Beyond the Chart: the Use of Satellite Remote Sensing for Assessing Chart Adequacy and Completeness Information

Shachak PE'ERI, Chukwama AZUIKE, Lee ALEXANDER, Christopher PARRISH and Andrew ARMSTRONG, U.S.A

SUMMARY

Chart adequacy and completeness information consists of the symbols, abbreviations and warnings used to inform mariners of the level of confidence that should be given to data on a nautical chart. This information is derived both from the nautical chart and sailing directions. However, analysis based solely on these datasets is limited without access to the sources (e.g., smooth sheets). Publically-available, multi-spectral satellite imagery and published algorithms can be used to derive estimates of the relative bathymetry in shallow, clear waters. In this study, we evaluate the potential of these methods for supplementing the procedure to assess the adequacy of hydrographic surveying and nautical charting coverage. Optically-derived bathymetry provides information in areas that have not been surveyed and monitor any seafloor changes that may have occurred since the last survey of the area. Preliminary results show that multi-spectral satellite remote sensing is also potentially beneficial as a reconnaissance tool prior to a hydrographic acoustic survey.

Key words: Bathymetry, Nautical Charting, Remote Sensing, Water Clarity, LANDSAT

1. INTRODUCTION

Information about the adequacy and completeness of a nautical chart is indicated by various symbols, abbreviations and warnings. This information is intended to inform mariners about the level of confidence that should be given to various types of data shown on a nautical chart. However, there are limitations as to what can be provided since the nautical chart contains less information than was recorded when acoustic hydrographic surveys (e.g., single-beam and MBES) were conducted. In this study, publically available multi-spectral satellite imagery is used to infer the relative bathymetry in shallow clear waters. Optically-derived bathymetry provides useful information in areas that have not been surveyed.

Since the 1970's, satellite remote sensing technology has been adopted as a possible technique in the collection of bathymetric data (Jensen, 2007). The wide area coverage, easy availability and dynamic nature of satellite remote sensing has made it a desirable alternate in mapping shallow areas where conventional ship-mounted and towed sonar systems cannot access. The ability of light to penetrate water columns provides the fundamental principle for inferring water depth using this technology. While high-resolution (e.g., 1 m) data are often required for mapping and charting applications, the chart adequacy assessment methods described here can be performed with ~30-m imagery readily available from Earth observation satellites with global coverage, such as Landsat ETM+.

This paper presents an investigation on the potential use of multi-spectral satellites (up to 8 bands) to map shallow-water bathymetry in a GIS environment using satellite imagery. The potential use of the satellite-driven bathymetry procedure in this study was confined only to the production of source layers for the adequacy and completeness evaluation of nautical charts. Different algorithms for extracting bathymetry using remote-sensing were evaluated and compared to a reference dataset over a test site offshore Massachusetts in the Gulf of Maine, U.S.A. The highest ranking algorithm was used to produce shallow-water bathymetry source layer in the chart adequacy and completeness process over Nigeria and Belize.

2. OPTICALLY DERIVED BATHYMETRY

2.1 Motivation

A standardized analysis and assessment methodology has been developed to evaluate the adequacy hydrographic surveying and nautical charting coverage. However, one of the limitations in this procedure is that the source layers for the procedure are based on the charts and the sailing directions that are sometimes out of date. The optically-derived bathymetry serves as a "smooth sheet", providing a detailed dataset that can be compared to the chart's symbols (*e.g.*, sounding depth and sounding distribution) and monitors any morphological changes of the seafloor. From a practical perspective, the bathymetry should be accessible to the user with a resolution and accuracy sufficient to provide a bathymetric estimate in unsurveyed areas and to indicate any major discrepancies between the current bathymetry to the chart's soundings and the depth contours.

2.2 Principles of optical remote sensing

The ability of light to penetrate the water provides the fundamental principle for inferring water depth using satellite remote sensing technology. The radiation reflected from the seafloor or the water column is captured by the sensor in the satellite platform using photo-detectors. A typical multi-spectral sensor contains several detectors, where each detector can capture a broad spectral range (70 to 150 nm) from the visible to the infrared portions of the electromagnetic spectrum.

Light transmittance through the water column varies as a function of wavelength. The spectral range of the sunlight that is able to penetrate seawater to appreciable depths is typically between 350 nm (ultraviolet-blue) to 700 nm (red), depending on the water clarity and the water depth (Jerlov 1976, Mobley 2004). Sunlight at wavelengths greater than 700 nm (infrared) has very low transmittance in seawater. Typically, satellite channels in the near-infrared ranges (800 to 900 nm) are used to delineate land/water boundary in coastal environments (Robinson, 2004).

