rectification and resampling of the image to the Universal Transverse Mercator (UTM) grid system of local maps of the Turks & Caicos Islands.
8. To compare measurements between points on the geometrically corrected and uncorrected images and see how much positional error may result from using uncorrected imagery.

Background Information

This lesson relates to material covered in Chapter 6 of the *Remote Sensing Handbook for Tropical Coastal Management* and you are recommended to consult this or a range of other remote sensing texts (e.g., Mather, 1999; Wilkie and Finn, 1996; ERDAS, 1994) for further details of the theory and techniques of geometric correction.

The *Bilko 3* image processing software

Familiarity with *Bilko 3* is required to carry out this lesson. In particular, you will need experience of using Transects and **Edit, Go To** to find out distances between points. A familiarity with switching geographical coordinates on and off using the **View, Coords** feature, connecting images using **Image, Connect**, and with the *Excel* spreadsheet package is also desirable. Tutorials 2, 3, 7 and the first part of Tutorial 8 in the *Introduction to using Bilko* are particularly relevant and provide a good grounding for this lesson.

Image data

For this lesson, you are presented with part of a scanned black and white aerial photograph of South Caicos Island, which, you are told, was taken in 1981. You want to use this image to look at how parts of the island have changed and thus need to geometrically correct it and georeference it to the local map, which uses Universal Transverse Mercator (UTM grid zone 19 N) coordinates, so that you can compare it with other similarly georeferenced images taken at later dates. The local maps (Ordnance Survey map Series E8112 DOS 309P) also use the Clarke 1866 spheroid and NAD (North American Datum) 27 (Bahamas) datum. A spheroid tries to account for the fact that the Earth is not a sphere but an oblate spheroid. The Clarke 1866 spheroid is appropriate for and often used in North and Central America and the Caribbean. A geodetic datum is a smooth mathematical surface that closely fits the mean sea-level surface in a specific area of interest. The NAD 27 (Bahamas) datum is appropriate for the Bahamas (except San Salvador Island) and the Turks & Caicos Islands. For further details of the UTM Grid System, spheroids and datums, a useful reference is Butler *et al*. (1987).

You are not quite sure whether the image was taken professionally or is a near vertical with significant distortion. You are told that the image was scanned so that the pixel size is approximately 3.5 m x 3.5 m but want to check this.

Field survey data

In order to carry out geometric correction we have looked for obvious points visible on the aerial photograph such as crossroads, corners of prominent buildings, corners of salinas (salt ponds), seaward or landward ends of jetties or piers, and ends of the airstrip, and then gone out with a Global Positioning System (GPS) to obtain the UTM coordinates of a series of ground control points (GCPs) scattered over the area covered by the aerial photograph. The location of each GCP was determined using a Differential Global Positioning System (DGPS) with a probable circle error of 2–5 m[1]. Their position was marked on a print out of the aerial and notes made of exactly where each GPS reading was taken to aid matching of column and row coordinates on the scanned image of the aerial to UTM Eastings and Northings of GCPs. We have entered most of the GCPs into a *Bilko* rectification table to save you time.

Geometric correction

Raw remotely sensed imagery is usually distorted in some way. Geometric correction of remotely sensed imagery is carried out so that (i) it can be represented on a plane (e.g. flat sheet of paper), (ii) it can be used like a map, or (iii) it will conform to other images to which you wish to compare it. *Rectification* is the process of projecting data onto a plane and making it conform to a map projection system such as the UTM Grid System. During the process of rectification the grid of raw data (usually just column and row coordinates) must be transformed onto a new grid (usually a map coordinate system). For UTM this new grid consists of Eastings and Northings in metres from a “false” origin. *Resampling* is the process of interpolating data values for pixels on the new grid from the values of the source pixels. *Georeferencing* is the process of assigning map coordinates to image data.

Sometimes you have geometrically corrected images of the same area, which have been rectified to different grid systems (e.g. one image might have been rectified to UTM zone 30 (Northern Hemisphere) with WGS 84 spheroid/datum and another to the UK National Grid using Airy (1844) spheroid and Ordnance Survey of Great Britain 1936 datum with a Transverse Mercator projection). If you wish to compare such images, you need to rectify and resample one image to conform to the other.

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[1] With more modern equipment and removal of “selective availability” error by US Department of Defense you would expect to achieve somewhat better accuracy nowadays.

The process of making image data conform to another image is called *registration* and need not necessarily involve a map coordinate system.

To rectify an image you need to relate specific pixels in the image to known map coordinates. The map coordinates of objects, which are clearly recognisable both on the ground and on the image, may be obtained from large-scale maps, directly using a GPS or from other images that are already georeferenced. The *Bilko* rectification table allows you link raw image pixels at known column and row coordinates with known map coordinates. Each linked pixel is a GCP. When you have enough GCPs you can get the computer to calculate a transformation, which maps the raw image grid to the new grid. For a linear transform you need an absolute minimum of 3 GCPs, for a quadratic transform a minimum of 6 GCPs, and for a cubic transform a minimum of 10 GCPs. However, you should try to use as many as can be easily obtained (up to 20 or more for quadratic or cubic transforms) and have them as evenly distributed across the image as possible.

To assess the goodness of fit of both the overall transform and individual GCPs, the inverse of the transformation matrix is used to retransform the reference coordinates of the GCPs back to the source coordinate system. Unless there is a perfect fit of the GCPs (unlikely!) to the curve described by the linear, quadratic or cubic transformation used, then some discrepancy (error) will exist between the original source coordinates and the retransformed coordinates. The distance between the input (source) location of a GCP and the retransformed coordinates of the same GCP is called the Root Mean Square (RMS) error. This is calculated for you in the rectification table as follows:

$$\text{RMS error} = \sqrt{(x_r - x_i)^2 + (y_r - y_i)^2}$$

where x_i and y_i are the input (source) coordinates, and x_r and y_r are the retransformed coordinates (see Figure 3.1 below). You can use the overall RMS error (the square root of the sum of squares of the individual RMS errors divided by the number of GCPs used in the transformation process) to judge which transform is most appropriate and use the individual RMS errors to see if any GCPs have unacceptably high errors and should be removed from the transformation calculation to improve the fit.

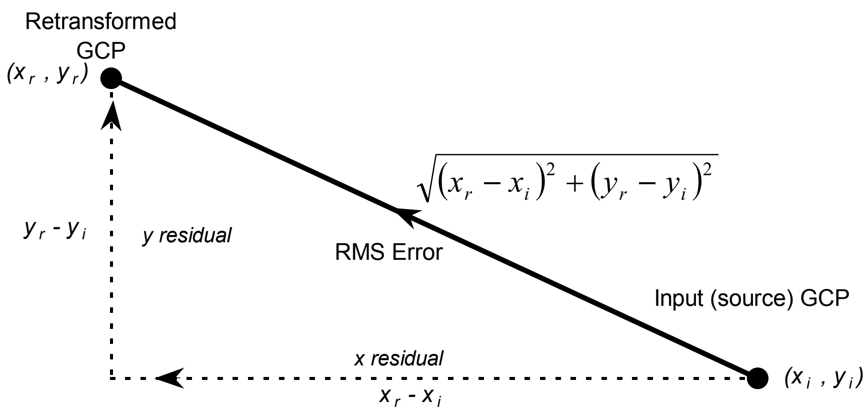

Figure 3.1. The calculation of the RMS error of an individual GCP.

Lesson Outline

Inspecting the uncorrected scanned aerial photograph

You have been presented with a scanned black-and-white (monochrome) aerial image from 1981. Before attempting to geometrically correct the image you will examine it so that you can better understand the need for geometric correction and consequences of not doing it.

Activity: Launch *Bilko,* select **File, Open** and make sure that **Extract** checkbox is checked and **Minimize** checkbox is unchecked. Then open the 8-bit integer image file ***Aerial_subimage_raw.gif*** noting the size of the image [*Hint:* remember to account for the fact that the first pixel is at coordinates (0, 0)]. Examine the image and identify the airstrip across the top of the image, the disused salinas (salt ponds) covering most of the centre of the image, the settlement in the bottom left (south-west) and the very dark strip of mangrove along the coast to the north of the settlement.

Question: *3.1.* How many columns and rows of pixels does the ***Aerial_subimage_raw.gif*** have?

Question: *3.2.* How many kilometres is the top of the image across if you assume that each pixel is 3.5 m wide?

To see the kind of effects that using an uncorrected image might cause, you will estimate the length of the tarmac on the runway both before geometrically correcting the image and after the image has been corrected. You have been told that the pixel size is 3.5 m x 3.5 m. Using this information and Pythagoras's theorem you can estimate the runway length. Pythagoras's theorem tells us that for right-angled triangles:

$$\text{Length of hypotenuse} = \sqrt{(\text{Distance in X direction})^2 + (\text{Distance in Y direction})^2}$$

This allows us to work out the diagonal distance (length of hypotenuse) between any two points on the image. Note that it is often easier to work out distances in pixels and then multiply the final result by the pixel size.

Activity: Click on the transect button and with the mouse lay a transect along the middle of the tarmac from the western end of the tarmac landing strip to the eastern end. Select **File, New** and then TRANSECT Document to display the transect. Make a note of the column and row coordinates at the start and end of the transect. Use this information (or **Edit, Go To**) to find the distances in the X and Y directions between the points at either end of the transect and then use Pythagoras's theorem to estimate the diagonal distance in metres along the runway tarmac.

Question: *3.3.* What is the estimated length in metres (to the nearest m) of the runway tarmac?

Geometric correction of the scanned aerial photograph

The next stage is to match pixels at particular column and row coordinates to Ground Control Points (GCPs) where readings of UTM coordinates have been made. To save you time 24 GCPs have already been entered into the rectification table ***South_Caicos_GCPs.tbl***.

Activity: Close the transect document. Select **File, Open** and set **Files of Type:** to TABLES (*.tbl), then select ***South_Caicos_GCPs.tbl*** as the rectification table and click on **Open** to open the table. Note that the **Master:** column is set to **Use Map (Gridded)** and contains the UTM coordinates of the GCPs, whereas the **Slave:** column is set to the ***Aerial_subimage_raw.gif*** image and contains the row and column coordinates for the GCPs.

Initially the transform is set to Linear. The average Root Mean Square (RMS) error is shown at the head of the last column. Its units are pixels. Note that the GCPs are now displayed in yellow on the image. Inspect the image and note that the GCPs are reasonably evenly distributed over the image. When you have satisfied yourself of this, make the rectification table the active window and answer the following questions.

Question: *3.4.* (a). What is the average RMS error for a linear transform? (b). What is this expressed in metres (assuming a pixel size of 3.5 m)? [Express answer to nearest 0.1 m.]

Activity: Right-click on the rectification table and change the Transform to quadratic. Note the dramatic improvement in the average RMS error.

Question: *3.5.* (a). What is the average RMS error for a quadratic transform? (b). What is this expressed in metres (assuming a pixel size of 3.5 m)? [Express answer to nearest 0.1 m.]

Activity: Right-click on the rectification table and change the Transform to cubic. Note the slight improvement in the average RMS error.

Question: *3.6.* (a). What is the average RMS error for a cubic transform? (b). What is this expressed in metres (assuming a pixel size of 3.5 m)? [Express answer to nearest 0.1 m.]

The huge improvement in the RMS error when the transform is changed from linear to quadratic suggests that a linear transform is totally inadequate to correct the distortions of this image. By contrast, the relatively minor improvement in the RMS error when the transform is changed from quadratic to cubic suggests that a quadratic transform is probably sufficient. Using a higher power transform will always improve the fit (reduce the overall RMS error) but cubic transformations are seldom necessary.

Given a 2–5 m probably circle error for the DGPS fixes as well as the likelihood of at least a one pixel (3.5 m) error in the X and/or Y direction in identifying the correct column and row coordinate on the image, an overall RMS error of around 5 m seems about as good as one is likely to get with the DGPS and image being used.

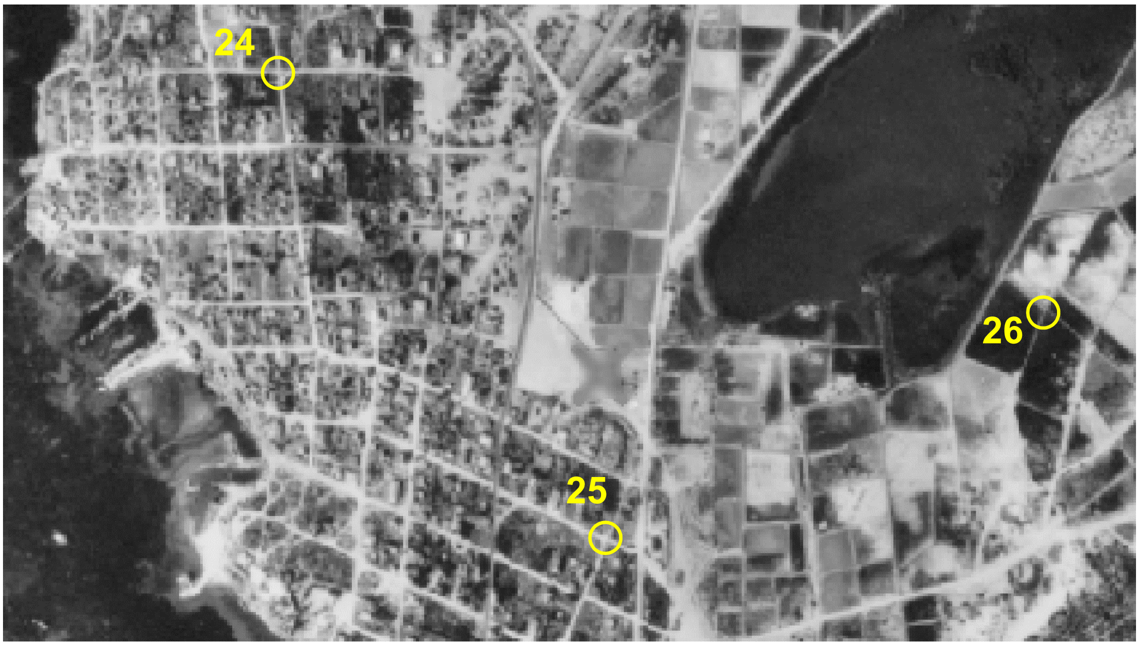

Figure 3.2. Locations of GCPs #24 to #26 on the scanned aerial photograph.

The next stage is to enter the three remaining GCPs into the rectification table. The differential GPS readings for these three GCPs are listed in Table 3.1 below and their locations on the image shown in Figure 3.2 above.

Table 3.1. Global Positioning System UTM coordinates for GCPs#24 to #26.

	Description	Easting	Northing
GCP#24	Centre of crossroads in town (north)	237437.5	2379087.5
GCP#25	Centre of crossroads in town (south)	237850.0	2378512.5
GCP#26	Salt pond boundary wall corner	238431.3	2378793.8

Activity: In the rectification table click on the Description for GCP#024 and type in the description for this GCP, then press the *<Tab>* key and enter the Easting and Northing separated by a space or a comma. At this point switch to the ***Aerial_subimage_raw.gif*** image and position the cursor as close as possible to the exact centre of the crossroads indicated in Figure 3.1 using the mouse. Then use the arrow keys with *<Ctrl>* depressed for final positioning. [*Hint:* It is easier if you zoom in to 200% to 400% to do this]. When you are satisfied that the cursor crosshair is right in the middle of the crossroads, press the *<Insert>* key to insert the column and row coordinates into the rectification table. [The correct column and row coordinates are (214, 685) and you should be within 1 pixel of these coordinates].

Repeat the process for GCPs #25 and #26. When all GCPs have been entered, right-click on the rectification table and make sure that the **Transform** is set to Quadratic. Check the average RMS for all 27 GCPs [*remember:* first GCP is #000]. This should be approximately 1.5. If not, then check that your new GCPs are correctly located!

Question: *3.7.* (a). What column and row coordinates do you have for GCP#25? (b). What column and row coordinates do you have for GCP#26? (c). What is the average RMS error for all 27 GCPs?

You now have a good series of fairly evenly spaced GCPs scattered across the most of the image. This should allow good rectification of the scanned aerial photograph with good confidence in the results. Before doing this you should note two further points about the raw image.

Activity: Firstly, although you have established details of the UTM Eastings and Northings and corresponding column and row coordinates for 27 GCPs in the image in the rectification table, if you click on the image you still only see column and row coordinates returned on the Status bar. Check this out. Note also that in the **View** menu, you do not have the option to view **Coords**.

Secondly, note if you hover the mouse pointer over the cross marking the position of each GCP you will see a pop-up that shows the GCP number and its description. If GCPs are very close to the image edge so that the yellow numbers are not fully visible, this is useful.

Finally, you need to check whether any individual GCPs are likely to spoil the fit of the image, that is, have anomalously large RMS errors associated with them. For the purposes of this exercise it has been decided that GCPs with RMS errors greater than 10 m should be rejected.

Activity: Work out how many pixels (to 2 decimal places) 10 m is equivalent to. Then check the rectification table to find out if there are any potentially problematic pixels that should be rejected.

Question: *3.8.* (a). Which GCP has the greatest (worst) RMS error? (b). What is this error in pixels? (c). Should this GCP be rejected on the basis of the criterion stated above?

Activity: You should have found a single GCP that needs to be rejected. Uncheck the checkbox for this GCP in the rectification table so that it is displayed in cyan on the image. The average RMS error should reduce to approximately 1.368 pixels (about 4.8 m).

At this point you need to link the UTM coordinates to the image and fix the transform prior to resampling. This is done by copying the rectification table to the clipboard and then pasting it to the image.

Activity: Click on the rectification table so that it is the active document and select the Copy button to copy the table. Now click on the ***Aerial_subimage_raw.gif*** image and click on the Paste button. Note that **View, Coords** can now be activated and that UTM coordinates now appear on the Status bar. If you position the cursor on the centre of the cross for any GCP, the Status bar will now show the coordinates of the centre of the pixel in which the GCP occurs. Compare the Status bar positions (pixel centres) for one or two GCPs with the UTM coordinates (read off the GPS) that are listed for the GCPs in the rectification table. Values should usually be within a few metres for both Eastings and Northings.

Although the computer can now calculate the UTM coordinates of each pixel, the image geometry has not yet been warped to display the image correctly in the new coordinate system. For this to occur the image must be resampled and redisplayed on a UTM grid.

Activity: With the image as the active document, select **Image, Resample**. This brings up the **Resample** dialog box with four tabs: **Window, Pixel, Image** and **Interpolation**. For the interpolation method, select Cubic convolution[2] and click the Apply button. Then click on the **Window** tab and set the **Easting (X):** to 236670 **to:** 240290 and **Northing (Y):** to 2381490 **to:** 2378110 and click the Apply button. This provides a window sufficiently large to accommodate a bit of warping of the original image (slightly larger than the original image in each dimension). Next click on the **Pixel** tab and set both pixel **Width:** and **Height:** to 3.5 (i.e. 3.5 m) and click Apply. [The default settings of 3.6 and 3.4 suggest that some warping is needed.] The original image was 990 columns by 980 rows. Click on the **Image** tab to find out the size of the new image in rows and columns.

Question: *3.9.* What size is the resampled image going to be in columns and rows?

The original image was the same width at top and bottom. You will now check to see whether geometric correction has changed this, by comparing the length of two transects, one at the top of the image and one at the bottom.

Activity: When you have applied the correct settings for interpolation, window and pixel size, click on OK to carry out the resampling. Select the resampled image and lay a horizontal transect from west to east from the top left hand corner of the image at column and row coordinates (1, 10) to the last non-zero pixel in that row at coordinates (1033, 10). Find out the east-west distance across top of the image [*Hint:* switch to viewing UTM coordinates once the transect is in place]. Starting at the bottom right of the image – column and row coordinates (983, 951) – draw a horizontal transect to the first non-zero pixel in the same row and measure the east-west distance across the bottom of the image.

Question: *3.10.* (a). What is the distance in metres across the top of the resampled image (to pixel edges) – from column and row coordinates (1, 10) to (1033, 10)? (b). What is the

[2] In this instance we are looking to achieve a reasonably smooth resampled image and are not interested in preserving spectral values; thus Cubic convolution is perhaps the best method and Bilinear interpretation which involves some averaging of pixel values would also be appropriate.

distance in metres across the bottom of the resampled image (to pixel edges) – from column and row coordinates (983, 951) to (5, 951)? (c). What is the difference in distance across the image between rows 10 and 951 (<u>not</u> counting zero value pixels!)?

Question: *3.11.* What do you estimate the length in metres (to the nearest m) of the runway tarmac to be now, using the geometrically corrected resampled image?

Question: *3.12.* How wrong was your estimate of the runway length using the raw (uncorrected) image?

The answers to questions 3.10 to 3.12 show you how important geometric correction is. If you had just assumed the aerial photograph was a true (undistorted, map-like) representation of the area, you would have made considerable errors, underestimating distances in the north of the image and overestimating distances in the south of the image due to the slightly oblique angle at which the image was taken.

To see more clearly how the aerial photograph was distorted, you will now stack the raw and geometrically corrected images in same sized windows with their top left corners mapped to the same point. From your earlier study of the resampled image you know that its top left hand corner is at column and row coordinates (1, 10) in the resampled image window. You thus need to (i) copy the raw image, (ii) make sure the image cursor is on column and row coordinate (1, 10) in a blank image the same size as the resampled image, and (iii) paste the raw image into the window.

Activity: Firstly, you need to retrieve a version of the raw image <u>without</u> the UTM coordinates applied. To do this, close the rectification table and the ***Aerial_subimage_raw.gif*** image. Then reopen the ***Aerial_subimage_raw.gif*** image, which will now be as it was before you started rectifying it. Select all of the image and Copy it.

With the geometrically corrected image as the active image select **Image, Connect** and connect the image to one blank in a stack. Select the blank image using the **Selector** drop-down list. Using either **Edit, Go To** or the mouse and arrow keys, place the image cursor on coordinates (1, 10). Paste the raw image into the blank window. Zoom out so that you can see the whole image and click on the Loop button (or select **Image, Animate** and click on OK). You will see clearly that the original aerial photograph was considerably distorted. When you have finished close all images.

The amount of distortion suggests that the original aerial photograph, of which the image was a part, was perhaps not flown as part of a vertical aerial survey or has become distorted with time. A normal aerial survey photograph would be expected to require much less geometric correction whilst near-vertical photographs taken from hand-held cameras (and thus likely to be somewhat oblique) would be expected to require considerable correction.

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Answers to Questions

3.1. The ***Aerial_subimage_raw.gif*** image has 990 columns of pixels and 980 rows. The **Extract** dialog box indicates that the first pixel has coordinate (0, 0) and the last pixel has coordinate (989, 979). Thus the image size is 990 columns by 980 rows (990 pixels by 980 lines). A perhaps easier way of determining the image size is to select all of the image (<*Ctrl*>+A or **Edit, Select All**) and then **Edit, Go To** (or <*Ctrl*>+G). The image size can then be read off from the **Selection Size** with the **DX:** value giving you the number of columns and the **DY:** value giving you the number of rows.

3.2. If you assume that each pixel is 3.5 m wide then the top of the image is 990 x 3.5 = 3465 m = 3.465 km across.

3.3. The transect starts at column and row coordinate (123, 44) and ends at coordinate (618, 126). [You should be within ±1 column or row coordinate at each end.] These coordinates can be read off from the transect chart. If you use the mouse to position the cursor at the right-hand end of the transect on the transect chart then the Status Bar shows that it has gone through 496 pixels. The **Selection Size** part of the **Go To** dialog box shows an west-east (**DX:**) difference of 496 (= 618 – 123 + 1) pixels and a north-south (**DY:**) difference of 83 (= 126 – 44 + 1) pixels between the two ends. If you use the two transect document end-points you find the distance in pixels between the middle of the pixels at either end of the transect. By contrast, the **Selection Size** part of the **Go To** dialog box shows the number of pixels included in each direction from the outer edges of the transect and will thus include two extra half-pixels. There are arguments for either approach and as long as one is aware of the one pixel difference, the results of both approaches are acceptable.

(1) Using transect end-points displayed on transect chart: Using Pythagoras the distance along the diagonal in pixels is $\sqrt{495^2 + 82^2} = \sqrt{245025 + 6724} = \sqrt{251749} = 501.7$. Multiplying by the presumed pixel size of 3.5 m; 501.7 × 3.5 = 1756.1 m = **1756 m** to the nearest metre.

(2) Using Selection Size information of Go To dialog box: Using Pythagoras the distance along the diagonal in pixels is $\sqrt{496^2 + 83^2} = \sqrt{246016 + 6889} = \sqrt{252905} = 502.9$. Multiplying by the presumed pixel size of 3.5 m; 502.9 × 3.5 = 1760.1 m = **1760 m** to the nearest metre.

3.4. (a). The average RMS error using a linear transform is 7.465 pixels. (b). This is equivalent to 7.465 × 3.5 = 26.1 m to the nearest tenth of a metre.

3.5. (a). The average RMS error using a quadratic transform is 1.517 pixels. (b). This is equivalent to 1.517 × 3.5 = 5.3 m to the nearest tenth of a metre.

3.6. (a). The average RMS error using a cubic transform is 1.322 pixels. (b). This is equivalent to 1.322 × 3.5 = 4.6 m to the nearest tenth of a metre.

3.7. (a). The column and row coordinates for GCP#25 should be within one pixel in either direction of coordinate (336, 861). (b). The column and row coordinates for GCP#26 should be within one pixel in either direction of coordinate (501, 775). (c). The average RMS error for all 27 GCPs should be close to 1.472 pixels.

3.8. (a). The GCP with the greatest (worst) RMS error is GCP#16. (b). It should have an RMS error of close to 2.97 pixels. [This will vary depending on how accurately GCPs #25 and #26 were entered.] (c). Yes. Its RMS error is equivalent to 10.4 m and thus exceeds the criterion for rejection (10 m or 2.86 pixels).

3.9. The resampled image will be 1035 columns by 967 rows in size.

3.10. (a). The distance across the top of the resampled image – from column and row coordinates (1, 10) to (1033, 10) is 1033 × 3.5 = 3615.5 m. (b). The distance across the bottom of the resampled image – from column and row coordinates (983, 951) to (5, 951) is 979 × 3.5 = 3426.5 m. (c). The difference in distance across the image between rows 10 and 951 is 189 m.

3.11. In the resampled image the transect along the runway tarmac starts at column and row coordinate (128, 56) and ends at coordinate (639, 136) [plus or minus a row or column]. These coordinates can be read off from the transect chart. If you use the mouse to position the cursor at the right-hand end of the transect on the transect chart then the Status Bar shows that it has gone through *ca* 512 pixels (511 plus 1 as transect starts at pixel 0). The **Selection Size** part of the **Go To** dialog box shows an west-east (**DX:**) difference of 512 (639 – 128 + 1) pixels and a north-south (**DY:**) difference of 81 (136 – 56 + 1) pixels between the two ends. If you use the two transect document end-points you find the distance in pixels between the middle of the pixels at either end of the transect. By contrast, the **Selection Size** part of the **Go To** dialog box shows the number of pixels included in each direction from the outer edges of the transect and will thus include two extra half-pixels. There are arguments for either approach and as long as one is aware of the one pixel difference, the results of both approaches are acceptable.

(1) Using transect end-points displayed on transect chart: Using Pythagoras the distance along the diagonal in pixels is $\sqrt{511^2 + 80^2} = \sqrt{261121 + 6400} = \sqrt{267521} = 517.2$. Multiplying by the pixel size of 3.5 m; 517.2 × 3.5 = 1810.3 m = **1810 m** to the nearest metre.

(2) Using Selection Size information of Go To dialog box: Using Pythagoras the distance along the diagonal in pixels is $\sqrt{512^2 + 81^2} = \sqrt{262144 + 6561} = \sqrt{268705} = 518.4$. Multiplying by the pixel size of 3.5 m; 518.4 × 3.5 = 1814.3 m = **1814 m** to the nearest metre.

3.12. The estimate of the runway length using the raw (uncorrected) image was 54 m too short using either method. Method (1) gives 1810 m after correction and 1756 m on the raw image; method (2) gives 1814 m after correction and 1760 m on the raw image.

4: RADIOMETRIC CORRECTION OF SATELLITE IMAGES: WHEN AND WHY RADIOMETRIC CORRECTION IS NECESSARY

Aim of Lesson

To develop your understanding of concepts underlying radiometric correction and how to carry out the radiometric correction of satellite imagery, using two Landsat Thematic Mapper images obtained at different seasons under different atmospheric conditions as examples.

Objectives

1. To understand the difference between DN values, radiance and reflectance.
2. To understand why radiometric correction of imagery is required if (i) you are mapping changes in habitat or other features, or (ii) you are using more than one image in a study.
3. To demonstrate how different atmospheric conditions can affect DN values by comparing these in two Landsat TM images acquired during different seasons.
4. To understand the basic concepts behind atmospheric correction algorithms.
5. To learn how to carry out the process of radiometric correction of two Landsat TM images obtained in different seasons and compare the resultant reflectance values.

Background Information

This lesson relates to material covered in Chapter 7 of the *Remote Sensing Handbook for Tropical Coastal Management* and readers are recommended to consult this for further details of the techniques involved. The lesson is rather a specialist one designed to guide practitioners in radiometric and atmospheric correction; it is advanced and is quite hard work (be warned!).

Atmospheric correction will be carried out on two Landsat Thematic Mapper images of the Caicos Bank obtained at different seasons and under somewhat different atmospheric conditions. The first Landsat TM image was acquired in November 1990 whilst the second image (simulated) is for the rather different atmospheric conditions and sun elevation of June 1990. At the time of the November overpass horizontal visibility was estimated at 35 km whilst for the June one it was only 20 km. The sun elevation angle for the winter overpass was 39° but that for the summer overpass was 58°. The DN values recorded for the same areas of the Earth's surface thus differ considerably between the two images.

The *Bilko 3* image processing software

Familiarity with *Bilko* is required to carry out this lesson. In particular, you will need experience of using Formula documents to carry out mathematical manipulations of images and should be familiar with creating colour composites and reading off pixel values from the status bar. These features are covered in Tutorials 10, 2 and 3 respectively of the *Introduction to using the Bilko 3 image processing software*. A familiarity with the *Microsoft Excel* spreadsheet package is also desirable because some calculations need to be performed independently; these can either be carried out on a spreadsheet or using a calculator.

Image data

The first image was acquired by Landsat-5 TM on 22 November 1990 at 14.55 hours Universal Time (expressed as a decimal time and thus equivalent to 14:33 GMT). The Turks & Caicos Islands are on GMT – 5 hours so the overpass would have been at 09:33 local time. You are provided with bands #1 (blue), #2 (green) and #3 (red) of this image as the files ***LandsatTM_Nov_DN#01.gif***, ***LandsatTM_Nov_DN#02.gif*** and ***LandsatTM_Nov_DN#03.gif***. These images are of DN values but have been geometrically corrected. The second Landsat-5 TM image has been simulated for the rather different atmospheric conditions and sun elevation of 22 June 1990 at 14.55 hours Universal Time by the reverse of the process you are learning to carry out in this lesson (i.e. surface reflectance values have been converted to DN values at the sensor). You are provided with bands #1 (blue), #2 (green) and #3 (red) of this image as the files ***LandsatTM_Jun_DN#01.gif***, ***LandsatTM_Jun_DN#02.gif*** and ***LandsatTM_Jun_DN#03.gif***. These images are also of DN values and have been geometrically corrected so that pixels can be compared between seasons. The centre of each scene is at 21.68° N and 72.29° W.

Concepts underlying atmospheric correction

Digital sensors record the intensity of electromagnetic radiation (ER) from each spot viewed on the Earth's surface as a digital number (DN) for each spectral band. The exact range of DN that a sensor utilises depends on its radiometric resolution. For example, a sensor such as Landsat MSS measures radiation on a 0–63 DN scale whilst Landsat TM measures it on a 0–255 scale. The DN values recorded by a sensor are *proportional* to upwelling ER (radiance), the true units of which are W m^{-2} $ster^{-1}$ μm^{-1} (Box 4.1).

Much image processing is based on raw DN values in which actual spectral radiances are not of interest (e.g. when classifying a single satellite image). However, there are problems with this approach. The spectral signature of a habitat (say seagrass) is not transferable if measured in digital numbers. The values are image specific; that is, they are dependent on the viewing geometry of the satellite at the moment the image was taken, the location of the sun, specific weather conditions, and so on. It is generally far more useful to convert the DN values to spectral units.

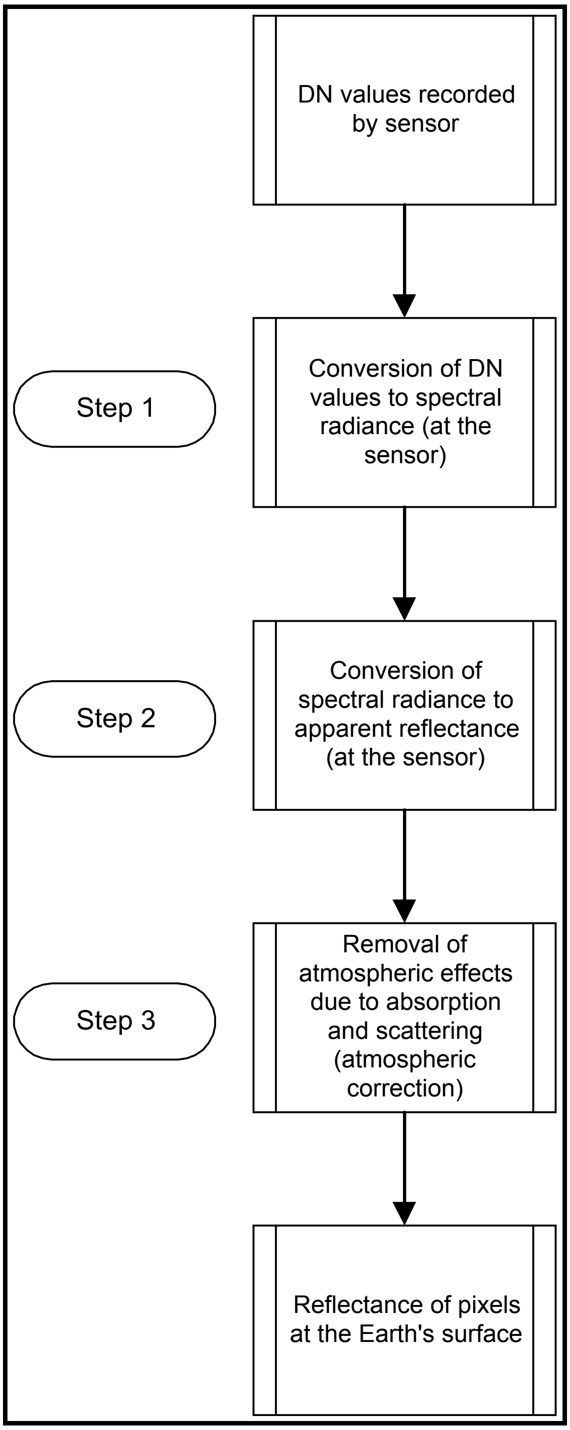
This has two great advantages:

1) A spectral signature with meaningful units can be compared from one image to another. This would be required where the area of study is larger than a single scene or if monitoring change at a single site where several scenes taken over a period of years are being compared.

2) There is growing recognition that remote sensing could make effective use of "spectral libraries", i.e. libraries of spectral signatures containing lists of habitats and their *reflectances* in different wavebands (see Box 4.1).

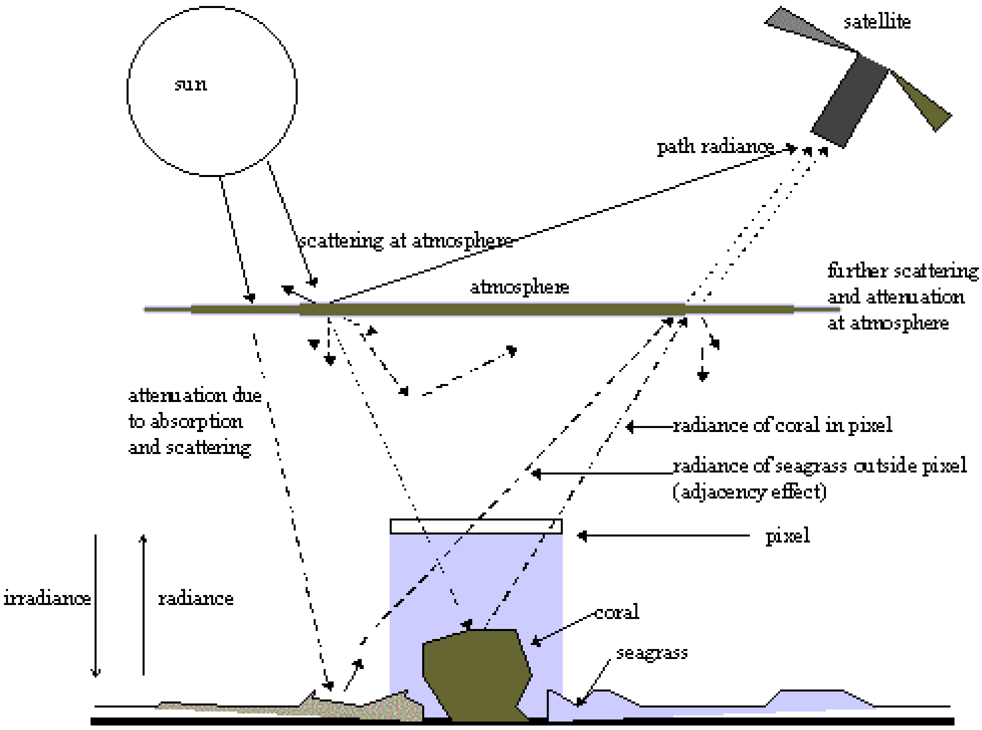
While spectral radiances can be obtained from the sensor calibration, several factors still complicate the quality of remotely sensed information. The spectral radiances obtained from the calibration only account

Figure 4.1. The process of radiometric correction.



for the spectral radiance measured *at the satellite sensor*. By the time ER is recorded by a satellite or airborne sensor, it has already passed through the Earth's atmosphere twice (sun to target and target to sensor).

Figure 4.2. Simplified schematic of atmospheric interference and the passage of electromagnetic radiation from the Sun to the satellite sensor.



During this passage (Figure 4.2), the radiation is affected by two processes: *absorption,* which reduces its intensity, and *scattering,* which alters its direction. Absorption occurs when electromagnetic radiation interacts with gases such as water vapour, carbon dioxide and ozone. Scattering results from interactions between ER and both gas molecules and airborne particulate matter (aerosols). These molecules and particles range in size from the raindrop (>100 µm) to the microscopic (<1 µm). Scattering will redirect incident electromagnetic radiation and deflect reflected ER from its path (Figure 4.2).

Box 4.1. Units of electromagnetic radiation

The unit of electromagnetic radiation is W m^{-2} $ster^{-1}$ μm^{-1}. That is, the rate of transfer of energy (Watt, W) recorded at a sensor, per square metre on the ground, for one steradian (three dimensional angle from a point on Earth's surface to the sensor), per unit wavelength being measured. This measure is referred to as the *spectral radiance*. Prior to the launch of a sensor, the relationship between measured spectral radiance and DN is determined. This is known as the sensor calibration. It is worth clarifying terminology at this point. The term *radiance* refers to any radiation leaving the Earth (i.e. upwelling, toward the sensor). A different term, *irradiance*, is used to describe downwelling radiation reaching the Earth from the sun (Figure 4.2). The ratio of upwelling to downwelling radiation is known as *reflectance*. Reflectance does not have units and is measured on a scale from 0 to 1 (or 0–100%).

Absorption and scattering create an overall effect of "haziness" which reduces the contrast in the image. Scattering also creates the "adjacency effect" in which the radiance recorded for a given pixel partly incorporates the scattered radiance from neighbouring pixels.

In order to make a meaningful measure of radiance at the Earth's surface, the atmospheric interferences must be removed from the data. This process is called "atmospheric correction". The entire process of radiometric correction involves three steps (Figure 4.1).

The spectral radiance of features on the ground is usually converted to reflectance. This is because spectral radiance will depend on the degree of illumination of the object (i.e. the irradiance). Thus spectral radiances will depend on such factors as time of day, season, latitude, etc. Since reflectance represents the ratio of radiance to irradiance, it provides a standardised measure that is directly comparable between images.

Additional data needed to carry out radiometric correction

A considerable amount of additional information is needed to allow you to carry out the radiometric correction of an image. Much of this is contained in header files, which come with the imagery. Two tables of information relating to the Landsat TM imagery are included here; other information is introduced in the lesson as needed. Table 4.1 has been extracted from the November 1990 Landsat TM image header, whilst Table 4.2 contains some satellite specific information you will need.

Table 4.1. In-band radiances from the TM header file, $Lmin_\lambda$ and $Lmax_\lambda$ in mW cm^{-2} $ster^{-1}$.

Band	Header values $Lmin_\lambda$	$Lmax_\lambda$
TM1	-0.00768	1.05572
TM2	-0.01501	2.60562
TM3	-0.01068	1.63441
TM4	-0.02098	2.94533
TM5	-0.00554	0.68583
TM6	0.12378	1.52431
TM7	-0.00312	0.42585

Table 4.2. Bandwidths for Landsat 4 and 5 Thematic Mapper sensors (μm).

Satellite	TM1	TM2	TM3	TM4	TM5	TM6	TM7
Landsat 4	0.066	0.081	0.069	0.129	0.216	1.000	0.250
Landsat 5	0.066	0.082	0.067	0.128	0.217	1.000	0.252

Lesson Outline

Comparison of the two Landsat image DN values.

Your first task is to compare the raw DN values of identical pixels in the November and June images prior to radiometric correction. You will enter these in Table 4.3.

Activity: Launch *Bilko* and open the geometrically corrected November Landsat TM image bands #1 to #3. In the **Open** dialog box select ***LandsatTM_Nov_DN#01.gif***, ***LandsatTM_Nov_DN#02.gif*** and ***LandsatTM_Nov_DN#03.gif*** with the mouse and click on OK. [*Hint:* after selecting the first file, hold down the *<Ctrl>* key when clicking on the other two files]. Each file will be opened in turn.

Connect the three images using the **Image, Connect** function. Set the **Selector** toolbar so that the TM band #3 image is image 1, TM band #2 is image 2, and TM band #1 is image 3 and use the **Image, Composite** function to make a colour composite with each band displayed on the appropriate gun. [*Note:* The composite will be dark and bluish but do not worry!] Select all the pixels in the colour composite image (*<Ctrl>+A*) and apply an automatic linear stretch (**Stretch, Auto Linear**); this will brighten it considerably. Use **View, Coords** to switch off the UTM coordinates.

