Satellite Derived Bathymetry Survey Method – Example of Hramina Bay

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Satellite Derived Bathymetry (SDB) method uses satellite or other remote multispectral imagery for depth determination in very shallow coastal areas with clear waters. Commonly, SDB survey method can be used when planning hydrographic surveying of marine areas not surveyed or areas with old bathymetric data. This method has become widely used in the past few years. SDB is a survey method founded on analytical modelling of light penetration through the water column in visible and infrared bands. In this article, SDB method was applied by using free-of-charge Landsat 8 and Sentinel 2 satellite images to get the bathymetric data in the area of Hramina Bay in the Central Adriatic. SDB processing procedures and algorithms were described. Processed satellite data was uploaded on geodetic software and ENC S-57 format. The bathymetric map of Hramina Bay obtained by the SDB method was compared with the approach usage band Electronic Nautical Chart (ENC) HR400512 with satisfying positional and vertical accuracy.

KEY WORDS

~ Satellite Derived Bathymetry
~ Hydrography
~ Middle Adriatic Sea

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1. INTRODUCTION

Satellite Derived Bathymetry (SDB) is a relatively new survey method which uses satellite or other remote multispectral imagery for depth determination (Marks, 2018). The results of SDB method are applicable in many hydrographic branches and generally in marine sciences (bathymetry, cartography, coastal management, water quality monitoring, etc.).

This method was developed in the late 1970s, but the frequency of its use has increased considerably in the last few years (UKHO, 2015). It should be mentioned that accuracy of SDB does not meet current International Hydrographic Organization (IHO) S-44 standards (IHO, 2008). However, according to Pe'eri et al. (2013), it can be used when planning hydrographic surveying of marine areas not surveyed or areas with old data. Since the data of some satellite missions is free or available for a relatively small price, it can be said that this is almost the cheapest source of spatial data in general.

Hydrographic surveying by conventional shipborne sounding techniques is time consuming, demanding, and expensive.

About 50 % of the USA territories were surveyed by using old hydrographic methods that do not meet today's requirements (Marks, 2018), while in the Republic of Croatia there is about 45 % of the marine territory with depths below 200 m, surveyed with inadequate hydrographic accuracy standards (Leder, 2016).

Analytical modelling of light penetration through the water column in visible, and infrared bands are the physical basis of the SDB method. SDB used optical remote sensing data for depth determination whose shortwave electromagnetic part of the spectrum has a strong penetration capacity (Stumpf et al., 2003). Solar radiation is absorbed and it scatters while spreading through water, and residue energy has been backscattered and recorded in remote sensing imagery. There are different methods of SDB determination over near-shore area which are mainly classified into analytical, empirical and combined models (Vinayaraj, 2017).

Model development requires a knowledge of the water optical properties in the coastal area, such as absorption coefficients of suspended and dissolved substances, attenuation, scattering and backscatter, bottom reflections, coefficient, etc. (Lee et al., 1998; Mobley et al., 2001). Such models are generally referred to as radiation transfer models and include the inherent assumption of bottom reflection, corresponding level of water quality and shallow depth (Baban, 1993; Muslim and Foody, 2008), and their use is not recommended in coastal waters with weak bottom reflection and high turbidity.

In empirical modelling, the relationship between remotely sensed radiance and the depth is established empirically regardless of whether the light propagates in the water or not. The correlation between water depth and spectral band radiation is used to calculate SDB. Empirical modelling is based on the assumption that the total reflectance is primarily related to water depth and the secondary to water turbidity (Vinayaraj, 2017). Empirical parametric regression based models, such as Stumpf et al. (2003), are very popular and easily applied. There is also nonparametric regression as explained by Ribeiro et al. (2008). These models enable fast data processing, but require depth point calibration.

A combination of analytical and empirical models is proposed by many authors in order to overcome the disadvantages of both models. The most popular and widest applicable model is suggested by Lyzenga et al., 2006 (Kanno and Tanaka, 2012; Su et al., 2013; Vinayaraj et al., 2016), as physically based algorithm, and the predictor can be analytically derived from a radiative transfer model. Calibration depth is used to calculate the attenuation of spectral band parameters as they are obligatory for low quality water areas. The empirically derived parameters are related to the inherent optical water properties. These models are faster and need less prior knowledge of water spectral properties. The method presented in this article is based on a combined model.

In this paper, SDB method will be applied in order to get bathymetric data in the area of Murter island Hramina Bay situated in the eastern part of the Central Adriatic (Figures 1 and 2) and compared with Electronic Nautical Chart (ENC) composed on the basis of echo-sounder bathymetric data.

