Chapter

Radar Satellite Altimetry in Geodesy - Theory, Applications and Recent Developments

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Abstract

Radar satellite altimetry has revolutionized our understanding of the Earth's sea-level shape and its change over time, monitoring of the natural and human-induced water cycle, marine gravity computations, seafloor relief (bathymetry) reconstruction, tectonics, water mass balance change monitoring, etc., thus providing significant impact in geodesy. Today satellite radar altimetry is critical for unifying the vertical height systems, regional and global geoid modeling, monitoring of the sea level rise impact, monitoring of the ice sheet melting, and others. This chapter gives an overview of the technology itself and the recent developments including the SAR (Synthetic Aperture Radar) altimetry, coastal altimetry retracking methods, and new satellite missions (e.g. Sentinel-6). Besides, the chapter presents recent applied studies utilizing the altimeter data for ice sheet monitoring, vertical land motion estimating, bathymetric computations, and marine geoid modeling.

Keywords: altimetry-derived bathymetry, coastal altimetry, geodesy, gravity modeling, radar satellite altimetry, sea level, sea topography

1. Introduction

Radar satellite altimetry provides global, frequent, and precise measurements of uniform accuracy of the sea level height related to a desired geodetic reference frame at different time epochs and from various altimeter sensors. Designed in 1969 at the Williamstown Conference on Solid Earth and Ocean Physics [1, 2], the technology was developed through the experimental missions Skylab (see [3]), Geodynamics Experimental Ocean Satellite 3 (GEOS-3, see [4]), and SEAfaring SATellite (SEASAT, see [5]). Since the early 1990s, different altimeter satellite missions provide reliable and solid information on the sea level thus enabling various applications in geodesy, oceanography, glaciology, climate research, atmosphere, wind, waves, biology, and navigation [6, 7]. To this day, more than 80,000 publications discuss or include altimeter data, technology, or products [8].

In geodesy, satellite altimetry is used to study Earth's shape and size, sea-level variability, Earth's gravity field over oceans and its change, tectonic plate motion, bathymetry, natural hazards, and inland water-related occurrences. The data acquired by the satellite altimeters are distributed at different levels of complexity and applicability; from source, non-processed measurements, which must be corrected using various atmospheric and geophysical models and corrections, up to complete products ready to use in different applications. The measurements are distributed with different timeliness, most often in near real-time (e.g., in less than 3 hours after the acquisition).

This book chapter presents the theoretical background of the technology, basic principles and data processing procedures, current trends in technology, and different applications of the technology. The chapter gives an overview of the relevant literature and points towards more specific studies.

2. Radar altimetry technology and principles

This section gives the theoretical background on the altimeter principles and concepts, the development of the technology and the satellite missions, and current advances on altimeter data processing and product deriving.

2.1 Concepts of satellite altimetry

Conceptually, satellite altimeters measure the distance from the satellite to the sea-level surface, i.e., the range R, thus enabling deriving of the sea level surface referred to any desired geodetic reference frame such as the ellipsoid or the geoid. The altimeter transmits a short pulse of microwave radiation with known power towards the sea surface, where it interacts with the sea surface. The range is measured from a time taken for incident radiation of a signal to reflect back to the altimeter, which enables determining of the sea surface height. Eq. (1) presents the basic principle of satellite altimetry, i.e., the measuring of the range $\hat{R}$ from the round-trip travel time, without refraction accounted for, based on the speed of light in vacuum c:

$$\hat{R} = \frac{ct}{2}. \tag{1}$$

After applying the corrections to the measurements, the basic equation can be modified to present corrected range R as [6, 9]:

$$R = \hat{R} - \sum_j \Delta R_j = \hat{R} - \left(\Delta R_{tropoD} + \Delta R_{tropoW} + \Delta R_{iono} + \Delta R_{od} + \cdots\right) \tag{2}$$

where $\Delta R_j, j = 1,\ldots$ is the sum of the atmospheric and technology corrections applied to the signal pulse, which encompasses dry and wet component of the tropospheric correction, R_{tropoD} and R_{tropoW}, ionospheric correction R_{iono}, the influences of the ocean dynamics R_{od}, and the other corrections [6]. Due to such influences, the propagation of the signal through the atmosphere is slowed down, meaning that the corrections of the R are positive values. The accuracy of the range is, naturally, directly correlated to the accuracy of the corrections applied to derive the sea surface height.

The basic principles of the technology integrated with the other related remote sensing systems are shown in **Figure 1**. The accuracy of determining the satellite altimeter position is critical for the measurements of the range. The accurate position of the satellite is ensured through the precise orbit computations in