Using the **Edit, Go To** command (with the **Selection Type:** as Point Selection) and Status Bar information, make a note of the DN values at each of the five column and row coordinates in Table 4.3 below. [*Note:* The order of bands in the Table is set to the same as the composite (RGB) so that you can read the values off easily. But make sure you read off the **underlying data values** in the first triplet on the Status Bar, **not** the values to which these have been stretched (in the second triplet at the far right)!]

Close the colour composite and the connected images window. **Minimise** the ***LandsatTM_Nov_DN#01.gif***, ***LandsatTM_Nov_DN#02.gif*** and ***LandsatTM_Nov_DN #03.gif*** images as these will be required later.

Then open the geometrically corrected June Landsat TM image bands #1–#3 (***LandsatTM_Jun_DN#01.gif***, ***LandsatTM_Jun_DN#02.gif*** and ***LandsatTM_Jun_DN #03.gif***), connect them and make a colour composite exactly as before. Make a note of the DN values at the same coordinates and enter these in Table 4.3.

Close the colour composite, the connected images window **and** the ***LandsatTM_Jun_DN#01.gif***, ***LandsatTM_Jun_DN#02.gif*** and ***LandsatTM_Jun_DN #03.gif*** files.

Table 4.3. Raw DN values for five row and column coordinates for each of the Landsat TM images.

	Coordinates		November image			June image		
			Red [1]	Green [2]	Blue [3]	Red [1]	Green [2]	Blue [3]
Habitat	Col (x)	Row (y)	TM3	TM2	TM1	TM3	TM2	TM1
Deep water	614	377						
Sand in very shallow water	537	82						
Mangrove	446	175						
Deep coral reef	270	426						
Seagrass	603	125						

Question: *4.1.* Why do you think the Landsat TM3 DN value for the deep water and for the deep coral reef area is the same?

Question: *4.2.* Why do you think the Landsat TM3 DN value for the shallow seagrass area is almost the same as that for deep water and deep coral reef?

Step 1. Conversion of DN to spectral radiance

This is a fairly straightforward process that requires information on the *gain* and *bias* of the sensor in each band (Figure 4.3). The transformation is based on a calibration curve of DN to radiance, which has been calculated by the operators of the satellite system. The calibration is carried out before the sensor is launched and the accuracy declines as the sensitivity of the sensor changes over time. Periodically attempts are made to re-calibrate the sensor.

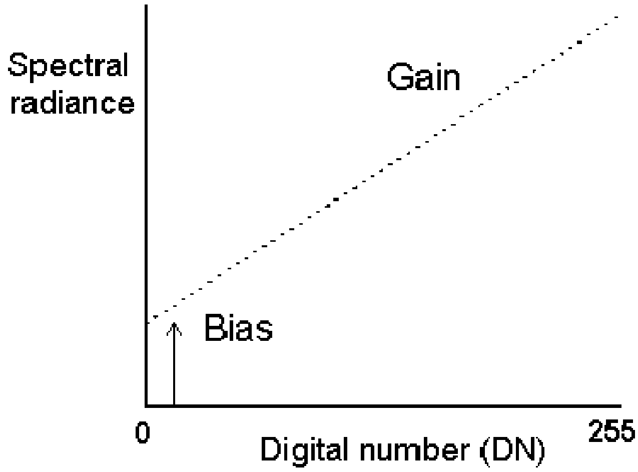


Figure 4.3. Calibration of 8-bit satellite data. Gain represents the gradient of the calibration. Bias defines the spectral radiance of the sensor for a DN of zero.

The calibration is given by the following expression for at satellite spectral radiance, L_λ:

$$L_\lambda = \text{Bias} + (\text{Gain} \times \text{DN})$$ *Equation 4.1*

units: $\text{mW cm}^{-2}\ \text{ster}^{-1}\ \mu\text{m}^{-1}$ (for Landsat)

Activity: **Connect** the three images of DN values (***LandsatTM_Nov_DN#01.gif***, ***LandsatTM_Nov_DN#02.gif*** and ***LandsatTM_Nov_DN#03.gif***) as a stacked set. This will make TM band #1, image 1; TM band #2, image 2; and TM band #3, image 3. Thus during processing using Formula documents the TM band #1 image will always be @1, the TM band #2 image will be @2, and so on. [*Note:* this is the reverse of the way these bands were connected to make a colour composite.]

Calibration of Landsat TM data

The method for calculating gain and bias varies according to when the imagery was processed (at least, this is the case for imagery obtained from EOSAT). Gains and biases for each band λ are calculated from the lower ($Lmin_\lambda$) and upper ($Lmax_\lambda$) limits of the post-calibration spectral radiance range (Table 4.1 and Figure 4.3). Since the imagery was **processed** after October 1st 1991 we can use Equation 4.2 to calculate the gains and biases for each waveband, which are needed to solve Equation 4.1 and convert the DN values to at satellite spectral radiances.

$$\text{Gain} = \frac{\text{Lmax}_\lambda}{254} - \frac{\text{Lmin}_\lambda}{255} \qquad \text{Bias} = \text{Lmin}_\lambda \qquad \textit{Equation 4.2}$$

Where data have been processed after October 1st 1991 (as in this case), the values of Lmax_λ and Lmin_λ for Landsat TM can be obtained from the header file that accompanies the data. The header file is in ASCII format and the gains/biases are stored in fields 21–33 in band sequence. The Lmin_λ and Lmax_λ have been extracted from the header file for you and are displayed in Table 4.1. These values are given as in-band radiance values (mW cm^{-2} $ster^{-1}$) and need to be converted to spectral radiances across each band (mW cm^{-2} $ster^{-1}$ μm^{-1}). This is done by dividing each value by the spectral band width in µm. Band widths for the TM sensors carried on Landsats 4 and 5 are listed in Table 4.2. The Landsat TM images used here were taken from the **Landsat-5** satellite.

Activity: Use a spreadsheet or calculator to calculate spectral radiances in mW cm^{-2} $ster^{-1}$ μm^{-1} using Lmin_λ and Lmax_λ in-band radiance values in Table 4.1 and bandwidth values in Table 4.2. Put your results into Table 4.4. [*Hint:* For each value in Table 4.1 you need to divide by the appropriate bandwidth in Table 4.2.]

Table 4.4. Spectral radiances from the TM header file, Lmin_λ and Lmax_λ in mW cm^{-2} $ster^{-1}$ μm^{-1}.

	Spectral radiances	
Band	Lmin_λ	Lmax_λ
TM1		
TM2		
TM3		

Activity: In *Bilko* open a new Formula document (**File, New** and select FORMULA Document from the list). Enter a header as a comment (i.e. preceded by a #) to indicate the purpose of the formula. For example,

```
# Bilko formula document to radiometrically correct Landsat-5 TM bands
# 1-3 collected over the Turks and Caicos on 22 November 1990.
#
#       Formula document 1. To carry out Steps 1 and 2.
#       ====================================
```

For each waveband the form of the formula to carry out Equation 4.1 will be:

Lmin_λ + (Lmax_λ/254 – Lmin_λ/255) x @*n*;

where *n* = 1, 2 or 3 depending on the TM band.

Activity: You need to create three lines of code, **one for each TM waveband**, but first enter comments (lines starting with #) and set up input values as constants using a series of **CONST name = value ;** statements in the Formula document.

The comment lines indicate what the values you are entering are. This makes the documents both easier to understand and easy to use with different images where you can just substitute new values.

Activity: To make the Formula document clearer, set up constants with the appropriate values for Lmin_λ and Lmax_λ substituted from your Table 4.4. For example, something of the type:

```
#       Step 1. Converting DN to spectral radiance using formulae of the type:
#       Lmin + (Lmax/254 - Lmin/255) * @n ;
#
```

```
#       Input values
#       =========
#       Lmin: TM1 = -0.???, TM2 = -0.??? TM3 = -0.???
#       Lmax: TM1 = ??.???; TM2 = ??.???; etc.
#
        CONST Lmin1 = -0.??? ;
        CONST Lmin2 = -0.??? ;
        CONST Lmin3 = -0.??? ;

        CONST Lmax1 = ??.??? ;
        CONST Lmax2 = ??.??? ;
        CONST Lmax3 = ??.??? ;

#       Intermediate formulae:
#
```

would be appropriate here (but with the correct values!). Once the constants are set up you type their names in the formulae instead of the values. Thus wherever you want the $Lmin_{\lambda}$ for Landsat TM1 to appear you just type Lmin1. Insert the formulae for each waveband (one per line) after this introductory information. Don't forget the **;** after each executable formula statement. **Save** your formula document as ***Radiometric_correction1.frm***.

Important: One would normally carry out all the radiometric and atmospheric correction calculations in one go. However, the complexity of the formulae needed here make this rather difficult so that we will carry them out in two stages. We will **not** copy and paste this formula to the connected images just yet, but will continue to build up the formula document so that it converts the DN values directly to exoatmospheric reflectances. This is not easy and will require considerable care on your part. **Before** proceeding, check that your formulae are like the *Checkpoint* example for Landsat TM band #4 below.

Checkpoint: Example of step 1 equation, correct for Landsat TM band #4:

```
CONST Lmin4 = -0.1639 ;
CONST Lmax4 = 23.010 ;
Lmin4 + (Lmax4/254 – Lmin4/255) * @4 ;
```

The predecence of operators (* / + -) means that only those brackets which have been included are needed. Thus division and multiplication always precede addition and subtraction. The brackets are needed to make sure that the subtraction of $Lmin_{\lambda}/255$ from $Lmax_{\lambda}/254$ to calculate the gain are carried out before the DN values are multiplied by the resultant gain.

Step 2. Conversion of spectral radiance to exoatmospheric reflectance

The apparent reflectance, which for satellite images is termed exoatmospheric reflectance, ρ, relates the measured radiance, *L* (which is what the formulae above will output), to the solar irradiance incident at the top of the atmosphere and is expressed as a decimal fraction between 0 and 1:

$$\rho = \frac{\pi . L . d^2}{\mathrm{ESUN}.\cos(\mathrm{SZ})} \qquad \textit{Equation 4.3}$$

ρ = unitless planetary reflectance at the satellite (this takes values of 0–1.)

π = 3.141593

L = Spectral radiance at sensor aperture in mW cm^{-2} $ster^{-1}$ μm^{-1}

d^2 = the square of the Earth-Sun distance in astronomical units = $(1 – 0.01674 \cos(0.9856 \times (JD – 4)))^2$ where JD is the Julian Day (day number of the year) of the image acquisition. [*Note:* the units for the argument of the cosine function of 0.9856 x (JD – 4) are in degrees; if your cosine function (e.g. the **cos** function in *Excel* is expecting the argument in radians, multiply by π/180 before taking the cosine).]

ESUN = Mean solar exoatmospheric irradiance in mW cm^{-2} μm^{-1}. ESUN can be obtained from Table 4.5.

SZ = sun zenith angle when the scene was recorded. *Note:* The *Bilko* formula expects this argument in radians.

☞ Both Landsat and SPOT products provide sun elevation angle. The zenith angle (SZ) is calculated by subtracting the sun elevation from 90° (π/2 radians).

Activity: Calculate the Julian Day (day number of the year) of the image acquisition. The date of acquisition can be found in the **Image data** section above. A quick way to do this is to enter the date of acquisition in one cell of an *Excel* spreadsheet and the date of the end of the previous year (e.g. 31 December 1989) in another cell. Then enter a formula in a next door cell which subtracts the second date from the first. Thus, 1 January 1990 is day 1, etc.

Having calculated the Julian Day (JD), work out the square of the Earth-Sun distance in astronomical units (d^2) using the equation above. Use a spreadsheet or calculator.

The sun elevation angle at the time the scene was recorded was 39°. Calculate the sun zenith angle in degrees for when the scene was recorded and convert to radians.

Using Table 4.5, determine the correct values of ESUN (Solar Exoatmospheric Spectral Irradiances) for the three TM bands you are correcting.

Table 4.5. TM Solar Exoatmospheric Spectral Irradiances (mW cm^{-2} μm^{-1}). *Source*: EOSAT.

Band	Landsat-4	Landsat-5
TM1	195.8	195.7
TM2	182.8	182.9
TM3	155.9	155.7
TM4	104.5	104.7
TM5	21.91	21.93
TM7	7.457	7.452

Question: *4.3.* What is the Julian Day corresponding to 22 November 1990?

Question: *4.4.* What was the square of the Earth-Sun distance in astronomical units (d^2) on that day?

Question: *4.5.* What is the sun zenith angle in degrees (SZ)? What is it in radians?

Question: *4.6.* What are the values of ESUN for Landsat-5 TM1, TM2 and TM3, which are to be used in Equation 4.3 to calculate the exoatmospheric reflectances for these bands?

Question: *4.7.* For SPOT images, spectral radiance values are provided in units of W m^{-2} $ster^{-1}$ μm^{-1}. If you needed to convert a SPOT XS band #1 solar exoatmospheric spectral irradiance of 1855 W m^{-2} $ster^{-1}$ μm^{-1} to units of mW cm^{-2} $ster^{-1}$ μm^{-1}, what would you multiply by and what is the resultant value in the new units?

Activity: Return to your formula document (***Radiometric_correction1.frm***). The formulae you have entered so far will convert DN values to at satellite spectral radiance (*L*) in Equation 4.3. You now need to multiply *L* by π and d^2, and divide by ESUN and cos(SZ).

Thus you need to substitute the formulae you have already entered for *L* in the equation.

[*Hint:* Enter details of what you are about to do as comments, after the formulae already entered. Also set up the new input values as constants. For example, the following might be appropriate:

```
# Step 2. Converting at satellite spectral radiance (L) to exoatmospheric reflectance
#
#          Input values
#          ==========
#          pi = 3.141593
#          d² = ?.?????? astronomical units.
#          SZ = ?.????? radians
#          ESUN: TM1 = ???.?, TM2 = ???.?, TM3 = ???.?
#
           const pi =3.141593 ;
           const dsquared = ?.?????? ;
           const SZ = ?.????? ;
           const ESUN1 = ???.? ; const ESUN2 = ???.?; const ESUN3 =  ???.? ;
#          Let at satellite spectral radiance = L
#
#          Converting L to exoatmospheric reflectance with formulae of the type:
#
#          pi * L * dsquared / (ESUN * cos(SZ)) ;
           Enter your formula here (see below)
```
]

☞ Note that you can enter several constant statements on one line.

Activity: Once the constants and comments are entered, use **Copy** and **Paste** to copy the intermediate formulae you created earlier, down to beneath this information before commenting the originals out (inserting a # before them). [If you get an *Error in formula* message, check for errors. If it recurs just retype the formulae.] Put brackets around the copied formulae (but leave the **;** outside!) and then add in the relevant values and mathematical operators to carry out Step 2 of the radiometric correction according to Equation 4.3.

When you have completed the formula document, you should have all lines as comments apart from the statements setting up the constants and the three lines of the final formulae, which will probably look horrendous. Each formula should have a total of **four** opening brackets and **four** closing brackets if written in the format suggested above.

Activity: **Save** the Formula document. Because the exoatmospheric reflectance ρ has a value between 0 and 1, the output image will need to be a floating point (32-bit image). So before applying your formula to the connected images you need to select **Options!** from the *Bilko* menu. In the **Formula Options** dialog box select 32-bit Floating point from the **Output Image Type:** drop-down menu. (You do <u>not</u> want any special handling of nulls.)

Question: *4.8.* What would happen if the output image were an 8-bit integer image like the input Landsat TM images?

Activity: Apply the Formula document to the connected images using **Copy** and **Paste**. It will apply the formula with @1 in it to the TM band #1 image of DN values, the formula with @2 in it to the TM band #2 image, etc. [If you get an *Error in formula* message, check for errors.] The three resultant images will show <u>exoatmospheric reflectance</u> on a scale of 0–1.

Close the connected images window and original images (***LandsatTM_Nov_DN#01.gif***, ***LandsatTM_Nov_DN#02.gif*** and ***LandsatTM_Nov_DN #03.gif***) as these are no longer required. **Close** the formula document.

Connect the three resultant (exoatmospheric reflectance) images as a stack. (The image derived from the TM band #1 image will be the @1 image, that from TM band #2 the @2 image, etc.)

Step 3. Removal of atmospheric effects due to absorption and scattering

A detailed discussion of the methods available for atmospheric correction is available in Kaufman (1989). Atmospheric correction techniques can be broadly split into three groups:

1. Removal of path radiance (e.g. dark pixel subtraction which will be carried out in Lesson 6),
2. Radiance-reflectance conversion, and
3. Atmospheric modelling (e.g. 5S radiative transfer code, which will be used here).

Atmospheric modelling is perhaps the most sophisticated method used to compensate for atmospheric absorption and scattering. Ideally, modelling approaches are best used when scene-specific atmospheric data are available (e.g. aerosol content, atmospheric visibility). However, such information is rarely available and while a range of models exist, the 5S (**S**imulation of the **S**ensor **S**ignal in the **S**olar **S**pectrum) radiative transfer code (Tanre *et al.*, 1986) atmospheric model is used here because it includes a variety of standard options which allow use with limited ancillary data. The outputs of 5S radiative transfer code will be used to convert the exoatmospheric reflectance to the reflectance at the Earth's surface.

Using the 5S Radiative Transfer Code: The model predicts the apparent (exoatmospheric) reflectance at the top of the atmosphere using information about the surface reflectance and atmospheric conditions (i.e. it works in the opposite way that one might expect). Since the true apparent reflectance has been calculated from the sensor calibration and exoatmospheric irradiance (above), the model can be inverted to predict the true surface reflectance (i.e. the desired output). In practice, some of the model outputs are used to create inversion coefficients, which may then be applied to the image file. We cannot run the model programme here but will introduce you to the inputs needed and provide you with the outputs from a Unix version of the model, which we have run for this Landsat TM data. There are three stages in using the 5S code.

Table 4.6. Inputs to the 5S radiative transfer code for atmospheric correction. With the exception of inputs highlighted in *bold*, general inputs can be used where specific information is not available. See text for further information.

Parameter	Specific Inputs	General Inputs
Viewing and illumination geometry*	◊ **Type of sensor (e.g. Landsat TM)** ◊ **Date and time of image acquisition** ◊ **Latitude and longitude of scene centre**	◊ None
Atmospheric profile	◊ Temperature (K) ◊ Pressure (mB) ◊ Water vapour density (g.m^{-3}) ◊ Ozone density (g.m^{-3})	◊ Tropical ◊ Mid latitude summer ◊ Mid latitude winter ◊ Subarctic summer ◊ Subarctic winter
Aerosol components	◊ Dust-like component (%) ◊ Oceanic component (%) ◊ Water soluble component (%) ◊ Soot component (%)	◊ Continental aerosol model ◊ Maritime aerosol model ◊ Urban aerosol model

Aerosol concentration	◊ Aerosol optical depth at 550 nm	◊ **Meteorological visibility (km)**
Spectral band	◊ Lower and upper range of band (μm)	◊ Band name (e.g. Landsat TM3)
Ground reflectance	(a) Choose homo- or heterogeneous surface (b) If heterogeneous, enter reflectance of target surface, surrounding surface and target radius (km)	As specific inputs except 5S supplies mean spectral value for green vegetation, clear water, sand, lake water

* this information is available in image header file and/or accompanying literature

Stage 1 *- Run the 5S code for each band in the imagery*

The inputs of the model are summarised in Table 4.6. Note that it is possible to input either a general model for the type of atmospheric conditions or, if known, specific values for atmospheric properties at the time the image was taken. In the event that no atmospheric information is available, the only parameter that needs to be estimated is the horizontal visibility in kilometres (meteorological range) which for our November image was estimated at 35 km (a value appropriate for the humid tropics in clear weather), but for the June image was significantly poorer at only 20 km.

Activity: Make a note of the following specific inputs needed to run the 5S code in Table 4.7. below:

Table 4.7. Specific inputs needed to run the 5S code for the two images.

Specific inputs	November image	June image
Type of sensor		
Date and time of image acquisition		
Latitude and longitude of scene centre		
Meteorological visibility (km)		

Stage 2 *- Calculate the inversion coefficients and spherical albedo from the 5S code output*

The 5S code provides a complex output but only some of the information is required by the user. The following example of the output for Landsat TM1 (Box 4.2) highlights the important information in bold.

Activity: Refer to Box 4.2 (see end of lesson) for Landsat TM1 values of key parameters (underlined and in bold) output by 5S atmospheric model and insert the global gas transmittance, total scattering transmittance, reflectance and spherical albedo values in Table 4.8 below. The values for bands TM2 and TM3 have already been entered from runs of the 5S radiative transfer code for these wavebands.

Table 4.8. Outputs from the 5S radiative transfer code and parameters calculated from these.

Parameter	TM1	TM2	TM3
Global gas transmittance		0.917	0.930
Total scattering transmittance		0.854	0.897
Reflectance		0.044	0.027
Spherical albedo		0.108	0.079
A_I (see Equation 4.4)			
B_I (see Equation 4.5)			

Activity: Use these values and Equations 4.4 and 4.5 below to calculate the inversion coefficients A_I and B_I for each waveband and then enter these values (to **4 decimal places**) in Table 4.8. This can be done on a spreadsheet or using a calculator.

$$A_I = \frac{1}{\text{Global gas transmittance} \times \text{Total scattering transmittance}} \quad \textit{Equation 4.4}$$

$$B_I = \frac{-\text{Reflectance}}{\text{Total scattering transmittance}} \quad \textit{Equation 4.5}$$

The coefficients A_I and B_I and the exoatmospheric reflectance data derived in Step 2 can then be combined using Formula documents to create new images Y for each waveband using Equation 4.6. [Note the minus sign in front of the Reflectance value in Equation 4.5, which means that B_I will always be negative.]

$$Y = \left(A_I \times \text{Exoatmospheric reflectance } [\rho]\right) + B_I \quad \textit{Equation 4.6}$$

where ρ are the values (exoatmospheric reflectances) stored in your new connected stacked images (@1, @2 and @3).

You now have the information needed to carry out Stages 2 and 3 of the atmospheric correction, which will convert your exoatmospheric reflectances to <u>at surface reflectances</u>. It is best to carry this out as two stages with intermediate formulae to create the new images Y for each waveband (Equation 4.6) and final formulae, incorporating these, to carry out Equation 4.7.

Activity: Open a **new** formula document and enter an appropriate header (modelled on what you did earlier) to explain what is being done and set up a series of constant statements for the new input data. Suggested constant names are AI1, AI2 and AI3 and BI1, BI2 and BI3 for the inversion coefficients.

For each waveband, create an intermediate formula to carry out Equation 4.6 of the type:

AI * @*n* + BI ;

where *n* = the waveband. **Save** the Formula document as ***Radiometric_correction2.frm***.

Stage 3 *- Implementation of model inversion to the Landsat TM satellite imagery*

Once you have set up the formulae to create the new images (Y) for each waveband using Equation 4.6, you can take the appropriate spherical albedo (S) values from Table 4.8 and use the following equation to obtain **surface reflectance** ρ_s on a scale of 0–1:

$$\rho_s = \frac{Y}{1 + SY} \qquad \textit{Equation 4.7}$$

Activity: The formulae so far entered create Y for each waveband. To carry out Equation 4.7 for each waveband you thus need to take this formula (wrapped in brackets) and substitute it in the equation for Y. The spherical albedo values (S) for each waveband are obtainable from Table 4.8 and should be entered as constants S1, S2 and S3.

Once you have successfully created the final formulae, **Save** the Formula document. Then **Copy** the Formula document and **Paste** it on the connected exoatmospheric reflectance images. The three new 32-bit floating point images resulting from this transformation will have **surface reflectance** values on a scale of 0–1 (with 0 representing 0% reflectance and 1 representing 100% reflectance).

Save these images as ***LandsatTM_Nov_SR#01.dat***, ***LandsatTM_Nov_SR#02.dat*** and ***LandsatTM_Nov_SR#03.dat***, making sure that ***LandsatTM_Nov_SR#01.dat*** is the image derived from ***LandsatTM_Nov_DN#01.gif*** and so on. [*Note:* the 32-bit floating point images must be stored with the *Bilko* ***.dat*** extension.]

Close the Formula document and the connected images window.

Now read off the pixel reflectances (on a scale of 0–1) at each of the two column and row coordinates listed in Table 4.9 for each of the three surface reflectance images ***LandsatTM_Nov_SR#01.dat***, ***LandsatTM_Nov_SR#02.dat*** and ***LandsatTM_Nov_SR#03.dat***. This is most easily done by connecting the images and making a colour composite with TM band #3 through the red gun, TM band #2 through the green gun and TM band #1 throught the blue gun. You can then read the image data values for all three bands off the Status Bar. Record them to **three** decimal places in Table 4.9. Use **Edit, Go To** to locate each of the column and row coordinate positions (switching off UTM coortinates with **View, Coords** command, if necessary). [The remaining data has been filled in for you.]

Important note: You will notice that some pixels, primarily those over deepwater areas, may have values that are very small negative numbers! Do not be alarmed. This can be quite a common occurrence in radiometric correction and shows that the atmospheric correction is not necessarily precise, particularly when inputs to the 5S radiative transfer code are limited. In this case we had very limited inputs (Table 4.7). As these small negative values are clearly errors it is good practice to set them to zero. This could be done with a simple formula document.

When you have completed Table 4.9 for the November image, close the surface reflectance files ***LandsatTM_Nov_SR#01.dat***, ***LandsatTM_Nov_SR#02.dat*** and ***LandsatTM_Nov_SR#03.dat*** and, if you've made it, the colour composite and connected images window.

Comparison of surface reflectance images from June and November

At the start of the lesson you compared the DN values of the November and June images at certain row and column coordinates. Now you will apply a pre-prepared Formula document to the June images to correct them and then compare the surface reflectance values at five coordinates in the corrected June images with those in the corrected November images.

Activity: Open the three bands of uncorrected DN values of the June 1990 image (***LandsatTM_Jun_DN#01.gif***, ***LandsatTM_Jun_DN#02.gif*** and ***LandsatTM_Jun_DN #03.gif***). **Connect** the three images as a stack. Open the Formula document ***Radiometric_correction_Jun.frm*** (listed in Appendix 4.2). This formula carries out the complete correction process in one go. Select **Formula, Options!** and make sure the output images will be 32-bit floating point. Then apply the formula to the connected images. Once the surface reflectance images have been created, close the connected images window and close ***LandsatTM_Jun_DN#01.gif***, ***LandsatTM_Jun_ DN#02.gif*** and ***LandsatTM_Jun_DN#03 .gif***.

Activity: Read off the pixel reflectances (on a scale of 0–1) at each of the two coordinates (sand in very shallow water, and coral reef) in Table 4.9. Record values to **three** decimal places (rounding appropriately). Use **Edit, Go To** to locate each of the coordinate positions and make a colour composite (as before) to save time in reading off the values.

Before closing the images you may wish to compare the corrected November and June images in one waveband. When you are finished, close all images (without saving).

Table 4.9. Surface reflectance values (on a scale of 0–1) for five row and column coordinates for each of the Landsat TM images. [Same order of images as for Table 4.3].

	Coordinates		**November image**			**June image**		
			Red	Green	Blue	Red	Green	Blue
Habitat	Col (x)	Row (y)	TM3	TM2	TM1	TM3	TM2	TM1
Deep water	614	377	-0.003	-0.002	0.004	-0.002	-0.003	0.004
Sand in very shallow water	**537**	**82**						
Mangrove	446	175	0.025	0.040	0.010	0.025	0.042	0.010
Deep coral reef	**270**	**426**						
Seagrass	603	125	0.000	0.019	0.006	0.000	0.019	0.006

Question: *4.9.* What is the principal difference you see when you compare the November and June image uncorrected raw DN values for these coordinates (Table 4.3) and the corrected surface reflectance values in Table 4.9 above? Why is this?

Question: *4.10.* If you were carrying out monitoring over time using remote sensing or were trying to use habitat spectra derived for one image in another image, why would you need to carry out radiometric and atmospheric correction?

To see the effect that radiometric and atmospheric correction have had one can compare the average absolute difference between the November and June TM band #2 surface reflectance values at the five coordinates expressed as a percentage of the average of the ten values, with the average absolute difference between the November and June TM band #2 DN values expressed as a percentage of the average of the ten DN values. [Dividing by the average allows the differences to be compared directly].

Activity: Use a calculator or spreadsheet to calculate the absolute differences (use the ABS function) between each of the five pairs of surface reflectance and five pairs of DN values for TM band #2 (from Tables 4.3 and 4.9). Express the average absolute difference in each case as a percentage of the average of the 10 values involved.

Question: *4.11.* What is the average absolute difference between the November and June TM band #2 **DN values** expressed as a percentage of the average of the ten DN values?

Question: *4.12.* What is the average absolute difference between the November and June TM band #2 **surface reflectance** values at the five coordinates expressed as a percentage of the average of the ten values?

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Box 4.2. Output of 5S Radiative Transfer Code for Landsat-5 TM1 waveband.

GEOMETRICAL CONDITIONS IDENTITY

T.M. OBSERVATION; MONTH: 11 DAY : 22 UNIVERSAL TIME: 14.55 (HH.DD); LATITUDE:21.68; LONGITUDE: -72.29; SOLAR ZENITH ANGLE: 51.16; SOLAR AZIMUTH ANGLE: 142.10; OBSERVATION ZENITH ANGLE: 0.00; OBSERVATION AZIMUTH ANGLE: 0.00; SCATTERING ANGLE:128.84; AZIMUTH ANGLE DIFFERENCE: 142.10

ATMOSPHERIC MODEL DESCRIPTION

ATMOSPHERIC MODEL IDENTITY: TROPICAL (UH2O=4.12 G/CM2 ,UO3=.247 CM)

AEROSOLS TYPE IDENTITY : MARITIME AEROSOLS MODEL

OPTICAL CONDITION IDENTITY : VISIBILITY 35.00 KM OPT. THICK. 550NM 0.1823

SPECTRAL CONDITION

TM 1 VALUE OF FILTER FUNCTION WLINF = 0.430 MICRON / WLSUP = 0.550 MICRON

TARGET TYPE

HOMOGENEOUS GROUND; SPECTRAL CLEAR WATER REFLECTANCE 0.042

INTEGRATED VALUES

APPARENT REFLECTANCE 0.108; APPAR. RADIANCE (W/M2/SR) 2.642

TOTAL GASEOUS TRANSMITTANCE 0.987

INT. NORMALIZED VALUES

% OF IRRADIANCE AT GROUND LEVEL			REFLECTANCE AT SATELLITE LEVEL		
% OF DIR. IRR.	% OF DIFF. IRR.	% OF ENV. IRR	ATM. INTRINS	BACKG.	PIXEL
0.668	0.325	0.006	0.076	0.007	0.025

INT. ABSOLUTE VALUES

IRR. AT GROUND LEVEL (W/M2)			RAD. AT SATEL. LEVEL (W/M2/SR)		
DIR. SOLAR	ATM.	DIFF. ENV.	ATM. INTRIN	BACKG.	PIXEL
43.582	21.169	0.421	1.858	0.180	0.604

INTEGRATED FUNCTION FILTER 0.061 (MICRONS)

INTEGRATED SOLAR SPECTRUM 122.586 (W/M2)

INTEGRATED VALUES

	DOWNWARD	UPWARD	TOTAL
GLOBAL GAS TRANS.	0.992	0.995	**0.987**
WATER GAS TRANS.	1.000	1.000	1.000
OZONE GAS TRANS.	0.992	0.995	0.987
CARBON DIOXIDE	1.000	1.000	1.000
OXYGEN	1.000	1.000	1.000
RAYLEIGH SCA.TRANS.	0.882	0.922	0.813
AEROSOL SCA. TRANS.	0.959	0.983	0.943
TOTAL SCA. TRANS.	0.849	0.915	**0.776**

	RAYLEIGH	AEROSOLS	TOTAL
SPHERICAL ALBEDO	0.129	0.044	**0.156**
OPTICAL DEPTH	0.164	0.188	0.352
REFLECTANCE	0.068	0.009	**0.077**
PHASE FUNCTION	1.043	0.102	0.540
SINGLE SCAT. ALBEDO	1.000	0.990	0.994

Answers to Questions

Table 4.3. Raw DN values for pixels at five row and column coordinates in each of the Landsat TM images (Bands #1–#3).

			November image			June image		
	Coordinates		Red [1]	Green [2]	Blue [3]	Red [1]	Green [2]	Blue [3]
Habitat	Col (x)	Row (y)	TM3	TM2	TM1	TM3	TM2	TM1
Deep water	614	377	9	13	52	13	17	66
Sand in very shallow water	537	82	98	97	179	129	129	234
Mangrove	446	175	17	23	55	23	31	70
Deep coral reef	270	426	9	19	75	13	25	96
Seagrass	603	125	10	18	53	14	24	67

4.1. The red band penetrates poorly so that by about 5–7 m depth even bright sand is not likely to reflect any more light back than deep water. The deep coral reef area will also have low reflectance in the red band due to the presence of zooxanthellae in the coral tissues (with similar pigments to other photosynthetic organisms) and is too deep (> 10 m) to reflect more red light than deep water areas.

4.2. The seagrass area, although shallow, has a very low albedo (is very dark) and being thick vegetation will have a very low reflectance in the red waveband anyway. Thus this area reflects only slightly more red light than deepwater.

Table 4.4. Spectral radiances from the TM header file, $Lmin_\lambda$ and $Lmax_\lambda$ in mW cm^{-2} $ster^{-1}$ μm^{-1}.

	Spectral radiances	
Band	$Lmin_\lambda$	$Lmax_\lambda$
TM1	-0.116	15.996
TM2	-0.183	31.776
TM3	-0.159	24.394

4.3. The Julian Day corresponding to 22 November 1990 is 326.

4.4. The square of the Earth-Sun distance in astronomical units (d^2) on 22 November 1990 is 0.975522 AU (Astronomical Units)? $[1 - 0.01674 \cos(0.9856 \times 322)]^2$

4.5. The sun zenith angle in degrees (SZ) is 90° – 39° = 51° (where 39° is the sun elevation angle). In radians this is $51 \times \pi/180 = 0.89012$.

4.6. The values of ESUN for Landsat-5 TM1, TM2 and TM3 are: 195.7, 182.9 and 155.7 mW cm^{-2} μm^{-1} respectively.

4.7. If you needed to convert a SPOT XS band #1 solar exoatmospheric spectral irradiance (ESUN) of 1855 W m^{-2} $ster^{-1}$ μm^{-1} to units of mW cm^{-2} $ster^{-1}$ μm^{-1}, you need to consider change in two of the four units. W are changing to mW (x 1000) and units of power per m² are changing to units of power per cm². There are 100 cm in a metre and thus 100 x 100 = 10,000 cm² in one square metre, so we need also to divide by 10,000. So the net result is x 1000/10,000 which is equivalent to dividing by 10. So 10 W m^{-2} $ster^{-1}$ μm^{-1} = 1 mW cm^{-2} $ster^{-1}$ μm^{-1}. Thus 1855 W m^{-2} $ster^{-1}$ μm^{-1} = 185.5 mW cm^{-2} $ster^{-1}$ μm^{-1}.

Table 4.7. Specific inputs needed to run the 5S code for the two images.

Specific inputs	November image	June image
Type of sensor	Landsat 5 TM	Landsat 5 TM
Date and time of image acquisition	14:55 UT, 22/11/1990	14:55 UT, 22/06/1990
Latitude and longitude of scene centre	21.68°N 72.29°W	21.68°N 72.29°W
Meteorological visibility (km)	35 km	20 km

Table 4.8. Outputs from the 5S radiative transfer code and parameters calculated from these.

Parameter	TM1	TM2	TM3
Global gas transmittance	0.987	0.917	0.930
Total scattering transmittance	0.776	0.854	0.897
Reflectance	0.077	0.044	0.027
Spherical albedo	0.156	0.108	0.079
A_I (see Equation 4.4)	1.3056	1.2769	1.1987
B_I (see Equation 4.5)	-0.0992	-0.0515	-0.0301

Table 4.9. Surface reflectance values (on a scale of 0-1) for the two row and column coordinates which have not been completed for each of the Landsat TM images.

Habitat	Coordinates		November image			June image		
	Col (x)	Row (y)	TM3	TM2	TM1	TM3	TM2	TM1
Sand in very shallow water	537	82	0.311	0.344	0.255	0.311	0.345	0.255
Deep coral reef	270	426	-0.003	0.023	0.051	-0.002	0.023	0.051

4.8. If the output image were an 8-bit integer image all pixel values would either be 0 or 1 (i.e. they would be rounded to the nearest integer).

4.9. Because of the extra haze in the atmosphere in June more of the incoming sunlight is reflected back at the sensor making the whole image brighter with higher DN values in each band at all pixels. Once the atmospheric conditions have been corrected for then the images appear remarkably similar with pixel values almost identical. In reality correction would not be this good but this is what it aims to do.

4.10. Because raw DN values recorded from given sites on the Earth's surface will vary with atmospheric conditions, time of year, etc. Thus unless radiometric and atmospheric correction have been carried out any comparison of pixel values at given locations is fairly meaningless. Any differences could be due as much to changes in sun angle, the distance of the Earth from the sun or atmospheric conditions as to changes in the habitat.

4.11. The average absolute difference between the November and June TM band #2 **DN values** expressed as a percentage of the average of the ten DN values is 11.2/39.6 x 100 = 28.28%.

Habitat	Nov TM2	Jun TM2	Difference
Deep water	13	17	4
Sand in very shallow water	97	129	32
Mangrove	23	31	8
Deep coral reef	19	25	6
Seagrass	18	24	6
Mean	39.6		11.2

4.12. The average absolute difference between the November and June TM band #2 **surface reflectance** values at the five coordinates expressed as a percentage of the average of the ten surface reflectance values is 0.008/0.085 x 100 = 0.94%.

