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Bathymetry mapping and sea floor classification using multispectral satellite data and standardized physics-based data processing

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ABSTRACT

Multispectral satellite data (WordView-2, IKONOS, QuickBird) are used to map bathymetry and spectral sea floor classes in a range of coastal areas. The standardized physics-based data processing integrates MODIS satellite data for the radiometric intercalibration and estimates of turbidity. This process includes corrections for sunglitter, the adjacency and the atmospheric effect. The water depth is calculated iteratively in combination with the spectral unmixing of the respective bottom reflectance on base of the subsurface reflectance. The final step of the processing classifies the bottom reflectance due to the spectral signature of different bottom types and biota using a specific cluster and classification approach. The comparison with in situ data at different sites worldwide proves the approach, but also emphasizes the necessity of radiometric well calibrated satellite data.

Keywords: Water depth, Bathymetry mapping, sea floor classification, Multispectral satellite

1 INTRODUCTION

Bathymetry is available worldwide at varied though often only coarse resolutions and is typically shown on nautical charts. For coastal areas however the local variation of depth in time and space can be quite high. For example, seasonal strength of long shore currents often alters sediment movement, storms and currents may increase erosion, resuspension or sedimentation processes. Fine scale bathymetric characteristics are often not captured in detail, however often required especially at depths up to 20 m for navigation or industrial offshore operations. Littoral habitats, sea bed structures and water depth are costly and time consuming when mapped with traditional ground truth methods using divers and echo sounding. Mapping these habitats at large spatial scales can be time- and cost effective for optically shallow waters by use of multispectral satellite data and standardized data processing approaches.

2 STATE OF THE ART

Generally, the techniques used to obtain bathymetry in full two-dimensional picture can be divided in to two groups, based on physical background of algorithms:

Direct depth estimation: Littoral sea bottom properties such as water depth can be mapped from earth observation sensors if the reflection of the sea bottom contributes a detectable part to the signal measured by the sensor. This sea bottom reflection must be separated from all other simultaneously measured portions of light for further mapping and classification procedures. Other contributors of light scattered to the sensor are atmospheric molecules and aerosols, the water surface reflection, and light scattered and absorbed due to particular properties of water constituents and the pure water itself. The pure water itself also absorbs light in a spectrally specific manner and therefore leaves unique signatures in the signal while the light passes through the water column and returns after reflection at the sea bottom [1]. This property is used to estimate water depth from optical remote sensing data. If water constituents vary significantly over the image, then an adequate number and position of channels are needed to solve this further problem [2]. Due to this, hyperspectral sensors are useful for applications in shallow waters and able to deliver spatial resolutions that fit the scales of habitats to be mapped. However, if atmospheric or sun glitter conditions and water constituent concentrations are assumed to be approximately constant over a specific area or image, even multispectral satellite sensors can be used to map sea bottom properties and water depth [3],[4]. Pre-conditions are a suitable radiometric sensitivity and adequate calibration accuracy if a physically-based processing procedure is to be applied. In this case, water constituent concentrations and atmospheric properties can be estimated in adjacent deep water areas where bottom influence is not a factor.

In contrast to pure statistical approaches that do not account for the changing magnitude of the varying water depth and visibility of the sea floor, there are currently two main strategies to at least account for or calculate the water depth: Mishra et al. [5] applied a non-linear interpolation technique for manually selected areas of homogenous definition at different depth. Different applications demonstrate the usability of this method. Heege et al. [6] and Wettle et al. [7] used full physically-based retrieval techniques to determine both sea bottom coverage properties and bathymetry concurrently. A few of these approaches were even coupled with retrieval of water constituents [7].

Non-direct estimation based on observation of physical processes like hydrodynamics, which are influenced by topography in a different way and thus reflect the underwater structures. The technique is based on observation of hydrodynamic processes i.e. the modification of surface currents and ocean waves by bathymetry. The current is modulated by underwater topography, which in turn causes variations of small-scale Bragg waves. As the Bragg waves are dominant for resonance with radar microwave, one can detect bottom topography depending on SAR image intensity variation, e.g., presented in [8],[9]. There are certain crucial meteorological and hydrodynamic conditions for applying this approach, e.g., wind speed ranges between 3 m/s to 10 m/s, and tidal current velocity higher than 0.5 m/s. On the other hand, in order to obtain the complete picture of bathymetry based on this approach, first guess of water depths derived from other sources for reference points are required.

