Bathymetry estimation from high-resolution satellite images.

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1. LONG TERMS GOALS

Our long-term goal is the development of spectral analysis tools that fully exploit the information content in optical imagery data, particularly it applies to remote sensing of ocean color and the extraction of bathymetry, water quality and bottom type information that can be used to assist in performing Rapid Environmental Assessment (REA). Remote spectral imaging of the littoral zone can provide valuable information for characterizing coastal waters. The use of multispectral imagery (MSI) from satellite sensors such as the Sea-viewing Wide Field-of view Sensor (SeaWiFS), and the Moderate Resolution Imaging Spectroradiometer (MODIS) has been established for many applications, including retrieving Inherent and Apparent Optical Properties (IOP and AOP) of the water. The methodologies to measure the optical water properties have been tested on data acquired by the NURC remote sensing ground station in 2005.

With the advent of high spatial resolution imaging sensors, such as Quickbird and Ikonos, there is the potential to retrieve additional information of the near-shore. Indeed, their small pixel size (4 m or better) could be a key factor to obtain accurate bathymetric computations. Applications include identifying and characterizing underwater objects and materials and mapping water depth. This poster describes three bathymetry methods and presents their performance evaluation.

2. THE SENSORS

With the launch of the sensors Ikonos in 1999 and Quickbird in 2002, high resolution multispectral imagery became available providing a new source for the oceanographic community. They are polar-orbiting satellites sun-synchronous operating at an altitude of 680 and 450 kilometers, respectively, with 98° inclination.
These systems capture solar reflected energy with the following spectral and spatial characteristics.

BAND	IKONOS			QUICKBIRD		
	Bandwidth [nm]	Center [nm]	Resolution at nadir [m]	Bandwidth [nm]	Center [nm]	Resolution at nadir [m]
Pan	403	727.1	1	455	672.5	0.66
MS–1 (Blue)	71.3	408.3	4	70	485	2.44
MS–2 (Green)	88.6	550.7	4	80	560	2.44
MS–3 (Red)	65.8	664.8	4	60	660	2.44
MS–4 (IR)	95.4	805	4	140	830	2.44

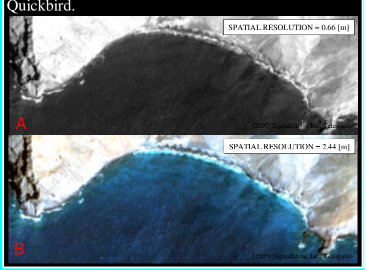
3. THE EXPERIMENTS

Support for bathymetry estimation was provided during two field exercitations.
Remote sensing acquisitions were available for both the study areas.
The first experiment allowed the development and the implementation of the algorithms, while the second was important to made a consistent performance evaluation using the available *in situ* measurements.

Steadfast Jaguar Experimentation exercise (SFJG 06 XREP), in June 2006.
Available data for the depth estimation:

- ✓ Quickbird acquisition;
- ✓ Bathymetric measurement from nautical chart data.

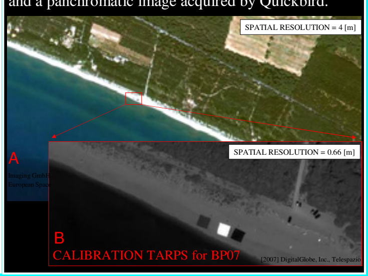
The area under study during SFJG06 was the Cape Verde Islands (500 km west of Africa). The figures show the available remote sensing data acquired with the panchromatic (A) and the MSI sensors on board Quickbird.



Battlespace Preparation sea trial (BP07), in April-May 2007.
Available data for the depth estimation:

- ✓ Simultaneous Quickbird and Ikonos data (date: 26 April 2007, time: 10:32 and 10:07 GMT, respectively);
- ✓ Bathymetric measurements from Ocean Explorer Autonomous Underwater vehicle (OEX-AUV);
- ✓ Italian Navy bathymetric survey (by Galatea Vessel)

The area under study during BP07 was along the coast of Tuscany (Grosseto). The figures below show a multispectral image (rgb) acquired by Ikonos (A) and a panchromatic image acquired by Quickbird.



