Shallow water bathymetry by satellite image: a case study on the coast of San Vito Lo Capo Peninsula, Northwestern Sicily, Italy

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*Abstract –*Mapping coastal areas and shallow water depth has become an interesting topic for hydrographers and scientists. Many techniques using traditional methods have been used to map and study seabed evolutions of these areas. However, ships, vessels and aircrafts used for bathymetric surveys in shallow water present some limitations, especially their inability to map hard-to-reach areas and very near shoreline waters. In addition, the cost and human resources deployed to conduct these surveys make them very expensive, even for small projects. In this paper we present a cost-effective tool and a practical method for bathymetric studies of shallow water using multispectral satellite images. We applied the Satellite-derived bathymetry (SDB) method on the coast of San Vito Lo Capo with a Geoeye-1 satellite image, using available field data for calibration and vertical referencing. The results show bathymetric information for a depth of 10 m with $R^2=0.753$, contributing to the management of ports, maritime transport and the coastal environment in general.

Keywords: Satellite-derived bathymetry (SDB); Geoeye-1 satellite image; coastal management; port; San Vito Lo Capo

I. INTRODUCTION

Mapping shallow water bathymetry in coastal and near-shore areas is of great interest to explorers, hydrographers and scientists who want to have a better understanding of this highly dynamic environment [1, 2]. Water depth information is essential for many applications, especially for coastal environment impact assessment and protection, nautical charting, construction planning and leisure, hydro-dynamic modeling, and environmental exploration [3, 4]. With on-going climate change, temporal monitoring of shallow water depth can reveal geomorphological and land cover changes occurring in coastal areas, which are important parameters for hydro-dynamic and wave modelling [3]. For example, the position of the shoreline is influenced by the level of the sea, and knowledge of water depth can help identify the location of the sand beach and sediment deposits and also improve coastal erosion studies [5]. In underwater archeology, water depth information is used for mission planning and therefore facilitates the discovery of lost objects and artifacts [6]. In seismic survey exploration, water depth information constitutes an important component for seabed determination and improves natural resources mapping.

Usually, ocean, sea and lake bathymetry studies are conducted using traditional methods such as multi beam echo sounder and single beam echo sounder (SBES) fixed on ships and vessels [7, 8] and Lidar fixed on aircraft [9, 10]. These methods need on-site deployment; exploration license permits and their equipment are very expensive [11]. They are highly precise but time-consuming when studying large areas. In addition, they present some challenges when they are used in very near-shore due to area inaccessibility and hidden seabed rocks which can halt the passage of ships and vessels [12]. For Lidar, the main challenge is in its high cost which makes it unsuitable for small projects; in addition administrative procedures needed for flight authorization can also complicate the planned missions.

To overcome these issues, SDB is presented as an answer for shallow water bathymetry mapping in order to complete the gap left by traditional methods as well as to update previously available bathymetric data [13]. Since the 1970s, different SDB approaches have been used to extract depth water information using multispectral satellite images [14]; however, advances in satellite sensors and the development of new algorithms are making this technology more attractive, and it is now being used in many sectors and industries such as oil and gas, coastal engineering [15], aquaculture and ports and

infrastructures.

Recently, SDB has been adopted as monitoring technique by numerous companies, such as EOMAP and TCARTA, offering commercial services related to shallow-water bathymetry and seabed surveys [16, 17]. These companies provide bathymetry information to different organizations but also to different national hydrographic offices especial for up-dating and improving nautical charts. As example, in October 2015, BA 2066 chart of Southern Antigua was published by the UK Hydrographic Office [18]. This chart was presented with information obtained from SDB conducted by EOMAP. Among other SDB studies conducted by these companies, we can cite the first high resolution seafloor and bathymetry survey of the Mexican Riviera provided by EOMAP for coral protection project, or bathymetric electronic nautical chart products derived by TCARTA from SDB and Global Bathymetry data. These examples show the application and interests of SDB in marine and coastal area studies.

Based on the International Hydrographic Organization's (IHO) S-44 standards [19] which determine the quality of survey methods, the SDB method can be classified as a special order survey method, (Table 1), with horizontal accuracy of about ± 2 m and vertical accuracy of ±0.25 m to ± 0.75 m where environmental conditions are ideal. Horizontal uncertainty is determined based on the position determined from GPS, while Total vertical uncertainty (TVU) is determined using the following relation, (Equation 1).

$$TVU = \pm\sqrt{a^2 + (b * d)^2} \qquad (1)$$

Where: a represents that portion of the uncertainty that does not vary with depth, b is a coefficient representing that portion of the uncertainty that varies with depth, and d is the depth, while b x d represents that portion of the uncertainty that varies with depth [18, 19].