3 DATA PROCESSING

The standardized physics based data processing for the generation of bathymetry maps and sea floor classification was performed using EOMAP's Modular Inversion and Processing System (MIP) [10]. The standardized processing chain was applied to all satellite scenes (here: MODIS, WorldView-2, IKONOS and Quickbird) and included the correction of the adjacency effect as well as the correction of impacts of the atmosphere, water surface and water column (Figure 1).

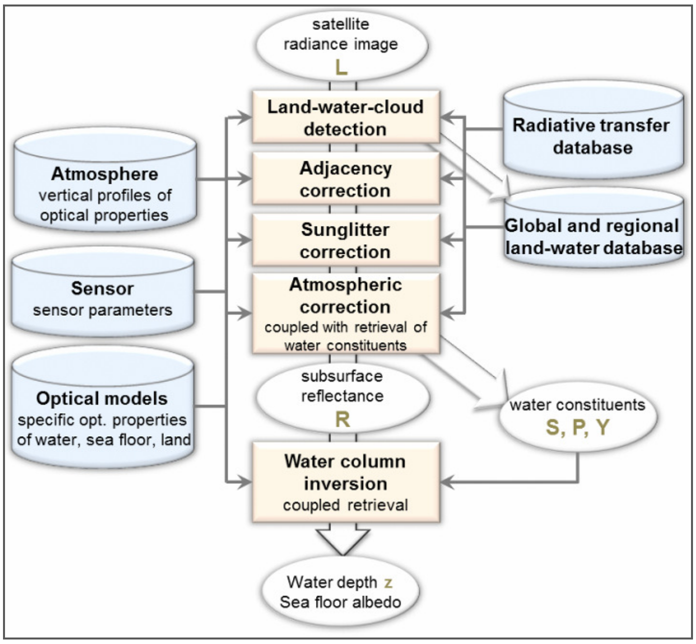

Figure 1 EOMAP's physics based data processing workflow

3.1 Calibration

All multispectral satellite data used for processing contained calibrated radiances supplied by the satellite data providers. Using a radiative transfer model [11] these calibrated radiances were analysed on correctness and corrected if necessary. Reference MODIS data that were recorded within two to three hours difference to the satellite data to be analysed were processed according to [12] to obtain independent optical conditions of water and atmosphere of the target area. These conditions served as input for the radiative transfer model to calculate expected sensor radiances for high resolution satellite data. Input and model radiance spectra as well as fitted and calculated reflectance spectra are displayed in Figure 2.

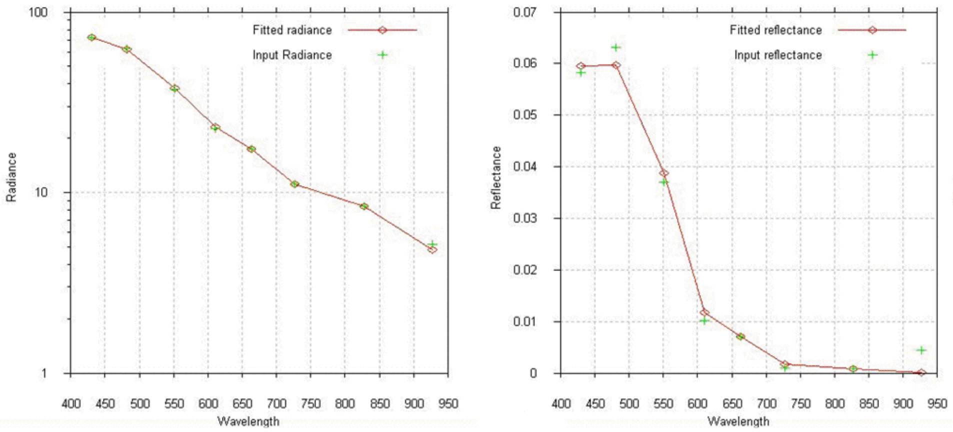

Figure 2. WorldView-2 calibrated radiance (left) and calculated subsurface reflectance (right) compared to radiative transfer model.

3.2 Adjacency and sunglitter correction

As a first step of processing the calibrated radiances of input imagery are corrected for the adjacency effect. This effect arises as increased radiances over water near the shoreline and has a range of up to 50km. The processor calculates the land albedo needed for correction directly from the satellite scene itself as far as land is covered. Adjacency effects of land-water border lines lying outside the satellite image are handled using the EOMAP global land-water data base.

