Water surface elevation in coastal and inland waters using satellite radar altimetry

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Abstract

This chapter provides an overview of the satellite altimetry measurement system, how it works and how the water surface elevation is derived. Satellite altimetry had originally been designed for open ocean studies, however a decade of progress has significantly improved the retrieval of data in the coastal zone and inland waters. Advances in observational techniques (Ka-band and delay-Doppler/SAR-mode), revisited data processing and improved corrections led to a

higher accuracy in water surface elevation retrieval in these challenging areas. The available data sets with consistent coastal processing as well as the existing products dedicated to inland waters are presented including their potential accuracy for exploitation. The latest developments and capabilities of the various altimetric missions around coasts and inland are illustrated, with an emphasis on describing the benefits to studies of extreme events (heavy river discharge and storm surges). The future satellite altimetry missions such as Sentinel-3 and Sentinel-6/Jason-CS are expected to increase capabilities and coverage and represent a great opportunity to stimulate further exploitation of altimeter data in coastal and inland water targets.

1. Introduction and rationale

Changes in water surface elevation are traditionally measured in situ by single instruments at a fixed point, yielding a measurement relative to the land where the instrument is installed. Values are generally taken with frequent sampling (order of minutes or less). Such an instrument is called *tide gauge* in the ocean environment and more generically *water gauge* in lakes and reservoirs. In rivers, the instrument is usually called *stream gauge,* because the water surface elevation is then used to derive discharges. Several types of installations are in current use in the hydrometric practice (Vuglinskiy et al., 2009; WMO 2010), depending on the kind of water target.

Many databases around the world collect and make available water surface elevations. Concerning extreme events, there is a clear requirement for high-frequency (i.e. sampling at sub-hour intervals) information. The GESLA-2 (Global Extreme Sea Level Analysis version 2) database is an updated dataset of high-frequency water surface elevations obtained from tide gauges operated by many agencies around the world (Woodworth et al., 2017). Fig. 1 shows the geographical distribution of the 1355 stations presently available in GESLA-2.

Figure 1: Map of tide gauge stations with water surface elevations in the GESLA-2 dataset. Data from Woodworth et al., (2017).

Tide gauges are located in protected environments around world's coastlines and some ocean islands and therefore are often not representative of offshore conditions. The distribution of tide gauge stations is particularly sparse in some regions (e.g., Africa). In other regions (e.g., India) GESLA-2 does not contain data, although such measurements are done. Some countries provide free access only to a limited number of tide gauges for commercial reasons or security policies. Recently, the EuroGOOS Tide Gauge working group launched a survey collecting responses from 40 organizations operating tide gauge networks across Europe and adjacent countries. The results indicated 674 tide gauge installations existing in 2016, however, 25% of these stations have problems of funding in some way for maintenance with respect to previous years (EuroGOOS 2017).

Figure 2: Distribution of stations measuring water surface elevations produced by University of Texas at Austin, Center for Research in Water Resources (UT CRWR). Data available at Esri ArcGIS Online web map viewer (http://bit.ly/19fUSPY) from different data producers of inland water surface elevations, e.g., GRDC (yellow and violet) and USGS (blue) in US; CONAGUA in Mexico and ISPRA in Italy (green); HRC in New Zealand (cyan); INDRHI in Dominican Republic (red).

A similar scenario is evident with reference to inland water surface elevations. Fig. 2 shows the distribution of stations produced by University of Texas at Austin, Center for Research in Water Resources (UT CRWR). The map contains locations of several data producers of inland water surface elevations. There are thousands of stations measuring water surface elevation showed in Fig. 2, at least half of which are in the U.S. However, many stations have only historical data, some stations are quite old, others also contain recent data (GEOSS 2014). The number of reporting stations reached the top in 1979 and decreased sharply thereafter (see Fig. 1 in Ruhi et al., 2018). There are various reasons for this decrease, including the lack of funding to maintain the stations, impossibility to collect data or restriction to access them for political reasons.

The advent of satellite altimetry (Fu and Cazenave, 2000) made it possible to obtain global surface elevation measurements in water targets with low temporal sampling (at the moment every 10 days or longer). The measurements are taken along the ground tracks, i.e., the projection of the altimeter orbit on the Earth's surface. Radar altimetry has the particular advantage of providing measurements at locations where in-situ data are not available due to remoteness or lack of investment. Satellite radar altimetry is also capable of characterizing, with a long-term observational dataset, how water surface elevation variability evolves from the open ocean to the coastal zone and inland waters. Satellite altimetry was designed for open ocean, however, as shown later, more than a decade of R&D has permitted to extend the satellite-based water surface elevation records towards the coast (Vignudelli et al., 2011; Cipollini et al., 2017) and inland (Crétaux et al., 2017) with quality comparable to open ocean measurements.

