

4: CRUDE BATHYMETRIC MAPPING USING LANDSAT TM SATELLITE IMAGERY

Aim of Lesson

To learn how bathymetry can be mapped crudely from digital imagery and the limitations of the results.

Objectives

1. To understand the rationale and assumptions underlying the depth of penetration zone method of Jupp (1988) for mapping bathymetry.
2. To use deep water pixels to determine maximum DN values returned over deep water for Landsat TM bands 1 to 4.
3. 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 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 create a palette to display depth contours.
7. To investigate the limitations of the method.

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 imagery of the Caicos Bank.

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 be much smaller than the sensor pixel and so will fail to be detected.

Among satellite sensors, the measurement of bathymetry can be expected to be best with Landsat TM data because that sensor detects visible light from a wider portion of the visible spectrum, in more bands, than other satellite sensors. Landsat 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 should therefore be removed from the image before bathymetric calculations are performed.

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 5 which deals with how one attempts to compensate for these effects.

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. 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 TMBATHY1.GIF, TMBATHY2.GIF, TMBATHY3.GIF, and TMBATHY4.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: 4.1. 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 p through water, is given by:

$$I_d = I_0 \cdot e^{-pk} \quad \text{Equation 4.1}$$

where I_0 = intensity of the incident light and k = attenuation coefficient, which varies with wavelength. Equation 4.1 can be made linear by taking natural logarithms:

$$\log_e(I_d) = \log_e(I_0) - pk \quad \text{Equation 4.2}$$

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.

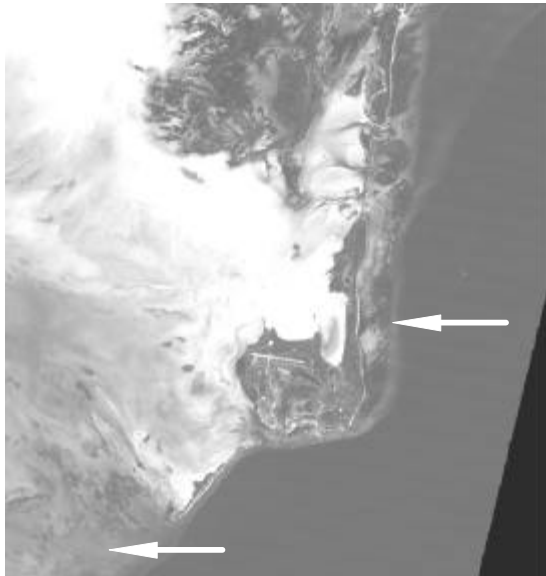
Depth of penetration zones method (modified from Jupp, 1988)

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.

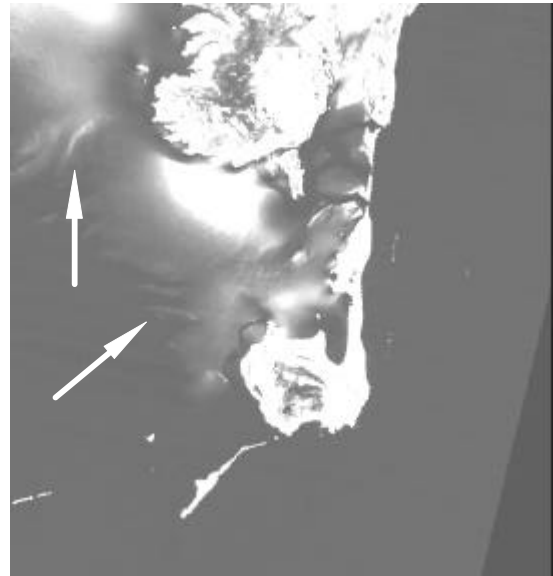
The coefficient of attenuation k depends on wavelength. Longer wavelength light (red in the visible part of the spectrum) has a higher attenuation coefficient than short wavelengths (blue). Therefore red light is removed from white light passing vertically through water faster than is blue. There will 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 4.1). 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 4.1. 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 4.2). 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 k) does not vary within an image.
3. The colour (and therefore reflective properties) of the substrate is constant.

Question: 4.2. 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 8.2 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 4.1. 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 deep water 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 deep water values then we assume the sensor is detecting light reflected from the seabed.

Activity: Launch *Bilko for Windows* if you have not already done so and use **File, Open** to open the files TMBATHY1.GIF, TMBATHY2.GIF, TMBATHY3.GIF, and TMBATHY4.GIF.

