## 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 $\mathbf{i}$. It is related to radiance and depth by the following equation where $\mathbf{a}$ is a constant, $\mathbf{r}$ is the reflectance of the bottom and $\mathbf{z}$ 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, $\mathbf{r}$ (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 $\mathbf{a}$, 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.
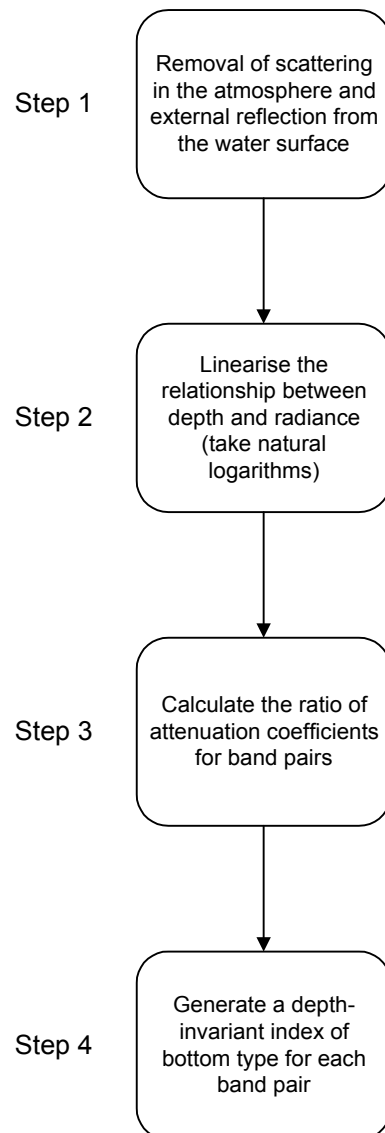
Of course, not all pixel values for a given bottom type lie along a perfectly straight line. This is because of natural variation in bottom reflectance, patches of turbid water and sensor noise. Nevertheless, each pixel can be assigned an index of bottom type once the ratio of attenuation coefficients 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.

Step 1 — Removal of scattering in the atmosphere and external reflection from the water surface

Step 2 — Linearise the relationship between depth and radiance (take natural logarithms)

Step 3 — Calculate the ratio of attenuation coefficients for band pairs

Step 4 — Generate a depth-invariant index of bottom type for each band pair

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):

$$X_3 = index + \frac{k_3}{k_4} . X_4 \qquad \qquad \textit{Equation 7.4}$$

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*:

$$index = X_3 - \frac{k_3}{k_4} . X_4 \qquad \qquad \textit{Equation 7.5}$$

The general equation for any pair of bands *i* and *j*, written in full is:

$$\text{depth - invariant index}_{ij} = \ln(L_i - L_{si}) - \left[\left(\frac{k_i}{k_j}\right).\ln(L_j - L_{sj})\right]$$     *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.
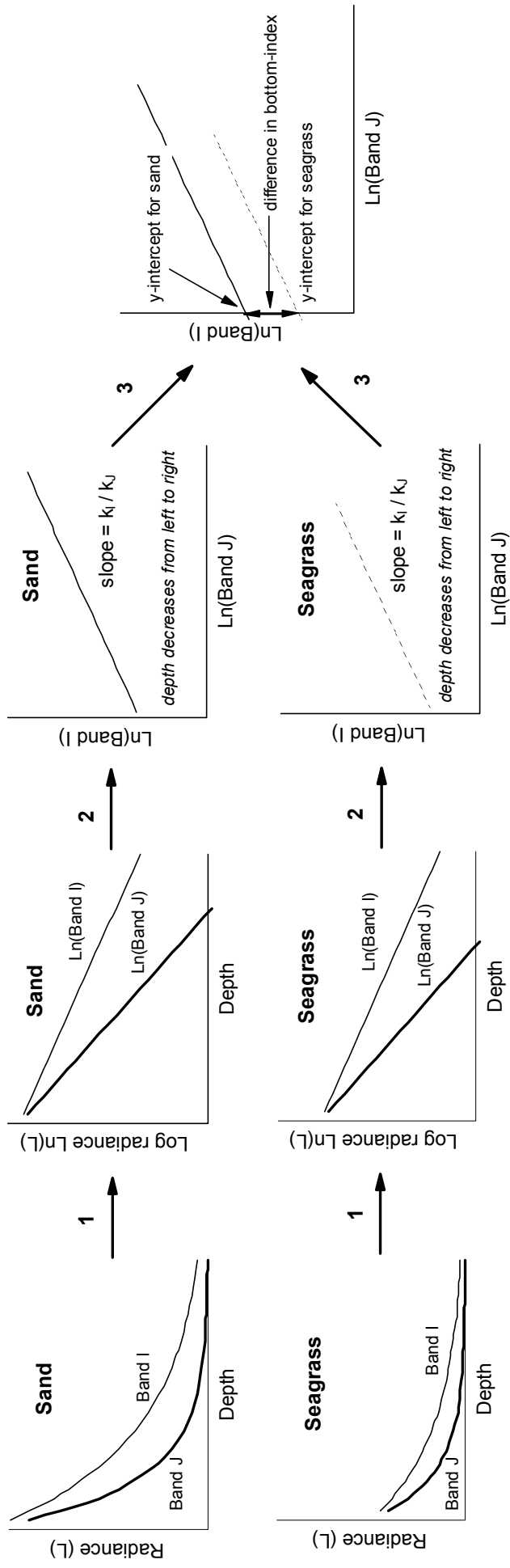
**Figure 7.1.** Processes of water column correction, showing the difference of sand and seagrass.

**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 <u>not</u> 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 <u>down</u> 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.
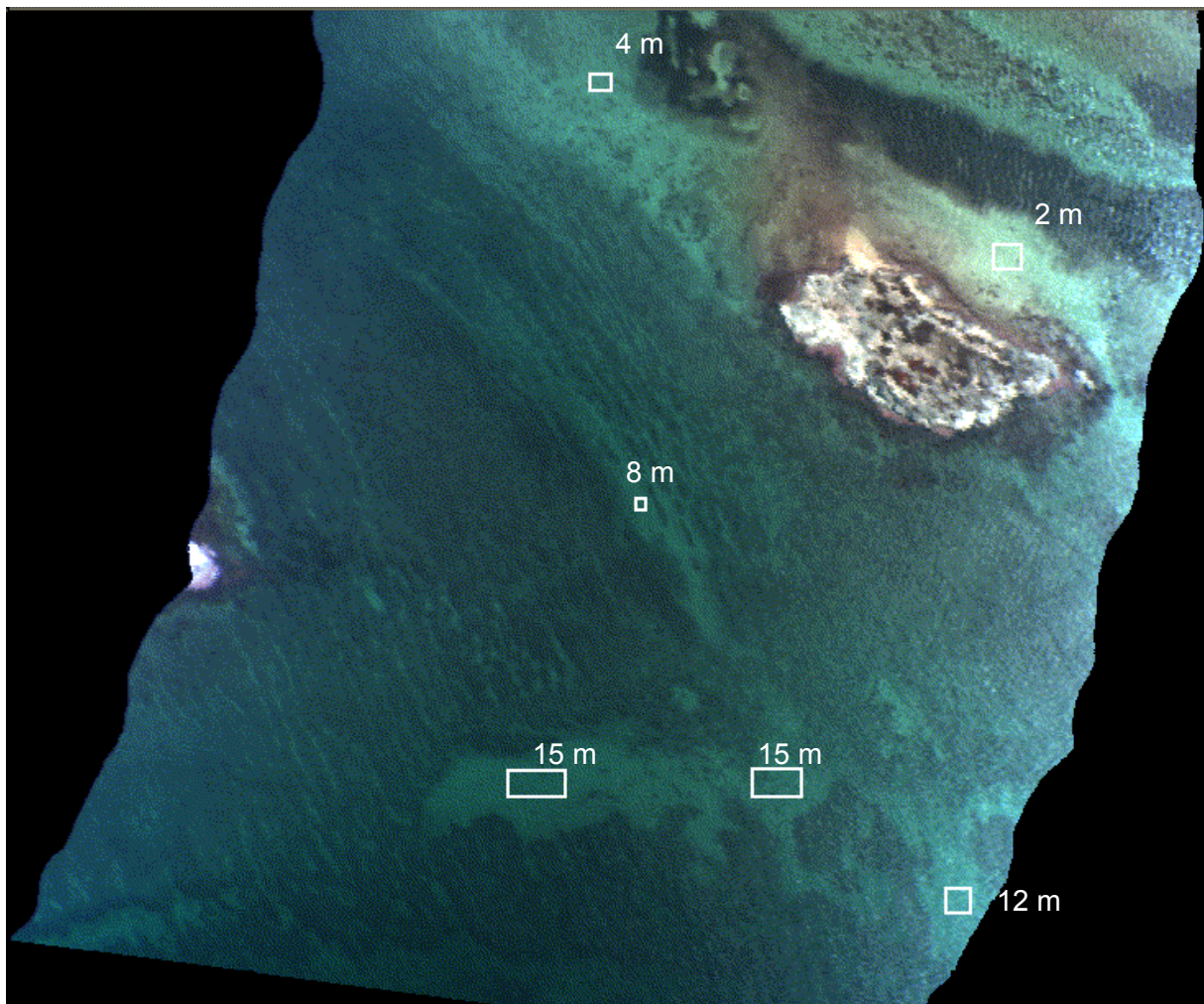