All satellite scenes were checked for impacts of sunglitter and corrected if necessary. For intermediate and slight sunglitter noise adaptive spatial filtering was used. Sunglitter affected data of satellites with high spatial resolution such as WorldView-2 was corrected according to Heege & Fischer [13]. For sensors with a large field of view such as MODIS a pixel wise operational approach after Kiselev (unpublished) was used. The impact of sunglitter and its correction can be clearly seen in Figure 3.

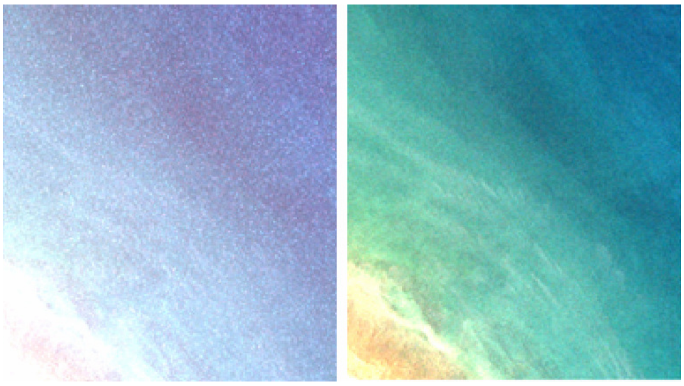

Figure 3 WV-2 input radiance image (left) and subsurface reflectance image after sunglitter, adjacency and atmospheric correction (right) both for bands 4,3,2

3.3 Coupled retrieval of atmospheric and in-water optical properties

The coupled retrieval of atmospheric optical thickness and water constituents was performed by minimising the mean square deviation of modelled top-of-atmosphere radiances and those measured for all sensor channels [12]. The radiances were modelled using the solution of the radiative transfer equation of atmosphere-water systems with the finite element method of Kiselev and Bulgarelli [11]. For optical properties of the atmosphere the parametrisation used in the MODTRAN code [14] was applied. The results of modelling were stored in an extensive database for a large set of atmospheric parameters and different concentrations of water species. For the process of minimisation all required values are then extracted from that existing database. The dependency of subsurface reflectance and water species concentration is described by an improved Gordon's formula [15]. After the aerosol concentration is retrieved the calculation of subsurface reflectance is just a transformation of sensor radiance to reflectance. Figure 4 shows a WV-2 radiance image (left) and the calculated aerosol concentration over water areas (middle). The right image of Figure 4 displays the subsurface reflectance, the result of atmospheric correction.

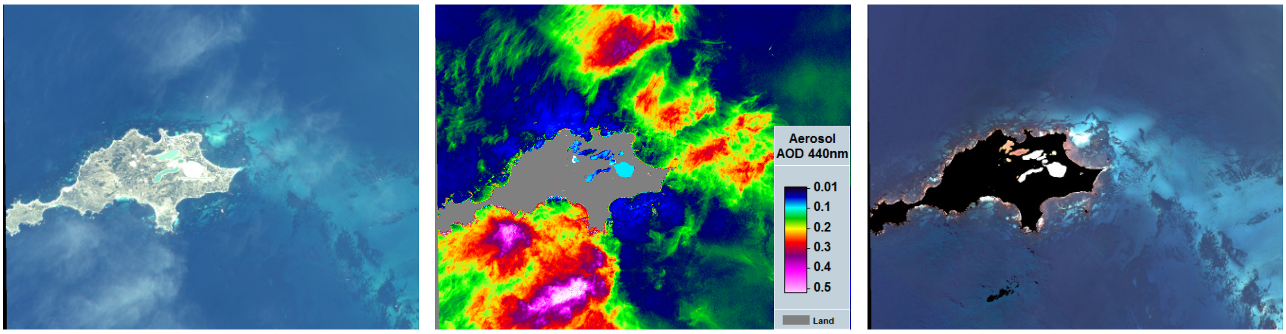

Figure 4 WV-2 scene of Rottnest Island, Australia: input radiance image (left), calculated aerosol concentration (middle), atmospheric corrected reflectance image (right)

3.4 Water depth retrieval and bottom reflectance calculation

The transformation of subsurface reflectance to bottom reflectance is based on the equations published by Albert and Mobley [15]. The water depth which is originally an input value for these equations is iteratively calculated in combination with the spectral unmixing of the corresponding bottom reflectance. By minimizing the residual error the final water depth is determined. This processing step results in two output images, one image containing water depth and another image containing bottom reflectances. The second image is the input of the following sea floor classification.

