

5: 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 show how depth dominates returns from the seabed.
3. 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 for Windows* image processing software

Familiarity with *Bilko for Windows 2.0* is required to carry out this lesson. In particular, you will need experience of using **Formula documents** to carry out mathematical manipulations of images.

Image data

A Canadian airborne multispectral digital imager called the 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 m² in 8 wavebands (Table 5.1) during flights over the Cockburn Harbour and Nigger Cay 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).

Table 5.1. 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 (CASI3C16.DAT and CASI4C16.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 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 were represented by extremely clear oceanic waters. Most clear coastal waters were 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 which 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 3) 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.

$$\text{Atmospherically corrected reflectance} = L_i - L_{si} \quad \text{Equation 5.1}$$

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 3 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 5.1 - 1). If values of light intensity (radiance) are transformed using natural logarithms (\ln), this relationship with depth becomes linear (Figure 5.1 - 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 is written as:

$$X_i = \ln(L_i - L_{si}) \quad \text{Equation 5.2}$$

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

The attenuation coefficient 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.

$$L_i = L_{si} + a \cdot r \cdot e^{-2k_i \cdot z} \quad \text{Equation 5.3}$$

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 5.3 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 5.1 - 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 represents the relative amounts of attenuation in each band. In fact, the slope represents the ratio of attenuation coefficients between bands. Conceptually, the line represents an axis of reflectance values for a unique bottom type. As one moves along the line, the only change is depth.

Step 4. Generate a depth-invariant index of bottom type

If reflectance values for another bottom type were added to the bi-plot (Figure 5.1), 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 5.1). 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.

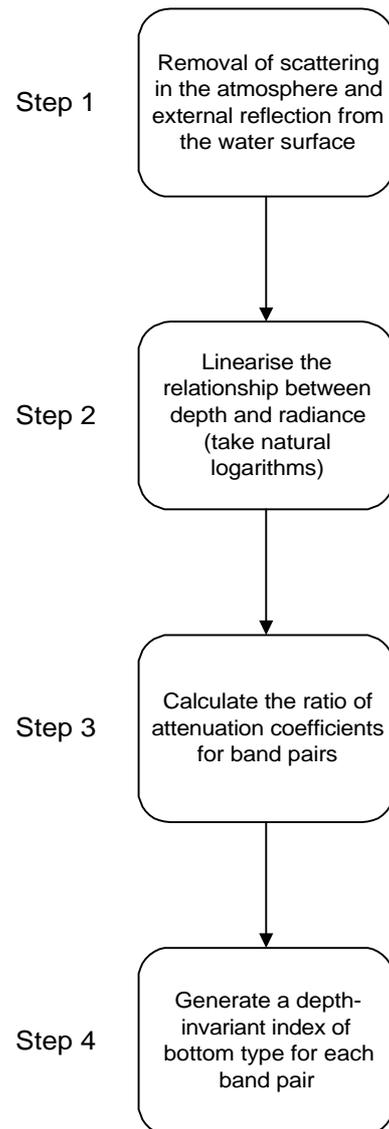
Of course, not all pixel values for a given bottom type lie along a perfectly straight line. This is because of natural variation in bottom reflectance, patches of turbid water and sensor noise. Nevertheless, each pixel can be assigned an index of bottom type once the ratio of attenuation coefficients 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 5.2):

$$X_3 = index + \frac{k_3}{k_4} \cdot X_4 \quad \text{Equation 5.4}$$

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*:

$$index = X_3 - \frac{k_3}{k_4} \cdot X_4 \quad \text{Equation 5.5}$$



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

$$\text{depth - invariant index}_{ij} = \ln(L_i - L_{si}) - \left[\left(\frac{k_i}{k_j} \right) \cdot \ln(L_j - L_{sj}) \right] \quad \text{Equation 5.6}$$

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, CASI), multiple depth-invariant bands can be created. The depth-invariant bands may then be used for image processing or visual inspection instead of the original bands.

