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Water column optical properties influence in satellite-derived bathymetry

Study case in Chrissi Island, Greece

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Satellite-derived bathymetry (SDB) has become increasingly recognised for its effectiveness in acquiring bathymetric data in recent decades. This method heavily relies on water properties to estimate depths accurately, assuming minimal backscatter from the water column and focusing mainly on seabed backscatter. In this study, we explore the potential benefits of incorporating water column properties information by calculating the absorption and scattering coefficients of remote sensing reflectance. By doing so, we aim to differentiate between the direct backscatter of the water column and that of the seabed. Our investigation focuses on Chrissi Island in Greece, known for its clear waters and distinctive geological and environmental features. Using SDB, we analyse changes in seabed morphology throughout the year 2022, revealing seasonal variations that influence water properties.

optical properties | satellite-derived bathymetry – SDB | change detection
optische Eigenschaften | satellitengestützte Bathymetrie – SDB | Änderungserkennung

Die satellitengestützte Bathymetrie (SDB) wurde in den letzten Jahrzehnten zunehmend für ihre Effektivität bei der Erfassung von bathymetrischen Daten anerkannt. Diese Methode stützt sich stark auf die Wassereigenschaften, um die Tiefe genau zu schätzen, wobei sie von einer minimalen Rückstreuung aus der Wassersäule ausgeht und sich hauptsächlich auf die Rückstreuung des Meeresbodens konzentriert. In dieser Studie untersuchen wir die potenziellen Vorteile der Einbeziehung von Informationen über die Eigenschaften der Wassersäule durch Berechnung der Absorptions- und Streukoeffizienten der Fernerkundungsreflexion. Auf diese Weise wollen wir zwischen der direkten Rückstreuung der Wassersäule und derjenigen des Meeresbodens unterscheiden. Unsere Untersuchung konzentriert sich auf die Insel Chrissi in Griechenland, die für ihr klares Wasser und ihre besonderen geologischen und ökologischen Merkmale bekannt ist. Mit Hilfe von SDB analysieren wir die Veränderungen der Morphologie des Meeresbodens im Laufe des Jahres 2022 und zeigen so die jahreszeitlichen Schwankungen auf, die die Wassereigenschaften beeinflussen.

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Introduction

Bathymetry, akin to terrestrial topography, holds immense importance in marine applications such as navigation, commerce and research. It facilitates safe passage for vessels, optimises resource allocation and guides fisheries operations. Traditional bathymetric data collection methods, like echo sounders or LiDAR, are expensive and labour-intensive, limiting repetitive surveys. In contrast, satellite-derived bathymetry (SDB) offers a cost-effective alternative, particularly in shallow waters, leveraging multispectral satellite imagery to swiftly map the seafloor and fill critical data gaps worldwide. Despite challenges posed by water's low reflectance, advancements in computational power and sensor technology have propelled SDB techniques forward. The dynamic nature of bathymetric data underscores the importance of studying spatio-temporal variations. Changes influenced by natural phenomena and human activities necessitate continuous monitoring and refinement of SDB models.

The concept of using satellites for mapping coastal seabed topography emerged in the 1970s as early optical satellite payloads demonstrated the ability to detect depth variations in very shallow coastal waters through the boundary between sea and land. Early experiments used multispectral imagery for coastal areas mapping, but accuracy was limited due to sensor and algorithm limitations (Bierwirth et al. 1993; Spitzer and Dirks 1987). Significant improvements occurred in the 2000s with the launch of hyperspectral and multispectral sensors with higher spectral and spatial resolution (Conger et al. 2006; Klonowski et al. 2007). Algorithms were refined using physics-based radiative transfer models. Projects in the 2000s demonstrated the feasibility of mapping depths up to 30 metres in clear waters using these satellites, significantly improving over previous techniques. However, accuracies still varied greatly depending on conditions (Miller et al. 2005).

A focused study in the Eastern Mediterranean, particularly on Chrissi Island, highlighted the significance of considering water column optical properties and integrating satellite-derived products for accurate SDB estimates. Greece's favourable conditions offer a promising environment for SDB's cost-effective, high-resolution capabilities to address various maritime challenges, from navigation safety to scientific research. Further research aims to refine depth estimations through in-situ measurements and algorithmic improvements, ensuring the reliability and applicability of SDB in hydrographic surveying and marine management.

