

Satellite-derived bathymetry in practice

Current examples for cable route surveys and coastal monitoring

An article by MARINA NIEDERJASPER*

Multibeam bathymetry surveying is a well-established method but limited to water depths accessible by vessels or small boats. Airborne LiDAR bathymetry (ALB) systems can cover this gap by surveying both the coastal topography and the shallower water regions. ALB surveys are mostly suitable for larger projects where accurate measurements are requested, as they require on-site mobilisation and a noticeable amount of costs. Satellite-derived bathymetry (SDB) can be seen as an option for an easy to implement, cost-effective and globally available solution to provide full coverage with moderate density and accuracy which may be suitable for certain projects in coastal regions or as a precursor survey before commissioning a targeted survey. This paper describes methods providing information to fill data gaps for cable landing sites and for coastal zone monitoring. They are based on the new SDB online software eoLytics SDB by EOMAP. Results obtained compare well against acoustic survey data. The procedure was found to be highly useful for the described purposes.

SDB – satellite-derived bathymetry | LiDAR | cable route survey | coastal zone monitoring | eoLytics SDB
SDB | LiDAR | Kabelvermessung | Küstenzonenüberwachung | eoLytics SDB

Die Vermessung mit Fächerecholoten ist etabliert, aber auf Wassertiefen beschränkt, die mit Schiffen oder kleinen Booten zugänglich sind. Luftgestützte LiDAR-Systeme (ALB) können diese Lücke schließen, indem sie sowohl die Küstentopographie als auch die flacheren Wasserregionen vermessen. ALB-Vermessungen eignen sich meist für größere Projekte, bei denen genaue Messungen erforderlich sind, da sie eine Mobilisierung vor Ort und einen spürbaren Kostenaufwand erfordern. Aus Satellitendaten abgeleitete Bathymetrie (SDB) ist eine einfach zu implementierende, kostengünstige und weltweit verfügbare Lösung, mit der eine vollständige Abdeckung mit angemessener Dichte und Genauigkeit erreicht werden kann und die für bestimmte Projekte in Küstenregionen geeignet sein kann oder als Vorabuntersuchung vor Beauftragung einer gezielten Vermessung. Dieser Artikel beschreibt Methoden, mit denen Datenlücken für Kabelanlandungsstellen und für die Überwachung von Küstengebieten geschlossen werden können. Sie basieren auf der neuen SDB-Online-Software eoLytics SDB von EOMAP. Die erzielten Ergebnisse sind mit akustischen Vermessungsdaten gut vergleichbar. Das Verfahren erwies sich für die beschriebenen Zwecke als sehr nützlich.

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Introduction: background and approach

Bathymetric mapping of coastal regions is always challenging for hydrographic surveys and cable route surveys. Hydrographic surveys with high accuracy requirements can be fulfilled by multibeam surveys at evenly falling coasts with a high tidal range only. Steep coastlines or areas inaccessible for vessels can only be covered by airborne LiDAR. Unlike multibeam and LiDAR surveys which comply with *International Hydrographic Organization (IHO) Standards for Hydrographic Surveys (S-44)*, satellite-derived bathymetry (SDB) may provide an alternative for certain applications with moderate accuracy and resolution.

For cable route surveys, the landing of a cable to the shore comprises the inshore survey by a vessel or small boat as well as the topographic survey on

the beach. The intermediate section was previously covered by a diver swim survey, which means a high logistical effort and potentially high risk. Diver swims usually covers only one line of depths along the planned cable route and thus provides a result of reduced robustness and accuracy. For this requirement SDB offers an easy to implement and cost-effective approach to retrieve a solution with higher accuracy at full coverage.

In case of sparsely available data coverage, such as single-beam data, or even if no data are available, satellite-derived bathymetry can be applied to extend the available information to the full coverage of an area of interest. Furthermore, if some of the available data covers an area with potentially no or little seabed change the existing data can be regarded as valid over a long period of time and

can be applied as control points for several satellite image processing tasks covering the time period of interest. Thus, satellite-derived bathymetry offers the possibility of time lapse monitoring of seabed morphology, for example for coastal zone management requirements.

For planning purposes, such as desktop studies for a cable route survey, where no survey data are available, it is even possible to use spot depths from a sea chart or ENC as a base for satellite-derived bathymetry.

The processing of satellite images is carried out by Fugro in a specific software called eoLytics SDB, provided by EOMAP, Seefeld, in Germany. This article describes the methodology and two current application examples: filling of a gap at a landing site for a cable route survey and coastal monitoring.

