BATHYMETRIC MAPPING OF CORAL REEFS IN THE RED SEA (HURGHADA – EGYPT) USING LANDSAT7 ETM+ DATA*

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ABSTRACT

For monitoring threats posed on coral reefs a bathymetric map is useful as a base to locate vulnerable areas. For mapping shallow features as coral reefs in the Red Sea, conventional echo sounding methods are usually inappropriate due to the draught of the vessels used. Here remote sensing can bring a solution. Different methods have already been developed to map bathymetry using passive remote sensing. In this paper the modified Depth of Penetration mapping method suggested by Green et al. (2000) is implemented on a Landsat7 ETM+ image. This method is mainly based on the different attenuation coefficients of sequencing wavelengths in water. Using additional ground-truth observations, depths can be estimated. Although this method results in an acceptable bathymetric map, some deviations from ground-truth occur. These differences caused by errors inherent to the method used, field sampling or implementation, are examined and possible solutions are presented.

1. INTRODUCTION

The PhD-study in which this paper concerning bathymetric mapping frames, investigates the possibilities to develop a monitoring system for the coral reefs in the Red Sea based on remote sensing. Remote sensing techniques are used firstly to derive information about the location of the coral reefs (X-, Y- and Z-coordinates), their structure (delineation between different seabed classes such as coral, algae, seagrass or sand) and their condition. Secondly remote sensing can also contribute in monitoring the physical and/or chemical conditions of the Red Sea. These remote sensing based results are combined in a GIS together with information concerning different threats posed on the coral reefs (e.g. coastal development, land-based pollution or rises in sea temperature). As one of the outcomes, a risk map will be created which marks the degree of stress posed on the reefs in the Red Sea. This map can be used as a back up for coastal planning by government, coastal developers, environmentalists or other decision makers.

This paper, specifically, is dealing with the problem of mapping bathymetry using passive remote sensing. Different methods have already been developed. One theory, the bottom-reflection based remote sensing theory (Ji et al., 1992), states that, up to a certain depth, part of the signal recorded by the sensor is coming from the reflectance of the bottom. In clear water the seabed can reflect enough light to be detected

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by the satellite sensor even when depth of water approaches 30m (Green et al., 2000). Green et al. (2000) evaluated some of the methods developed (Benny & Dawson, 1983; Jupp, 1988; Lyzenga, 1978; Van Hengel & Spitzer, 1991) based on this theory. Using the Pearson product moment correlation coefficient, the Depth of Penetration (DOP) mapping method developed by Jupp (1988) was considered the most accurate method.

The basic principle behind the method of Jupp (1988) is that different wavelengths of light penetrate water to varying degrees. Longer wavelength light (red in the visible part of the spectrum) has a higher attenuation coefficient than short wavelengths (e.g. blue). There will be a depth, the maximum depth of penetration for red light, at which all the light detected by band 3 of the Landsat7 ETM+ sensor (0.63 - 0.69nm) has been fully attenuated. However at this depth there will still be some light that is detectable by bands 2 (green) and 1 (blue) of the ETM+ sensor. DOP zones are delineated by the maximum depths of penetration of successive bands with shorter wavelengths (Green et al., 2000).

To build up the method of Jupp (1988) 3 additional assumptions have to be made (Green et al., 2000):

- light attenuation is an exponential function of depth,
- water quality (hence the attenuation coefficient k) does not vary within the image,
- reflectance properties of the substrate are fairly constant (homogeneous substrate).

A depth of penetration mapping method modified from Jupp (1988) by Green et al. (2000) will be used in this paper to calculate bathymetry.

2. METHODS

2.1 STUDY AREA

As study area the coral reefs near Hurghada (Egypt) (27°14'N 33°54'E), situated in the northern part of the Red Sea, are selected (Figure 1). The coral reefs are located in a unique environmental setting: the enclosed Red Sea is completely surrounded by deserts, has almost no water input from rivers and hence very stable physical characteristics such as salinity, temperature and water quality. Although the coral reefs are not under great natural threat, they are suffering from the negative effects of booming tourism and urban coastal development projects mainly for tourist accommodation and in support of the relocation policy executed by the Egyptian government.