Habitat	Nov TM2	Jun TM2	Difference
Deep water	-0.002	-0.003	0.001
Sand in very shallow water	0.344	0.345	0.001
Mangrove	0.040	0.042	0.002
Deep coral reef	0.023	0.023	0.000
Seagrass	0.019	0.019	0.000
Mean	0.085		0.0008

APPENDIX 4.1A: STEPS 1-2 OF RADIOMETRIC CORRECTION. CONVERTING DN VALUES TO EXOATMOSPHERIC REFLECTANCE

```
# Start of Bilko formula document to radiometrically correct Landsat-5 TM bands
# 1-3 collected over the Turks and Caicos on 22 November 1990.
#
#       Formula document 1.
#       =================
#
#       Step 1. Converting DN to at satellite spectral radiance (L) using formulae of the type:
#
#               Lmin + (Lmax/254 - Lmin/255) * @n ;
#
#       Input values
#       ==========
#       Lmin: TM1 = -0.116, TM2 = -0.183, TM3 = -0.159
#       Lmax: TM1 = 15.996; TM2 = 31.776; TM3 = 24.394
#
        CONST Lmin1 = -0.116 ;
        CONST Lmin2 = -0.183 ;
        CONST Lmin3 = -0.159 ;

        CONST Lmax1 = 15.996 ;
        CONST Lmax2 = 31.776 ;
        CONST Lmax3 = 24.394 ;

#       Intermediate formulae for L for each TM band:
#
#       Lmin1 + (Lmax1/254 - Lmin1/255)*@1;
#       Lmin2 + (Lmax2/254 - Lmin2/255)*@2;
#       Lmin3 + (Lmax3/254 - Lmin3/255)*@3;
#
#       Step 2. Converting at satellite spectral radiance (L) to exoatmospheric reflectance
#
#       Input values
#       ==========
#       pi = 3.141593
#       d² = 0.975522 JD = 326 for 22/11/90 image. (call dsquared)
#       sun_zenith = 90-39 = 51° = 0.89012 radians
#       ESUN: TM1 = 195.7, TM2 = 182.9, TM3 = 155.7

        CONST pi =3.141593 ;
        CONST dsquared = 0.97552 ;
        CONST sun_zenith = 0.89012 ;
        CONST ESUN1 = 195.7 ;
        CONST ESUN2 = 182.9 ;
        CONST ESUN3 =  155.7 ;
#
#       Let at satellite spectral radiance = L  (see intermediate formulae above)
#
#       Converting L to exoatmospheric reflectance (on scale 0-1) with formulae of the type:
#
#               pi * L * dsquared / (ESUN * COS(sun_zenith)) ;
#
        pi * (Lmin1 + (Lmax1/254 - Lmin1/255)*@1) * dsquared / (ESUN1 * COS(sun_zenith)) ;
        pi * (Lmin2 + (Lmax2/254 - Lmin2/255)*@2) * dsquared / (ESUN2 * COS(sun_zenith)) ;
        pi * (Lmin3 + (Lmax3/254 - Lmin3/255)*@3) * dsquared / (ESUN3 * COS(sun_zenith)) ;
```

APPENDIX 4.1B: STEP 3 OF RADIOMETRIC CORRECTION (STAGES 2-3 OF ATMOSPHERIC CORRECTION).

```
# Start of Bilko formula document to atmospherically correct Landsat-5 TM bands
# 1-3 collected over the Turks and Caicos on 22 November 1990.
#
#       Formula document 2.
#       =================
#       Stage 2 of atmospheric correction using 5S radiative transfer model outputs
#
#       Input values
#       ==========
#       AI = 1 / (Global gas transmittance * Total scattering transmittance)
#               TM1 = 1.3056, TM2 = 1.2769, TM3 = 1.1987
#
#       BI = - Reflectance / Total scattering transmittance
#               TM1 = -0.0992, TM2 = -0.0515, TM3 = -0.0301
#
        CONST AI1 = 1.3056 ;
        CONST AI2 = 1.2769 ;
        CONST AI3 = 1.1987 ;
        CONST BI1 = -0.0992 ;
        CONST BI2 = -0.0515 ;
        CONST BI3 = -0.0301 ;

#       Let exoatmospheric reflectance = @n  (i.e. images output by first formula document)
#
#       Converting exoatmospheric reflectance (scale 0-1) to intermediate image Y with formulae of
the type:
#                AI * @n + BI;
#
#       Intermediate formulae for Y:
#
#       AI1 * @1  + BI1;
#       AI2 * @2  + BI2;
#       AI3 * @3  + BI3;
#
#       Stage 3 of atmospheric correction using 5S radiative transfer model outputs
#
#       Input values
#       ==========
#       S = Spherical albedo: TM1 = 0.156, TM2 = 0.108, TM3 = 0.079
#
        CONST S1 = 0.156 ;
        CONST S2 = 0.108 ;
        CONST S3 = 0.079 ;

#       Let intermediate image  = Y  (see intermediate formulae above)
#
#       Converting Y to surface reflectance (on scale 0-1) with formulae of the type:
#
#               Y / (1 + S * Y) ;
#
        (AI1 * @1 + BI1) / (1 + S1 * (AI1 * @1 + BI1) ) ;
        (AI2 * @2 + BI2) / (1 + S2 * (AI2 * @2 + BI2) ) ;
        (AI3 * @3 + BI3) / (1 + S3 * (AI3 * @3 + BI3) ) ;
```

APPENDIX 4.2: FORMULA FOR RADIOMETRIC CORRECTION OF JUNE 1990 LANDSAT TM IMAGES.

```
# Start of Bilko formula document to radiometrically correct Landsat-5 TM bands
# 1-3 collected over the Turks and Caicos on 22 June 1990.
#
#       Formula document 1.
#       =================
#
#       Converting DN to at satellite spectral radiance (L) using formulae of the type:
#
#               Lmin + (Lmax/254 - Lmin/255) * @n ;
#
#       Input values
#       ==========
#       Lmin: TM1 = -0.116, TM2 = -0.183, TM3 = -0.159
#       Lmax: TM1 = 15.996; TM2 = 31.776; TM3 = 24.394
#
        CONST Lmin1 = -0.116 ;
        CONST Lmin2 = -0.183 ;
        CONST Lmin3 = -0.159 ;

        CONST Lmax1 = 15.996 ;
        CONST Lmax2 = 31.776 ;
        CONST Lmax3 = 24.394 ;

#       Intermediate formulae for L for each TM band:
#
#       Lmin1 + (Lmax1/254 - Lmin1/255)*@1;
#       Lmin2 + (Lmax2/254 - Lmin2/255)*@2;
#       Lmin3 + (Lmax3/254 - Lmin3/255)*@3;
#
#       Converting at satellite spectral radiance (L) to exoatmospheric reflectance
#
#       Input values
#       ==========
#       pi = 3.141593
#       d² = 1.032829 astronomical units (JD = 173 for 22/6/90)
#       sun_zenith = 90-58 = 32 degrees = 0.5585 radians
#       ESUN: TM1 = 195.7, TM2 = 182.9, TM3 = 155.7

        CONST pi =3.141593 ;
        CONST dsquared = 1.032829 ;
        CONST sun_zenith = 0.5585 ;
        CONST ESUN1 = 195.7 ;
        CONST ESUN2 = 182.9 ;
        CONST ESUN3 =  155.7 ;
#
#       Let at satellite spectral radiance = L  (see intermediate formulae above)
#
#       Converting L to exoatmospheric reflectance (ER)  with formulae of the type:
#
#               pi * L * dsquared / (ESUN * COS(sun_zenith))  ;
#
#
#       ER1 = pi * (Lmin1 + (Lmax1/254 - Lmin1/255)*@1) * dsquared / (ESUN1 * COS(sun_zenith));
#       ER2 = pi * (Lmin2 + (Lmax2/254 - Lmin2/255)*@2) * dsquared / (ESUN2 * COS(sun_zenith));
#       ER3 = pi * (Lmin3 + (Lmax3/254 - Lmin3/255)*@3) * dsquared / (ESUN3 * COS(sun_zenith));
```

```
#
#       Formula document 2.
#       =================
#
#       Stage 2 of atmospheric correction using 5S radiative transfer model outputs
#
#       Input values
#       ==========
#       AI = 1 / (Global gas transmittance * Total scattering transmittance)
#               TM1 = 1.2561, TM2 = 1.2344, TM3 = 1.1716
#
#       BI = - Reflectance / Total scattering transmittance
#               TM1 = -0.0957, TM2 = -0.0539, TM3 = -0.0341
#
        CONST AI1 = 1.2561 ;
        CONST AI2 = 1.2344 ;
        CONST AI3 = 1.1716 ;

        CONST BI1 = -0.0957 ;
        CONST BI2 = -0.0539 ;
        CONST BI3 = -0.0341 ;

#       Let exoatmospheric reflectance = ERn where n=1-3  (i.e. images output by first formula
document)
#
#       Converting exoatmospheric reflectance to intermediate image Y with formulae of the type:
#
#               AI * ER + BI;
#
#       Intermediate formulae for Y:
#
#       AI1 * ER1 + BI1;
#       AI2 * ER2 + BI2;
#       AI3 * ER3 + BI3;
#
#       Stage 3 of atmospheric correction using 5S radiative transfer model outputs
#
#       Input values
#       ==========
#       S = Spherical albedo: TM1 = 0.167, TM2 = 0.121, TM3 = 0.092
#
        CONST S1 = 0.167 ;
        CONST S2 = 0.121 ;
        CONST S3 = 0.092 ;

#       Let intermediate image  = Y  (see intermediate formulae above)
#
#       Converting Y to surface reflectance (on scale 0-1) with formulae of the type:
#
#               Y / (1 + S * Y)  ;
#
#       Note that the intermediate formula for Y should appear in the equation twice.
#

#       (AI1 * ER1 + BI1) / (1 + S1 * (AI1 * ER1 + BI1) ) ;
#       (AI2 * ER2 + BI2) / (1 + S2 * (AI2 * ER2 + BI2) ) ;
#       (AI3 * ER3 + BI3) / (1 + S3 * (AI3 * ER3 + BI3) ) ;

#       Substituting for ER1-3 with intermediate formulae above:
```

(AI1 * (pi * (Lmin1 + (Lmax1/254 - Lmin1/255)*@1) * dsquared / (ESUN1 * COS(sun_zenith))) + BI1) / (1 + S1 * (AI1 * (pi * (Lmin1 + (Lmax1/254 - Lmin1/255)*@1) * dsquared / (ESUN1 * COS(sun_zenith))) + BI1));

(AI2 * (pi * (Lmin2 + (Lmax2/254 - Lmin2/255)*@2) * dsquared / (ESUN2 * COS(sun_zenith))) + BI2) / (1 + S2 * (AI2 * (pi * (Lmin2 + (Lmax2/254 - Lmin2/255)*@2) * dsquared / (ESUN2 * COS(sun_zenith))) + BI2));

(AI3 * (pi * (Lmin3 + (Lmax3/254 - Lmin3/255)*@3) * dsquared / (ESUN3 * COS(sun_zenith))) + BI3) / (1 + S3 * (AI3 * (pi * (Lmin3 + (Lmax3/254 - Lmin3/255)*@3) * dsquared / (ESUN3 * COS(sun_zenith))) + BI3));

Intentionally blank

5: REMOVING SUN GLINT FROM COMPACT AIRBORNE SPECTROGRAPHIC IMAGER (CASI) IMAGERY

Aim of Lesson

To learn how to remove sun glint from high resolution airborne and satellite imagery to reveal bottom features and improve classification.

Objectives

1. To understand the rationale underlying the method of sun glint removal developed by Hochberg *et al.* (2003) as modified by Hedley *et al*. (2005).
2. To choose a reference near infra-red (NIR) band and find out the ambient NIR signal in the absence of sun glint.
3. To select areas of deep water with varying sun glint intensities and find out the linear relationship (regression) between each visible band and the chosen NIR band pixels.
4. To use the information from 2 and 3 above to remove the component of visible band values that is due to sun glint and thus "deglint" each pixel of the visible bands.

Background Information

This lesson relates to recent research published by Hochberg *et al.* (2003) and developed by Hedley *et al.* (2005). You are recommended to consult these papers for further details of the techniques involved. This lesson uses the modified approach of Hedley *et al.* (2005) to show how to remove sun glint from Compact Airborne Spectrographic Imager (CASI) imagery flown in the vicinity of the island of St John in the US Virgin Islands.

The *Bilko 3* image processing software

Familiarity with *Bilko 3* is required to carry out this lesson. In particular, you will need experience of stacking images and creating colour composites and of using Formula documents to carry out mathematical manipulations of images. Tutorials 2 and 10 in the *Introduction to using the Bilko 3 image processing software* are particularly relevant and provide a good grounding for this lesson. A familiarity with the Microsoft *Excel* spreadsheet package or the *Minitab* statistical package is also highly desirable. You will need access to one or other of these two packages to complete this lesson.

Image data

A Compact Airborne Spectrographic Imager (CASI) instrument was mounted on a light aircraft and flown at 4100 ft (1250 m) altitude over shallow coral reef areas off the coast of St John in the USVI at a speed of 130 nautical miles per hour (240 $km.h^{-1}$) in an East–West direction. An incident light sensor (ILS) was fixed to the fuselage so that simultaneous measurements of irradiance could be made and radiance measurements thus converted to reflectances. A Differential Global Positioning System (DGPS) was mounted to provide a record of the aircraft's flight path. Data were collected at a spatial resolution of 2 x 2 m (4 m^2) in 19 wavebands (Table 5.1). The images were geometrically corrected using a UTM projection and WGS 84 spheroid/datum. The width of the groundtrack recorded by the CASI was approximately 1 km.

The final geometrically and radiometrically corrected images were stored in a 16-bit unsigned integer format. For the purposes of this lesson the coordinate information has been removed from the images. However, if you wish to replace this, the coordinates of the upper left pixel are Easting 322978.0 m

Northing 2032462.0 m (UTM zone 20 N). The pixel DX: = 2.0 m and DY: = 2.0 m. (If you correctly edit the coordinates you should find that the lower right pixel has an Easting of 326066.0 m and Northing of 2031302.0 m.) Each image consists of 581 rows and 1545 columns of pixels.

Table 5.1. Band settings used on the CASI. Bands 8-16 have not been included with the lesson data.

Band	Part of electromagnetic spectrum	Mid-wavelength (nm)	Width of waveband (nm)	Regions of peak sensitivity in eye
01	Blue	442.4	13.1	Blue cones
02	Blue	465.6	10.4	Blue cones
03	Blue	488.0	12.3	
04	Green	507.6	7.6	
05	Green	519.7	4.8	
06	Green	530.0	5.8	
07	Green	540.3	4.9	Green cones
08	Green	549.7	4.9	Green cones
09	Green	560.1	5.8	
10	Green	570.4	4.9	
11	Green	579.9	4.9	
12	Yellow	589.3	4.9	Red cones
13	Orange	599.7	5.8	Red cones
14	Orange	618.6	5.8	
15	Red	639.4	5.8	
16	Red	668.9	6.8	
17	Near infra-red	698.4	5.9	
18	Near infra-red	756.6	8.8	
19	Near infra-red	809.3	11.7	

Geometrically and radiometrically corrected Compact Airborne Spectrographic Imager (CASI) data for 10 bands are provided for the purposes of this lesson as a set (***St_John_USVI_CASI.set***) of 10 *Bilko* ***.dat*** files (***St_John_USVI_CASI#01.dat – St_John_USVI_CASI#19.dat***). These files are unsigned 16-bit integer files (each pixel recording a reflectance value converted to an integer between 0 and 65535). This means that there are two bytes needed per pixel.

The problem of sun glint

The mapping of benthic features can be seriously impeded by sun glinting on the water surface. When skies are clear and the water surface is rippled, specular reflection of the incident radiation occludes the benthic signal with bright ‘sun glint’. Unfortunately the problem of sun glint is particularly acute under conditions when remote sensing might otherwise be most effective: clear skies, shallow waters (which, when wind-blown, form waves), and when images are collected at a high spatial resolution. Typically, sun glint forms bands of white along wave edges on the windward side of near shore environments (Figure 5.1). These white bands confound the visual identification of bottom features, and will confuse both supervised and unsupervised classifications (with the presence or absence of sun glint dominating the categorisation in affected areas).

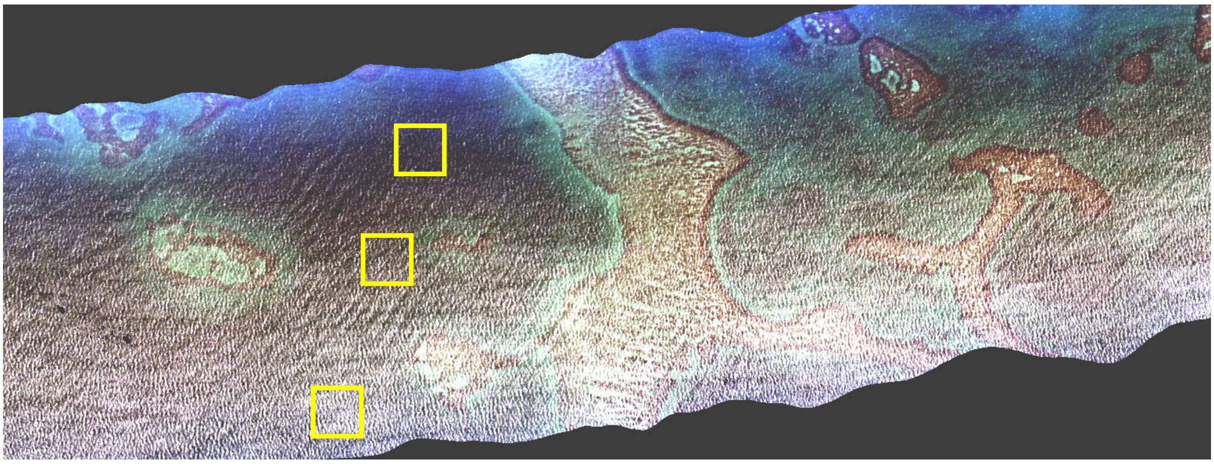


Figure 5.1. A colour composite (if printed, this may be in shades of grey), showing the CASI image before sun glint removal. Specular reflection along wave edges is obscuring much of the image and sun glint is generally bad along the southern side of the ground-track. Three areas of deepish water showing varying sun glint are outlined by boxes.

Although in areas with sun glint the recorded signal appears almost entirely composed of the water surface specular reflectance signal, the component caused by water leaving radiance may be recoverable providing that the sensor remains spectrally unsaturated. A recent paper by Hedley *et al.* (2005) presents a conceptually simple method whereby sun glint can be removed from visible wavelength spectral bands of remotely sensed images using a spectral band in the near infra-red (NIR) part of the electromagnetic spectrum (around 700–910 nm). The method is particularly applicable to high-resolution imagery such as that obtained using airborne sensors such as CASI or satellite sensors such as IKONOS. Image pixels are adjusted to remove the sun glint component of the recorded signal, thereby leaving only the component derived from benthic reflectance and processes within the water column. This leads to a substantial visual improvement in the 'deglinted' images and can also lead to an increase in user accuracies on maximum likelihood classifications of such images.

Outline of the 'deglinting' method

The deglinting method relies on two simple assumptions:

1) That the signal in the NIR is composed only of sun glint and a spatially constant 'ambient' signal. In particular, there is no spatially variant benthic contribution to the NIR.

2) That the amount of sun glint in the visible bands is linearly related to the signal in the NIR band.

The first assumption is justified by the fact that water is relatively opaque to NIR wavelengths (700-1000 nm) (Mobley, 1994), so that even shallow waters (e.g. those only 1.5–2 m deep) have a low water-leaving radiance in the NIR regardless of bottom type. Although a minimum NIR signal over deep water might be expected to be zero, in practice the minimum NIR (Min_{NIR}) signal is usually greater than zero. In particular, if images are not atmospherically corrected this 'residual' or 'ambient' NIR signal corresponds to NIR backscatter in the atmosphere. The method assumes a constant 'ambient' NIR (Min_{NIR}) signal level, which is removed from all pixels during the analysis.

The assumption of a linear relationship between the NIR signal and the amount sun glint in the visible bands holds because the real index of refraction (which governs reflection) is nearly equal for NIR and visible wavelengths (Mobley, 1994). Therefore the amount of light reflected from the water surface in the NIR is good indicator of the amount of light that will be reflected in visible wavelengths, and a linear relationship exists between the two. The deglinting method proceeds by establishing the linear relationship between NIR signal and the amount of sun glint in each visible band. This information, combined with the NIR signal in each image pixel, is used to work out how much to reduce the signal in each band to remove the sun glint in each pixel.

Firstly a linear relationship is established between a NIR band and each visible band using linear regression. To do this one or more regions of the image are selected which provide a range of sun glint, but where the underlying signal would be expected to be consistent (areas of deep water are ideal for this, Figure 5.1). For each visible band all the selected pixels are included in a linear regression of the visible band signal (y-axis) against the NIR signal (x-axis) (Figure 5.2).

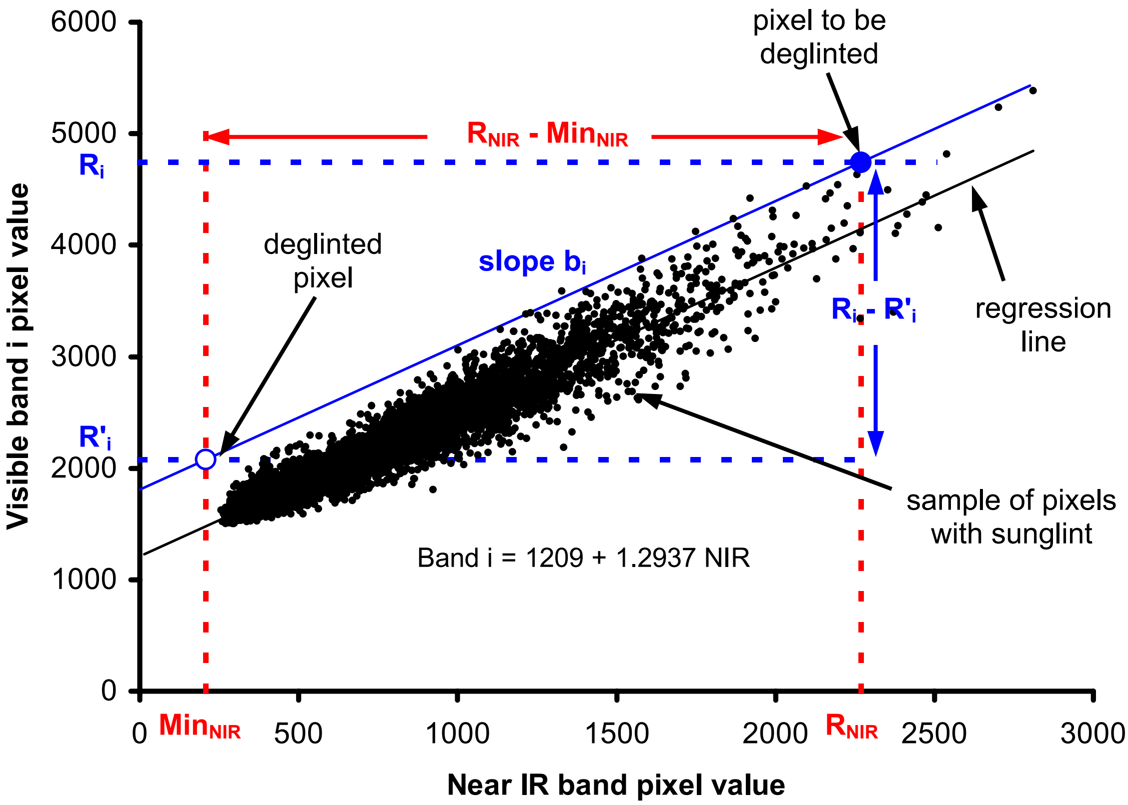


Figure 5.2. Graphical illustration of how the deglint method works. A regression is carried out between a sample of visible band (band i) pixels from areas of varying sun glint intensity and corresponding pixels in the chosen NIR band. The assumption is made that all the NIR pixels would have the 'ambient' NIR (Min_{NIR}) value in the absence of sunglint. Knowing the slope (b_i) of the regression and the value of Min_{NIR}, you can then work out the proportionate reduction in the visible band signal (R_i) required to remove the component of the signal that is due to sun glint; the magnitude of the glint being obtainable from the NIR band ($R_{\text{NIR}} - \text{Min}_{\text{NIR}}$). This allows you to calculate a 'deglinted' value (R'_i) for each visible band pixel.

If the slope of the regression line for band i is b_i, then all the pixels in the image can be deglinted in band i by the application of following equation:

$$R_i' = R_i - b_i \times (R_{\text{NIR}} - \text{Min}_{\text{NIR}}) \quad \text{[Equation 5.1]}$$

which simply means: reduce pixel signal in band i (R_i) by the product of regression slope (b_i) and the difference between the pixel's NIR signal (R_{NIR}) and the ambient NIR level (Min_{NIR}). Min_{NIR} essentially represents the NIR signal in a pixel with no sun glint and can be estimated by the minimum NIR found in the regression sample or alternatively as the minimum NIR found across the whole image. In general, the minimum NIR pixel is less prone to problematic outliers than the maximum NIR pixel.

If you find problems with understanding the derivation of equation 5.1, we can look at the diagrammatic interpretation of the method in Figure 5.2 and derive the equation step by step.

By definition, the slope (b_i) of the regression line is just the amount of change in the visible band value divided by the amount of change in the NIR band value, between any two points on the regression line. Thus if, between two points on the regression line, the visible band changed from 1000 to 4000 (change = 4000 – 1000 = 3000) whilst the NIR band changed from 1500 to 3000 (change = 3000 – 1500 = 1500) then the slope of the line would be (4000 – 1000)/(3000 – 1500) = 3000/1500 = 2.

For each pixel in the image we know its NIR value (R_{NIR}) and its value in the visible band i (R_i). We also know the 'ambient' NIR value (Min_{NIR}) and assume that all reflectance in the NIR above this value is due to specular reflection at the sea surface. After carrying out regression analysis between selected pixels in our visible band i and the corresponding pixels in the NIR band, we know the slope of the regression line b_i. This allows us to work out how much of the signal of each pixel in band i is due to specular reflection. From figure 5.2 we can see that:

$$\frac{(R_i - R'_i)}{(R_{NIR} - Min_{NIR})} = b_i$$ which translates as:

$$\frac{\text{Amount of signal due to specular reflection in visible band}_i}{\text{Amount of signal due to specular reflection in NIR band}} = \text{Slope}$$

The only value we do not know in the equation is the value (R'_i) of the deglinted pixel. We thus need to rearrange the equation so that it can be solved to give us R'_i. This can be done in 3 steps. Firstly, we must multiply each side by (R_{NIR} – Min_{NIR}). This gives:

$$(R_i - R'_i) = b_i \times (R_{NIR} - Min_{NIR})$$

Secondly, to isolate R'_i on the left-hand side of the equation, we next need to subtract R_i from each. This gives us:

$$-R'_i = b_i \times (R_{NIR} - Min_{NIR}) - R_i$$

Finally, to make R'_i positive, we need to multiply each side of the equation by –1. This gives us equation 5.1:

$$R'_i = R_i - b_i \times (R_{NIR} - Min_{NIR})$$

Since the method relies on a user-based selection of a sample set of pixels it is not necessary to mask out non-submerged or cloud pixels prior to deglinting. It is prudent to ensure that the sample pixels do not contain any non-submerged objects, but the regression will nevertheless mitigate the impact of isolated invalid pixels. However, non-submerged areas will not contain valid data after deglinting since the algorithm is valid only for submerged pixels. Note also, that as the method operates purely on the relative magnitudes of values, the absolute units of the pixel values are unimportant. Therefore, there is no need to transform pixel values into radiance and deglinting can be applied to the original image digital numbers. It is however advisable to ensure floating-point arithmetic is used in order to correctly handle fractional values and negative numbers.

Lesson Outline

Before proceeding with the deglinting you should examine the CASI images to judge the magnitude of the sun glint problem.

Activity: Open the set ***St_John_USVI_CASI.set*** (select **File, Open** and then select SETS (*.set) from the **Files of type**: drop-down menu). Make sure the **Extract** checkbox is unchecked and in the **Redisplay Image** dialog box check the **Null Value(s): == 0** checkbox and select an and Auto linear stretch as the stretch to use, before clicking on the All button to apply the stretch to all of the images in the set. You should have a stack of 10 images displayed. Holding down the *<Ctrl>* key, double-click on the top image to zoom out so that you can see the whole image. Then use the *<Tab>* key to look at each image in turn, noting how details of the seabed become progressively less distinct in bands #5–#7 and abruptly disappear when you move from band #7 to band #17 in the NIR. Note also that sun glint is concentrated on the southern half of the ground-track. For bands #17, #18 and #19 in the NIR part of the electro-magnetic spectrum, there should in theory be no return over deep (> c. 1 m depth) water and bright pixels should be due entirely to sun glint. In bands #17 and #18 note the series of parallel wave-fronts orientated in a south-west to north-east direction.

To see the extent of the sun glint more clearly and provide a reference image against which you can judge the success of the deglinting, you need to create a false colour composite image of bands #1, #3 and #5. [This combination was found to give a reasonable image and the final comparison will be with a composite made from deglinted bands #1, #3 and #5.]

Activity: Click on **Image, Connect** and select ***St_John_USVI_CASI#01.dat, St_John_USVI_CASI#03.dat*** and ***St_John_USVI_CASI#05.dat*** as the three images to be connected. Do <u>not</u> check the **Stacked** checkbox and use the **Selector** toolbar to designate band #05 as image 1 (@1: red gun), band #03 as image 2 (@2: green gun) and band #01 as image 3 (@3: blue gun). [This is achieved by clicking each button in turn from right to left.] When you have done this, select **Image, Composite** to generate the colour composite. Zoom out so that you can see the whole image. Note the serious sun glint, which is obscuring the coral reefs along the southern part of the CASI ground-track. Save this image for reference as a Windows .bmp image. [*Note:* a Windows bitmap (***.bmp***) image can be readily inserted into a *Word* document using **Insert, Picture, From File** menu in *Word*.]

Choosing a NIR band

Three CASI bands were recorded in the near infra-red (NIR): bands #17, #18 and #19. Of these, band #17 is on the border between the far red and NIR part of the spectrum but we would not expect any bottom reflectance for water more than c. 1.0 m deep for any of these wavelengths (see Table 5.1). You need to decide which of the three NIR bands will be best to use for deglinting. Normally you would need to check which NIR band gives best results in the deglinting process. There appear to be at least two criteria for deciding this: (i) how good the deglinted visible bands look, and (ii) the goodness of fit of the regression lines between the sample(s) of pixels in the visible bands and the NIR bands. To find (i) out, you would need to carry out the whole deglinting process using all three NIR bands; to find (ii) out you can regress a couple of sample bands on each NIR band. This involves carrying out later parts of the deglinting process; thus to save you time this has been done for you for bands #2 and #7. The results are shown in Table 5.2.

Table 5.2. Comparisons of linear regressions of visible bands #2 and #7 on each of NIR bands #17, #18 and #19. Slopes of regressions lines and coefficients of determination (R^2), which indicate the proportion of the variance accounted for by the regressions, are shown.

Test bands for regression	**Band 17 (698.4 nm)**		**Band 18 (756.6 nm)**		**Band 19 (809.3 nm)**	
	Slope	R^2	Slope	R^2	Slope	R^2
Band 2 (blue)	1.2515	0.8928	1.6163	0.8481	1.6372	0.7293
Band 7 (green)	1.2760	0.9432	1.6681	0.9182	1.8247	0.8518

Table 5.2 shows that coefficients of determination are highest for band #17 and worst for band #19. If you study the band #19 image you will notice that it appears less focused (less sharp) than bands #17 and #18.

Activity: Use the <*Tab*> key to move between bands #17, #18 and #19 in the stack of CASI bands and <*Shift*>+<*Tab*> key to move back again. Note that the sun glint on band #19 appears less clearly delineated than that on bands #17 or #18.

Given both the relatively low coefficients of determination and slight blurriness of band #19, you should not consider it further but concentrate on band #17 as your first choice NIR band. Given the relatively short IR wavelength of band #17, you should, however, carry out deglinting using band #18 for comparison.

Determining the minimum NIR value over deep water

To determine the minimum NIR (Min_{NIR}) value of an image you need to select an area of water that is (a) relatively dark and (b) reasonably deep (≥ 2 m depth) so that there is no chance of bottom reflectance from coral or sand close to the surface. You want a representative sample of pixels with which to calculate the Min_{NIR} but can fit a maximum of 256 columns in an *Excel* spreadsheet. Thus the suggested sample size is 256 x 100 pixels from an area with top left coordinates at X: 1200 and Y: 5 which covers a substantial area of reasonably deep water on the north side of the ground-track in the darkest part of the image. You will now determine the Min_{NIR} for bands #17 and #18 using *Excel*.

Activity: Inspect bands #17 and #18 and note that the north-east of the images appears darkest. Start *Excel* and open the *Excel* workbook called ***Lesson05_deglinting_St_John.xls***, making sure to click the Enable Macros button (if this appears). Select the **MinNIR** worksheet by clicking on its tab. Rows 2 to 101 are empty, ready to receive the sample of band #17 pixels needed to determine Min_{NIR} for band #17.

Returning to *Bilko*, select band #17 (***St_John_USVI_CASI#17.dat***) as the active image in the stack and then select **Edit, Go To** from the menu. In the **Go To** dialog box, make sure **Selection Type:** is set to Box Selection and then set **X:** to 1200, **Y:** to 5, **DX:** to 256 and **DY:** to 100 and click OK. Copy the block of pixels using the Copy button or by pressing <*Ctrl*>+*C*. Switch to *Excel*, click on cell A2 of the **MinNIR** worksheet and paste the cells (using Paste button, <*Shift*>+<*Insert*> or <*Ctrl*>+*V*). Scroll down to row 103 and you will see that a formula in cell B103 has calculated the minimum NIR value for band #17. [Make a note of this as it will be needed later; it should be 208.] Note that rows 108 to 207 are empty and ready to receive the sample of band #18 pixels needed to determine Min_{NIR} for band #18.

Returning to *Bilko*, press the <*Tab*> key to make band #18 the active image in the stack. The box selection should already be in place so you just need to copy the sample of band #18 pixels and paste it to cell A108.

Question: *5.1.* What is the Min_{NIR} for band #18? [Consult the spreadsheet below where you pasted the band #18 sample.]

Selecting areas of varying sunglint to calculate regression of each visible band on the chosen NIR band

For the purposes of this lesson you will select a 50 x 50 pixel area from each of three areas on the image; one from a low sun-glint area, one from an area with high sun glint and one from an area with intermediate sun-glint problems (Figure 5.1). The top left coordinates of each of these areas are given in Table 5.3.

Table 5.3. Column and row coordinates for three areas of varying sun glint. (Settings for **Go To** dialog box.).

Level of sun glint	Top left X: coordinate	Top left Y: coordinate	DX:	DY:
Low	490	150	50	50
Intermediate	450	300	50	50
High	400	500	50	50

Question: *5.2.* What is the area in both hectares (ha) and m^2 of each of the areas of sun glint? How many pixels are in each area sampled?

Activity: In the *Excel* workbook called ***Lesson05_deglinting_St_John.xls*** click on the tab labelled **Band samples** and you will see that for all bands except band 5, the 7500 pixels from the three areas of varying sun glint have already been entered. Your task is to enter those for band #5.

The top 2500 rows below the headings contain the pixels from the low sun glint area (Table 5.3 and Figure 5.1), the next 2500 rows contain those from the intermediate sun glint area, and the final 2500 rows contain those from the high sun glint area. In each case the rectangular sample of pixels has been copied and pasted into a *Minitab* worksheet and then "stacked" into one column. If you have access to the *Minitab* statistical package you can do the same. If you only have access to the *Excel* spreadsheet package, a "macro" is provided to allow you to do the stacking in the worksheet labelled **Stacking_sheet**. Instructions will be given to assist you to prepare the band #5 sun glint samples in both *Excel* and *Minitab*. Choose which package you will use and follow the appropriate set of instructions below. Instructions for *Excel* are given first, followed by those for *Minitab*.

Stacking the band 5 sun glint samples for regression analysis using Excel

Activity: In the *Excel* workbook ***Lesson05_deglinting_St_John.xls*** click on the tab labelled **Stacking_sheet**. This worksheet should be empty. Switch to *Bilko* and select the image stack. Use the **Selector** toolbar to select @5 St_John_USVI_CASI#05.dat as the active image. Now use **Edit, Go To** to select the low sun glint area, referring to Table 5.3 for the coordinates. When the box selection is in place, Copy the selection. Switch to *Excel* and paste the values to cell A1 (i.e. make sure cell A1 is highlighted when you click on the Paste button).

Checkpoint:	You should see the value 1534 in cell A1 of the **Stacking_sheet** worksheet. If you press *<Ctrl>+<End>* you should find the cell AX50 highlighted and this cell should contain the value 1305. If all is well, congratulations! If not, undo the paste and check that (i) you have the right image in the stack and (ii) the box selection is correctly positioned. Then try again.

Activity: With **Stacking_sheet** as the active worksheet in *Excel* select **Tools, Macro, Macros**. Select the macro called **Stack_columns** and click the Run button. The macro takes each column of 50 pixels in turn and stacks them in column A of the worksheet. The next step is to transfer the 2500 stacked cells to the Band#05 column in the **Band samples** worksheet.

Activity: To do this select cell A1 in the **Stacking_sheet** worksheet and press *<Ctrl>+<Shift>+<Down arrow>.* This will select the whole column of cells. (You should see that cell A2500 now has the value 1305.) Click on the Cut button (or **Edit, Cut**) and then click on the **Band samples** tab to make this the active worksheet. Now click on cell E3 at the top of the blank part of the Band#05 column and click on the Paste button to paste the stacked cells. Before doing anything else press *<Ctrl>+<Down arrow>* which should take you to cell E2502 which should have the value 1305. Note the thick horizontal line through neighbouring columns, which marks the end of the low sun glint pixel sample. If you now click on the **band#5_17** tab you will see that these pixels now feature on the graph.

In order to complete the graph and obtain the regression equation and hence slope for band #5, you need to repeat this procedure for the intermediate and high sunglint samples, adding the stacked pixel values to the Band#05 column until all 7500 pixels are present.

Activity: Make **Stacking_sheet** the active worksheet again. Then switch to *Bilko* and select the intermediate sun glint sample in band #5 using Table 5.3 for guidance. Copy and paste the cells to the **Stacking_sheet** (making sure that the first value is pasted in cell A1) and then run the macro again to stack the values into one column. Select the column with *<Ctrl>+<Shift>+<Down arrow>* and cut and paste it to cell E2503 in the **Band samples** worksheet. If you now click on the **band#5_17** tab you will see that these intermediate sun glint pixels now feature on the graph.

Checkpoint:	The value of E2503 should be 1572 and the value of E5002 (press *<Ctrl>+<Down arrow>* to move to bottom of column) should be 1676.

Activity: Repeat the exercise for the high sun glint sample area (Table 5.3). This time the stacked column of pixel values will be pasted to cell E5002 in the **Band samples** worksheet. If you now click on the **band#5_17** tab you will see that these high sun glint pixels now feature on the graph.

Checkpoint:	The value of E5003 should be 2034 and the value of E7502 should be 1296.

If all is well, congratulations! You can now progress to the section headed *Deglinting the visible bands*.

Stacking the band 5 sun glint samples for regression analysis using Minitab

Activity: Leave the *Excel* workbook open at the worksheet labelled **Band samples.** Start *Minitab* and make sure you have a blank worksheet showing as the active window. Switch to *Bilko* and select the image stack. Use the **Selector** toolbar to select @5 St_John_USVI_CASI#05.dat as the active image. Now use **Edit, Go To** to select the low sun glint area, referring to Table 5.3 for the coordinates. When the box selection is in place, Copy the selection. Switch to *Minitab* and paste the values to row 1 of column C1 (i.e. make sure this cell is highlighted when you click on the Paste button).

Checkpoint: You should see the value 1534 in the first cell of the worksheet. If you press *<Ctrl>+<End>* you should find the row 50 cell in column C50 highlighted and this cell should contain the value 1305. If all is well, congratulations! If not, undo the paste and check that (i) you have the right image in the stack and (ii) the box selection is correctly positioned. Then try again.

Activity: Select **Manip, Stack/Unstack, Stack Columns** from the *Minitab* menu. In the **Stack Column** dialog box enter C1-C50 in the **Stack the following columns:** text box and C1 in the **Store the stacked data in:** text box and click on OK. All the data is now stacked in column C1 so you can delete the data in columns C2-C50. To do this, select **Manip, Erase Variables** and enter C2-C50 in the **Columns, constants, and matrices to erase:** text box. You are now left with just a single column of the data you want. The next step is to transfer the 2500 stacked cells to the Band#05 column in the **Band samples** worksheet in *Excel*.

To do this click on the first cell in column C1 and press *<Ctrl>+<Shift>+<End>* to select the whole column of 2500 cells. Click on the Cut button (or **Edit, Cut Cells**) and switch to the **Band samples** worksheet in the *Excel* workbook. Click on cell E3 at the top of the blank part of the Band#05 column and click on the Paste button to paste the stacked cells. Before doing anything else press *<Ctrl>+<Down arrow>* which should take you to cell E2502 which should have the value 1305. Note the thick horizontal line through neighbouring columns, which marks the end of the low sun glint pixel sample. If you now click on the **band#5_17** tab you will see that these pixels now feature on the graph.

In order to complete the graph and obtain the regression equation and hence slope for band #5, you need to repeat this procedure for the intermediate and high sunglint samples, adding the stacked pixel values to the Band#05 column until all 7500 pixels are present.

Activity: Switch to *Bilko* and select the intermediate sun glint sample in band #5 using Table 5.3 for guidance. Copy and paste the cells to the *Minitab* worksheet (making sure that the first value is pasted in row 1 of column C1). Stack the contents of columns C1-C50 in C1 as before, and then erase columns C2-C50. [Note that your previous settings are preserved in the two dialog boxes, which makes life easier the second time round!] With the first cell of C1 highlighted, select the stacked column with *<Ctrl>+<Shift>+<End>* and cut and paste it to cell E2503 in the **Band samples** *Excel* worksheet. If you now click on the **band#5_17** tab you will see that these intermediate sun glint pixels now feature on the graph.

Checkpoint: The value of E2503 should be 1572 and the value of E5002 (press *<Ctrl>+<Down arrow>* to move to bottom of column) should be 1676.

Activity: Repeat the exercise for the high sun glint sample area (Table 5.3). This time the stacked column of pixel values will be pasted to cell E5002 in the **Band samples** worksheet. If you now click on the **band#5_17** tab you will see that these high sun glint pixels now feature on the graph. Well done! – that was the hardest part of the practical. You can now close *Minitab*.

Checkpoint: The value of E5003 should be 2034 and the value of E7502 should be 1296.

Deglinting the visible bands

You now have the full sample of 7500 band #5 pixels in column E of the **Band samples** worksheet. This is plotted against the corresponding pixels in the NIR band #17 (in column I) in the **band#5_17** chart. A linear regression (trendline) has been fitted to the data and the slope and intercept of the regression are automatically displayed on the chart.

Question: *5.3.* What is the slope and intercept for the regression of band #5 pixel values on the corresponding NIR band 17 pixel values?

You now have the necessary information to carry out the deglinting of the 7 visible bands using band #17 to estimate the amount of specular reflection in each pixel. This is done using Equation 5.1:

$$R_i' = R_i - b_i \times (R_{\mathrm{NIR}} - \mathrm{Min}_{\mathrm{NIR}})$$

expressed in a Formula document. To save time most of the formula document has been written for you. You only need to enter the $\mathrm{Min}_{\mathrm{NIR}}$ value and the slope values for bands #5−#7 (b_5, b_6 or b_7 in the equation).

Activity: Open the formula document ***Deglinting_band17.frm***. Study the formula document and note how the b_i and $\mathrm{Min}_{\mathrm{NIR}}$ values are set up as a series of constants in the CONST = statements. You need to fill in the $\mathrm{Min}_{\mathrm{NIR}}$ value for band #17 and also the regression slope values for bands #5, #6 and #7, which can be found on the relevant charts in the ***Lesson05_deglinting_St_John.xls*** spreadsheet. Do this, remembering that each statement must end with a '**;**'. Note that there is a separate formula for each band.

Let us briefly examine the first of the formulas.

```
IF (@1 == 0) 0 ELSE
(@1 - Band01_Slope * (NearInfraRed - MinNIR)) ;
```

The background in each image (areas outside the CASI groundtrack) have been set to zero and thus should not be processed. Thus the first part of each formula says that if the visible band pixel value is equal to zero then the output image pixel will be 0. Else (otherwise) for all other pixels Equation 5.1 is applied. Thus each pixel (R_1) of the @1 (= band#01) image has the Band01_Slope (b_1) multiplied by the difference between the corresponding band#17 (@8 image) pixel (R_{NIR}) and the $\mathrm{Min}_{\mathrm{NIR}}$ value for band #17 (= 208). This effectively removes the component of the signal due to specular reflection. The formula just mimics Equation 5.1.

Activity: When you have completed the formula document, save it. Then select **Options!** from the menu, set the **Output Image Type:** to Floating point 32-bit, and uncheck the **Use special handling for Nulls** checkbox (if checked) because the formula deals with these already. Copy the formula and paste it to the stack of connected images. You should get 7 deglinted images produced. Connect the first (deglinted band#01), third (deglinted band#03) and fifth (deglinted band#05) of the output images (using **Image, Connect**) but do not stack them. Use the **Selector** toolbar to designate the deglinted band#05 as image 1 (@1: red gun), the deglinted band#03 as image 2 (@2: green gun) and the deglinted band#01 as image 3 (@3: blue gun). When you have done this, select **Image, Composite** to generate the false colour composite. Save the deglinted composite as either a Bilko .set or Windows .bmp file. When you have done this, you should close the individual deglinted images, leaving only the composite open, in order to reduce clutter.

The deglinted composite should look similar to Figure 5.3. Zoom out to 50% and compare the deglinted composite with the original raw composite you saved as a Windows .bmp image at the start of the lesson.

Question: *5.4.* In what specific ways has the deglinted composite image improved compared to the raw composite?

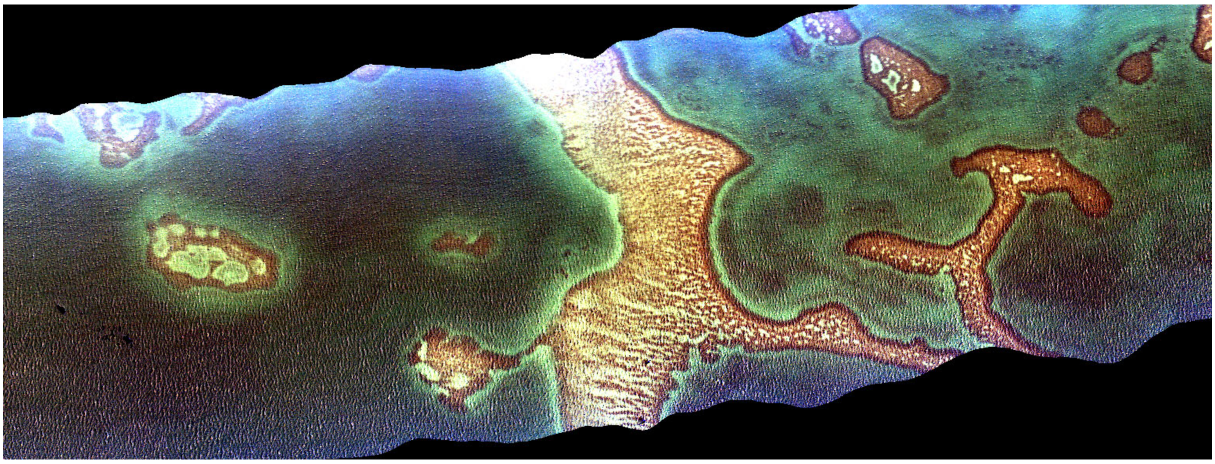


Figure 5.3. A colour composite (if printed, this may be in shades of grey), showing the CASI image after 'deglinting'.