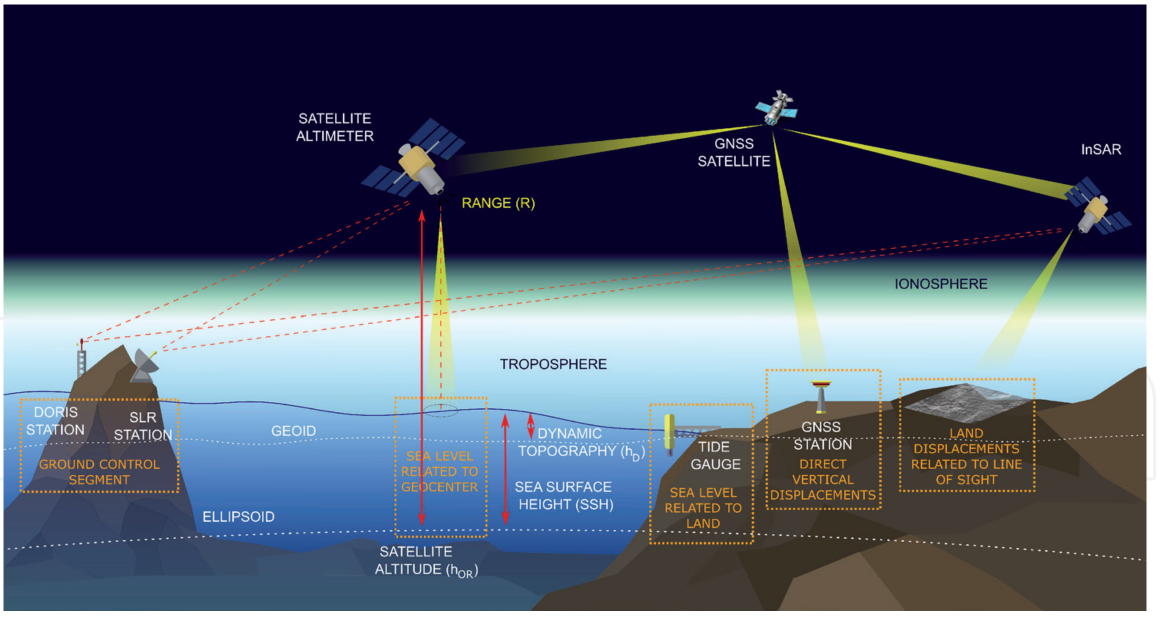

Figure 1.
Satellite altimetry and related observation systems (tide gauge sea level measurements, interferometric synthetic aperture radar (InSAR), GNSS (global navigation satellite system), Doppler Orbitography and Radiopositioning integrated by satellite (DORIS) and satellite laser ranging (SLR)) shown in integrated observation systems of the earth (adapted from [10]).

combination with satellite and ground-based tracking systems. Satellite altimeters are usually equipped with GNSS and DORIS receivers to ensure onboard satellite tracking. Some of the altimeters are additionally equipped with star trackers, which give altitude and position information when GNSS is not available [11]. The ground tracking system is most often based on satellite laser ranging (SLR) tracking methods that provide satellite position from a global network of observation stations.

Besides the on-board navigation devices and retroreflectors for laser tracking, satellites carry microwave radiometers, which usually operate on two or more frequencies. A radiometer is an instrument that measures radiant energy reflected from the oceans and serves to estimate the surface water vapor (see e.g., [12]). The measurements depend on surface winds, ocean and near-ocean air temperature, salinity, foam, and the absorption by water vapor and clouds [7].

As shown in **Figure 1**, satellite altimeters are measuring ranges relative to the center of the Earth, i.e., to the reference ellipsoid. Satellites are flying in known pre-defined orbits h_{OR} that are computed with respect to the fixed coordinate system hence enabling straightforward deriving of the Sea Surface Height (SSH), which is related to a reference ellipsoid, from a measured range (Eq. (3)).

$$SSH = h_{OR} - R = h_{OR} - \hat{R} + \sum_j \Delta R_j. \tag{3}$$

The analyses of the shapes of signals returned from the sea surface are used for derivation of the Significant Wave Height (SWH) information. SWH is defined as four times the standard deviation of sea surface elevation and it corresponds to the average crest-to-trough height of 1/3 of the highest waves [6]. Therefore, it is often denoted as $h_{1/3}$. Also, the sea roughness, which is correlated with surface wind speed can be estimated from the power of the returned signal.

For more details, please see [6, 7].

2.2 Previous and current satellite altimeter missions

Overall, the development of the satellite altimetry can be divided into three phases – (1) experimental, (2) modern, and (3) future phase (following [6, 9]). **Figure 2** present the timeline overview of the altimeter satellite missions launched during all three phases along with the origin of the satellite missions and their period of orbit repeating. The modern (current) era can be defined from the launch of the ERS-1 and TOPEX/Poseidon missions in 1991 and 1992 onwards. European ERS-1 was launched on July 17, 1991, into a sun-synchronous polar orbit (Francis, 1984) with three setups of repetitivity: 3-day, 35-day (the most used), and 336-day repeat cycle. The mission lasted till March 2000, exceeding its expected lifespan by far. To support ERS-1, ESA (European Space Agency) developed a satellite-based tracking system within Precision Range and Range-Rate Equipment (PRARE) mission and widespread ground segment that enabled:

- calibration of the radar altimeter to 10 cm using the ground-based laser retroreflector,
- real-time data acquisition,
- data processing and generation of fast-delivery products [13].

Data were disseminated as low-rate fast-delivery products and high-rate products via the Broadband Data Dissemination Network. At the same time, the efforts by NASA (National Aeronautics and Space Administration) and CNES (French National Centre for Space Studies) resulted in TOPEX/Poseidon mission, being the product of 20 years of technological and engineering development [14]. That satellite mission has revolutionized satellite altimetry by introducing the second altimeter frequency (C-band, 5.3 GHz) and the third frequency on the microwave radiometer (18 GHz), which enabled computations of ionospheric delay corrections, and removing of the effects of wind speed on measurements, respectively [14]. The mission provided high measurement precision of measured data with an

