Abstract: Bathymetry maps derived with satellite-based multispectral sensors have been used extensively for environmental and engineering coastal studies and monitoring. However, so far this technique has not been widely exploited in other coastal applications, such as underwater archaeology. Submerged settlements and shipwrecks are often located in water depths where the application of multispectral satellite data is feasible. This could lead to more efficient field work practices thus enabling more optimal allocations of costs and labour during archaeological excavations. This study explores the contribution of processed satellite bathymetry maps to the recording of two archaeological coastal sites: a submerged prehistoric settlement in Greece and a shipwreck of a modern cargo vessel in Italy. The results indicate that even though the accuracy of satellite derived bathymetry is high, the level of detail (spatial resolution) is not sufficient to fully replace field-based measurements. However, the use of satellite data complements the existing techniques and can help to place the archaeological sites within a broader spatial context as well as to efficiently monitor the deterioration of a site due to natural causes or human activity, which inevitably leads to risk management. When the study of larger objects is involved (for example First World War shipwrecks) the potential of using satellite data in underwater archaeological studies becomes more promising.

Keywords: Bathymetry, underwater archaeology, satellite data

1 Introduction

The logistics of an underwater archaeological field research often appear to be particularly complicated in comparison to a terrestrial field research. Although some attempts to conduct scientific underwater field research can be traced back to the late 19th/early 20th century AD (Muckelroy, 1978), it was from the late 1960s when maritime archaeology was established as a specialized field of the archaeological discipline. At that time scholars undertook the task of providing a well elaborated theoretical background within which the underwater research could be conducted (Babits & Van Tilburg, 1998; Barron & Taylor,
R. Guzinski, et al. (1966; Bass, 1966; Frost, 1963; Green, 1990; Linder & Raban, 1975; Muckelroy, 1978; Throckmorton, 1977; Wilkes, 1971). Their contribution stressed the need for a multi-disciplinary and inter-disciplinary approach that would allow research with non-destructive investigations. During the decades that followed, the application of innovative technologies contributed to the archaeological science, in order to limit the difficulties encountered by the peculiar environment within which an underwater archaeologist is forced to operate. Since the methodology of archaeological field research is divided to an intrusive (excavation) and non-intrusive (survey) approach, it is the latter that has and still continuous to benefit the most from the application of such technologies. By no means do we exclude the evolution of multi-disciplinary scientific approaches and technologies at the level of data processing and laboratory analyses; However, it is not the objective of the present paper to analyse the stages which follow the acquisition of data.

"The underwater archaeological survey (pre-disturbance survey and site monitoring survey) comprises the process of locating, exploring and recording a site. Its aims and objectives are determined in the project design, thus the survey is an end point in itself" (Maarleveld, Guérin, & Egger, 2013). Even with the development on new technologies, the survey usually takes the form of diver, or ship-based assessments. Both of those require significant human resources and specialised equipment to conduct even close-to-shore excavations in very shallow waters (Gkionis, 2013). Therefore, the application of any method which can reduce the time spent underwater and simultaneously the amount of fieldwork required during an underwater survey, could lead to significant efficiency improvements and cost savings.

One such technique is the use of autonomous underwater vehicles and other robotic technologies during underwater surveys (Allotta et al., 2015). Another is the derivation of shallow water bathymetry from airborne LIDAR measurements, which was shown to offer valuable input during excavation of a submerged coastal settlement (Doneus et al., 2013). A further elaboration of this technique is the derivation of shallow water bathymetry using satellite-based multispectral measurements. While those bathymetric maps might not provide the same level of detail (spatial resolution) as the maps derived with LIDAR measurements, they have the advantages of providing an overview of a larger area and even lower costs. Modern satellites can acquire multispectral images (up to 6 spectral bands in the visible part of the electromagnetic spectrum) with a resolution of around 1.5 – 2m for nadir observations (Puetz, Lee, & Olsen, 2009). This resolution can be further enhanced by exploiting the spatial information contained in the panchromatic band, which can be acquired with a spatial resolution of up to 0.4 m, to sharpen the multispectral image in a process called pan-sharpening (Fasbender, Radoux, & Bogaert, 2008). However, in the underwater domain this technique might not always provide useful additional information.

Bearing this in mind, the ITACA project (www.itaca-fp7.eu) investigated the use of satellite derived bathymetry at two archaeological sites: a submerged prehistoric settlement at Metohi on the west coast of the south Pagasetikos Gulf (northern Greece) (Figure 1), and a modern shipwreck of Elphis I cargo vessel off the west coast of Sicily (Figure 2). This paper presents the methodology applied at those two sites and compares the bathymetric maps derived from satellite measurements with those obtained by traditional methods, i.e. using manual depth measurements performed at Metohi and side-scan sonar measurements obtained at the Elphis I wreck site. Firstly, an overview of the techniques employed in the satellite bathymetry processing chain is provided, followed by the description of the two study sites. Consequently the bathymetric maps obtained from the satellite and field datasets are compared and the utility of satellite observations in underwater archaeology is discussed.