Figure 1.
Murter island, Hramina Bay: Google (top) and photo from N (Source: https://www.apartmanija.hr/apartmani/murter; bottom).

2. STUDY AREA

Murter is an island in the middle of the Adriatic Sea at 43°49'37"N 15°35'50"E, inhabited in prehistoric times. In the 18th century, it was named after a stone grove of oil presses. The island's area is 17.58 km^2, the coastline length is 42,605 km (Duplančić Leder et al., 2004). There are 4 settlements on the island: Murter, Betina, Jezera, and Tisno, with 5,138 inhabitants. In Hramina Bay, there are remains of the ancient Roman settlement Colentum.

The island's largest settlement is Murter in Hramina Bay, situated in the north-western part of the island (Figures 1 and 2). It is a shallow bay with a maximum depth of 7 m (HIRC, 2004), making it suitable for SDB survey method. The Adriatic is a very clear and transparent sea; therefore, this method can be applied to the entire area. In the NE part of the bay, there is Marina Hramina.

The area of the central Adriatic is commonly a nautical area, especially in the summer period when the traffic increases, especially by tourist and excursion boats. The last survey on this area is over 70 years old - methods that were used were not contemporary; a very shallow area with a sandy bottom is suitable for using the SDB method.

Satellite derived bathymetry method is convenient for bathymetric survey of shallow areas with clear water. In practice, it is being used approximately to the depth of 2 secchi disc depth - measure of sea water transparency or turbidity. The eastern Adriatic Sea coastal area has mostly very shallow water, very clear in a greater part of the year. Thus, SDB method met two basic components which are the prerequisites for its usage.

The transparency of the area as well as the transparency of the entire Adriatic is high, especially in the spring, except in periods when sudden warming causes the phenomenon of sea bloom, which is a relatively rare occurrence. The Mediterranean Sea water clarity is 23-30 m (Hartman et al., 2017), and the average transparency value in the Adriatic is 10-20 m (Žuljević et al, 2016; Morović et al., 2008). Turbidity and the sea currents of this area are also not expressed because it is a relatively closed area. The bottom type is sand (Figure 1), where sand has high and kelp has low albedo or reflection (Hartman et al., 2017).

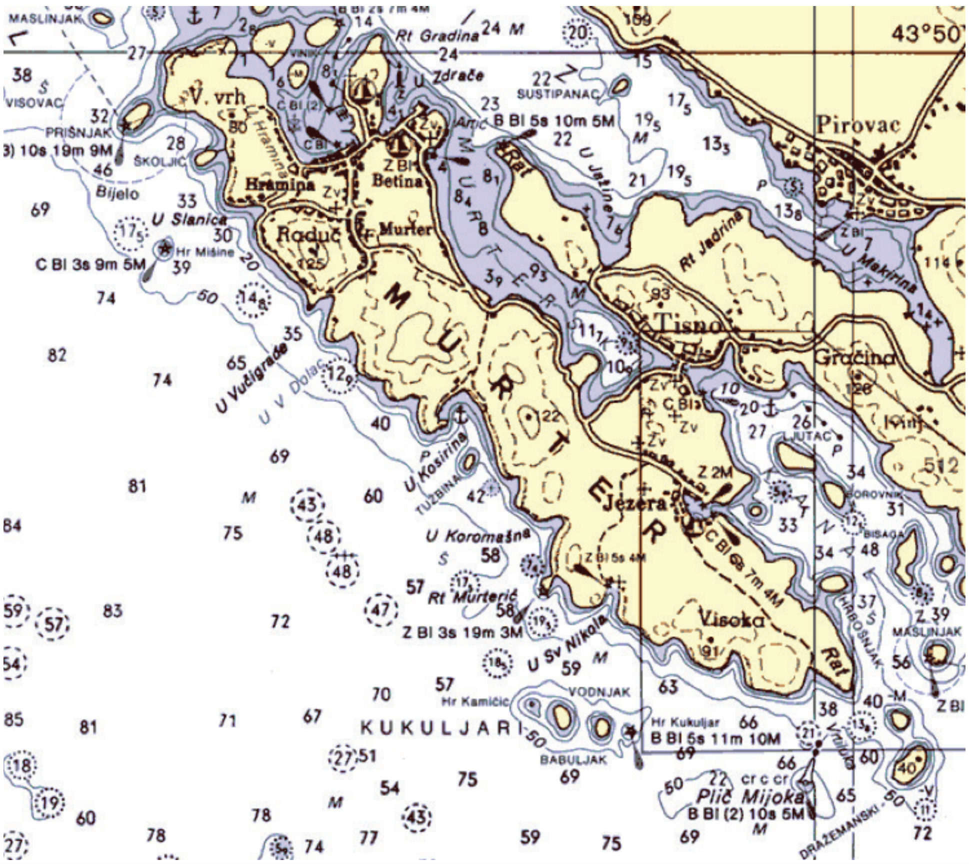

Figure 2.
Part of the nautical chart 100-21 with the island of Murter (Hydrographic Institute of the Republic of Croatia).

