PASSIVE MULTISPECTRAL BATHYMETRY MAPPING OF NEGRIL SHORES, JAMAICA

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ABSTRACT

A new method was tested using SPOT images for mapping of variations of the reflectances and depth of sea-bottom French Polynesia, where the standard error on computed depth was less than 0.2 m for average depths of 2 m. The method uses "soils line" for zero-depth calibration and "brightest pixels line" for diffuse attenuation coefficients and actual value of K as linear functions of band ratios, thus providing bottom depth and reflectances without field data. This method has been blind-tested using Landsat TM data. TM should improve the possibilities of mapping deeper waters thanks to blue wavelength band. Preliminary results show very promising correlations with the echo-sounded sections along the Negril coast of Jamaica, where the bottom is a mixture of sand, corals and sea grass and 2K values of at 0.179, 0.251, 0.899 m-1 are estimated from the image at 486, 570 and 660 nm respectively. The outlines and performances of the PMBM process are presented, and the results of its application at Negril are presented and discussed.

1.0 INTRODUCTION, LOCATION AND PREREQUISITES

Jamaica, located in central Caribbean with a size of about 11000 km2 and a population of 2.5 mill. inhabitants, has an economy that is strongly dependent on operations in the coastal area. The foremost national income emanates from beach based tourism. One of the latest, highly tourist developed areas is Negril (Fig. 1), with mile long beaches and nice coral reefs outside. This area is dominated by a flat lowland coastal zone with a marsh back land. The beach and the near shore bottom consist of white sand. The bottom elsewhere is of very complex nature, with a mixture of sand, sea grass, scattered coral heads and reefs (Fig. 1). Most of the coastal waters around Jamaica are clear, nutrient and suspended poor. The Negril area has been heavily expanding, causing hygienic water problems, but the exchange of water in this region is large, making the water still quite clear. During recent years the EU has contributed to restoration measures in Negril.

Sea-charts of the area are very rudimentary and need updating. During a coastal zone planning project (Norrman *et. al.*,1997), one of the tasks was to map the bottom characteristics around Jamaica. For this purpose, a number of Landsat TM scenes were used in combination with aerial photos and extensive field data sampling. Many different approaches from the literature were used to try to efficiently make depth charts of the coastal zone, but with limited success. For more than two decades, many efforts have been applied to operate various types of models to map bottom depths, starting with the early research at ERIM (Polcyn *et al.*,1970; Lyzenga, 1978). Much of this research was based on the assumption that the diffusion and reflectance in the water and the atmosphere followed models, neglecting all types of disturbances like suspended matter etc. and therefore using a simple "darkest pixel" correction. Mapping of water depths in areas with complex and varying bottom conditions has been performed by Luczkovich *et al.*(1992) using separate training areas for different types of bottom cover. However, few constructive solutions have been presented where models for reflectance conditions for different surfaces have been used. One of us, a marine geologist (Morel, 1996), spent the last four years reviewing recently published contributions and testing new concepts on a large data bank of SPOT images of Pacific islands: the purpose of this paper is to provide a brief outline a new method, called PMBM, to conduct a blind test using a Landsat TM image, and then evaluate it with field data.

2.0 THE PASSIVE MULTISPECTRAL BATHYMETRY MODELER (PMBM)

This expression refers to the modeling of the variations of the bottom depth and reflectance in clear and shallow waters using bottom-reflected sun light captured in two or more wavebands by an airborne or space borne imager. In contrast with all other methods in use to-date, the PMBM process does not rely, for the calibration of the model parameters, on the acquisition, reduction, classification and statistical analysis of a preliminary set of field data which are costly to obtain and difficult to process. The basic equation used is directly derived from the simplified radiative transfer equation for optically shallow water. The theory behind this equation has been discussed in detail by Philpot (1989), and Maritorena *et al.*(1994) found it to be consistent with detailed measurements of diffuse irradiance in the underwater light field in the clear waters of French Polynesia, and also with a Monte Carlo simulation of bottom-reflected photon paths. Following is its transcription for nadir radiances at the water-air interface (BOA):

$$\mathbf{L = Lw\ [1 - exp(-KZ)] + LB\ exp(-KZ)} \quad (1)$$

with

L nadir radiance measured over a shallow bottom;

Lw nadir radiance measured over a water column of infinite optical height;

LB nadir radiance measured over the bottom if it were placed at a null depth;

Kin m^{-1} an operational two-way diffuse attenuation coefficient;

Zin m the actual depth of the bottom.