At this point you have seen the effectiveness of the deglinting method and hopefully understood the concepts underlying it. If you are feeling ambitious or curious or both, you may wish to discover whether band #18 is a better NIR band to choose for deglinting. As we noted earlier, band #17 is only just into the near infra-red part of the electro-magnetic spectrum and one might achieve better results with band #18, despite the coefficients of determination (R^2) in the test regressions being less than for band #17 (Table 5.2). To allow you to test this fairly easily, the formula ***Deglinting_band18.frm*** is included. All you need to add is the Min_{NIR} value for band #18, which you calculated earlier, into the CONST statement at the start.

Activity: Either finish by closing all documents (**Window, Close All**) or deglint the stack of images using the ***Deglinting_band18.frm*** formula with the **CONST MinNIR = ;** statement completed. Create a colour composite of deglinted bands #1, #3 and #5 and compare with the one you created using band #17 as the NIR band. When you are finished, close all documents.

You will find that there is little to choose between deglinting with band #17 or band #18.

References

Hedley, J.D., Harborne, A.R. and Mumby, P.J. 2005. Simple and robust removal of sun glint for mapping shallow-water benthos. *International Journal of Remote Sensing* (in press).

Hochberg, E.J., Andréfouët, S. and Tyler, M.R. 2003. Sea surface correction of high spatial resolution Ikonos images to improve bottom mapping in near-shore environments. *IEEE Transactions on Geoscience and Remote Sensing* **41** (7): 1724-1729.

Mobley, C. D. 1994. *Light and Water*. Academic Press.

Answers to Questions

5.1. The Min_{NIR} for band #18 is 141. This value is automatically calculated in cell B209 from the minimum of the 256 × 100 = 25,600 values pasted into cells in rows 108 to 207.

5.2. Each pixel is 2 m × 2 m. Thus each area of sun glint is 2 m × 50 pixels on each side = 100 m × 100 m = 10,000 m^2 = 1 ha. For each area of sun glint 50 × 50 pixels = 2500 pixels are sampled. This seems a good sample size to achieve representative samples of low, medium and high sun glint pixels. Overall, 7500 pixels are sampled to establish the regression relationship between each visible band and NIR band.

5.3. The slope is 1.2261 and the intercept is 919.98 for the regression of band #5 pixel values on the corresponding NIR band #17 pixel values.

5.4. The sun glint along the southern side of the CASI ground-track has been almost completely removed revealing the detailed structure and shape of the reefs there. These were largely obscured by the sun glint. Shallow-water sandy areas around the coral reefs are also more clearly visible.

6: CRUDE BATHYMETRIC MAPPING USING LANDSAT TM SATELLITE IMAGERY

Aim of Lesson

To learn how bathymetry can be crudely mapped using digital optical imagery and the limitations of the results in terms of accuracy.

Objectives

1. To understand the rationale and assumptions underlying the depth of penetration zone method of Jupp (1988) for mapping bathymetry.
2. To learn how to sample deep-water pixels to determine maximum DN values returned over deep water for Landsat Thematic Mapper (TM) bands 1 to 4.
3. To learn how to derive maximum depth of penetration estimates for Landsat TM bands 1 to 4 for the Caicos Bank using UTM coordinate referenced field survey data of depths.
4. To learn how to combine these data to define depth of penetration (DOP) zones, assign pixels to these zones, and display a very crude bathymetric map of these depth zones.
5. To refine this map by interpolation using information on maximum and minimum DN values in each DOP zone and create an image where pixel values correspond to depth.
6. To learn how to create a palette to display depth contours effectively.
7. To investigate the limitations of the method in terms of the accuracy of image-predicted depths.

Background Information

This lesson relates to material covered in Chapter 15 of the *Remote Sensing Handbook for Tropical Coastal Management* and readers are recommended to consult this for further details of the techniques involved. This lesson describes an empirical approach to mapping bathymetry using Landsat Thematic Mapper (TM) imagery of the Caicos Bank. Similar results would be expected with imagery from the Enhanced Thematic Mapper (ETM+) sensor on Landsat-7.

Depth information from remote sensing has been used to augment existing charts (Bullard, 1983; Pirazolli, 1985), assist in interpreting reef features (Jupp *et al*., 1985) and map shipping corridors (Benny and Dawson, 1983). However, it has not been used as a primary source of bathymetric data for navigational purposes (e.g. mapping shipping hazards). The major limitations are inadequate spatial resolution and lack of accuracy. Hazards to shipping such as emergent coral outcrops or rocks are frequently much smaller than the sensor pixel and so will fail to be detected. With the launch of the IKONOS-2 satellite with 4 m multispectral and 1 m panchromatic resolution, the lack of spatial resolution is now less of an issue.

Among satellite sensors, the measurement of bathymetry can be expected to be best with Landsat TM (and ETM+) and IKONOS-2 data because those sensors detect visible light from a wider portion of the visible spectrum, in more bands, than most other satellite sensors. Landsat TM (and ETM+) bands 1, 2 and 3 are all useful in measuring bathymetry; so too is band 4 in very shallow (<1 m), clear water over bright sediment (where bands 1–3 tend to be saturated). Bands 5 and 7 are completely absorbed by even a few cm of water and can therefore be ignored for bathymetric calculations.

This lesson will help you understand the importance of water depth in determining the reflectance of objects on the seabed and prepare you for understanding Lesson 7 which deals with how one attempts to compensate for these effects.

The *Bilko 3* image processing software

Familiarity with *Bilko* is required to carry out this lesson. In particular, you will need experience of using Formula documents to carry out mathematical manipulations of images. This feature is covered in Tutorial 10 of the *Introduction to using the Bilko 3 image processing software*. Spreadsheet skills are also essential to benefit fully from the lesson. Instructions for spreadsheet manipulations are given for *Excel* and should be amended as appropriate for other spreadsheets.

Image data

The image you will be using was acquired by Landsat-5 TM on 22nd November 1990 at 14.55 hours Universal Time (expressed as a decimal time and thus equivalent to 14:33 GMT). The Turks & Caicos are on GMT – 5 hours so the overpass would have been at 09:33 local time. You are provided with bands #1 (blue), #2 (green), #3 (red) and #4 (near-infrared) of part of this image as the files ***LandsatTM_bathymetric#1.gif***, ***LandsatTM_bathymetric#2.gif***, ***LandsatTM_bathymetric#3.gif*** and ***LandsatTM_bathymetric#4.gif***. These images are of DN values but have been geometrically corrected. The post-correction pixel size is 33 x 33 m and each image is 800 pixels across and 900 pixels along-track.

Question: *6.1.* How many kilometres wide and long is the image?

Concepts underlying the remote sensing of bathymetry

The fundamental principle behind using remote sensing to map bathymetry is that different wavelengths of light will penetrate water to a varying degree. When light passes through water it becomes attenuated by interaction with the water column. The intensity of light remaining (I_d) after passage length *d* through water, is given by:

$$I_d = I_0 . e^{-k.d} \qquad \text{Equation 6.1}$$

where I_0 = intensity of the incident light and k = attenuation coefficient, which varies with wavelength. Equation 6.1 can be made linear by taking natural logarithms:

$$\log_e(I_d) = \log_e(I_0) - k.d \qquad \text{Equation 6.2}$$

Red light attenuates rapidly in water and does not penetrate further than about 5 m in clear water. By contrast, blue light penetrates much further and in clear water the seabed can reflect enough light to be detected by a satellite sensor even when the depth of water approaches 30 m. The depth of penetration is dependent on water turbidity. Suspended sediment particles, phytoplankton and dissolved organic compounds will all effect the depth of penetration (and so limit the range over which optical data may be used to estimate depth) because they scatter and absorb light, thus increasing attenuation.

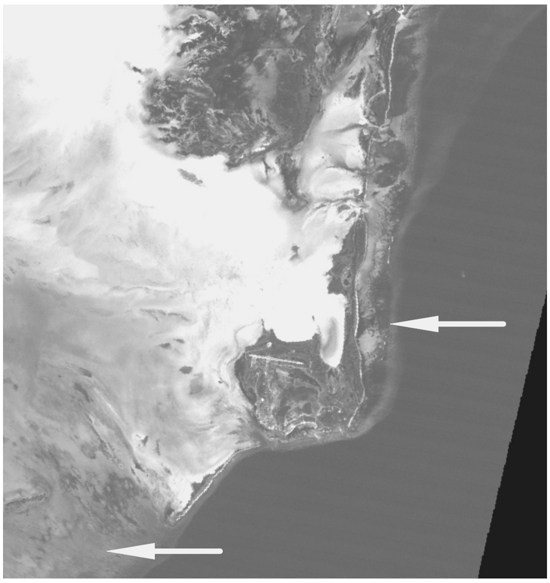
Depth of penetration zones method (modified from Jupp, 1988)

There are two parts to Jupp's method: (i) the calculation of depth of penetration zones or DOP zones, (ii) the interpolation of depths within DOP zones.

The coefficient of attenuation *k* depends on wavelength. Longer wavelength light (red in the visible part of the spectrum) has a higher attenuation coefficient than short wavelengths (blue). Therefore red light is removed from white light passing vertically through water faster than is blue. There will therefore be a depth at which all the light detected by band #3 (visible red, 630–690 nm)) of the Landsat TM sensor has been attenuated (and which will therefore appear dark in a band #3 image). However not all wavelengths will have been attenuated to the same extent – there will still be shorter wavelength light at this depth which is detectable by bands #2 and #1 of the Landsat TM sensor (visible green, 520–600 nm; and visible blue, 450–520 nm respectively). This is most easily visualised if the same area is viewed in images consisting of different bands (Figure 6.1). The shallowest areas are bright even in band #4 but deeper areas (> about 15 m) are illuminated only in band #1 because it is just the shorter wavelengths which penetrate to the bottom sufficiently strongly to be reflected back to the satellite.

Figure 6.1. Band #1 and #4 Landsat TM images (DN) of the area around South Caicos. Deeper areas are illuminated by shorter wavebands. There is deep (30–2500 m) water in the bottom right hand corner of the images - this is not completely dark because some light is returned to the sensor over these areas by specular reflection and atmospheric scattering. Band #1 illuminates the deep fore reef areas (as indicated by the arrows). The edge of the reef or 'drop-off' can be seen running towards the top right hand corner of the band #1 image. In areas of shallow (<1 m) clear water over white sand band #4 reveals some bathymetric detail (as indicated by the arrows).

Landsat TM Band #1



Landsat TM Band #4

The attenuation of light through water has been modelled by Jerlov (1976) and the maximum depth of penetration for different wavelengths calculated for various water types. Taking Landsat MSS as an example, it is known that green light (band #1, 0.50–0.60 μm) will penetrate to a maximum depth of 15 m in the waters of the Great Barrier Reef, red light (band #2, 0.60–0.70 μm) to 5 m, near infra-red (band #3, 0.70–0.80 μm) to 0.5 m and infra-red (band #4, 0.80–1.1 μm) is fully absorbed (Jupp, 1988).

Thus a "depth of penetration" zone can be created for each waveband (Figure 6.2). One zone for depths where green but not red can penetrate, one for where red but not near infra-red can penetrate, and one for where near-infrared (band #3) but not infra-red (band #4) can penetrate. Thus for the Landsat MSS example over clear Great Barrier Reef water three zones could be determined: 5–15 m, 0.5–5 m and surface to 0.5 m depth.

The method of Jupp (1988) has three critical assumptions:

1. Light attenuation is an exponential function of depth.
2. Water quality (and hence the attenuation coefficient *k*) does not vary within an image.
3. The colour (and therefore reflective properties) of the substrate is constant.

Question: *6.2.* Which assumption do you think is most likely not to be satisfied in the clear waters over the Caicos Bank?

Field survey data

UTM coordinate referenced field survey depth measurements for 515 sites on the Caicos Bank are provided in the *Excel* spreadsheet file ***Depths.xls***. This includes the date, time, UTM coordinates from an ordinary or Differential Global Positioning System (GPS or DGPS), depth in metres (to nearest cm) measured using a hand-held echo-sounder, and DN values recorded in Landsat Thematic Mapper bands #1 to #4 at each coordinate (obtained using ERDAS Imagine software).

The *Tidal Prediction by the Admiralty Simplified Harmonic Method* NP 159A Version 2.0 software of the UK Hydrographic Office was used to calculate tidal heights during each day of field survey so that all field survey depth measurements could be corrected to **depths below datum** (Lowest Astronomical Tide). [Admiralty tide tables could be used if this or similar software is not available.] The predicted tidal height at the time of the satellite overpass at approximately 09.30 h local time on 22 November 1990 was 0.65 m (interpolated between a predicted height of 0.60 m at 09.00 h and one of 0.70 m at 10.00 h). This height was added to all measured depths below datum to give the depth of water at the time of the satellite overpass.

Table 6.1. For each band *i,* the maximum depth of penetration z_i is listed for the clear waters of the Great Barrier Reef (Jupp, 1988).

Landsat TM band *i*	Depth of penetration z_i
#1	25 m
#2	15 m
#3	5 m
#4	1 m

Lesson Outline

Step 1. Calculating depth of penetration zones

The first task is to find out what the maximum DN values of deepwater pixels are for bands 1–4 of the Landsat TM image. At the same time we will note the minimum values. If the image had been radiometrically and atmospherically corrected, the reflectance from deep water would be close to zero but because it has not although no light is being reflected back from the deep ocean the sensors will be recording significant DN values because of atmospheric scattering, etc. Knowing the highest DN values over deep water provides us with a baseline that we can use to determine the depth at which we are getting higher than background reflectance from the seabed. For each waveband, if DN values are greater than the maximum deepwater values then we assume the sensor is detecting light reflected from the seabed.

Activity: Launch *Bilko* if you have not already done so and use **File, Open** to open the set ***LandsatTM_bathymetric.set,*** which contains a stack of the four files ***LandsatTM_bathymetric#01.gif*** – ***LandsatTM_bathymetric#04.gif***. Use **View, Coords** to switch off UTM coordinates.

The quickest way to determine maximum and minimum pixel values over deep water is to copy a block of deepwater pixels to a spreadsheet where a formula to calculate maximum and minimum has been previously set up. An alternative method is to examine a histogram of a block of deepwater pixels in *Bilko*. Use one or other method.

Activity: 1. *Excel spreadsheet method:* Open an *Excel* worksheet and in the top left corner (cell A1) type in “Max =” (but **without** the quotes!). In the next cell to the right enter the formula “=max(a2:ax51)”. In the next cell to the right type in “Min =” and in the cell to the right of that enter the formula “=min(a2:ax51)”. In the next cell to the right type in “Mean =” and in the cell to the right of that enter the formula “=average(a2:ax51)”. When you paste in a block of 50 by 50 pixels from an image these formulae will immediately calculate and display the maximum, minimum and mean pixel values.

Return to *Bilko* (using the *<Alt>+<Tab>* keys held down at the same time is a quick way) and select the TM band #1 (top) image in the stack. Then select **Edit, Go To** and in the dialog box enter the (X:, Y: row and column) **Position** as 585, 250 (off Long Key), set the **Selection Type:** to Block Selection, and the **Selection Size** to 50 by 50 pixels. This selects a block of 2500 pixels in deep water. Use **Edit, Copy** to copy the pixels and return to your spreadsheet. Click on cell A2 just under where you should have typed “Max =” and **Paste** the pixels. You will see the DN values of the pixels displayed in the cells of the spreadsheet.

Make a note of the maximum, minimum and mean (**to nearest whole number**) deepwater DN values for the TM band #1 image in Table 6.2. Use the *<Tab>* key to move the selection to the next image in the stack and repeat the procedure for each of the other images (bands #2 to #4) for exactly the same area, pasting each block of pixels over the existing ones in the spreadsheet each time. When you have finished **Close** the spreadsheet file.

Or 2. *Histogram method:* Select the TM band #1 (top) image in the stack. Then select **Edit, Go To** and in the dialog box enter the (X, Y row and column) **Position** as 585, 250 (off Long Key), set the **Selection Type:** to Block Selection, and the **Selection Size** to 50 by 50 pixels. This selects a block of 2500 pixels in deep water. Now open a Histogram document for the block selection (using **File, New**) and use the cursor and status bar to read off the highest and lowest DN values in the block from the histogram and the histogram header to read off the mean.

Activity: Make a note of the maximum deepwater ($L_{deep\ max}$), minimum deepwater ($L_{deep\ min}$) and mean deepwater ($L_{deep\ mean}$) DN values (**to nearest whole number**) for the TM band #1 image in Table 6.2. Use the *<Tab>* key to move to the histogram for the same area for the next band and repeat the procedure for each of the other bands (bands #2 to #4). When you have finished, **Close** the histogram document.

Table 6.2. DN values for deepwater pixels (sample size = 2500).

	Landsat TM band			
	#1	**#2**	**#3**	**#4**
Maximum deepwater DN value ($L_{deep\ max}$)				
Minimum deepwater DN value ($L_{deep\ min}$)				
Mean deepwater DN value [nearest integer] ($L_{deep\ mean}$)				

The next stage is to use UTM coordinate referenced field survey data to estimate the maximum depths of penetration for each waveband. This can be done by inspecting the file ***Depths.xls,*** which contains details of measured depths and DN values for 515 field survey sites. The survey sites have been sorted on depth with the deepest depths first. Table 6.1 lists the maximum depths of penetration recorded by Jupp (1988) for bands #1–#4 of Landsat TM. This gives us a starting point for searching for pixels near the maximum depth of penetration.

Note: The (D)GPS derived UTM coordinates for the depth measurements had positional errors in the order of 18–30 m for GPS coordinates and 2–4 m for DGPS ones. The Landsat TM pixels are 33 x 33 m in size. The reflectances recorded at the sensor are an average for the pixel area with contributions from scattering in the atmosphere. There is thus spatial and radiometric uncertainty in the data which needs to be considered. At the edge of the reef, depth may change rapidly and spatial uncertainty in matching pixel DN values to depths is likely be most acute.

Activity: Open the spreadsheet file ***Depths.xls*** and note the various column headings. For now, the critical columns are H to L which contain data on the depth in metres of each field survey site (corrected to the time of the satellite overpass) and the DN values for the Landsat TM image in bands #1–#4 for the UTM coordinates recorded on the (D)GPS. From Table 6.2 we can see that we should start looking for z_1 (maximum depth of penetration of TM band #1) at around 25 m depth and you should have found that the maximum deepwater DN value for TM band #1 was 57 (Table 6.2). Pixels with DN values > 57 should thus be at less than the maximum depth of penetration.

The deepest site was recorded as 25.35 m deep and has a DN value of 61; this is greater than 57 indicating some bottom reflectance. However, if you move down the TM#1 column you will see that there are three pixels recorded at a shallower depth with DN values ≤ 57 indicating no reflectance (i.e. they must be either at or deeper than the maximum depth of penetration). These apparent inconsistencies are due to the spatial and radiometric uncertainties mentioned above. To cope with these, the following protocol may be used to determine z_i.

Find the first pixel in the waveband with a DN value > $L_{deep\ max}$ for that waveband. Then move down the column (i.e. to progressively shallower depths) until you find the last pixel which has a value ≤ $L_{deep\ max}$. This determines a range of depths between which z_i. must lie.

Activity: **Copy** the spreadsheet cells containing the depth and DN values for the sites in this depth range and paste (use **Paste Special** and select **Values**) these cells to the right of the main spreadsheet in the area indicated. Then sort them in descending order of DN value and calculate the average depth of pixels with DN values > $L_{deep\ max}$ and the average depth of pixels with values equal to $L_{deep\ max}$ **(but since the sample size is so small for TM band #1 we will also include the site at 18.70 m depth with a DN value of 56)**. [Use a calculator if your spreadsheet skills are not up to it!]

Question: *6.3.* What are the depths between which z_1 must lie?

Question: *6.4.* What is the average depth of pixels in this range with DN values > $L_{deep\ max}$ for TM band #1?

Question: *6.5.* What is the average depth of pixels in this range with DN values ≤ $L_{deep\ max}$ for TM band #1?

Activity: Enter your answers into Table 6.3.

Table 6.3. Calculating the maximum depth of penetration (z_i) in metres.
[Note that average depths refer only to pixels in protocol determined depth range for z_i].

[Depths in metres]	**Landsat TM band**			
	#1	**#2**	**#3**	**#4**
Depth of deepest pixel with DN > $L_{deep\ max}$			4.70	1.55
Depth of shallowest pixel with DN ≤ $L_{deep\ max}$			3.71	0.66
Average depth of boundary pixels with DN values > $L_{deep\ max}$			4.3	1.0
Average depth of boundary pixels with DN values = $L_{deep\ max}$			4.2	1.1
Estimated maximum depth of penetration (z_i)			4.2	1.0

For Landsat TM band #1 you will find that the average depth of those pixels which have DN values > $L_{deep\ max}$ is slightly less than that for pixels with values of 56–57. Given the small sample size and spatial and other errors this is understandable. The maximum depth of penetration for TM band #1 (z_1) presumably lies somewhere between these two depths and for our protocol we will take the average of the two depths as being our best estimate.

Activity: Calculate the average of the two depths and enter the value in Table 6.3 as the estimate of z_1 (maximum depth of penetration for TM band #1).

Repeat part of the exercise for band #2 (the values have been pre-sorted for you) and enter the appropriate values into Table 6.3.

Inspect the spreadsheet to see how the values were calculated for bands #3 and #4. Note that the estimate of z_4 is unlikely to be very accurate, however, study of the near-infrared image does indicate significant reflectance in very shallow water over white sand.

Combining the data you have collected together in Tables 6.2 and 6.3 you can construct a decision tree for assigning pixels to depth zones. This is illustrated in Table 6.4 below.

Figure 6.2. Diagram to show the rationale behind Jupp's depth of penetration (DOP) zones.

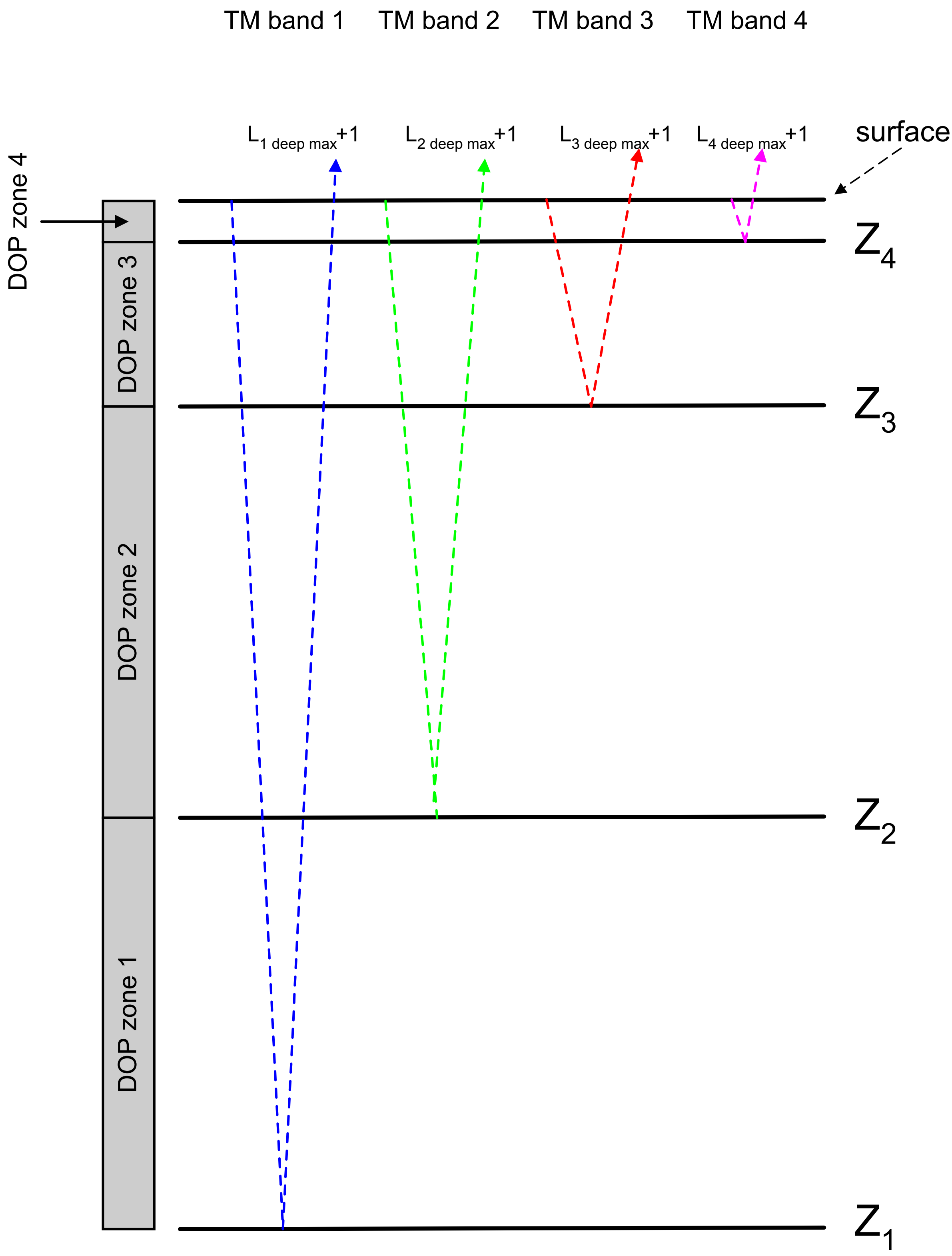


Table 6.4. A decision tree to assign pixels to depth zones.

Landsat TM band	#1	#2	#3	#4	DOP zones
Deepwater maximum DN	57	16	11	5	
If DN value (L_i) of pixel	≤57	≤16	≤11	≤5	then depth > 20.8 m
If DN value (L_i) of pixel	>57	≤16	≤11	≤5	then depth = 13.5–20.8 m (zone 1)
If DN value (L_i) of pixel	>57	>16	≤11	≤5	then depth = 4.2–13.5 m (zone 2)
If DN value (L_i) of pixel	>57	>16	>11	≤5	then depth = 1.0–4.2 m (zone 3)
If DN value (L_i) of pixel	>57	>16	>11	>5	then depth = 0–1.0 m (zone 4)

If none of these conditions apply, then pixels are coded to 0. A few pixels may have higher values in band #2 than band #1, which should not happen in theory. These will also be coded to zero and filtered out of the final depth image.

To implement this decision tree you will need to set up a Formula document with a series of conditional statements. This is primarily a lesson in remote sensing not computing so I have prepared a formula document for you that creates four new images, showing the four DOP zones. However, firstly you need to mask out land areas using a land-mask image ***Landmask_lesson6.gif.***

Activity: **Close** the stacked set and **Open** the file ***Landmask_lesson6.gif*** and then **Connect** it to the images ***LandsatTM_bathymetric#01.gif***, ***LandsatTM_bathymetric#02.gif***, ***LandsatTM_bathymetric#03.gif*** and ***LandsatTM_bathymetric#04.gif***. The land mask image will initially be @1; to make it @5 as required for the formula, press the <5> key whilst it is selected. Use the **Selector** toolbar drop-down list to check that the TM band #1 image is @1, the TM band #2 image @2, etc. and the land mask image @5.

Open the formula document file ***DOP_zones.frm*** and study how it works. Essentially each formula creates a mask where pixels in a DOP zone are coded to one and pixels outside the depth zone are coded to zero. Note that for DOP zone 4, defined by near-infrared penetration, that the land areas will also be coded to one; a land mask image (***Landmask_lesson6.gif***) is thus be needed to separate land from very shallow water. Make sure the formula document **Options!** menu is set so that the output images are the Same as @1 or 8-bit unsigned integer.

Copy the formula document and **Paste** it to the connected images to create the four DOP zone mask images.

Close the connected images window.

Connect the four DOP zone images as a stacked set. [DOP zone 1 should be @1, DOP zone 2, @2, etc.] Apply an **Auto Linear** stretch to the stack (with **Stretch, Options Min%** set to 0 and **Max%** set to 100) and use the <*Tab*> key or loop button to inspect zone mask images. Note the thin band of DOP zone 1 around the edge of the Caicos Bank (becoming broader as one moves south) but huge extent of DOP zone 2.

The next stage is to create a crude depth zone bathymetric map in which each depth zone is displayed as a different evenly-spaced grey level, and land and deep water are set to 0 (black). We can accomplish this using the four DOP zone masks and the land mask. We will use a Formula document to set the pixels in DOP zone 1 (c. 13.5–20.8 m depth) to 63, those in zone 2 (c. 4.2–13.5 m depth) to 127, those in zone 3 (c. 1.0–4.2 m depth) to 191, and those in zone 4 (c. 0–1.0 m depth) to 255. Since the pixels in the masks are currently set to 0 or 1, all we have to do is multiply each DOP zone mask by the relevant value and add the resultant images together.

Activity: If you feel confident, set up your own formula document to do this (or at least give it a try!). If not, open the formula document ***DOP_4zones.frm*** and apply it to the connected images. This creates a grey scale image with shallower water in progressively lighter shades of grey. To add a bit of colour, first making sure that the new image is the active window, open the palette file ***DOP_4zones.pal***. This displays DOP zone 1 as blue, DOP zone 2 as green, DOP zone 3 as red, and DOP zone 4 as yellow. Inspect the bathymetric image and look for anomalies i.e. areas of very deep or very shallow water where they shouldn't be.

There are two types of anomalies on this crude bathymetric image. One type is responsible for very shallow water apparently being present around coordinates 165, 752 and 523, 615. The other is responsible for very deep water (displayed as colour black) apparently being present around coordinates 769, 120 and 776, 133 close to the shore off the east side of South Caicos Island.

Question: *6.6.* What is causing the shallow water anomalies (around coordinates 165,752 and 523, 615)? [*Hint:* Use the Landsat TM band #4 (near-infrared) image to help identify the cause.]

Question: *6.7.* What habitat do you think is causing the deep water anomalies (around coordinates 769, 120 and 776, 133)? [*Hint:* Use the Landsat TM band #1 image to help identify the cause.]

Activity: The final stage for finishing your DOP zone bathymetric image is to smooth out odd pixels. To do this run a 3 x 3 median filter over the image (**Image, Filter, Median**). Note the improved look to the image as a result of smoothing. **Save** the image as ***DOP_4zones.gif*** and then close it. **Close** the stack but **Save** the individual DOP zones 1–4 mask images as ***DOP_Mask1.gif***, ***DOP_Mask2.gif***, ***DOP_Mask3.gif*** and ***DOP_Mask4.gif***.

Congratulations! You have achieved as much as what several applied remote sensing papers have reported in international journals, but you will now go a step further.

Step 2. Interpolation of DOP zones

Calculating DOP zones does not assign a depth to each pixel, instead it assigns a pixel to a depth range (e.g. 13.5–20.8 m). Step two of Jupp's method involves interpolating depths for each pixel within each DOP zone. We will only work with DOP zone 2.

In DOP zone 2, the DN value of any submerged pixel in TM band #2 (L_2) can be expressed as:

$$L_2 = L_{2deepmean} + \left(L_{2surface} - L_{2deepmean}\right)e^{-2k_2z} \qquad \text{Equation 6.3}$$

where $L_{2\ deep\ mean}$ is the average deep-water pixel value for TM band #2 calculated in Table 6.2, $L_{2\ surface}$ is the average DN value at the sea-surface (i.e. with no attenuation in the water column), k_2 is the attenuation coefficient for TM band #2 wavelengths through the water column, and z is the depth. Thus for a particular bottom type the DN value can vary between a minimum, which is the mean deep-water DN, and a maximum, which is the DN that would be obtained if that bottom type was at the surface and **no** attenuation was occurring. In between the maximum depth of penetration for TM band #2 (z_2) and the surface, the DN value is purely a function of depth (z), with the rate of decrease in DN with depth determined by the attenuation coefficient for band #2 (k_2).

Equation 6.3 can be rewritten as:

$$L_2 - L_{2deepmean} = \left(L_{2surface} - L_{2deepmean}\right)e^{-2k_2z} \qquad \text{Equation 6.4}$$

If we define X_2 as follows: $X_2 = \log_e\left(L_2 - L_{2deepmean}\right)$

we can get rid of the exponential thus:

$$X_2 = \log_e\left(L_{2surface} - L_{2deepmean}\right) - 2k_2z \qquad \text{Equation 6.5}$$

Now for a given bottom type in TM band #2, $\log_e\left(L_{2surface} - L_{2deepmean}\right)$ will be a constant, which to simplify the look of Equation 6.5, we will call A_2 to give the following linear regression relationship:

$$X_2 = A_2 - 2k_2z \qquad \text{Equation 6.6}$$

This gives us our basis for interpolating depths in each DOP zone. We will illustrate the rationale behind the interpolation continuing to take DOP zone 2 as an example. If a pixel is only just inside DOP zone 2 as opposed to DOP zone 1 (the zone with the next lowest coefficient of attenuation, Figure 6.2) then it has a value of $X_{2\ min}$ given by Equation 6.7 as:

$$X_{2\ min} = A_2 - 2k_2z_2 \qquad \text{Equation 6.7}$$

The minimum TM band #2 DN in DOP zone 2 ($L_{2\ min}$) will be one more than $L_{deep\ max}$ for band #2, thus $X_{2\ min}$ is $\log_e([L_{2\ deep\ max} + 1] - L_{2\ deep\ mean})$. A_2 and the attenuation coefficient k_2 are specific to TM band #2, and z_2 is the maximum depth of penetration of TM band #2 (c. 13.5 m [Table 6.3] and the depth at which minimum reflectances are obtained in DOP zone 2).

Now consider another pixel that is only just inside DOP zone 2 as opposed to DOP zone 3 (the zone with the next highest coefficient of attenuation, Figure 6.2). This has a value of $X_{2\ max} = \log_e(L_{2\ max} - L_{2\ deep\ mean})$ defined by the equation:

$$X_{2\ max} = A_2 - 2k_2z_3 \qquad \text{Equation 6.8}$$

where values are as for Equation 6.7 except that z_3 marks the upper end of DOP zone 2 (c. 4.2 m and the depth at which maximum reflectances are obtained in DOP zone 2).

The values of z_2 and z_3 are known (Table 6.3), $L_{2\ min}$ will generally be $L_{2\ deep\ max} + 1$ (see Table 6.4 for $L_{deep\ max}$ values for each band), and $L_{2\ max}$ and thus $X_{2\ max}$ can be determined from histograms of the appropriate images multiplied by their corresponding DOP zone masks (in this example, ***LandsatTM_bathymetric#2.gif*** multiplied by the DOP zone 2 mask image). For the purposes of this lesson we will only carry out the procedure for DOP zone 2.

Activity: **Connect** the images ***LandsatTM_bathymetric#02.gif*** and ***DOP_Mask2.gif*** images and create a formula document to multiply them together. The resultant image will give you the DN values of TM band #2 pixels lying in DOP zone 2. If you need to stretch this image because it is too dark, make sure that **Apply stretches to charts, clipboard, etc.** of the **Stretch, Options** is **not** checked. Select the whole image and examine a histogram of these pixels to check values for $L_{2\ min}$ and find the value of $L_{2\ max}$. [*Hint:* Right-click on the histogram, select **Scale** and check the **Ignore zero** checkbox of the **Scale** dialog box to see more clearly the frequency-distribution on the non-zero pixels that you are interested in.]

Note that the $L_{deep\ max}$ value for TM band #2 was 16 (Table 6.4) and the histogram begins at a DN value of 17 as expected. Note also the tail of higher DN values.

Question: *6.8.* How many TM band #2 pixels in DOP zone 2 have values = 17 ($L_{2\ min}$)?

Question: *6.9.* What is the highest DN value of the TM band #2 pixels in DOP zone 2?

Activity: The highest DN value is only found in 4 pixels and given the various spectral and spatial uncertainties it is perhaps better to set our estimate of $L_{2\ max}$ at slightly below this value. For this exercise we will take a statistical sample of the top approximate 0.1% of pixels and take the lowest DN value in this sample as our estimate of $L_{2\ max}$. In the histogram, drag the cursor leftwards from the highest pixel value until the status bar indicates that about 0.1% of pixels have been highlighted. [*Hint:* The nearest you can get is 0.08% highlighted.] Note the lowest DN value in the highlighted range displayed on the status bar and use this value as your estimate of $L_{2\ max}$. Enter your values for $L_{2\ min}$ and $L_{2\ max}$. in Table 6.5.

Question: *6.10.* What is your estimate of $L_{2\ min}$?

Close the connected images window and then **Connect** your new image of TM band #2 in DOP zone 2 with one blank image (set **Blanks:** to 1 in the **Connect** dialog box) as a stacked set. Make sure that the "TM band #2 in DOP zone 2" image is @1 and the blank image (which will become the depth image) is @2.

Table 6.5. $L_{i\ min}$ and $L_{i\ max}$ for each DOP zone *i* derived from Landsat TM image of the Caicos Bank. (k_i and A_i are calculated using Equations 6.9 and 6.10 below).

	TM Band #1	TM Band #2	TM Band #3	TM Band #4
DOP zone 1	58 – 69			
DOP zone 2				
DOP zone 3			12 – 53	
DOP zone 4				6 – 42
k_i	0.0797		0.4196	1.4722
A_i	4.9236		4.6234	3.6376

The $L_{i\ min}$ and $L_{i\ max}$ values for DOP zones *i* = 1, 3 and 4 have already been entered in Table 6.5 using the same method, and k_i and A_i have already been calculated using the two equations below. For each band, we can calculate the attenuation coefficient because we know how much the DN value has changed over a known depth range, thus for TM band #1, the DN value has changed from 58 to 69 between 20.8 and 13.5 m depth (i.e. by 11 units in 7.3 m).

In our example for DOP zone 2, Equations 6.7 and 6.8 form a pair of simultaneous equations that can be solved for k_2 (Equation 6.9). Once this is known Equation 6.7 can be re-arranged to find A_2 (Equation 6.10).

$$k_2 = \frac{(X_{2\ max} - X_{2\ min})}{2(z_2 - z_3)} \qquad \text{Equation 6.9}$$

$$A_2 = X_{2\ min} + 2k_2 z_2 \qquad \text{Equation 6.10}$$

Activity: Use a calculator or spreadsheet to work out firstly, k_2 [using Equation 6.9 and remembering that $X_{2\ max} = \log_e(L_{2\ max} - L_{2\ deep\ mean})$ and $X_{2\ min} = \log_e(L_{2\ min} - L_{2\ deep\ mean})$] and secondly, A_2 (using Equation 6.10). Enter your answers (to **4** decimal places) in Table 6.5 above.

Once A_i and k_i are known Equation 6.6 can be inverted and the depth of water, *z*, for any pixel with value X_i [= $\log_e(L_i - L_{deep\ mean})$] in band *i* can be calculated using the following equation:

$$z = \frac{(A_i - X_i)}{2k_i} \qquad \text{Equation 6.11}$$

Activity: Using your stacked set with your new image of TM band #2 in DOP zone 2, create a formula document to interpolate the depth in metres of each TM band #2 image pixel in DOP zone 2 using Equation 6.11. Design the formula to put the output image in the blank layer of the stack (@2). Remember that X_i for each pixel is $\log_e(L_i - L_{2\ deep\ mean})$ where L_i is the DN value of the pixel in the original image (@1).

Since we know that depths are spread over about 21 m whilst our display scale is 0–255, multiply the final result by 10 so that the output pixel values divided by 10 will equal the depth in metres (to the nearest 10 cm). Thus a pixel value of 127 will be equivalent to a depth of 12.7 m. [*Hint:* the $\log_e$ function in a Formula document is the same as in *Excel*, thus the function LN(*x*) will return the natural logarithm of *x*. For clarity you may also wish to set up the constants in the formula document (A_2, k_2 and $L_{2\ deep\ mean}$) using a series of **CONST =** statements.]

Checkpoint:	To check whether your formula worked, use the **Edit, Go To** option to check the values of (i) the pixel at column and row coordinate 395, 305 (original DN = 23), which should have the value 87 in the output image (8.7 m deep), and (ii) the pixel at coordinate 450, 350 (original DN = 19), which should have the value 114 in the output image (11.4 m deep). You can use these input and output values to check your formula on a calculator or spreadsheet. Once each coordinate is located, you can use the *<Tab>* key to move between input (@1) and output (@2) images in stack.

Activity: The @2 image in the stack now shows depths in DOP zone 2. Because deeper depths have higher values in the image, shallower depths appear darker on the image. This can be reversed by applying a reverse palette (***Bathymetric_grey.pal***) where 1 displays as 255 and 255 displays as 1. Land and deep water, which have been set to 0, still display as zero. Open and apply this palette to the image. This gives a more natural display of your bathymetric map of DOP zone 2, with deeper depths appearing progressively darker.

Close your images and formulae when you are satisfied your formula has worked.

The same formula with different constants can be used to calculate the depths for DOP zones 1, 3 and 4. To save time you will **not** do this. A formula document that does this for all 4 DOP zones at once is stored as ***Bathymetric_map.frm***.

Activity: Open the formula document ***Bathymetric_map.frm*** and examine the formulae, noting how they work. You started with an image made by multiplying band #2 by its DOP zone mask. In these formulae this is carried out as part of the process. This formula document produces 4 depth images (one for each DOP zone); these have been added together in another formula document to produce the image ***Bathymetric_map.gif***. [If you wish to test the formula, connect the 8 images as indicated in the formula header and then add the 4 output images together.]

Open the crude bathymetric map image ***Bathymetric_map.gif*** and then the palette ***Bathymetric_blue.pal***, which displays the depths as progressively paler shades of blue/cyan as you get shallower. Also try another palette ***Bathymetric_contours.pal*** which splits the depths into 0–2.5, 2.5–5, 5–7.5, 7.5–10, 10–15, 15–20, and > 20 m depth zones. [If you wish to see how the palettes are set up you should uncheck the **Apply** checkbox in the **Open** dialog box.]

Question: *6.11.* Which type of palette do you think is most useful and why?

Activity: Use the **Edit, Go To** option to select 20 x 20 blocks of pixels at the following coordinates and then use their histograms to answer the following questions.

Question: *6.12.* What is the modal (most common) depth in the 20 by 20 block with coordinates 220, 800 as its north-west corner?

Question: *6.13.* What is the modal depth in the 20 by 20 block with coordinates 650, 55 as its north-west corner?

Question: *6.14.* What is the modal depth in the 20 by 20 block with coordinates 395, 480 as its north-west corner?

Question: *6.15.* What is the modal depth in the 20 by 20 block with coordinates 100, 515 as its north-west corner?

Activity: When you have finished, close all images and associated files.

Accuracy assessment of the crude bathymetric map

Using the ground measurements of depth listed in the spreadsheet ***Depths.xls*** one can compare the depths predicted by the image at each UTM coordinate with those measured on site using a depth sounder. The results of plotting measured depth against predicted depth, for the image made using the modified Jupp's method, are presented in Figure 6.3.