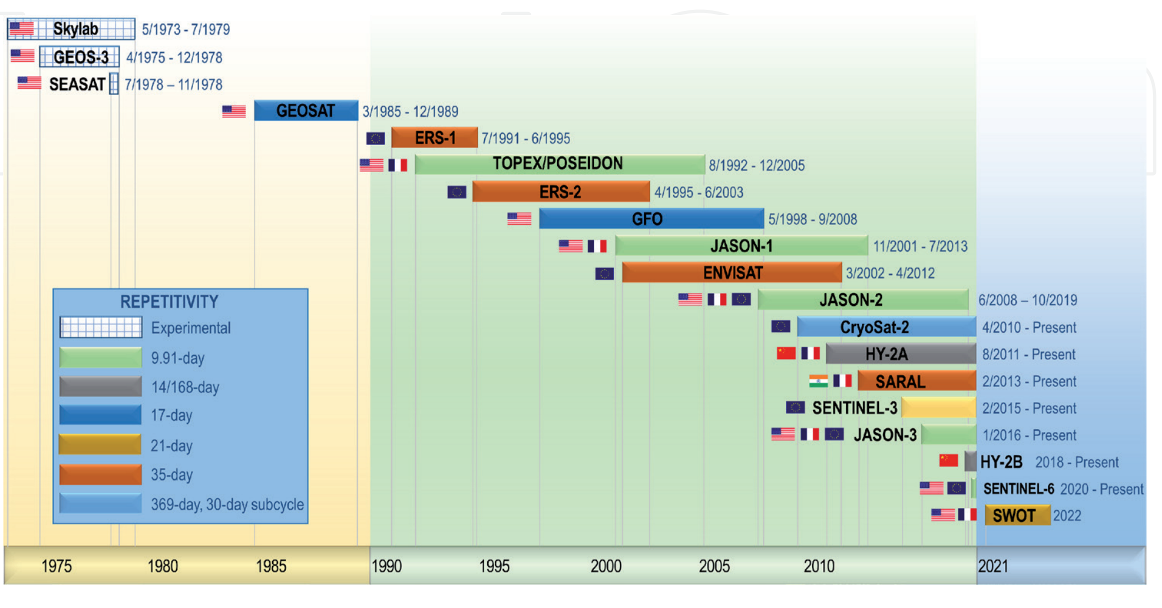

Figure 2.
Altimeter satellite missions' timeline overview divided into an experimental era (yellow), modern era (green), and future altimetry era (blue) along with the missions' orbit reportativity and information about their countries of origin (following and updating from [9]).

RMSE (Root Mean Square Error) of 2 cm and orbit accuracy estimated at around 2.5 cm (see [6, 9]). Later improvements of the TOPEX/Poseidon data processing based on its dual-frequency altimeter estimates of sea-surface height resulted in an overall precision expressed with root-sum-of-squares (RMS) of about 4 cm [6], which today is an expected accuracy of altimeter data from different satellite missions and can get up to RMS of 2 cm for open ocean altimetry [9]. The advances in orbit determination were due to the development of the DORIS satellite tracking system. DORIS was developed by CNES to determine the satellite orbits with centimeter accuracy from a network of 60 ground stations settled worldwide [15].

At present, several satellites are providing measured altimeter data:

- Cryogenic Satellite (CryoSat)-2 designed and built by ESA and launched in 2010,
- Haiyang (HY)-2a approved and led by China National Space Administration (CNSA) launched in 2011,
- SARAL launched in 2013 as a cooperative mission between the Indian Space Research Organization (ISRO) and CNES,
- Sentinel-3 launched in 2015 by ESA and operated by EUMETSAT,
- Jason-3 designed in collaboration of the NASA and ESA as the successor of TOPEX/Poseidon and Jason 1/2,
- Haiyang (HY)-2b launched as the second in the series of Chinese Haiyang satellites in 2018,
- and Sentinel-6 Michael Freilich (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.

Sentinel-6 satellite mission is currently in its commissioning phase, i.e., in the calibration/validation phase. **Figure 3** presents Sentinel-6 sea-level anomaly derived from 'Short Time Critical Level 2 Low Resolution' data, overlaid on a map showing similar products from the other Copernicus altimetry missions: Jason-3, Sentinel-3A, and Sentinel-3B (for details and original research, please see [17]). The background image is a map of sea-level anomalies from satellite altimeter data provided by the Copernicus Marine Environment Monitoring Service for 4 December 2020. The data for this image were taken from the Sentinel-6 products generated on 5 December 2020. Being in its commissioning phase, the measurements obtained by the Sentinel-6 are promising [17].

The characteristics of previous and current satellite missions are given in **Table 1**.

Surface Water Ocean Topography (SWOT) mission is planned to be launched primarily to enable terrestrial water monitoring. The mission is a joint project of NASA, CNES, the Canadian Space Agency, and the UK Space Agency. It is expected to operate in Ka-band with a 0.86 cm radar wavelength [18].

2.3 Advanced altimeter processing methods – retracking

Pulse-limited altimetry, often referred to as low resolution mode (LRM) altimetry, or traditional altimetry, is limited by the size of the radar surface footprint,

