Chapter

# Introductory Chapter: Satellite Altimetry – Overview

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## 1. Introduction

Radar satellite altimetry is one of the basic satellite measurement techniques intended primarily for solving global geodetic tasks by means of radar measurements from satellites toward the Earth. Satellite altimetry ensures the collection of high-precision global data of uniform accuracy on sea level, which enables monitoring of the geophysical characteristics of the sea and larger water surfaces, that is, marine topography and circulation within liquid water bodies. During the last four decades, satellite altimetry has revolutionized geosciences, especially oceanography, geophysics, and geodesy. This measurement method found its application in modeling the shape of the Earth and the Earth's field of acceleration of gravity, modeling the relief of the seabed and vertical displacements of the Earth's crust in coastal areas, and monitoring climate phenomena and long-term climate changes. Satellite altimetry data is distributed in the form of original measurements and products ready for use in geosciences, most often calculated models, or calculation services. This chapter presents the fundamental principles of the radar altimetric measurement method, its historical development, achievements, and expected improvements in technology soon, as well as the scientific and professional results achieved so far in the development and application of technology.

## 2. Evolution of technology

The concept of satellite altimetry was developed in the sixties of the twentieth century as part of NASA's (National Aeronautics and Space Administration) NGSP (National Geodetic Satellite Program) initiative for the development of a space geodetic program and was formalized in 1969 during a conference on solid Earth and ocean physics [1]. During that time of conceptual development, satellite altimetry's main goal was to determine the Earth's shape, which today can really be considered a limited ambition [2].

Following the timeline of technology development, the operational characteristics of the satellite missions launched to date are given in **Table 1**. The variety of satellite missions is shown regarding the height of the satellite orbits, the inclination angles of the orbits, the coverage of the geographical area of the Earth, the distances of the satellite paths on the Equator, and the frequency band and altimeter frequencies.

| Mission | Orbit height (km) | Inclination | Latitude coverage | Equator track distance (km) | Band | Frequency (GHz) |
|---|---|---|---|---|---|---|
| GEOSAT | 785 | 108° | 72° | 163 | Ku | 13.5 |
| ERS-1/2 | 785 | 98° | 81° | 80 | Ku | 13.8 |
| TOPEX/ POSEIDON<br>Jason-1/2/3<br>Sentinel-6 | 1336 | 66° | 66° | 315 | Ku/C | 13.6/5.3 |
| GFO | 785 | 108° | 72° | 163 | Ku | 13.5 |
| Envisat | 785 | 98° | 81° | 163 | Ku/S | 13.6/3.2 |
| CryoSat-2 | 717 | 92° | 88° | 7 | Ku | 13.6 |
| HY-2A/2B | 964 | 99° | 60° | 90 | Ku/C | 13.6/5.3 |
| SARAL/ ALTIKA | 800 | 98° | 81° | 90 | Ka | 35 |

**Table 1.**
*Operational characteristics of satellite altimetry missions.*

### 2.1 Development phase of technology

With the launch of the Skylab satellite in 1973, the development and experimental era of satellite altimetry began, revealing the great potential of radar altimetry. Already in 1975, the GEOS-3 (Geodynamics Experimental Ocean Satellite) satellite was launched, as the third satellite in the NGSP program [3]. The satellite mission achieved measurement precision in a one-second interval of about 25 cm, which, along with the low accuracy of determining the satellite's orbit of about 5 m, could not meet the requirements for application in geodetic purposes [4].

Significant progress was made during the SEASAT satellite mission, which achieved 5-centimeter precision of altimetry measurements, and methods of determining satellite orbits and geophysical corrections applied during altimetry data processing were significantly improved [5]. This was achieved by simultaneous observation with different instruments from the satellite: (1) a SAR instrument (Synthetic Aperture Radar), (2) a scattering meter, which was used to determine the wind speed and direction above the water surface, (3) a multi-frequency microwave radiometer, which was used for determining water surface temperature, and (4) radar altimeter [4]. The data thus collected enabled the modeling of the circulation of ocean waves and wind along the sea surface, the geoid model in the sea area, and the topography of the seabed.