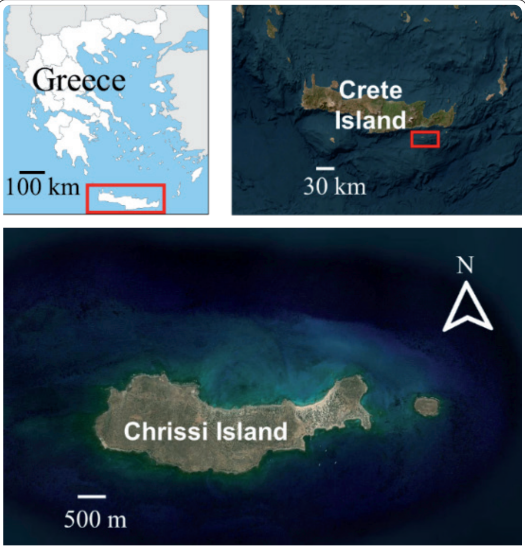

Fig. 1: Study area

Material and methods

The broader study area is on Crete Island in Greece, which lies in the Southern Aegean Sea, part of the Eastern Mediterranean basin. The Aegean Sea, and explicitly the southern region surrounding Crete Island, is the deepest basin in Greece, with a depth of approximately 2500 m. Chrissi is a very low-lying island, almost flat, with an average height of 10 m. The longest side is about 5 km long, while the average width is 1 km, ranging from a maximum of 1.5 km to a minimum of 0.5 km. Its total perimeter is close to 14.5 km, and the area it covers approaches 5.5 km^2. The seabed around the island, up to a depth of 20 m, covers an area of about 30 km^2, and it is characterised by sand, shingle and rocky outcrops (Natura 2000, 2023). Chrissi Island is located SE of Crete in the open seas. Hence, investigating SDB estimates under different hydrodynamic conditions can produce significant insights for the Eastern Mediterranean as seen in Fig. 1. The field data were used to calibrate and validate the different SDB models performed in this study. Calibration data consists of approximately 20 to 25 points distributed in depths from 2.4 m up to 24 m.

From this specific area, the SDB models under investigation are the linear-logarithmic algorithm proposed by Lyzenga (1978), the band-ratio transformation developed by Stumpf et al. (2003) and the inherent optical properties linear model (IOPLM) proposed by Zhang et al. (2020). Lyzenga developed a method for studying marine environments with low suspended particles, chlorophyll and organic matter levels. This method assumes that the physical and chemical properties of the water column depicted in a satellite image remain consistent. The ratio of attenuation coefficients due to light diffusion in two spectral zones, for instance, (i) and (j), should remain constant (K_i/K_j = constant) across the entire image (Lyzenga 1978). However, this assumption may only hold in some cases, as reflectances from the water bottom may vary depending on the sediment composition.

A significant disadvantage of the linear-logarithmic algorithm in coastal environments consisting of underwater vegetation, such as algae or seagrass, is that the bottom reflectance in shallow water is lower than that in deep water. As a result, in shallower waters, the difference is smaller than zero, thus the natural logarithm ln is not defined. The different spectral zones of passive sensors exhibit distinct spectral absorptions (attenuations), and the depth values in the Lyzenga equation vary as a function of the logarithm; therefore, the ratio of the logarithms, for example, between blue and green spectral bands, will also change according to the depth.

A variation in the bottom albedo, caused by changes in underwater vegetation or sediment, affects both spectral zones similarly, while changes in depth significantly impact the zone with higher absorption. Thus, the variation in the reflectance ratio between spectral zones due to depth will be much more significant than the variation caused by changes in bottom quality (Philpot 1989). Consequently, when investigating a coastal area with a constant depth but different bottom compositions, satellite imagery pixels that display varying reflectance due to sediment and vegetation will have a nearly consistent logarithmic ratio of reflectance.

Hereafter, Stumpf et al. (2003) proposed a ratio transform algorithm to determine the bottom