Methodology

Basic theory

Satellite-derived bathymetry (SDB) uses satellite data taken from passive multispectral sensors for calculating depths down to the light penetration depth. There are several SDB approaches, ranging from fully physics-based to simple empirical approaches. The physics-based approach models the depths by considering the various influences of the light penetrating the atmosphere, water surface and water column and the adjacent bright land reflectance. This involves all physical factors during sunlight propagation and other physical processes before the reflected radiance is captured by the multispectral sensors. This complex concept comes with the significant benefit of being independent of on-site surveys or training data. It can therefore be applied worldwide without a priori in situ data or the need to deploy survey teams, even for greenfield locations.

The empirical method on the other hand predicts depths based on an empirical relationship between the recorded radiances in the different spectral bands and sample depth points in the area of study. Thus, in contrast to physics-based methods, empirical-based methods require known depths as control points to predict the depths for an extended area adjacent to the control points. The advantage of empirical methods is that they are rapid, easier to implement and considerably more user friendly than physics-based methods. The eoLytics SDB software used in this work (see next section) is based on an empirical approach, but with an important distinction. Pure empirical methods are prone to hidden error sources: environmental conditions which impact SDB can change within very short distances without being noticed or accounted for in empirical concepts. The eoLytics SDB software therefore also includes physical corrections in order to improve the reflected radiance quality as well as to reduce bias caused by environmental effects.

Software and workflow

eoLytics SDB is a novel, cloud-based processing SDB solution developed by EOMAP, following a joint requirement analysis with the Fugro team. The software includes automatic online access to the most up-to-date satellite data archives. It is easy and rapid to use and offers full control through the integration of local survey data (control points). The usual satellite image input is from Sentinel-2 sensors; other commercial images of higher resolution and accuracy may be imported in near future with accounted additional processing effort.

Within the software, the satellite image is processed pixelwise for atmospheric and water surface corrections, furthermore a land/cloud-versus-water classification. The control points are firstly checked and resampled to the satellite image resolution and then separated into a set of training data and a set of validation data. The training data set is used as a base to process the satellite image and derive the bathymetry for the complete image – this is the main process. The validation data set is then used to qualify the result, which means the SDB-derived depths are compared against the depths of the validation data set. The complete calculation procedure from online satellite image selection to final product access takes less than one hour for one satellite image.

The output can be exported to an ASCII-file containing positions and depths for the area of interest in full coverage, a georeferenced TIFF-file containing depths (underwater digital elevation model), the processed satellite image as a real-colour TIFF-file, the statistics of the quality control and metadata. Fig. 1 shows a flow chart of the workflow.

Accuracy

The horizontal accuracy of SDB is mainly based on the geolocation accuracy of the satellite imagery used. Multispectral satellite imagery differs in spatial resolution and accuracy. Commercial satellite imagery offers higher resolution and accuracy, whereas publicly-available satellite imagery such as Sentinel-2 has moderate resolution and accu-

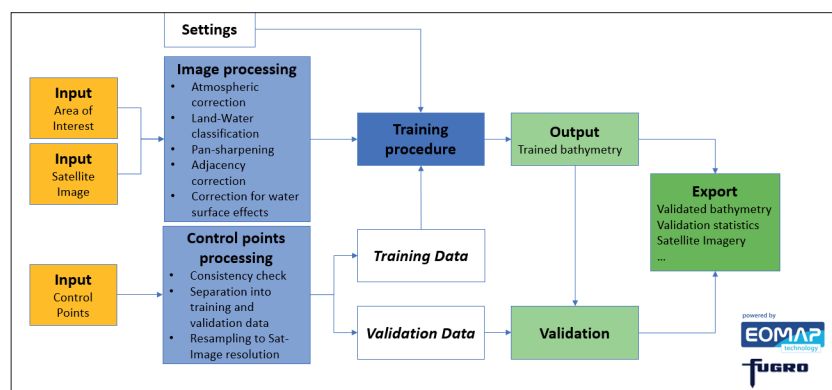


Fig. 1: Satellite-derived bathymetry, workflow of methodology applied in eoLytics SDB

racy. Sentinel-2 images have a spatial resolution of 10 m and a horizontal accuracy of 12.5 m (2σ).

The vertical accuracy of SDB is normally assessed by comparing the result or estimated depth with ground truth data in the same area of interest. The differences reflect the vertical accuracy of SDB and are qualified in the validation process mentioned above. The common vertical accuracy of SDB achieved by eoLytics SDB using reliable training data is typically ± 1.0 m RMSE and increases with water depth due to the reduced signal to noise ratio.

