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Satellite-derived bathymetry – An effective surveying tool for shallow-water bathymetry mapping

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Satellite-derived bathymetry

An effective surveying tool for shallow-water bathymetry mapping

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Unlike other survey methods satellite-derived bathymetry (SDB) offers a remote mapping of shallow water zones. It is based on the concept of using the reflectance intensity of different wavelengths (colours) of the sunlight which is recorded by the satellite sensor. This information in combination with relevant databases and physical models determines the shallow water depth down to the light penetration depth. In the last decade, there has been an increasing interest of SDB methods and derived data. Various exercises have been done by academia and industry to validate and evaluate SDB data sets (REF). This awareness is based on two major developments: the recent availability of very high-resolution satellite data mapping the seafloor in sufficient detail and the design of robust and standardised algorithms and workflows. The demand of accessing bathymetric data for the shallow water zone, costs and the ability to map with ship and airborne sensors have also led to high interest in this effective surveying tool. The zone is still poorly surveyed for various locations worldwide (IHO 2016a). This article provides an overview of all aspects of SDB surveys from satellite sources, SDB workflows and methods to use cases.

Satellite-derived bathymetry – SDB | Remote sensing | Earth observation | Mapping depth

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Satellite data sources: Whole-earth imagery and its archives

Depending on the spatial resolution/pixel size of the satellite images they are typically classified in very high resolution (<2 m spatial resolution), high (<10 m), moderate (better than 100 m) and coarse (several hundred metres) data sets. Only the first three are typically of interest for shallow-water bathymetric mapping. Imaging satellite data recorded every place on earth in high frequency and archive the image data. We can now look back to an archive of about 15 years for very high-resolution data and almost 40 years of moderate resolution data sets which allows not only mapping of most recent condition but also the change over time. Satellite data coverage is not equally distributed around the globe and ranges from few data sets (e.g. remote places in the higher latitudes) to several hundreds to thousands of data sets (e.g. urban areas).

Every satellite sensor comes with unique specifications determining its feasibility for SDB methods. The most important factor is the spatial resolution: The ability to map the seafloor in highest detail, the amount of spectral information and the bit depths in which they are recorded, signal-to-noise ratio and the geolocation accuracies. Modern satellite sensors such as WorldView-2 and 3, Pleiades, Sentinel-2 and Landsat 8 have been used intensively and can be seen as feasible sensors to apply SDB methods. Because light penetration depth into the water column decreases with increasing light wavelength (see Fig. 1) those satellite sources which have the ability to record in multiple optical wavelength (bands) are of particular importance for optical SDB methods. However, more than the choice of the correct sensor, the bathymetric data quality is the outcome of selecting the ideal data set and extracting bathymetric grids in the correct manner. The next paragraphs highlight these necessary steps in the SDB workflow.

SDB workflow

Similar to other survey methods SDB requires preparation, data processing, data post-processing and QA/QC routines. For all these steps trained experts are required for these remote sensing, geomatic and hydrographic exercises.

Feasibility assessment and selection of best data sets

The objective of this task is to identify satellite image data recorded in near-ideal environmental conditions, in terms of spatial resolution and recording dates and other specifications. This process is similar to the pre-planning phase of acoustic or LiDAR shallow-water surveys where information on local environmental conditions is accessed. But in contrast to survey campaign planning SDB can make use of already archived image data which allows to select the image captures which has most feasible environmental conditions. This is of importance because it allows already at planning phase to quickly provide reliable information on final bathymetric grid coverage and maximum mapping depth.

Extra care is compulsory for this selection process as it can significantly influence the following data processing and finally the data quality and data coverage of the final bathymetric grid.

The feasibility assessment includes the check of the archived data from one or typically multiple