For clarity, the wavelength subscripts have been omitted. Note that, because the " ratio methods" of bathymetric modeling are only concerned with ratios, the unit for the reflectance values does not need to be specified. For a remote sensing application, the atmospheric path radiance -La- and the sun and sky glints -Lg- must be added to both sides of equation (1), so that the nadir radiance Ls measured by the remote sensor at the top of the atmosphere (TOA) is the sum L+La+Lg. Finally, the optical properties of the atmosphere and water are assumed to be homogeneous. Some uncertainties remain about what actually is represented by the term K in this model, but the last mentioned authors conclude that *" this approximate formulae can be safely adopted in operation when ... interpreting the reflectance of shallow waters, in particular if Lw and K have been estimated from remotely sensed data ".* A detailed presentation of this optical theory will be published shortly by Andréfouët *et al.*(1998?).Readings from Jerlov (1974 and 1976), Kirk (1989 and 1994) and Maritorena (1996) complete the basis of the PMBM process.

In the case of a pair of wavebands i and j, two concepts are central to the PMBM process:

- assuming a constant value of the ratio LB_i/LB_j of bottom reflectances: this concept was introduced by Polcyn *et al.*(1970) in the " simple ratio " method for computing bottom depths;
- measuring the ratio K_i/K_j of the attenuation coefficients directly in the remotely sensed data; this concept was introduced by Lyzenga (1978) for producing a " depth-invariant " image of the bottom.

But the PMBM process is original on the following three accounts:

- the non-vegetated areas on the dry land part of the image are analyzed in all possible pairs of wavebands i and j, in order to provide the operational values of the ratios LB_i/LB_j. These values are then assumed to apply to spectrally non-differentiated shallow water pixels;
- the shallow water part of the image, which is assumed to contain at least some stretches of bright sands at various depths, is analyzed in order to provide the operational values of the ratios K_i/K_j in all possible pairs of wavebands;

- these values of K_i/K_j are used as entry points for deriving the actual values K_i and K_j of the attenuation coefficients in wavebands i and j directly from the diffuse attenuation properties of marine waters in the visible domain (400-700 nm) described in table XXVII of Jerlov (1976).

Along with the measurement of the deep water radiance values in optically deep parts of the image, this completes the set of parameters that are necessary for operating equation (1) without the need or use o+f any field data. For a given shallow water pixel, Z takes the value which, for that particular pixel, is consistent with the assumptions made on the relative values of the various ratios LB_i/LB_j in the pairs of wavebands which actually exhibit bottom detection. If the bottom is detected in two wavebands only, a non-spectral LB value is obtained, with which to form a " depth-invariant " image of the bottom as proposed by Lyzenga; but Z can be offset by up to approximately plus or minus 25 % of the maximum depth range if the bottom at that pixel actually has a strongly differentiated spectral signature. Detection of the bottom in more than two wavebands allows for a better estimation of Z, and therefore yields a more spectrally consistent set of spectral bottom reflectances associated to the pixel, which are then available for thematic classification.