4. CONCEPTS UNDERLYING THE REMOTE SENSING OF BATHYMETRY, BASIC PRINCIPLE

The fundamental principle behind using optical remote sensing image to map bathymetry is that different Wavelengths of light penetrate water to a varying degree. It is important to point the attention on the fact that the measured at sensor radiance is directly related:

- Incoming solar radiation;
- Attenuation of radiation into and out of the atmosphere;
- Attenuation of radiation into and out of the water column;
- Reflectance properties of the seabed;
- Depth of the water.

Therefore to estimate the depth the first four physical parameters must be known. In case of water type and the bottom reflectance are uniform over the study area, bathymetric mapping is relatively straightforward and requires a minimum of field data. The problem becomes much more complex when the water type and the bottom type vary over the scene, in this case, bathymetric mapping is thus an inherently multivariate problem requiring at least several spectral bands (the method 5c should be more appropriate). NURC's approach on bathymetry estimation follows three methodologies, the first two (linear solution) are appropriate in homogeneous environment, while the third (ratio transform) is more general with respect to the others.

5a. THE LINEAR TRANSFORM SOLUTION[1]

The relationship of observed top-of-atmosphere reflectance (R) to depth (z) and the sea bottom (albedo, A_d) can be described as:

$$R(\lambda) = [A_d - R(\lambda, z=\infty)]\exp(-2K(\lambda)z) + R(\lambda, z=\infty)$$

If the reflectance for deep water, $R(\lambda, z=\infty)$, and for zero depth and the attenuation coefficient K are known, the above equation can be inverted and the depth can be estimated:

$$z = (2K(\lambda))^{-1}[\ln(A_d - R(\lambda, z=\infty)) - \ln(R(\lambda) - R(\lambda, z=\infty))]$$

It's important to point the attention on the fact that this methods do not require atmospherically corrected data (water leaving) because all the parameters are retrieved directly from the values of pixel images (intensity). Indeed, to estimate the reflectance values the concept for which the light attenuates rapidly in the red channel (higher attenuation coefficient) while, by contrast, the blue light penetrates much further (smallest attenuation coefficient) was used . For these reasons, the blue channel was used to estimate the reflectance for deep water, while the IR band (very low penetration depth, less than 1 m) was used to determine the water line and to identified the land's pixels for the albedo estimation. The K estimation should be performed using Hyperspectral Imagery (HSI) and/or *in situ* optical measurements. Unfortunately, this information was not available, and so alternative methods[4] were used.

5b. THE JUPP'S METHOD[3]

The depth of penetration zone (DOP) method proposed by Jupp[3] is based on a combination of water leaving reflectances in different spectral channels as follows:

$$z = \sum_{i=1}^{N} \frac{\ln(R)_i}{-2K_i N} - \sum_{i=1}^{N} \frac{\ln(A_d)_i}{-2K_i N}$$

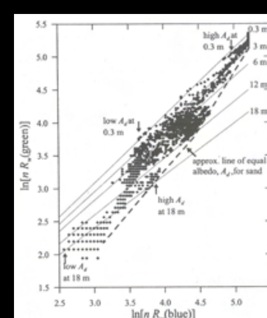
, where N is the number of spectral bands.

The above equation can be used in case of homogeneous environment (same bottom type and uniform K).

5c. THE RATIO TRANSFORM [2]

The linear solutions presented above can be problematic with variable bottom type and even with relatively small variations in water quality (K). In these cases, the band ratio transform could be an alternative solution. This method is based on the following two conditions:

1. With bands having different water absorptions, one band will have arithmetically lesser values than the others;
2. A change in bottom albedo affects both bands similarly (cf. Philpot 1989), but change in depth affect the high absorption band more.



To clarify these concepts we show the example of Log transformation used by Stumpf *et al*[2] for ratio algorithm with data in the northwest Hawaiian Islands.
The figure plots the natural logarithm (*ln*) of R_w in the blue band against the logarithm of R_w in the green band.
Accordingly with condition 1, when the depth increase the reflectance of both bands decreases and the *ln* of the green R_w (higher absorption) decreases proportionately faster than the *ln* of the blue R_w (lower absorption).
Accordingly with condition 2, the approximate values for a sand bottom plot on the dashed line and the changes in depth affect the green band more. Moreover, when the depth is constant and the albedo changes, the ratio has the same value.