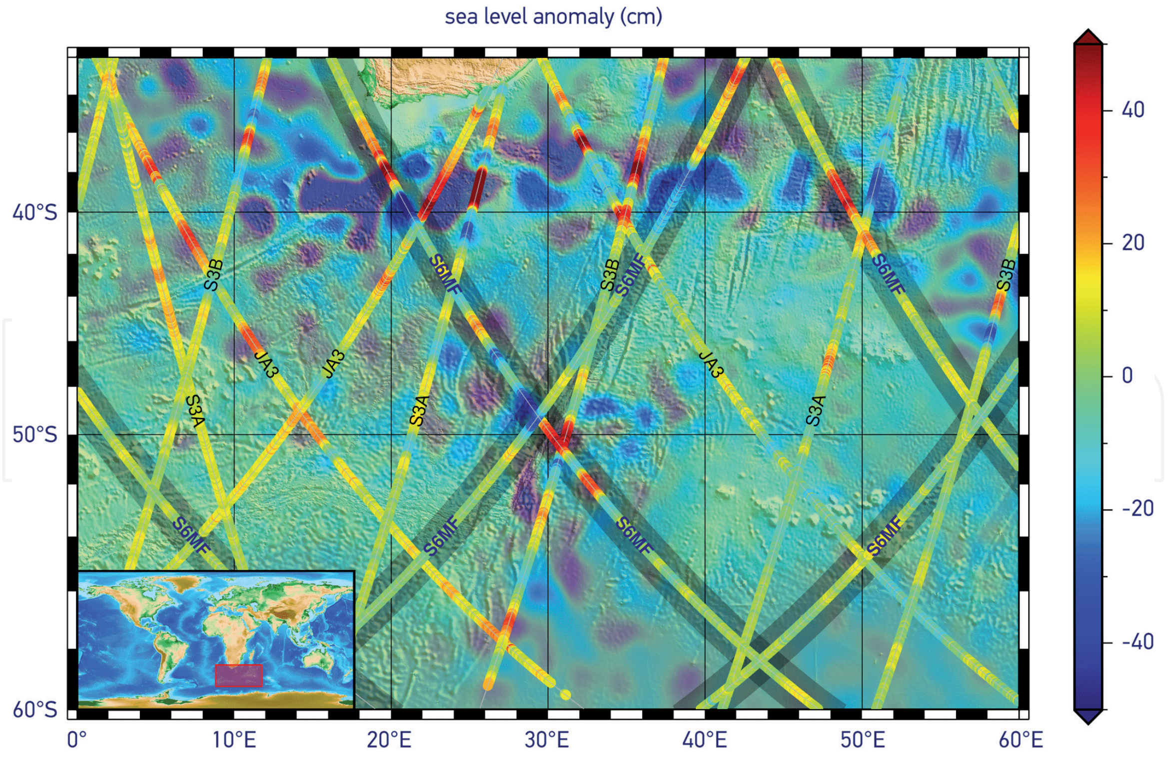

Figure 3.
Early Sentinel-6 measurements validation comparing to Jason-3, sentinel-3A, and sentinel-3B [16].

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 Jason-1/2/3 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.
An overview of the basic characteristics of satellite altimetry missions.

i.e., the size of the area illuminated by the radar from the satellite [6]. Depending on the SWH, the radius of the altimeter footprint can range from 1 km up to 7 km (e.g. for Jason missions), which enables high accuracy of the altimetry in open ocean areas, and on the other side, due to the contamination in the reflected radar altimeter signal caused by the land [19], lower accuracy in the coastal and inland areas (see e.g., [14]).

Significant efforts were done to overcome coastal altimetry issues through different projects, e.g., for the Mediterranean Sea projects were conducted such as ALBICOCCA (Altimeter-Based Investigations in Corsica, Capraia and Contiguous Areas), ALTICORE (Altimetry for Coastal Regions), COASTALT (Development of

Radar Altimetry Data Processing in the Coastal Zone), SAMOSA (SAR Altimetry Mode Studies and Applications), and the PISTACH (Coastal and Hydrology Altimetry product) [20]. The projects resulted in improvements of the onboard trackers and developments of the waveform retrackers. On-board trackers are devices used for the prediction of surface measurements thus enabling outlier detection and easier surface tracking [21]. The waveform retrackers work on the ground after the waveform data are downloaded from a satellite. The retrackers most often attempt to fit the model or function to the measured waveform to provide as accurate as possible results [21]. The retrackers integrate physical functions (such as the Brown ocean retracker) or empirical functions. Altimeter retrackers are further discussed in [22–27].

Different retrackers process different satellite mission data for different areas. For instance, ALES (Adaptive Leading Edge Subwaveform) is designed to be applied to Jason 1/2 and Envisat in both open ocean and coastal zones [27], X-TRACK retracker was designed particularly for coastal areas, ALES+ was later designed for the sea ice leads, coastal and inland waters [28], Goddard Space Flight Center (GSFC) designed several retrackers for ice areas [29], etc. Such retrackers nowadays enable utilizing of satellite altimetry in the coastal zones, and inland water areas. All the retracked data is available through the Coastal altimetry community [30].

2.4 Advanced altimeter processing methods – Delay-Doppler altimetry

One of the most significant recent developments in satellite altimetry technology was the introduction of the Delay-Doppler (DD) or SAR-mode altimetry that enables better observations of the small-scale features (below 50 km) and improved spatial resolution along the satellite track compared to conventional pulse-limited altimeters (see [31]). DD satellite altimeters employ the Doppler effect caused by the movement of the satellite in the along-track direction to improve the spatial resolution in the same direction [31] enabling the data sampling along-track e.g., up to 300 m for Sentinel-3. In other words, the altimeter footprint of the DD altimeters is reduced by an order of magnitude with respect to conventional altimeters – from a few kilometers up to a few hundreds of meters [32]. Hence, DD altimeters, such as those on the CryoSat-2 (SIRAL, SAR Interferometric Radar Altimeter), Sentinel-3 (SRAL, Synthetic Aperture Radar Altimeter), deliver more and/or improved data over the ocean, and, especially, in sea ice areas and coastal areas in general.