2 Methods

2.1 Satellite Derived Shallow Water Bathymetry

In order to be able to derive bathymetry using satellite multispectral observations the light emitted by the sun must be able to penetrate the atmosphere and the water column, reflect from the benthic layer and once again penetrate the water column and atmosphere to reach the satellite sensor. This places some constraints on when the bathymetric estimates can be obtained. Firstly, the atmosphere must be cloud free.
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and clear. Secondly the water column must also be clear, that is without substantial suspended sediment or organic material. Thirdly, the water surface conditions must be such that there is no excessive reflection of the light from the water surface (sun-glint) either due to the relative locations of the sun and the satellite sensor or due to waves. And lastly, the depth of the water column must be less than 20-25 m (in clear water conditions), since even pure water is a strong absorber of light, especially in the longer wavelengths (Pope & Fry, 1997). However, when the above conditions are met then reliable and detailed bathymetric maps can be obtained with satellite observations (Dekker et al., 2011).

There are three major categories of methods for deriving shallow water bathymetry from multispectral optical data: empirical, look-up table based and semi-analytical. A good review of the various approaches is provided by Gao (2009) and Dekker et al. (2011) with a short summary also presented below.

The empirical methods of deriving bathymetry are mainly based on study of Lyzenga (1985) and further work by the same team (e.g. Lyzenga, Malinas, & Tanis, 2006). Bathymetry at each pixel is estimated through a linear combination of log-transformed reflectances from that pixel. The weight given to each spectral band is determined during model calibration through a least-square regression optimization of weight values against points of known depth. Although the algorithm uses just one linear equation, it is able to account for a number of water quality and benthic zone conditions and depth ranges. However, it depends on the data set of known depths used during the calibration. Only the conditions which are present in the training data set can be accommodated in the final equation. This dependence on an extensive training data set is one of the main weaknesses of the empirical methods.

The look-up table methods (e.g. ALLUT - J. Hedley, Roelfsema, & Phinn, 2009), do not require any training dataset with known depths. Instead they rely on a database (look-up table) of spectral reflectance signals corresponding to various combinations of water depths, water column constituents, benthic types and observation and illumination geometries. This database needs to be prepared using advanced water radiative transfer models and should contain spectral information close to what would be expected in the conditions during which the image to be analysed was acquired. The reflectance spectrum of each pixel in the image is then compared against the spectra stored in the database and the conditions which generated the spectrum with the closest match are considered the true conditions in that pixel.

The semi-analytical methods of deriving bathymetry try to do away with the need for the training dataset and pre-determined database. To do this they replace the empirical relationship between depth and measured reflectances by a (simplified) physically-based model of reflectances from a water surface of varying depth, water quality and benthic type. The difference between the modelled and measured reflectances is minimised through a multivariate optimisation of the model parameters, one of which is depth. When the minimum solution is obtained, it is assumed that the value of the depth parameter is the actual depth in a given pixel. The semi-analytical methods are generally slower than both empirical and look-up table methods but offer more flexibility in the area of application. There are two main semi-analytical bathymetry retrieval methods: HOPE (Lee, Carder, Mobley, Steward, & Patch, 1999) and BRUCE (Klonowski, Fears, & Lynch, 2007). Both models were designed for hyperspectral measurements of water leaving reflectances but it is possible to adjust them for application with multispectral data. The HOPE model was chosen for deriving bathymetry in this study since it avoids the need for field measurements of depths (required for empirical methods) and for database of known spectral profiles (required for the look-up table methods).

The multispectral bathymetry processing chain (including more details about HOPE model) is described in the sections below.

2.2 Input Satellite Data

The input multispectral data set must satisfy certain strict requirements in order to prove suitable for underwater archaeological applications. The objects of interest are usually quite small, on the order of tens of centimetres to tens of meters. Even larger objects, such as more modern wrecks or settlement foundations are usually long but narrow. Therefore, the spatial resolution of the satellite images should be on the order of meters, with possible pan-sharpening to sub-meter range.
In addition, the spectral properties of the satellite sensors are also very important, especially if the image is to be analysed with semi-analytical bathymetry methods. Since those methods work on a spectral-matching principle, the more spectral channels/bands a sensor has (and the narrower they are) the more likely it is for the model to achieve a unique optimal solution. The location of those bands in the electromagnetic spectrum is also important since water is a very strong absorber of light in the red and near-infrared (NIR) wavelengths. Therefore majority of the bands should be of shorter wavelengths. Finally, temporal resolution might play a part if the objective is to perform regular monitoring of submerged objects or to quickly respond to unexpected events (such as storms which could have uncovered new artefacts at the sea bottom).

The sensors which were assessed to be best able to satisfy those requirements were WorldView-2 (Puetz et al., 2009) and WorldView-3. The two satellites are able to acquire images in six bands in the blue-red part of the electromagnetic spectrum and in two bands in the near-infrared part of the spectrum (useful for sunglint correction). The spatial resolution of the multispectral sensors is around 1.5 m to 2 m (depending on the viewing angle) while for the panchromatic sensor it can be as high as 40 cm.