Filling gaps for cable route surveys

Requirement

Despite the use of satellites for communication purposes, fibre optic cables are vital as more than 90 % of our international voice communication, internet and data run through world-wide spanned submarine cable systems. A continuously increasing number of world-wide spread locations are being planned, laid and connected to new cable network components. One of the main hydrographic survey markets within Fugro is the survey of planned telecommunication cable routes. This comprises the bathymetric survey as well as geological and geophysical investigations of the seafloor and the shallow geology beyond. The routes typically consist of main trunk lines covering large distances crossing oceans or surrounding specific countries or even parts of continents in a relatively great distance and great water depths. Diverting from these trunk lines, there are branches to connect single countries or landing sites of interest. The survey of the branches covers a large depth range from deep water at the junction point up to the landing site on the beach. For this pur-

pose, ocean going vessels are deployed for the major part of the route and shallow water inshore vessels with very small draught for the shallowest part. For the landing of the cable onto the shore, a topographic survey is required to cover the complete range of the potential cable route from deep ocean to connection to the land infrastructure.

Unfortunately, the transition between water and land is always a challenge to be covered. A typical example is shown in Fig. 2. The bathymetry collected by the inshore vessel is shown colour coded by depth. The shallowest depth surveyed is about 3.5 m LAT. In the front on the left side of the figure, a rocky feature reaches into the survey corridor, which prevented the survey vessel from achieving more coverage and created breaking waves. The red spots on the beach represent the spot heights measured during a topographic survey.

Obvious is the gap between inshore survey and topographic survey, which needs to be closed. Previously such a case required a diver swim survey. Divers were equipped with lead line positioning and a pressure sensor to determine water depths and followed a single line along the route from the beach to the shallowest depth the inshore vessel reached. This did not provide complete coverage of the survey corridor, nor was the accuracy expected to be very high. Additionally, as can be derived from the image, it bore a certain risk for the divers due to breaking waves in a rocky area. Due to the general risk in performing diving operation, this procedure is no longer supported at Fugro.

Solution

Satellite-derived bathymetry was proposed and tested in this case as an alternative to provide the

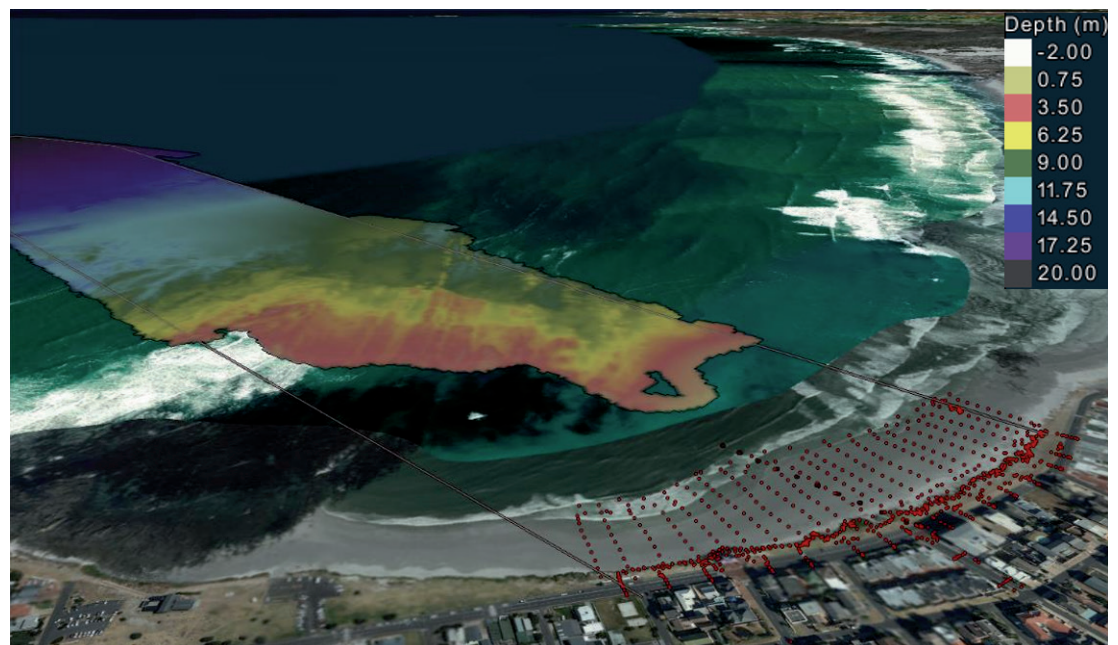


Fig. 2: Landing site showing coverage gap between vessel-based bathymetry (colour coded by depth) and topographic survey (red dots) (Note: 3D imagery taken from web map server)

missing depth coverage. The settings for the test are listed as follows:

- The area of interest was easily defined by the outline of the survey corridor, the seaward boundary of the inshore vessel coverage and the beach line.
- The control points were taken from both the topographic survey (spot heights on the beach) and the inshore survey (an extract of the shallowest part, covering the complete corridor width). This provided at least the coverage of the complete depth range anticipated, although missing the central part. Control points of both sources needed to be referred to the same vertical datum.
- The best suitable satellite image needed to be chosen. This proved to be difficult, as the major part of the available images showed breaking waves, which hamper the depth derivation process. Apart from this, it is preferred to choose an image at highest tide thus having as much water coverage as possible on the beach. The best image nearest in time was chosen.