The SAR altimetry is based on the coherent processing of multiple echoes (e.g., 64 Ku-band pulses emitted by CryoSat-2 and Sentinel-3) within each altimeter burst (aperture duration of approx. 3.5 ms for CryoSat-2 and Sentinel-3), which enables resolving the reflected signals for along-track cells rather than the large footprints generated by the pulse limited altimeters. That naturally results in an improved resolution in the along-track (azimuth) direction of the satellite with the pulse-limited form that depends on the altimeter footprint maintained in the across-track direction (see [31, 32]).

Figure 4 presents the SAR technology and processing compared to the conventional satellite altimeters. The SAR processing includes counting for the along-track phase shift within each echo obtained from different radar burst, which depends on the geometry of the observation [31]. That produces the multiple echoes gathered at the same ground cell, which allows for the subsequent averaging (i.e., summing coherently) that increases the signal-to-noise ratio, i.e., it results in improved observations of the sea surface.

In [33] different studies on satellite radar altimetry pointed out that the SAR altimetry already performs better over the coastal zones than the conventional altimetry (see also [34]). They also emphasized the potential of the SAR technology

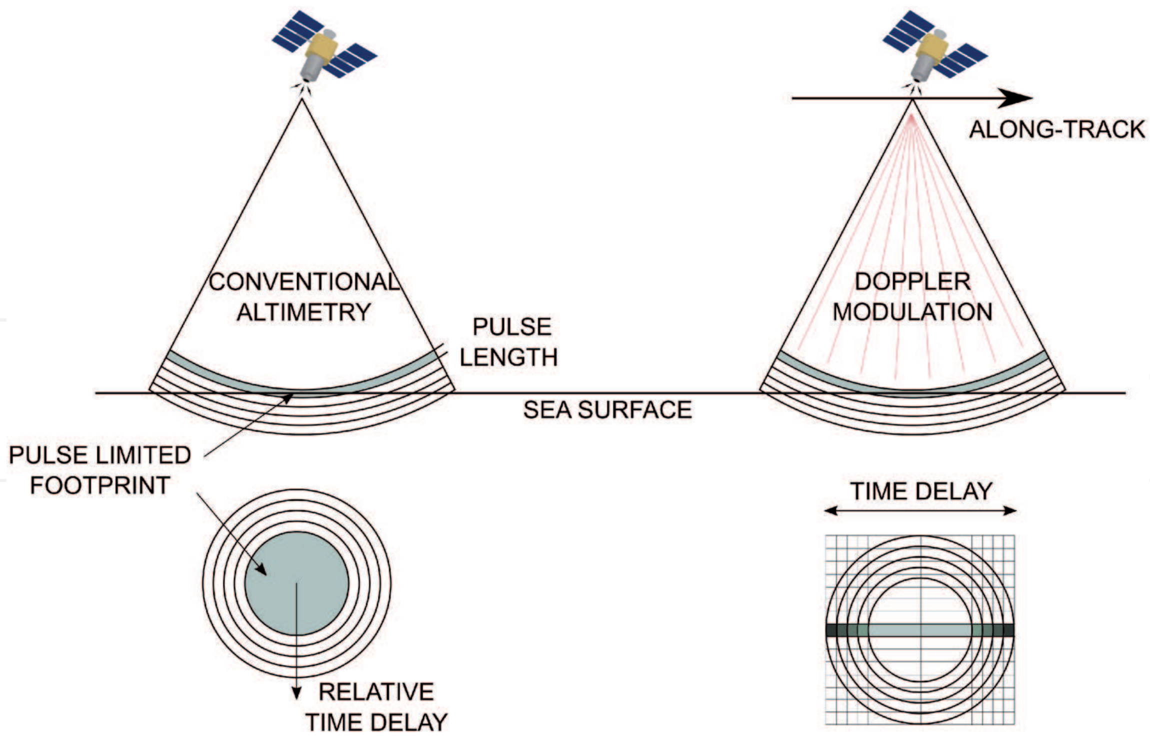

Figure 4.
Comparison of the principles of the conventional and SAR altimetry (adapted from the [7]).

for applications to inland water monitoring as well as the applications in cryosphere studies, such as measuring the ice sheet elevation change and sea ice freeboard.

2.5 Altimeter data download and processing

Altimeter data are available at different levels of complexity through different platforms and for various purposes. AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic Data) for instance offers gridded and along-track multi-mission altimeter data products (not) corrected for the geophysical effects and for different purposes [35]. Besides, AVISO offers access to Basic Radar Altimetry Toolbox (BRAT) software as well as the tools such as Marine Geospatial Ecology Tools (MGET). On top of that, through the Live Access Server (LAS), AVISO offers on-the-fly data visualization, metadata access, and quick comparisons of the measurements. For geodetic purposes, AVISO's most valuable products are related to the SSH, often upgraded to show ocean variability or cryosphere changes.

Near-real-time along-track satellite altimeter data are available also through the Jet Propulsion Laboratory (JPL) PO.DAAC Drive system (Physical Oceanography Distributed Active Archive Center). The data are delivered as a map or digital data, focusing on the SSH, wind speed, wave heights, and geostrophic velocity vectors [36].

Different products are also available from Copernicus Marine Service [16], which offers complete studies on sea-related topics. That includes original measurements, sea-level-related maps, and sea-level forecasts.

Finally, all the georeferenced source altimeter measurements and many corrections for the measurements are available through the RADS (Radar Altimeter Database System) [37]. RADS provides harmonized, validated, and cross-calibrated sea level altimeter data for the desired area and period of the observations, and it is probably the best place to start with the altimetry for the geodetic studies. Also, RADS offers data preprocessing and processing steps integrated within the system and available through the additional tools.