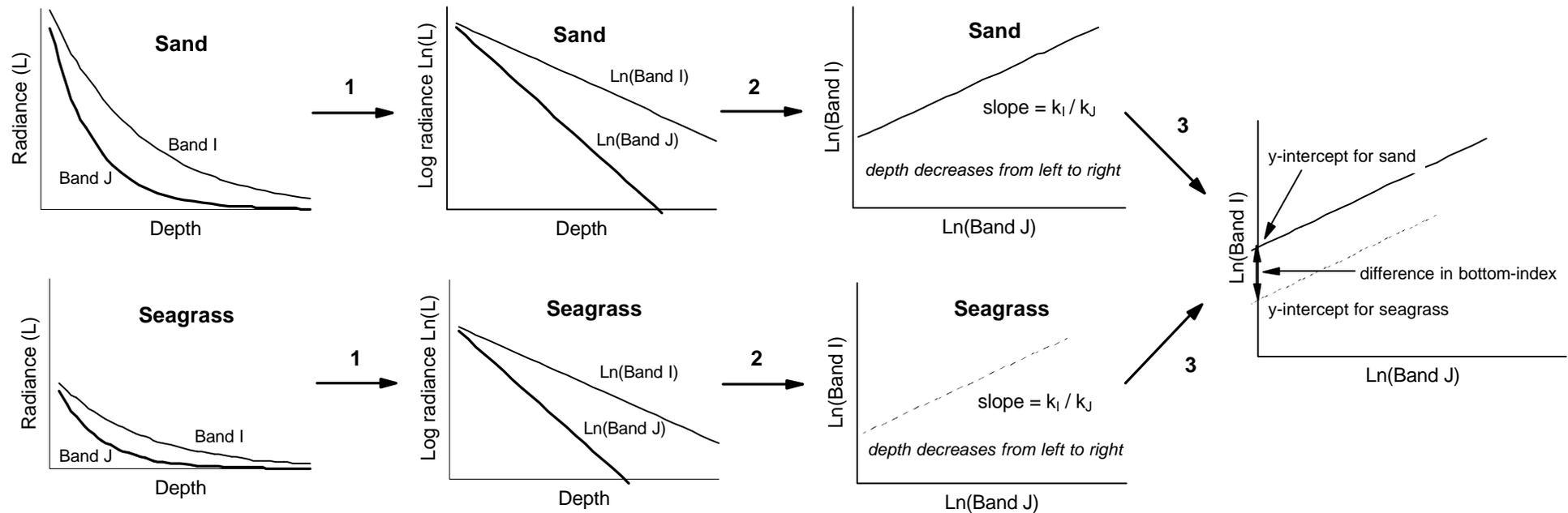


Figure 5.1. Processes of water column correction, showing the difference of sand and seagrass.

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

We will look at one image in the green part of the spectrum (CASI3C16.DAT) and use a transect to quantify the effect of depth on reflectance.

Activity: Open the file CASI3C16.DAT. Use **Stretch, Options** to ensure that stretches are NOT applied to charts, clipboard, etc. Then select the whole image and apply a stretch to make it easier to see. [*Hint:* Try a histogram equalization stretch]. Make sure the bottom of the image is in view, then click on the transect button and use **Edit, GoTo** to select a transect line running vertically down the image (DX: 0) from shallow water to deep water starting at pixel coordinates 150, 685 and with a DY: of 205 (so that it will end at 150, 890). This provides a transect covering about 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. To see the transect more clearly, adjust the y-axis scale using **Options, Scale**, setting the Maximum to 50.

Question: 5.1. Roughly how much has display scale (0-255) reflectance changed over the 225 m transect? What is this expressed as a percentage of the average pixel value over the first 10 m of the transect?

Once you have answered the question you can close the transect document.

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. If we can compensate for the depth effect then the major factor determining its 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 5.1), the four CASI bands (2, 3, 4 and 5 in Table 5.1) which 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 which can be produced from the four bands were found to be most useful; these were b2_b4, b3_b5 and b3_b4 combinations (where b2_b4 means a depth-invariant index image produced from bands 2 and 4 of the CASI data). For this lesson we will just create the b3_b4 depth-invariant index image from CASI bands 3 and 4 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 (reflectance) is fairly straightforward. A group of pixels are selected which represent deep water (i.e. greater than 40 m). The pixel data are transferred to a spreadsheet (e.g. Microsoft *Excel*). The mean and standard deviation of radiance (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 CASI4C16.DAT (CASI3C16.DAT should be open already). Apply a stretch as necessary to view the image well. You may need to examine the histogram of the image and create a Manual stretch to achieve reasonable brightness in deep water.

[If you cannot obtain a satisfactory stretch use the stretches CASI3.STR and CASI4.STR for the respective images]. You then 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. Click on the block selection button and use the **Edit, GoTo** option to select a block of 20 (**DX:**) by 10 (**DY:**) pixels at X, Y coordinates 235, 915 in CASI3C16.DAT and **Copy** this block. Launch *Excel* and open the spreadsheet file DEEP.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 5.2 below (to **two** decimal places).