2.3 Satellite Data Pre-processing

The amount of light in the visible part of the spectrum in the water leaving reflectance typically ranges from 0.5% to 3% of the incoming light, depending on the wavelength, depth of the water, water optical properties and bottom albedo. This relatively weak signal is contaminated on the way to the satellite sensor, mostly by scattering due to atmospheric aerosols (i.e. haze) but also through absorption by water vapour, ozone and other atmospheric constituents. Additional contamination of the signal can be caused by the noise in the sensor itself and by sunglint caused by observation and illumination geometry or waves on the water surface. It is therefore important to account for, and minimise, this noise before the satellite data can be used for bathymetry retrieval.

The atmospheric correction in this study was performed using the Second Simulation of a Satellite Signal in the Solar Spectrum - Vector (6SV - Vermote et al., 2006) atmospheric radiative transfer model. As input 6SV requires observation and illumination conditions (solar and view zenith and azimuth angles, day and month of observation), the spectral response function of each sensor band and some information about the atmospheric conditions (atmospheric gases and aerosol profiles). The first two pieces of information can be obtained from image metadata. For atmospheric conditions it is possible to use predefined profiles (e.g. midlatitude summer atmospheric profile and maritime aerosol profile) or to manually set the values for ozone, water vapour and aerosols in the atmosphere. In this study, the initial estimates of those values were obtained from the MODIS sensor on Terra satellite, which has an overpass time very close to the overpass of WV2/WV3 and is able to retrieve the necessary atmospheric parameters (King et al., 2003). The initial estimates had to be adjusted manually in case the obtained bottom-of-atmosphere reflectance values were not realistic (e.g. high NIR reflectance over deep clear water).

Due to the low reflectance values, the technical limitations of the sensor can result in random noise visible in the image as a speckle or salt-and-pepper effect. There are various filtering techniques to minimize this effect and thus to improve the signal-to-noise ratio (SNR) of the image. However, it is important to choose a technique which can increase the SNR while not blurring the fine details present within the image. One such technique (employed in this study) is a hybrid principal component analysis (PCA) and wavelet thresholding algorithm, based on the work of Chen and Qian (2011). The technique is suitable for hyperspectral imagery with already high SNR and limits the noise while preserving the fine details. The original image is first transformed through PCA into high and low energy output channels. The first output channels contain most of the information, while the latter ones contain less information content and more noise. Therefore, the low energy PCA output channels are transformed into wavelet space where wavelets below certain threshold are removed, while the high energy PCA channels remain unchanged. After the thresholding, the original image is rebuilt.

Sun glint is caused by specular reflectance of light from the water surface, either due to water surface roughness caused by waves or due to illumination and observation geometry. It can obscure the water
column and benthos reflectance signal and therefore multiple methods have been developed to deal with this problem (e.g. J. D. Hedley, Harborne, & Mumby, 2005; Lee et al., 1999; Lyzenga et al., 2006). They rely on the fact that clear water is a very strong absorber of light in the NIR part of the spectrum. Therefore, after accurate atmospheric correction any significant remaining NIR reflectance in reasonably deep (more than 1 meter) and clear water can be attributed to sun glint. By assuming a statistical relationship between the sun glint caused reflectance in the NIR part of the spectrum and sun glint caused reflectance in the visible (VIS) part of the spectrum, it is possible to minimize this effect across the whole VIS-NIR spectrum while leaving the spectral profile of areas not affected by sun glint intact.

2.4 Satellite Bathymetry Retrieval

The satellite bathymetry was estimated using the HOPE model (Lee, Carder, Mobley, Steward, & Patch, 1998; Lee et al., 1999) with the pre-processed WorldView-2 and WorldView-3 images used as input. As mentioned previously, the model estimates the per-pixel water leaving reflectance across the visible part of the electromagnetic spectrum by varying 5 parameters which are adjusted through an optimisation method in order to minimise the difference between the estimated and observed reflectance spectra. The parameter set which achieves the minimum difference is assumed to represent the conditions (including depth) in a given pixel at the time of the satellite overpass. The five optimisation parameters (output layers) are: phytoplankton pigment absorption at 440 nm, gelbstoff absorption at 440 nm, backscattering coefficient of particles at 440 nm, bottom albedo at 550 nm and water depth.

Apart from outputting the 5 parameters, HOPE can also provide an estimate of the accuracy of the estimated depth. The accuracy can be deduced from the euclidean distance between the modelled and measured spectra as well as from the fraction of the modelled signal originating in the benthic zone and not in the water column.

The model requires some spectral shapes (e.g. of phytoplankton pigment absorption or bottom albedo) normalised at the given wavelength to be able to model the reflectance across all the VIS wavelengths. Those spectral shapes can be based either on field or laboratory measurements, or on outputs of more advanced models. Some of the shapes can be applied across many different satellite scenes (e.g. absorption of pure water) while others need to be selected depending on the expected local environment (e.g. bottom albedo). The majority of this information can be obtained from existing studies and literature (e.g. Kutser, Vahtmae, & Metsamaa, 2006; Lee et al., 1998; Pope & Fry, 1997; Smith & Baker, 1981), which limits the need for field measurements in new environments.