The last mission of the development phase, GEOSAT (GEOdetic SATellite), was launched in 1985 with the basic goal of determining the potential of the acceleration of gravity at sea and modeling the topography of the sea primarily for the needs of the US Navy [6]. The success of the satellite mission is evidenced by the calculation that the satellite mission saved the Navy in the amount of about 280 million US dollars by replacing the long-term shipboard gravimetric measurement [7].

Practical calculations of gravity anomalies and geoid undulations from satellite altimetry data began already during the development phase. As an example, we cite the usage of GEOS-3, SEASAT, and GEOSAT altimetry data and ETOPO5U bathymetry data to globally determine gravity anomalies and sea surface heights in the ocean areas, using the least squares collocation method [8, 9].

## 2.2 The modern and future era of technology

The 1990s represent a turning point in the application of technology, during which significant advances were made toward operational oceanography, that is, the possibility of forecasting sea level and temperature and sea currents, for which the basic prerequisites are reliable and high-frequency measurements with altimeters that are available in real-time. The potential of the technology was also recognized by the European Space Agency (ESA), which defined the basic goals of future missions in the PRARE (Precision Range and Range-Rate Equipment) project: (1) calibration of radar altimeters within 10 cm using laser retroreflectors on Earth, (2) download and distribution of measured data in real-time, and (3) automation of data processing and development of rapidly available standardized products [10], which began to be realized with the ERS-1 (European Remote Sensing) satellite mission. **Figure 1** displays a view of the current and future altimetry constellations [11].

At the same time, NASA, and the French agency CNES (Centre National d'Etudes Spatiales) developed and launched TOPEX/Poseidon, one of the most significant satellite geodetic missions in history that revolutionized satellite altimetry as a technology [12, 13]. The radar altimeter of the TOPEX/Poseidon satellite, in addition to the standard microwave frequency of about 12 GHz (Ku band), was also equipped with another frequency in the C-band (about 5 GHz), which became the standard for later satellite missions. This, along with the introduction of the third frequency on the satellite's microwave radiometer, enabled the efficient calculation of the ionospheric correction and the removal of the influence of wind on altimetry measurements [2]. This satellite mission achieved the accuracy of the determination of the satellite's orbit expressed by the root mean square error of about 2.5 cm and the measurement precision with a standard deviation of 2 cm, which achieved the estimated precision of