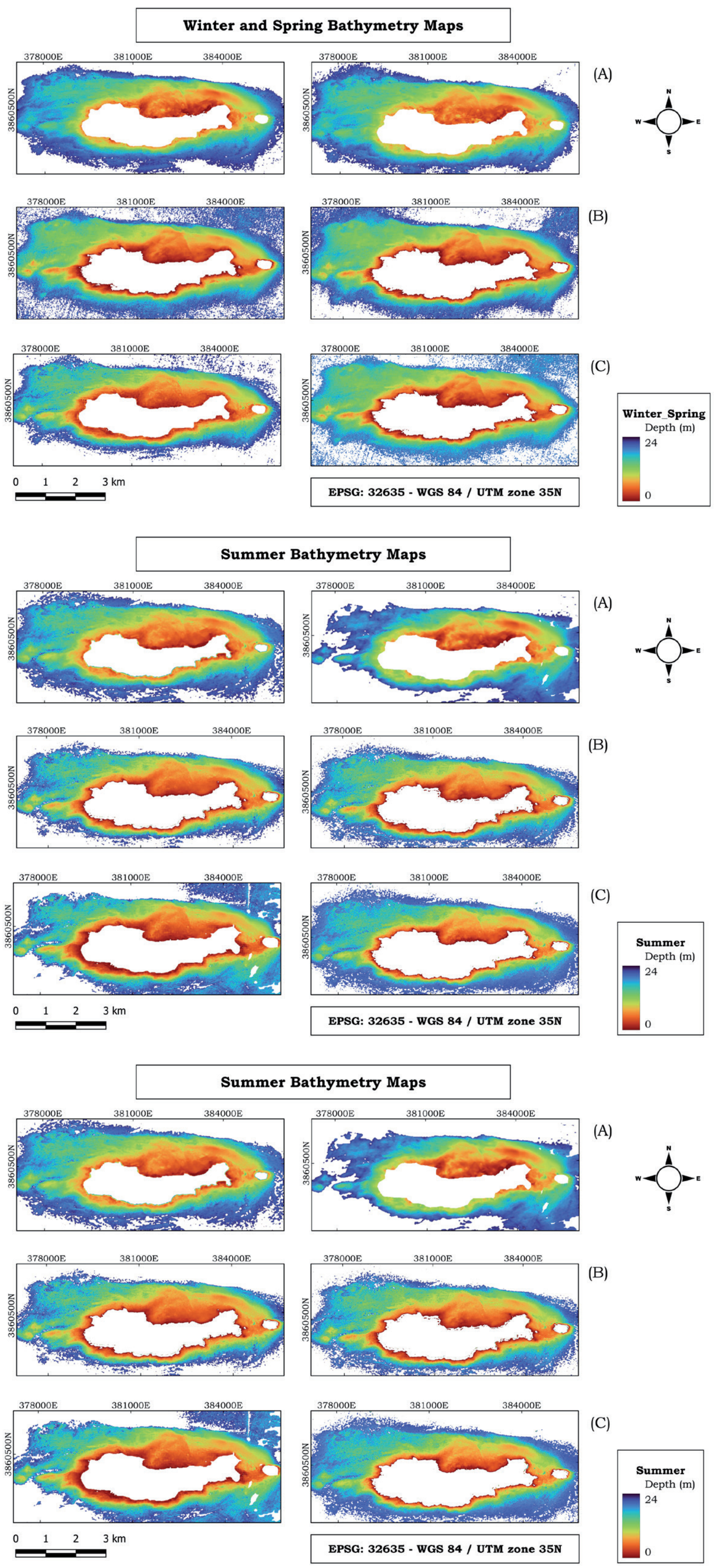

Fig. 2: Typical SDB model in different seasons. The first row indicated by (A) illustrates on the left the best Linear performance bathymetry map of this period, while the right bathymetry map delineates its less effective outcome. Likewise, the second row (B) indicates the Band Ratio's outcome for the best (right) and the least effective (left) performance. Lastly, row (C) referred to the IOPLM outcome where the left map is the best, and the right is the worst performance of this method throughout the seasons

depth, regardless of the bottom quality or existing vegetation. It can be calibrated to actual depths using data from a nautical chart or a bathymetric plot or through field measurements. The last SDB method tested in this study is based on the IOPs and their fluctuations with depth; thus, the IOPLM was developed by Zhang et al. (2020). This model utilises the blue and green bands from multispectral images, which offer very high resolution, to gather a wide range of water depth data. An important note is that this IOPLM method was initially developed for very high spatial resolution (~2 m) satellites such as WV-2, SPOT and Pleiades. In this study, the Sentinel-2 products belong to the high spatial resolution and all the tests executed with the best value of 10 m of visible bands.