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 for Windows*. 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 for Windows* (using the <ALT>+<TAB> keys held down at the same time is a quick way) and select the TM1 image. Then select **Edit, GoTo** 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 4.2. Then repeat the procedure for each of the other images (bands 2-4) 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 TM1 image. Then select **Edit, GoTo** 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. In this case-study, the

modes of each histogram are equal to the mean deepwater DN values (to the nearest whole number). Use the cursor to find the DN of the modes.

Make a note of the maximum deepwater ($L_{\text{deep max}}$), minimum deepwater ($L_{\text{deep min}}$) and modal deepwater ($L_{\text{deep mean}}$) DN values for the TM band 1 image in Table 4.2. Then repeat the procedure for each of the other images (bands 2-4) for exactly the same area. When you have finished, **Close** all the histogram documents.

Table 4.2. DN values for deepwater pixels (sample size = 2500).

	Landsat TM band			
	1	2	3	4
Maximum deepwater DN value ($L_{\text{deep max}}$)				
Minimum deepwater DN value ($L_{\text{deep min}}$)				
Mean deepwater DN value ($L_{\text{deep mean}}$)				

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 4.1 lists the maximum depths of penetration recorded by Jupp (1988) for bands 1-4 of Landsat TM which 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 to 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 4.2 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 4.2). 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 which is greater than 57 indicating some bottom reflectance. However, if you move down the TM1 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 $> L_{\text{deep max}}$ for that waveband. Then move down the column (i.e. to progressively shallower depths) until you find the last pixel which has a value $\leq L_{\text{deep max}}$. This determines a range of depths between which z_i must lie.

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 $> L_{\text{deep max}}$ and the average depth of pixels with values equal to $L_{\text{deep max}}$ (**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!].

- Questions:*
- 4.3. What are the depths between which z_1 must lie?
 - 4.4. What is the average depth of pixels in this range with DN values $> L_{\text{deep max}}$ for TM band 1?
 - 4.5. What is the average depth of pixels in this range with DN values $\leq L_{\text{deep max}}$ for TM band 1?

Enter your answers into Table 4.3.

Table 4.3. Calculating the maximum depth of penetration (z_1) in metres.

[Note that average depths refer only to pixels in protocol determined depth range for z_1].

[Depths in metres]	Landsat TM band			
	1	2	3	4
Depth of deepest pixel with $DN > L_{\text{deep max}}$			4.70	1.55
Depth of shallowest pixel with $DN \leq L_{\text{deep max}}$			3.71	0.66
Average depth of boundary pixels with DN values $> L_{\text{deep max}}$			4.3	1.0
Average depth of boundary pixels with DN values $= L_{\text{deep max}}$			4.2	1.1
Estimated maximum depth of penetration (z_1)			4.2	1.0

For Landsat TM1 you will find that the average depth of those pixels which have DN values $> L_{\text{deep max}}$ 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 TM1 (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 4.3 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 4.3.

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 4.2 and 4.3 you can construct a decision tree for assigning pixels to depth zones. This is illustrated in Table 4.4 below.

Figure 4.2. Diagram to show the rationale behind Jupp's depth of penetration (DOP) zones.