The result is an extension of the depth coverage as shown in Fig. 3.

The additional coverage extends the coverage significantly and closes the gap up to the beach, providing sufficient overlap between topographical survey and satellite-derived bathymetry. This also offered the possibility to additionally check the quality of the SDB result, which was found to be mostly in a range of about ± 0.1 m to the topography data, well within the requirements. Unreliable areas needed to be removed for example in the rocky feature as well as some areas in the

transition zone at the land/water interface on the beach, where the image showed breaking waves and no results obtained.

Nevertheless, from this additionally depth data the missing contours and a depth profile could be derived continuously up to the beach using a remote method in a relatively short time and at low costs, without any potential risk for a diver resulting in improved coverage and accuracy compared to diver swim.

Moreover, the resulting data set could be used as a base for further SDB calculations in regular intervals so that a monitoring case could be established for observing the dynamics and possible changes in the seabed morphology.

Specific approach: Satellite-photogrammetry-based topographic survey

In some remote regions for cable route survey landings, it might be difficult to reach the beach to complete a topographical survey. This might be the case due to logistic, safety, environmental and political constraints. In such cases, satellite-derived bathymetry would not help, as this methodology can only supply results for areas covered with water, but a different type of remote sensing method can be used.

For that purpose, Fugro evaluated EOMAP's digital elevation model solution which applies a photogrammetric approach using stereo satellite imagery. It uses two or more very-high-resolution satellite images of 30 to 50 cm spatial resolution, which were recorded with different viewing geometries ideally almost the same time. These images are aligned to each other and correlated to find matches for each pixel in both images. The

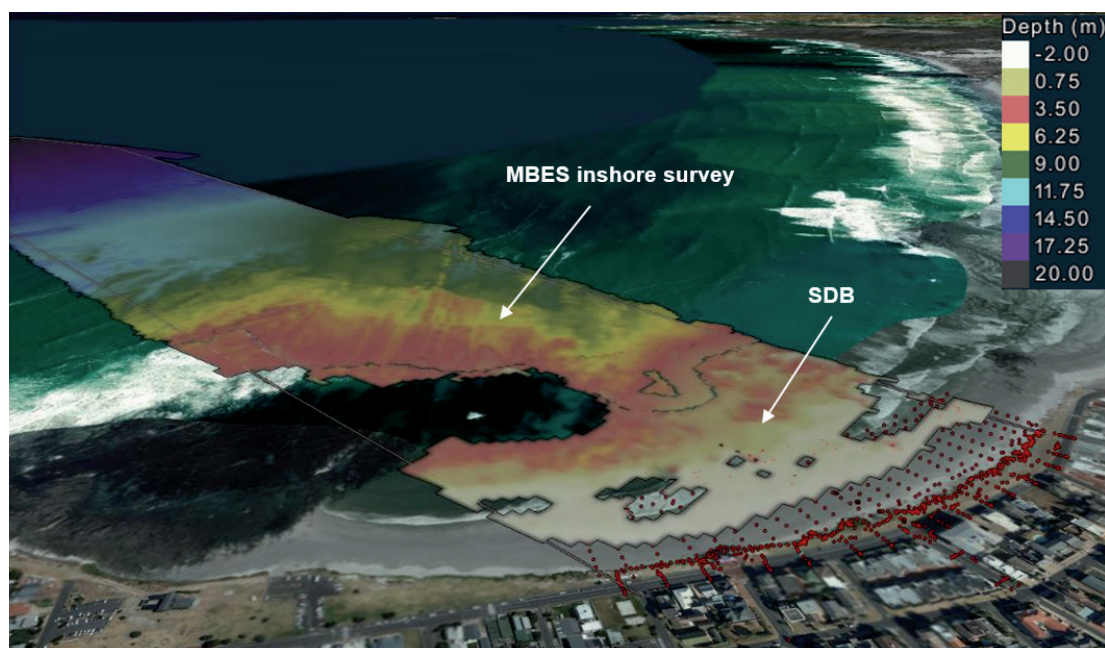


Fig. 3: Landing site showing satellite-derived bathymetry filling the coverage gap between vessel-based bathymetry (colour coded by depth, referenced to Fig. 2) and topographic survey (red dots) (Note: 3D imagery taken from web map server)

generated disparity image is then refined on sub-pixel level. The result is vertically transferred to the required height level by using only three to five control points from site; the result is a digital elevation model which can be exported. Current stereo imagery is taken at 0.3 to 0.5 m spatial resolution, which allows to map digital elevation models of 1 to 2 m spatial resolution.