Sequential Least SQuares Programming (SLSQP) (Kraft & others, 1988) was chosen as the optimization method for minimizing the differences between the modelled and measured spectra. A major advantage of SLSQP algorithm is the ability to set bounds and constraints on the parameters being optimized. Bounds specify a minimum and a maximum value that a given parameter can lie between (e.g. water depth must be between 0 and 30 m), while constraints are more complex conditions that must be satisfied in the optimal solution (e.g. for water depths deeper than 15 m, phytoplankton absorption must be below a certain value). The ability to set bounds and constraints is very important when attempting to optimize HOPE using multispectral, as opposed to hyperspectral (tens or hundreds of spectral bands) data. This is because HOPE was designed for operation with hyperspectral data which have much richer information content than multispectral data. Therefore, when using multispectral data the optimization process must be “guided” to converge to a plausible solution. The bounds and constraints must be chosen based on past experience, the expected conditions within the scene being processed and literature review. Coarser resolution water quality products (e.g. from MODIS sensor - Carder, Chen, Cannizzaro, Campbell, & Mitchell, 2004) could also be used as guidance for bounds setting.

Since the parameter space is quite complex, it is possible that the optimization might converge to a local and not global minimum, thus setting the model with less-than-optimal parameter values. This can be avoided by combining SLSQP with a global optimization algorithm, such as Basin Hopping (Wales & Scheraga, 1999). In Basin Hopping, a specified number of semi-random jumps are performed around the solution space and a jumped solution can be accepted with a certain probability even if it is less optimal.
than the original solution. Finally, it is also possible to perturb the initial parameter values when the values set by default lead to inaccurate final results.

### 2.5 Bathymetry Map Post-processing

Certain amount of noise is to be expected in the output bathymetry maps, even after careful input data pre-processing and proper parameterization of the bathymetry retrieval algorithm. This is because HOPE is sensitive to noise in the input image which might lead it to converge to local (and not global) minimum in some pixels. This can result in those pixels having bathymetry values far removed from those of their neighbours. In order to correct those values, each pixel in the bathymetry map is compared with its eight neighbours. If the depth value differs by more than a certain threshold with four or more of its neighbours, then that pixel is considered an impulse pixel and its value is replaced by the median of the values of the valid pixels in its neighbourhood (Garcia, Fears, & McKinna, 2014). Additionally, the quality layer produced by the semi-analytical model can be used to treat low-quality pixels as impulse pixels and replace their values in similar fashion. In case of this study, the threshold must be carefully chosen to remove the noise while not removing abrupt changes in bathymetry due to underwater archaeological artefacts.

Another commonly used post-processing technique is binomial smoothing of the depth value of each pixel based on the values of its neighbours. It might be of less use in the archaeology context, where small objects are often of interest, but in general it improves the accuracy of the derived bathymetry. Finally, when using the semi-analytical methods for bathymetry estimation the depth retrieval depends on the fraction of the spectral signal that is due to the reflectance of solar light from the benthic surface. Therefore, the deeper the water, the smaller the signal from the bottom and the less sensitive is the bathymetry algorithm to the changes in water depth. This can lead to underestimation of bathymetry and this underestimation can linearly increase with depth. If enough information about the expected depth is present, then this effect can be corrected by using a linear transformation of the estimated bathymetry, which can greatly increase the correlation and decrease the error when compared to field measured depths.

### 3 Site and Field Campaign Description

#### 3.1 Metohi

In the year 2000, the Hellenic Institute of Marine Archaeology set out to conduct an underwater archaeological survey along the west coast of the southern part of the Pagasetikos Gulf, under the direction of the archaeologist Elias Spondylis. To this day 16 archaeological sites have been located along a coastal zone of 7 nautical miles. Among them, 13 shipwrecks have been recorded which can be dated from the Hellenistic period to the early 20th century. Since 2009, the recording of a prehistoric settlement at Metohi became one of the priorities of the Institute’s research objectives.

Metohi is a low swelling in the centre of the Bay of Nies, in the form of a small peninsula, which joins with the coast with a low and thin causeway (Figure 1). Much of its area is occupied by monastery facilities that served, until the 1960’s, the harvesting and processing of olives coming from the extensive olive grove situated in the coastal plain, beyond the Bay.

Its earliest occupation dates back to the first half of the 2nd millennium BC. It is the third settlement in Greece to be discovered submerged, together with Methoni (Spondylis, 1996a; 1996b; 1999; 1999) and Pavlopetri (Spondylis, 2015), bearing well-hidden traces of the Middle Bronze Age era (2100/1950 - 1650/1550 BC).

The settlement covers an area of at least 10,000 m2 at a depth of 0.2 m to 2.5 m (50% of the area is at depth of less than 1 m). It would have provided shelter to a small farming community that had access to an abundant source of water, a hospitable sea and an arable land. Within the pile of stones that cover most of the sea bottom, at least twenty one partially preserved walls have been located, two of which have been laid in the herringbone pattern. In addition, two wall corners are visible. The house walls would have been
built by packed clay or unfired bricks resting on substantial stone foundations. Eighteen cist graves have been documented, which are made of limestone slabs laid in rectangular shape. At least three of them, as excavation revealed, accommodated infants. It was a common practice during that period to bury the children within the house, underneath the floor.

Figure 1: An overview of the Meothi archaeological site using WorldView-2 true-color composite image.