The solar radiant energy that is able to penetrate the water surface decays through the water column is an exponential function of the diffuse attenuation function, $K(\lambda)$,and depth, z (Jerlov 1976, Mobley 2004). The observed radiance in shallow waters can be expressed as (Philpot 1989, Maritorena et al. 1994):

$$L_{obs} = L_b e^{-2K(\lambda)z} + L_W \qquad [1]$$

where L_{obs} is the radiance observed at the sensor's detector, L_b is the radiance contribution from the bottom, and L_w is the observed radiance over optically deep water with no bottom contribution. As a result, only a subset of the spectral range from the downwelling irradiance reaches the bottom and is reflected back.

2.3 Optically-derived bathymetry algorithms

Retrieving depth information from the spectral imagery requires removal of spectral contributions from the water column, unwanted path radiance (atmospheric effects) and sea surface reflections. Several models have been developed for the determination of bathymetry from satellite images which broadly all into two approaches. The linear method approach focuses on the inversion of the radiative transfer equation of electromagnetic radiation in waters that light attenuates exponentially with depth (Lyzenga, 1978; Philpot, 1989). The ratio method approach of models derives bathymetry based on the ratio of two bands (Dierssen et al., 2003; Stumpf et al, 2003). Based on the challenges to derive the diffuse attenuation coefficients, this study focused only on algorithms from the ratio method approach:

2.3.1 Stumpf et al. (2003) algorithm

$$Z = m_1 \left(\frac{\ln(nR_W(\lambda_1))}{\ln(nR_W(\lambda_2))} \right) - m_0 \qquad [2]$$

Where $R_w(\lambda_1)$ and $R_w(\lambda_2)$ are the pixel values at band λ_1 and λ_2, respectively. m_1 and m_o are the gain and offset to scale the algorithm results to depth. The value of n is chosen to ensure that the logarithm will be positive under all circumstances and the ratio will produce a linear response.

2.3.2 Dierssen et al. (2003) algorithm

$$z = m_1 \cdot \ln\left(\frac{R(\lambda_1)}{R(\lambda_2)}\right) - m_0 \quad [3]$$

Where $R_w(\lambda_1)$ and $R_w(\lambda_2)$ are the pixel values at band λ_1 and λ_2, respectively. m_1 and m_o are the gain and offset to scale the algorithm results to depths relative to a chart datum.

3. METHODOLOGY AND RESULTS

The methodology of the study was conducted in two steps: 1) evaluate the different optically-derived bathymetry algorithms and 2) quantify the potential improvements that a satellite derived bathymetry can add to the evaluation process to assess adequacy of hydrographic surveying and nautical charting coverage. Landsat satellite imagery from the United States' Geological Survey (USGS) public web archives was used in the study. Only four channels (Blue, Green, Red, and Near Infrared) were used in the study (Table 1). The satellite imagery was loaded into a GIS environment (ArcMap10) and processed using the available functions in the software without the need to code any new tools. The output of the process was a geo-referenced raster layer with relative bathymetry that can be loaded into the chart adequacy evaluation process as a source layer.

TABLE 1. Landsat spectral bands used in the study

Spectral region	**Spectral bands (nm) Landsat-7**
Blue	450-520
Green	530-610
Red	630-690
Near Infrared	780-900

Bathymetry-extraction algorithms from both approaches (linear and ratio) were evaluated in a well-controlled study site. Bathymetry models from a Landsat image over the northern coast to Cape Ann, Massachusetts, U.S.A were compared to a high resolution reference dataset and to the chart's soundings (NOAA chart 13279). An Airborne LIDAR Bathymetry (ALB) survey that was collected in 2007 by the US Army Corps of Engineers was used as reference dataset. The LIDAR measurements were gridded at the Landsat's image resolution (28.5 m). Bathymetry was derived using a ratio of Green-Blue and the Red-Green band pairs. Although the main focus was on the algorithms, spatial filters in the pre-processing procedures were also evaluated.

The study results from the New England test site showed that the highest ranking algorithm was Stumpf et al. (2003) using the Blue/Green bands. The effective depth of penetration, where submersed features are inferred, is between 5 and 6 m. The algorithm results were transformed to the Mean Low Lower Water (MLLW) tidal datum using the chart soundings. In addition, the optically-derived bathymetry product was compared to a bathymetric model derived from the lidar survey for evaluation. The depth difference between the two bathymetric datasets ranged up to 2 m in most areas. The comparison results indicated that there is a correlation between the accuracy of the bathymetric model and the water clarity.

Next, the highest ranking algorithm was used to produce shallow-water bathymetry in the coastal waters of Nigeria and Belize. These two sites were selected based on the IHO publication C-55 (IHO, 2004) that identified the nautical charts of Nigeria and Belize as containing gaps in their hydrographic data. In Nigeria, the optically-derived bathymetry correlated well with areas that have been recently surveyed (a commercial survey from 2004) near the entrance to Escravos River. However, a discrepancy was noticed between the chart soundings and the optically-derived bathymetry in the northern section of the chart over a large area (several tens of square kilometers). The large shoal area was noticed in the optically-derived bathymetry at the Benin River mouth north to Escravos River. Based on the source diagram and the chart symbols, it seems that the reason for this discrepancy is that the area has not been surveyed since 1913. During this period, the sandy seafloor could have shifted due to natural or anthropogenic processes. In Belize, the optically-derived bathymetry correlated well with coral seafloor. However, it was hard to infer the excavated channel leading from the main Inner Channel to Big Creek port.