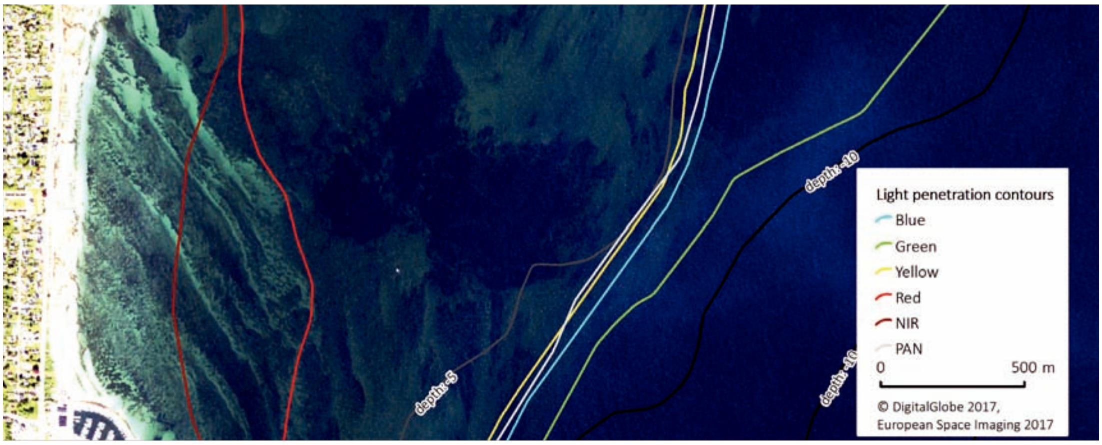

Fig. 1: Maximum light penetration depth of sunlight highlighted for the Baltic Sea (Denmark) using very high-resolution WorldView-2 satellite image data. The colours represent the different wavelengths of the sensor (colours) which are overlaid by 5 m and 10 m depth contours of the nautical chart. With increasing depth seafloor reflectance is dominated by shorter wavelengths. In organic rich waters such as the Baltic Sea the green wavelength(s) penetrate deepest

image data sources, which can contain commercial and none commercial image data. In total, about a dozen satellite data archives are being accessed for each site. For each stored data set – alongside accessing tidal information, multi-temporal image data comparisons and charting data checks – an assessment of, e.g., cloud coverage, turbidity conditions, sunglint risk is generated.

With the feasibility assessment one or more options for creating bathymetric grids including estimated data coverage area and approximate depth range are available.

SDB processing

SDB data processing or the extraction of bathymetric grids based on the selected image data sets is the centre of the workflow. Two methods can be classified: empirical and physics-based methods.

Initially, empirical methods were used to require known depth information over the study area. By comparing these known depths with the satellite signal, a statistical relationship can be derived that adequately describes depth as a function of the signal. Aside from requiring known data, these methods will only work for a given satellite image. A subsequent satellite scene, even of the same location, may contain different atmospheric and in-water parameters the statistical relationship needs to be recalculated. Another aspect of these methods is that the statistical relationship is valid for one water type and one seafloor type. And one also need to apply the correct formula to each pixel in the image, i.e., you need to inform the algorithm a priori which substrate type is encountering in that image pixel. This brings the problem full circle back to one of the fundamental challenges of satellite-derived bathymetry: How do you know that a darker signal is due to deeper water, a darker substratum, or a bit of both? Still, these methods find their use as they are relatively straightforward to apply (»Cookbook approach«, IHO 2016b) and, as well as being computationally fast and could serve as an initial step to identify seafloor topography.

Physics-based methods on the other hand do not require known depth information for the study area, and can therefore be applied independent of satellite data type and study area. These methods rely on fully describing the physical relationship between the measured light signal and the water column depth (Fig. 2). Variability in the atmosphere and water column is accounted for within the algorithm inversion, and no ›tuning‹ to known depths is required. In principle, therefore, an area can be targeted that is physically inaccessible and for which there is no previous known information. Not surprisingly, these physics-based methods do require more sophisticated algorithms and powerful processing capacity. But they also proof more accurate, especially in areas with various bottom type, turbidity or atmospheric conditions. Amongst these methods CSIRO's SAMBUCA (Wettle et al. 2006) and EOMAP's MIP are most used (Siermann et al. 2014). Although not mandatorily necessary these algorithms can include vertical sounding information in calibration of the model to optimise the vertical quality.

Because of the advantages of physics-based methods they must be seen as the modern state-