3. MATERIALS USED FOR SDB METHOD

In this research the Landsat 8 and Sentinel 2, both open data satellite missions, were used. The closest time scenes from the winter-spring period were selected. In this period, there is no heavy boat traffic in this area, and the seawater is very transparent.

3.1. Landsat 8

Landsat program is the most timely satellite imagery mission of series of Earth-observing satellites. Landsat 8 satellite was launched on 11 February, 2013. It is a collaboration between the National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS). Landsat scene is 185 km long and 185 km wide (Figure 3). The data can be downloaded through the USGS EarthExplorer, GloVis or the LandsatLook Viewer websites. Landsat's most important tasks are observation and exploration of the Earth's surface, which has a wide range of applications.

Landsat 8 carries two push-broom instruments: The Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). The OLI sensor acquires a total of 9 bands: eight multispectral bands with 30 m, and one panchromatic band with 15 m spatial resolution (Figure 5). The TIRS instrument collects two spectral bands for the thermal infrared wavelength.

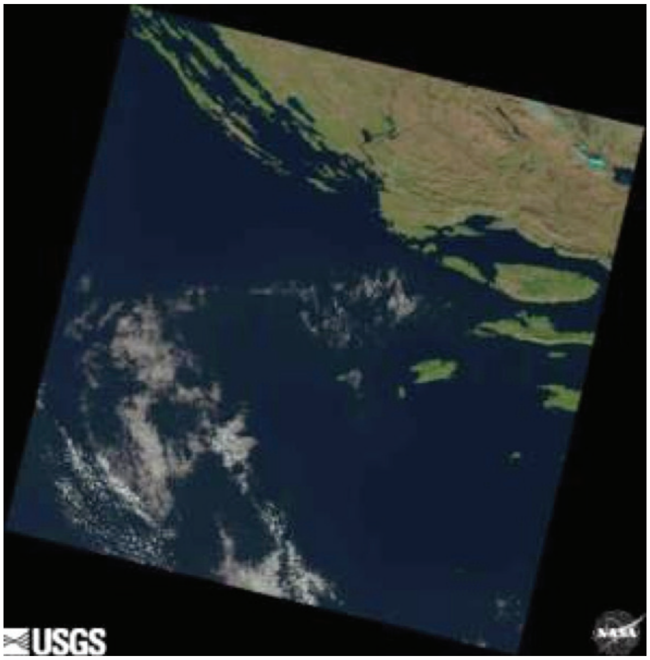

Figure 3.
Landsat 8 image of the Central Adriatic area on February 14th, 2017.

The temporal resolution of this mission is 16 days. Landsat orbit is un-synchronous at an altitude of 705 km, with 233 orbit cycles per day. The orbit inclination is 98.2°, and the equatorial crossing time is 10:00 a.m. +/-15 minutes. The sensors both provide improved 12-bit radiometric resolution data (4096 level of grey).

3.2. Sentinel 2

Sentinel-2 is the European Space Agency (ESA) Earth observation mission as part of the Copernicus Program. Sentinel-2A was launched on 23 June, 2015 and Sentinel-2B was launched on 7 March, 2017 from French Guiana. The mission performs terrestrial observations to support services such as forest monitoring, land cover changes detection, and natural disaster management. All Sentinel mission data can be downloaded through Copernicus Open Access Hub and USGS Earth Explorer.

The mission consists of two identical satellites, Sentinel-2A and Sentinel-2B. The satellites' orbit is Sun synchronous at 786 km (488 mi) altitude and 14.3 revolutions per day. The orbit inclination is 98.62°, and the Mean Local Solar Time (MLST) at the descending node is 10:30 (am). The Sentinel-2 swath width is 290 km (Figure 4).

The temporal resolution of this mission is 10 days with one satellite, and 5 days with 2 satellites. Sentinel-2 is a multi-spectral mission with 13 bands in the visible, near infrared, and short wave infrared part of the spectrum and spatial resolution of 10 m, 20 m and 60 m (Figure 5), and 12-bit radiometric resolution.