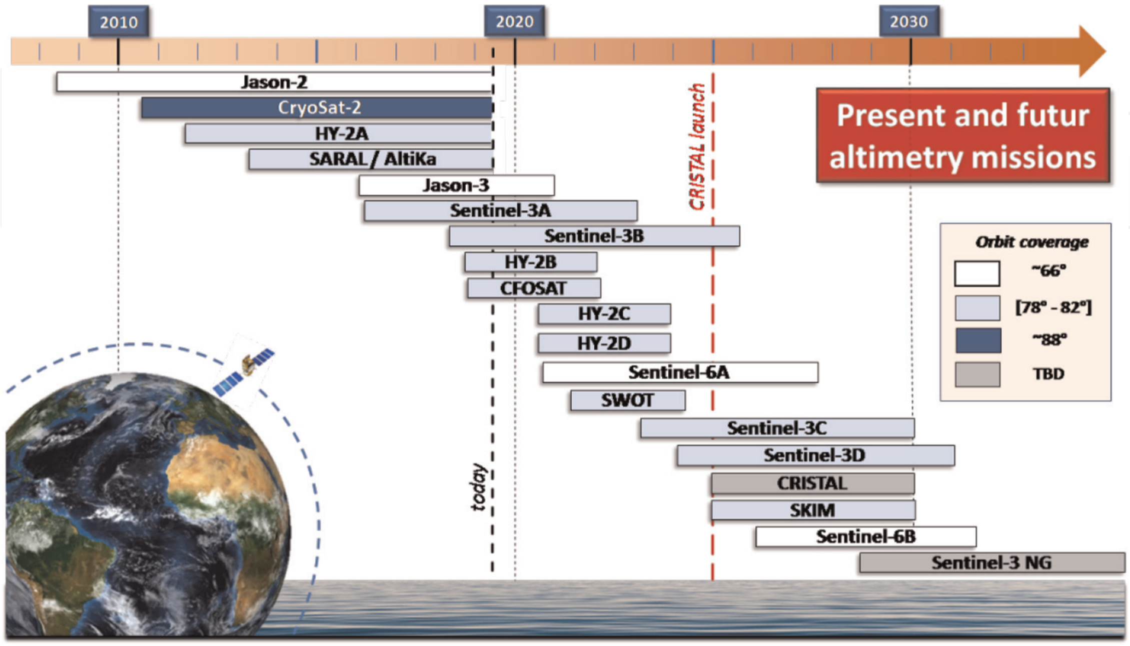

**Figure 1.**
*Present and future altimetry missions [11].*

determining the sea level in the open sea by satellite altimetry of about 4 cm [14]. Considerable progress in the accuracy of satellite orbit determination was achieved with the DORIS measuring system for tracking satellites from Earth.

During the nineties, the ERS-2 mission (the successor to ERS-1) and the GFO (Geosat Follow-On), which succeeded the GEOSAT mission, were launched. A similar intensity of the frequency of launching altimetry satellite missions continued in the first years of the twenty-first century, when the JASON-1 (Joint Altimetry Satellite Oceanography Network) mission succeeded TOPEX/Poseidon, with a four-year period of simultaneous observation of the two satellites. JASON-1 was designed primarily to determine trends in mean sea level change, or to assess the consequences of climate change [15]. In 2002, the Envisat satellite mission was launched, which succeeded the ERS missions, with the basic goal of enabling the creation of environmental studies, the development of biological oceanography studies, and the mapping of ice surfaces on Earth [16].

The following satellite missions are currently active [17]: CryoSat-2 (Cryogenic Satellite), a mission created as part of ESA's space program in 2010, HY-2a (Haiyang), mission realized in 2011 under the leadership of CNSA (China National Space Administration), SARAL, a mission launched in 2013 with the cooperation of ISRO (Indian Space Research Organization) and CNES, SENTINEL-3, a mission launched in 2015 as part of ESA's Copernicus space program with the leadership of EUMETSAT, JASON-3, a designed in collaboration of NASA and ESA as the successor of TOPEX/Poseidon and Jason 1/2, HY-2b (Haiyang), launched as the second in the series of Chinese Haiyang satellites in 2018, and Sentinel-6 (previously referred to as Jason CS), launched in late 2020, which continues the EU Copernicus and NASA program and previous TOPEX/Poseidon and Jason 1/2/3 satellite missions.

Satellite altimetry missions of the near future should enable and improve the efficient monitoring of the surface level of lakes, rivers, and coastal areas, forecast the intensity of tropical cyclone disturbances, hurricanes, and enable the development of improved models of sea changes and currents. In the future, the launch of SWOT (Surface Water Ocean Topography) satellite mission is expected, primarily to enable terrestrial water monitoring.

## 3. Principle of satellite altimetry measurement

Satellite altimetry is a method of determining the height of the sea surface in relation to a defined geodetic reference frame (ellipsoid or geoid) based on the measurement of the distance between the satellite and the instantaneous sea surface. Distance measurement is based on the measurement of the time required for the radar signal to travel from the satellite to the water surface and from the water surface to the satellite, with a series of corrections necessary due to signal propagation through the atmosphere and the influence of geophysical phenomena of water surfaces on the reflected signal [2]. A prerequisite for determining the height of the water surface is knowledge of the position of the satellite in a clearly defined geodetic reference system.