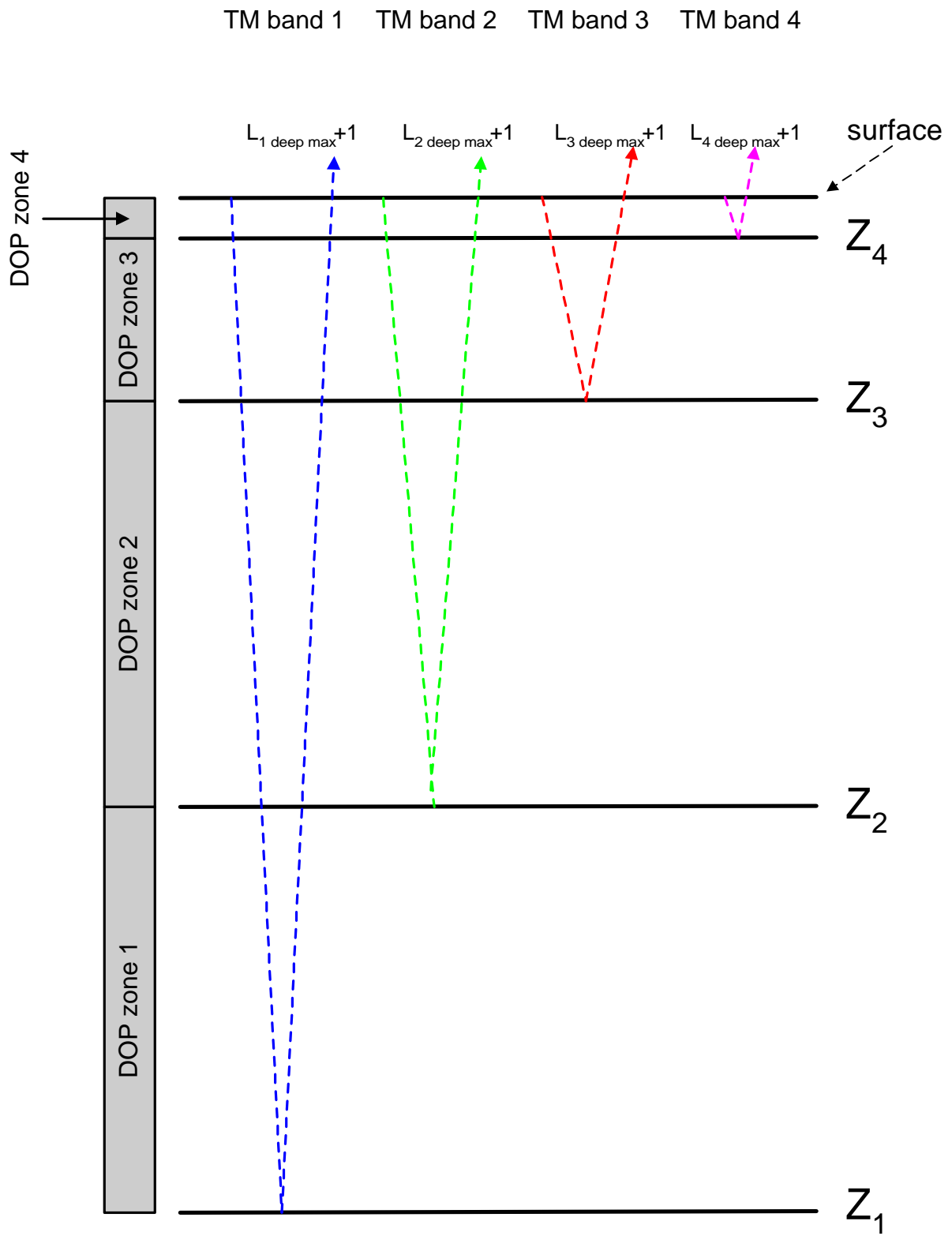


Table 4.4. A decision tree to assign pixels to depth zones.

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 one for you which creates four new images, showing the four DOP zones.

Activity: **Open** the file LANDMSK4.GIF and then **Connect** the images TMBATHY1.GIF, TMBATHY2.GIF, TMBATHY3.GIF, TMBATHY4.GIF and LANDMSK4.GIF. Use the connect toolbar to make sure the TM1 image will be @1 in any formula, the TM2 image @2, etc. and the land mask image @5.

Open the formula document file DOPZONES.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 (LANDMSK4.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**.

Copy the formula document and **Paste** it to the connected images to create the four DOP zone mask images.

Close the connected images window.

Inspect the four DOP zone mask images having stretched them (**Auto Linear**). 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.

Connect the four DOP zone images, using the connect toolbar to make sure that DOP zone 1 is @1, DOP zone 2 is @2, etc.

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 DOP4ZONE.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 DOP4ZONE.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 apparently being present around coordinates 769, 120 and 776, 133 off the east side of South Caicos Island.

Questions: 4.6. What is causing the shallow water anomalies (around coordinates 165,752 and 523, 615)? [*Hint:* Use the Landsat TM4 (near-infrared) image to help identify the cause.]

4.7. What habitat do you think is causing the deep water anomalies (around coordinates 769, 120 and 776, 133)? [*Hint:* Use the Landsat TM1 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 DOP4ZONE.GIF and then close it. **Close** the connected images window and **Save** the DOP zones 1-4 mask images as DOPMASK1.GIF, DOPMASK2.GIF, DOPMASK3.GIF and DOPMASK4.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:

$$L_2 = L_{2\text{deepmean}} + (L_{2\text{surface}} - L_{2\text{deepmean}})e^{-2k_2z} \quad \text{Equation 4.3}$$

where $L_{2\text{deepmean}}$ is the average deep water pixel value for TM band 2 calculated in Table 4.2, $L_{2\text{surface}}$ 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 which 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 being controlled by the attenuation coefficient for band 2 (k_2).