Result and discussions

The present sub-section of findings offers a comprehensive overview of the statistical metrics of SDB estimates of every tested method aligned with the analysis approach in a seasonal context as seen in Fig. 2. The performance of the three methods was evaluated concerning metric responses, maximum depth estimation achieved and band combinations for the years 2019 to 2023. The Linear method consistently exhibits stable performance throughout the year, primarily leveraging the reflectance of the green band, with its winter predictions proving to be the most accurate. The Band Ratio and IOPLM methods consistently yield superior results across all seasons, displaying good performance metrics. However, a subtle decline was discerned during the autumn season. Regarding band combinations, the IOPLM method predominantly employed the coastal blue paired with the green band across all seasons. On the other hand, the Band Ratio method was based on the blue-green combination for winter and fall, while the green-blue pairing was used during summer. A mild underestimation of depth calculations by the Band Ratio method was evident during the winter and summer. Notably, the depth estimates from all methods approximated 24 m during autumn. The general overview of depth profile can be seen in the Fig. 3.

As for the seasonality, during the winter and spring, it obtained the best performance in a percentage of 73.33 % (11 of 15 cases), while during summer, the best performance was up to 20 % (3 of 15 cases), and the remaining one in a percentage of 6.66 % (1 of 15 cases) belonged to autumn. Contrarily, the least effective outcome variations for autumn reached 40 % (6 of 15 cases), and the rest obtained during summer (9 of 15 cases) at 60 %. The results indicate that Band Ratio and IOPLM methods performed effectively across all seasons, while the Linear method delivered consistent but less accurate estimates. Moreover, IOPLM pre-