Coastal monitoring application for the City of Gold Coast

Requirement

The City of Gold Coast is a community in Queensland, Australia, located at the eastern coast, about 70 km south of Brisbane close to the border to New South Wales.

The Council of the City of Gold Coast spends a noticeable amount of effort to maintain and protect especially their beaches, which are prone to coastal erosion due to severe storms as they are exposed to the open ocean without any natural protection. The measures taken contain, amongst others, the nourishment of the beaches, which means delivering additional sand to the beaches to compensate for loss due to erosion and making the beaches more resilient to heavy weather.

As coastal management is an important aspect of the Council of the City of Gold Coast's work, they are especially interested in a monitoring solution providing depth information along their coast in regular and preferably short intervals. This is essential to observe the sand movements along the coast and to possibly predict further threats and

thus be capable to take proactive measures in time. As the satellite-derived bathymetry can offer regular intervals of observation through satellites and a cost-efficient process of deriving depths from the images, it was agreed with Fugro to implement the monitoring using satellite-derived bathymetry for a period of one year with the aim to receive processed depths each month. The project started in July 2019 and has been running for half a year at the time of writing this article; the monitoring is still ongoing.

The area of interest defined comprises a 30 km long section of coast with a width of about 1.7 km to 2.5 km (see Fig. 4).

Project method

Fugro has undertaken an airborne LiDAR bathymetry (ALB) survey covering the complete area with a final resolution of 4 m in July 2019 to act as a base and initial reference for the SDB calculations.

In order to get an initial impression of the reliability that the SDB procedure can offer, a first SDB result was derived from a satellite image taken close to the time the LiDAR data were gathered and using part of the LiDAR data as control points. Due to the shape and position of the area, in fact two images were processed for full coverage. The statistical results of the validation presented a depth determination coefficient of 96 % and 97 % respectively, which shows that the method to derive depths from the satellite images is valid.

Additionally, difference grids comparing the initial SDB data to the LiDAR data were computed, which show a good coincidence with a mean difference of about 0.2 m in depth.

A second initial check was made by comparing vertical profiles of the LiDAR data and the SDB result. These profiles are based on the position of five single-beam data survey profiles the Council of the City of Gold Coast regularly undertakes. Throughout the project these surveys were planned to be repeated in regular intervals and used as the reference control points for the subsequent SDB calculations. Up to now further three times single-beam data surveys were provided by the council.

Fig. 5 shows the position of the profiles, an extract of the first SDB result, colour coded by depth, and the profile section through the central profile comparing LiDAR data (blue) with SDB data (orange). The profile comparison shows a good repeatability. This comparison also shows that the used method of deriving depths based on eOlytics from the satellite images is suitable for SDB.

Once a month the best suitable satellite image is selected and an SDB result is derived based on the latest control point data set available using the software eOlytics SDB. Some further processing needs to be done with respect to evaluating and finalising the result. Areas of the satellite images, where the light is not reflected by the seafloor and thus the

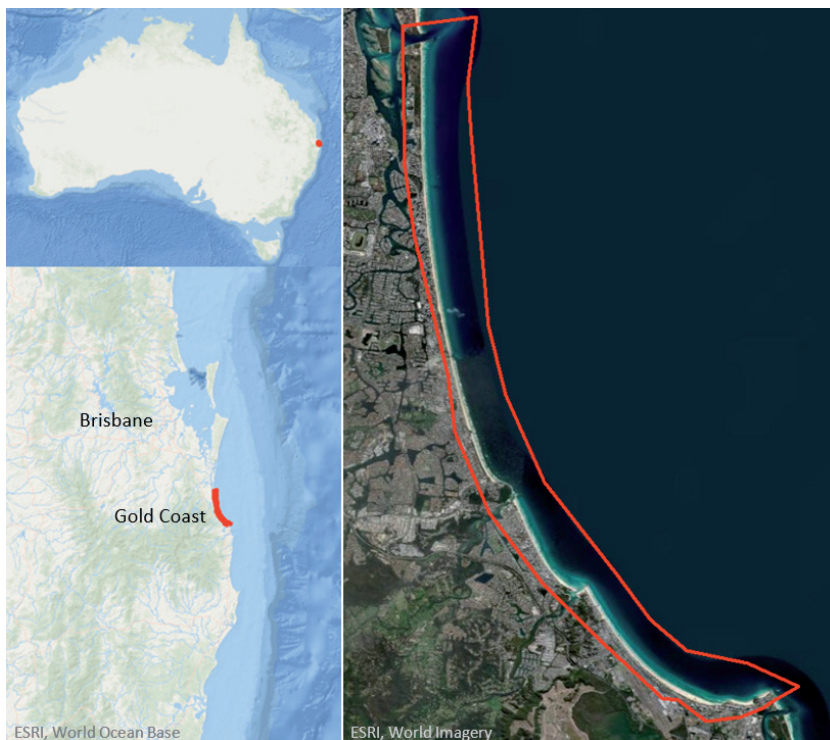


Fig. 4: Area of interest (approximately 30 km length) for coastal monitoring application, City of Gold Coast, Australia