Figure 4.
Sentinel 2 image of the Central Adriatic area on 9 May, 2017.

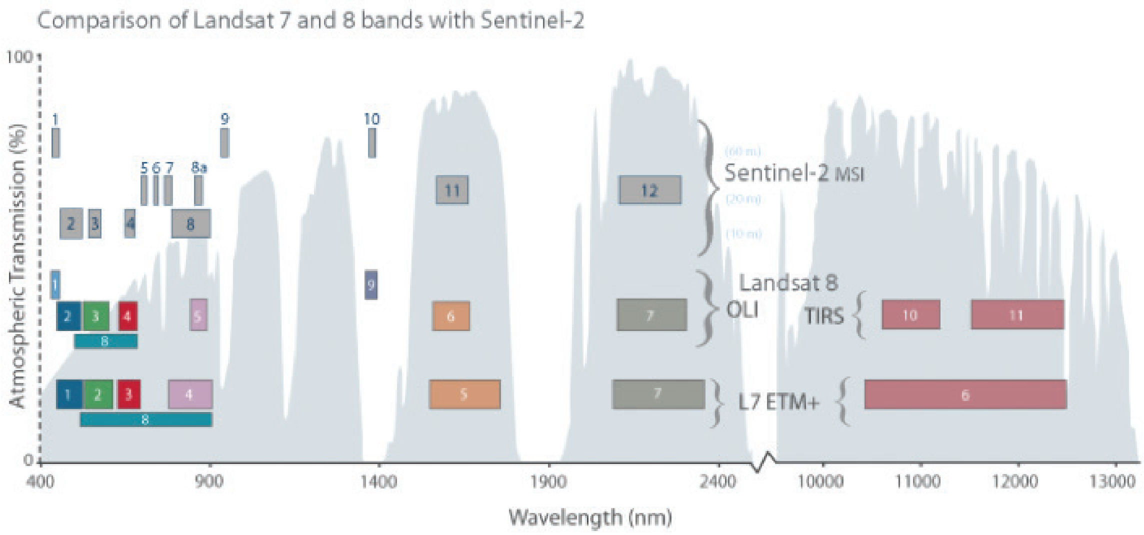

Figure 5.
Comparison of Landsat 7 and 8 bands with Sentinel 2 (Source: https://landsat.gsfc.nasa.gov).

3.3. Electronic Navigational Charts

In today's modern digital era technology advances also affect the design and publishing of maritime navigational charts, i.e. paper navigational charts are rapidly replaced by electronic navigational charts. Electronic Navigational Chart (ENC) is a digital version of the paper navigational chart. It is a vector database (chart) whose content, structure and format are standardized according to S-57 - Transfer Standard for Digital Hydrographic Data (IHO, 1994; IHO, 2017) suggested by both