**Figure 7.2.** CASI image of Cockburn Habour (Turks and Caicos Islands) showing the selection of pixels of sand at variable depth.

**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.]

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*Checkpoint:* The value of the top cell in the $\ln(b4 - Ls_4)$ column should be 8.1659.

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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:

$$\frac{k_i}{k_j} = a + \sqrt{(a^2 + 1)}$$

*Equation 7.7*

where

$$a = \frac{\sigma_i - \sigma_j}{2\sigma_{ij}}$$

*Equation 7.8*

and ($\sigma_i$ is the variance of band $i$, $\sigma_j$ is the variance of band $j$, $\sigma_{ij}$ 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 $L_{s3}$, deepwater4 is $L_{s4}$, 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**.

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*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**.

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*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!

## 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.

Jerlov, N.G. 1951. Optical studies of ocean water. *Reports of Swedish Deep-Sea Expedition* **3**: 73-97.

Jerlov, N.G. 1964. Optical classification of ocean water. In: *Physical Aspects of Light in the Sea.* Univ. Hawaii Press, Honolulu, Hawaii. pp. 45-49.

Jerlov, N.G. 1976. *Applied Optics.* Elsevier Scientific Publishing Company, Amsterdam.

Lyzenga, D.R. 1978. Passive remote sensing techniques for mapping water depth and bottom features. *Applied Optics* **17** (3): 379-383.

Lyzenga, D.R. 1981. Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data. *International Journal of Remote Sensing* **2**: 71-82.

Maritorena, S. 1994. Diffuse reflectance of oceanic shallow waters: influence of water depth and bottom albedo. *Limnology and Oceanography* **39** (7): 1689-1703.

Maritorena, S. 1996. Remote sensing of the water attenuation in coral reefs: a case study in French Polynesia. *International Journal of Remote Sensing* **17** (1): 155-166.

Mumby, P.J., Clark, C.D., Green, E.P., and Edwards, A.J. 1998. Benefits of water column correction and contextual editing for mapping coral reefs. *International Journal of Remote Sensing* **19**: 203-210.

The Open University. 1989. *Seawater: its Composition, Properties and Behaviour*. A. Wheaton and Co. Ltd., Exeter, UK. 165 pp.

Spitzer, D. and Dirks, R.W.J. 1987. Bottom influence on the reflectance of the sea. *International Journal of Remote Sensing* **8**(3): 279-290.