### 3.1 Basic formulas and corrections of satellite altimetry data

The altimeter from the satellite sends a short pulse of microwave radiation of known power toward the sea surface at regular time intervals. The pulse interacts with the rough sea surface and part of the radiation is reflected toward the altimeter. With the known speed of the radar signal, that is, the speed of light in a vacuum c, and neglecting refraction, the distance of the satellite from the sea surface Robs can be calculated based on the time t required for the signal pulse to travel twice [14]. The fundamental equation of altimetry then takes the form:

$$R_{obs} = \frac{ct}{2} \tag{1}$$

After applying the corrections, the basic equation for calculating the corrected distance $R$ has the form:

$$R = R_{obs} - \sum_i \Delta R_i = R_{obs} - \left(\Delta R_{tdry} + \Delta R_{twet} + \Delta R_{iono} + \Delta R_{dyn} + \ \dots\right), \tag{2}$$

where the values $\Delta R_i$, $i$ = 1 … represent corrections, $\Delta R_{tdry}$ and $\Delta R_{twet}$ are the influence of the dry and wet components of the troposphere, $\Delta R_{iono}$ is the influence of the ionosphere, physical influences on the surface of the sea such as sea currents and tides, motion of the Earth's pole, solid Earth tides and the dynamics of the sea (sea state bias) $\Delta R_{dyn}$.

The consequence of the latter can most often be expressed by the slope of the waves that cause the radar signals to bounce with a small displacement, which is related to local conditions (wind and waves). An offset correction due to sea position is attempted to account for the difference between the scattered surface and the true mean sea level within the altimeter footprint. The correction is a combined effect of electromagnetic and asymmetric shifts [2].

The most common corrections and models used today in the processing of original altimetric measurements, namely orbit, dry/wet tropospheric correction, ionospheric correction, inverse barometric correction, Sea tides and solid Earth tides, and geodetic reference surface can be found in example [18]. All influences on the signal cause a delay in the return signal, so the corrections are positive amounts (Eq. (2)). The distance estimate is variable along the satellite orbit due to changes in sea surface topography and changes in the height of the orbit relative to the center of the Earth.

The basic prerequisite for determining the height of the water surface based on the measured distance from the satellite is the knowledge of the position of the satellite flying in a predefined orbit, that is, its height $h_{OR}$ in a fixed geocentric reference system. Determining the position of satellites today is done through DORIS and SLR tracking from Earth and GNSS technology from space. The estimated accuracy of determining the orbit of modern satellites is 1 cm. The sea surface height (SSH), or the water surface in general, in the reference system in which the position of the satellite is expressed (as a rule, the ellipsoidal height) can be expressed as:

$$SSH = h_{OR} - R = h_{OR} - R_{obs} + \sum_i \Delta R_i. \tag{3}$$

The dynamic effects of geostrophic sea currents are of primary importance for satellite altimetry applications in oceanography [14]. Therefore, the dynamic topography of the sea (SST; **Figure 2**) can be represented mathematically by the equation:

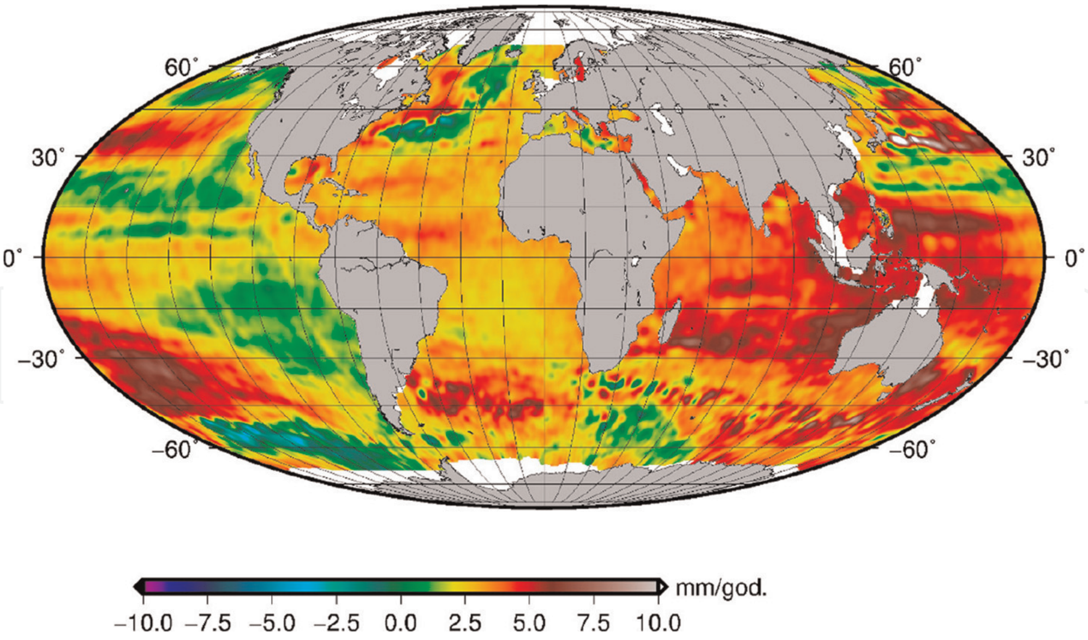

**Figure 2.**
*Global trend of mean sea level change based on CU data [19], adjusted by the method of least squares for the period 1993–2012.*

$$SST = SSH - N - h_T - h_A, \tag{4}$$

where $N$ is the undulation of the geoid, and $h_T$ and $h_A$ are the influence of sea tides or atmospheric pressure, which are calculated from the model or corrections for the moment of measurement. The influence of atmospheric pressure can be described by the inverse barometric (IB) effect, that is, the direct influence of changes in atmospheric pressure on the level of the water surface, whereby the level of the water surface decreases with an increase in air pressure and vice versa. Changes in air pressure of 100 Pa cause changes of about 1 cm in the water surface level. The average monthly influence of atmospheric pressure on sea level in the Mediterranean area is about 3 cm [20].

By determining the average change in SSH heights over a period, we can also define the mean sea surface MSS. The level of the mean sea level above the geoid is called the mean dynamic ocean topography which provides data on the magnitude of ocean circulations. To define the MSS size, it is important to use the latest data due to the development of radar altimeters themselves, precise calculation of orbits, geophysical corrections, and slow changes in ocean currents. The mean sea level is a surface created by averaging a longer period of sea level observations lasting a minimum of one year due to pronounced seasonal effects of sea level change, and optimally 18.6 years due to the Earth's nutation period [21].

The sea level can also be expressed by the sea level anomaly SLA in relation to the mean sea surface MSS:

$$SLA = SSH - MSS. \tag{5}$$

The mean level shown on the geoid represents the topography of the sea (sea surface topography, [22]), which is one of the basic variables in determining the model of the shape of the Earth—the geoid.

### 3.2 Advanced altimeter processing methods

Satellite altimetry provides centimeter accuracy over the open ocean from orbits more than 1000 km above Earth. However, the estimation of the height of the water level is significantly less accurate in coastal and inland areas, mainly due to difficulties in estimating tropospheric corrections, high-frequency atmospheric signals, tides, and mostly problems related to land contamination in radar altimeter footprints [23].

Improved altimetry data in coastal areas and on land is obtained through retracking —signal reprocessing procedures using complex algorithms. Problems related to data processing procedures are explained in detail in Ref. [2]. Today, the most used data processing algorithms in the coastal area are ALES (Adaptive Leading Edge Subwaveform) and X-TRACK [24, 25]. Altimetry retrackers compare the wave strength of return signals most often with previously known wave models, and in this way, reconstruct measurements of water surfaces [24]). ALES+ was later designed for sea ice, coastal and inland waters [26], while Goddard Space Flight Center (GSFC) designed several retrackers for ice regions. Thanks to such retrackers, altimeter errors are reduced, ensuring coverage and use of satellite altimetry in coastal zones and inland water areas. All retracked data is available through the coastal altimetry community.

The most significant recent development in satellite altimetry technology has been the introduction of Delay-Doppler (DD) or SAR-mode altimetry, which allows better observation of small-scale features (below 50 km) and improved spatial resolution along the satellite track compared to conventional pulse-limited altimeters [27]. DD altimetry uses the Doppler effect, caused by satellite motion in the along-track direction, to improve spatial resolution in the same direction and thus enable along-track data sampling (e.g., up to 300 m for Sentinel-3). In other words, the footprint of the DD altimeter is reduced by an order of magnitude compared to conventional altimeters (from several kilometers to several hundred meters) [28]. Therefore, DD altimetry, such as those on CryoSat-2 (SIRAL, SAR Interferometric Radar Altimeter) and Sentinel-3 (SRAL, Synthetic Radar Altimeter), provide more and/or improved data over the ocean, especially in sea ice areas and coastal areas.