Repeat the operation for the same coordinates for the CASI4C16.DAT image. Then calculate the mean minus two standard deviations to the *nearest integer* for each image and enter these values in Table 5.2.

Table 5.2. 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 5.2 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 x 5 areas of pixels from areas 4 and 7 (asterisked in Table 5.3) in CASI bands 3 and 4 (CASI3C16.DAT and CASI4C16.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.

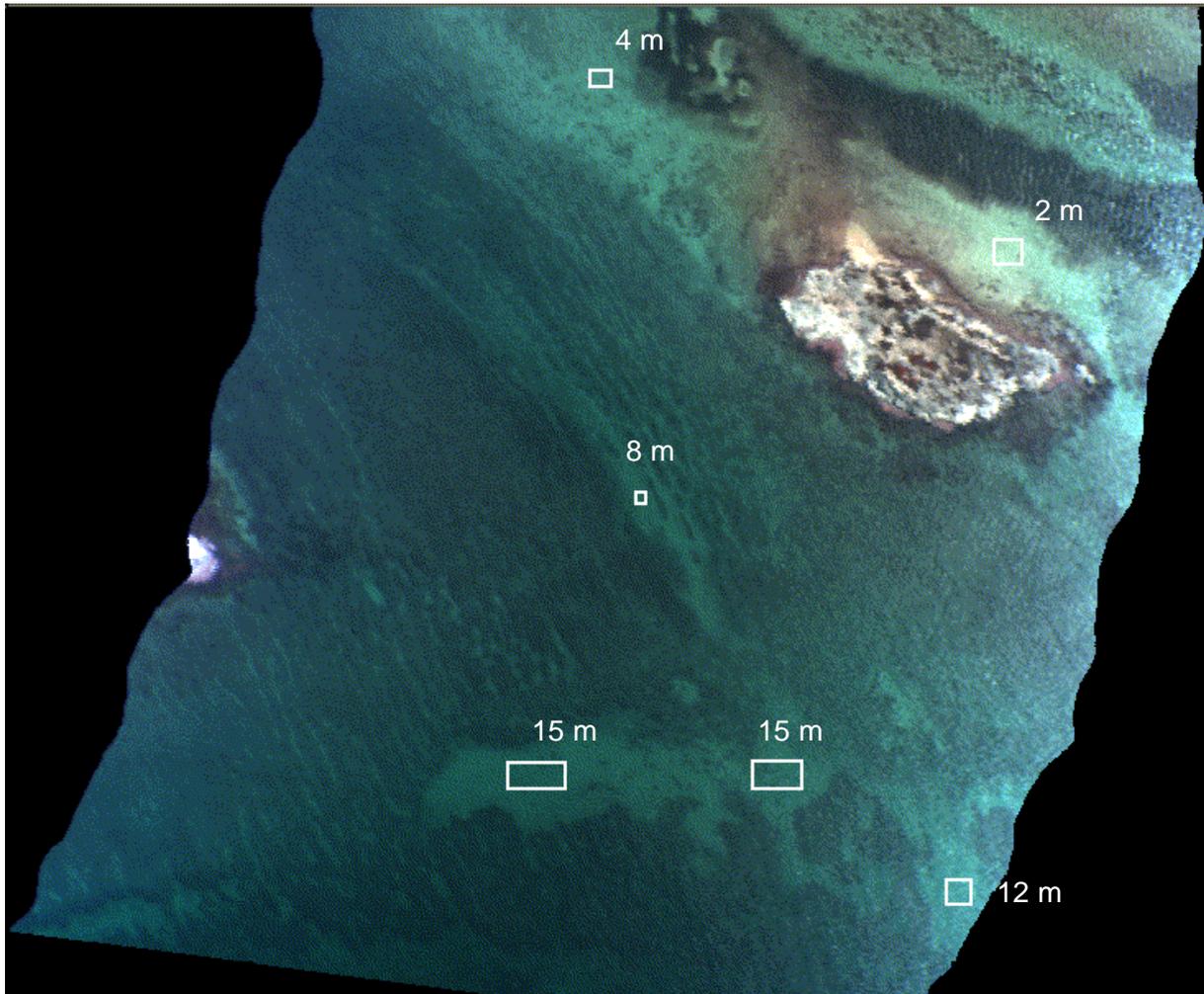


Figure 5.2. CASI image of Cockburn Harbour (Turks and Caicos Islands) showing the selection of pixels of sand at variable depth.