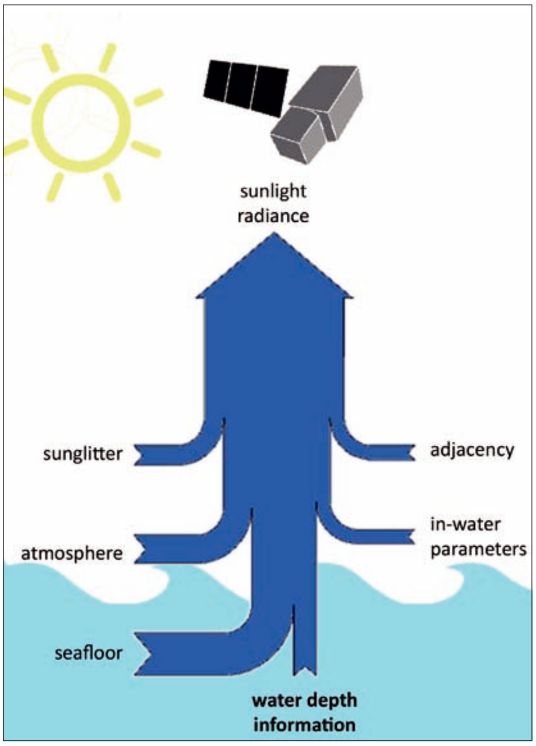

Fig. 2: Where does all the light come from? The diagram shows the relative amount of measured light energy which contains water depth information. It is critical to accurately account for the other sources of light energy in order to separate out the relevant water column depth contribution to the measured signal

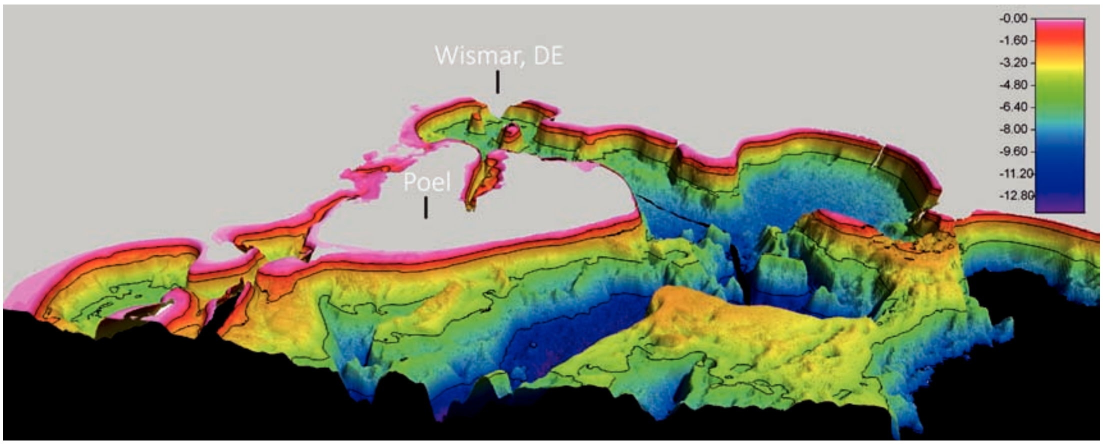

Fig. 3: Satellite-derived bathymetry grid for the shallow waters of Poel down to 10 m depth using satellite image data recorded in 2016

of-the-art for processing optical satellite image data (see Fig. 3).

Post-processing

Data cleaning, peak detection and QA/QC procedures are as important to shallow-water bathymetric grids as they are to LiDAR and acoustic point clouds. The post-processing cleans data sets for biased data, such as ship wakes, cloud shadows or wave breaking areas and distinguishes between shallow-water bathymetric information and information that cannot be interpreted in this way. Furthermore, information on vertical and horizontal displacement introduced by the water refraction are minimised and the bathymetric data are corrected to a relevant vertical datum (LAT). Parts of these steps can be automised but a QA/QC procedure is an expert's tasks which requires knowledge and relevant hydrographic software tools.

Results and use cases

The result of the SDB workflow is a bathymetric grid whose file formats are fully in line with other surveys and includes the bathymetric grid and metadata (ISO 19115).

The data coverage ranges from coastline to light extinction depth at time of the satellite image recording (known as optically shallow-water zone). It is strongly depending on water clarity and as a rule of thumb is found to be in the range of 1 to 1.2 times Secchi disc depth. As already highlighted, a great advantage of SDB methods is the use of already archived data and the selection of an ideal image. This is of particular importance for areas with a high seasonal dynamic of turbidity and ice coverage. For example, for the Wadden Sea area classified as a high-turbid coastal zone it is possible to map down to 7 m to 9 m (below LAT) in good environmental conditions and selecting feasible data sets (see Fig. 4), and in the southern Baltic Sea region mapping can be done down to approximately 10 m (see table and Fig. 1).