2.2 DATA SOURCES

2.2.1 Field Data

A field survey has been executed between August 25th, and August 31st, 2001. During the campaign, 159 observations (Figure 1, marked in red) were made at sea. X- and Y-coordinates were measured using a GPS (Garmin GPS 12 XL) in the UTM 36 – WGS84 coordinate system. Depth values were derived using a hand-held sonar (Manta Dive Ray DR-100) with an accuracy of 0.3m above and 1.0m below 10m. A Zodiac was used in order to reach shallow areas. Besides 31 ground control points have been measured on the land (Figure 1, marked in blue). These points are necessary to georeference the satellite image used. The X- and Y-coordinates were again measured using the GPS.

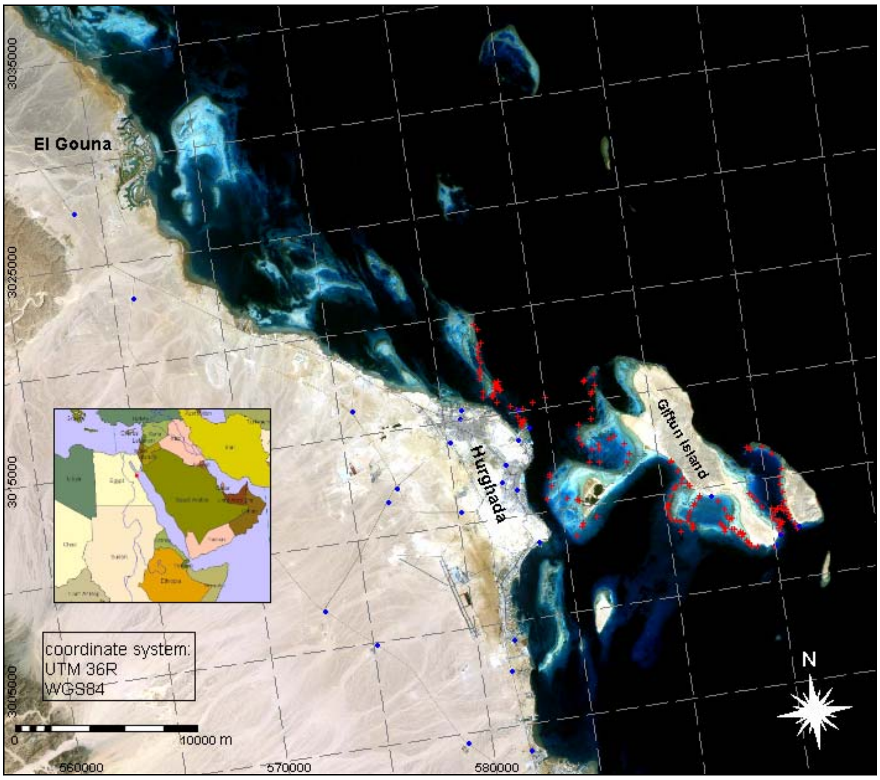

Figure 1. Study Area with Localisation of the Observation Points

2.2.2 Tidal Data

Tidal data are derived using the free tidal prediction program *WXTide32 version 2.6* (©1998-2000, M. Hopper) for 3 stations in the neighbourhood of Hurghada (Shadwan Island (27°17' N, 34°02'E), Quseir (26°06'N, 34°17'E) and Ashrafi Island (27°47' N, 33° 43'E)). The tide for Hurghada has been extrapolated using these data based on a weighted distance method. The depths measured during field survey are then corrected to datum (Lowest Astronomical Tide) based on these tidal values. The tide at the moment of the image recording (10/09/2000, 08:03 GMT) is calculated to be 0.24m above datum.

2.2.3 Satellite Data

A level-2 Landsat7 ETM+-image (ID: LE7174041000025450; path/row: 174/041) dating from 10/09/2000 is used to delineate the depth of penetration zones in the study area. Wavebands 1, 2, 3 and 4 are used because these wavelengths are not totally absorbed by the water column. The ILWIS 2.3 – software is utilized to georeference a sub-scene covering the study area. As ground control points, 21 points measured on the land during the field survey are used. The georeference is based on a specific UTM- coordinate system (UTM R36 – WGS84) using a 'full second order' equation. Satellite images are only roughly atmospherically and radiometrically corrected because no adequate correction model was available during implementation.

2.3 MODIFIED DEPTH OF PENETRATION MAPPING METHOD (Green et al., 2000)

For the exact procedure of the modified depth of penetration mapping method is referred to Green et al. (2000) and the ‘BILKO for WINDOWS-manual’ (Edwards, 1999) where the method is applied to a Landsat TM image over part of the Turks and Caicos Islands. The procedure can be split in two sections: first the determination of the different DOP zones and secondly the interpolation of depths in each zone.