Table 5.3. UTM coordinates 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	Upper Left X	Upper Left Y	Columns x Rows
Goto	X:	Y:	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 CASISAND.XLS. 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 $\ln(b_4-L_{s_4})$ and $\ln(b_3-L_{s_3})$. 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. Leaving the spreadsheet open, return to *Bilko* and the CASI4C16.DAT image.

Set **View, Coords** on, and then use **Edit, GoTo** to select the block of 3 (**DX:**) by 5 (**DY:**) pixels in area 4 (see Table 5.3), starting at UTM coordinates 237820 (**Upper Left X:**) and 2377846 (**Upper Left Y:**). [*Hint:* Once you have entered the UTM coordinates in the **GoTo** dialog box, click the UTM 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 -6 (5.5 m south)].

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 5.3), 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 CASI3C16.DAT 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 5.2). 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 CASISAND.XLS enter appropriate formulas at the top of the $\ln(b_4-L_{s_4})$ and $\ln(b_3-L_{s_3})$ columns and then copy these down each column. [*Hint:* the formula for the first cell in the $\ln(b_4-L_{s_4})$ column should be =LN(D5-186) where D5 is the cell with the first Band 4 pixel value and 186 is the deep water correction calculated for Band 4 in Table 5.2].

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:

$$\frac{k_i}{k_j} = a + \sqrt{a^2 + 1} \quad \text{Equation 5.7}$$

where
$$a = \frac{s_i - s_j}{2s_{ij}} \quad \text{Equation 5.8}$$

and (σ_i is the variance of band i , σ_j is the variance of band j , σ_{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 $\ln(b4-L_{S4})$ column,
- 2) calculate the variance of the transformed Band 3 values in the $\ln(b3-L_{S3})$ column,
- 3) calculate the covariance of the transformed Band 4 and Band 3 values,
- 4) calculate \mathbf{a} [Equation 5.8],
- 5) calculate the ratio of the attenuation coefficients (k_3/k_4) [Equation 5.7].

Activity: 1) and 2). In the spreadsheet CASISAND.XLS go to the bottom of the $\ln(b4-L_{S4})$ column and use the VAR function to calculate the variance of the values in this column. **Repeat** for the $\ln(b3-L_{S3})$ column. [*Hint:* the formula in the cell beneath the $\ln(b4-L_{S4})$ column should be =VAR(F5:F34) where F5:F34 are the cells of the $\ln(b4-L_{S4})$ column]. Enter your results in Table 5.4.

3) The COVAR function takes two arguments separated by a comma. The first is the cells in the $\ln(b4-L_{S4})$ column, the second those in the $\ln(b3-L_{S3})$ 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 $\ln(b4-L_{S4})$ and $\ln(b3-L_{S3})$ columns]. Enter your result in Table 5.4.

4) Use a calculator (or the spreadsheet) to calculate the value of \mathbf{a} from the variances and covariance using Equation 5.8. Enter your result in Table 5.4.

5) Use a calculator (or the spreadsheet) to calculate the ratio of the attenuation coefficients (k_3/k_4) using Equation 5.7. Enter your result in Table 5.4.

Table 5.4. 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 \mathbf{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 CASISAND.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: 5.2. What are the coefficients of variation for the raw CASI band 3 and band 4 pixels in the two sand areas? [One coefficient for each band (i.e. column of data)].

The results from a larger dataset for our CASI Bands 3 and 4 data are available for inspection in the *Excel* spreadsheet file CASIB3B4.XLS.

Activity: Open CASIB3B4.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 5.5 based on the larger dataset. When you have finished close CASIB3B4.XLS.

Table 5.5. Ratio of attenuation coefficients for CASI bands 2/4, 3/4 and 3/5 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)

Prior to execution of 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 5.6 can now be used to generate a depth-invariant index image for bands 3 and 4. This is repeated below for your convenience:

$$\text{depth invariant index}_{ij} = \ln(L_i - L_{si}) - \left[\left(\frac{k_i}{k_j} \right) \ln(L_j - L_{sj}) \right] \quad \text{Equation 5.6}$$

where in this case $i = \text{CASI band 3}$ and $j = \text{CASI band 4}$.

Activity: **Connect** CASI3C16.DAT and CASI4C16.DAT and make sure the band 3 image is @1 and band 4 image is @2 using the connect toolbar. Then open the Formula document CASI3_4.FRM. The formula in Equation 5.6 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 is to enter the values for the three constants (CONST) above the formula from Tables 5.2 and 5.5. [Note: deepwater3 is L_{S_3} , deepwater4 is L_{S_4} , and k3k4ratio 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 the output depth-invariant bottom index image will be a **32 bit floating point image**. Then **Copy** the formula and **Paste** it to the connected images.