The recovery of architectural features, mostly walls, depends on the lighting conditions at each hour of the day and the visibility angle, as well as the experience of the observer. A great part of the seabed around the Metohi Peninsula is covered with stones which originate from the dismantling of the walls. Consequently, it is very difficult to discriminate the walls from their surrounding environment even with a detailed visual inspection. On the other hand, it is relatively easier to locate the cist graves because of their shape and the fact that the rectangular slabs usually protrude from the seabed. However, in some cases, a cist grave might be located in a sandy or muddy sea-bottom and can be covered or un-covered periodically, depending on the seasonal sea currents. Needless to say, the same current activity also affects the documentation of the walls. Another drawback is the growing vegetation upon the architectural features that together with the surrounding one, distorts them and makes them invisible or unnoticeable. This description applies to the area between the coastline and down to 2.5 m in depth (Michalis & Spondylis, 2012; Spondylis, 2012).

Previously to the beginning of the ITACA project, topographical plan of the area was established through the application of tacheometry by using the total station. From the plan a set of 35 georeferenced (originally in the Greek Grid GCSGGRS-1987 reference system) points grouped into 0.5 m bins and ranging in depth from 0.5 m to 2.5 m were extracted. Due to the limited depth range of this dataset it was decided to conduct a very limited field campaign in order to obtain a second depth dataset including the deeper waters. The campaign consisted of performing geolocated depth measurements and of taking photographs of the benthos and the view towards the Metohi peninsula at the depth measurement points. The campaign resulted in a dataset of 43 points ranging in depth from 0.2 m up to 10.3 m. It must be noted that the two above mentioned datasets have relatively large uncertainties in both horizontal and vertical accuracies and therefore care must be taken when using this data for comparison with satellite derived maps.

In the years 2014 and 2015, the Hellenic Institute’s Research Team revisited the site in order to conduct an archaeological survey and contribute to the objectives of the ITACA Project. The 2014 field campaign lasted from 1st to 15th of September and involved the participation of 19 divers, while the 2015 campaign was conducted between 21st of May and 21st of June and involved the participation of 29 divers. The campaigns led to the enrichment of topographical and architectural recording of the Meothi site. A topographic map of the area resulting from the campaigns was also used in this study for visual comparison with the satellite bathymetric map.
3.2 Elphis I

The shipwreck of Elphis I, a modern 400 ton cargo vessel, is about 50 meters long and 8 meters wide and located 400 m from Maraone Islet in the south-east direction (Figure 2). The Japanese ship, flying a Cypriot flag, was carrying an illegal cargo of cigarettes when on the night between the 12th and the 13th of January 1978 it run ashore on the Maraone Islet and two days later sunk, due to the heavy seas. For several years its mast surfaced a few meters above the sea, though was then cut off for safer navigation.

The wreck is lying up-right on a sandy-bottom at a depth of 16 m, with currently the highest part of the wreck (chimney) covered by 7 m of water. On the north-eastern part of the wreck there is a large rocky shelf at a depth of 10-12 meters.

Sonar measurements of bathymetry around the shipwreck site were obtained during a ship-based field campaign conducted between 7th and 9th of September 2015 as part of the ITACA project (Figure 3). On the 8th of September 2015 a search close to the estimated coordinates of Elphis I wreck was conducted with a low-resolution survey (130° beam, 60 cm swath). As the wreck was found, the team conducted a high-resolution survey (beam 50°-65°, 10 cm swath) on the same day. The aim of the survey was to determine the morphological features of wreck and the surrounding areas in order to compare the high resolution bathymetry with the satellite derived bathymetry.

The team that conducted the field campaign consisted of the Soprintendenza del Mare divers and Codevintec technicians. The system used was composed of:

- Multibeam echosounder, 512 beams, double frequency 200/400 kHz, for high resolution bathymetric surveys (RESON Seabat 7125 SV2)
- Integrated Navigation System for positioning, heading and dynamic correction of boat asset (Applanix POSMV)
- Probe to measure sound velocity in water, at different depths (YSI CASTAWAY-CTD)
- Hydrographic software for bathymetric data acquisition and processing (PDS 2000)
- GPS/RTK double frequency receiver, as reference station (Leica SR530)

The acquired data have been processed with PDS2000 software in order to apply sound velocity measurements and perform data clean up (spikes removal, multipath smoothing with automatic filters and manual removal). The processed data were then georeferenced and visualized with the POSPac software.

![Figure 2: An overview of the Elphis I wreck site using WorldView-2 true-color composite image. The location of the wreck is highlighted in red.](image-url)
4 Results

4.1 Metohi Settlement

Three WorldView-2 images were used at the Metohi peninsula site. The images were retrieved from a historical acquisition archive and their acquisition dates were: 26.10.2010, 31.01.2013 and 19.09.2013. Those three images were chosen as having the least cloud coverage, least sun-glint and the clearest atmosphere from among the other images present in the archive.

All three images have a multispectral spatial resolution of 1.6 m and a panchromatic band with spatial resolution of 0.4 m. The images were georeferenced to a common external dataset (Bing maps) in order to ensure geolocation consistency between the scenes. Further pre-processing of the three images included atmospheric correction and de-nosing as described in the Methods section. Bathymetry maps were derived using the HOPE model and during the post-processing only the impulse filtering was applied.