## 4. Altimeter products

### 4.1 Sea-level change

The use of satellite altimetry data to monitor changes in the mean sea level, as a basic geodetic task, is one of the most effective ways of monitoring climate change. The assessment of the change in mean sea level today indicates a trend of increase of 3.1 ± 0.4 mm/year (**Figure 2**), which is agreed upon by five leading scientific institutions in the field of research: AVISO, CSIRO (Commonwealth Scientific and Industrial Research Organisation), CU (University of Colorado Boulder), GSFC (Goddard Space Flight Center), and NOAA, whose trend estimates are in good agreement, although the data processing and trend calculation methods differ.

### 4.2 Gravity model

With satellite altimetry, it is possible to calculate the mean sea level in relation to the geoid, which enables efficient and high-quality modeling of the geoid surface, especially for the sea and ocean area [8, 29].

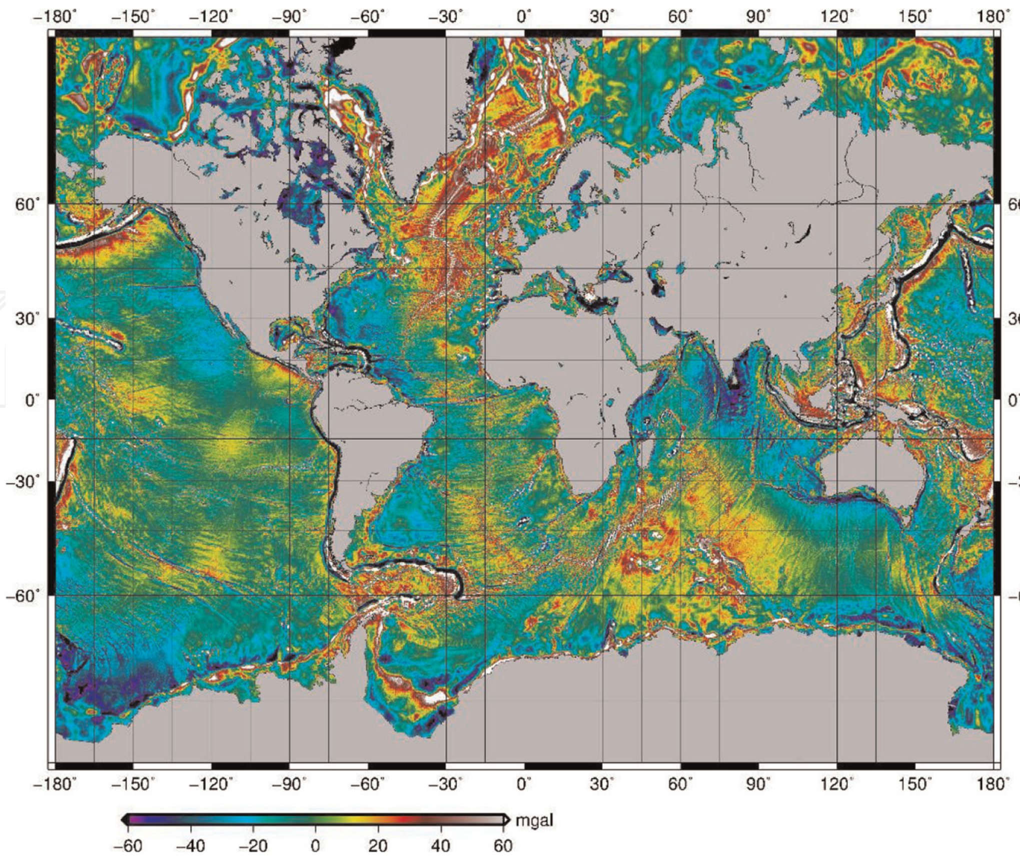

**Figure 3.**
*Altimetry-derived global ocean gravity map DTU15 [30].*

From the satellite altimetry missions data, it is possible to reconstruct the gravity field on water surfaces. Usually, three procedures for calculating the anomalies of the Earth's gravity acceleration field from altimetric data are used: (1) by applying the least squares collocation method with altimetric data and calculated surface slopes along the satellite path, (2) by applying the least squares collocation method with altimetry data and calculated vertical deflections, and (3) by applying the Vening-Meinesz formula to the vertical deflection data on water surfaces obtained from altimetry. **Figure 3** shows the global model of free air anomalies DTU15, calculated from several altimetry missions [30].