Equation 4.3 can be rewritten as:

$$L_2 - L_{2\text{deepmean}} = (L_{2\text{surface}} - L_{2\text{deepmean}})e^{-2k_2z} \quad \text{Equation 4.4}$$

If we define X_2 as follows: $X_2 = \log_e(L_2 - L_{2\text{deepmean}})$

we can get rid of the exponential thus:

$$X_2 = \log_e(L_{2\text{surface}} - L_{2\text{deepmean}}) - 2k_2z \quad \text{Equation 4.5}$$

Now for a given bottom type in TM band 2, $\log_e(L_{2\text{surface}} - L_{2\text{deepmean}})$ will be a constant which to simplify the look of Equation 4.5, we will call A_2 to give the following linear regression relationship:

$$X_2 = A_2 - 2k_2z \quad \text{Equation 4.6}$$

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 4.2) then it has a value of $X_{2\min}$ given by Equation 4.7 as:

$$X_{2\min} = A_2 - 2k_2z_2 \quad \text{Equation 4.7}$$

The minimum TM band 2 DN in DOP zone 2 ($L_{2\min}$) will be one more than $L_{\text{deep max}}$ for band 2, thus $X_{2\min}$ is $\log_e([L_{2\text{ deep max}} + 1] - L_{2\text{ deep mean}})$. 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 4.3] and the depth at which minimum reflectances are obtained in DOP zone 2).

Now consider another pixel which is only just inside DOP zone 2 as opposed to DOP zone 3 (the zone with the next highest coefficient of attenuation, Figure 4.2). This has a value of $X_{2\max} = \log_e(L_{2\max} - L_{2\text{ deep mean}})$ defined by the equation:

$$X_{2\max} = A_2 - 2k_2z_3 \quad \text{Equation 4.8}$$

where values are as for Equation 4.7 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 4.3), $L_{2\min}$ will generally be $L_{2\text{ deep max}} + 1$ (see Table 4.4 for $L_{\text{deep max}}$ 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, TMBATHY2.GIF multiplied by the DOP zone 2 mask image). For the purposes of this lesson we will just carry out the procedure for DOP zone 2.

Activity: **Connect** TMBATHY2.GIF and DOPMASK2.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:* Set the display of the histogram to **Ignore zero** (using **Options, Scale**)].

Note that the $L_{\text{deep max}}$ value for TM band 2 was 16 (Table 4.4) and the histogram begins at a DN value of 17 as expected. Note also the tail of higher DN values.

Question: 4.8. How many TM2 pixels in DOP zone 2 have values = 17 ($L_{2\min}$)?

4.9. What is the highest DN value of the TM2 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 our estimate of $L_{2\max}$ as the lowest DN value in the sample. 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 as your estimate of $L_{2\max}$. Enter your values for $L_{2\min}$ and $L_{2\max}$ in Table 4.5.

Question: 4.10. 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). Make the “TM2 in DOP zone 2” image @1 and the blank @2.

Table 4.5. $L_{i \min}$ 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 4.9 and 4.10 below).

	TM Band 1	TM Band 2	TM Band 3	TM Band 4
DOP 1	58 - 69			
DOP 2				
DOP 3			12 - 53	
DOP 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 4.5 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 4.7 and 4.8 form a pair of simultaneous equations which can be solved for k_2 (Equation 4.9). Once this is known Equation 4.7 can be re-arranged to find A_2 (Equation 4.10).

$$k_2 = \frac{(X_{2 \max} - X_{2 \min})}{2(z_2 - z_3)} \quad \text{Equation 4.9}$$

$$A_2 = X_{2 \min} + 2k_2 z_2 \quad \text{Equation 4.10}$$

Activity: Use a calculator or spreadsheet to work out firstly, k_2 [using Equation 4.9 and remembering that $X_{2 \max} = \log_e(L_{2 \max} - L_{\text{deep mean}})$ and $X_{2 \min} = \log_e(L_{2 \min} - L_{\text{deep mean}})$] and secondly, A_2 (using Equation 4.10). Enter your answers (to 4 decimal places) in Table 4.5 above.

Once A_i and k_i are known Equation 4.6 can be inverted and the depth of water, z , for any pixel with value $X_i = \log_e(L_i - L_{\text{deep mean}})$ in band i calculated:

$$z = \frac{(A_i - X_i)}{2k_i} \quad \text{Equation 4.11}$$

Activity: Using your new image of TM band 2 in DOP zone 2, create a formula document to interpolate the depth in metres of each TM2 image pixel in DOP zone 2 using Equation 4.11 and remembering that X_i for each pixel is $\log_e(L_i - L_{2 \text{ deep mean}})$ where L_i is the DN value of the pixel. 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 $L_{2 \text{ deep mean}}$) using the **const =** option.]