3.0 THE PERFORMANCES OF THE PMBM PROCESS WITH SPOT HRV

The PMBM process has been tested extensively with a data bank of over 100 SPOT HRV images across the Pacific islands, where optical oceanic water types OI to OIII of Jerlov are found. It has also been tested with two SPOT images of the Atlantic coast of France where optical coastal water types C5 are found. It is being tested presently with Landsat TM images, airborne spectrographic imagers data, and scanned aerial color photographs. As illustrated in Table 1, the PMBM calibration of the attenuation properties of visible light for nadir radiance in marine -mostly oceanic- waters is satisfactory. The table lists the two-ways attenuation coefficients in the Blue, Green and Red wavebands for Jerlov's marine water types OI to OIII and C1 to C9. ZM values are for a bottom contrast of 200 (the bottom contrast is the quantity LB-Lw): ZM=ln(200)/K. General results for 39 calibrations are summarized: 36 are for waters of various coral reef lagoons, mostly atolls, while two are for the Atlantic coast of France and one is for coral reef waters in Jamaica. All these calibrations, and many more, proved to be straightforward, thanks to the presence of bright sands at various depths. Note that, except in the case of the Jamaican image, those calibrations have been done using SPOT HRV images; therefore their K[490] values could not be confirmed. 15 of these results, including the three outside the Pacific, have been confirmed to be correct using field data, and none has showed to be incorrect. Maximum depths of bottom detection for Blue-Green-Red wavebands, noted ZM in table 1, have been confirmed in the Green waveband in atolls where the bottom type throughout is bright coral sand/mud. For example, under this last assumption and using the Green waveband, we have been able to produce depth contour lines down to a maximum of 40 m for the lagoons of Manihi and Takapoto atolls (water type OI), 32 m for Rangiroa and Taenga (water type OIB), 25 m for Takume (water type OII) and 15 m for Tarawa (water type OIII+); these performances, and more, have been confirmed with precision bathymetric sounding lines or existing nautical charts; they outpass by far those predicted by Maritorena *et al.*(1994) on the basis of diffuse attenuation of down welling irradiance. Observed K value for the NIR band at 850 nm is stable around 5. With regards to precision, we have conducted a sea truth exercise in the lagoon of Moorea, located next to Tahiti in French Polynesia, with over 1000 20 m pixels tested in over 40 sounding lines extending EW or NS from fringing reef to reef crest at an average depth of 2 m: we observed an average of 0.19 m on the absolute difference ZR-ZC between recorded and computed depths. This result is consistent with that predicted by Philpot (1989), being of approximately 10 % of the average depth and increasing exponentially according to the actual value of Z.

4. PMBM BLIND-TESTED IN JAMAICA WITH LANDSAT TM

4.1. FIELD AND SATELLITE DATA

Field data was collected during 1986-87 using an automated system, consisting of a lap-top, an echo-sounder with thermistor and log, and a GPS. Data could be collected either continuously or on command. The standard setting was "continuous" and thus all sensors, including positions, were logged every 8-10 seconds, which was more or less a depth recording similar to a paper chart. When our boat crossed from one type of bottom to another, this information was added in text format to the stream of data. The data was then used in a supervised classification by means of a maximum likelihood classifier. This crude classification was then edited and improved by interpretation of color aerial photos. The final classification was used in the separation of bottoms types for the present task. The satellite dataused was a Landsat TM image from 1985, one of very few scenes with cloud-free Jamaican coastline. The tide in Jamaica is less than 0.5 m, and should not complicate the present work. No differential GPS was used, but the ordinary accuracy was considered sufficient for the satellite image spatial resolution of 30*30 m.

4.2. APPLICATION OF PMBM TO LANDSAT IMAGE OF NEGRIL

As part of a public offer for this new process to be tested, a 500*500 subset of this Landsat image representing Negril was provided through the Internet. No location or information of any sort were communicated until the time of final writing of this paper. This image conveniently shows to have been acquired on a " calm and clear " day, as it contains no evidence of strong wind nor of clouds. Its histograms extend continuously through almost all of the 0-255 dynamic range of 8 bits images. Of 250.000 pixels, 53% are over deep ocean water, 36 % over dry land, and 10.6 % over shallow water. Of 26.574 shallow water pixels, 15 % show bottom detection in the BGR bands, 83 % in GB bands, and 1.6 % in the Blue band only. Because less than 4,000 pixels show bottom detection in the three RGB bands, the calibration of optical properties of the water is mainly based on the value of the K[Blue]/K[Green] ratio. Indeed, after linearization of the data (X=ln[Ls-Lsw]), the brightest pixels plot in a reasonably linear manner in the G vs B space, which testifies of the presence of bright sands over the whole shallow depth range. The slope of this " exponential decay " is measured at K[Blue]/K[Green]=0.7 with good precision, which makes for a water type approximately halfway between OII and OIII of Jerlov.