4. DISCUSSION

4.1 Performance evaluation

Preliminary results of the optically-derived bathymetry indicate a good correlation between the algorithm results and the water depths. The bathymetry was verified in a New England test site (Rockport, MA) that contains a bathymetric reference dataset from an ALB survey and tidal information. Although the optically-derived bathymetry was able to indicate the shallow-water bathymetry, it also mapped deeper areas and underestimated their depth values due to water clarity. This error is due to the water clarity and can be reduced by selecting a satellite image that is collected on the flood stage of the tide, when the suspended particulates in the deeper part of the waters are at a minimum within the tidal cycle. However, it is hard to identify water clarity issues in areas closer to the shoreline where turbidity is caused from waves, current and sharp changes in the seafloor morphology. It is important to note that the optically-driven bathymetry should be used as a reconnaissance tool and not a replacement for an acoustic (*e.g.*, interferometric sonar or multibeam echosounders) or optic (*e.g.*, ALB) hydrographic survey.

4.2 Optically-derived bathymetry applications

Water depth is one of the key factors in the assessment process of chart adequacy and completeness (Azuike et al., 2012). Based on the soundings and the navigational significant contours, four classes of depths are defined in process: navigation critical waters, navigational shallow waters, navigational deep waters and deep waters. The water depth boundary between the navigation critical waters and the navigational shallow waters is different between harbor to harbor and is defined by the water depth in the channel leading to the harbor. This depth is typically between 4 to 8 m. In many areas, optical-driven bathymetry can acheive water depth beyond the boundary between the navigation critical waters and the navigational shallow waters. An additional application using optically-derived bathymetry is the assessment and monitoring of seafloor changes. Following the availability of multiple satellite images covering the same areas, it is possible to compare between the bathymetric dataset over a period of years or to the last hydrographic survey of the area.

REFERENCES

Azuike, C., Pe'eri, S., Alexander, A., Armstrong, A, Parrish, C., 2012. Development of a Geo-spatial Analysis Methodology for Assessing the Adequacy of Hydrographic Surveying and Nautical Charting, *Proceedings in the Canada Hydrographic Conference 2012*, Niagara Falls, Canada 15-17 May.

Dierssen, H. M., Zimmerman, R. C., Leathers, R. A., Downes, T. V., and Davis, C. O., 2003, Ocean color remote sensing of seagrass and bathymetry in the Bahamas Banks by high-resolution airborne imagery, *Limnology and Oceanography*, **48,** 444-455.

International Hydrographic Organization (IHO), 2004, C-55: Status of Hydrographic Surveying and Nautical Charting Worldwide, IHO Publication, Monaco, third edition (Latest Update 27 September 2011).

Jensen, J.R., 2006, *Remote Sensing of the Environment: An Earth Resource Perspective (2nd. Edition),* Prentice Hall Prentice Hall, pp. 608.

Jerlov, N.G., 1976, *Marine Optics* (New York, NY: Elsevier Scientific Publication).

Lyzenga, D. R., 1978, Passive remote sensing techniques for mapping water depth and bottom features. *Applied Optics*, **17,** 379–383.

Maritorena, S., A. Morel, and Gentili, B, 1994, Diffuse reflectance of oceanic shallow waters: Influence of water depth and bottom albedo, *Limnology and Oceanography*, **39,** 1689–1703.

Mobley, C. D., 2004, *Light and Water: Radiative transfer in neutral waters,* Academic press, (CD version).
Philpot, W. D., 1989, Bathymetric Mapping with Passive, Multispectral Imagery. *Applied Optics*, **28**, p. 1569-1578.
Robinson, I.S., 2004. *Measuring the Oceans from Space: The principles and methods of satellite oceanography*, Chichester, UK: Praixs Publishing LTD, pp. 714.
Stumpf, R. P., Holderied, K., and Sinclair, M., 2003, Determination of water depth with high-resolution satellite imagery over variable bottom types, *Limnology and Oceanography*, **48,** 547-556.

BIOGRAPHICAL NOTES

Shachak Pe'eri is a research assistant professor at the Center of Coastal and Ocean Mapping, University of New Hampshire. His research focus is in airborne remote sensing with a focus on experimental and theoretical studies of airborne lidar bathymetry, topographic lidar, terrestrial laser scanning and hyperspectral imaging.

CONTACTS

Shachak Pe'eri
Center for Coastal and Ocean Mapping
24 Colovos Rd
Durham, NH
U.S.A.
Tel. +1 603 862-1892
Fax + 1 603 862-0389
Email: shachak@ccom.unh.edu
Web site: ccom.unh.edu