Figure 4 contains scatter plots of the estimated bathymetry versus the measured depths, together with the statistics for those comparisons, while Figure 5 shows visual comparison of satellite bathymetries obtained from the three satellite images.

The three bathymetry maps show very similar performance up to around 4 meters depth, with the image from 26.10.2010 showing a bit of underestimation of the derived depth. Beyond 4 meters the differences between the maps are more pronounced with the image from 19.09.2013 being the only one in which high quality depth retrievals were obtained up to 10 m. The reason why the bathymetry derived on 31.01.2013 does not reach such a depth is probably due to the illumination conditions. In January the sun is much lower above the horizon than in September, meaning that there is less light to penetrate through the water column, reflect from the sea bottom and reach the satellite sensor. In October the sun is also lower than in September but not too such a large degree. However, the image from 26.10.2010 was characterized by a significant sun glint which also makes it harder to retrieve deeper depths.

The obtained statistics are satisfactory for all three dates with very high correlation and low bias and root mean square error (RMSE). The difference in bias between the three images is around 35 cm (between 26.10.2010 and 19.09.2013). However, neither the field data nor the satellite derived estimates have been adjusted for tides, which in this area can lead to depth difference of over 50 cm. In addition, it must once again be mentioned that the field measurements have high vertical and horizontal uncertainty.
Figure 4: Comparison between field-measured bathymetry (x-axis) and satellite bathymetry (y-axis) at the Metohi peninsula site on three study dates.

Figure 6 illustrates two depth profiles extracted from the three bathymetric maps. Similarly to the scatter plots, it can be observed that the three maps agree very well up to the depths of around 4 m, although there is some scatter present, particularly to the east of the peninsula where the seagrass cover was quite thick even at shallow depths, thus decreasing the bottom albedo.

The topographic map created during the 2014 field campaign was used in Figure 7. The black lines indicate the depth isolines, which were obtained from field measurements at 0.2 m depth spacing. In addition, the color code represents bathymetry derived from WV2 image taken on 19.09.2013, and it is categorized into the same 0.2 m depth bins. The figure clearly shows the similarities between the two datasets, e.g. the location of a large beach rock to the west of the peninsula.

Even though the satellite derived bathymetric maps are able to accurately capture the sea bottom topography around the Metohi peninsula, there are no artefacts (i.e. cist graves or wall foundations) visible in those maps. This is mainly due to the size of those features being less than the spatial resolution of the multispectral satellite data. The attempt to increase the spatial resolution of the bathymetric maps through pan-sharpening is described in the Discussion section below.
Figure 5: True color composite WorldView2 images (left column) and HOPE derived bathymetry maps (right column) of the area surrounding the Metohi peninsula. (a) and (b) – image taken on 26.10.2010; (c) and (d) – image taken on 31.01.2013; (e) and (f) – image taken on 19.09.2013.
Figure 6: Example of two depth profiles extracted from the three bathymetric maps produced at Metohi: 26.10.2010 (green), 31.01.2013 (blue) and 19.09.2013 (orange).

Figure 7: Comparison between depth isoline map (0.2 m separation) created during the 2014 Metohi field campaign and bathymetry map (also 0.2 m separation) produced with WorldView-2 data acquired on 19.09.2013.

4.2 Elphis I Ship Wreck

No suitable WorldView-2 or WorldView-3 data could be found in the archive for this site. Therefore two WorldView-2 images covering the Elphis I ship wreck were acquired on the 30.08.2015 and 10.09.2015, together with a WorldView-3 image acquired on 25.08.2015. However, the images from the 25.08.2015 and 10.09.2015 were considered to be too affected by wave induced sun-glint (Figure 8) and consequently only the image from 30.08.2015 was further analysed.
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The selected image has a multispectral spatial resolution of 2 m and a panchromatic band with a resolution of 0.5 m. The image processing followed similar procedure to the one performed with the Metohi images, with the image being first accurately geolocated using an external dataset (Google maps) and then atmospherically corrected and passed through the noise reduction pre-processing steps. After bathymetry derivation using the HOPE model the output image was post-processed using impulse-filtering, binomial smoothing and depth stretching.

The comparison between the sonar-based depth measurements and the satellite derived bathymetry map are presented in Figure 9 with visual comparison shown in Figure 10. It can be noticed that the multispectral bathymetry retrieval is generally accurate up to the deepest depth present at Elphis I site which is around 18 m. The RMSE is about 10% of the maximum depth and the correlation has a value of 0.77. The Elphis I site is characterised by steep and abrupt changes in bathymetry due to the nature of the Elphis I wreck and the adjacent rocky shelf. The higher spatial resolution of the sonar bathymetry presents a clear advantage when trying to capture this variability. This can be seen on the scatter plot, where the major discrepancies between the two datasets occur between the depths of 10 and 15 meters which is the transition zone between the depth on top of the rocky shelf and the wreck and the depth on the sandy bottom. Also, it can be observed that for each satellite derived depth, there is a range the sonar derived depths corresponding to all the sonar measurement points falling within one satellite pixel.