This method produced a correlation of 0.82 between predicted and measured depth but required extensive field bathymetric data. Even this method does not produce bathymetric maps suitable for navigation since the average difference between depths predicted from imagery and ground-truthed depths ranged from about 0.8 m in shallow water (<2.5 m deep) to about 2.8 m in deeper water (2.5–20 m deep).

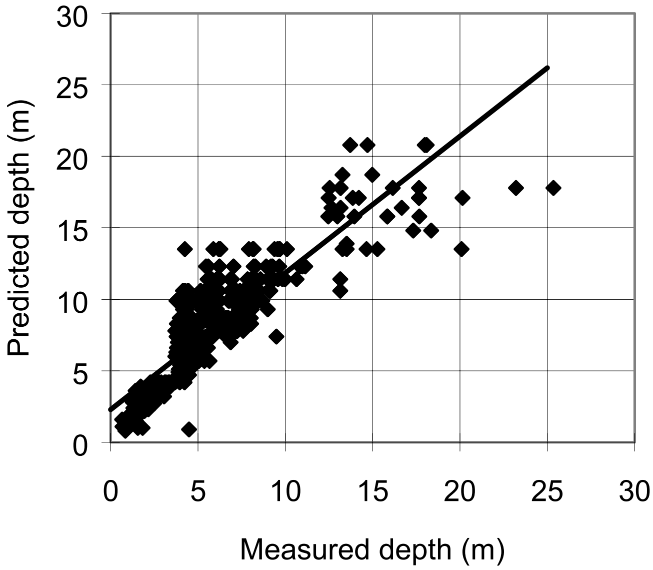


Figure 6.3. Plot of depth predicted from satellite imagery using the method (modified) of Jupp (1988) and depth measured in the field. Both have been corrected to chart datum.

Clearly, although bathymetric maps that look quite nice can be made from optical satellite imagery, they provide little more than crude maps of depth. These may be quite useful in planning surveys but are not reliable enough for most navigation purposes. If used for navigation, they would need to be used with extreme caution!

This lesson is complex and challenging. Congratulations if you have understood and completed the exercise satisfactorily! You will now find it much easier to understand the next lesson, which is all about trying to compensate for the effect of depth on bottom reflectance so that one can map submerged habitats.

References

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Answers to Questions

6.1. The image is 26.4 km across and 29.7 km along track (north-south).

6.2. The assumption which is most likely not to be satisfied in the clear waters over the Caicos Bank is that the colour and hence reflective properties of the substrate are constant. The water quality is likely to be worse in rough areas where sediment is stirred up and so the attenuation coefficient for each band may also vary across the image.

Table 6.2. DN values for deepwater pixels (sample size = 2500).

	Landsat TM band			
	#1	**#2**	**#3**	**#4**
Maximum deepwater DN value ($L_{deep\ max}$)	57	16	11	5
Minimum deepwater DN value ($L_{deep\ min}$)	49	11	7	3
Mean deepwater DN value [nearest integer] ($L_{deep\ mean}$)	53	13	9	4

6.3. The depth of penetration (z_1) for TM band #1 must lie somewhere between 18.70 and 25.35 m.

6.4. The average depth of pixels in this range which have DN values greater than $L_{deep\ max}$ (57) is 21.7 m.

6.5. The average depths of pixels in this range which have values less than or equal to $L_{deep\ max}$ (57) is 19.9 m.

Estimating the depth of penetration (z_1) for TM band #1.

Depth range of boundary pixels: 18.70-25.35 m

	Depth	DN	Average depths	Z1
	20.14	62		
	25.35	61		
	23.20	61		
	21.01	60		
	20.45	59		
> V deep max	20.09	59	21.7	20.8
<= V deep max	21.04	57	19.9	
	20.09	57		
	18.70	56		

Table 6.3. Calculating the maximum depth of penetration (z_i).

	Landsat TM band			
	#1	#2	#3	#4
Depth of deepest pixel with DN > $L_{deep\ max}$	25.35	15.26	4.70	1.55
Depth of shallowest pixel with DN ≤ $L_{deep\ max}$	18.70	12.46	3.71	0.66
Average depth of boundary pixels with DN values > $L_{deep\ max}$	21.7	13.8	4.3	1.0
Average depth of boundary pixels with DN values = $L_{deep\ max}$	19.9	13.2	4.2	1.1
Estimated maximum depth of penetration (z_i)	20.8	13.5	4.2	1.0

Estimating the depth of penetration (z_2) for TM band #2.

Depth range of boundary pixels: 12.46-15.26 m

	Depth	DN	Average depths	Z2
	13.14	20		
	13.14	19		
	15.26	17		
	14.65	17		
	13.50	17		
> V deep max	13.26	17	13.8	13.5
= V deep max	14.20	16	13.2	
	13.95	16		
	13.85	16		
	13.70	16		
	13.50	16		
	13.15	16		
	13.15	16		
	12.98	16		
	12.77	16		
	12.65	16		
	12.54	16		
	12.48	16		
	12.46	16		

6.6. These shallow water anomalies (areas which seem to be very shallow water on the image but shouldn't be) are caused by clouds over the area. These clouds are particularly visible in the near-infrared.

6.7. These deepwater anomalies (areas which seem to be deep water on the image but which common sense says cannot be) are caused by dense seagrass beds which have a very low reflectance right across the spectrum and thus, even though shallower than the depth of penetration for TM band 1, reflect no more light than deep water.

6.8. 14320 TM band #2 pixels in DOP zone 2 have values = 17 ($L_{2\ min}$).

6.9. The highest DN value of the TM band #2 pixels in DOP zone 2 is 41.

6.10. The top 0.1% of pixels are highlighted at a DN value of 37, so your estimate of $L_{2\ min}$ should be 37.

Table 6.5. $L_{i\ min}$ and $L_{i\ max}$ for each DOP zone i derived from Landsat TM image of the Caicos Bank. (k_i and A_i are calculated using Equations 6.9 and 6.10).

	TM Band #1	TM Band #2	TM Band #3	TM Band #4
DOP zone 1	58–69			
DOP zone 2		17–37		
DOP zone 3			12–53	
DOP zone 4				6–42
k_i	0.0797	0.0963	0.4196	1.4722
A_i	4.9236	3.9872	4.6234	3.6376

6.11. It is difficult to judge fine gradations in colour such as the ***Bathymetric_blue.pal*** palette displays. So the ***Bathymetric_contours.pal*** palette conveys the most information, allowing you to assign areas to depth zones very easily.

6.12. The modal depth (in the 20 by 20 block with coordinates 220, 800 as its north-west corner) is 1.6 m. Mode is at a pixel value of 16; it includes 24.8% of pixels in the block.

6.13. The modal depth (in the 20 by 20 block with coordinates 650, 55 as its north-west corner) is 0.8 m. Mode is at a pixel value of 8; it includes 21.0% of pixels in the block.

6.14. The modal depth (in the 20 by 20 block with coordinates 395, 480 as its north-west corner) is 18.7 m. Mode is at a pixel value of 187; it includes 28% of pixels in the block.

6.15. The modal depth (in the 20 by 20 block with coordinates 100, 515 as its north-west corner) is 8.3 m. Mode is at a pixel value of 83; it includes 52.5% of pixels in the block.

7: COMPENSATING FOR VARIABLE WATER DEPTH TO IMPROVE MAPPING OF UNDERWATER HABITATS: WHY IT IS NECESSARY

Aim of Lesson

To learn how to carry out "depth-invariant" processing in order to compensate for the effect of light attenuation in the water column (i.e. water depth) on bottom reflectance using a CASI airborne image.

Objectives

1. To understand the concepts underlying depth-invariant processing.
2. To inspect an unprocessed image using transects to discover how depth dominates returns from the seabed.
3. To learn how to carry out depth-invariant processing of a CASI airborne image.
4. To compare false colour composites of the processed and unprocessed images to see the results of compensating for the effects of water depth.

Background Information

This lesson relates to material covered in Chapter 8 of the *Remote Sensing Handbook for Tropical Coastal Management* and readers are recommended to consult this for further details of the techniques involved. Some familiarity with *Excel* spreadsheets is needed to complete the lesson in full.

The *Bilko* image processing software

Familiarity with *Bilko* is required to carry out this lesson. In particular, you will need experience of using Formula documents to carry out mathematical manipulations of images. This feature is covered in Tutorial 10 of the *Introduction to using the Bilko 3 image processing software*.

Image data

A Canadian airborne multispectral digital imager called the Compact Airborne Spectrographic Imager (CASI: see Appendix 1.4 for more details) was mounted on a locally-owned Cessna 172N aircraft using a specially designed door with mounting brackets and streamlined cowling. An incident light sensor (ILS) was fixed to the fuselage so that simultaneous measurements of irradiance could be made. A Differential Global Positioning System (DGPS) was mounted to provide a record of the aircraft's flight path. Data were collected at a spatial resolution of approx. 1 m^2 in 8 wavebands (Table 7.1) during flights over Cockburn Harbour and adjacent areas of South Caicos, Turks and Caicos Islands (21^o 30' N, 71^o 30' W) in July 1995. Further details are given in Clark *et al.* (1997).

Table 7.1. Band settings used on the CASI.

Band	Part of electromagnetic spectrum	Wavelength (nm)
1	Blue	402.5–421.8
2	Blue	453.4–469.2
3	Green	531.1–543.5
4	Green	571.9–584.3
5	Red	630.7–643.2
6	Red	666.5–673.7
7	Near Infrared	736.6–752.8
8	Near Infrared	776.3–785.4

Water column correction (depth-invariant processing) will be carried out on a CASI image of the area to the south of the island of South Caicos. The CASI image was acquired at approximately 10 a.m. local time on 16 July 1995. For the purposes of this lesson Bands #3 and #4 (green) of the CASI image (***Casi_SCaicos#03.dat*** and ***Casi_SCaicos#04.dat***) will be processed to create a depth-invariant image. The CASI image has undergone geometric correction and radiometric correction to apparent reflectance. Full atmospheric correction to surface reflectance would require use of the 6S radiative transfer code but we will carry out a crude correction using the dark pixel subtraction (DPS) method. The images are stored as unsigned 16-bit integer data (2 bytes per pixel) although the underlying sensor data is 12-bit (allowing a radiometric resolution of 4096, which is 16 times as sensitive as Landsat TM and SPOT XS).

Concepts underlying depth-invariant processing

When light penetrates water, its intensity decreases exponentially with increasing depth. This process is known as attenuation and it exerts a profound effect on remotely sensed data collected over water. The severity of attenuation differs with the wavelength of electromagnetic radiation. The red part of the visible spectrum attenuates more rapidly than shorter wavelength blue light and infra-red light hardly penetrates water at all. Thus as depth increases, longer wavelengths are progressively absorbed and the spectra of habitats as seen at the water surface change. The spectrum of sand at a depth of 2 m will be very different to that at 20 m – yet the substratum is the same. In fact, the spectral signature of sand at 20 m may be similar to that of seagrass at (say) 3 m. The spectral radiances recorded by a sensor are therefore dependent both on the reflectance of the substrata and on depth. The influence of depth on the signal will create considerable confusion when attempting to use visual inspection or multispectral classification to map habitats. Since most marine habitat mapping exercises are only concerned with mapping benthic features, it is useful to remove the confounding influence of variable water depth. This lesson describes a fairly straightforward means of compensating for variable depth, which is applicable to clear waters such as those surrounding coral reef environments.

Classification of water bodies

Jerlov (1951) formally classified oceanic water types according to their optical attenuation properties. Type I waters are represented by extremely clear oceanic waters. Most clear coastal waters are classified as Type II, because attenuation tends to be greater than that for oceanic waters of low productivity. Most reefal waters fall into categories I or II. Type III waters are fairly turbid and some regions of coastal upwelling are so turbid that they are unclassified.

Lyzenga (1978, 1981) described a simple technique for removing the influence of depth from spectral data for Type I and II waters. This is thus suitable for the clear reefal waters of the Caicos Bank and is the method that will be used in this lesson.

The method involves four steps.

Step 1. Removal of scattering in the atmosphere and external reflection from the water surface

The first step is a crude atmospheric correction based on the "dark pixel subtraction" method. If a full atmospheric correction (as done in Lesson 4) had already been carried out this step would not be needed and the surface reflectance values could be used directly. The CASI image we are using here has not been atmospherically corrected so that you should carry out this step. This involves selecting a large number of pixels from "deep water" and calculating their average apparent (at sensor) reflectance (and its standard deviation). This value minus two standard deviations is then subtracted from all other pixels in each band respectively to give a crudely corrected reflectance.

$$\text{Atmospherically corrected reflectance} = L_i - L_{si} \qquad \textit{Equation 7.1}$$

where L_i is the apparent pixel reflectance in band i and L_{si} is the average apparent reflectance for deep water in band i minus two standard deviations.

[*Note:* In practice, full atmospheric correction as carried out in Lesson 4 would be preferred to the cruder, dark pixel subtraction method we are using here, but this method is useful if you do not have access to atmospheric models such as the 5S or 6S radiative transfer codes].

Step 2. Linearise relationship between depth and radiance

In relatively clear water, the intensity of light will decay exponentially with increasing depth (Figure 7.1 – 1). If values of light intensity (radiance) are transformed using natural logarithms (ln), this relationship with depth becomes linear (Figure 7.1 – 2). Transformed reflectance values will therefore decrease linearly with increasing depth. If X_i is the transformed reflectance of a pixel in band i, this step can be written as:

$$X_i = \ln(L_i - L_{si}) \qquad \textit{Equation 7.2}$$

Step 3. Calculate the ratio of attenuation coefficients for band pairs

The attenuation coefficient $\mathbf{k_i}$ describes the severity of light attenuation in water for each spectral band ***i***. It is related to radiance and depth by the following equation where **a** is a constant, **r** is the reflectance of the bottom and **z** is depth.

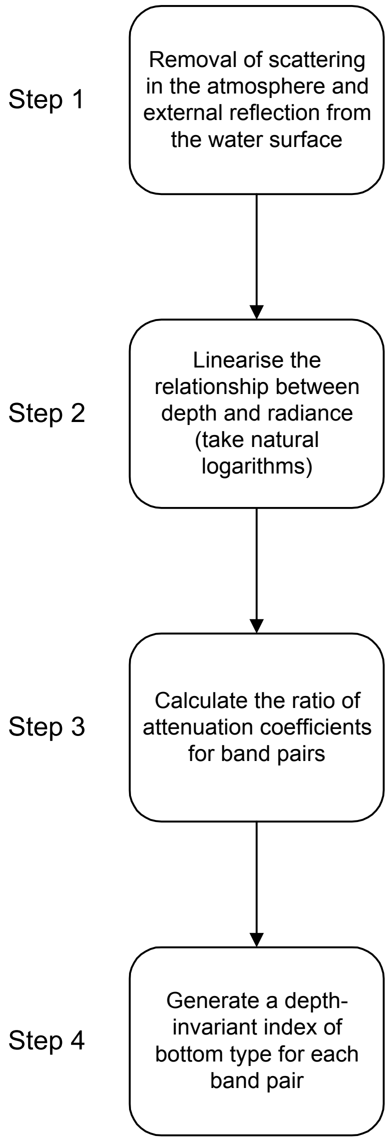
$$L_i = L_{si} + a \cdot r \cdot e^{-2K_i \cdot z} \qquad \textit{Equation 7.3}$$

Theoretically, it would be possible to rearrange the equation and generate an image of bottom type, **r** (reflectance), which is the measurement we seek. However, this approach is not feasible because there are too many unknown quantities – i.e. the value of the constant **a**, the attenuation coefficient for each band and the depth of water at each pixel. The method developed by Lyzenga does not require the actual calculation of these parameters but gets around the problem by using information from more than one band. All that is required is the *ratio* of attenuation coefficients between pairs of spectral bands. Use of ratios cancels out many of the unknowns in Equation 7.3 and the ratios can be determined from the imagery itself.

Two bands are selected and a bi-plot made of (log transformed) reflectances for the *same substratum* at differing depths (Figure 7.1 – 3). Since the effect of depth on measured radiance has been linearised and the substratum is constant, pixel values for each band will vary linearly according to their depth (i.e. points will fall on this straight line). The slope of the bi-plot is proportional to the difference in the amount of attenuation between the two bands. In fact, the slope represents the ratio of the attenuation coefficients of the two bands. Conceptually, the line represents an axis of reflectance values for a unique bottom type. As one moves along the line, the habitat stays constant but the depth of the habitat changes.

Step 4. Generate a depth-invariant index of bottom type

If reflectance values for another bottom type were added to the bi-plot (Figure 7.1), a similar line would be obtained – once again, the only change between data points would be depth. However, since the second bottom type will not have the same reflectance as the first, the new line will be displaced either above or below the existing line (e.g. if line 1 was derived from sand which generally has a high reflectance, and line 2 was generated from seagrass with lower reflectance, the latter line would lie below that for sand). The gradient of each line should be identical because the ratio of attenuation coefficients k_i/k_j is only dependent on the wavelength of the bands and clarity of the water.



An index of bottom type can be obtained by noting the *y*-intercept for each bottom type (Figure 7.1). For example, while pixel values lying on the line for sand show considerable variation in radiance, they all represent the same bottom type and have the same *y*-intercept. The *y*-intercept for pixels of seagrass is considerably different. The *y*-axis therefore becomes an axis (or index) of bottom type with bi-plots for each habitat crossing at a characteristic point.

Of course, not all pixel values for a given bottom type lie along a perfectly straight line. This is because of natural variation in bottom reflectance, patches of turbid water and sensor noise. Nevertheless, each pixel can be assigned an index of bottom type once the ratio of attenuation coefficients has been estimated (k_i/k_j). This is accomplished by "connecting" each pixel on the bi-plot to the *y*-axis using an imaginary line of gradient k_i/k_j. Pixel values on the bi-plot are then converted to their corresponding positions on the *y*-axis (index of bottom type). Using this method, each pixel value is converted to a depth-invariant index of bottom type, which is (as its name implies) **independent of depth**. These depth-invariant indices of bottom type lie along a continuum but pixels from similar habitats will have similar indices.

The mathematics of the depth-invariant index are simple. For this lesson we will be working with bands #3 and #4 of the CASI image and making a bi-plot of the transformed and corrected band #3 and band #4 values (respectively X_3 and X_4 from Equation 7.2):

$$X_3 = index + \frac{k_3}{k_4} . X_4 \qquad \textit{Equation 7.4}$$

where X_3 is the *y*-axis variable, ln ($L_3 - L_{s3}$), *index* is the intercept of the regression line with the *y*-axis (the depth-invariant index of bottom type), k_3/k_4 is the gradient of the regression line and X_4 represents the *x*-axis variable, ln($L_4 - L_{s4}$). The equation can be rearranged to give the *depth-invariant index of bottom type*:

$$index = X_3 - \frac{k_3}{k_4} . X_4 \qquad \textit{Equation 7.5}$$

The general equation for any pair of bands *i* and *j*, written in full is:

$$\text{depth-invariant index}_{ij} = \ln(L_i - L_{si}) - \left[\left(\frac{k_i}{k_j}\right).\ln(L_j - L_{sj})\right] \qquad \textit{Equation 7.6}$$

Each pair of spectral bands will produce a single depth-invariant band of bottom type. If the imagery has several bands with good water penetration properties (e.g. Landsat TM and ETM+, CASI, Ikonos), multiple depth-invariant bands can be created. The depth-invariant bands may then be used for supervised classification or visual interpretation instead of the original bands.

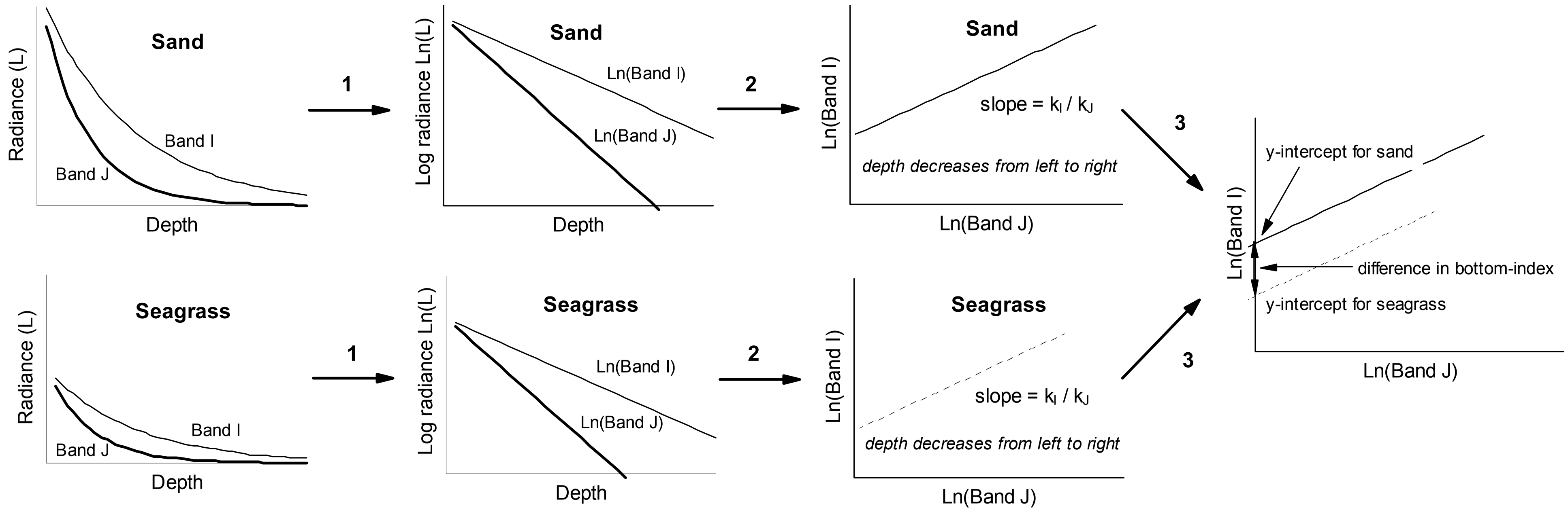


Figure 7.1. Processes of water column correction, showing the difference of sand and seagrass.

Step 1: Exponential attenuation of radiance with depth linearised for bands I and J using natural logarithms. (Band I has a shorter wavelength, and therefore attenuates less rapidly, than band J).

Step 2: Plot of (transformed) band I against (transformed) band J for a unique substratum at various depths. Gradient of line represents the ratio of attenuation coefficients, K_I / K_J. The ratio is the same irrespective of bottom type.

Step 3: Plotting of multiple bottom types. Each bottom type has a unique y-intercept (regardless of its depth). The y-intercept therefore becomes a depth-invariant index of bottom type.

Lesson Outline

Inspection of image to see the effect of water depth on reflectance

Firstly, you will look at one image (***Casi_SCaicos#03.dat***) prior to depth-invariant processing and use a transect, running from shallow to deep water, to quantify the effect of depth on reflectance.

Activity: Open the file ***Casi_SCaicos#03.dat***. In the **Redisplay Image** dialog box set null values to zero and apply a histogram equalization stretch. Scroll down to the bottom of the image, then click on the transect button and use **Edit, Go To** to select a transect line running vertically down the image (DX: 1) from shallow water to deep water starting at UTM coordinates 237413, 2377566 and with a DY: of –225 (or 225S) (i.e. running 225 m due south). This provides a transect running 225 m in a north-south direction from water about 7 m deep to water about 15 m deep. To inspect the transect use **File, New** to open a transect document (making sure that the **Apply stretches to new documents** checkbox in the **New** dialog box is not checked because you want to view the underlying image data values). Note the general trend of decreasing pixel value with increasing depth and local variation due to changes in habitat (e.g., between light sand patches and darker *Montastraea* reef).

Question: *7.1.* Inspect the transect document to find out the maximum and minimum value along the transect. What is the difference between these two values, expressed as a percentage of the maximum pixel value? [Give your answer to nearest 0.1%.]

This gives you a rough idea of the change in reflectance between 7 m and 15 m depth expressed as a percentage of the maximum reflectance along the transect. A better estimate can be obtained by averaging out the habitat differences at the start and end of the transect. To do this, you can calculate the average reflectance over the first 15 pixels and last 15 pixels. This is perhaps most easily done in an *Excel* spreadsheet.

Activity: Launch *Excel*. Then return to your transect document in *Bilko* and while it is the active document, click on the Copy button (or select **Edit, Copy**). Return to *Excel* and with the top left (A1) cell of the worksheet selected, click on the Paste button (or select **Edit, Paste**). The pixel values along the transect should have been pasted down column A. [*Note:* Transects are pasted down columns because rows are only 256 cells long.] You can now set up formulae to calculate the average values of the 15 pixels at the start and at the end of the transect.

Question: *7.2.* What is the average of the first 15 pixels? What is the average of the last 15 pixels? What is the difference between these two values, expressed as a percentage of the average of the 15 pixels at the start of the transect? [Give your answers to one decimal place.]

Activity: Once you have answered the question you can close the transect document but you may wish to save your *Excel* spreadsheet for use later when you will compare a transect from a depth corrected image.

The point being made is that for a given submerged pixel the two principal factors determining its spectral reflectance are its habitat type and depth. From the transect you can see that depth has a profound effect on the reflectance as the habitat is largely *Montastraea* reef with bare substratum yet reflectance declines dramatically with depth along the transect, with that at the deeper end being about half of that at the shallower end. If we can compensate for the depth effect then the major factor determining reflectance will be habitat type, allowing us to map habitats with some confidence.

Band selection

Pairs of spectral bands are selected which have different bottom reflectances but good penetration of water (i.e. visible wavebands). Out of 10 possible depth-invariant index bands which can be produced from bands 1–5 of the CASI in the visible blue to red (Table 7.1), the four CASI bands (#2, #3, #4 and #5 in Table 7.1) that produced the most useful depth-invariant index images have been used in this lesson. For display and analysis purposes, three of the six depth-invariant index images that can be produced from the four bands were found to be most useful; these were b#2_b#4, b#3_b#5 and b#3_b#4 combinations (where b#2_b#4 means a depth-invariant index image produced from bands #2 and #4 of the CASI data). For this lesson we will just create the b#3_b#4 depth-invariant index image from CASI bands #3 and #4, both of which record wavelengths in the green part of the visible spectrum.

Calculation of deep water radiance (reflectance) in the absence of a full atmospheric correction

Calculation of the parameter L_{si}, deep water radiance (or reflectance) is fairly straightforward. A group of pixels are selected which represent deep water (i.e. water more than 40 m deep). The pixel data are transferred to a spreadsheet (e.g. *Excel*). The mean and standard deviation of radiance (or reflectance) are calculated for each band. Armstrong (1993) recommended subtracting two standard deviations from the mean to account for sensor noise. This (lower) value is then used as L_{si} in subsequent calculations.

Activity: Open the image file ***Casi_SCaicos#04.dat*** (***Casi_SCaicos#03.dat*** should be open already). In the **Redisplay Image** dialog box set null values equal to zero and apply a stretch to view the image clearly. You may need to use a Gaussian stretch to achieve reasonable brightness in deep water (south of image). Connect the two images as a stacked set. You can use the <*Tab*> key to switch between the two bands in the set and can minimize or close the two original images.

You now need to select a rectangle of pixels at the mid-bottom of each image where water is deepest and the image darkest to estimate deep water radiances (L_{s3} and L_{s4}) and copy these to a spreadsheet to calculate the mean and standard deviation of the deepwater pixels.

Activity: It is easier to select a rectangle of pixels using row and column coordinates, so switch to these in the stacked set using **View, Coords**. Click on the box or block selection button and use the **Edit, Go To** option to select a block of 20 (**DX:**) by 10 (**DY:**) pixels at X, Y coordinates 235, 915 in ***Casi_SCaicos#03.dat*** and **Copy** this block. In *Excel* open the spreadsheet file ***Deepwater_pixels.xls*** which has formulae already entered to calculate the mean and standard deviation of the values in cells A2 to T11 (20 columns by 10 rows). **Paste** the copied block to cell A2 of the spreadsheet below the word "Mean"**.** Note the mean and standard deviation and enter values in Table 7.2 below (to **two** decimal places).

With the stack as the active document, press the <*Tab*> key to switch to the band #4 image and repeat the operation (the box should already be selected) for the ***Casi_SCaicos#04.dat*** image. Then calculate the mean minus two standard deviations to the *nearest integer* (= nearest whole number) for each image and enter these values in Table 7.2. When finished, close the spreadsheet file ***Deepwater_pixels.xls.***

Table 7.2. Calculation of deep-water radiance (reflectance).

Band	Deepwater Mean	Deepwater Standard Deviation	Deepwater Mean – 2 Standard deviations (L_{si})
CASI band #2	688.71	56.15	576
CASI band #3			
CASI band #4			
CASI band #5	154.70	35.83	83

Selection of pixels of uniform substratum and variable depth

When water column correction of this CASI image was carried out, nine sand areas of varying depth were selected and bi-plots of the natural logarithms of atmospherically corrected reflectances of all the pixels in each area for each pair of bands were examined. Figure 7.2 shows approximate positions of some of the sandy areas selected. The areas are chosen so that neither of the bands is saturated and both bands penetrate to the seabed. To understand how this is done you will select two 3 pixel x 5 pixel samples from sand areas 4 and 7 (asterisked in Table 7.3) in CASI bands #3 and #4 (***Casi_SCaicos#03.dat*** and ***Casi_SCaicos#04.dat***) and arrange these in a spreadsheet so that for each pixel you have the reflectance in each band. This will allow you to estimate the ratio of the attenuation coefficients (k_3/k_4) for this band pair.

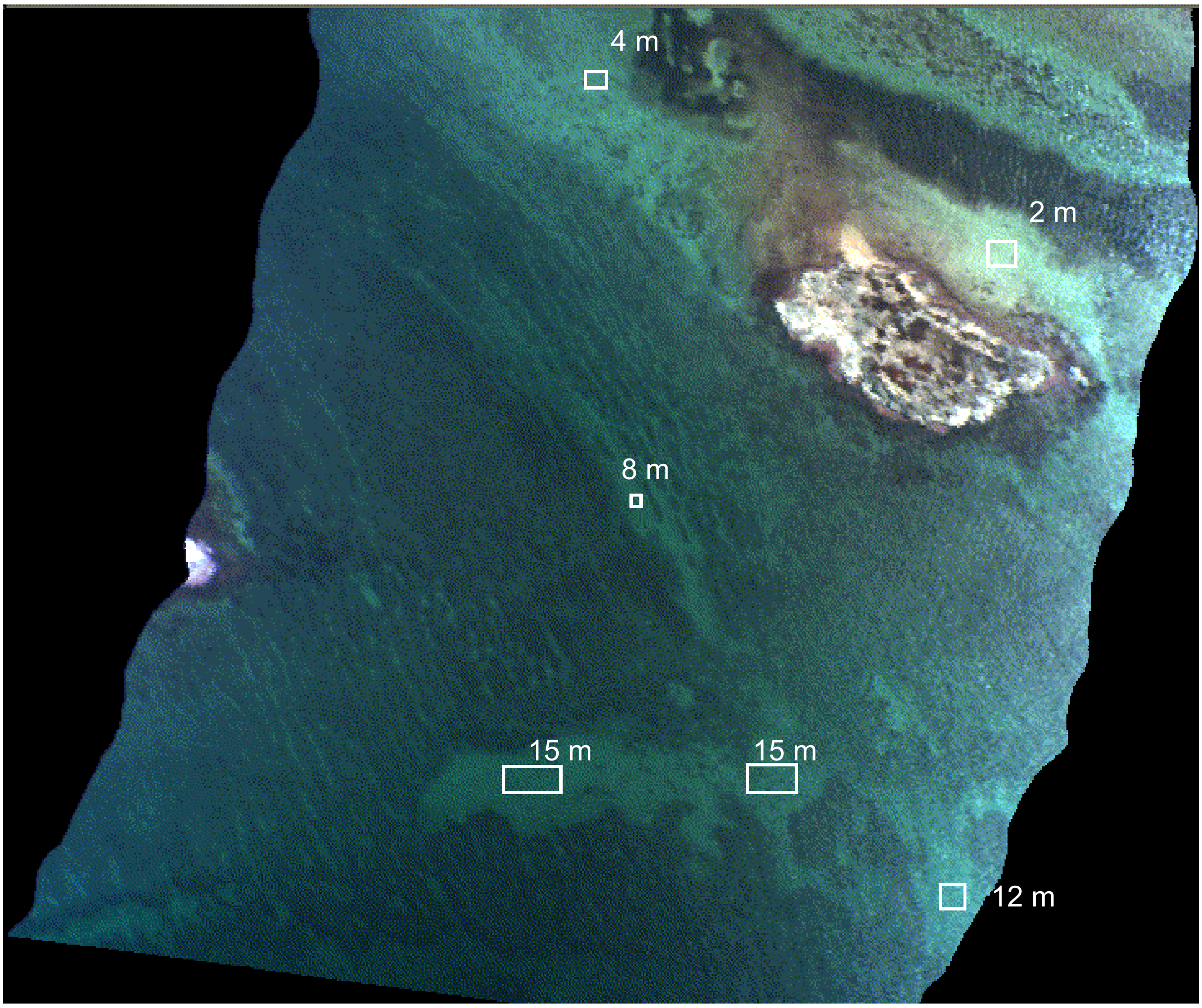


Figure 7.2. CASI image of Cockburn Habour (Turks and Caicos Islands) showing the selection of pixels of sand at variable depth.

Table 7.3. UTM coordinates (to nearest m) of the sandy patches selected for bi-plots. For this lesson you will only deal with pixels in two 3 x 5 sand patches, one in the deeper part of the image and one in the shallower part.

Area Goto	Upper Left X X:	Upper Left Y Y:	Columns x Rows DX: and DY:
1	237372	2378427	8 x 4
2	237582	2378246	3 x 3
3	237591	2378244	4 x 4
4*	**237820**	**2377846**	**3 x 5** (out of 5 x 5)
5	237643	2377450	7 x 5
6	237530	2377442	12 x 9
7*	**237477**	**2377439**	**3 x 5** (out of 10 x 8)
8	237658	2377934	3 x 3

Activity: Open the *Excel* spreadsheet file ***Casi_sand_patches.xls*** and examine it, noting the points below.

You will see the worksheet has column headings for UTM coordinates, for raw data values for CASI Band #4 and Band #3, and for working out the corrected and transformed values $\ln(b4\text{-}Ls_4)$ and $\ln(b3\text{-}Ls_3)$. The sand pixel coordinates have already been entered. Your task is to get the 15 pixel reflectances in each block in Band #4 and Band #3 lined up in the appropriate columns. This is most easily done by copying the block (3 pixels wide by 5 pixels long) from the image to the spreadsheet and then using cut and paste to arrange the pixels values into the correct column.

Activity: Leaving the spreadsheet open, return to *Bilko* and the ***Casi_SCaicos#04.dat*** image in the stacked set. Set **View, Coords** on, and then use **Edit, Go To** to select the block of 3 (**DX:**) by 5 (**DY:**) pixels in area 4 (see Table 7.3), starting at UTM coordinates 237820 (**X:**) and 2377846 (**Y:**). [*Hint:* Once you have entered the UTM coordinates in the **Go To** dialog box, click the **Coords** check box off and then select the number of pixels. If you don't then you must select number of metres east and south to get the correct number of pixels; in this case **DX:** is 3 and **DY:** is –5.5 or 5.5S (5.5 m south) as pixels are 1.0 m wide x 1.1 m long.]

Copy these pixels, return to the spreadsheet and paste them under the label Band #4 at the top of Column D. Then select the second column of 5 pixels and use **Cut** and **Paste** to move them below the first five pixels in the Band #4 column. Repeat with the remaining column of five pixels. Repeat this operation for area 7 (Table 7.3), stacking the pixel values immediately beneath those for area 4. You should now have a column with reflectances for 30 pixels from Band #4 (15 from area 4, followed by 15 from area 7).

Return to *Bilko* and repeat this procedure for the ***Casi_SCaicos#03.dat*** image in the stack so that you have the corresponding reflectances of each pixel in Band #3 in the next column of the spreadsheet.

Calculation of ratio of attenuation coefficients

The ratio of the attenuation coefficients of CASI Bands #4 (571.9–584.3 nm) and #3 (531.1–543.5 nm) is given by the slope of the bi-plot of the logarithmically transformed atmospherically corrected data. In this case we are using a crude atmospheric correction involving subtraction of the deep water value calculated earlier (Table 7.2). Thus all we have to do is to take natural logarithms of the reflectance of each pixel in the Band #4 column minus the deep water reflectance for Band #4, and then do the same for the Band #3 column.

Activity: In the spreadsheet ***Casi_sand_patches.xls*** enter appropriate formulas at the top of the $\ln(b4 - Ls_4)$ and $\ln(b3 - Ls_3)$ columns and then copy these down each column. [*Hint:* the formula for the first cell in the $\ln(b4 - Ls_4)$ column should be =LN(D5-?) where D5 is the cell with the first Band #4 pixel value and ? is the deep water correction calculated for Band #4 in Table 7.2. This could be entered as a number or as an absolute reference to a cell with this value in it.]

Checkpoint:	The value of the top cell in the $\ln(b4 - Ls_4)$ column should be 8.1659.

The gradient of the bi-plot of the logarithmically transformed corrected data in each band is *not* calculated using conventional least squares regression analysis (which is the standard equation given by most statistical packages). Instead, the following equations, which minimise the mean square deviation perpendicular to the regression line, are used:

$$\frac{k_i}{k_j} = a + \sqrt{(a^2 + 1)} \qquad \textit{Equation 7.7}$$

where

$$a = \frac{s_i^2 - s_j^2}{2 s_{ij}^2} \qquad \textit{Equation 7.8}$$

and (s_i^2 is the variance of band *i*, s_j^2 is the variance of band *j*, s_{ij}^2 is the covariance between bands *i* and *j*). In this case $i = 3$ and $j = 4$. Calculation of variance (spreadsheet function VAR) and covariance (function COVAR) is relatively straightforward. Let us do this in five steps:

1) calculate the variance of the transformed Band #4 values in the $\ln(b4 - Ls_4)$ column,

2) calculate the variance of the transformed Band #3 values in the $\ln(b3 - Ls_3)$ column,

3) calculate the covariance of the transformed Band #4 and Band #3 values,

4) calculate **a** [Equation 7.8],

5) calculate the ratio of the attenuation coefficients (k_3/k_4) [Equation 7.7].

Activity: 1) and 2). In the spreadsheet ***Casi_sand_patches.xls*** go to the bottom of the $\ln(b4 - Ls_4)$ column and use the VAR function to calculate the variance of the values in this column. **Repeat** for the $\ln(b3 - Ls_3)$ column. [*Hint:* the formula in the cell beneath the $\ln(b4 - Ls_4)$ column should be =VAR(F5:F34) where F5:F34 are the cells of the $\ln(b4 - Ls_4)$ column]. Enter your results in Table 7.4.

3) The COVAR function takes two arguments separated by a comma. The first is the cells in the $\ln(b4 - Ls_4)$ column, the second those in the $\ln(b3 - Ls_3)$ column. Enter the formula beneath that for the band #4 variance. [*Hint:* the formula should be =COVAR(F5:F34,G5:G34) where F5:F34 and G5:G34 are the cells of the $\ln(b4 - Ls_4)$ and $\ln(b3 - Ls_3)$ columns]. Enter your result in Table 7.4.

4) Use a calculator (or the spreadsheet) to calculate the value of **a** from the variances and covariance using Equation 7.8. Enter your result in Table 7.4.

5) Use a calculator (or the spreadsheet) to calculate the ratio of the attenuation coefficients (k_3/k_4) using Equation 7.7. Enter your result in Table 7.4.

Table 7.4. Parameters needed to work out the slope (k_3/k_4) of the bi-plot of transformed and corrected band #3 and band #4 values. [List parameters to **4 decimal places**.]

Parameter	Result
Variance of transformed and corrected Band #4 reflectances	
Variance of transformed and corrected Band #3 reflectances	
Covariance of Band #4 and Band #3 reflectances	
Value of a	
Ratio of attenuation coefficients (k_3/k_4)	

The depth-invariant processing will be removing the variation in reflectance that is due to water depth. To illustrate this you will look at the *coefficient of variation* (standard deviation/mean) of the **30 pixels** in **each** band and compare these with the coefficient of variation of the same pixels in the depth-invariant bottom index image you will produce later.

Activity: In your spreadsheet ***Casi_sand_patches.xls*** calculate the coefficients of variation for the raw CASI band #3 and band #4 data. [*Hint:* Use the STDEV function to calculate the standard deviation of each column and the AVERAGE function to calculate the mean].

Question: *7.3.* What are the coefficients of variation for the raw CASI band #3 and band #4 pixels in the two sand areas? [You should calculate one coefficient for each band (i.e. column of data). Express your answers to 4 decimal places and show your working.]

The results from a larger dataset for our CASI Bands #3 and #4 data are available for inspection in the *Excel* spreadsheet file ***Casi_depth-invariant_bands#3_#4.xls***.

Activity: Open ***Casi_depth-invariant_bands#3_#4.xls***. To the right of the data columns, the data are plotted along with a line of best fit. The slope of the line is equivalent to the ratio of the attenuation coefficients k_3/k_4 and one can see how good the fit is from the very low spread of the data points. If you compare your values for the variances, covariance and ratio of the attenuation coefficients with that calculated from the full dataset (see bottom of data columns), you will see that with your small sample size the variances and covariance are larger but that the k_3/k_4 ratio is reasonably close despite your very small sample size. However, for the next section you should use the value of k_3/k_4 in Table 7.5 based on the larger dataset. When you have finished close ***Casi_depth-invariant_bands#3_#4.xls***.

Table 7.5. Ratio of attenuation coefficients for CASI bands #2 and #4, #3 and #4 and #3 and #5 obtained using a large dataset.

CASI band	Deepwater correction (L_{si})	Ratio of attenuation coefficients	
#2	576	k_2/k_4	0.56688
#3	344	k_3/k_4	0.73393
#4	186	k_3/k_5	0.64990
#5	83		

Implementation of depth-invariant algorithm to whole image (band pairs)

Before you carry out the depth-invariant processing all areas of land and cloud should be masked out. It is best to set pixels for these areas to zero. Note that this has already been done on the CASI images you are using. Once the ratios of attenuation coefficients have been calculated for band pairs, the depth invariant algorithm can be implemented. Equation 7.6 can now be used to generate a depth-invariant index image for bands #3 and #4. This is repeated below for your convenience:

$$\text{depth invariant index}_{ij} = \ln(L_i - L_{si}) - \left[\left(\frac{k_i}{k_j}\right).\ln(L_j - L_{sj})\right] \qquad \textit{Equation 7.6}$$

where, in this case, i = CASI band #3 and j = CASI band #4.