It's straightforward that as the *ln* values change with depth the ratio of the blue to the green will change. In particular, the ratio will increase when the depth increases, independently of bottom albedo. Therefore, it can be used to approximate the depth using the formula:

$$z = m_1 \frac{\ln[nR_w(\lambda_{blue})]}{\ln[nR_w(\lambda_{green})]} - m_0$$

The solution requires empirically derived coefficients that normalize the *ln* of the ratio of reflectance values to retrieve a depth term (in meters). The first coefficient, m_1, is a tunable constant to scale the ratio to a relative depth in meters; while m_0, is an offset value to reference the first term to 0 meters of depth. The *n* coefficient is a fixed constant that guarantees that both the logarithms will be positive. A regression algorithm was used with few known depths to determine respective values of these coefficients.

6. RESULTS

We have compared depths derived from the remote sensing acquisitions with the in-situ data that have been taken during BP07 with two different data-set collected by the OEX-AUV (Figure 1) and the Galatea vessel (Figure 2). The comparison between the two data show good agreement, as presented in figure 3.

Figure 1: this figure represents the Quickbird image on which we have been overlapped the available AUV data. The red circles represent the selected transects for the comparisons.

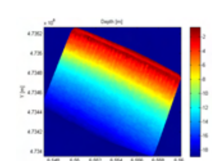


Figure 2: this figure represent the interpolated bathymetric data (grid 5 x 5 m) from the beach survey that has been done by the Italian Navy.

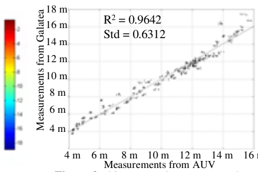


Figure 3: this scatter plot represents the comparison between the two different in-situ measurements

The depths values were estimated using both Quickbird and Ikonos acquisitions, on the basis of the three approaches described before and they have been compared with the AUV *in-situ* data. As proved by the following figures the ratio model gives the best fits (in terms of the coefficient of determination, R^2 , and standard deviation, Std).

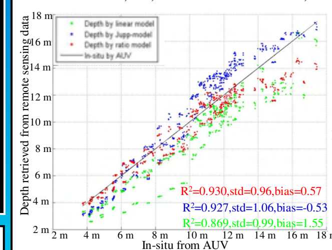


Figure 4: this figure represents the comparison between the depths retrieved from remote sensing and in-situ sensors.

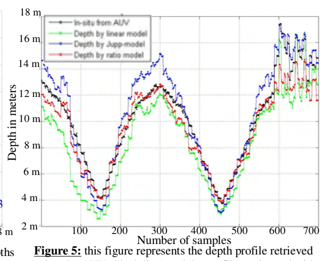


Figure 5: this figure represents the depth profile retrieved using the AUV (black line) and the profiles estimated with the method presented before.

On the basis of the retrieved results, the best depth's Map retrieved from Quickbird data (a grid with 2.4 meter of resolution, see Figure 6) was compared with the Map retrieved from the Galatea measurements (Figure 2). The remote sensing derived depths present a mean error of 11%.

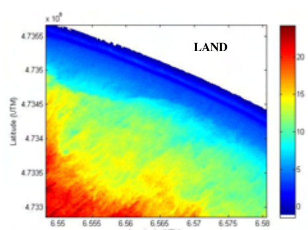


Figure 6: depth Map retrieved from Quickbird data (2.4 m x 2.4 m)

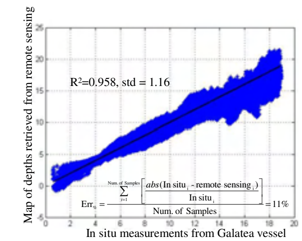


Figure 7: comparison between the in-situ and remote sensing derived maps.

7. CONCLUSION and FUTURE ANALYSIS

This study uses multispectral Quickbird and Ikonos images to derived the depth in coastal water (shallow water areas, depth < 30 m) with three different methodologies. These algorithms have been developed during SFJG 06 XREP that has provided an excellent opportunity for NURC to made a preliminary analysis of these techniques in an operational environment. The second field exercise was important because allows to made a performance evaluation using the available *in-situ* measurement and to improve the algorithms. The results show that the ratio model is more robust in case of non-homogeneous environment (that presents changes in bottom seabed and it doesn't require the K estimation). We are currently working to apply these methodologies to hyperspectral imagery (which will be available from CHRIS and Hyperion sensor).

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