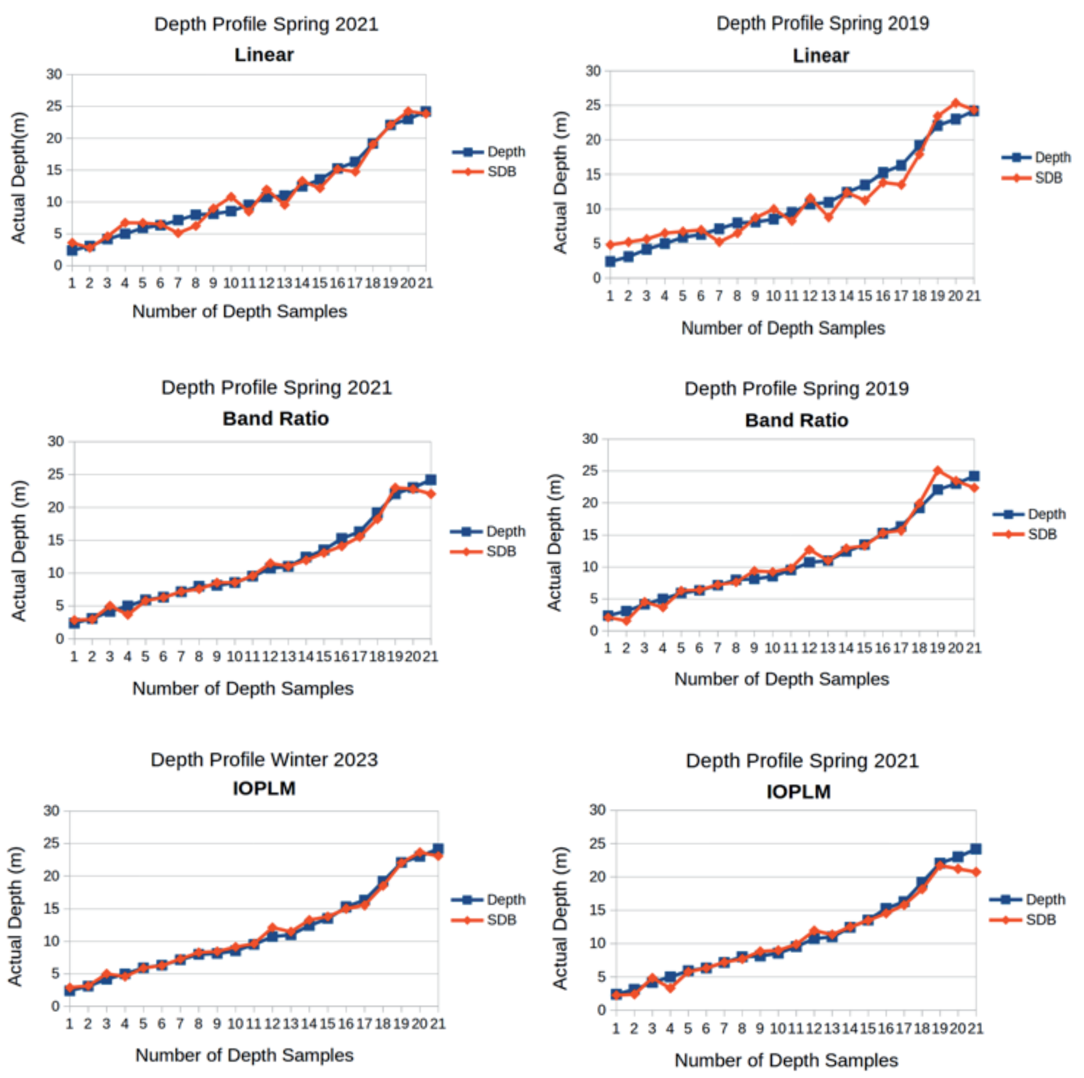

Fig. 3: Typical depth profiles of SDB estimated with different methods throughout the year:
(a) Linear, (b) Band Ratio, (c) IOPLM

dicted better depth estimates in almost the entire study period. Fig. 4 represents the average RMSE metrics of every year and every method to provide a more comprehensive view of the performance. It is noticeable that the Linear method delivered the less accurate estimates; however, with consistency around the mean RMSE of 1.5 m.

Conclusion

The study focused on estimating water depth using satellite imagery in the Eastern Mediterranean. Rigorous preprocessing of satellite data was performed, selecting products with minimal cloud coverage. Multiple SDB algorithms, including the Linear Logarithmic algorithm, Band Ratio transformation and the IOPLM, were evaluated. Notably, a strong correlation was found between water column optical properties and SDB accuracy. The Band Ratio transform algorithm performed consistently across study sites but declined during autumn. In contrast, the IOPLM method demonstrated adaptability, albeit with sensitivity to specific environmental conditions. The study highlighted limitations related to atmospheric distortions, sensor resolution and

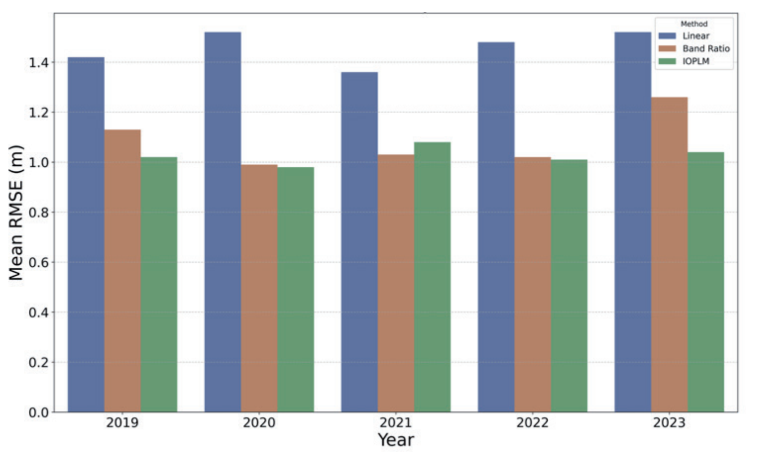

Fig. 4: Multiplot of the different performances of SDB methods in Chrissi Island

georeferencing inaccuracies. Additionally, access to high-resolution commercial satellite data was challenging. Temporal analyses revealed patterns and fluctuations in SDB estimates and water optical characteristics.

Outlook

Several recommendations emerge in the context of advancing SDB research, particularly in the vital Eastern Mediterranean. First, it is imperative to examine the influence of anthropogenic activities, such as maritime shipping and offshore exploration, on the water column's optical properties for more accurate algorithmic modelling. Developing region-specific SDB models that account for unique oceanographic phenomena, like complex current systems and high salinity, is crucial for enhancing bathymetric accuracy. Third, leveraging advancements in Machine Learning and Artificial Intelligence in combined high-resolution commercial data offers promising avenues for automating data processing and overcoming spatial limitations. Fourth, integrating real-time or near-real-time corrections for optical properties into existing SDB algorithms could provide greater adaptability to dynamically changing environmental conditions. Fifth, incorporating the Extended Kalman Filter can serve as a robust method for quantifying the uncertainties associated with SDB estimates. Lastly, exploring alternative calibration and validation data sources like ICESat-2 may reduce dependency on in-situ data and contribute to more reliable SDB applications. Collectively, these recommendations aim to address the current challenges in SDB and enhance its applicability in diverse hydrospatial tasks. //

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