Activity: Return to *Bilko* and the stacked set of the two images ***Casi_SCaicos#03.dat*** and ***Casi_SCaicos#04.dat***. Note that in the drop-down list of the **Selector** toolbar, the band #3 image is @1 and the band #4 image is @2. Then open the Formula document ***Casi_depth-invariant#3_#4.frm***. The formula in Equation 7.6 has been implemented as the last line. Study this to see how it works. Note that masked areas (with pixels set to 0) are omitted from processing using the IF ... ELSE statement.

All you need to do in the formula is to enter the values for the three constants (CONST) above the formula from Tables 7.2 and 7.5. [*Note:* deepwater3 is Ls_3, deepwater4 is Ls_4, and k3_k4ratio is k_3/k_4.] Once you have typed in the correct values for the three constants, use the **Options!** menu available from the formula document to make sure (i) the output depth-invariant bottom index image will be a 32-bit floating point image and (ii) that **Use special handling for Nulls** checkbox is <u>not</u> checked. Then **Copy** the formula and **Paste** it to the connected images.

Note the remarkable clarity with which details of the deep part of the image are now revealed. Save your output file as ***Casi_depth-invariant#3_#4.dat***.

Checkpoint:	To check whether you have done the depth-invariant processing correctly, inspect the value of the pixel at *x, y* coordinates 395, 190 (i.e. column 395, row 190) in ***Casi_SCaicos#03.dat*** and ***Casi_SCaicos#04.dat***. Then use a calculator to work out what the output depth-invariant index value should be in ***Casi_depth-invariant#3_#4.dat***.

Question: *7.4.* What are pixel values at coordinates 395, 190 in bands #3 and #4 of the CASI image? What should the depth-invariant bottom index be for that pixel [show your working and use equation 7.6]?

It is now time to re-examine the 225 m transect you started the lesson with, but in the depth-invariant image.

Activity: To see how the effect of water depth has been compensated for in the depth-invariant image ***Casi_depth-invariant#3_#4.dat***, click on the transect button and then use **Edit, Go To** to select the transect line running vertically down the image (DX: 1) from shallow water (7 m deep) to deep water (15 m deep) starting at UTM coordinates 237413, 2377566 and with a DY: of –225 (or 225S). This is the same transect you looked at earlier. To inspect the transect use **File, New** to open a transect document.

Note that there is no longer any trend of decreasing pixel reflectance with increasing depth. Instead, the reflectance depends on the habitat type with sand areas such as that at the south end of the transect having relatively high depth-invariant bottom index values. Note that the lowest values are from sudden drops in the reef that are shaded from the incoming sunlight.

Activity: If you have the *Excel* worksheet where you made calculations on the raw band #3 transect, open this; if not, open a new *Excel* worksheet. Then return to your transect document in *Bilko* and while it is the active document, click on the Copy button. Return to *Excel* and Paste the transect values to an appropriate cell. The pixel values along the transect will have pasted down a column. Format the column so that the values are displayed with 4 decimal places. Now set up formulae to calculate the average values of the 15 pixels at the start and at the end of the transect.

Question: *7.5.* What is the average of the first 15 pixels? What is the average of the last 15 pixels? What is the difference between these two values, expressed as a percentage of the average of the 15 pixels at the start of the transect? [Give your answers for the pixel values to 4 decimal places and for the percentage to one decimal place.]

Note that the difference expressed in percentage terms is almost a tenth of what it was before depth-invariant processing. A better way of showing the effectiveness of the depth-invariant processing is to look at the *coefficient of variation* for the shallow and deep sand patches you studied earlier. This removes habitat effects.

Activity: Earlier you calculated the coefficients of variation for each constituent band used to make the depth-invariant band. To see how much of the variation in reflectance (which should mainly have been due to the different depths of the two sand patches) has been accounted for by the depth-invariant processing, copy the same 15 pixels (see Table 7.3 for the coordinates) from each of areas 4 and 7 to your ***Casi_sand_patches.xls*** spreadsheet and calculate the coefficient of variation (standard deviation/mean). [Remember: coordinates are for NW of blocks and you want 5 pixels south i.e. 5.5S as **DY:** value.]

Question: *7.6.* What is the coefficient of variation of the 30 sand pixels in the depth-invariant bottom index image? What is this expressed as a percentage of the average coefficient of variation of the raw pixel data for the two constituent bands? [Work out answers to four and one decimal places respectively and show your working.]

These measurements show just how effective your depth-invariant processing has been in removing the effects depth. Congratulations! With the light-attenuation effects removed, the images become much clearer, particularly in deeper water. This is best demonstrated by comparing colour composites or raw and depth-invariant images. So to finish, you will do this.

Comparison of colour composites of raw images and depth-invariant images

Firstly, you will examine a false colour composite of the raw CASI data using bands #2 (blue), #4 (green) and #5 (red) and inspect the deep water part of this at the south (bottom end) of the image. This composite has been saved as a set to save you time.

Activity: Close the stacked set of ***Casi_SCaicos#03.dat*** and ***Casi_SCaicos#04.dat*** images. Open the set ***Casi_SCaicos#05+#04+#02.set***. In **the Redisplay Image** dialog box, set the null value as 0, select a histogram equalization stretch and click on the All button to apply the settings to all three bands. The false colour composite is displayed. This displays band #5 through the red gun, band #4 through the green gun and band #2 through the blue gun. The resultant composite is by no means as one would see the image from the air because the CASI wavelengths are rather different to those that our eyes see in the blue, green and red.

Note **two** things about the image: 1) there is quite a lot of sun glint and specular reflection off the sea surface on the right hand side (east) of the image, 2) at the bottom (south) of the image (you will probably need to scroll down to see this) little of the detail in the deep water area is revealed even though we used the good penetration blue band in making the composite. Basically the increased depth of water at the south of the image area obscures the detail of the reef structure.

Close the three raw images ***Casi_SCaicos#02.dat***, ***Casi_SCaicos#04.dat*** and ***Casi_SCaicos#05.dat*** but leave the composite open.

Secondly, you will make a false colour composite of three CASI depth-invariant index images. These are the ***Casi_depth-invariant#3_#4.dat*** image that you made earlier and two more made using the formula document ***Depth_invariant.frm*** (which you can inspect if you wish). These latter two were made using the CASI band pairs #2 and #4 (***Casi_depth-invariant#2_#4.dat***) and #3 and #5 (***Casi_depth-invariant#3_#5.dat***).

Activity: Open the depth-invariant bottom index images ***Casi_depth-invariant#2_#4.dat***, ***Casi_depth-invariant#3_#4.dat***, and ***Casi_depth-invariant#3_#5.dat***. For each image, in the **Redisplay Image** dialog box, set the null value as 0 and select a histogram equalization stretch before clicking on the Apply button.

Look at the south (bottom) ends of each of the images. Note how the reef front is visible in all of them (except the band#3_#5 image where the red light's lack of penetration makes the extreme south of the image dark) as the effect of attenuation of light due to depth has been compensated for. Connect these images and use the **Selector** toolbar to make sure the ***Casi_depth-invariant#3_#4.dat*** image is displayed through the red gun (@1), the ***Casi_depth-invariant#3_#5.dat*** image through the green gun (@2), and the ***Casi_depth-invariant#2_#4.dat*** through the blue gun (@3). This gives a reasonable image (perhaps the best of the six possible combinations available).

Question: *7.7.* What two things do you particularly notice about the depth-invariant bottom index composite image compared to the raw data composite image? [In particular, compare the depth-invariant index image composite with the raw data composite to see how the effect of depth has been compensated for by the depth-invariant processing.]

Activity: When you are finished, close all the images. Congratulations!

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Answers to Questions

7.1. The transect document shows a maximum value of 1159 and a minimum value of 456 along the transect. The difference between these two values is 703. This is 60.7% (703/1159 x 100) of the maximum pixel value.

7.2. The average of the first 15 pixels at the start of the transect at 7 m depth is 1093.6. The average of the last 15 pixels at the end of the transect at 15 m depth is 542.6. The difference between these two values is 551.0. The difference is 50.4% (551.0/1093.6 x 100) of the average pixel value at the start of the transect.

Table 7.2. Calculation of deep water radiance (reflectance) for bands #3 and #4.

Band	Deepwater Mean	Deepwater Standard Deviation	Deepwater Mean – 2 Standard deviations (L_{si})
CASI band #3	419.65	37.86	344
CASI band #4	255.84	34.91	186

Table 7.4. Parameters needed to work out the slope (k_3/k_4) of the bi-plot of transformed and corrected band #3 and band #4 values for sand areas 4 and 7.

Parameter	Result
Variance of transformed and corrected Band #4 reflectances	1.4841
Variance of transformed and corrected Band #3 reflectances	0.8056
Covariance of Band #4 and Band #3 reflectances	1.0556
Value of a	-0.3214
Ratio of attenuation coefficients (k_3/k_4)	0.7290

7.3. The coefficients of variation (standard deviation/mean) are 1765.5/2799.2 = **0.6307** for band #3 and 1697.5/2187.8 = **0.7759** for band #4.

7.4. The pixel values at column and row coordinate 395, 190 are 2104 (band #3) and 1632 (band #4). Taking away the respective deepwater reflectances gives 2104 – 344 = 1760 (band #3) and 1632 – 186 = 1446 (band #4). Taking natural logarithms gives 7.4731 (band #3) and 7.2766 (band #4). The attenuation coefficient ratio is 0.73393 so the depth-invariant bottom index value is:

$$\text{index} = 7.4731 - 0.73393 \times 7.2766 = 2.1326$$

7.5. The average of the first 15 pixels at the start of the transect at 7 m depth is 2.0295. The average of the last 15 pixels at the end of the transect at 15 m depth is 1.9075. The difference between these two values is 0.1220. The difference is 6.0% (0.1220/2.0295 x 100) of the average pixel value at the start of the transect.

7.6. The coefficient of variation (standard deviation/mean) of the 30 pixels in the ***Casi_depth-invariant#3_#4.dat*** depth-invariant bottom index image is 0.0461/2.3143 = 0.0199. The average coefficient of variation of the same pixels in the two raw bands is (0.6307 + 0.7759)/2 = 0.7033. 0.0199/0.7033 x 100 = 2.8%. Thus over 95% of the variation in reflectance between the two sand patches was due to the effect of water depth!

7.7. 1) At the bottom (south) of the depth-invariant bottom index image the structure of the reef front in deep water is clearly revealed and no longer does the image get darker as the water depth increases. 2) There is little evidence of sunglint and much less sign of reflection off the sea surface on the right (east) of the bottom-index image.

8: MAPPING THE MAJOR INSHORE MARINE HABITATS OF THE CAICOS BANK BY MULTISPECTRAL CLASSIFICATION USING LANDSAT TM

Aim of Lesson

To learn how to undertake a simple supervised classification of a Landsat TM image to show the major marine and terrestrial habitats of the Caicos Bank.

Objectives

1. To prepare a mask for the land areas of the Landsat TM image and apply this mask to the depth-invariant bottom index images to be used for classification.
2. To learn how to link UTM coordinate referenced field survey data of shallow water marine habitats to the Landsat TM image to derive simple spectral signatures for the major marine habitats (sand, seagrass, algae, gorgonian plain, coral reef).
3. To understand the concepts underlying a simple box classification of marine habitats into sand, seagrass, algae, gorgonian plain, and coral reef, and perform the classification of each habitat in turn.
4. To learn how to combine these separate images (GIS layers) into a single image and use an appropriate palette to display the habitats.

Background Information

This lesson relates to material covered in Chapters 9–11 of the *Remote Sensing Handbook for Tropical Coastal Management* and readers are recommended to consult this for further details of the techniques involved. The lesson introduces you to multispectral classification of imagery using a simple two-dimensional box-classification of the “feature space” of two depth-invariant bottom index images.

The *Bilko 3* image processing software

Familiarity with *Bilko 3* is required to carry out this lesson. In particular, you will need experience of using Formula documents to carry out mathematical manipulations of images; these are introduced in Tutorial 10 of the *Introduction to using the Bilko 3 image processing software*. Some calculations need to be performed independently; these can either be carried out on a spreadsheet such as *Excel* or using a calculator.

Image data

The image used as the basis for this lesson was acquired by Landsat-5 TM on 22nd November 1990 at 14.55 hours Universal Time (expressed as a decimal time and thus equivalent to 14:33 GMT). The Turks & Caicos are on GMT – 5 hours so the overpass would have been at 09:33 local time. This image has been geometrically corrected (see Lesson 3), radiometrically and atmospherically corrected (Lesson 4), and finally water column corrected (Lesson 7) to produce two depth-invariant bottom index bands; one from bands #1 and #3 (***Depth-invariant_LandsatTM#1_#3.dat***) and one from bands #2 and #3 (***Depth-invariant_LandsatTM#2_#3.dat***). The third depth-invariant band (from bands #1 and #2) will not be used here. The sub-scenes provided are of the South Caicos area only and are 32-bit floating-point images, i.e. each pixel is stored as a floating-point number and occupies four bytes. To allow a mask image to be made to mask out the land areas, you are also provided with the band #5 (near infra-red) image of the same area (***LandsatTM_Caicos#05.gif***).

Field survey data

You are provided with a spreadsheet (***Habitats_Lesson8.xls***) containing field survey data on seven habitat classes:

1. Dense seagrass,
2. Sparse seagrass,
3. Sand,
4. Dense *Montastraea* reef,
5. Gorgonian plain,
6. *Lobophora* dominated macroalgal areas,
7. Coral patch reefs.

For each habitat class you are provided with GPS-derived UTM coordinates of 7 sites where the habitat occurred. The reflectance values for each ground-truthing site in each of the two depth-invariant bottom index image bands (***Depth-invariant_LandsatTM#1_#3.dat*** and ***Depth-invariant_LandsatTM #2_#3.dat***) are provided for most sites but you will be asked to collect the spectra for two sand and two sparse seagrass sites.

Lesson Outline

The first task is to mask out the land areas on the two depth-invariant bottom index images (***Depth-invariant_LandsatTM#1_#3.dat*** and ***Depth-invariant_LandsatTM#2_#3.dat***). We will use the near-infrared Landsat TM band #5 image to make the mask and then multiply the depth-invariant images by it.

Making a land mask

The main task in this lesson is to classify major submerged habitats. To allow contrast stretches, which will display these habitats optimally, and to remove the distraction of terrestrial habitats, which are best classified separately using a combination of infra-red and visible wavebands, you should mask out the land areas. This is easily achieved using a Landsat TM band #5 infra-red image (***LandsatTM_Caicos#05.gif***) where there will be very little reflectance from water covered areas but considerable reflectance from land areas. This allows water and land areas to be fairly easily separated on the image and a mask of either land or water to be created with a simple Formula document.

A land mask image has all land pixels set to zero and all water pixels set to 1, so when used to multiply another image it leaves sea pixel values unchanged but sets all land pixels to zero.

Activity: Launch *Bilko* if you have not already done so. Open the two depth-invariant images (***Depth-invariant_LandsatTM#1_#3.dat*** and ***Depth-invariant_LandsatTM#2_#3.dat***), setting null value as zero and applying histogram equalization stretches to each image in the **Redisplay Image** dialog box. Also open the band #5 image (***LandsatTM_Caicos#05.gif***). Connect the three images together as a tiled set using the **Image, Connect** command. Use the **Selector** toolbar to ensure that ***LandsatTM_Caicos#05.gif*** becomes image 1, ***Depth-invariant_LandsatTM#1_#3.dat*** becomes image 2, and ***Depth-invariant_LandsatTM#2_#3.dat*** becomes image 3.

The next step is to make a mask using ***LandsatTM_Caicos#05.gif***. You need to produce an image from it that has all sea pixels set to 1 and all land pixels to 0. Minimize the two depth-invariant images and apply an automatic linear stretch to the original ***LandsatTM_Caicos#05.gif*** image. Note that the sea pixels are uniformly dark whilst the land pixels are variable but generally bright. It will thus be fairly easy to find out what the maximum reflectance of the sea pixels are, then to consider any pixels above this threshold value as being land. Use **View, Coords** to switch off UTM coordinates.

Activity: You can either move the cursor around in areas which are clearly sea and note the highest pixel value you record or copy some 10 x 10 groups of sea pixels to an *Excel* spreadsheet and use the MAX function or inspection to find out what the largest value is. [*Suggestion:* Use **Edit, Go To** to select 10 x 10 pixel box starting at coordinates 382, 82 off the east coast of South Caicos, **Copy** this block of pixels and **Paste** it to a spreadsheet. Note the highest value. Repeat with a 10 x 10 pixel box from the salinas on South Caicos starting at coordinates 300, 105.]

Question: *8.1.* What is the highest pixel value in areas that are clearly water covered?

Having established what the highest reflectance from water covered areas is, you need to create a Formula which will set all pixels which are brighter (greater than) than this threshold value to zero and all pixels which are less than the threshold to 1.

This requires a formula of the type:

IF (@1 <= threshold) 1 ELSE 0 ;

where @1 is the ***LandsatTM_Caicos#05.gif*** image. The formula takes each pixel in the @1 image and compares it to the threshold value, then IF the pixel has a value which is less than or equal to (<=) the threshold value it sets the output image pixel to 1. Otherwise (ELSE) the output image pixel is set to 0. Thus the output image has all land pixels set to 0 and all water pixels set to 1.

Activity: Open a new Formula document. Type in some title as a comment (i.e. preceded by #) so that you will remember what the formula does. Set up a constant statement (CONST name = value ;)which sets a constant (CONST) called "threshold" (omit the quotation marks!) equal to the highest pixel value you found in the water covered areas of the Landsat TM band #5 image. Then type in the formula as above. [*Remember:* All formula statements have to end in a semi-colon.] Use the **Options!** menu available from a Formula document to ensure that the **Output Image Type:** will be the same as @1 (or an 8-bit unsigned integer image), and that there is no special handling for nulls.

Copy the formula and **Paste** it to the connected images window where ***LandsatTM_Caicos#05.gif*** is @1. The resultant image should look all black since the brightest pixel has a value of only 1. Save this image immediately as ***Landmask_lesson8.gif***. Apply an automatic linear contrast stretch to the image. All the land should be black and all the water areas white.

Close the connected images window, ***LandsatTM_Caicos#05.gif***, and the formula document (without saving any changes).

You now need to create two new depth-invariant bottom index images with the land masked out. This is achieved by multiplying the images by the land mask image.

Activity: **Connect** ***Landmask_lesson8.gif*** with the two depth-invariant images and use the **Selector** toolbar to make ***Depth-invariant_LandsatTM#1_#3.dat*** image 1, ***Depth-invariant_LandsatTM#2_#3.dat*** image 2, and ***Landmask_lesson8.gif*** image 3. Then open a new Formula document. You want to multiply each of the depth-invariant images by the mask to produce two output images which will be the depth-invariant bottom index images with the land areas masked out. This will require two simple formula statements.

Question: *8.2.* What two formula statements are required to make the two masked images?

Activity: When you are satisfied with your formula statements, ensure that the **Output Image Type:** will be the same as @1 (or 32-bit floating point), and that there is no special handling for nulls. Apply your formula to the connected images and inspect the resultant images to see if the land pixels have been set to zero as expected. Save the new images as ***Depth-invariant_masked#01.dat*** (for the ***Depth-invariant_LandsatTM#1_#3.dat*** masked image) and ***Depth-invariant_masked#02.dat*** (for the ***Depth-invariant_LandsatTM#2_#3.dat*** masked image). Close the connected images window, the ***Landmask_lesson8.gif*** image, and the unmasked depth-invariant images.

Determining the spectral signatures of the major submerged habitats using UTM coordinate referenced field survey data

In this section you will use field survey data on where different habitats are located on the images (in ***Habitats_Lesson8.xls***) to derive spectral signatures for major marine habitats and then use these signatures to classify the image. The classification method that you will test, is to create a simple box (parallelepiped) classifier for each habitat using the two depth-invariant bottom-index images. That is, you are seeking to define discrete two-dimensional areas in feature space that relate to specific habitats.

The first step is to find out what reflectance values in each depth-invariant band relate to which habitats.

Activity: Open the spreadsheet file ***Habitats_Lesson8.xls***. This gives a listing of the training sites that provide the basis of your supervised classification of the images. Seven field survey sites for each habitat are included with the pixel values for each site in each of the depth-invariant images. However, two sand and two sparse seagrass sites are missing the image data values from two survey points. Once you have these four data values you will be able to calculate the maxima and minima (box limits) for each habitat in each depth-invariant image. Switch back to *Bilko*.

Connect the ***Depth-invariant_masked#01.dat*** and ***Depth-invariant_masked#02.dat*** images as a stack. Make sure **View, Coords** is checked, then use **Edit, Go To** to locate the relevant pixels, which are listed in Table 8.1 for your convenience. Once at a GPS location, you can use the *<Tab>* key to move to the same position on the other image and read off its value. Enter the pixel values to **3 decimal places** in Table 8.1.

Table 8.1. Locate the pixels nearest to the GPS coordinates from the field survey and fill in the missing pixel values (rounded to 3 decimal places).

GPS coordinates		Depth-invariant bottom-index bands		
Easting (X:)	Northing (Y:)	TM bands #1/#3	TM bands #2/#3	Habitat
237382	2378154			Sparse seagrass
237176	2378235			Sparse seagrass
241743	2381866			Sand
242177	2382234			Sand

Activity: Switch back to the ***Habitats_Lesson8.xls*** spreadsheet and enter the missing values. The formulae already entered under the sparse seagrass and sand columns should automatically calculate the maxima and minima for these two habitats. Transfer the maximum and minimum data to Table 8.2, rounding the maxima and minima to **2 decimal places.** The reason for this is that if you have too many decimal places, it is difficult to see the wood for the trees.

Inspect the completed Table 8.2 and note that sand and possibly sparse seagrass appear to be fairly readily separable from other habitats on the basis of their depth-invariant bottom-index values whilst there appears to be a lot of overlap in the other classes. You will probably agree that it is very difficult to see the relationship of the signatures in the table in the two bands.

To see whether the signatures and box-classifiers based on the maxima and minima are likely to allow you to classify the habitats, you need to plot the pixel values in one band against those in the other band and draw in the boundaries of the boxes. To save time, this has already been done using your spreadsheet data and is displayed as Figure 8.1. This figure shows the distribution of the habitats in a two-dimensional "feature space" based on their pixel values in the two depth-invariant bands. Study this figure and answer the following questions.

Question: *8.3.* Which two habitats are clearly separable from all other habitats?

Question: *8.4.* Which two habitats occupy very similar areas in feature space?

Question: *8.5.* Which two habitats are likely to be confused with dense *Montastraea* reef patches?

Question: *8.6.* With which two habitats is gorgonian plain likely to be confused?

Table 8.2. Minimum and maximum reflectances in depth-invariant bottom index images for 7 major marine habitats. (Taken from completed ***Habitats_Lesson8.xls*** and rounded to 2 decimal places.)

	TM bands #1/#3 depth-invariant		TM bands #2/#3 depth-invariant	
Habitat class	Minimum	Maximum	Minimum	Maximum
Dense seagrass				
Sparse seagrass				
Sand				
Dense *Montastraea* reef				
Gorgonian plain				
Lobophora dominated algal areas				
Coral patch reef				

Clearly it is not feasible to separate *Lobophora* dominated algal areas from coral patch reefs using just these two depth-invariant bands. Thus these two habitats need to be combined for classification.

Activity: Combine the two classes and calculate the minima and maxima for a combined class and enter the results in Table 8.3.

Table 8.3. Combined class boundaries for *Lobophora* dominated algal areas and coral patch reefs.

	TM bands #1/#3 depth-invariant		TM bands #2/#3 depth-invariant	
Habitat class	Minimum	Maximum	Minimum	Maximum
Lobophora dominated algal areas and coral patch reefs				

This improves the classification scheme but two further anomalies need addressing. As is evident from Figure 8.1 the *Montastraea* reef class swallows the dense seagrass class because of two outliers. For the purposes of this simple box-classification it is perhaps best to risk misclassification of some of the *Montastraea* reef by restricting the *Montastraea* class to a box around the five training sites which group together (Figure 8.2). Similarly, the one gorgonian plain outlier with a high depth-invariant TM band #2/#3 bottom-index results in a lot of overlap with the coral patch reef/*Lobophora* class. Restricting the gorgonian plain class box to the remaining points risks leaving gorgonian plain unclassified but should improve classification of the coral patch reef/*Lobophora* class. The revised box-classifier boundaries, which reflect the classification scheme in Figure 8.2 are listed below in Table 8.4.

Figure 8.1. Box-classification using full range of values for all seven classes.

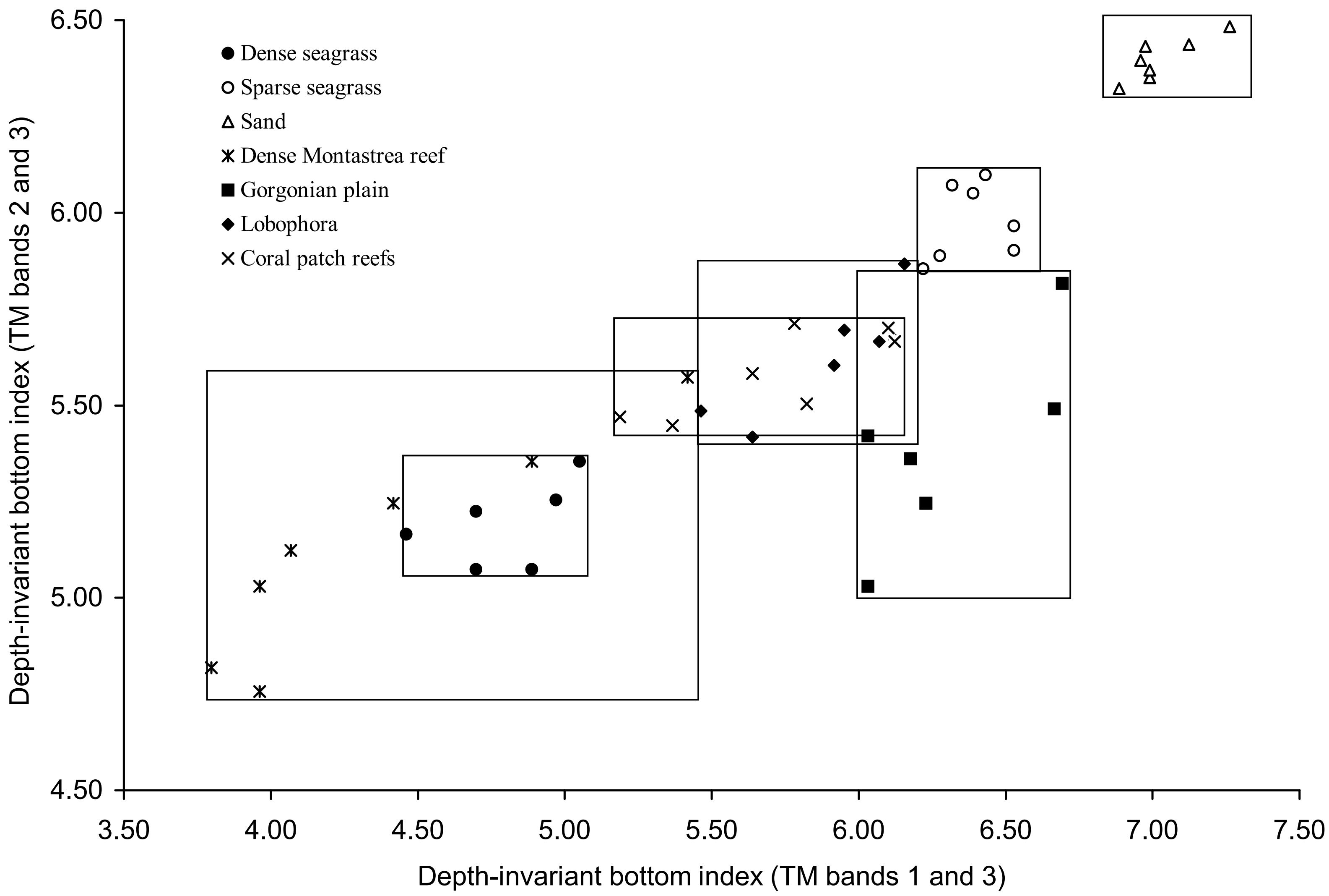
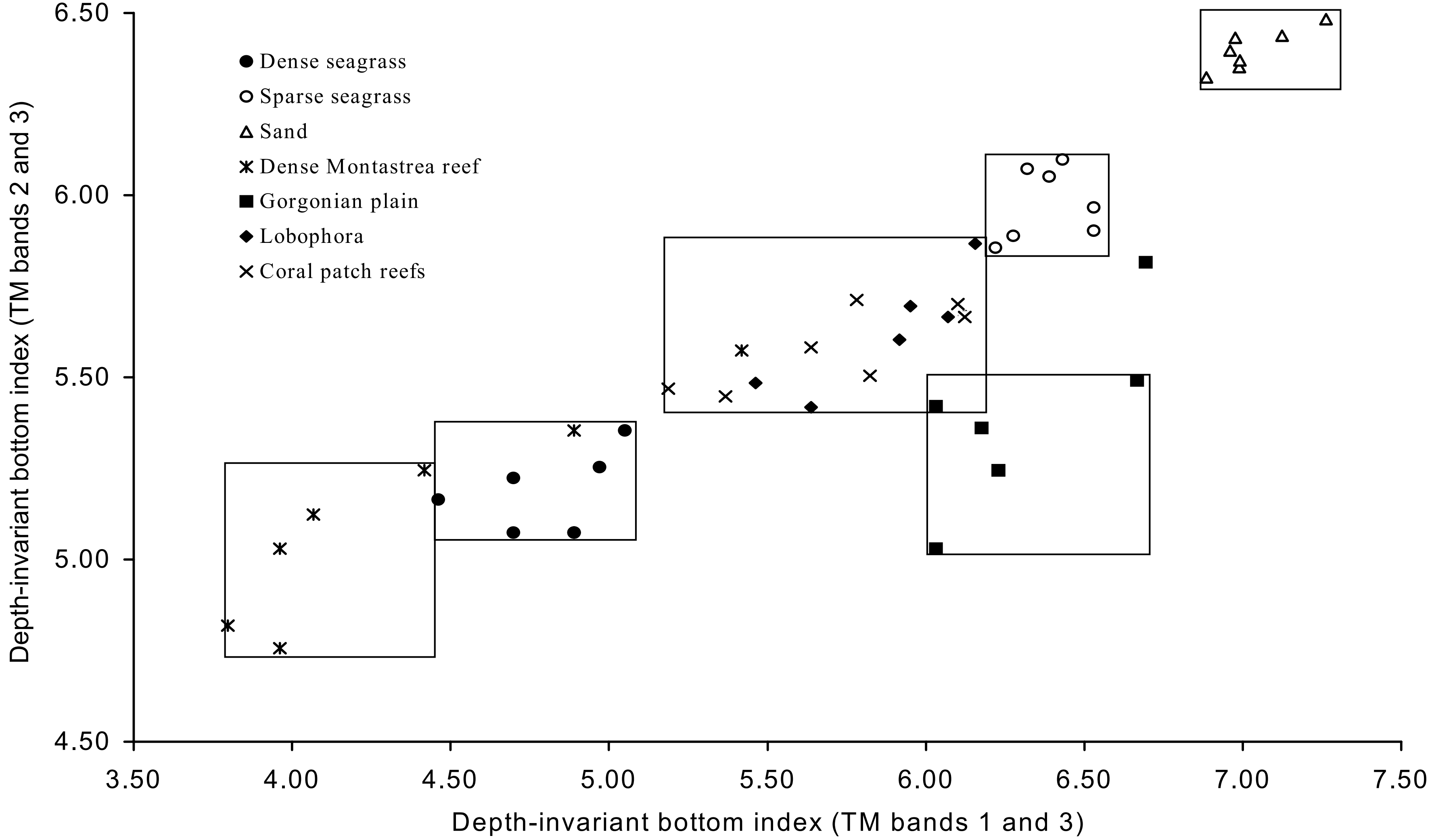


Figure 8.2. Box-classification where *Lobophora* and coral patch reef classes are merged, some gorgonian plain is left unclassified, and some dense *Montastraea* reef class is mis-classified as dense seagrass or a coral patch reef/*Lobophora*. However, this scheme is likely to produce a better map than Figure 8.1.



Bear in mind that we have used a *very small* sample of field survey points in constructing our classification and thus may be underestimating the spread of values in feature space. This could lead to a lot of the image being unclassified.

Table 8.4. Minimum and maximum reflectances in depth-invariant bottom index images for 6 major marine habitats, using box-classifiers illustrated in Figure 8.2. Changes are in bold type.

Habitat class	TM bands #1/#3 depth-invariant		TM bands #2/#3 depth-invariant	
	Minimum	Maximum	Minimum	Maximum
Dense seagrass	4.46	5.05	5.07	5.35
Sparse seagrass	6.22	6.53	5.86	6.10
Sand	6.89	7.26	6.32	6.48
Dense *Montastraea* reef	3.80	**4.42**	4.76	**5.25**
Gorgonian plain	6.03	6.69	5.03	**5.50**
Lobophora dominated algal areas and coral patch reefs	See Table 8.3			

Activity: Return to your stacked set of two masked depth-invariant bottom-index images ***Depth-invariant_masked#01.dat*** and ***Depth-invariant_masked#02.dat***. Open the Formula document ***Classification1.frm***. Study the formula document to see how it works (see notes below).

Note that the CONST statements set up the maxima and minima for each habitat class, whilst the box-classifier statements check whether pixels in each of the two images lie within the box boundaries. If they do, it sets output image pixels to a value unique to that class (see Table 8.5), if they don't it sets output image pixels to 0. One output image is created per habitat class so each can be regarded as being like a layer in a Geographical Information System (GIS). If you add all the output images (layers) together then each habitat class will have a different pixel value and can be displayed as a different colour using an appropriate Palette document. Since some habitat classes overlap, a power of 2 series of pixel values has been chosen (Table 8.5) so that during addition one cannot create a valid pixel value for another class. Thus any pixel values in the image, which are not in the power series in Table 8.5, are unclassified because of falling into more than one class.

Table 8.5. Habitat classes used in classification with pixel values and colours assigned to each habitat by the formula and palette documents respectively.

Habitat class	**Pixel value**	**Palette colour**
Classified in more than one class (unclassified)	Not values below	Grey
Sand	32	Yellow
Sparse seagrass	16	Pale green
Gorgonian plain	8	Magenta
Lobophora dominated algal areas and coral patch reefs	4	Cyan
Dense seagrass	2	Dark green
Dense *Montastraea* reef	1	Khaki
Land or not classified in any class	0	Black

You will now try a classification based on the tight boxes in Figure 8.2 and the very limited number of training sites (field survey stations).

Activity: Make sure that the output images will be 8-bit unsigned integer images and that there will be no special handling of nulls, using the **Options!** menu available for Formula documents**.** Then **Copy** the Formula document ***Classification1.frm*** and **Paste** it to the connected images window. It will produce 6 images, one for each habitat class. [These will all look black as no pixels have values above 32. If you apply a stretch you should be able to see the patches of each habitat.] When the six images have been produced, minimize the stacked set of two masked depth-invariant images, close ***Classification1.frm***, and minimize the ***Depth-invariant_masked#01.dat*** and ***Depth-invariant_masked#02.dat*** images. Then connect the 6 new images as a new stacked set. Finally, open a new Formula document and enter a formula to add all 6 images in the stack together.

Question: *8.7.* What is the simple formula that will add the six images together?

Activity: **Copy** this formula and **Paste** it to the stack of six images. Save the resultant image as ***Classification1.gif*** and the formula as ***Add_6_layers.frm***. Then apply the palette ***Classification.pal*** (i.e. open and apply the palette while ***Classification1.gif*** is the active window). Close the stacked set of the six images and all six of the constituent habitat images without saving them.

Question: *8.8.* What is the primary problem with the resultant classified image (***Classification1.gif***)?

As mentioned earlier the limited number of training sites are unlikely to adequately represent the habitat classes. To see the effect of using more training sites, you will now classify the marine habitats using box-classifiers based on twice as many training sites.

Activity: Restore your stacked set of two masked depth-invariant bottom-index images ***Depth-invariant_masked#01.dat*** and ***Depth-invariant_masked#02.dat***. Open the Formula document ***Classification2.frm***. Study the formula document and note that some of the CONST statements use different maxima and minima. Also a "bespoke" box-classifier consisting of two boxes has been created for the gorgonian plain habitat. This should allow a better classification. Make sure that the output images will be 8-bit unsigned integer images with no special handling of nulls, using the Formula document **Options!** dialog box. Then apply the new formula to the stacked set of two images and wait until the six new (very dark if not stretched) habitat maps (GIS layers) have been created. Then close the ***Depth-invariant_masked#01.dat*** and ***Depth-invariant_masked #02.dat*** images and their stacked set, and close ***Classification2.frm***.

Finally, as before, use **Image, Connect** to stack the 6 new images and then use your ***Add_6_layers.frm*** formula to add the 6 images together. Save the resultant image as ***Classification2.gif*** and apply the ***Classification.pal*** palette to it to display the different habitats.

Question: *8.9.* In what way has the habitat map improved with the extra field data?

Activity: Compare the two classifications and experiment with passing a 3x3 and 5x5 **Median** smoothing filter over the image to allow the broad distribution of the habitats to more clearly seen. When you have finished close all files. Do not save the 6 habitat images.

This lesson has demonstrated a very simple box-classification method. The box-classifier could be further refined to give better results. In reality more sophisticated classification methods, such as minimum distance to means and maximum likelihood classification, are used (see, for example, Mather, 1999: Chapter 8) but the principles remain the same. Training sites are used to establish how habitat classes are distributed in feature space, and pixels are then assigned to habitats on the basis of their position in feature space. For this lesson our feature space is only in two dimensions as shown in Figures 8.1 and 8.2 but it can be in three or more dimensions (one for each band used).

References

Green, E.P., Mumby, P.J., Edwards, A.J. and Clark, C.D. (Ed. A.J. Edwards) (2000). *Remote Sensing Handbook for Tropical Coastal Management. Coastal Management Sourcebooks 3.* UNESCO, Paris. ISBN 92-3-103736-6 (paperback).

Mather, P.M. 1999. *Computer Processing of Remotely-Sensed Images: an Introduction.* Second Edition. Wiley and Sons, Chichester, New York. 292 pp.

Answers to Questions

8.1. The highest pixel value in both blocks is 7. Thus pixels with values above 7 can be considered as being land.

8.2. On line one you should have @1 * @3 ; On line two you should have @2 * @3 ; Alternatively you could have used a constant statement and comment to make action clearer, e.g.

```
# Masking out land on two depth-invariant images. @3 is the landmask image.
CONST Landmask = @3 ;
@1 * Landmask ;
@2 * Landmask ;
```

Table 8.1. The values of the pixels nearest to the GPS coordinates obtained during the field survey.

GPS coordinates		Depth-invariant bottom index bands		
Easting (X:)	Northing (Y:)	TM bands #1/#3	TM bands #2/#3	Habitat
237382	2378154	6.529	5.966	Sparse seagrass
237176	2378235	6.277	5.888	Sparse seagrass
241743	2381866	6.991	6.370	Sand
242177	2382234	6.976	6.432	Sand

8.3. Sand and sparse seagrass have clear non-overlapping boxes and are thus clearly separable from all other habitats.

8.4. Coral patch reefs and *Lobophora* dominated algal areas occupy very similar areas in feature space for these two depth-invariant bands and are hopelessly confused spectrally. The dense seagrass category is contained within the dense *Montastraea* reef parallelepiped, although the majority of pixels in each class cluster in different parts of feature space.

8.5. There is overlap between dense *Montastraea* reef areas and both dense seagrass and coral patch reef habitats.

8.6. Because of the outlier with a relatively high depth-invariant bottom index value in Landsat TM band#2_#3, gorgonian plain is likely to be confused with both *Lobophora* dominated algal areas and coral patch reefs.

Table 8.2. Minimum and maximum reflectances in depth-invariant bottom index images for 7 major marine habitats.

Habitat class	TM bands #1/#3 depth-invariant		TM bands #2/#3 depth-invariant	
	Minimum	Maximum	Minimum	Maximum
Dense seagrass	4.46	5.05	5.07	5.35
Sparse seagrass	6.22	6.53	5.86	6.10
Sand	6.89	7.26	6.32	6.48
Dense *Montastraea* reef	3.80	5.42	4.76	5.57
Gorgonian plain	6.03	6.69	5.03	5.82
Lobophora dominated algal areas	5.46	6.16	5.42	5.87
Coral patch reef	5.19	6.12	5.45	5.71

Table 8.3. Combined class boundaries for *Lobophora* dominated algal areas and coral patch reefs.

Habitat class	TM bands #1/#3 depth-invariant		TM bands #2/#3 depth-invariant	
	Minimum	Maximum	Minimum	Maximum
Lobophora dominated algal areas and coral patch reefs	5.19	6.16	5.42	5.87

8.7. @1 + @2 + @3 +@4 + @5 + @6 ;

8.8. The main problem with the ***Classification1.gif*** file is that too much of the submerged area is unclassified. Given the broad classes involved, which include most of the habitats likely to be encountered, this suggests that the training sites do not adequately represent the habitat classes in question. Also areas of water on land, such as the salinas, classify as various marine habitats as they have similar pixel values.

8.9. Much more of the submerged habitats are classified as the greater number of training sites has better sampled the spread in feature space for each habitat.

Appendix 8.1

Ground-truthing data from 7 training sites for each of 7 habitat classes.