![Figure 8: A stretched true-color composite of the WV-3 image acquired on 25.08.2015 (left), WV-2 image acquired on 30.08.2015 (center) and WV-2 image acquired on 10.09.2015 (right).](image)

![Figure 9: Density scatter plot comparing sonar bathymetry (x-axis) and satellite bathymetry (y-axis) over the Elphis I wreck. Brighter colours indicate higher density of points, darker colours lower density.](image)
Despite this, the profiles from the sonar and satellite bathymetries at the Elphis I site agree very well, with the location and shape of the wreck clearly identifiable (Figure 11). The spatial resolution difference between the two dataset is also clearly visible with the lower-resolution satellite bathymetry not being able to represent the sharp depth changes visible in the higher-resolution sonar image. There is also clear difference in amount of detail being captured in the sonar and satellite bathymetry measurements (Figure 10 (b) and (c)).

It is also interesting to note that while the true-colour composite image (Figure 2 and Figure 10a) mostly highlights the changes in bottom albedo (e.g. the bright sandy bottom extending to the north-west of the wreck), the HOPE-derived bathymetry is insensitive to the bottom type and instead captures the depth changes related to the ship wreck and rocky shelf (Figure 10c) which are not clearly visible in the true-colour composite.

Figure 10: Overview of Elphis I bathymetry maps: (a) true color composite WorldView2 image; (b) sonar-derived bathymetry; (c) satellite-derived bathymetry.

Figure 11: Three examples of bathymetry transects at the Elphis I wreck. Red line represents the sonar bathymetry while green line represents the satellite bathymetry. Maps show sonar bathymetry of Elphis I wreck overlaid on satellite bathymetry of the surrounding area.
5 Discussion

5.1 Spatial Resolution Enhancement

In a field of application like underwater archaeology, where the benthic features under investigation are usually quite small, pan-sharpening might offer an opportunity to obtain more informative satellite-derived bathymetry maps by increasing their spatial resolution. In the case of WorldView-2 and WorldView-3 satellites, that increase is by around a factor of four. At the same time, the panchromatic band has a very broad spectral range and therefore might be strongly absorbed by the water column. In addition, the process of pan-sharpening might introduce additional noise into the image.

To test the effect of pan-sharpening on the accuracy of the bathymetric maps and on the ability to capture fine details, we have performed bathymetry retrieval using the pan-sharpened images at Metohi and Elphis I sites. The pan-sharpening was performed as the first step in the processing chain, before other pre-processing steps and the bathymetry retrieval.

The image from 19.09.2013 was pan-sharpened at the Metohi peninsula and the results are presented in Figures 12-14. There is no significant difference between the original and pan-sharpened bathymetries, both when comparing them quantitatively (Figure 12) and qualitatively (Figures 13 and 14). This was partially expected since the underwater topography at that site is relatively smooth and is equally well captured by both 1.6 m and 0.4 m spatial resolutions. At the same time, the density (and accuracy) of the measured depth points is not enough to reach solid conclusions in a statistical sense. Also the cist graves and walls present at the investigation site are too small to be reliably identified even at the increased resolution (Figure 13). However, it can be inferred that performing the pan-sharpening did not introduce additional noise, which would have resulted in degraded accuracy of the output map.

The results of deriving bathymetry from pan-sharpened images at the Elphis I site (Figure 15, Figure 16 and Figure 17) show both the advantages and the limitations of pan-sharpening. The profiles shown in Figure 17 illustrate the strong relationship between the spatial resolution and the ability to capture sharp changes in depth often present at shipwreck sites. However, the profiles (as well as the two other figures) also illustrate that at this site pan-sharpening mostly led to enhancement of surface features (i.e. waves) as opposed to bottom features. This is because the shipwreck is lying at a significant depth and has a dark surface (see Figure 10a) that it is not well captured by the panchromatic band. This shows that it is important to evaluate the utility of pan-sharpening on a site-by-site basis, instead of applying it automatically and expecting an improvement in the results.

![Figure 12](image-url)

**Figure 12:** Comparison between field-measured bathymetry (x-axis) and satellite bathymetry (y-axis) over the Metohi peninsula on 19.09.2013 using the original resolution image (left) and the pan-sharpened image (right).
Figure 13: True color composite WorldView 2 images (left column) and HOPE derived bathymetry maps (right column) of the area surrounding the Metohi peninsula. (a) and (b) – image taken on 19.09.2013 at 1.6m spatial resolution; (c) and (d) – pan-sharpened image taken on 19.09.2013 at 0.4 m spatial resolution.

Figure 14: Two examples of bathymetry profiles at the Metohi peninsula on the 19.09.2013. Red line represents bathymetry derived with WorldView-2 data with a resolution of 1.6 m, while green line represents bathymetry derived with pan-sharpened data with a resolution of 0.4 m.
Figure 15: Density scatter plot comparing field-measured bathymetry (x-axis) and satellite bathymetry (y-axis) over the Elphis I wreck using the original resolution image (left) and the pan-sharpened image (right). Brighter colours indicate higher density of points, darker colours lower density.

Figure 16: Overview of Elphis I bathymetry maps: (a) sonar-derived bathymetry; (b) original resolution (2 m) satellite-derived bathymetry; (c) higher resolution (0.5 m) pan-sharpened satellite-derived bathymetry.