Location	Maximum
Southern Baltic Sea	8 m to 10 m
Northern Baltic Sea	1 m to 3 m
North Sea, Wadden Sea area	7 m to 9 m
Caspian Sea	5 m to 10 m
Black Sea	3 m to 5 m
Red Sea	25 m to 30 m
Persian Gulf, southern Arabian countries	10 m to 15 m
Persian Gulf, northern Arabian countries	2 m to 10 m
Mediterranean Sea	20 m to 30 m

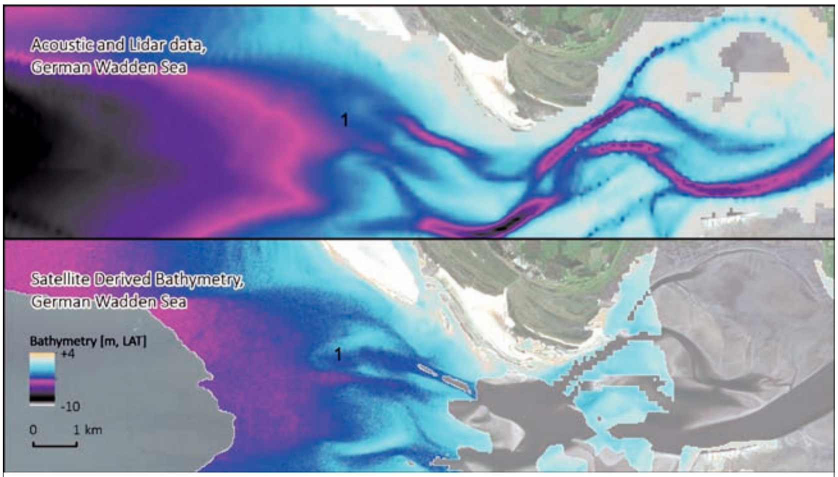

Fig. 4: Comparison of acoustic and LiDAR bathymetric data sets and a satellite-derived bathymetric grid for the German Wadden Sea area. It shows the validity and relatively deep mapping potential of the Wadden Sea area as well as the ability to identify movements of seabed topography

Since the last decade, SDB has been seen as an effective surveying tool. Motivations to consider SDB data sets differ depending on the final application as described below.

Use case: Access to historical data

Using archived image data allows creating historic topographic conditions. This information is of vital interest to understand the impact of human activities and/or natural disasters such as hurricanes and tsunamis. The arbitration of the United Nations Convention on the Law of the Sea between the Republic of the Philippines and the People's Republic of China is one of special use cases where historic information was necessary. Access rights and responsibilities to certain areas in the South China Sea were disputed, especially on reefs which have significantly been reshaped by engineering activities in the past years. The court required an objective view to shallow-water bathymetric data in order to understand the presence of historical low-tide features. These features determine the responsibilities and boundaries and are of high importance. EOMAP provided this data using SDB methods obtained in archived imagery and supplied strong arguments for this international court case (Permanent Court of Arbitration, 2016).

Use case: Integrated survey concept of SDB and acoustic methods

Although SDB can be seen as a stand-alone method the combination of SDB and acoustic survey methods form a powerful combination. The shallow-water areas of down to 5 m or 10 m are often not accessible for acoustic methods or require significantly higher survey efforts and costs. This is the depth range in which SDB methods work best and by combining acoustic and SDB survey methods a perfect data coverage from shore to deep can be obtained. The overlapping of SDB and acoustic methods can also serve to calibrate and validate SDB methods and thus provide detailed information on data quality of the derived SDB methods (Fig. 4). This concept has been successfully applied by the UK Hydrographic Office in the recent British Admiralty Chart BA 2066 of Southern Antigua. EOMAP's SDB grid has been selected by the UKHO following a competitive exercise and is now an integrated part of the BA 2066 chart.

Future perspectives – Where are we heading?

Over the intermediate term it is expected that satellite-derived mapping of the seafloor will continue to be increasingly accepted and integrated as a survey tool – as is now already the case for a number of innovative user groups. Certain developments still need to be done on how to best quantify uncertainties, standardised error budget, operationalise workflows and last but not least an international agreement on standards.

One likely technical development will be the multi-temporal and sensor-agnostic mapping approach which oversimplified means: Use all the image data which is available and do the best out of it. With the advances of cloud computing, physics based algorithms and an increasing selection of image data, this would be a natural evolution phase for satellite-derived bathymetry.

Parts of these future developments are currently co-funded by the European Commission in the frame of the EU Horizon 2020 BASE-platform project, which furthermore introduces other remote mapping solutions for the worlds ocean. ⚓

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