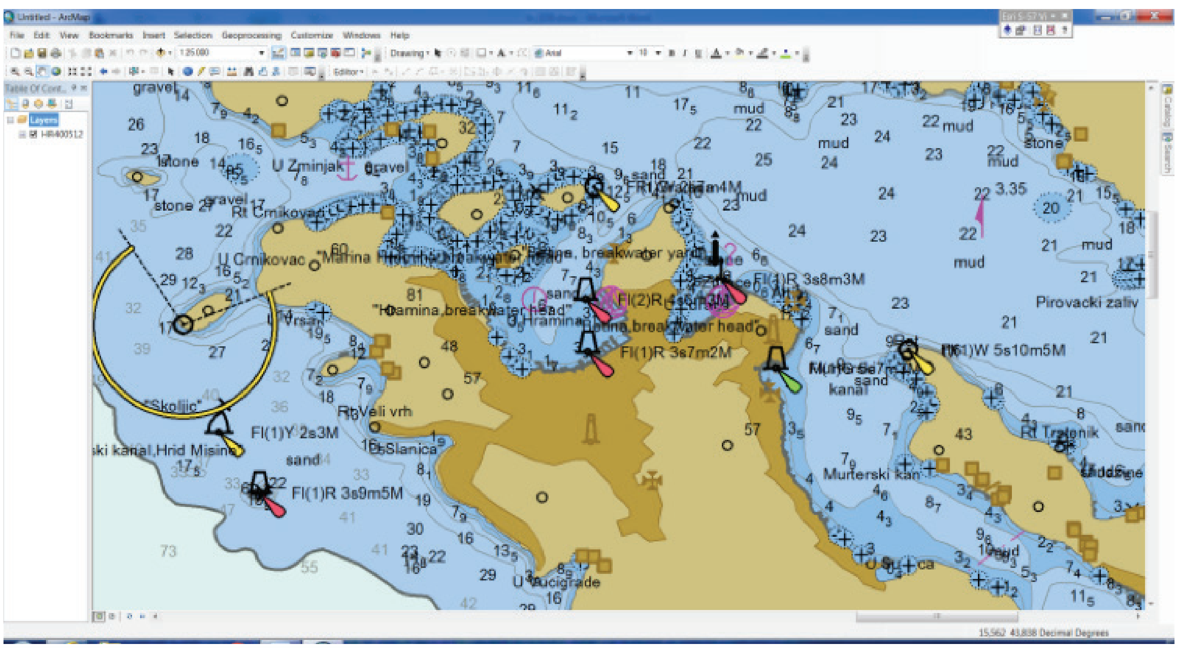

Figure 6.
Part of the Croatian ENC HR400512 with Hramina Bay area.

the International Hydrographic Organization (IHO) and the International Maritime Organization (IMO). ENC contains all the chart information necessary for safe navigation, but it may also include additional information (e.g. information contained in the Pilot, List of Lights and Fog Signals) (IHO, 1997; IMO, 1995). Together with the positioning system and the information on positions obtained from navigational sensors (e.g. radar, echo sounder, ship's speedometer), ENCs make up an Electronic Chart Display and Information System - ECDIS (IMO, 1995; IHO, 1997; Hecht et al., 2002). ENCs are published by national hydrographic offices and authorized data providers which are obliged to keep ENCs up to date in the same manner as paper navigational charts (Hecht et al., 2002).

ENC data is forwarded to users on board, grouped into usage bands according to navigational purposes: overview, general, coastal, approach, harbour and berthing (most details), which mariners use depending on the situation.

The Hydrographic Institute of the Republic of Croatia (HIRC) released more than 120 overview, general, coastal approach, harbour and berthing ENCs through PRIMAR Norway as the Regional Coordination Centre for ENC distributions. ENC HR400512 Kornat - Murter is an approach usage band ENC, scale 1:40,000 (Figure 6), HR500512 Murterski kanal - SE part is a harbour usage band, issued by HIRC. ENC HR400512 chart was used in this research as a basis, and for control depths data obtained by the SDB method.

4. METHODS USED FOR PROCESSING SATELLITE IMAGES

Depth estimation from satellite images is based on the theory that light is attenuated exponentially in the water. The procedure (workflow) to obtain bathymetric data from satellite imagery includes the following basic steps (Figure 7), according to Gao (2009):

1. Pre-processing
2. SDB Depth Calculation
   a. Water separation
   b. Spatial image filtering
   c. Glint/cloud correction
   d. Bathymetry algorithm application
   e. Vertical referencing or Tidal Correction
3. Post processing (QA/QC).

4.1. Pre-Processing

Similarly, as pre-planning phase for the acoustic survey, it is necessary to download satellite imagery based on the geographic location and optimal environmental conditions (e.g. cloud coverage and sun glint). After this phase, it is necessary to do radiometric and geometric correction (if necessary). Radiometric correction converts digital number values to Top of Atmosphere (ToA) radiance and reflectance. Corrected digital numbers to ground reflectance significantly reduced the accuracy of SDB estimates (Marks, 2018). The next phase is sun glint correction or noise reduction created by the sun's reflectance (USGS, 2015).

4.2. SDB Depth Calculation

The first phase of SDB calculation is water separation or removed dry land and most of the clouds by the obtained threshold value from Blue and Green band images and converting each pixel of the satellite image into a floating point representation. Thereafter comes the second phase with spatial image filtering with low-pass filter to remove "speckle noise" from the satellite imagery. The next phase is glint/cloud correction by using Hedley et al. (2005) algorithm to correct radiometric contributions from the sun glint and low clouds which is calculated according to the formula:

$$R'_i = R_i - b_i\,(R_{NIR} - Min_{NIR}) \qquad (1)$$

where:

R'_i = Sun glint-corrected pixel

R_i = pixel value in the B and G bands;

b_i = regression slope;

R_{NIR} - Min_{NIR} = difference between pixel NIR (near infrared) value of R_{NIR} and ambient NIR level Min_{NIR} which gives the R'_i Sun glint-corrected pixel brightness of NIR with no Sun glint and can be assessed by the minimum NIR value.