2.3.1 Calculation of Depth Of Penetration (DOP) Zones

The image is divided into different DOP zones. Green et al. (2000) define a DOP zone as “a region in which light is reflected in one band but not in the next”. For example, the first DOP zone represents those depths in the image where only band 1 of the ETM+ sensor is still receiving some reflectance of the bottom. DOP zone 2 receives reflection in the blue and green band but not in the red and near infrared, and so on.

First, reflection over a deepwater area, $L_{i\,\infty}$, needs to be examined. These reflection values are necessary for different reasons. It is assumed that the signal received at the sensor over deep water is entirely composed of reflection by the atmosphere, the water surface and the water column. Therefore, the mean deepwater reflectance, $L_{i\,\infty\,mean}$, will be used to eliminate roughly the atmospheric and water column effects on the signal. The maximum deepwater reflectances, $L_{i\,\infty\,max}$, will be used to delineate the different DOP zones. If the DN-value in an image of a waveband *i* is greater than $L_{i\,\infty\,max}$, some reflectance of the seabed is assumed to be present in the signal received by the sensor (Green et al., 2000). These deep water DN-values are determined in a subset (UL: 587 131 N / 3 037 526 E; LR: 608 218 N / 3 025 559 E) over an area with depths greater then 50m as determined on the nautical chart 3034-B Hurghada (UK Hydrographic Office, 1997).

Table 1. Maximum, Mean and Minimum DN-Value in ETM+ Band 1,2,3 and 4 over a Deepwater Area

	LANDSAT 7 ETM+ (Path/row: 174/41; date: 10/09/2000)			
	Band 1	Band 2	Band 3	Band 4
Max. DN-value for deep water	65	41	36	21
Min. DN-value for deep water	54	32	25	15
Mean DN-value for deep water	60	37	30	18

Secondly, the maximum depth of penetration for the Landsat7 ETM+ bands 1 to 4 is calculated (Table 2). For each band *i*, this depth is determined by the deepest pixels with a DN-value greater than the maximum deepwater value, $L_{i\,\infty\,max}$.

116 out of the total of 169 observation points are used to estimate the maximum depth of penetration for each waveband. These points are selected based on homogeneous substrate and reliability. Observed depth values referred to datum are corrected for the tide at the moment of image acquisition (0.24m above datum). These points are located on the georeferenced satellite image and the DN-value, for each band, of every observation point is derived. An exact explanation of the procedure to determine the values in table 2 is given in Edwards (1999).

Table 2. Determination of Maximum Depth of Penetration for ETM + Waveband 1,2,3 and 4

	LANDSAT 7 ETM+ (Path/row: 174/41; date: 10/09/2000)			
	Band 1	Band 2	Band 3	Band 4
Deepest pixel: DN > $L_{i\,\infty\,max}$	18.00	18.00	10.81	8.01
Shallowest pixel: DN ≤ $L_{i\,\infty\,max}$	16.00	16.00	3.65	0.99
Average depth: DN > $L_{i\,\infty\,max}$	18.00	18.00	5.36	2.95
Average depth: DN = $L_{i\,\infty\,max}$*	16.81	16.81	7.35	2.67
Max Depth of Penetration: z_i	17.41	17.41	6.35	2.81

* There are no pixels in the selection for bands 1 and 2 with a DN-value equal to $L_{i\,\infty\,max}$. Therefore, instead, the average depth of pixels with DN ≤ $L_{i\,\infty\,max}$ is calculated.

In table 2 the maximum depth of penetration is presented. These depths are equal for ETM+ band 1 and band 2. This means that the green light penetrates the water to the same depth as the blue light. This is in contradiction with the theory that longer wavelengths are more attenuated. Two explanations can be found. First the physical and/or chemical composition of the water can cause a higher attenuation of the blue light than expected based on the model. A second, more probable, explanation is based on the fact that little depth observations below 10m are used to estimate maximum depth of penetration. In that case it is difficult to determine the maximum depth at which blue light is still reflected by the seabed and recorded by the sensor. Due to this problem, the first Depth of Penetration zone (DOP zone 1) will not be used to map bathymetry.