3. Altimeter products and study cases

A wide variety of satellite altimetry products cover many research fields. In the following section, we focus on presenting the application of altimetry in geodesy.

3.1 Sea-level change

Sea level change is studied as the global and local phenomena (**Figure 5**). Today, the global sea-level change is routinely computed from the altimetry for the period from 1992 onwards by AVISO, Commonwealth Scientific and Industrial Research Organization (CSIRO), University of Colorado Boulder (CU), NASA - Goddard Space Flight Center (GSFC), The National Oceanic and Atmospheric Administration (NOAA), and others. All the global research studies agree on the current sea level linear trend of approx. 3.2 mm/yr. although the processing methods could differ slightly. The estimates on the global sea-level change trends from satellite altimetry are regularly reported within the IPCC (The Intergovernmental Panel on Climate Change) reports that provide policymakers with regular scientific assessments on climate change. Several studies reported on the regional and local sea-level change, e.g., [39] consolidated the trends and expected sea-level change globally and for the ocean regions, [40] reported on the projections of the regional sea level for the 21st century, [41, 42] recomputed all satellite altimeter data to get more pronounced sea-level change estimates and a better perspective on the impact of future sea-level rise.

The satellite altimetry enabled finer detection of the current acceleration of global and regional sea-level rise. E.g., [38] reported on the climate-change-driven acceleration in sea level rise over the altimeter era, [43] investigated the regional sea-level rise during the altimeter era with previous studies done on uncovering the anthropogenic influence on the sea level rise in some regions [44]. With the climate change acceleration, monitoring of the sea-level change and its variation is going to be even more important. A future perspective on gauging the sea-level change and the needed improvements, both for the satellite observations and the terrestrial (tide gauge and other) measurements, is summarized in [45].

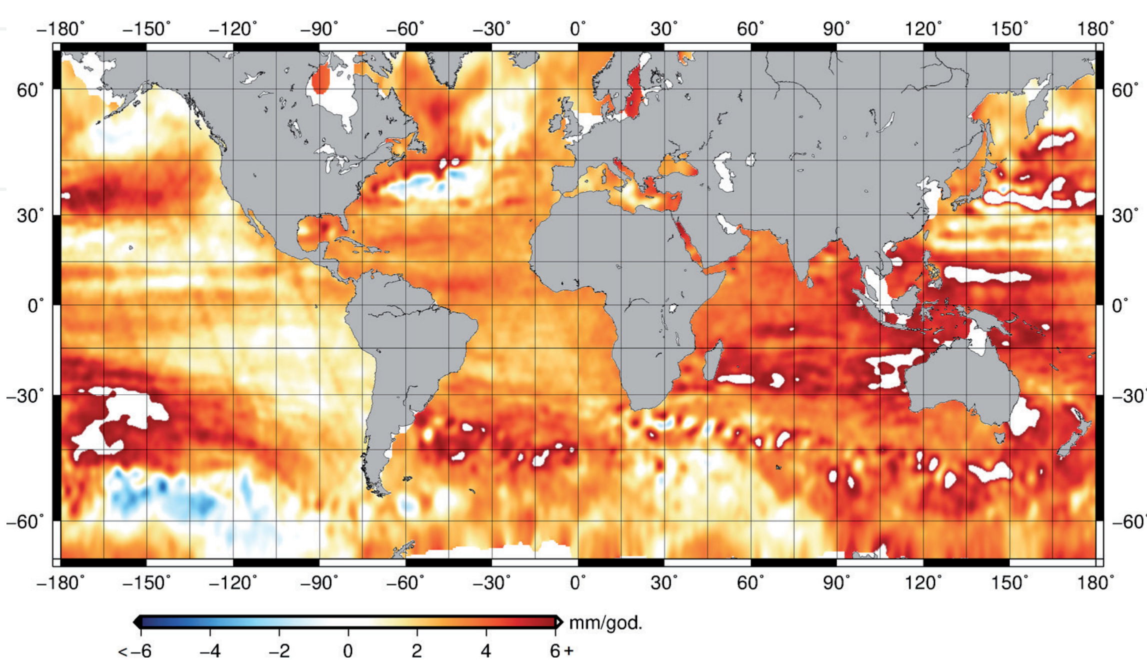

Figure 5.
Global Sea level trends (data downloaded from [38]).

The mean sea surface and its change are one of the bases for vertical height system modeling and implementation. A wide initiative on unifying the vertical height reference systems (for details see [46–48]) most usually encompasses absolute sea-level modeling from satellite altimetry extended for the tide gauge measurements at the coast (see e.g., [49]) along with the extensive analysis of vertical land movements, GNSS measurements, gravity estimations, etc. For such purposes, further progress in coastal altimetry and altimetry, in general, is crucial.

3.2 Gravity models

One of the basic geodetic tasks is determining the Earth's shape and size. The satellite altimetry gave an insight into the topography of the oceans, which later enabled the reconstruction of the Earth's gravity field over the oceans through gravity recovery. Gravity recovery stands for the geodetic operations and procedures of fitting the (altimeter) data to a gravity field that allows for the determination of the gravity information at any location [6]. Three standard procedures can be used to compute the gravity field from the altimetry: (1) employing the least-squares collocation on the altimeter measurements with the computed slopes of the sea surfaces along the satellite tracks or (2) along with the computed deflections of the vertical (e.g. [50, 51]), and (3) using the Vening Meinesz formula for the computations of the gravity field from the deflections of the vertical derived from satellite altimetry [52] (**Figure 6**).