Easting	Northing	TM_#1_#3	TM_#2_#3	Habitat
237117	2378610	4.889	5.074	dense seagrass
237434	2378308	5.050	5.354	dense seagrass
237552	2378205	4.889	5.074	dense seagrass
238546	2377947	4.698	5.224	dense seagrass
238572	2378124	4.971	5.254	dense seagrass
239496	2378272	4.461	5.165	dense seagrass
241581	2379096	4.698	5.074	dense seagrass
	Max	5.05	5.35	
	Min	4.46	5.07	
241286	2378559	6.319	6.072	sparse seagrass
239489	2378411	6.389	6.051	sparse seagrass
239040	2378316	6.431	6.098	sparse seagrass
239091	2378132	6.219	5.855	sparse seagrass
237544	2378051	6.529	5.902	sparse seagrass
237382	2378154	6.529	5.966	sparse seagrass
237176	2378235	6.277	5.888	sparse seagrass
	Max	6.53	6.10	
	Min	6.22	5.86	
235585	2377564	6.886	6.323	sand
235298	2378205	6.960	6.396	sand
231917	2376695	7.262	6.483	sand
230746	2378117	7.124	6.437	sand
235762	2380341	6.990	6.351	sand
241743	2381866	6.991	6.370	sand
242177	2382234	6.976	6.432	sand
	Max	7.26	6.48	
	Min	6.89	6.32	
242207	2380628	3.962	4.756	dense *Montastraea* reef
242192	2379616	3.962	5.030	dense *Montastraea* reef
242030	2382809	3.798	4.819	dense *Montastraea* reef
241846	2379428	4.068	5.123	dense *Montastraea* reef
241919	2379045	4.417	5.245	dense *Montastraea* reef
241536	2378743	4.889	5.354	dense *Montastraea* reef
241205	2378132	5.418	5.573	dense *Montastraea* reef
	Max	5.42	5.57	
	Min	3.80	4.76	

241809	2378330	6.693	5.816	Gorgonian plain
242538	2379096	6.031	5.030	Gorgonian plain
242847	2379781	6.031	5.421	Gorgonian plain
242833	2381019	6.176	5.361	Gorgonian plain
240247	2377756	6.666	5.491	Gorgonian plain
236896	2377233	6.228	5.245	Gorgonian plain
235445	2375834	6.228	5.245	Gorgonian plain
	Max	6.69	5.82	
	Min	6.03	5.03	
234716	2375289	6.122	5.670	*Lobophora*
235224	2375826	5.638	5.418	*Lobophora*
235453	2376224	6.070	5.666	*Lobophora*
236160	2377034	5.952	5.695	*Lobophora*
236918	2377395	5.916	5.603	*Lobophora*
239724	2378161	6.155	5.867	*Lobophora*
234392	2374876	5.463	5.485	*Lobophora*
	Max	6.16	5.87	
	Min	5.46	5.42	
233412	2376408	5.781	5.712	Coral patch reef
231919	2376445	6.101	5.701	Coral patch reef
242037	2382411	5.638	5.582	Coral patch reef
242295	2382124	6.122	5.666	Coral patch reef
241875	2381433	5.823	5.504	Coral patch reef
242111	2381306	5.188	5.469	Coral patch reef
238119	2377690	5.367	5.447	Coral patch reef
	Max	6.12	5.71	
	Min	5.19	5.45	

Appendix 8.2

The ***Classification1.frm*** formula document, which uses the Figure 8.2 boxes as a basis for classification.

```
# Formula document to classify a Landsat TM image of the shallow sea around South Caicos.
#
# This document uses two depth-invariant bottom index images:
# Depth-invariant_masked#01.dat (@1)
# and Depth-invariant_masked#02.dat (@2)
#
# Dense seagrass class boundaries
        CONST DenSeagMin1 = 4.46 ; CONST DenSeagMax1 = 5.05 ;
        CONST DenSeagMin2 = 5.07 ; CONST DenSeagMax2 = 5.35 ;

# Sparse seagrass class boundaries
        CONST SpSeagMin1 = 6.22 ;    CONST SpSeagMax1 = 6.53 ;
        CONST SpSeagMin2 = 5.86 ;    CONST SpSeagMax2 =6.10 ;

# Sand class boundaries
        CONST SandMin1 = 6.89 ; CONST SandMax1 = 7.26 ;
        CONST SandMin2 = 6.32 ; CONST SandMax2 = 6.48 ;

# Lobophora dominate algal area and coral patch reef class boundaries
        CONST LobCoralMin1 = 5.19 ; CONST LobCoralMax1 = 6.16 ;
        CONST LobCoralMin2 = 5.42 ; CONST LobCoralMax2 = 5.87 ;

# Dense Montastraea reef class boundaries
        CONST MontMin1 = 3.80 ; CONST MontMax1 = 4.42 ;
        CONST MontMin2 = 4.76 ; CONST MontMax2 = 5.25 ;

# Gorgonian plain class boundaries
        CONST GorgMin1 = 6.03 ; CONST GorgMax1 = 6.69 ;
        CONST GorgMin2 =5.03 ; CONST GorgMax2 =5.50 ;

# Sand box-classifier
        IF ( (@1 >= SandMin1) AND (@1 <= SandMax1) AND (@2 >= SandMin2) AND (@2 <= SandMax2) )  32  ELSE 0 ;

# Sparse seagrass box-classifier
        IF ( (@1 >= SpSeagMin1) AND (@1 <= SpSeagMax1) AND (@2 >= SpSeagMin2) AND (@2 <= SpSeagMax2) )  16 ELSE 0 ;

# Gorgonian plain box-classifier
        IF ( (@1 >= GorgMin1) AND (@1 <=GorgMax1) AND (@2 >= GorgMin2) AND (@2 <= GorgMax2) ) 8 ELSE 0 ;

# Lobophora dominated algal areas and coral patch reef  box-classifier
        IF ( (@1 >= LobCoralMin1) AND (@1 <= LobCoralMax1) AND (@2 >= LobCoralMin2) AND (@2 <= LobCoralMax2) )  4 ELSE 0 ;

# Dense seagrass box-classifier
        IF ( (@1 >= DenSeagMin1) AND (@1 <= DenSeagMax1) AND (@2 >= DenSeagMin2) AND (@2 <= DenSeagMax2) )  2 ELSE 0 ;

# Dense Montastraea reef box-classifier (sets this class to value of 1)
        IF ( (@1 >= MontMin1) AND (@1 <= MontMax1) AND (@2 >= MontMin2) AND (@2 <= MontMax2) )  1 ELSE 0 ;
```

9: PREDICTING SEAGRASS STANDING CROP FROM SPOT XS SATELLITE IMAGERY

Aim of Lesson

To learn how to derive a map of seagrass standing crop from a SPOT XS or similar appropriate image.

Objectives

1. To understand the importance of field survey and the methods used to calibrate imagery and thus allow seagrass standing crop to be estimated.
2. To investigate the relationship between seagrass standing crop and the single depth-invariant "bottom index" image derived from SPOT XS bands #1 and #2 (green and red wavebands) using field survey data referenced to UTM coordinates.
3. To learn how to mask out non-seagrass areas of the SPOT XS depth-invariant image.
4. To learn how to construct a palette to display seagrass standing crop densities effectively.
5. To analyse the image in order to estimate areas of dense, medium and sparse seagrass.

Introduction

Ecologists and managers of seagrass systems may require a range of data on the status of seagrass habitats. Those seagrass parameters that can be measured using remote sensing are listed in Table 9.1.

Table 9.1. Seagrass parameters which can be measured using optical remote sensing. MSS = multispectral scanner, CASI = Compact Airborne Spectrographic Imagery, TM = Thematic Mapper.

SEAGRASS PARAMETER	SENSOR	AUTHORS
Boundaries of seagrass beds	Aerial Photography	Greenway and Fry, 1988; Kirkman, 1988; Robblee *et al*., 1991; Ferguson *et al*., 1993; Sheppard *et al*., 1995
	Landsat TM	Lennon and Luck, 1990
Seagrass cover (semi-quantitative)	Airborne MSS	Savastano *et al*., 1984
	Landsat TM	Luczkovich *et al*., 1993; Zainal *et al*., 1993
	SPOT XS	Cuq, 1993
Seagrass biomass/standing crop	Landsat TM	Armstrong, 1993
	CASI, Landsat TM, SPOT XS	Mumby *et al*., 1997b

Of the studies listed in Table 9.1, the most detailed obtained a quantitative empirical relationship between seagrass standing crop (biomass of above-ground leaves and shoots) and remotely sensed imagery (Armstrong, 1993; Mumby *et al*., 1997b). Standing crop is a useful parameter to measure because it responds promptly to environmental disturbance and changes are usually large enough to monitor (Kirkman, 1996). The methods used to map seagrass standing crop are explored in this lesson.

Essentially, this involves five stages:

1. Measurement of seagrass standing crop in the field.
2. Relating seagrass standing crop to remotely-sensed image data using linear regression. The regression equation represents the calibration of imagery to seagrass standing crop and the coefficient of determination (r^2) indicates how much of the variation in standing crop is explained by the remotely-sensed data.
3. Using the regression equation to convert (calibrate) the image data in each pixel to seagrass standing crop (g. m^{-2})
4. Masking out land and non-seagrass habitats to leave a map of seagrass standing crop.
5. Assignment of a colour palette to standing crop for easy visual interpretation.

Background Information

This lesson relates to material covered in Chapters 12 and 16 of the *Remote Sensing Handbook for Tropical Coastal Management* and readers are recommended to consult these for further details of the techniques involved. This lesson describes an empirical approach to mapping seagrass standing crop using SPOT XS. The seagrass was located on the Caicos Bank in shallow (<10 m deep) clear water (horizontal Secchi distance 20–50 m) and was dominated by the species *Syringodium filiforme* (Kützing) and *Thalassia testudinum* (Banks ex König).

The *Bilko 3* image processing software

Familiarity with *Bilko 3* is required to carry out this lesson. In particular, you will need experience of using Formula documents to carry out mathematical manipulations of images and Histogram documents to calculate the area of particular features on the imagery. These features are covered in Tutorials 10 and 4 respectively of the *Introduction to using the Bilko 3 image processing software*. A familiarity with *Excel* is also desirable.

Image data

This lesson will use a SPOT XS image of the Caicos Bank as this imagery covers a large area while having a reasonably high spatial resolution (20 m[1]). To obtain a quantitative relationship between image data and seagrass standing crop, it is important to compensate for the effects of variable depth. Therefore, the image you are provided with has undergone the depth-invariant processing described in Lesson 7 of this module. SPOT XS bands #1 (green) and #2 (red) were processed to form a single depth-invariant bottom index band and you are provided with a subset of the Caicos Bank showing South Caicos (file ***SPOTXS_depth-invariant.dat***). This is a 32-bit floating-point file where each pixel value is represented by a real number stored in four bytes. To illustrate the importance of compensating for variable depth; when seagrass standing crop was regressed on reflectance (**not** corrected for depth), the coefficient of variation (r^2) ranged from 0.05 to 0.32 for SPOT XS (and was similarly low for other sensors). These values are too low for adequate prediction of seagrass standing crop.

You are also provided with two mask files. The first is a land mask (***Landmask_lesson9.gif***) in which all land pixels are set to zero and all submerged pixels are set to a value of 1. When another image is multiplied by the land mask, all land pixels are set to zero whilst submerged pixels are unaffected. The second mask removes all non-seagrass habitats in the imagery (***Seagrass_mask.gif***). This was created from an image of coral reef, algal, sand and seagrass habitats. Land, coral reef, sand and algal pixels were set to zero leaving only seagrass habitats set to a value of 1.

[1] Note that the SPOT-5 High Geometric Resolution (HRG) sensor (launched in 2002) offers 10 m resolution multispectral data.

Field survey data

A variety of techniques exist for measuring seagrass standing crop including destructive and non-destructive approaches. We recommend non-destructive methods because they allow repeated monitoring, are less harmful to the environment and are generally faster than destructive methods. Good general texts on seagrass sampling include Unesco (1990), English *et al.* (1997) and Kirkman (1996). The non-destructive visual assessment method of Mellors (1991) for estimating seagrass standing crop *in situ* was modified for use here.

Standing crop is measured in units of dry weight organic matter per unit area (g. m^{-2}) and is correlated with shoot density and leaf area index. The visual assessment method uses a linear scale of biomass categories, which are assigned to seagrass samples in $0.25m^2$ quadrats. A six-point integer reference scale of quadrats is used (1–6). The technique is summarised in Figure 9.1 and a thorough analysis of its errors and limitations is given by Mumby *et al.* (1997a).

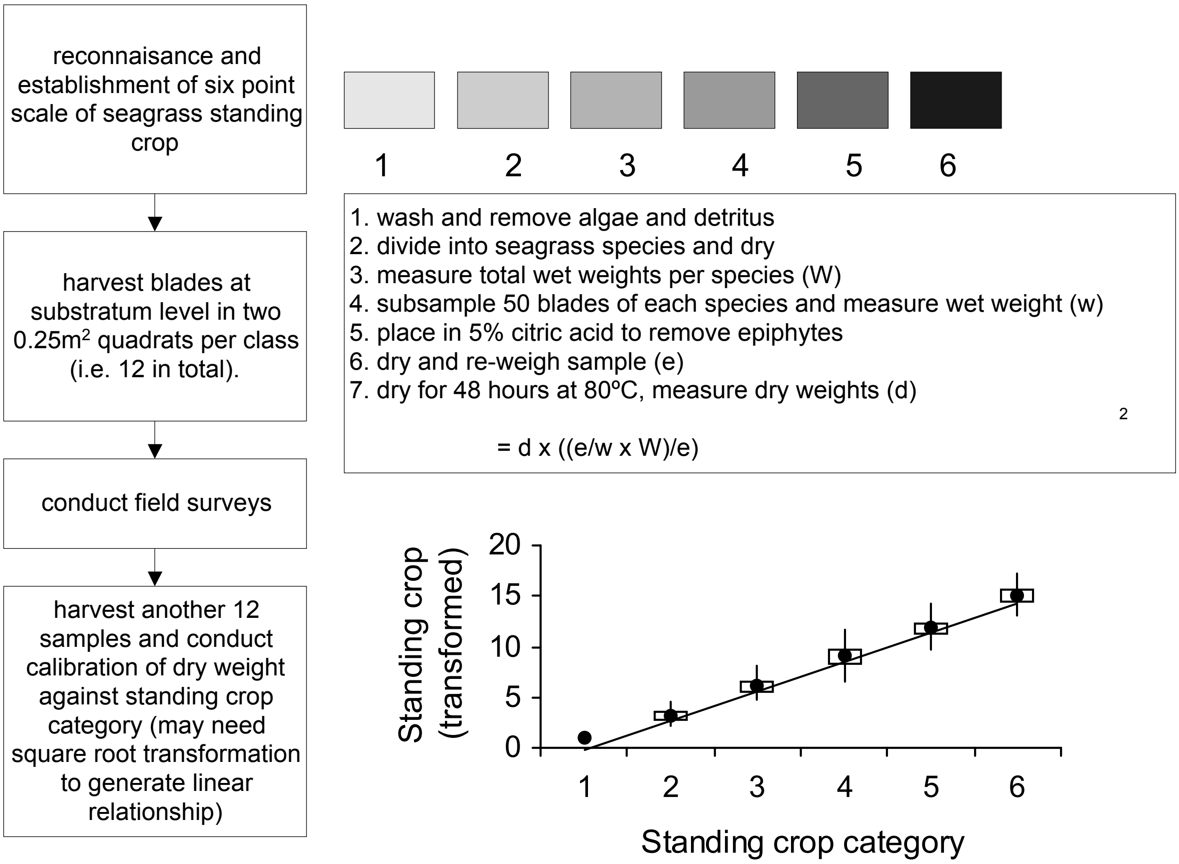


Figure 9.1. Visual assessment of seagrass standing crop

At least 30 seagrass sites should be surveyed and these should represent the entire range of standing crop in the area of interest. The size of each site will depend on the spatial resolution of the remotely-sensed imagery; larger sites are required to represent the standing crop in larger pixels. As a general guideline, we found a 10 m diameter site size to be acceptable for SPOT XS imagery. At each site, the mean standing crop of seagrass is estimated from a number of randomly placed $0.25m^2$ quadrats. For medium to dense seagrass beds, a sample size of 6 quadrats is probably acceptable. However, a larger sample size should be used in patchier seagrass areas (for further discussion see Downing and Anderson, 1985).

Lesson Outline

This lesson assumes that stage 1, the collection of field data, has already been undertaken using the guidelines set out above. The first practical activity will be the second stage of preparing a map of seagrass standing crop, namely, relating field data to image data to derive a calibration graph.

Relating field data to image data: calibration of SPOT XS data into units of seagrass standing crop ($g.m^{-2}$)

Activity: Launch *Bilko* and use **File**, **Open** to view the depth-invariant SPOT XS band of South Caicos, ***SPOTXS_depth-invariant.dat***. This image is stored as floating point (32-bit) data with pixel values ranging from around -2.7736 to 6.7822. Zero is used to denote background pixels in the image; so in the **Redisplay Image** dialog box check the **Null value(s):** checkbox so that null value **== 0**. For the stretch, select Gaussian or Equalize from the drop-down menu and then click [Apply] to display the depth-invariant image. Note that the image has been geometrically corrected and has UTM coordinates applied.

We surveyed the standing crop of 110 seagrass sites, the positions of which were fixed using a Global Positioning System (GPS). In order to calibrate the image, the seagrass standing crop at each site needs to be related to the corresponding depth-invariant image pixel value. You will do this for just a few sites. You are provided with the UTM coordinates for five sites (Table 9.2) and the standing crops estimated at these locations during the field survey. You need to find the corresponding pixel values.

Activity: Click the point selection button and use the **Edit**, **Go To** command to find the pixel value at each coordinate. **Note that the status bar will display the coordinates of the centre of the pixel that overlaps the GPS position.** [The first pixel is in the extreme west of the image.] Enter the pixel values into Table 9.2 rounded to 4 decimal places. These five points can be used to generate a regression of seagrass standing crop on image data (SPOT XS depth-invariant data). Launch *Microsoft Excel* and open the workbook file ***Lesson9.xls***. This file contains three worksheets: a data matrix called **Lesson**, a data matrix called **Area calculation** and a chart called **Calibration graph**. Click on *Lesson* if this is not the default sheet and enter your values into the table (the table is identical to Table 9.2, except that the coordinates are those of the centre of the pixels containing the GPS coordinates you entered; i.e. those displayed on the status bar).

Table 9.2. Relating image data to field-measured estimates of seagrass standing crop at a series of GPS coordinates. [Enter data values to **4 decimal places**, rounding as necessary.]

Site Number	Easting	Northing	Image data	Seagrass standing crop ($g.m^{-2}$)
1	235077	2378832		3.79
2	242919	2392609		200.59
3	238570	2378027		109.20
4	238788	2377912		37.21
5	238669	2378027		57.00

To obtain a linear calibration graph for this image, values of seagrass standing crop must be square root transformed. This transformation has already been undertaken and the transformed values of standing crop are held in Column I labelled *y*-axis. The pixel values you entered in the table are copied automatically to the *x*-axis (Column H) and the calibration graph is constructed for you. Click on the worksheet labelled **Calibration graph** to see the plot.

Question: *9.1.* What is the calibration equation derived from the 5 data points and what do the axes *y* and *x* represent? [Be as precise as possible in your answer.]

Question: *9.2.* What is the coefficient of determination (r^2)? What percentage of the measured variation in seagrass standing crop is explained by the depth-invariant image pixel values?

Implementation of the calibration equation

The calibration equation calculated above was based on only five samples of field data. When we used 110 seagrass sites, we obtained the following equation, which is not dissimilar to that which you have already calculated.

$$y = 38.6 - 5.6x$$

This is the standard equation of a straight line regression where 38.6 is the intercept of the line with the *y*-axis (i.e. the value of *y* when $x = 0$), 5.6 is the magnitude of the gradient and the minus sign indicates that the slope is negative (i.e. as *x* gets bigger, *y* gets smaller).

Question: *9.3.* Why do low pixel values equate to high seagrass standing crop and high pixel values equate to low seagrass standing crop?

As the *y*-axis variable is the square root of seagrass standing crop, the left hand side of the equation must be squared to give values in original units of seagrass standing crop ($g.m^{-2}$). The equation can be re-written in a slightly easier format to give:

$$\text{Seagrass standing crop} = [38.6 - (5.6 * \text{depth-invariant SPOT data})]^2$$

The calibration will be implemented at the same time as applying the land mask. Seagrass standing crop does not exceed 255 $g.m^{-2}$ at the study site and therefore, it can be represented directly on an 8-bit image with 256 possible values for each pixel.

Activity: Open ***Landmask_lesson9.gif***, select all pixels and apply an **Auto Linear** stretch. The land (and background areas) will appear black and all submerged areas will appear white. Select **Image**, **Connect** to link ***Landmask_lesson9.gif*** with ***SPOTXS_depth-invariant.dat***. Ensure that the land mask is selected as image 1 in the **Selector** toolbar (***SPOTXS_depth-invariant.dat*** should be set to image 2). Close the component mask and image files leaving only the connected tiled images in the viewer.

Use **File**, **Open** to open and view the formula document ***Seagrass_step1.frm***. Note how the formula is constructed and the use of constant statements to make the formula more understandable. Make sure using the Formula document **Options!** that (i) the output image will be either the Same as @1 or 8-bit unsigned integer, and (ii) the **Use special handling for Nulls** checkbox is unchecked. Then **Copy** the formula and **Paste** it to the connected images window.

Once the new image of seagrass standing crop in $g.m^{-2}$ has been generated, close the connected images window and select all pixels in the new image. Apply a histogram equalization contrast stretch. The land will appear black and seagrass areas will be clearly visible as grey patches in the submerged areas. Using **File**, **Save As,** save the image giving it the name ***Seagrass_step1.gif***.

Congratulations! Each pixel has now been calibrated to represent the mean standing crop of seagrass ($g.m^{-2}$) in that pixel. However, such values are meaningless in habitats that are not seagrass! The next stage is to remove the non-seagrass habitats.

Masking out non-seagrass habitats

Activity: Open the seagrass mask (***Seagrass_mask.gif***) in which all non-seagrass marine areas have a pixel value of zero (both land and seagrass areas have the value 1).

The mask could be applied directly to the image of standing crop (***Seagrass_step1.gif***) but this would lose the distinction of land and sea (as both would be set to zero). Instead, you are going to produce an image that shows land boundaries, the standing crop of seagrass, and the location of all other submerged habitats. This process requires two masks, the first of which (land) has already been applied. When two masks are used (in this case land and non-seagrass habitats), two pixel values must be available to represent the masked categories. Since land already has a value of zero, this means that one value of standing crop must be sacrificed from our 1–255 g.m^{-2} scale in order to assign non-seagrass habitats a pixel value. No seagrass areas in the image actually have a standing crop as high as 255 g.m^{-2} so this value is free to be assigned to non-seagrass marine areas. Thus we need a formula to create an output image where land is set to zero, non-seagrass marine areas are set to 255, and pixel values in between indicate the standing crop of seagrass areas in g.m^{-2} from 1–254 g.m^{-2}.

Activity: Use **Image**, **Connect** to link the ***Seagrass_mask.gif*** and processed file, ***Seagrass_step1.gif***. Make sure that ***Seagrass_step1.gif*** becomes image 1 (@1 in formula) and the seagrass mask becomes image 2 (@2 in formula) using the **Selector** toolbar (this is necessary to ensure that the formula chooses images in the correct sequence). Open the formula document, ***Seagrass_step2.frm*** and examine how it works. If pixel values in ***Seagrass_mask.gif*** are 0 (indicating non-seagrass marine areas) then the output image is set to 255, otherwise (ELSE) the output image is the same as ***Seagrass_step1.gif***. **Copy** the formula and **Paste** it to the connected images window. Save the output file as ***Seagrass_step2.gif***, and close the connected images window and formula document.

In ***Seagrass_step2.gif*** dense seagrass beds should be clearly distinguishable from the land and non-seagrass habitats. Verify the designation of pixel values by clicking on land areas and non-seagrass marine areas; the pixel values should be 0 and 255 respectively. To see sparse seagrass areas more clearly you can open and apply the manual stretch ***Seagrass_step2.str***.

The land and non-seagrass marine pixels will swamp any histogram of the whole image, so to see the spread of standing crop values in a seagrass bed you will need to select a subset of pixels.

Activity: Use **Edit, Go To** to select a box or block of pixels in the large seagrass bed near the north-east of the image with **top-left** UTM coordinate at position Easting: 242858, Northing: 2393518 and with a **DX:** of 943 m and **DY:** of -828 m or 828S. [*Hint:* It is important to specify the direction of block from the starting point. If the DY: is just entered as 828, *Bilko* will assume you mean a block running 828 m north of the position. Since the block is south of the position you need to either enter "–828" or "828S" or "828s".] Use **File, New** to bring up a HISTOGRAM document of this pixel block (making sure that the **Apply stretches to new documents** checkbox is <u>not</u> checked). Then answer the following questions. [*Checkpoint:* there should be 1476 pixels in the block.]

Question: *9.4.* What is the lowest value of the *seagrass* pixels and what does this represent in terms of standing crop?

Question: *9.5.* What is the highest standing crop in the block and how many pixels have this standing crop?

Question: *9.6.* What is the modal standing crop in the seagrass bed (based on this block sample)? How many pixels have this value?

Question: *9.7.* What is the mean standing crop in the block sample? [Express answer to nearest whole gram per square metre.]

Activity: When you have answered the questions, close the histogram document.

Assigning a colour palette to seagrass standing crop

The next step is to create a colour palette to display the seagrass standing crop as five colour-coded categories corresponding to the top five classes on the visual assessment scale. The palette applies to the display image values (mapped by the Look Up Table - LUT) as opposed to the underlying data values. We want to map the underlying data values to colours and so must make sure there are no stretches in operation. Thus before proceeding further you should clear any stretches applied to ***Seagrass_step2.gif***.

Activity: Clear any stretches of ***Seagrass_step2.gif***, if present. Load a new colour palette using **File**, **New**. Select the first (top left) of the 256 cells, which represents a pixel value of zero (land). Choose an arbitrary colour for this layer but preferably an unobtrusive colour such as mid-grey.

[*Hint*: Click the upper of the palette boxes beneath the colour space and then set the **Red:, Green:** and **Blue:** guns to 127, then click on Update. This should set the first cell to grey. To check whether this has worked, copy the palette and paste it to the unstretched ***Seagrass_step2.gif*** image. All land areas (and background) should become mid-grey].

Next, select the last cell, which represents a pixel value of 255 (non-seagrass marine habitats). Set this to cyan (R=0, G=255, B=255) using the same procedure. You must now choose a colour scheme for seagrass standing crop (i.e. the remaining pixels). You can experiment, creating your own scheme and applying your palettes to the image.

For guidance, two palettes have been prepared already (these have land set to black, non-seagrass marine areas to white and seagrass to shades of green. Open the palette document ***Seagrass1.pal*** making sure, as you do so, that the **Apply** check-box in the **Open** dialog box is not checked.

This palette was created by selecting all seagrass boxes (i.e. boxes 1 to 254) and assigning a pale green colour to the upper palette box and a dark green colour to the lower palette box.

Activity: Try this on your palette. [*Hint*: To select the seagrass boxes, click on box 1 on your palette, and then click on box 24 while depressing <*Shift*>. You should see 001 254 in the status bar panels.]

The end result is a gradient of green pertaining to standing crop, with the depth of colour increasing smoothly with increasing standing crop. The limitation of this approach is that the scale is not quantified (i.e. how much seagrass = dark green?). To remedy this, a series of distinctive categories can be displayed. In the next example palette, different colours have been assigned to the top six classes of the visual assessment scale for surveying standing crop (i.e. 1–5; 6–20; 21–70; 71–130; 131–200; 201–254 $g.m^{-2}$).

Open the palette ***Seagrass2.pal*** in which standing crop has been divided into 6 classes and apply this palette to the image. In this case, the colours can be related to levels of seagrass standing crop immediately by eye and you have a clear picture of the structure of the seagrass beds. Examine the large seagrass bed in the north-east of the image, zooming in to see detail. One can immediately pick out areas of dense and sparse seagrass. If you wish, experiment with improving the palette (e.g. setting non-seagrass marine habitats to cyan, or land areas to grey).

When you are finished, close the palettes and ***Seagrass_step2.gif***.

Estimating the area of seagrass standing crop classes

Now that you have created a map of seagrass standing crop, the final objective is to calculate the area of seagrass in each standing crop category. In a practical situation, this might be repeated every few years to monitor changes in the coverage of particular types of seagrass bed.

Activity: Open the file ***Seagrass_area.gif*** which has all land and non-seagrass marine pixels set to zero but is otherwise the same as the file ***Seagrass_step2.gif***. Apply the ***Seagrass2.pal*** palette to display the image more clearly. Ensure that all pixels are selected in the image and then create a histogram document using **File**, **New**. The *x*-axis displays pixel values 0–255 and the *y*-axis shows the number of pixels of each value. Because there are so many pixels with the value 0, you can't see the frequencies of most of the seagrass pixels so right-click on the histogram and select **Scale**. In the **Scale** dialog box select the **Ignore zero** check-box and click on OK.

The total size of the image is 444 x 884 pixels (see top of histogram) so there are a total of 392496 pixels in the image. Place the mouse pointer at any point on the *x*-axis and view the status bar at the bottom right-hand corner of the display. You will see four sets of numbers. The two middle numbers indicate the lowest and highest values in the range of pixel values that you have highlighted. If only one value has been selected (e.g. by clicking on a particular value on the *x*-axis) then both values will be the same. The right panel shows the number of pixels highlighted on the histogram and the left panel shows the percentage of pixels which have been highlighted. This percentage is calculated by dividing by the total number of pixels in the image. Therefore, 10% would equal 10/100 x 392496 pixels = 39250 to the nearest whole number.

Use the histogram to determine the **percentage of pixels** and **number of pixels** in each standing crop class. For example, the first class, which represents a standing crop from 1 to 5 $g.m^{-2}$, is displayed as pixel values 1–5. To estimate the percentage of pixels in this class, position the mouse pointer on a pixel value of 1 and drag it to the right until it reaches 5. [*Hint:* You may find it easier to use the keyboard. Press *<F1>* while the histogram is the active document and click on the "selecting data in a histogram" link in the Help to find out how.] The percentage displayed on the status bar will show the total percentage of pixels in this class (to the nearest 0.01%) and the right hand panel will show the total number of pixels that this represents.

Enter both values into the appropriate columns of Table 9.3 and calculate the area of each class in hectares using a calculator. Alternatively, launch *Microsoft Excel*, open the file ***Lesson9.xls*** and select the worksheet **Area calculation.** This sheet contains Table 9.3 and formulae to automate the area calculation. You can check your working by typing the numbers of pixels in each standing crop class into this table and comparing the area estimates to those calculated by hand. Complete Table 9.3 with the areas of each seagrass class in hectares.

Table 9.3. Calculating the area of seagrass standing crop classes around South Caicos. Total number of pixels = 392496, area of a single SPOT pixel = 23 x 23 m = 529 m^2, 1 hectare (ha) = 10, 000 m^2.

Seagrass standing crop	Pixel Range	Percent of total number of pixels	Number of pixels	Area of standing crop class (m^2)	Area of standing crop class (ha)
1 to 5	1 - 5				
6 to 20	6 - 20				
21 to 70	21 - 70				
71 to 130	71 - 130				
131 to 200	131 - 200				
201 to 254	201 - 254				
(units = $g.m^{-2}$)					
Land	0	50.47	198101	104795429	10479.5
Non-seagrass	255	40.45	158778	83993562	8399.4

Question: *9.8.* How many pixels have a value between 201 and 254? What area in hectares (to nearest 0.1 ha) of high density (> 200 $g.m^{-2}$) seagrass does this represent?

Question: *9.9.* What is the total area of seagrass in the image in hectares (to nearest whole ha)?

Activity: When you've answered questions, close all files.

Congratulations! You've managed to produce a sophisticated map of seagrass standing crop for the Caicos Bank area around South Caicos Island by establishing an empirical model linking standing crop to pixel values in a depth-invariant image. This technique of using ground-truthing to establish an empirical relationship between image data values and some quantitative measure of an object you are interested in, has wide application.

Using a Map of Seagrass Standing Crop

A map of seagrass standing crop could be used in several ways. The simplest of these would be the provision of extra information on the status of seagrass beds in a particular area of interest. However, the maps might also be used to identify the location and extent of important fisheries habitats. For example, the juvenile conch (*Strombus gigas*) is often associated with seagrass habitats of low standing crop (Appeldoorn and Rolke, 1996). Monitoring of seagrass standing crop over time would also be possible, particularly if the remotely sensed data had a high spatial resolution. Maps showing changes in standing crop could be created and possibly related to the causes of the change (e.g. point sources of pollutants). However, if monitoring is going to be undertaken, it is important to quantify errors and assess the confidence with which remote sensing predicts seagrass standing crop. For further details of these methods, readers are referred to Mumby *et al*. (1997b). Alternatively, a simpler monitoring programme could compare the coverage of seagrass classes from, say, year to year (as outlined in this lesson).

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Answers to Questions

Table 9.2. Relating image data to field-measured estimates of seagrass standing crop at a series of GPS coordinates.

Site Number	Easting	Northing	Image data	Seagrass standing crop (g.m^{-2})
1	235077	2378832	6.4691	3.79
2	242919	2392609	4.5640	200.59
3	238570	2378027	5.1796	109.20
4	238788	2377912	6.0031	37.21
5	238669	2378027	5.4686	57.00

9.1. The calibration equation derived from the 5 data points is $y = 42.230 - 6.175x$. The y-axis represents the square root of seagrass standing crop. The x-axis represents the pixel value of the depth-invariant bottom-index image derived from SPOT XS bands #1 and #2.

9.2. The coefficient of determination (r^2) = 0.978. This indicates that 97.8% of the measured variation in seagrass standing crop is explained by the depth-invariant image pixel values.

9.3. Dense seagrass has low albedo (low reflectance) whereas sparse seagrass, pixels of which contain much white sand, has relatively high albedo (high reflectance). In the depth-invariant image dense seagrass will thus have relatively low pixel values (appear dark) and sparse seagrass will have high pixel values (appear bright).

In the 943 m x 828 m block of seagrass pixels with top-left UTM coordinates Easting: 242858, Northing: 2393518:

9.4. The lowest value of the seagrass pixels is 7, representing a standing crop of 7 g.m^{-2}. One pixel has this value.

9.5. The highest standing crop in the area is 253 g.m^{-2}, there are 3 pixels with this standing crop.

9.6. The modal (most frequent) pixel value is 142, indicating a modal standing crop of 142 g.m^{-2}. Eighty-one pixels have this value.

9.7. The mean standing crop of the block sample is 128 g.m^{-2}; this can be read off the histogram document along with the standard deviation, skewness, kurtosis and entropy of the pixels in the histogram.

Table 9.3. Calculating the area of seagrass standing crop classes around South Caicos. Total number of pixels = 392496, area of a single SPOT pixel = 23 x 23 m = 529 m^2, 1 hectare (ha) = 10, 000 m^2.

Seagrass standing crop	Pixel Range	Percent of total number of pixels	Number of pixels	Area of standing crop class (m^2)	Area of standing crop class (ha)
1 to 5	1 – 5	1.70	6674	3530546	353.1
6 to 20	6 – 20	3.44	13506	7144674	714.5
21 to 70	21 – 70	2.11	8271	4375359	437.5
71 to 130	71 – 130	1.39	5463	2889927	289.0
131 to 200	131 – 200	0.40	1567	828943	82.9
201 to 254	201 – 254	0.03	136	71944	7.2
Land	0	50.47	198101	104795429	10479.5
Non-seagrass	255	40.45	158778	83993562	8399.4

9.8. 136 pixels have a value between 201 and 254. This represents an area of 7.2 ha of high density seagrass.

9.9. The total area of seagrass in the image is 1884 ha (to nearest whole hectare).

10: ASSESSING MANGROVE LEAF-AREA INDEX (LAI) USING CASI AIRBORNE IMAGERY

Aim of Lesson

To learn how to assess and map mangrove leaf-area index (LAI) using Compact Airborne Spectrographic Imager (CASI) imagery as an example.

Objectives

1. To understand what field survey of the mangroves is necessary to calibrate imagery and allow Leaf-Area Index (LAI) to be estimated.
2. To understand how LAI data is derived from field measurements.
3. To learn how to prepare a Normalised Vegetation Difference Index (NDVI) of mangrove areas from CASI imagery
4. To investigate the relationship between NDVI and LAI using UTM coordinate referenced field survey data and use this relationship to create an image of mangrove Leaf Area Index.
5. To learn how to create a palette to display mangrove LAI effectively.
6. To calculate net canopy photosynthetic production from LAI and thus obtain a crude estimate of the mangrove forest primary productivity.

Background Information

This lesson relates to material covered in Chapters 13 and 17 of the *Remote Sensing Handbook for Tropical Coastal Management* and readers are recommended to consult these for further details of the techniques involved. This lesson describes an empirical approach to mapping mangrove leaf-area index (LAI) using Compact Airborne Spectrographic Imager (CASI) imagery. The mangrove was located on the island of South Caicos.

In the eastern Caribbean the limited freshwater run off of the low dry islands and the exposure of a large portion of the shoreline to intense wave action imposes severe limits on the development of mangroves. They typically occur in small stands at protected river mouths or in narrow fringes along the most sheltered coasts (Bossi and Cintron 1990). As a result most of the mangrove forests in this region are small. Nevertheless they occur in up to 50 different areas where they are particularly important for water quality control, shoreline stabilisation and as aquatic nurseries. Mangroves in the Turks and Caicos Islands are typical of this area but completely different to the large mangrove forests that occur along continental coasts and at large river deltas.

The *Bilko 3* image processing software

Familiarity with *Bilko 3* is required to carry out this lesson. In particular, you will need experience of using Formula documents to carry out mathematical manipulations of images and Histogram documents to calculate the area of particular features on the imagery. These features are covered in Tutorials 10 and 4 respectively of the *Introduction to using the Bilko 3 image processing software*. A familiarity with the *Microsoft Excel* spreadsheet package is also desirable.

Image data

A Compact Airborne Spectrographic Imager (CASI) was mounted on a locally-owned Cessna 172N aircraft using a specially designed door with mounting brackets and streamlined cowling. An incident light sensor (ILS) was fixed to the fuselage so that simultaneous measurements of irradiance could be made. A Differential Global Positioning System (DGPS) was mounted to provide a record of the aircraft's flight path. Data were collected at a spatial resolution of 1 m^2 in 8 wavebands (Table 10.1) during flights over the Cockburn Harbour and adjacent areas of South Caicos, Turks and Caicos Islands (21° 30' N, 71° 30' W) in July 1995. Further details are given in Clark *et al.* (1997) and Appendix 1.4.

Table 10.1. Band settings used on the CASI for this study.

Band	Part of electromagnetic spectrum	Wavelength (nm)
1	Blue	402.5–421.8
2	Blue	453.4–469.2
3	Green	531.1–543.5
4	Green	571.9–584.3
5	Red	630.7–643.2
6	**Red**	**666.5–673.7**
7	**Near Infrared**	**736.6–752.8**
8	Near Infrared	776.3–785.4

Geometrically and radiometrically corrected Compact Airborne Spectrographic Imager (CASI) data from bands #6 (red) and #7 (near infra-red) of the area around South Caicos island are provided for the purposes of this lesson as files ***Casi_mangrove#06.dat*** and ***Casi_mangrove#07.dat***. These files are unsigned 16-bit integer files (integers between 0 and 65535). This means that there are two bytes needed per pixel rather than the one byte needed for the Landsat TM and SPOT XS images, which are only 8-bit data. Mangrove areas have to be separated from non-mangrove areas and a mask used to set water pixels and non-mangrove land pixels to zero.

Field survey data

Three species of mangrove, the red mangrove *Rhizophora mangle*, the white mangrove *Laguncularia racemosa,* and the black mangrove *Avicennia germinans* grow with the buttonwood *Conocarpus erectus* in mixed stands along the inland margin of the islands fringing the Caicos Bank. The field survey was divided into two phases. Calibration data were collected in July 1995, accuracy data in March 1996. Species composition, maximum canopy height and tree density were recorded at all sites (Table 10.2). Species composition was visually estimated from a 5 m x 5 m plot marked by a tape measure. Tree height was measured using a 5.3 m telescopic pole. Tree density was measured by counting the number of tree trunks at breast height. When a tree forked beneath breast height (~1.3 m) each branch was recorded as a separate stem (after English *et al.,* 1997). The location of each field site was determined using a Differential Global Positioning System (DGPS) with a probable circle error of 2–5 m.

Table 10.2. A summary of the field survey data. Data were collected in two phases; the first in 1995 for the calibration of CASI imagery and the second in 1996 for accuracy assessment. The number of sites at which each type of data was collected during each phase is shown. Category "Other" refers to field survey data for three non-mangrove categories (sand, saline mud crust, and *Salicornia* species).

Purpose of data	Number of sites surveyed Calibration (1995)	Accuracy (1996
Species composition (%)	81	121
Tree height	81	121
Tree density	81	121
Canopy transmittance	30	18
Percent canopy closure	39	20
Other	37	67

A habitat classification was developed for the mangrove areas of the Turks and Caicos Islands using hierarchical agglomerative clustering with group-average sorting applied to the calibration data. The calibration data were 4th root transformed in order to weight the contribution of tree height and density more evenly with species composition (the range of data was an order of magnitude higher for density and height and would cluster accordingly). This identified seven classes, which separated at a Bray-Curtis Similarity of ~85% (Figure 10.1). Categories were described in terms of mean species composition (average percentage of each species), mean tree height and mean tree density (Table 10.3). One category, *Laguncularia* dominated mangrove, was discarded because white mangrove was rare in this area; in both the calibration and accuracy field phases it was observed at only two locations. Three other ground cover types were recorded: (i) sand, (ii) saline mud crust, and (iii) mats of the halophytic succulents *Salicornia perennis* and *S. portulacastrum*. These nine habitat categories (six mangrove, three other) were used to direct the image classification of the CASI data and the collection of accuracy data in 1996.

Two useful ways of describing or modelling the canopy structure of a vegetated area are *leaf area index* (LAI, Box 10.1) and *percent canopy closure*. Both can be estimated from remotely sensed data, which is advantageous in areas where access is particularly difficult or when alternative methods are laborious and difficult to replicate properly over large areas.

Leaf area index

Many methods are available to measure LAI directly and are variations of either leaf sampling or litter-fall collection techniques. These methods tend to be difficult to carry out in the field, extremely labour intensive, require many replicates to account for spatial variability in the canopy and are thus costly in terms of time and money. Consequently many indirect methods of measuring LAI have been developed (see references in Nel and Wessman, 1993). Among these, are techniques based on gap-fraction analysis that assume that leaf area can be calculated from the *canopy transmittance* (the fraction of direct solar radiation which penetrates the canopy). This approach to estimating LAI uses data collected from beneath the mangrove canopy and was the technique used in this study.

Figure 10.1. Dendrogram of 78 mangrove sites using group-average clustering from Bray-Curtis similarities (bottom axis). Seven clusters which are <85% similar were identified. One consisting of sites 67 and 68 was discarded for reasons explained in the text: the other six, were used to direct the supervised classification of the CASI data and an accuracy assessment.