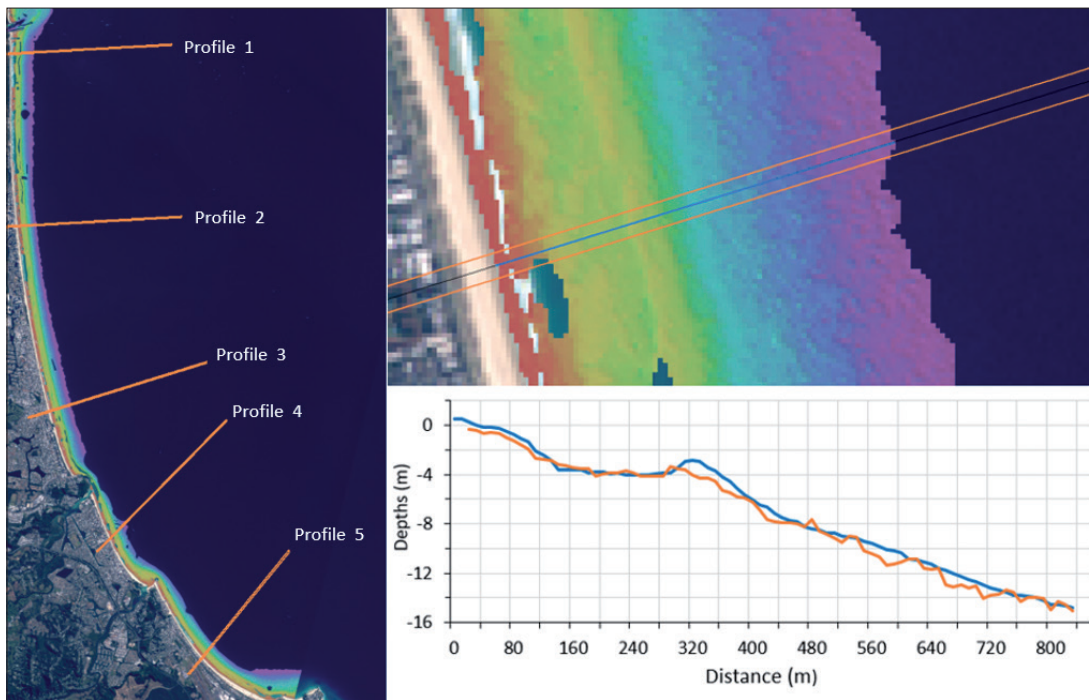


Fig. 5: Position of profiles sections, an extract of the first SDB result colour coded by depth and the profile section through the central profile (profile 3) comparing LiDAR data (blue) with SDB data (orange)

SDB result cannot provide reliable bottom depth values are excluded; additional areas where impact may be given by features that produce a misleading colour on the image are also removed. These are for example created by vessels, waves, which are reflected in bright colours, especially breaking waves reaching up to the beach, and rocky areas, which are reflected in dark colours. These areas are removed from the generated bathymetric grid.

An additional issue is turbidity, caused either from a natural or man-made source. It prevents SDB from giving reliable results, because the sunlight is reflected by the contents within the water column and not by the seafloor. Nevertheless, turbidity influenced regions are, in most cases clearly identified, and thus can also give valuable information about sand movements or currents. Thus, these areas are left within the data set delivered, if deemed suitable, but marked separately.

Deliverables are typically an ASCII-file with positions and depths with 10 m spatial resolution (the resolution of the satellite image), a georeferenced TIFF-file colour coded (RGB) and depth encoded (digital elevation model), the applied satellite images as TIFF-files, the boundaries of the cut-off and turbidity areas in shape-format and a report outlining the current findings.

First results and discussion

The general light penetration throughout the so far investigated satellite images was good. Commencing in July with a maximum achieved depth of up to 15 m which has varied between August and November between 8 m to 10 m and 10 m to 12 m. In

December, due to limited suitable satellite images, only 4 m to 6 m could be reached and unfortunately for January no image at all was deemed to be suitable, while in February the achieved depth range was found to be 8 m to 12 m again.

It became obvious over the months, that the seabed is highly varying, especially movements parallel to the shore line became visible in the difference grids as well as in profiles. These ranged in the first months up to ± 1.5 m in depth and became more significant towards the summer period (December) with depth variations of up to ± 3 m in comparison to the LiDAR survey of July.