The bottom reflectances are classified due to representing spectral signatures of potential classes. These can be extracted from a given spectral library or obtained by an unsupervised spectral cluster algorithm. Depending on the case habitat classes have to be assigned to the spectral maps later. See Figure 5 for a summary of this approach (Ohlendorf, unpublished).

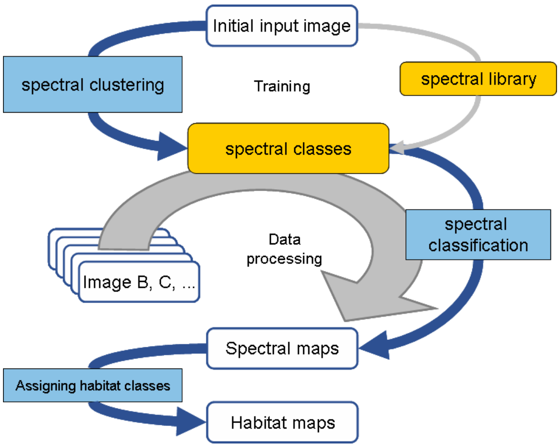

Figure 5 EOMAP's cluster and classification approach

4 APPLICATIONS

4.1 Application Area: Carribean Coast, Quintana Roo

Location Description

The application area is located on the Yucatán Carribean Coast in the Mexican state of Quintana Roo, south of the city of Cancún. The climatic conditions are tropical with a distinct rainy and dry season. Tropical storms regularly affect the region between May and December, resulting in high precipitation and hurricane force winds. Water temperatures are between 25 -30°C throughout the year. The area is a popular tourist destination. The natural landcover concerning the coastal transition band between land and water consists of dense mangrove forest. The shallow water areas are natural habitat of different coral species which are forming a big fringing reef along the Mexican Caribbean. Coral Reefs form an ecosystem with the second highest biodiversity on earth, after tropical rainforests. Such reefs grow best in warm, clear and clean, shallow water. These conditions can be found in the investigation area, which also makes it a perfect location for aquatic optical remote sensing.

The coastal mangrove belt acts like a filter for harmful substances, which are threatening the coral reef ecosystem.

Due to the increasing number of hotels which are built along the coast, the mangrove belt becomes more and more destroyed. Harmful substances as well as suspended matter are not prevented from reaching the coral reef ecosystem. Rising amounts of suspended matter reduce sunlight, one important constraint for the growth of tropical coral reefs. Consequently dramatic impacts like coral bleaching can occur. Coral bleaching can result in the death of the whole reef ecosystem.

Marine habitat monitoring based on classification of calculated bottom reflection data is an important contribution to get more information about the development and changes within the reef ecosystem. Therefore, processing and mapping of large areas in preferably high (geometric) resolution is an essential task. Besides habitat maps, large area satellite-based bathymetry data is important for environmental monitoring of marine shallow water ecosystems.

4.2 Application Area: Rottnest Island, Western Australia

Location Description

Rottnest Island is a marine reserve which is located 20km offshore west of Perth, Western Australia. It has a subtropical climate and due to the south flowing warm Leeuwin Current many tropical as well as temperate marine species are found here. Many marine organisms are considered as isolated, at their southernmost extent. [16]

The marine reserve is located mostly in shallow water areas (less than 20m depth) and is made up by the following main categories of habitats: sand, seagrass mixed seagrass and reef, reef, intertidal platform and reef wash. The largest area is made up by the reef habitat (~45%), followed by sand (20%) and seagrass (21%). The island also has important but not extensive cover of coral communities. Bathymetry of the waters surrounding Rottnest Island is quite varied, owing to the presence of many submerged limestone formations, favourite spots for divers and snorkellers. Waters along the west coast of WA are generally nutrient poor and low in turbidity which makes them ideal for optical remote sensing methods. The ability of the environmental management agencies to sustainable manage marine parks is closely linked to the availability of basic data sets such as high resolution marine habitat maps and bathymetry. [16]

The aim was to produce a habitat map based on the calculated bottom reflectance data similar to the Mexican investigation area mentioned above.

Figure 4 shows a WorldView-2 scene of Rottnest Island. As it can be seen in the aerosol image the atmospheric conditions in this scene are suboptimal. Nevertheless, it was possible to retrieve water depth information.

4.3 Further Application Areas

Concerning bathymetry and habitat monitoring further data sets have been processed, namely the Ningaloo Reef near the coast of Western Australia [17], industrial requested areas in the Persian Gulf and the Indian Ocean.

5 RESULTS

A mosaic of the bathymetry products of three different WV-2 scenes of the Quintana Roo coast near Puerto Morelos is shown in Figure 6.