The following calibration parameters were obtained at 486, 570, 660 and 830 nm respectively:

- Lsw deep water radiances values at 64, 16, 12 and 4. Strong striping is observed in band TM4 only. Sky glint is strong in band TM1 (Lsw at 65 to 71, average 68). A distinct loss of deep water radiance (Lsw at 63 to 69, average 65) is observed along the outer slope of the reef, suggestive of deep water welling up and moving outwards from the coast;
- Lw+Lg radiances finally estimated at 9 in band TM1 and null in other bands;
- LsBmax radiances for a bright coral reef sand at 190, 100, 135 and 150;
- K values at 0.179, 0.251, 0.899 and 5 m^{-1}.

These parameters were then provided in the command line of the PMBM software to compute, using the original TM image, one value of Z and N spectral values of LB for each shallow water pixel in one single run, where N is the number of bands assumed to have detected the bottom at that pixel. Close inspection of the Z image and of the LB images obtained then warrants a number of iterative runs until parameters are finally adjusted to values that are compatible with a consistent and satisfactory result, the most sensitive parameter being Lw in the Blue band. Figure 3A displays the image of computed depths, and figure 3B displays the image of computed bottom reflectances in the Green band.

4.3. SEA TRUTH OF COMPUTED DEPTHS

The comparison of computed depths ZC with field-recorded depths ZR is presented in figure 2for 83 pixels which evenly sample the variety of bottom types mapped in the classified image of figure 1. Field data indicate that the terrain is far from level: indeed, for 21 pairs of contiguous pixels, 6 pairs exhibit a difference in recorded depth in excess of 2 m with a maximum of 4.7 m. For 24 of these 83 points (29%) ranging from 1.9 to 17.2 m with an average depth of 7.3 m, an agreement of ZC is found within 0.5 m of ZR. As for the remaining 59 points (71%) ranging from 1.5 to 16.6 m with an average depth of 7.5 m, a best fit was also noted within a 3*3 neighborhood for two points out of three, or within a 5*5 pixels neighborhood for one point out of three. For these 59 points, the discrepancies ZR-ZC range from 0.6 to 6.8 m; this best fit method reduced this by an absolute average of 2.1 m. With regard to the bottom type at each of these points, there are 13 seaweed at an average depth of 3.5 m, 30 sand at 6.8 m, 19 mixed bottom at 7.9 m, 18 sand/coral at 9.1 m, and 3 NA. Discrepancies, at an average absolute ZR-ZC value of

1.3 m, show no particular trend among the first three categories; but they are twice higher for the sand/coral category which lies deeper and contains coral growths.

5. DISCUSSION AND CONCLUSIONS

The test was not entirely blind, as a great improvement was gained in the >10 m depth range by ultimately increasing Lsw[Green] from 16 to 16.5: this last-minute change allowed us to compute increased depths -and brighter bottom reflectances- with negligible change in the <10 m range. As shown in figure 2, these improved depths compare well with the field data provided. Not only sky glint adds to the data, but it is also a source of noise; therefore the same values of Lsw do not apply to each and every pixel across the image, although we cannot account for that limitation. In PMBM, the pixels which are automatically selected for the estimation of Lsw_j and K_i/K_j are those containing lowest sky glint, while the majority of pixels are best treated with slightly higher Lsw values.

The innovations introduced with the PMBM approach warrant an in-depth inspection of a number of points, particularly a study of the sensivity and the mapping of the potential final error, which is out of the scope of this brief presentation. Remarkably, we have observed an excellent linearity of the exponential decay with 20 m pixels in atolls, and it is even more the case with airborne imagery. The reason is that the higher the resolution, the greater the number of " pure " spectral signatures, of bright sands in particular, are present over the whole depth range. The values of K_i/K_j ratios are thus determined with a very good confidence, particularly so with a pair involving the Blue and Green wavebands because K[Blue] varies by large proportions compared to K[Green] across Jerlov 's classification of marine water types (table 1). It is now likely that the values of the attenuation coefficients derived using Jerlov's data for worldwide marine waters may be used with acceptable confidence. The lack of a good representation of diversified barren dry land in the image, from very bright to very dark, sometimes precludes a satisfactory study of the LB_i/LB_j ratios and of the split of Lsw values; this is the case for the image of Negril, where hardly any dry land pixel is vegetation-free. Lsw values are very sensitive parameters, and particularly how they are to be split into Lw, La and Lg; the Blue band is the most sensitive in this regard, because of the extremely low attenuation contributed by the water component itself.