Warning!!! Unless you have a very fast computer, the formula may take a few minutes to do its stuff. Be patient.

To check whether your formula worked use the **Edit, GoTo** option to check the values of the pixel 395, 305 (DN = 23) which should have the value 87 in the output image (8.7 m deep) and pixel 450, 350 (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 as well.

The image you now have 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 (BATHYGRY.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** this palette and apply it. This gives a more natural display of your bathymetric map of DOP zone 2.

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. However, a Formula document which does this for all 4 DOP zones at once is stored as BATHYMAP.FRM.

Activity: **Open** the file BATHYMAP.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) which have been added together in another Formula document to produce the image BATHYMAP.GIF.

Open the crude bathymetric map image BATHYMAP.GIF and then the palette BATHYBLU.PAL which displays the depths a progressively paler shades of blue/cyan as you get shallower. Also try another palette BATHYCON.PAL which splits the depths into 0-2.5, 2.5-5, 5-7.5, 7.5-10, 10-15, 15-20, > 20 m depth zones. [If you wish to see how the palettes are set up you should uncheck the **Apply** checkbox in the **File Open** dialog box].

Question: 4.11. Which type of palette do you think is most useful?

Use the **Edit, GoTo** option to select 20 x 20 blocks of pixels at the following coordinates and then use their histograms to answer the following questions.

Question: 4.12. What is the modal depth (in the 20 by 20 block with coordinates 220, 800 as its north-west corner)?

4.13. What is the modal depth (in the 20 by 20 block with coordinates 650, 55 as its north-west corner)?

4.14. What is the modal depth (in the 20 by 20 block with coordinates 395, 480 as its north-west corner)?

4.15. What is the modal depth (in the 20 by 20 block with coordinates 100, 515 as its north-west corner)?

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 4.3.

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).

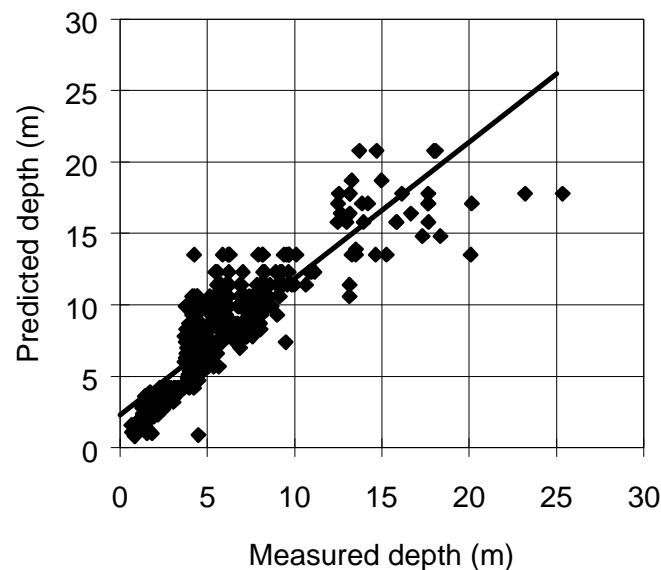


Figure 4.3. Plot of depth predicted from satellite imagery using the method (modified) of Jupp (1988) and depth measured in the field. Both have been corrected to chart datum.

Clearly, although bathymetric maps which look quite nice can be made from optical satellite imagery they provide little more than crude maps of depth which may be quite useful in planning surveys but cannot be used for much more.

However, if you have understood this exercise in trying to predict depth from satellite imagery you will 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

- Benny, A.H., and Dawson., G.J., 1983, Satellite imagery as an aid to bathymetric charting in the Red Sea. *The Cartographic Journal* **20** (1): 5-16.
- Bullard, R.K., 1983, Detection of marine contours from Landsat film and tape. In *Remote Sensing Applications in Marine Science and Technology*, edited by A.P. Cracknell (Dordrecht: D.Reidel) pp. 373-381.
- Jerlov, N.G., 1976, *Marine Optics*. (Amsterdam: Elsevier)
- Jupp, D.L.B., 1988, Background and extensions to depth of penetration (DOP) mapping in shallow coastal waters. *Proceedings of the Symposium on Remote Sensing of the Coastal Zone*, Gold Coast, Queensland, September 1988, IV.2.1-IV.2.19.