2.3.2 Interpolation and Calibration of Depths within the DOP Zones

In between the maximum depth of penetration for each band and the surface, assuming the substrate remains constant, the DN value is purely a function of depth. The value, L_i, of any submerged pixel can be expressed as (Green et al., 2000):

$$L_i = L_{i\,\infty\,mean} + (L_{i\,surface} - L_{i\,\infty\,mean})e^{-2\,k_i z} \quad (1)$$

Where $L_{i\,\infty\,mean}$ = the average pixel value for band *i* over deep water, due to the reflection from the water column, the surface and scattering from the atmosphere
$L_{i\,surface}$ = the average DN value at the sea surface,
k_i = the attenuation coefficient for band *i*, and
z = depth.

Jupp (1988) and Green et al. (2000) transformed this equation until they reached following formula to interpolate depth, z, for each DOP zone:

$$z = (A_i - X_i)/\,2k_i \quad (2)$$

With:

$$X_i = \log_e (L_i - L_{i\,\infty\,mean}) \quad (3)$$

$$k_i = (X_{i\,max} - X_{i\,min})\,/\,2(\,z_i - z_{i+1}) \quad (4)$$

With:

$$X_{i\,max} = \log_e (L_{i\,max} - L_{i\,\infty\,mean}) \quad (5)$$

$$X_{i\,min} = \log_e (L_{i\,min} - L_{i\,\infty\,mean}) \tag{6}$$

$$A_i = X_{i\,min} + 2z_ik_i \tag{7}$$

Where: L_i: DN-value for a pixel in band *i*
$L_{i\,\infty\,mean}$ can be found in table 1
$L_{i\,min}$ and $L_{i\,max}$ are given in table 3. Again, for an exact procedure to determine these values, is referred to Edwards (1999).
z_i can be found in table 2

Table 3. Different Parameters Necessary for Interpolating Depth in Each DOP Zone.

	LANDSAT 7 ETM+ (Path/row: 174/41; date: 10/09/2000)			
	Band 1	Band 2	Band 3	Band 4
$L_{i\,min.}$–$L_{i\,max.}$ in DOP 1	66-68	▨	▨	▨
$L_{i\,min.}$–$L_{i\,max.}$ in DOP 2	▨	42-63	▨	▨
$L_{i\,min.}$–$L_{i\,max.}$ in DOP 3	▨	▨	37-82	▨
$L_{i\,min.}$–$L_{i\,max.}$ in DOP 4	▨	▨	▨	22-99
k_i	/	0.075	0.279	0.537*
A_i	/	4.217	5.511	4.394

* Remark: for the calculation of k_4: z_{4+1} is set to 0 (sea surface)