The mean depth difference between SDB result and LiDAR surface was found to be 0.2 m in July, representing the initial comparison. In August and September, the difference was with 0.3 m still close to the initial value, and here the first slight coast parallel movements were observed. Within the southern part of the satellite images processed for October turbidity effects caused by incoming waters or activities could be observed and some specific dark features appeared in the water column that are due to their colour detected as deeper than they most probably are. They seemed unreliable but were nevertheless valuable information. The mean difference value for October of 0.5 m includes these features. Within November and December these types of features increased in variable shape and covered larger areas, which could be marked easily by polygons and treated separately, so that a mean difference of SDB result and LiDAR surface without these features of 0.4 m could be determined for November and 0.7 m for December. The latter partly results

from a lower light penetration, but also shows increasing depth differences. There was unfortunately no suitable satellite image found for SDB processing in January, the February result shows some flare like dark features but does not show these coherent areas of dark features anymore.

Fig. 6 and Fig. 7 show one example area covered by these features as a series of satellite images and a series of SDB results from September to December 2019.

Without specific knowledge of the circumstances within the area, it is not possible to interpret the

dark features. At first glance they look like specific turbidity areas but could also be some growing plants or dead organic material waving in the water column. As they might be of interest, data sets with and without these features were delivered.

For one of the five given profiles (profile 4 in Fig. 5) some vertical sections are shown exemplarily for the base survey of July 2019 (ALB) and the SDB results for September and October 2019 and February 2020 in Fig. 8. As can be seen, at a distance from 80 m to 200 m from shore a certain portion of sea floor was lost between July and



Fig. 6: Satellite image example showing dark flared features occurring in the water column between September and December 2019

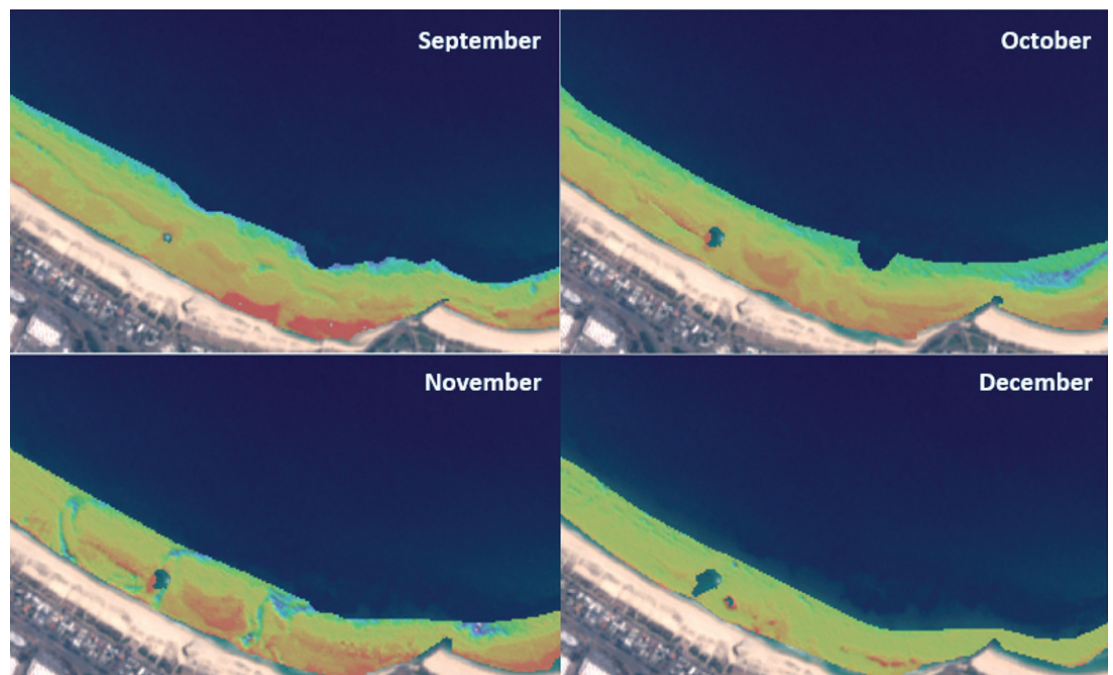


Fig. 7: Satellite-derived bathymetry results (colour coded by depth) of the same example area between September and December 2019

September 2019 and the new profile shape stayed almost stable until the currently latest observation in February 2020; at a distance from 280 m to 440 m from shore there is also a loss to be observed, but here it occurs more gradually, while between 200 m to 280 m from shore the section of February 2020 shows a slight refill compared to July 2019. The losses and fills for this example are summarised in Fig. 9.

Summary, challenges and benefits

The shown example applications demonstrate two already established implementations of the eoLytics SDB software's satellite-derived bathymetry product in coastal areas. It provides depths as a gap filling possibility between vessel-based bathymetric surveys and topographical survey on land at the landfall for a cable route survey and provides monitoring capabilities for coastal zone management. Applications for these two subjects can comprise the following.