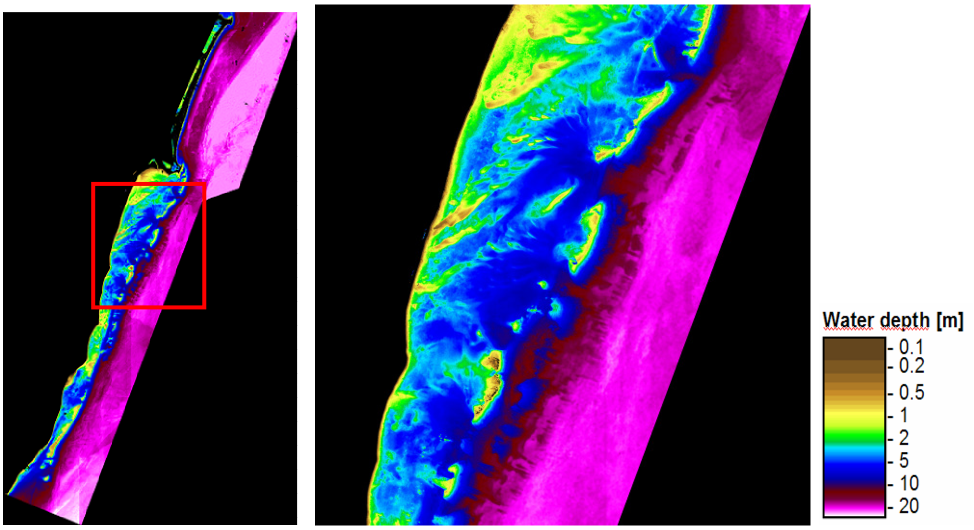

Figure 6 Bathymetry data (spatial subset) of the Quintana Roo coast near Puerto Morelos

Bathymetric data obtained from three WV-2 satellite records were compared to bathymetric data acquired with echo sounding for the Mexican application area. The results are displayed in Figure 8. The tree different charts represent the independent validations of the three WV-2 scenes that were used to generate the bathymetry map shown in Figure 6. The satellite bathymetry values range from 0.1 to 23m. Depth differences of 10cm can clearly be identified in the shallow water regions of the coast. Errors are sparsely distributed and mostly located in the areas of breaking waves and white caps, as well as in the backwash of ships. Hence, doing such a survey in calm-sea-state conditions is desirable. The comparison with the echo sounding data (where the error bar was unknown) indicated that bathymetry was determined successfully. Further data products such as habitat maps of the main components (Figure 7) give reasonable results but are not to be compared with ground truth here. However, comparisons with ground truth data were done for a large area survey using hyperspectral airborne data which were processed using the presented method [17].

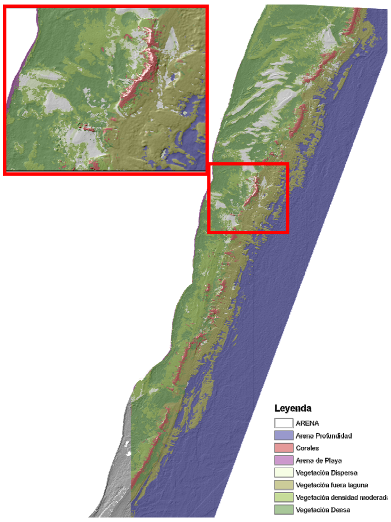

Figure 7 Marine habitat classification based on WV-2 bottom reflection data

The satellite data clearly provides more detail than the echo sounding data of the same area in shallow water areas, because the echo sounding data only consists of parallel measure lines. Benthic structures are virtually "blown away" through the interpolation of the sounding data. It seems obvious that the boat carrying the echo sounder could not pass over very shallow reef areas. This fact demonstrates another advantage of the satellite-based bathymetry, especially in the shallow areas of coral reef ecosystems. Only at depths more than 10 m, we realize an increase of inaccuracy in the satellite-derived bathymetry data due to the optical thickness of the water column. The variability of the retrieval results increases especially in areas below 15m as you can see in Figure 8. Figure 9 shows bathymetric validation charts of other areas like in the Persian Gulf, the Indian Ocean and the coast of West Australia with different satellite sensors (WV-2, IKONOS, Quickbird). It can be clearly seen that there is a good correspondence between bathymetry derived from satellite data and ground truth data.