With intense activities and high levels of interaction occurring in coastal areas, special order surveys are more preferable in water shallower than 40 m where under-keel clearance is important for navigation safety, minimizing coastal environmental disasters and maintaining the economic benefits of these areas [18].

Table 1: minimum standards for special order hydrographic Surveys

Order	Special
Description of area	Areas where under-keel clearance is critical
Maximum allowable Total vertical uncertainty (TVU) 95 % confidence level: depth accuracy	a= 0.25 m b= 0.0075
Maximum allowable Total horizontal uncertainty (THU) 95 % confidence level: positioning accuracy	2 m
Full sea floor search	required
Feature detection	Cubic features> 1 m
Recommended maximum line spacing	Not defined as full sea floor search is required
Positioning of fixed aids to navigation and topography significant to navigation (95 % confidence level)	2 m
Positioning of the coastline and topography less significant to navigation (95% confidence level)	10 m
Mean position of floating aids to navigation (95 % confidence level)	10 m

II. METHOD AND MATERIAL

A. Area of study

The study area is located in northwestern Sicily on the coast of the San Vito Lo Capo peninsula (Fig 1). It has important archeological and touristic sites with a large sand beach and port facilities. This area was selected because of constant coastal erosion [20] with the wind transporting beach sand from East to West and depositing it in the port; this phenomenon affects maritime transport by reducing the space for boat maneuvering. Using SDB it is possible to provide shallow water information and determine regions occupied by these sand deposits. This can help improve the functioning of the port and possibly contribute to economic development.

Fig.1.Study Area of San Vito Lo Capo

B. Data used

With currently available satellites, it is possible to have water depth information for every 2 m of spatial spacing when using DigitalGlobe WorldView-2/-3, for every 10 m when using EU Copernicus Sentinel-2A/B, and for every 30 m when using NASA/USGS Landsat 7/8. In this study we used DigitalGlobe Geoeye-1 (Table 2) acquired on 18 October 2014 on the coast of San Vito Lo Capo, in conjunction with field data acquired in December 2013 (Table 3)

Table 2: GeoEye-1 satellite image used

Image type	Panchromatic	Multispectral		
Spectral Resolution/ Band	450-900 nm	450-520 nm / Blue 520-600 nm / Green 625-695 nm / Red 760-900 nm / Near IR		
Image calibration parameter	Gain	Offset	Gain µw/(cm2*nm*sr)	Offset
	0.08715 mw/(cm2*nm*sr)	0	0.14865 / Blue 0.10135 / Green 0.16194003 / Red 0.05705 / Near IR	0 0 0 0
Metric accuracy/Geolocation without ground control points	90 % circular error for horizontal, CE mono: 2 m 90% linear error for vertical error, LE stereo: 3 m			
Off-Nadir Imaging	26 degrees			
Coordinate system	WGS 1984 UTM Zone 33N			
Cloud cover	0.00			

Table 3: In-situ data acquired using Single Beam Echo Sounder Garmin 550C

Positional instrument	DGPS Garmin CSX 60 signal differential WAAS EGNOA	
Coordinate system	Datum: Roma 1940 (Monte Mario), Projection: (Gauss Boaga)	
Navigation software	Qinsy QPS 8.1.0	
Tide station	National mareographic network_Station of Palermo	
	Date: 07-11-2013	Date: 08-11-2013

	High value: 0.225 m Low Value: -0.024 m	High value: 0.2 m Low value: -0.026
Bathymetric map scale	1:2250	
Area surveyed	San Vito Lo Capo	
Scientist in charge	Prof. Giovanni Randazzo	

C. Methodology

In this paper we used an optical-based approach [21], a log-band ratio method using empirical data suitable for bathymetry estimation focusing on two spectral bands, green and blue. The third band, near infrared, was used for land/water masking, while field data were used for calibration and vertical referencing to the local datum.