There are several algorithm models developed for deriving bathymetry data from satellite images. This study uses the two most accepted empirical algorithm band Ratio Model. Band Ratio Model (Stumpf et al., 2003) compares band ratios with in situ data to obtain a mathematical relation between the ratio and the depth. Different bands of light will be absorbed to different degrees based on the water's inherent optical properties. For example, in clear waters with low quantities of sediment, phytoplankton and dissolved organic matter, blue light will be less absorbed than green light, while in coastal waters green light will penetrate to greater depths than blue light. This relationship is used to derive the depth of a pixel and the exact mathematical representation is identified empirically through SDB natural logarithm ratio of the blue and green band illustrated by Equation 2:

$$z = m_1\left(\frac{\ln(L_{obs}(Band_i))}{\ln(L_{obs}(Band_j))}\right) - m_0 \qquad (2)$$

where:

L_{obs} = observed radiance of bands;

m_1, m_0 = offset and gain determined empirically;

($Band_i$) = B band; ($Band_j$) = G band;

z = depth.

Identifying the extinction depth or the optic depth limit for inferring bathymetry (also known as the extinction depth) is specified by calculated m_1, m_0 parameters. This is understandable as these bands can penetrate deeper than other colours, and they are available with most sensors.

The final stage of calculating the depth is data vertical referencing, i.e. reference depth to the chart datum.

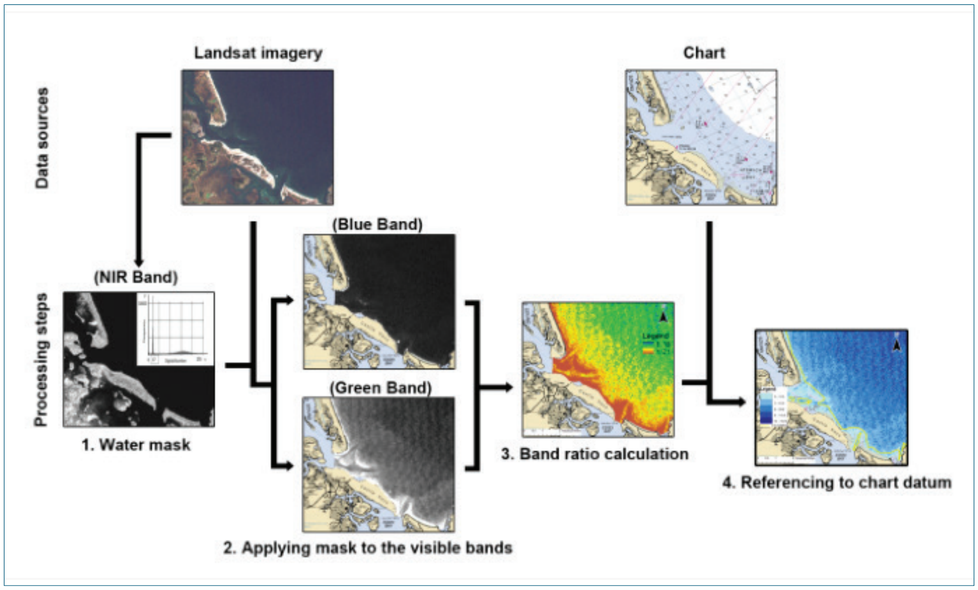

Figure 7.
Key step of SDB procedure (according to Pe'eri et al., 2013).

4.3. Post Processing (QA/QC)

The final phase of SDB process is the quality assurance process used to measure and assure the quality of a product and quality control, which ensures that products and services meet consumer expectations.

4.4. Processing Software

After the processing of satellite data, the product obtained was uploaded on ESRI ArcMap software Version 10.6 with the support of 3D Analyst Tool and ENC S-57 format capabilities for estimating the bathymetry using the log transformation algorithm. ArcMap Raster Calculator and Model Builder features were used for the majority of the works which involved geoprocessing. Landast 8 image data has been geometric and radiometric Top-of-Atmosphere (ToA) Radiance, ToA Reflectance, Sun Glint and Atmosphere Correction corrected. Sentinel 2 image data has been geometrically and radiometrically corrected in SNAP program. The median filter, a nonlinear digital filtering technique used for removing the noise from images, was applied to this study. A median filter was used to manage the reduction of high frequency noise.

5. RESULTS

The result of satellite derived bathymetry (SDB) method for the acquisition of bathymetric data by the non-survey vessels, which used free of charge Landsat 8 image on 14 February, 2017 (Figure 3) and Sentinel 2 image taken on 09 May, 2017 (Figure 4), for depth assessment in the area of Hramina Bay is shown in Figures 1 and 2. The only Landsat 8 and Sentinel 2 image was processed because of a small number of images that have recently been at disposal (free of charge) and without atmospheric/oceanographic "noise".