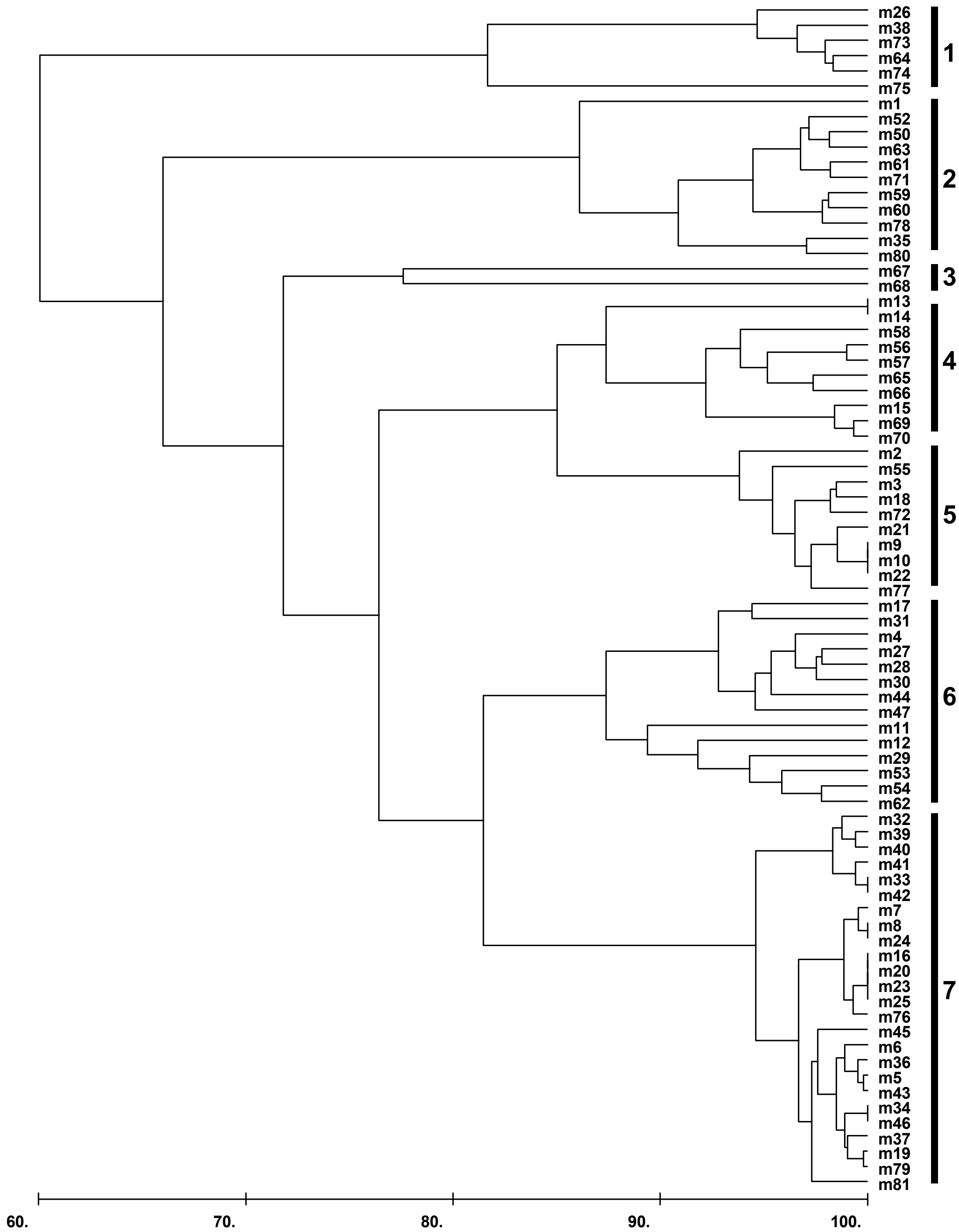

Table 10.3. Descriptions for each of the mangrove habitat categories identified in Figure 10.1. N = number of calibration sites in each category. Rhz = *Rhizophora*; Avn = *Avicennia*; Lag = *Laguncularia*; Con = *Conocarpus*.

Habitat Category Description	N	Species Composition %				Tree Height (m)	Tree Density (m^{-2})
[dendrogram group]		Rhz	Avn	Lag	Con	mean (range)	mean (range)
Conocarpus erectus [1]	6	0	0	0	100	2.4 (1.8–4.5)	0.6 (0.5–1.0)
Avicennia germinans [2]	11	0	100	0	0	2.6 (0.8–6.0)	0.6 (0.2–1.0)
Short, high density, *Rhizophora mangle* [5]	10	100	0	0	0	1.1 (0.5–2.0)	8.0 (6.0–10.0)
Tall, low density, *Rhizophora mangle* [7]	25	100	0	0	0	3.7 (2.0–7.0)	0.3 (0.2–0.5)
Short mixed mangrove, high density [4]	10	62	38	0	0	1.7 (0.8–2.5)	8.1 (5.0–15.0)
Tall mixed mangrove, low density [6]	14	56	43	0	1	3.5 (2.0–5.0)	0.6 (0.2–1.2)
Laguncularia dominated mangrove [3]	2	35	5	45	0	3.8 (3.5–4.0)	2.2 (0.5–4.0)
Unclassified	3						

Box 10.1. Leaf area index (LAI).

LAI is defined as the single-side leaf area per unit ground area, and as such is a dimensionless number. The importance of LAI stems from the relationships that have been established between it and a range of ecological processes such as rates of photosynthesis, transpiration and evapotranspiration (McNaughton and Jarvis, 1983; Pierce and Running, 1988), and net primary production (Monteith, 1972; Gholz, 1982). Measurements of LAI have been used to predict future growth and yield (Kaufmann *et al.,* 1982) and to monitor changes in canopy structure due to pollution and climate change. The ability to estimate leaf area index is therefore a valuable tool in modelling the ecological processes occurring within a forest and in predicting ecosystem responses.

Mangroves are intertidal, often grow in dense stands and have complex aerial root systems that make extensive sampling impractical, with the difficulty of moving through dense mangrove stands and the general inaccessibility of many mangrove areas posing a major logistic problem. Luckily field measurements indicate that there is a linear relationship between mangrove LAI and normalised difference vegetation index (Ramsey and Jensen, 1995; 1996). NDVI can be obtained from remotely sensed data. This means that a relatively modest field survey campaign can be conducted to obtain LAI measurements in more accessible mangrove areas and these used to establish a relationship to NDVI using regression analysis. Once this relationship is known then NDVI values for the remainder of the mangrove areas can be converted to LAI.

Measurement of canopy transmittance and calculation of LAI

LAI is a function of canopy transmittance, the fraction of direct solar radiation that penetrates the canopy. Canopy transmittance is given by the ratio I_c/I_o where I_c = light flux density beneath the canopy and I_o = light flux density outside the canopy. LAI can then be calculated, and corrected for the angle of the sun from the vertical, using the formula:

$$\mathrm{LAI} = \frac{\log_e\left(\frac{\mathrm{I_c}}{\mathrm{I_o}}\right)}{-k} \times \cos\theta$$

where LAI = leaf area index, θ = sun zenith angle (angle between the sun and the horizon; this can be calculated from time, date and position), k = canopy light extinction coefficient, which is a function of the angle and spatial arrangement of the leaves. The derivation of this formula is given in English *et al.* (1997). For each field site $\log_e(I_c/I_o)$ was calculated for 80 pairs of simultaneous readings of I_c and I_o around the position fix and averaged. A value for k of 0.525 was chosen as being appropriate to mangrove stands.

Measurements were taken on clear sunny days between 10:00 and 14:00 hours, local time. The solar zenith angle was judged to be sufficiently close to normal (i.e. perpendicular) two hours either side of noon for directly transmitted light to dominate the radiation spectrum under the canopy. At other times the sun is too low and diffuse light predominates. Photosynthetically active radiation (PAR) was measured using two MACAM ™ SD101Q-Cos 2π PAR detectors connected to a MACAM ™ Q102 radiometer. One detector was positioned vertically outside the mangrove canopy on the end of a 40 m waterproof cable and recorded I_o. The other detector recorded I_c and was connected to the radiometer by a 10 m waterproof cable. If the mangrove prop roots and trunk were not too dense to prevent a person moving around underneath the canopy this detector (which was attached to a spirit level) was hand-held. If the mangroves were too dense then the I_c detector was attached to a 5.4 m extendible pole and inserted into the mangrove stand. The spirit level was attached to the end of the pole to ensure the detector was always vertical. All recordings of I_c were taken at waist height, approximately 0.8 m above the substrate.

Lesson Outline

Creating a Normalized Difference Vegetation Index (NDVI) image

Since NDVI is calculated using near infra-red and red bands there were four options for calculating NDVI from the CASI data with combinations of Bands 5 to 8 (Table 10.4). The relationships between NDVI calculated from Bands 8 and 5 or from Bands 8 and 6, and values of LAI estimated from *in situ* measured canopy transmittance, were not significant. However, there were significant relationships when LAI was regressed against NDVI calculated either from Bands 7 and 6 or 7 and 5 (Table 10.4). NDVI derived from Bands 6 and 7 was deemed most appropriate for the prediction of LAI because (i) it accounts for a much higher proportion of the total variation in the dependent variable, and (ii) the accuracy with which the model predicts the dependence of LAI on NDVI is higher (the standard error of estimate is lower). This is why CASI bands #6 and #7 have been selected for this exercise.

Activity: Launch *Bilko* and use **File, Open** to open the 16-bit integer image files ***Casi_mangrove#06.dat*** and ***Casi_mangrove#07.dat.*** In the **Redisplay Image** dialog box set the **Null value(s):** to zero and initially use an automatic linear stretch for each image. These images show most of the mangroves along the west coast of the southern part of South Caicos Island. Note that the ***Casi_mangrove#06.dat*** image in the red part of the spectrum (666.5–673.7 nm) is very dark as mangroves have low reflectances in the red part of the visible spectrum. By contrast, mangroves and other vegetation reflect quite strongly in the near-infrared so that ***Casi_mangrove#07.dat*** (recorded in the near-IR at 736.6–752.8 nm) is comparatively bright.

Visually inspect the two images, right-clicking on the images to **Redisplay** them using different stretches, if necessary, to see them more clearly. Note that with a spatial resolution of around 1 m, there is quite a lot of texture visible in the mangrove canopy.

Using <u>both</u> images and the **Edit, Go To** function answer the following question. [*Hint:* you may find it useful to connect the two images as a stacked set.]

Question: *10.1.* Is the mangrove vegetation thicker and the canopy closure greater at UTM coordinates 236520 E, 2379938 N than at 236600 E, 2379945 N, or is the reverse true? Explain the reasons behind your conclusion. [Both coordinate positions are near the bottom of the image].

Table 10.4. Four possible CASI red (Bands 5 and 6) and near-infrared (Bands 7 and 8) band combinations could have been used to calculate NDVI. The results of regressing NDVI, calculated from the four different combinations, on LAI are summarised below. R^2 = coefficient of determination, p = probability of the F statistic for the model, NS = not significant at the p = 0.05 level of confidence, SE = standard error of the estimate. Degrees of freedom = 1, 29 in all cases. For combinations marked * the F-test and t-test for the slope estimate were both significant at the 0.001 level of confidence, indicating that they may used to convert NDVI values to LAI.

NDVI equation	R^2	Intercept	Slope	p	SE
(Band 8 - Band 5)/(Band 8 + Band 5)	0.22	0.19	0.05	NS	1.93
(Band 8 - Band 6)/(Band 8 + Band 6)	0.12	3.68	2.29	NS	2.18
(Band 7 - Band 6)/(Band 7 + Band 6)*	**0.77**	**0.31**	**9.76**	**<0.001**	**0.99**
(Band 7 - Band 5)/(Band 7 + Band 5)*	0.43	1.81	5.71	<0.001	1.69

The next step is to calculate a Normalised Difference Vegetation Index (NDVI) image (Box 10.2) from the CASI bands #6 and #7. In a real life situation you would need to check all possible band-pair combinations and see which was best for predicting LAI. We have done this for you, and you will just work with the band pair that we found to give best results.

Box 10.2 The use of vegetation indices in the remote sensing of mangroves

Vegetation indices are complex ratios involving mathematical transformations of spectral bands. As such, vegetation indices transform the information from two or more bands into a single index. For example, the normalised difference vegetation index or NDVI is a common vegetation index calculated from red and infra-red bands. For each pixel in the two wavebands the following is calculated:

$$\text{NDVI} = \frac{\text{infrared} - \text{red}}{\text{infrared} + \text{red}}$$

Since dense vegetation reflects strongly in the near-IR and reflects poorly in the red part of the electromagnetic spectrum, the NDVI can approach a value of 1 in areas of dense vegetation. By contrast areas with little or no vegetation will have similar reflectances in the near-IR and red part of the spectrum or in some cases lower reflectances in the near-IR than red, giving NDVI values approaching 0 or even negative values (with theoretical lower limit of –1).

Activity: **Connect** the ***Casi_mangrove#06.dat*** and ***Casi_mangrove#07.dat*** images as a tiled pair and use the **Selector** toolbar to make sure ***Casi_mangrove#07.dat*** (the infra-red image) is image 1 (@1 in a Formula document) whilst ***Casi_mangrove#06.dat*** is image 2 (@2 in a formula).

You will now write a simple Formula document to calculate the NDVI for each pixel; this will help you understand better what is being calculated (see Box 10.2). This should be of the form of the equation in Box 10.2. Thus our Formula document equation should look something like this:

```
(@1 - @2) / (@1 + @2) ;
```

Activity: Prepare a Formula document to carry out the NDVI. [Ideally, follow best-practice as taught in Tutorial 10 of the *Introduction to using the Bilko 3 image processing software* and use constant statements and comments to make a generic NDVI formula which you can save and easily modify for use with other images.] Since the resultant image will display NDVI on a scale of -1 to +1, use the Formula document **Options!** to select the **Output Image Type**: as 32-bit floating point then **Copy** and **Paste** the formula to the connected images. [You do not need to use special handling for nulls as they are zero on both images.]

Checkpoint: If the value of the pixel at coordinate 236395E, 2381050N is 0.810328 then your formula has worked. If it is not, check the formula and re-read the instructions carefully. [To display the UTM coordinates of the cursor on the status bar use the **View, Coords** function.]

To establish a regression relationship that will allow Leaf Area Index (LAI) to be predicted from NDVI, we have noted the NDVI corresponding to 30 ground-truthed points where we have measured LAI in the field. This is done by averaging the NDVI of the nearest nine pixels to the UTM coordinates of the ground-truthing site. The average NDVI is considered to correspond to the recorded LAI. Thus each NDVI value is averaged across a 3.0 m x 3.3 m square on the ground-surface. This allows for some error in the UTM coordinates obtained from the Differential GPS (probable circle error of 2–5 m) during the ground-truthing surveys and corresponds to the approximate area surveyed as the 80 readings were taken at each site (see section on *Measurement of canopy transmittance and calculation of LAI* above).

The results of this calibration exercise are summarised in Table 10.6 below but the calculation of average NDVI for two sites has been left for you to do. Site 72 has short sparse mangrove and thus a relatively low LAI, whereas site 79 is on the edge of a reasonably dense stand of mangrove and has a much higher LAI. Both sites are towards the south-east of the image.

Activity: Save the NDVI image as ***Mangrove_NDVI.dat*** and, if you have followed best-practice and created a generic NDVI formula, you may wish to save this as ***NDVI.frm***. If UTM coordinates are not displayed on the status bar, select the **View, Coords** command to display them. Scroll to the bottom of the image, which is where the two calibration sites are located. You now need to use **Edit, Go To** to locate site 72 on the image and once you have done this you need to read off (from the status bar) the data values at the coordinates (central pixel) and the eight surrounding pixels and enter these in Table 10.5 below. The central pixel at site 72 should have the value 0.1967 (to 4 decimal places). [*Hint:* Hold down the *<Ctrl>* key and use the arrow keys to move one pixel at a time.]

Table 10.5. Calculating average NDVI for two ground-truthing sites.

[Round values to **4 decimal places**].

Site 72
Central pixel: X: 236700, Y: 2379827

Site 79
Central pixel: X: 236693, Y: 2380127

Activity: Use a calculator (or spreadsheet) to work out the average NDVI for sites 72 and 79 and answer the question below.

Question: *10.2.* What are the average NDVIs at sites 72 and 79 (to **four decimal places**)?

Activity: Enter the values (to **two decimal places**) in Table 10.6 (see next page). Congratulations! You now have a complete set of data to calculate the regression relationship between LAI and NDVI.

Table 10.6. Calibration data for regression of LAI on NDVI (calculated for CASI bands #7 and #6).

Site	UTM coordinates Easting	Northing	NDVI CASI 7/6	Mangrove LAI
31	237118	2378993	0.70	6.61
33	237105	2378990	0.75	7.32
34	237094	2378986	0.81	8.79
36	237114	2379026	0.63	6.62
37	237103	2379022	0.78	7.83
39	237087	2379071	0.79	6.17
40	237092	2379075	0.73	6.87
43	237115	2379080	0.69	6.96
44	237070	2379373	0.47	2.53
47	237038	2379376	0.75	6.61
52	237026	2379456	0.28	2.52
53	237005	2379491	0.64	5.04
54	236989	2379500	0.63	5.35
56	237008	2379445	0.61	4.76
59	237020	2379567	0.29	2.33
61	236997	2379540	0.42	4.34
62	236978	2379547	0.47	4.96
64	236932	2379588	0.24	1.93
65	236890	2379549	0.47	5.82
66	236872	2379554	0.42	3.74
67	236759	2379649	0.49	6.58
68	236731	2379664	0.43	3.89
71	236718	2379777	0.59	5.59
72	**236700**	**2379827**		**1.64**
73	236723	2379825	0.29	2.33
75	236668	2379932	0.19	1.99
78	236579	2380039	0.35	2.03
79	**236693**	**2380127**		**5.83**
80	236703	2380141	0.61	2.95
81	236728	2380128	0.47	5.05

Regression of LAI on NDVI

You now need to carry out the regression of Leaf Area Index on NDVI to allow you to map LAI from the CASI imagery. Luckily there is a simple linear relationship between LAI and NDVI defined by the regression equation:

$$\text{LAI} = \text{intercept} + \text{slope} \times \text{NDVI}$$

Activity: Open the *Excel* spreadsheet file ***Mangrove_NDVI.xls***. Insert your NDVI values for sites 72 and 79. Examine the graph of LAI against NDVI and note that LAI is roughly ten times NDVI. Use **Tools, Data Analysis** to regress the column of LAI values (Input Y Range:) against the column of NDVI7/6 values (Input X Range:). For the Output Range: just select a cell below the calibration dataset. Note that the regression is very significant, i.e. that NDVI is a good predictor of Leaf Area Index. You only need two pieces of information from the output of the regression analysis, the slope of the regression line and where it intercepts the y-axis. The **intercept** (which should be a small negative number) is labelled as such, whilst the value for the **slope** of the line is labelled “X Variable” in the regression output.

Two alternative approaches are (1) to copy and paste the numerical values for LAI and corresponding NDVI (in columns D and E, rows 3 to 32) into *Minitab* and carry out the regression there, or (2) to right-click on a data point in the graph of LAI against NDVI and select **Add Trendline**; in the **Add Trendline** dialog box select Linear (default) as the trendline type, then click on the **Options** tab and select the **Display equation on chart** checkbox before clicking on OK. Both approaches will give you the slope and intercept of the regression equation.

Question: *10.3.* What is the intercept and slope of the regression of LAI on NDVI (**to 4 decimal places**)?

Knowing the relationship between NDVI on the image and LAI measured in the field we can now make an 8-bit (byte) image of Leaf Area Index by applying a Formula document to convert NDVI to LAI. From the graph of LAI against NDVI we know that the maximum LAI we will find is about 10. To spread our LAI measure over more of the display scale (0–255) whilst making it easy to convert pixel values to LAI we can multiply by 10. This means that LAI values up to 2 will map to pixel values between 1 and 20, and so on (see table to right). Thus a pixel value of 56 in the output image will indicate an LAI of 5.6.

LAI range	Pixel values
< 2	1–20
2-4	21–40
4-6	41–60
6-8	61–80
> 8	81–100

The Formula document will thus need to be something like this:

(intercept + slope * @*x*) * 10 ;

where you substitute the values you obtained in the regression analysis for the *intercept* and *slope* and @*x* is the NDVI image.

Activity: Use **File, New** to open a new Formula document and enter a formula (see above for a model) to carry out the conversion of NDVI to LAI (use constant statements as appropriate to set up input values and make the formula easy to understand). Use the Formula document **Options!** to make sure the output image is an 8-bit unsigned integer and then **Copy** the formula and **Paste** it to the ***Mangrove_NDVI.dat*** image you saved earlier. The resultant image will be dark because the highest pixel value is only 100. To see the distribution of mangrove with different levels of LAI, open the Palette document ***Leaf_Area_Index.pal*** whilst the LAI image is the active document. The palette will be automatically applied to the image [assuming **Apply** is checked in the **Open** dialog box] and displays each of the five ranges of LAI in a different shade of green to green-brown. Note that mangrove areas with a Leaf Area Index greater than 8 are very rare.

Checkpoint: Note the value of the pixel at *x, y* (column, row) coordinate 324, 1167 in the ***Mangrove_NDVI.dat*** image. It should be 0.8333. Use a calculator to work out what its LAI value should be using your equation. It should be 7.8 and thus the pixel value at 324, 1167 on the LAI image should be 78. If it isn't something has gone wrong.

The next stage is to assess the status of the mangroves in the image area. Firstly, you will calculate what proportion of the mangrove area consists of each LAI class. The easiest way to do this is to use *Bilko*'s histogram capabilities. [*Note:* If you originally set the **Null value(s):** to zero, this should have carried through and the histogram will ignore these values; if you didn't, then you will need to set the null value as zero.]

Activity: Check that background pixels (black) of the LAI image are set as null (they will display a "?" in the value panel on the status bar). <u>If they are not</u>, right-click on the image and use the **Redisplay** option to set zero as the null value. This will mess up the display so, after closing the dialog box, select **Stretch, Clear** to restore the display).

Select all of the image and use **File, New** to bring up a histogram showing the frequencies of pixel values. Position the mouse pointer at 100 on the *x*-axis and holding down the left mouse button drag it until it is over 81. The status bar should indicate that 0.09% of the mangrove pixels are highlighted. Non-mangrove pixels are null and thus ignored. Note the number of pixels and percentage of mangrove pixels between 81 and 100 and record these in Table 10.7 below. Repeat for pixel values of 80 to 61, 60 to 41, 40 to 21 and 20 to 1. Make sure the percentages add up to 100. Now note the total number of mangrove pixels.

From the histogram header one can see that the image is 500 pixels wide and 1325 pixels long. Enter the total number of pixels in the image in Table 10.7. Knowing that each pixel is 1.0 m wide and 1.1 m long, calculate the area of the whole image in hectares (1 ha = 100 x 100 m = 10,000 m²). Complete Table 10.7 with all areas recorded in hectares to two decimal places, then answer the questions below.

Question: *10.4.* What percentage of the image area is mangrove?

Question: *10.5.* What is the area of the whole image in hectares (to the nearest hectare)?

Question: *10.6.* What is the total area of mangrove in hectares (to the nearest hectare)?

Question: *10.7.* How many hectares of mangrove have an LAI > 6 and what proportion of the total mangrove area does this represent?

Table 10.7. Analysing the image regarding the status of the mangroves. Record % mangrove pixels and area in hectares to **two decimal places**.

LAI range	Pixel values	Number of pixels	% mangrove pixels	Area (hectares)
< 2	1–20			
2–4	21–40			
4–6	41–60			
6–8	61–80			
> 8	81–100		0.09	
Mangrove total				
Image total				

Estimation of net canopy photosynthetic production (P_N)

The approximate net photsynthetic production of the whole mangrove canopy per m² of ground area over a day can be described by the following equation:

$$P_N = A \times d \times LAI$$

where A = average rate of photosynthesis (g-C m^{-2} leaf area hr^{-1}) for all leaves in the canopy, d = daylength (hr), and LAI is the leaf area index already estimated for each pixel (English *et al.* 1997). For mangroves in high soil salinities in the dry season a reasonable estimate for A = 0.216 g-C m^{-2} hr^{-1} and daylength in the Turks and Caicos is on average about 12 hours. Using this relationship we can make a rough estimate of the net photosynthetic production in each LAI class, indeed, if one had good field data on the average rate of photosynthesis (A) one might in theory make an image where pixel values related to P_N. For the purpose of this lesson we are just going to make a crude estimate of the number of tonnes of carbon fixed per hectare each year (t-C ha^{-1} $year^{-1}$) by the mangrove area with an LAI of 6–8.

Activity: Let the average LAI of the mangrove area with an LAI of 6–8 be 7. Using the equation estimate the daily net photosynthetic production per m² (in g-C m^{-2}). Convert this to t-C ha^{-1} $year^{-1}$. Use your value for the area occupied by mangrove with LAI 6–8 to estimate how many tonnes of carbon are fixed per year by the these mangroves.

Question: *10.8.* What do you estimate the daily net photosynthetic production of the mangroves with LAI 6–8 in g-C m^{-2}? What is this as an annual production in units of t-C ha^{-1} $year^{-1}$? [Show your working].

Question: *10.9.* How many tonnes of carbon are fixed per year by the mangroves with LAI 6–8 in the area of the image? [Give your answer to nearest whole tonne C.]

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Answers to Questions

10.1. The mangrove vegetation is thicker and has greater canopy closure at UTM coordinates 236520 E, 2379938 N than at 236600 E, 2379945 N. In the near infra-red band the image is much brighter at the former position (reflectance 5287 as opposed to 2290), whilst in the red waveband it is darker (reflectance 462 as opposed to 865). Vegetation reflects in the near-IR and absorbs in the red. [*Note:* Reflectances have been scaled as 16-bit integer values rather than being stored as 4-byte real numbers.]

Table 10.5. Calculating the average NDVI for two ground-truthing sites. Sum the individual pixel values and divided by 9 to get average NDVI in original image units for Table 10.6.

Site 72
Central pixel: X: 236700, Y: 2379827

0.3859	0.4196	0.2701
0.2974	0.1967	0.1584
0.1840	0.1967	0.2190

Site 79
Central pixel: X: 236693, Y: 2380127

0.5803	0.6553	0.6553
0.5118	0.6065	0.6723
0.3783	0.5077	0.5718

10.2. The average NDVIs at site 72 is 0.2586 (i.e. 0.26). The average NDVI at site 79 is 0.5710 (i.e. 0.57).

10.3. The intercept of the regression line with the *y*-axis is -0.3123. The slope of the regression line is 9.7566.

Table 10.7. Analysis of the LAI image regarding the status of the mangroves.

LAI range	Pixel values	Number of pixels	% mangrove pixels	Area (hectares)
< 2	1–20	56958	15.55	6.27
2–4	21–40	58227	15.89	6.40
4–6	41–60	163759	44.69	18.01
6–8	61–80	87120	23.78	9.58
> 8	81–100	332	0.09	0.04
	Mangrove total	366396	100.00	40.30
	Image total	662500		72.88

10.4. The percentage of the image area that is occupied by mangroves is 366396/662500 x 100 = 55.3%.

10.5. The area of the whole image is approximately 73 ha (to nearest ha).

10.6. The total area of mangrove habitats is approximately 40 ha (to nearest ha).

10.7. 9.62 ha of mangrove have an LAI of > 6 (and are thus dense mangroves). This represents about a quarter [23.87%] of the total area of mangroves.

10.8. A = 0.216 g-C m^{-2} hr^{-1}, d = 12 hours, LAI = 7. So the daily net photosynthetic production P_N = 0.216 x 12 x 7 = 18.144 g-C m^{-2}. To convert to units of t-C ha^{-1} $year^{-1}$ you need to multiply by 10,000 (m^{-2} to ha^{-1}), multiply by 365 (days to years) and divide by 1,000,000 (grams to tonnes). Thus the annual net photosynthetic production of this type of mangrove is about 66.2 t-C ha^{-1} $year^{-1}$.

10.9. The 9.62 ha of mangrove with an LAI of 6–8 would thus fix 9.62 x 66.2 = approximately 637 tonnes C annually.

Example Formula documents:

1) To calculate NDVI:

```
# Formula to calculate NDVI [Lesson 10]

# @1 = near infra-red image (in this case Casi_mangrove#07.dat)
# @2 = red image (in this case Casi_mangrove#06.dat)

# The output image needs to be Floating point (32-bit)

        CONST Infrared = @1 ;
        CONST Red = @2 ;

        (Infrared - Red) / (Infrared + Red)  ;
```

2) To calculate LAI:

```
# Formula to calculate LAI from NDVI for CASI mangrove image [Lesson 10]

# LAI has been regressed against NDVI and the intercept and slope of the linear
# relationship have been found. These will be set up as constants.

# The formula assumes Mangrove_NDVI.dat is @1 and the blank image is @2.
# The output image is an 8-bit GIF file where pixel value = LAI * 10.

        CONST intercept = -0.3123 ;
        CONST slope = 9.7566 ;
        CONST ScaleFactor = 10 ;

        (intercept + slope * @1) * ScaleFactor ;
```

***Photographic credits*:**

A number of photographic images are made available in this module as Windows bitmap (***.bmp***) files. Photographs were provided by Alasdair Edwards, Edmund Green, Peter Mumby and Jonathan Ridley. Those provided by Jonathan Ridley (Coral Cay Conservation) have image names suffixed with "CCC".

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Appendix A

Contents of Module 7

The programme file for *Bilko* v. 3.0, associated Help files, documentation, files containing images (***.bmp, .gif***, ***.dat, .n1, .hdf, .nc, .pcx, .tif*** and ***.bin*** files), look-up tables (***.str***), palettes (***.pal***), formulas (***.frm***), sets of images (***.set***), rectification tables (***.tbl***), filters (***.flt***) and *Excel* spreadsheet files associated with some lessons, are either available on a CD-ROM distributed with this booklet or can be downloaded over the internet.

The total amount of free disk space required for all the files associated with Module 7 is over 100 Mbytes.

CD-ROM

1. Insert the compact disc into your CD-ROM drive.
2. In *Windows 98, Windows ME, Windows 2000* or *Windows XP* (or later) the installation should start automatically (autoplay). (The software will run under Windows 95 but it is not recommended.) If you right-click the Bilko-CD icon in "My Computer" the menu should include **AutoPlay**; if it doesn't, click on the **Start** button and select the **Run** option. In the **Open** dialog box, type **e:\setup** where **e:** is the drive letter of your CD-ROM drive or use the **Browse** menu to find the ***Setup.exe*** program on the CD-ROM. Then click on OK.
3. Follow the Install Shield instructions.

Note: All the files required for modules 1–6 and 8 are also included on the CD-ROM and may be installed if required.

Downloading over the internet

An "anonymous ftp" site has been set up from which all the files needed for Module 7 can be downloaded. All the files have been zipped to make them as small as possible. Even so the largest lesson is still several Mbytes in size so a reasonably fast internet connection is needed to download. You can either download using ftp or via some specially prepared web pages using a web browser. For details of where to find the files and how to download them you should visit the web page on URL:

http://www.unesco.bilko.org/

and fill in an electronic form which can be accessed from that page. You will then be e-mailed instructions on how to download the files.

Note: All the files required for modules 1–6 are also available in zipped form on the anonymous ftp site and may be downloaded if required.

The text of the Introduction and lessons for Module 7 is stored as a series of Adobe Acrobat files (***.pdf***). The Acrobat files were originally formatted for A4 paper.

The contents of Module 7 are listed on the following pages under the section heading of the modules to which files belong.

Contents of Module 7

The CD-ROM and *Bilko* anonymous ftp site contain the self-installing programme ***Bilko3.exe*** and its help file ***Bilko3.chm*** which is used by all the lessons and exercises. They also contain all the documentation and other files required for the introduction and the lessons themselves. For a number of lessons, trainer resources have been developed to aid those using this module to train others and are included in a ***Trainer resources*** folder. Document files are issued in Acrobat format (***.pdf*** extension) but are also available on the CD-ROM as Word documents (***.doc*** extension) for those who wish to edit the lessons.

Programme ***Bilko3.exe***
Help file ***Bilko3.chm***

Module introduction and appendices

Module07\Lesson documentation
Text file ***Module07.pdf***

Section 1: Introduction to using the *Bilko 3* image processing software

Module07\Introduction tutorials
Text files
Introduction_to_Bilko_00.pdf
Introduction_to_Bilko_01.pdf
Introduction_to_Bilko_02.pdf
Introduction_to_Bilko_03.pdf
Introduction_to_Bilko_04.pdf
Introduction_to_Bilko_05.pdf
Introduction_to_Bilko_06.pdf
Introduction_to_Bilko_07.pdf
Introduction_to_Bilko_08.pdf
Introduction_to_Bilko_09.pdf
Introduction_to_Bilko_10.pdf

Module07\Introduction
Image files
AVHRR_ID2497481.bin
AVHRR_Mulls#02.bmp
AVHRR_Mulls#04.bmp
AVHRR_Mulls_col#04.bmp
AVHRR_West_Africa#04.dat
Casi_16-bit_unsigned#2.bin
Filter_test.gif
Global_SST_Dec2000.gif
Littleport_TM#01.gif
Littleport_TM#02.gif
Littleport_TM#03.gif
Littleport_TM#04.gif
Littleport_TM#05.gif
Littleport_TM#07.gif
MER_RR__1_Mediterranean.n1
Mulls_coastline.gif

Module07\Introduction\Composite
AVHRR_ID2497481#01.dat
AVHRR_ID2497481#02.dat
AVHRR_ID2497481#03.dat

Module07\Introduction

Accessory files	***AVHRR_ID2497481_composite.set*** ***Bitwise.frm*** ***Draw_Mulls_coastline.frm*** ***High_pass.flt*** ***Littleport_TM.set*** ***Mulls_coastline.tbl*** ***Pathfinder_SST.frm*** ***SST_Exercise.pal*** ***SST_Pathfinder.pal***

Section 2: Practical lessons using coastal image data of the Caicos Bank and Virgin Islands

Lesson documentation

Module07\Lesson documentation

Lesson01.pdf
Lesson02.pdf
Lesson03.pdf
Lesson04.pdf
Lesson05.pdf
Lesson06.pdf
Lesson07.pdf
Lesson08.pdf
Lesson09.pdf
Lesson10.pdf

Images and other files needed for each lesson

Lesson 1: Visual interpretation of images with the help of colour composites: getting to know the study area

Module07\Lesson01

Image files	***CASI_Cockburn_Harbour#01.dat*** ***CASI_Cockburn_Harbour#03.dat*** ***CASI_Cockburn_Harbour#05.dat*** ***SPOTXS_SCaicos#01.gif*** ***SPOTXS_SCaicos#02.gif*** ***SPOTXS_SCaicos#03.gif***
Scanned photographs	***Brown_algae.bmp*** ***Casi_sensor.bmp*** ***Cockburn_harbour.bmp*** ***Elkhorn_A-palmata_CCC.bmp*** ***Gorgonian_plain.bmp*** ***Mangrove_aerial.bmp*** ***Mangrove_black.bmp*** ***Mangrove_red_short.bmp*** ***Mangrove_red_tall.bmp*** ***Mangrove_white.bmp*** ***Montastraea_colonies.bmp*** ***Montastraea_survey.bmp*** ***Sand_habitat_CCC.bmp***

Seagrass_blowout.bmp
Seagrass_dense.bmp
Seagrass_sparse.bmp

Accessory files ***CASI_Cockburn_Harbour#05+#03+#01.set***

Lesson 2: The importance of acquiring images of the appropriate scale and spatial resolution for your objectives

Module07\Lesson02

Image files
AP_east_SCaicos.gif
AP_mangrove_SCaicos.gif
AP_south_SCaicos.gif
CASI_Cockburn_Harbour#01.dat
CASI_Cockburn_Harbour#03.dat
CASI_Cockburn_Harbour#05.dat
CASI_mangrove#03.dat
CASI_mangrove#05.dat
CASI_mangrove#07.dat
Ikonos_Caicos#01.dat
Ikonos_Caicos#02.dat
Ikonos_Caicos#03.dat
Ikonos_Caicos#04.dat
Ikonos_Caicos_pan.dat
LandsatMSS_Caicos#01.gif
LandsatMSS_Caicos#02.gif
LandsatMSS_Caicos#03.gif
LandsatTM_SCaicos#01.gif
LandsatTM_SCaicos#02.gif
LandsatTM_SCaicos#03.gif
SPOTXP_SCaicos.gif
SPOTXS_SCaicos#01.gif
SPOTXS_SCaicos#02.gif
SPOTXS_SCaicos#03.gif

Scanned photographs
Montastraea_colonies.bmp
Seagrass_blowout.bmp
Seagrass_dense.bmp

Accessory files
CASI_Cockburn_Harbour#05+#03+#01.set
CASI_mangrove#07+#05+#03.set
Ikonos_Caicos#03+#02+#01.set

Lesson 3: Geometric correction of an aerial image of South Caicos Island

Module07\Lesson03

Image files ***Aerial_subimage_raw.gif***

Accessory files ***South_Caicos_GCPs.tbl***

Lesson 4: **Radiometric correction of satellite images: when and why radiometric correction is necessary**

Module07\Lesson04

Image files

LandsatTM_Jun_DN#01.gif
LandsatTM_Jun_DN#02.gif
LandsatTM_Jun_DN#03.gif
LandsatTM_Nov_DN#01.gif
LandsatTM_Nov_DN#02.gif
LandsatTM_Nov_DN#03.gif

Accessory files

Radiometric_correction_Jun.frm

Lesson 5: **Removing sun glint from Compact Airborne Spectrographic Imager (CASI) imagery**

Module07\Lesson05

Image files

St_John_USVI_CASI#01.dat
St_John_USVI_CASI#02.dat
St_John_USVI_CASI#03.dat
St_John_USVI_CASI#04.dat
St_John_USVI_CASI#05.dat
St_John_USVI_CASI#06.dat
St_John_USVI_CASI#07.dat
St_John_USVI_CASI#17.dat
St_John_USVI_CASI#18.dat
St_John_USVI_CASI#19.dat

Accessory files

Deglinting_band17.frm
Deglinting_band18.frm
Lesson05_deglinting_St_John.xls
St_John_USVI_CASI.set

Lesson 6: **Crude bathymetric mapping using Landsat TM satellite imagery**

Module07\Lesson06

Image files

Landmask_lesson6.gif
LandsatTM_bathymetric#01.gif
LandsatTM_bathymetric#02.gif
LandsatTM_bathymetric#03.gif
LandsatTM_bathymetric#04.gif

Accessory files

Bathymetric_blue.pal
Bathymetric_contours.pal
Bathymetric_grey.pal
Bathymetric_map.frm
Bathymetric_map.gif
DOP_4zones.frm
DOP_4zones.pal
DOP_zones.frm

Lesson 7: **Compensating for variable water depth to improve mapping of underwater habitats: why it is necessary**

Module07\Lesson07

Image files

Casi_depth-invariant#2_#4.dat
Casi_depth-invariant#3_#5.dat
Casi_SCaicos#02.dat
Casi_SCaicos#03.dat
Casi_SCaicos#04.dat
Casi_SCaicos#05.dat

Accessory files

Casi_depth-invariant#3_#4.frm
Casi_depth-invariant_bands#3_#4.xls
Casi_sand_patches.xls
Casi_SCaicos#05+#04+#02.set
Deepwater_pixels.xls
Depth_invariant.frm

Lesson 8: **Mapping the major inshore marine habitats of the Caicos Bank by multispectral classification using Landsat TM**

Module07\Lesson08

Image files

Depth-invariant_LandsatTM#1_#3.dat
Depth-invariant_LandsatTM#2_#3.dat
LandsatTM_Caicos#05.gif

Accessory files

Classification.pal
Classification1.frm
Classification2.frm
Habitats_Lesson8.xls

Lesson 9: **Predicting seagrass standing crop using SPOT XS satellite imagery**

Module07\Lesson09

Image files

Landmask_lesson9.gif
Seagrass_area.gif
Seagrass_mask.gif
SPOTXS_depth-invariant.dat

Accessory files

Lesson9.xls
Seagrass1.pal
Seagrass2.pal
Seagrass_step1.frm
Seagrass_step2.frm
Seagrass_step2.str

Lesson 10: **Assessing mangrove leaf-area index (LAI) using CASI airborne imagery**

Module07\Lesson10

Image files

Casi_mangrove#06.dat
Casi_mangrove#07.dat

Accessory files

Leaf_Area_Index.pal
Mangrove_NDVI.xls

Trainer resources:

Module07\Trainer resources

AVHRR_Mulls#04_TR.str
Casi_depth-invariant#3_#4_TR.frm
Casi_sand_patches_TR.xls
Deglinting_band17_TR.frm
DOP_zone2_interpolation_TR.frm
Habitats_Lesson8_TR.xls
Introduction_Questions_Worksheet_TR.doc
Lesson05_deglinting_TR.xls
Lesson09_TR.xls
Lesson10_LAI_TR.frm
Lesson10_NDVI_TR.frm
Mangrove_NDVI_TR.xls
Module07_Questions_Worksheet_TR.doc
Radiometric_correction1_TR.frm
Radiometric_correction2_TR.frm
SST_Exercise_TR.pal
Trainer_resources_index.txt

Appendix B

Contents of First Module (MARINF/70, July 1989)

Contents of Second Module (MARINF/81, February 1991)

Contents of Third Module (MARINF/83, February 1992)

Contents of Fourth Module (MARINF/90, July 1993)

Note: Module 4 is also available in **Russian** (see Module04 folder on the CD-ROM for Russian documentation and 6 additional lessons on Baltic in Russian).

Contents of Fifth Module (MARINF/96, December 1995)
Originally issued in Spanish (MARINF/96, September 1994)

Contents of Sixth Module

REPLY SHEET

Seventh computer-based learning module (3rd Edition) on
Applications of Satellite and Airborne Image Data to Coastal Management

Name and address of respondent:

....
....
....
....
Fax number:......................……… E-mail:...

Respondent's discipline or interest (*): *coastal zone management/ socio-economics / environment / coastal planning / cultural issues / physical oceanography / marine biology / marine pollution / meteorology / hydrology / marine geology / other (please specify)*...

(a) I *am / am not* (*) in a position to contribute a lesson to a further module. If affirmative:
(i) tentative title ....
(ii) tentative date for first draft...
(iii) what additional software function(s), if any, would enhance your lesson?
....
(iv) I *would/ would not* (*) like my lesson to make use of HTML.

(b) I *will/ will not* (*) contribute additional material to enhance lessons in existing modules. If affirmative: *additional images/ alternative questions/ further explanations* (*) for lesson no...... in module...........

(c) Among future lesson subjects, the following applications, phenomena, data or geographical area would be of particular interest to me and/or my students
....
....

(d) I am using the *Bilko* software and modules for the following purposes (tick as appropriate):

Teaching	( ):	University level ( )	High school ( )	Other, please specify ....
Research	( ):	Please specify discipline ....…..		
Other	( ):	Please specify ....…..........................…..		

(e) I recommend that a copy of the seventh module be sent to the following person(s) who is (are) likely to be in a position to contribute lessons to further modules:
....
....
....
(*) Please delete or encircle as appropriate

Return to: UNESCO-Bilko,
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2 *Coasts of Haiti. Resource assessment and management needs.* 1998. 39 pp. (English and French). www.unesco.org/csi/pub/papers/papers2.htm www.unesco.org/csi/pub/papers/papiers2.htm

3 *CARICOMP – Caribbean Coral Reef, Seagrass and Mangrove Sites.* Edited by Björn Kjerfve. 1999. 185 pp. (English only). www.unesco.org/csi/pub/papers/papers3.htm

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