During the acquisition of satellite imagery, Top of atmosphere (TOA) reflectance, (Equation 2), saved over water is expressed as a function of water depth (Z), (Equation 3), and varies with absorption (α), backscattering (β) and water reflectance (ρ).

$$\rho \text{ (TOA)} = \frac{\pi \times L\lambda \times d^2}{ESUN\lambda \times \cos(\theta s)} \qquad (2)$$

Where ρ (TOA) is the top-of-atmosphere reflectance, ESUNλ is mean solar extra-atmospheric irradiance expressed in $W \times m^{-2} \times \mu m^{-1}$, d is Earth-sun distance obtained from Julian Day acquisition time, Lλ represents Top-of-atmosphere spectral radiance and θs is solar zenith angle equal to 90 degrees minus the sun elevation angle at the time of image acquisition in the .IMD files.

$$\rho \text{ (TOA)} = f(Z_{\alpha,\beta,\rho}) \qquad (3)$$

ρ (TOA)Reflectance is affected by atmosphere and it has been noted that less than 1% of TOA contains information about the water [22], thus an atmospheric correction is needed to remove the noise which can affect the quality of image during water depth estimation.

We computed Fast Line-of-sight Atmospheric Analysis of Hypercube (FLAASH) [23], a physics-based atmospheric correction that corrects wavelengths from the visible to near-infrared and shortwave infrared regions by removing absorption (α) and backscattering (β) to obtain the water reflectance. FLAASH is a tool that is integrated in ENVI & IDL software.

No sun glint correction [24] was needed to remove sea surface reflection, as the image used (Table 2) was acquired in good conditions.

Thus, after all corrections, the shallow water reflectance equation can be defined as it is shown in Equation (4).

$$Rw = \rho_b \cdot e^{-2KZ} \qquad (4)$$

Where Rw is water reflectance, ρ_b is bottom reflectance, **Z** is the depth of the seabed, **e** is logarithmic base and 2k is the (up-welling and down-welling) operational two-way diffuse attenuation coefficient.

Assuming that the area of study has a uniform bottom reflectance and water attenuation, we applied Stumpf et al. 2003[21], equation (Equation 5), for SDB calculation using two spectral bands in blue and green. This equation minimizes the influence bottom reflectance and water attenuation parameters, of area of study, with respect to water depth variation. It takes into account known water depth for calibration and vertical referencing. It is a log-band ratio method using an empirical, iterative solution and attenuation coefficient assumption for bathymetry estimation.

$$Z = m1 \frac{\ln(nRw(\lambda i))}{ln(nRw(\lambda j))} - m0 \qquad (5)$$

Where Z is absolute depth (SDB), m1 (gradient of the line) is a tunable constant to scale the ratio to the depth, Rw is water reflectance, n is fixed value for all areas to ensure the logarithm will be positive and the relationship will be linear, m0 is the offset for the depth of 0 m (z=0), the interception with the Y axis, λi=band i, λj= band j,

The log-band ratio equation (Equation 5) was computed in ArcGIS software in two main steps: first by integrating two bands (blue and green) after applying a low-pass 3-by-3 (kernel size 3×3) filter while the second step begins by determining extinction depth on relative bathymetry and finally the determination of constants (m1 and m0) used for vertical referencing to local datum.

$$Z = 87,868x - 73,281 \qquad (6)$$

These constants (m1=87,868 and m0=73,281) were introduced in Equation (6), in order to transform relative bathymetry into absolute bathymetry (Fig. 3). The process requires information obtained from available known water depth which respects international hydrographic organization standards.

III. RESULTS

The application of log-band ratio method in highly dynamic area of San Vito Lo Capo using blue and green spectral bands provided, in the first step, the relative bathymetry. This bathymetry was later calibrated and vertically referenced to the local datum using available in-situ data in order to obtained absolute bathymetry. The Figure 2 shows SBD obtained from Geoeye-1 satellite image, we noticed the variation of water depth from 0 m to 9 m with high values observed in the northwestern part and low values near the shoreline of the sand beach. The

western near-shoreline part shows relatively high values, suggesting the impact of the wind transporting sand from East to West as testified by the local population during our visit on 28 May 2019 to this area.
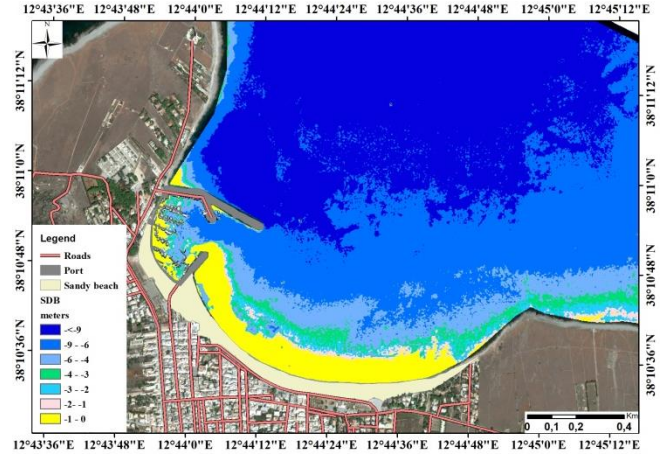