The maximum tidal range in Hramina Bay was about 40 cm (calculated from the Tide tables for the secondary port) on the date and time of the satellite scene recording. The depth values determined were referenced to the chart datum level.

Consequently, the bathymetric map of the wider area of Hramina Bay (Figures 8 and 9) could be treated as a "preliminary" bathymetric map. Figures 8 and 9 illustrate the estimated water depths computed by the satellite bathymetry model developed by Stumpf et al. (2003) from Landsat 8 and Sentinel 2 satellite images. In Figures 8 and 9, the depths are shown in the colour range from 0 m (red) to 50 m (dark blue).

By comparing the "preliminary" bathymetric map (depths and depth contours in the background) shown in Figure 2 with ENC HR400512 (Figure 6), it can be concluded that the depth gradients and coastline are actually very well surveyed by using SDB method, while individual shoals are not revealed because of the low spatial resolution of SDB method.

Figure 9 shows a more detailed view of the calculated depths, on Landsat 8 image (left) and on Sentinel 2 image (right). The figure shows that the depths shown on the right hand side image are much better because Sentinel 2 resolution is three times better than Landsat 8 resolution.

For better results, SDB method should be used on commercial satellite data in which the current image resolution reaches up from 0.5 to 0.3 m (WorldView 3 and 4).

According to SHOM (2015) and ARGANS (2016), almost all the available SDB data were within positional accuracy ±500 m and depth accuracy of ±2 m + 5 % of depth. In Hramina Bay, SDB data positional accuracies were 10 and 30 m (pixel size of the used satellite images), while the vertical accuracy was ±2-3 m.

In very shallow waters (shallower than 10 m), SHOM researchers compared the results of different methods to obtain the bathymetry data (Table 1). The table has been updated with the data used from free satellite missions from this research.

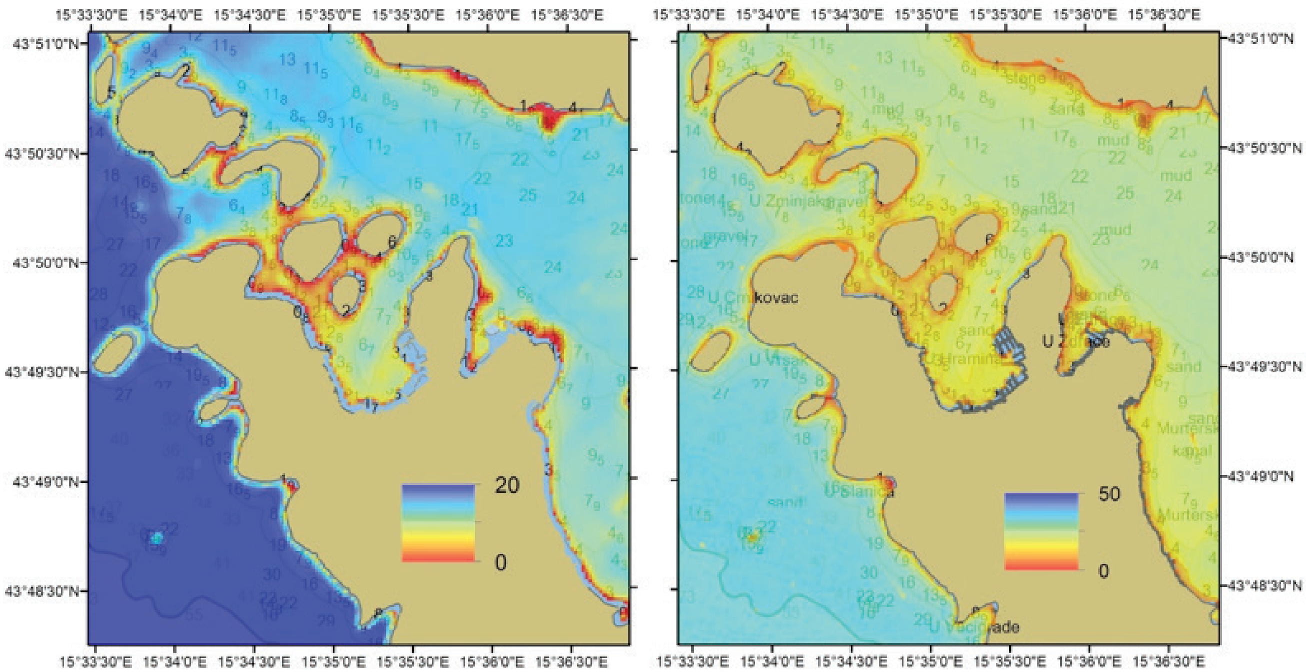

Figure 8.
Satellite-derived water depth of Hramina Bay obtained from Landsat 8 (left) and Sentinel 2 (right).