It is therefore demonstrated that the PMBM process is about to reach an operational status using satellite data, but more blind tests ought to be conducted using the Blue band. This may potentially lead to the systematic processing of the large data banks of TM and HRV coastal images, thus providing reference data in view of the rising move worldwide towards a permanent monitoring of the status and health of the coastal environment. The very high spatial and spectral resolution of the various sensors which will shortly be placed in orbit will add to the potential interest of the PMBM process.

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W-type (Jerlov)	Nber test'd	Nber conf'd	K[490] (m^{-1})	K[550] (m^{-1})	K[650] (m^{-1})	*ZM[490] (m)*	*ZM[550] (m)*	*ZM[650] (m)*
OI	1	1	0,047	0,126	0,72	*112,7*	*42,1*	*7,4*
OIA	3	2	0,06	0,135	0,741	*88,3*	*39,2*	*7,2*
OIB	8	6	0,079	0,145	0,752	*67,1*	*36,5*	*7,0*
OII	16	3	0,139	0,181	0,805	*38,1*	*29,3*	*6,6*
OIII	9	1	0,224	0,236	0,884	*23,7*	*22,5*	*6,0*
C1	0	0	0,304	0,24	0,9	*17,4*	*22,1*	*5,9*
C3	0	0	0,519	0,398	0,933	*10,2*	*13,3*	*5,7*
C5	2	2	0,777	0,601	1,08	*6,8*	*8,8*	*4,9*
C7	0	0	1,272	0,923	1,262	*4,2*	*5,7*	*4,2*
C9	0	0	2,172	1,26	1,52	*2,4*	*4,2*	*3,5*

Table 1. Performances of the PMBM process
for three Landsat TM wavebands in various marine water types of Jerlov.
Attenuation coefficients in m^{-1} and maximum depth of bottom detection in meters are shown.

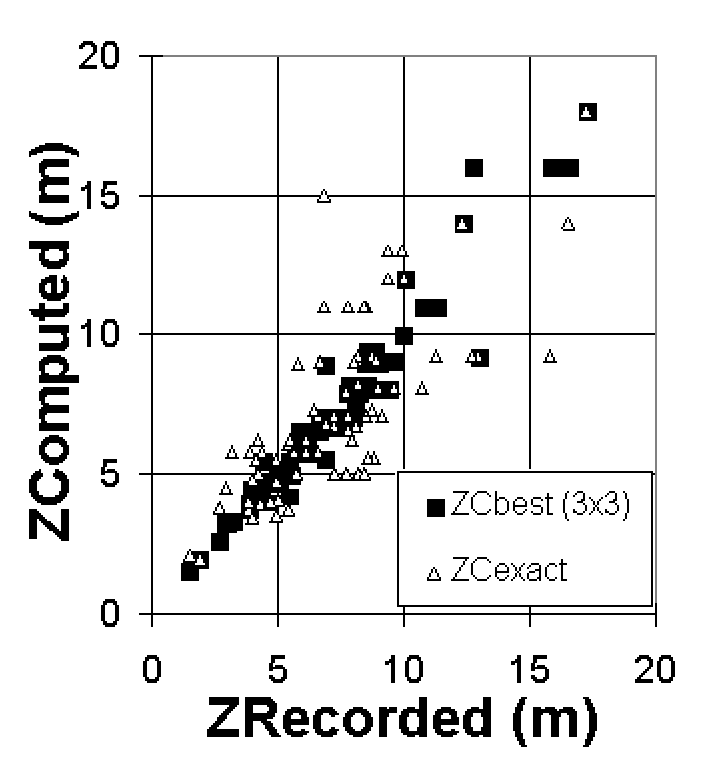

Figure 2: Plot of computed depths ZC
versus field-recorded depths ZR at Negril Shores