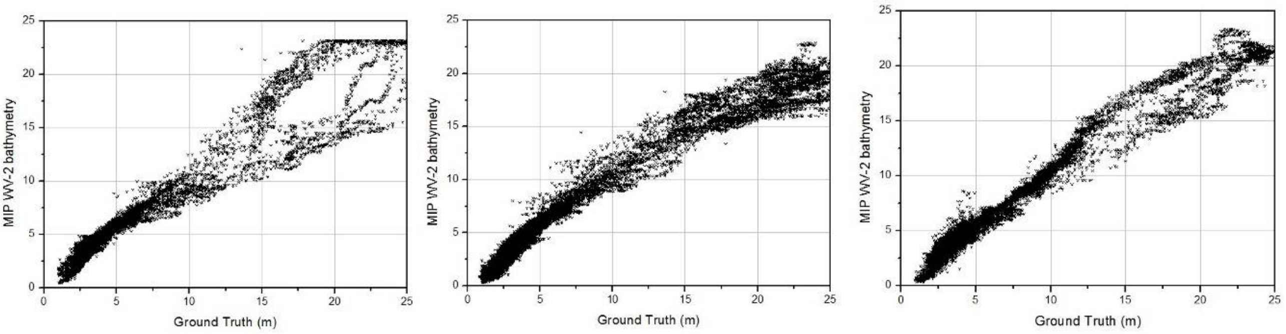

Figure 8 Accuracy assessment (WV-2-bathymetry / echo sounding measurements) of the three Scenes used for the bathymetry map of Quintana Roo coast

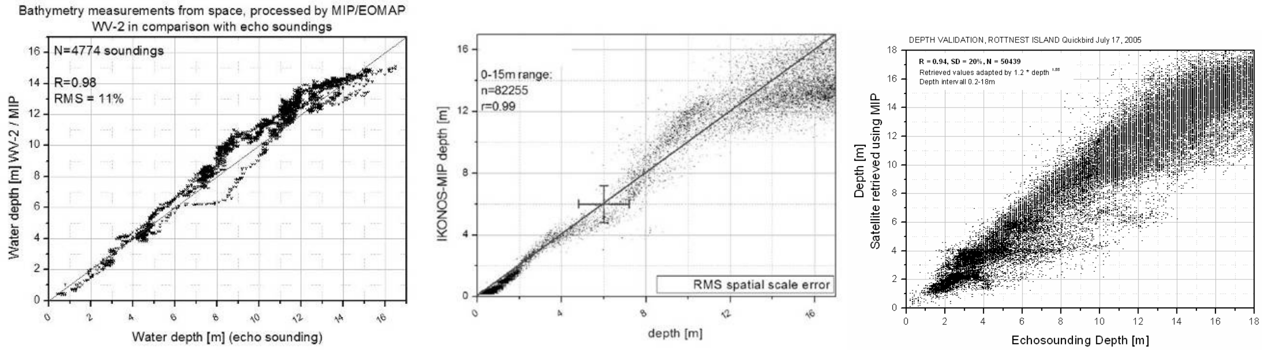

Figure 9 Accuracy assessment (satellite derived bathymetry / echo sounding measurements) for different satellite sensors and different locations

6 CONCLUSION AND DISCUSSION

The application of the multispectral method to retrieve water depth depends on several sensor parameters and environmental recording conditions. A professional feasibility forecast with respect to the conditions of an area of interest is therefore essential for reliable satellite based mapping services. The performance of the physics based data processing described in this paper depends on a list of parameters. Most of these such as atmospheric turbidity, impact of sun glitter or adjacency effects can be corrected to a certain extent.

For adequate recording conditions, clear atmospheric and in-water conditions, promising accuracies with a RMS of 8 % to 20% between the optical product and echo sounding data could be achieved for a depth between 0.1 and 20m at different coastal sites worldwide using IKONOS, QuickBird and WirdView-2 satellite data. Reflecting the satellite sensor properties of with only few bands and uncertainties in the radiometric calibration, taking into account the temporal shift and spatial geolocation errors between ground truth and satellite data, we interpret this as a good result. The lowest differences between ground truth and satellite retrieved water depth measurements were regular retrieved for temporal close high precision ground truth measurements. Comparable results with a similar processing procedure were retrieved for inland waters such as Lake Constance, in Germany and costal sites (Ningaloo Reef, Australia) using hyperspectral airborne data [17].

A new synergetic approach to combine SAR (synthetic aperture radar) and multispectral satellite data demonstrated that also a large depth range between 0 and 100m can be mapped using satellite data [18].

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