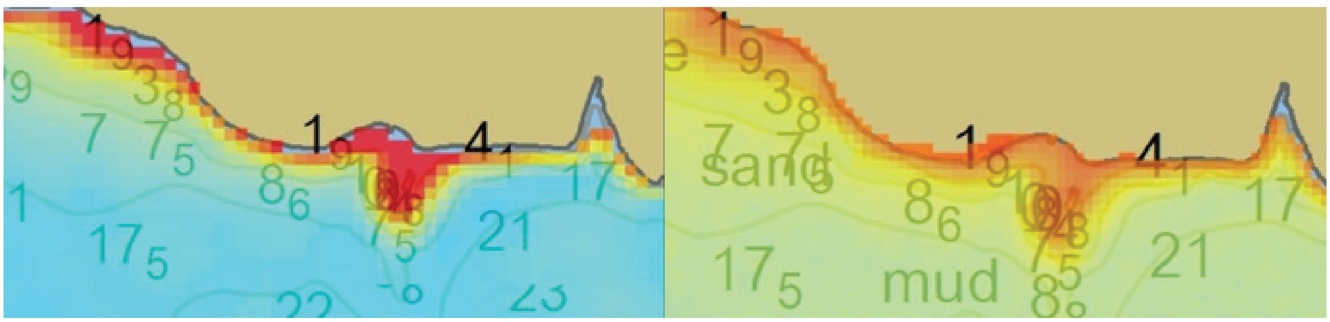

Figure 9.
A more detailed view of satellite-derived bathymetry obtained from Landsat 8 (left) and from Sentinel 2 (right).

Table 1.
Comparison of the characteristics of acoustic and Lidar method (ARGANS, 2016; SHOM, 2015) and SDB methods (this study).

	Acoustic	Lidar	Satellite		
Device	EM204	CZMI	Landsat 8	Sentinel 2	Palaides
Survey (€/km^2)	2.5	1.5	0	0	0.01
Survey (hour/km^2)	7	0.08	0	0	0
Prosessing (hour/ km^2)	21	4	2	2	3
Total cost (€/km^2)	3.3	1.7	0	0	0.1
Total duration (hour/km^2)	28	4	3	3	3
Hor. resolution (m)	0.2	0.5	30	10	2
Ver. resolution (m)	0.1	0.2	1	1	1
Density (depth/m^2)	25	4	0.01	0.01	0.25
Hor. acc. (m)	0.5	1	30	10	10
Ver. acc. (m)	0.2	0.3	30 % of depht	30 % of depht	10-30 % of depht

6. CONCLUSION

Satellite-derived-bathymetry survey method can be used when planning hydrographic surveying of marine areas not surveyed or areas with old bathymetric data. Unlike hydrographic surveying performed by conventional shipborne sounding techniques, SDB method for depth determination is not time consuming, demanding or expensive. SDB cost generally depends on the costs of satellite images, which ranges from 0 (free of charge) to 60 €/km2, depending on the image quality.

By applying SDB method in Hramina Bay area in the eastern part of the Central Adriatic, it could be concluded that the method is suitable for a bathymetric survey of shallow areas with clear water (approximately to the depth of 2 secchi disc depth), which the researched area fills during most of the year.

In Hramina Bay SDB data, the positional accuracies were 10 and 30 m (pixel size of used satellite images), while vertical accuracy cannot be exactly estimated because the depths measured by the echo sounder and the depth estimated from the satellite images do not have the same spatial resolution.

From the satellite-derived depths, it is obvious that the depth gradients and coastline are actually very well surveyed by using SDB method, while individual shoals are not revealed because of the low spatial resolution of SDB method. SDB depth data has better result by using Sentinel 2 scenes, because Sentinel 2 space resolution is three times better than Landsat 8 resolution. The results obtained are satisfying for only one satellite scene and without knowledge of the atmospheric/oceanographic conditions in Hramina Bay area.

When choosing the satellite scene, we chose the free Landsat and Sentinel missions, but on the same principle the depth can be calculated with commercial satellite mission, which has a higher spatial resolution (e.g. Worldview 3 or 4 with spatial resolution of 0.3 m).

Finally, it can be concluded that SDB method presented in this paper can be scientifically improved by satellite scenes obtained from commercial satellite data, all in order to achieve current International Hydrographic Organization (IHO) S-44 standards for hydrographic survey (IHO, 2008).

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