- Jupp, D.L.B., Mayo, K.K., Kuchler, D.A., Classen, D van R., Kenchington, R.A. and Guerin., P.R., 1985, Remote sensing for planning and managing the Great Barrier Reef Australia. *Photogrammetrica* **40**: 21-42.
- Lyzenga, D.R., 1978, Passive remote sensing techniques for mapping water depth and bottom features. *Applied Optics* **17**: 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.
- Lyzenga, D.R., 1985, Shallow water bathymetry using a combination of LIDAR and passive multispectral scanner data. *International Journal of Remote Sensing* **6**: 115-125.
- Lantieri, D., 1988, Use of high resolution satellite data for agricultural and marine applications in the Maldives. Pilot study on Laamu Atoll. *Fisheries and Agricultural Organisation Technical Report TCP/MDV/4905*. No. 45.
- Pirazzoli, P.A., 1985, Bathymetry mapping of coral reefs and atolls from satellite. *Proceedings of the 5th International Coral Reef Congress, Tahiti*, **6**: 539-545.
- Warne, D.K., 1978, Landsat as an aid in the preparation of hydrographic charts. *Photogrammetric Engineering and Remote Sensing* **44** (8): 1011-1016.
- Van Hengel, W. and Spitzer, D., 1991, Multi-temporal water depth mapping by means of Landsat TM. *International Journal of Remote Sensing* **12**: 703-712.
- Zainal, A.J.M., Dalby, D.H., and I.S. Robinson., 1993, Monitoring marine ecological changes on the east coast of Bahrain with Landsat TM. *Photogrammetric Engineering and Remote Sensing* **59** (3): 415-421.

Answers to Questions

- 4.1. The image is 26.4 km across and 29.7 km along track (north-south).
- 4.2. 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 4.2. DN values for deepwater pixels (sample size = 2500).

	Landsat TM band			
	1	2	3	4
Maximum deepwater DN value ($L_{\text{deep max}}$)	57	16	11	5
Minimum deepwater DN value ($L_{\text{deep min}}$)	49	11	7	3
Mean/modal deepwater DN value ($L_{\text{deep mean}}$)	52.706/53	13.364/13	8.842/9	3.937/4

- 4.3. The depth of penetration (z_1) for TM band 1 must lie somewhere between 18.70 and 25.35 m.
- 4.4. The average depth of pixels in this range which have DN values greater than $L_{\text{deep max}}$ (57) is 21.7 m.
- 4.5. The average depths of pixels in this range which have values less than or equal to $L_{\text{deep max}}$ (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		
	20.14	62		
	25.35	61		
	23.20	61		
	21.01	60		
	20.45	59		
> $V_{\text{deep max}}$	20.09	59	Average depths	Z_1
			21.7	20.8
$\leq V_{\text{deep max}}$	21.04	57	19.9	
	20.09	57		
	18.70	56		

Table 4.3. Calculating the maximum depth of penetration (z_i).

	Landsat TM band			
	1	2	3	4
Depth of deepest pixel with $DN > L_{\text{deep max}}$	25.35	15.26	4.70	1.55
Depth of shallowest pixel with $DN \leq L_{\text{deep max}}$	18.70	12.46	3.71	0.66
Average depth of boundary pixels with DN values $> L_{\text{deep max}}$	21.7	13.8	4.3	1.0
Average depth of boundary pixels with DN values $= L_{\text{deep max}}$	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		
	13.14	20		
	13.14	19		
	15.26	17		
	14.65	17	Average depths	Z2
	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		

- 4.6. 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.
- 4.7. 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.
- 4.8. 14320 TM2 pixels in DOP zone 2 have values = 17 ($L_{2 \min}$).
- 4.9. The highest DN value of the TM2 pixels in DOP zone 2 is 41.
- 4.10. 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 4.5. $L_{i \min}$ 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 4.9 and 4.10).

	TM Band 1	TM Band 2	TM Band 3	TM Band 4
DOP 1	58 - 69			
DOP 2		17-37		
DOP 3			12 - 53	
DOP 4				6 - 42
k_i	0.0797	0.0963	0.4196	1.4722
A_i	4.9236	3.9872	4.6234	3.6376

- 4.11. It is difficult to judge fine gradations in colour such as the BATHYBLU.PAL palette displays. So the BATHYCON.PAL palette conveys the most information, allowing you to assign areas to depth zones very easily.
- 4.12. 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.
- 4.13. 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.
- 4.14. 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.
- 4.15. 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.