### 4.3 Bathymetry

Satellite altimetry data regularly distributed over seas and oceans can be combined with infrequent and relatively expensive depth measurements by ultrasonic depth sounders at specific ship locations to produce bathymetric models [31]. Maps created in this way cannot be used for precise underwater navigation, but they can indicate the topography of the seabed, that is, larger geo-tectonic structures, such as lithospheric plate boundaries, etc. **Figure 4** shows a depth map derived from altimetry data [32].

Calculated gravity acceleration anomalies and bathymetric maps are very often used in interdisciplinary research related to geodesy—for example, tectonophysics, and studies on tectonic movements because they effectively reveal the boundaries of tectonic plates and the specificities of local areas. In addition, satellite altimetry data are successfully used for applications in oceanography and glaciology [14], but also in multidisciplinary early warning systems, such as those predicting floods or tsunamis

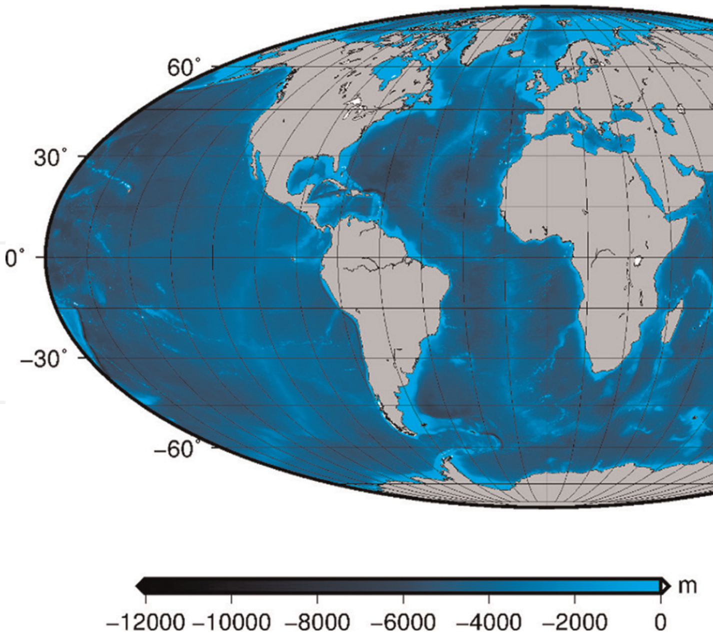

**Figure 4.**
*Global depth model created based on altimetry data [32].*

and other climate-related forecasting systems, which lead to operational oceanography, i.e. a system of predicting sea-related variables, such as sea level, temperature, and currents, based on long-term routine measurements and real-time observations of the ocean and atmosphere.

In Ref. [33], the conjoint analysis of vertical land motion of the Dubrovnik area was derived from the ESA's Sentinel-1 InSAR data, continuous GNSS observations, and differences in the sea-level change obtained from all available satellite altimeter missions for the Dubrovnik area and tide gauge measurements.

## 5. Conclusion

Since the early nineties of the twentieth century, satellite altimetry has been applied in various geodetic and interdisciplinary research. Satellite altimetry enables advanced determination of the Earth's shape by implementing a model of the acceleration of the Earth's gravity. Furthermore, satellite altimetry enables efficient, global, and relatively frequent monitoring of changes in mean sea level as an indicator of climate change and serves as a basis for the establishment of height systems at sea and on land. Finally, as part of interdisciplinary research, satellite altimetry enables the determination of global depth models, the assessment of the impact of sea level changes, vertical movements of the Earth's crust in coastal areas, and obtaining the tectonic geomorphology of the seabed.

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