Figure 17: Two examples of bathymetry transects over the Elphis I wreck. Red line represents bathymetry derived with sonar measurements, green line bathymetry derived with WorldView-2 data with a resolution of 2.0 m, while blue line represents bathymetry derived with pan-sharpened data with a resolution of 0.5 m. Maps show sonar bathymetry of Elphis I wreck overlaid on satellite bathymetry of the surrounding area.
5.2 Utility of Satellite Derived Bathymetric Maps

The main advantages of satellite observations, apart from the cost difference when compared to field campaigns, are their large spatial and temporal extents. The relative ease with which bathymetry maps can be produced not only for the immediate vicinity of the archaeological sites but also for larger surrounding areas can be used to set the archaeological discoveries within a spatial context and thus to provide another source of information and a new point of view. In other words, this could be a cheap and quick way to have an overview of the many sites where, according to the UNESCO convention on the Protection of Underwater Cultural Heritage, it is decided to leave objects in their original context. At selected sites the bathymetry maps could also be useful for planning the location of paraphernalia beneficial for the visits to those sites by tourist divers or for producing touristic waterproof maps to give to those divers.

It is also possible to combine the underwater maps together with data concerning the coastal zone (Muslim & Foody, 2008), either by using colour composite image or a digital elevation model, in order to evaluate present (or past) coastal geomorphology and its correlation to the site. As an example, Figure 18 shows a true-colour composite image of the Meothi peninsula overlaid on a digital elevation model created by merging the bathymetry measurements and SRTM data (Jarvis et al., 2008) of the adjacent land. Some unwanted products of the merge are clearly visible in the figure, due to the spatial resolution mismatch between land (30 m) and bathymetry (1.6 m) elevation models. However, it is possible to obtain land digital elevation models with much higher spatial resolution (Büyüksalih, Baz, Alkan, & Jacobsen, 2012), which would provide a better fit with the bathymetry data.

The temporal extent of the satellite data is of use when, for example, monitoring the deterioration of a site due to human activity or natural causes and processes (e.g. harbour developments or erosion) which can affect, or have already affected, the historical sites over time. This information can then be used optimise the location of mechanical devices aimed at protecting the archaeological artefacts from currents and sea movements. Conversely, as is the case in Metohi peninsula, the multi-temporal images can also reveal the stability of the site (Figure 6). Even though the WorldView-2 data archive only goes back to 2009, other satellite sensors with lower spatial resolution have much longer archives. It is also possible to combine historical airborne photography with modern satellite images to extend the historical reach up to 50 years back, although in that case bathymetry might be more difficult to derive.

Since the recent centenary of the outbreak of the First World War, many of the shipwrecks from that period became protected under the UNESCO 2001 Convention on the Protection of Underwater Cultural Heritage (UNESCO, 2015). This implies that thousands of shipwrecks, many of them in shallow waters (e.g. see http://www.atlas2seas.eu/ - last accessed 16/12/2015, Momber & Bowens, 2015), now need to come under the investigation of archaeologists and the supervision of public authorities and research bodies.
In addition, the First World War shipwrecks are generally of larger size and better state than their older counterparts. This makes them very suitable candidates for initial exploration and continuous monitoring through the use of satellite derived bathymetry maps.

6 Conclusions

This study has demonstrated the utility of bathymetry maps derived from high resolution (2 m or less) multispectral satellite observations in the field of underwater archaeology. The satellite-based maps showed good accuracy when compared to field-based depth measurements (either using manual measurements or sonar) at the two study sites: a submerged prehistoric settlement at Metohi and a modern shipwreck Elphis I. The shape and position of the Elphis I wreck were identifiable in the bathymetric map, although the fine details were obscured due to spatial resolution limitations of the satellite observations. Similarly, at the Metohi site the satellite data enabled a geomorphological overview of the vicinity of the settlement while not providing enough detail to discern individual artefacts or structures. Even pan-sharpening of the satellite images did not increase the information content of the bathymetry maps. At the Metohi peninsula site no artefacts (i.e. cist graves) become observable after the pan-sharpening while at the Elphis I site the procedure decreased the map’s accuracy due to the enhancement of water surface features to the detriment of benthic features.

On the other hand, the satellite observations enable the placement of the archaeological sites in a spatial context of the surrounding underwater and surface features. In addition, they can be used to monitor and record anthropogenic or natural risks to the cultural heritage sites over time, which could lead to the development of preventive conservation. Therefore, the satellite observations and, in particular, satellite derived bathymetry maps, can complement the existing archaeological techniques and methods. Although the road to a complete and optimum use of satellite images in the above mentioned fields is still ahead, it is clear that in the near future they will have an important function as low cost activity for research, protection and management of underwater cultural heritage.

The ITACA project, under which this study was conducted, is also investigating other methods of exploiting satellite bathymetry in the context of underwater archaeology. Those include the use of radar-based satellite observations for the derivation of bathymetry between the depths of 20 m and 60 m and the use of various shape detection algorithms in order to automatize information extraction from the bathymetric maps. The results of those investigations will be presented in future publications.

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References