Fig.2. SDB extracted on the coast of San Vito Lo Capo

In comparison with traditional method results obtained using SBES, the Figure 3 shows that SDB provides additional information, especially in near-shore waters. In additon to water depth information, the use of satellite images provides information on the position of the shoreline, on the extent of sand beach, on the sand beach dynamics, as well as on built-up areas. These are useful information for scientists, hydrographers and policymakers operating in coastal areas especially in the coastal management plannings.
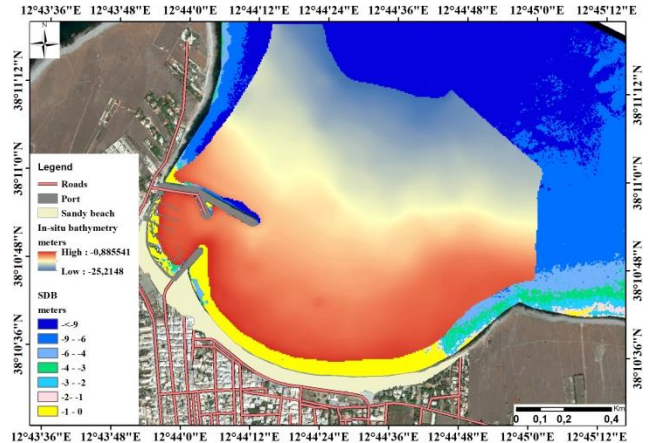

Fig.3. Spatial coverage comparison of SDB and SBES on the coast of San Vito Lo Capo

The comparison of SDB information with in-situ bathymetry shows a good relationship with a correlation coefficient R^2 = 0,7534, (Fig. 4). This demonstrates the ability of our SDB methodology to provide shallow water bathymetry even in highly dynamic environment.
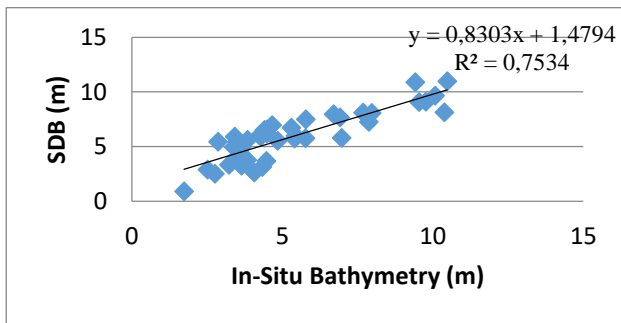
Fig.4. the relationship between SDB and In-situ bathymetry

Qualitative assessment of the results, (Table 3), showed values for different depth ranges on which errors were calculated in function with available in-situ bathymetry in order to determine the overestimated and underestimated values on SDB. While some of these vertical uncertainties are in the range of Maximum allowable TVU values in ideal environment conditions, the outrange ones may be resulted in the presence of suspended sediments in this area.

Table 3: Quality assessment of SDB results

Depth range (m)	Error (m)
1-2	-0.85
2-3	0.98
3-4	1.01
4-5	0.87
5-6	0.79
6-7	0.27
7-9	0.02
9-10	-0.75

IV. CONCLUSION

This study constitutes the first SDB study conducted on the coast of San Vito Lo Capo and demonstrates the application of satellite images in shallow water bathymetry studies. The Stumpf et al. 2003 equation applied on Geoeye-1 satellite image in conjuction with available in-situ data provided useful water depth information for the first 9 m. This depth is the most challenging for traditional bathymetry survey and the methodology used can be adopted as regular monitoring technique in vulnerable and rapidly evolving coastal areas. Advances both in algorithms and Satellite sensors have improved the capability of providing variable water depth information in shallow waters. In addition, the ability to cover inaccessible, large and high dynamic areas with high temporal revisit and high spatial resolution make SDB technique an alternative and cost-effective method for bathymetric studies.

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