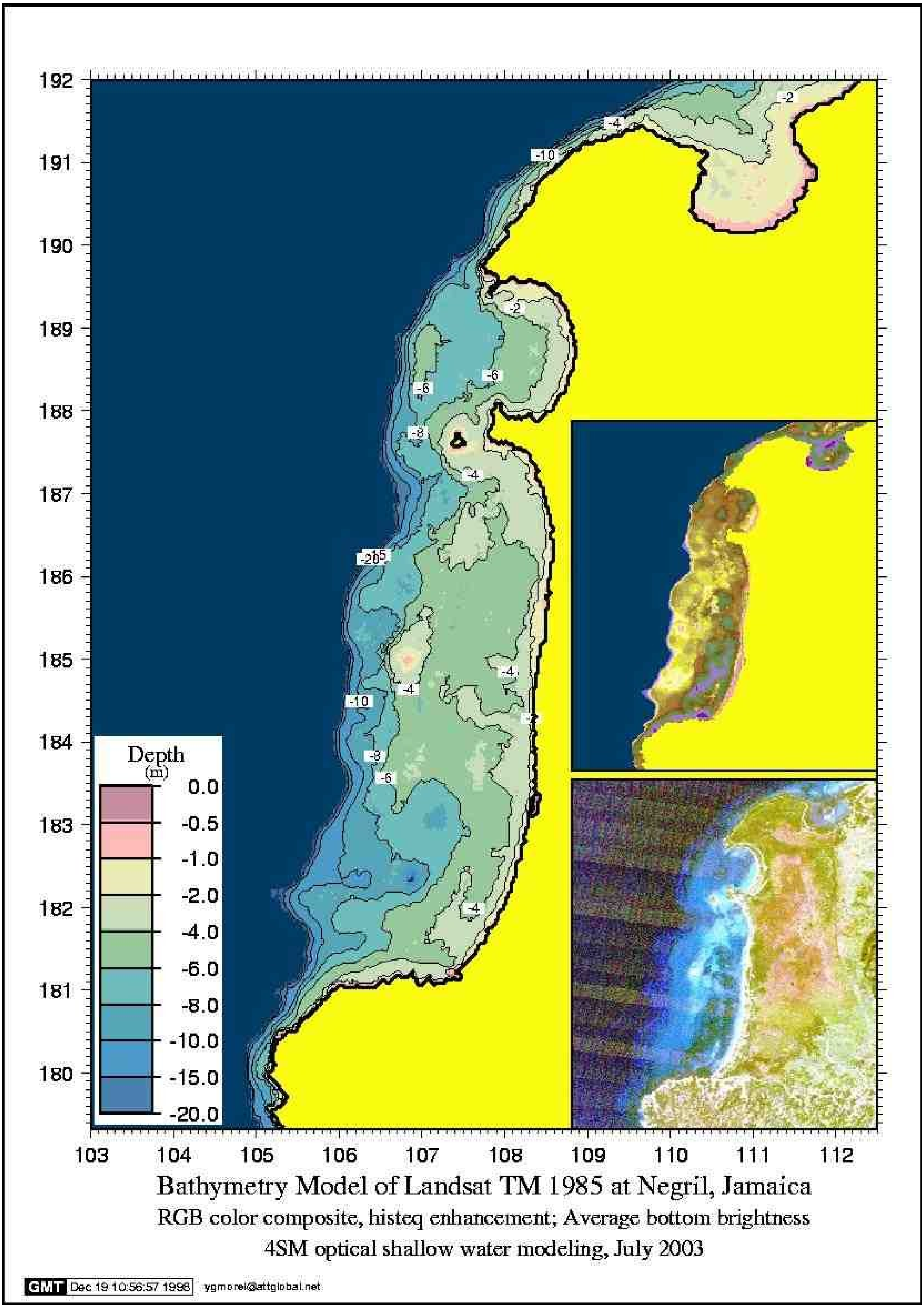

Figure 3: Display of the depth and bottom reflectance images at Negril Shores