For cable route surveys:

- derive full depth coverage from ENC spot data for desktop studies and planning purposes;
- create time series of satellite images or SDB results for planning purposes;
- fill gaps between vessel-based survey and topographic survey;
- extend available single-beam bathymetric survey data to full corridor coverage.

For a coastal zone management requirement:

- derive bathymetric results in a regular interval independent of vessel ability for monitoring;
- derive full depth coverage from available single-beam bathymetric survey data;
- present possibilities to calculate fills and losses for specific time ranges;
- visualise appearances in the water column.

There are general challenges to be dealt with, such as the unpredictable weather in the regions where an investigation is planned. This influences the quality of a potential satellite image to be used with respect to cloud coverage, waves, turbidity and white water reaching up to the beach. Limited water clarity and reflectivity of the seabed might result in gaps or limited coverage. When the applied image does not meet optimal conditions, the maximum depth gained might be small, and the accuracy decreases with depth.

A certain portion of uncertainty might be induced within the method, when there is a great time difference between the control points taken as training data and the date of the satellite image, as the seabed might have changed at the position of the control points.

The general horizontal grid resolution of 10 m may be a disadvantage in case a higher resolution

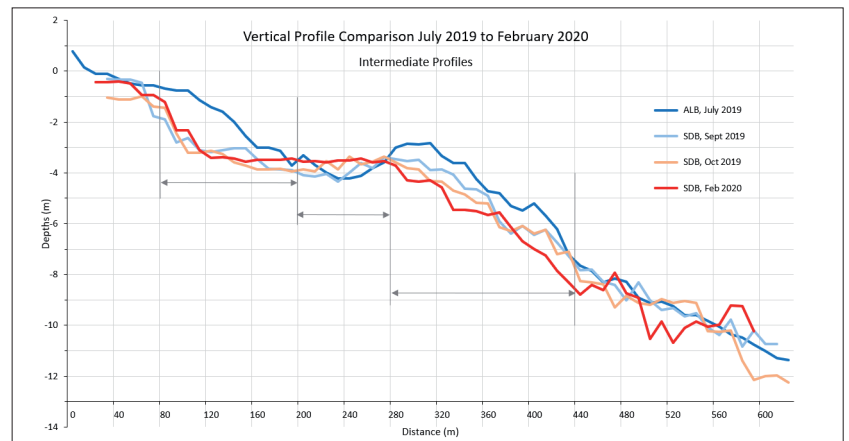


Fig. 8: Vertical profile comparison of ALB survey July 2019 (blue) and SDB result February 2020 (red) with two intermediate profiles indicating the development

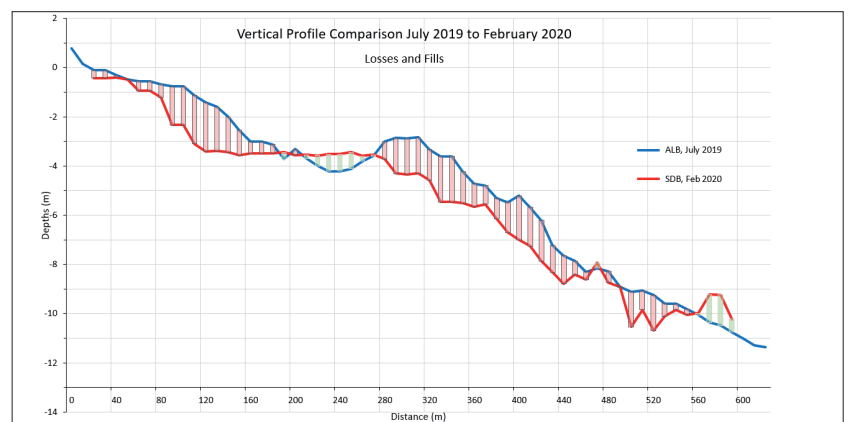


Fig. 9: Vertical profile comparison of ALB survey July 2019 (blue) and SDB result February 2020 (red) losses and fills outlined

result is required. Nevertheless, for more accurate requirements, results from 2 m resolution images could be derived at respective adapted costs.

But when taking the above into account while selecting and processing the satellite images, a reliable result for the respective requirement is possible in most cases. The benefits are numerous:

- There is no logistical effort to be spent and the satellite images in the above described approach are available for free, the solution is generated at low costs.
- The processing procedure is easy to apply.
- As satellite images are available with global coverage, all required regions can be served.
- Global coverage provides access to remote regions, which might be logistically difficult to reach.
- Global coverage provides access to regions which might be reached only at risk, so risk is reduced.

As the described approach is rather new other solutions are under investigation and further developments of the eoLytics SDB software are expected. The above demonstrates that there is major potential in the use of SDB which Fugro Germany Marine and EOMAP are willing to explore. //