Today, the global gravity field models are usually derived from gravity satellite mission(s) only or from combined observations (both ground and satellite data). When using combined data, satellite altimetry is most often included in

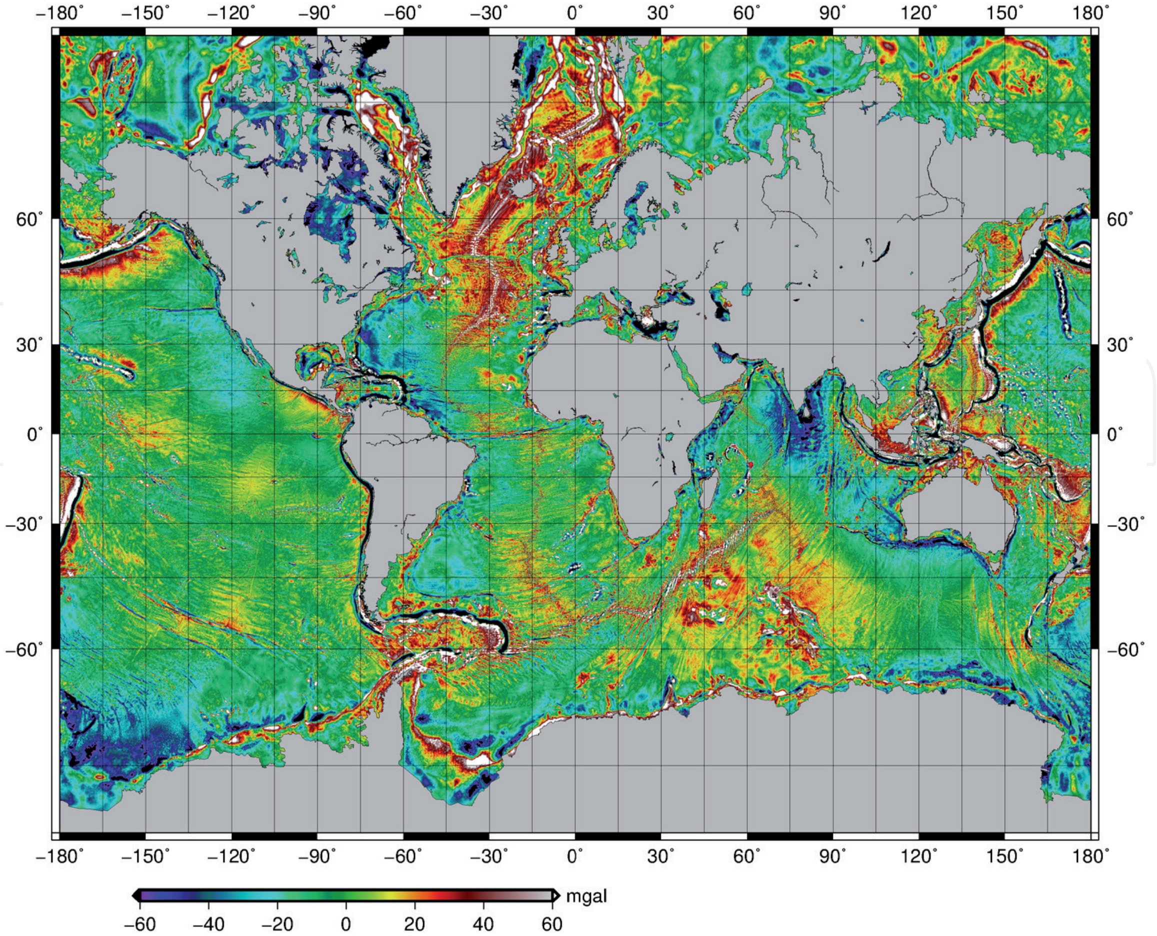

Figure 6.
Altimetry-derived global ocean gravity map (data downloaded from [53]).

modeling. Such combined models are, e.g., XGM2019e_2159 [54], GAO2012 [55], EIGEN-6C4 [56], and EGM2008 [57]. Models derived from altimetry only are given in, e.g., [53, 58].

3.3 Bathymetry

Due to the expenses of the traditional bathymetric measuring methods (e.g., weighted lines/poles), the information about the water depths and topography of the seafloor remained mainly unexplored over the open ocean until the utilization of satellite altimetry. Today, with the global and uniform coverage, satellite altimetry is crucial in computations of the global bathymetric models fulfilling the in-situ data gaps.

Predicting the bathymetry from the altimetry relies on the method developed in 1983 by [59], who have shown the potential of such modeling using the Seasat altimetry data. Over the years, the methods were further developed (e.g., [58]). Today most of the bathymetric models integrate the same altimetry-derived bathymetry. **Table 2** presents some of the most common global bathymetric models starting from the most recently updated: (1) GEBCO_2019 (The General Bathymetric Chart of the Oceans) [60], (2) SRTM15+ (Shuttle Radar Topography Mission: Global Bathymetry and Topography at 15 arcseconds) [61], (3) EMODnet (European Marine Observation and Data Network) [62], (4) SRTM30_PLUS [63], (5) S&S V19.1 (Smith & Sandwell) [59], (6) DTU10BAT (Technical University of Denmark) [57], and (7) ETOPO1 (National Oceanic and Atmospheric Administration's dataset) [64, 65].

Bathymetric models derived from satellite altimetry are not reliable enough for underwater navigation, construction works, or similar, as the errors of the bathymetric estimates sometimes exceeds 100 m but do offer general insight onto the seafloor topography and make the best available bathymetric data for many areas (see e.g., [60, 66]). **Figure 7** presents an example of the global bathymetric model.