The depth-invariant processing is a computing intensive step and may take quite a long time to complete. Be patient. Save your output file as CASI3_4.DAT.

Check: 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 CASI3C16.DAT and CASI4C16.DAT. Then use a calculator to work out what the output depth-invariant index value should be in CASI3_4.DAT.

Question: 5.3. 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]?

To see how the effect of water depth has been compensated for in the depth-invariant image CASI3_4.DAT, click on the transect button and then use **Edit, GoTo** to select a transect line running vertically down the image from shallow water to deep water starting at pixel coordinates 150, 685 and with a DY: of 205 (so that it will end at 150, 890). This is the same transect you looked at earlier on the uncorrected image and covers about 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.

Note that there is no longer any trend of decreasing pixel reflectance with increasing depth. You may need to adjust the y-axis scale to see this properly. 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 which are shaded from the incoming sunlight.

Earlier you calculated the coefficients of variation for each constituent 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 5.3 for the coordinates) from each of areas 4 and 7 to an *Excel* spreadsheet and calculate the coefficient of variation (standard deviation/mean).

Question: 5.4. What is the coefficient of variation of the 30 sand pixels in the depth-invariant bottom index image? What is this as a percentage of the average coefficient of variation of the raw pixel data for the two bands?

Comparison of colour composites of raw images and depth-invariant images

Firstly, you will make 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.

Activity: Close CASI3C16.DAT and the connected images window. Open the files CASI2C16.DAT and CASI5C16.DAT (CASI4C16.DAT should already be open). **Connect** the images and use the connect toolbar to make sure that the Band 5 image displays through the red gun (i.e. is @1), Band 4 displays through the green gun (is @2), and Band 2 displays through the blue gun (is @3). Now use **Image, Composite** to make the false colour composite. [This may take some time to load as these images are big!] Select all of the composite image (<CTRL>+A) and apply an histogram equalization stretch to the composite (this stretches all three bands). 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 which our eyes see in the blue, green and red.

Note **two** things about the image: 1) there is quite a lot of sunglint 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 CASI2C16.DAT, CASI4C16.DAT and CASI5C16.DAT and the connected images window. Leave the composite open.

Secondly, you will make a false colour composite of three CASI depth-invariant index images. These are the CASI3_4.DAT image you made earlier and two more made using the formula document DEPTHINV.FRM (which you can inspect if you wish). These latter two were made using the CASI band pairs 2 and 4 (CASI2_4.DAT) and 3 and 5 (CASI3_5.DAT).

Activity: Open the depth-invariant bottom index images CASI2_4.DAT, CASI3_4.DAT, and CASI3_5.DAT.

Look at the south (bottom) ends of each of the images. Note how the reef front is visible in all of them as the effect of attenuation of light due to depth has been compensated for. Connect these images and use the connect toolbar to make sure the CASI3_4.DAT image is displayed through the red gun (@1), the CASI3_5.DAT image through the green gun (@2), and the CASI2_4.DAT through the blue gun (@3). This gives a reasonable image (perhaps the best of the six possible combinations available).

Question: 5.5. 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. When you are satisfied, close all the images. Congratulations!

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Answers to Questions

5.1. The display scale (0-255) reflectance changes from about 35 (approx. average value over first 20 m) to 10 (approx. average value over last 20 m) over the 225 m transect. Expressed as a percentage of the average pixel value over the first 10 m of the transect (about 35) this is $25/35 = 70\%$ change. If you take the highest value of 40 and lowest of 5 and the exact mean of the pixels from 0-10 m along the transect (36), then the change is $35/36 = 97.2\%$ change.

Table 5.2. 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 5.4. 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

5.2. The coefficients of variation are 0.6307 (band 3) and 0.7759 (band 4).

5.3. The pixel values at column and row coordinates 395, 190 are 2104 (band 3) and 1632 (band4). 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:

$$\text{index} = 7.4731 - 0.73393 \times 7.2766 = 2.1326$$

5.4. The coefficient of variation of the 30 pixels in the CASI3_4.DAT depth-invariant bottom index image is 0.0199. The average coefficient of variation of the same pixels in the two raw bands is 0.7033. $0.0199/0.7033 \times 100 = 2.8\%$. Thus over 95% of the variation in reflectance was due to the effect of water depth.

5.5. 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.

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