3. RESULTS

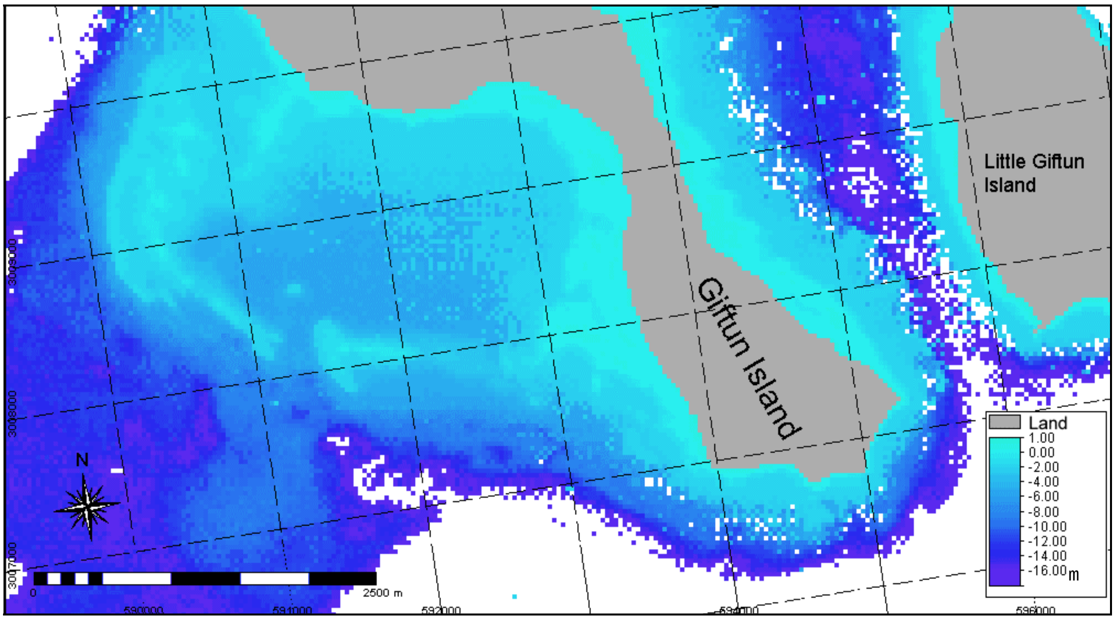

Figure 2. Bathymetric Map of Part of the Study Area

The result of equation (2) can be seen in figure 2 showing a bathymetric map with pixel-based (900m²) depth values. No additional field data so far is available to check independently for accuracy of the estimated depth values. Nevertheless, if the same observed depth values are used as for calculation, an indication of the level of accuracy can already be given. The strength of correlation, expressed by the Pearson product moment correlation coefficient, between predicted depth and actual depth, and the average difference between measured depths and calculated depths are used as a measure of accuracy. A correlation coefficient of 0.80 is reached compared to a correlation coefficient of 0.91 obtained by Green et al. (2000). A mean difference of 1.6m is calculated but with a standard deviation of 2.2m. Green et al. (2000) became an average difference ranging from about 1.0m in shallow (<2.5m deep) to about 2.7m in deeper water (10 - 20m deep). The average difference calculated in this paper is more or less corresponding with the accuracy reached in Green et al. (2000), though the Pearson correlation coefficient in this case is slightly smaller.

4. DISCUSSION

Although the method presented by Green et al. (2000) is promising and offers results in a reasonable fast and easy way, some differences with ground-truth occur. These deviations originate from different sources.

Some errors are caused by assumptions or formulas inherent to the method used. The albedo and reflective properties of the substrate and the quality of the water are likely to vary in such a heterogeneous structure as coral reefs are. So the assumption of homogeneous substrate, in the first place, and unchanging water quality all over the image, is one potential source of errors.

As already mentioned by Ji et al. (1992) the crude method of atmospheric and water column correction will introduce an error in model calculations. Due to overdeduction at locations having lower water column contribution ($L_i \leq L_{i \infty \text{ mean}}$), a zero or negative value for ($L_i - L_{i \infty \text{ mean}}$) occurs. These values cannot be used to calculate valid natural logarithms necessary in equation (3). Results should therefore be more accurate if radiometric and atmospheric corrections are applied to the satellite data.

Other errors are generated by characteristics of the field, the sampling method or the satellite data used. While making depth measurements from the Zodiac, the position of the vessel is unstable due to movements caused by currents and waves. This will generally not produce large deviations and, with a resolution of 30m of the satellite data used, the deviations will be negligible. Nevertheless if an observation is situated near the edge of a pixel, uncertainty can raise which DN-value corresponds to the depth measured. Errors of GPS-readings are also occurring, but with a general deviation of 4m, these errors are again most of the time negligible confronted with the spatial resolution of the data. Secondly, errors are caused due to the very heterogeneous character of the study area. Coral cays and reef fronts are interspersed by bare sand over a few meters. Due to the resolution of the data used, a generalisation of reflectance over a very heterogeneous area of 900m² is made. These problems are referred to as the spatial and radiometric uncertainty of the satellite data (Edwards, 1999).

Finally, as the Pearson coefficient obtained using the same observed depth values as the ones used in the model is only 0.80, some errors are also due to inefficiency during model implementation. First of all, only 116 observations points are used instead of the 750 sites measured by Green et al. (2000). This may cause inaccuracies in the interpolation of depth. Secondly, due to lack of field observations in areas deeper then 10m, the first DOP zone using the ETM+ waveband 1, couldn't be delineated. This lack of observations is partly caused by the general topography of the seabed were steep 'drop-offs' are common between the relatively undeep coral reefs and coral flats and the deep seafloor of the Red Sea.

During a new field campaign from March 21st, till April 4th, 2002 new field observations will be made in order to refine the model and to check accuracy of the method applied independent from the observations used for modelling. This will make it possible to give more accurate judging of the method used.

5. CONCLUSIONS

Bathymetric mapping of coral reefs, necessary as a base for monitoring them, using remote sensing has the advantage of reaching areas not easily accessible by conventional sounding boats. In the method described in this paper additional in situ depth measurements are still necessary for adequate depth estimations. Although some adjustments have to be made during implementation of the model, the preliminary results presented here are promising. The paper expresses the need for sound atmospheric and radiometric correction of the satellite data and a sufficient set of ground-truth data and observations spread over the total depth range occurring in the area, preferably over a homogeneous highly reflective substrate.

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