3.4 Altimeter data with the other technologies and potential studies

As mentioned above, the satellite altimeter data for geodetic purposes can be integrated with tide gauges when estimating the sea-level change, with shipborne bathymetry obtained by echo sounders when modeling the bathymetry, and with discrete gravity measurements or satellite gravity when computing Earth's gravitational field. Furthermore, the satellite altimetry can be used to access the vertical land motion over the coastal area by comparing the sea level change trends from

Name	Year of issue/update	Resolution
GEBCO_2019	2019	15”
SRTM15 + V2.1	2019	15”
EMODnet	2018	1/16”
SRTM30_PLUS	2014	30”
S&S V19.1	2014	1’
DTU10BAT	2010	1′-2′ (Equator)
ETOPO1	2008	1’

Table 2.
Basic details on the most common global bathymetric models derived from satellite altimetry and shipborne data.

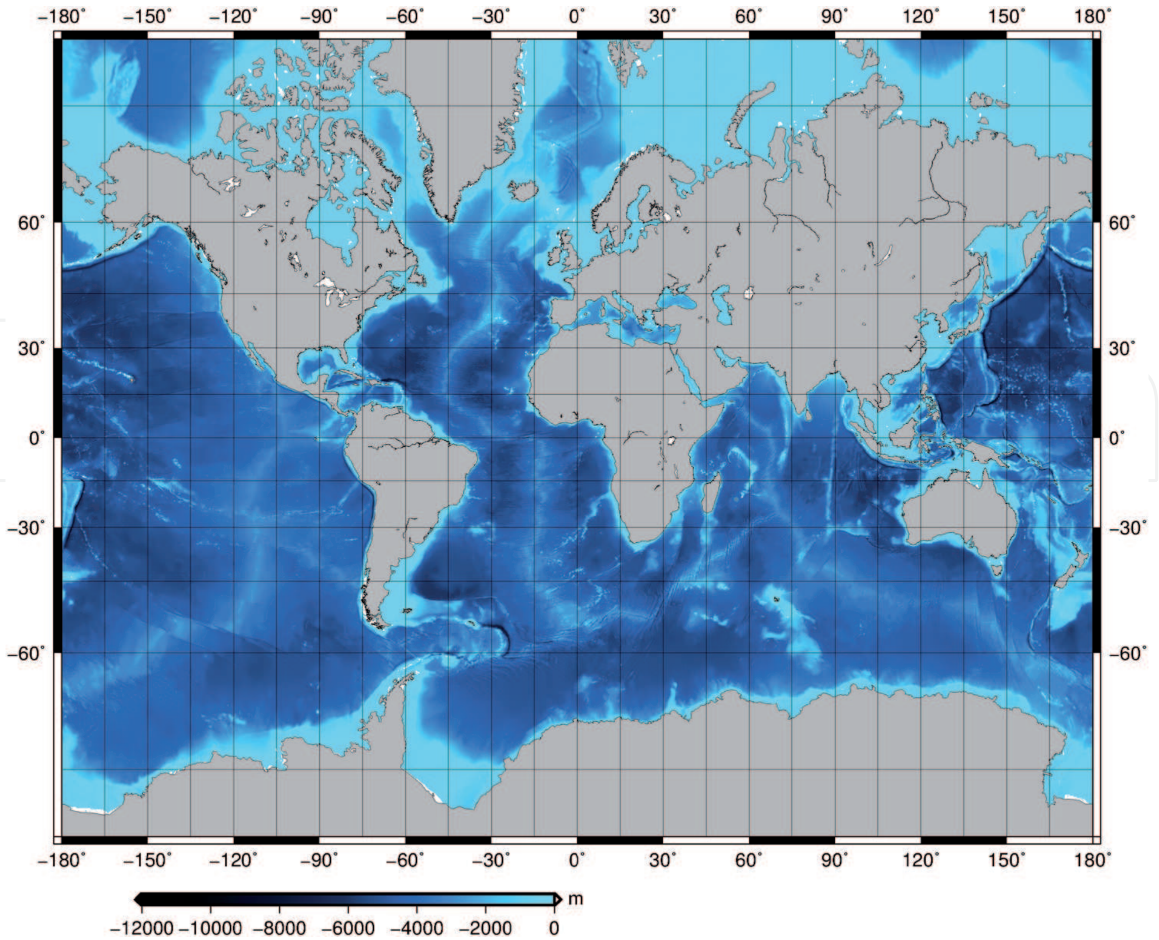

Figure 7.
Altimetry-derived global ocean bathymetric map (data downloaded from [53]).

satellite altimetry and from tide gauges where the latter obtain the trend accounted for the vertical land change (e.g., [10, 67, 68]). The altimetry can further be employed in multidiscipline-based early warning systems such as those forecasting the floods [69], or tsunamis [70], and the other climate-related forecasting systems that lead towards the operational oceanography, i.e., to the forecasting system of the sea-related variables such as sea level, temperature, and currents, based on the long-term routine measurements and real-time observations of the oceans and atmosphere (see e.g., [71]).

4. Conclusion

Satellite altimetry has proven over the years to be a reliable source of the information on the oceans. Many of the applications of the technology are related to the geodetic tasks, out of which some are almost exclusively reserved for geodesy (such as the gravity field modeling), and some are taking a great part in multidisciplinary research (e.g., as in the climate-related studies). The overview given in this book chapter summarized the theoretical basis of the technology, its evolution, and current developments with insight on the availability of different altimetry data and the ready-to-use altimeter products. The chapter could be a good starting point for diving into the geodetic or related research and practical studies on satellite altimetry.

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