One of the advantages of satellite radar altimetry is that measurements are collected globally in any weather conditions and regardless of the time of overpass. The coastal zone is affected by several local ocean processes, all impacting the sea surface elevation at different scales. Coastal dynamics has smaller spatial and temporal scales than open ocean and requires a monitoring at finer-scale that is difficult to satisfy with only sparse tide gauges.

The usage of altimeter data over inland waters was initially restricted to a limited number of large water targets, due to the large native footprint size of the radar altimeter. Over the recent years, the quality and quantity of data has been enhanced by refining the processing and therefore making the estimation of water surface elevations possible over much smaller water targets, as initiated by Berry et al. (2005).

This chapter aims at providing an overview of the satellite altimetry measurement system, with focus on the latest developments and possibilities offered by the various past, present and future missions to extract water surface elevations around coasts and inland. The chapter also discusses the potential usage of these measurements in applications, which will be then explored further in the second part of the book. Section 2 provides an illustration of how the satellite altimetry system works. Section 3 shows how the water surface elevation is extracted in open ocean conditions. Section 4 outlines the past, present and future satellite radar altimetry missions. Section 5 illustrates the main processing aspects regarding the coastal zone and inland waters applications. Section 6 provides an overview of the data sets available for usage in the coastal zone and inland waters. The improvements in quality and quantity are shown in

Section 7. Two case studies of extreme events are illustrated in Section 8 to demonstrate the benefits of using satellite-based water surface elevations. Finally, Section 9 summarizes the perspectives from coming satellite radar altimetry missions over coastal zone and inland waters and future developments of radar altimetry in these challenging domains.

2. The concept of satellite radar altimetry

In satellite radar altimetry, a radar on board a satellite sends a sequence of short electromagnetic pulses to the surface of the earth by a nadir-pointed antenna. The echoes returned by the illuminated surface are collected by the antenna and forwarded to the internal processing. The carrier frequencies of the main pulses used for the measurement are in the Ku- or Ka- microwave bands, interspersed with less-frequent pulses in the C- or S- bands, which are used for atmospheric correction purposes. The pulse sequences can be continuous or organised in bursts, and the pulse repetition frequency (PRF) depends on the specifications of the adopted radar and the objectives of the mission. As an example, the RA-2 sensor (Radar Altimeter-2) on board the Envisat satellite had a PRF of about 1800 Hz, with a continuous transmission scheme. The received signal is sampled at regular intervals (called “gates” or “range bins”), with a regular sampling during a fixed-length time window. The satellite altimetry community usually calls “waveform” the sequence of samples that is collected.

The time the radar pulse takes to travel from the satellite to the illuminated surface and back again is deduced from the waveform and then converted into a range measurement, i.e., the distance between the satellite antenna and the reflective surface. Over open ocean, the waveform has a characteristic shape that can be described analytically through the Brown model (Brown, 1977). The model assumes that the returned signal is a combination of elemental specular reflections uniformly distributed over the wave surface, and a wave height distribution given by the sea state.

The noisiness of each individual waveform is reduced by averaging multiple successive waveforms. Generally, until Sentinel-3 a number of waveforms were incoherently averaged on board the satellite, before being transmitted to the ground stations. With the advent of Sentinel-3, data are transmitted globally to the ground at full rate for the first time. Averaged measurements are delivered at reduced rates, typically in the range between 80 Hz to 1 Hz, which corresponds to 7 km of flight (in the case of 1 Hz), down to less than 100m (at 80 Hz rate) in the along-track direction.

In order to extract the relevant parameters (e.g. range, wave height, wind speed) a procedure called “retracking” is used. The procedure consists in fitting the theoretical Brown model to the collected waveforms and estimating the geophysical parameters by applying specific metrics (i.e., “estimators”) during the fitting procedure (Gommenginger et al., 2011).

Figure 3: Example of 18 Hz Envisat RA-2 ocean signal (black) and best-fitting signal after retracking (red) (adapted from from Gomez-Enri et al. 2009). The figure highlights how the location, slope and maximum amplitude of the waveform are related to range (hence sea level height, significant wave height and wind speed.

Fig. 3 shows an example of a real averaged waveform with a retracked waveform overlapped (red line). In particular, the range estimation is derived from the epoch (time delay) at midheight of the fitted function, the signal strength is related to the backscatter coefficient, which in turn depends on the wind speed at sea surface, and the leading edge slope is affected by the significant wave height (SWH). As it will be seen later in this chapter, the retracking procedure based on the Brown model is effectively applicable only to open ocean conditions, while in the coastal zone and for inland waters other approaches are proposed, based on specific model functions, fitting estimators and procedures.

The altimetric range estimated by retracking, needs to be further modified by several corrections, such as those needed to compensate for the variable delays introduced by the radiative transfer in the atmosphere. Range ($R_{altimeter}$) is usually corrected for the various effects with an equation of the form:

$$R_{corr} = R_{altimeter} + \sum R_{instr} + \sum R_{atmos} + \sum R_{surface}$$

where:

$\sum R_{instr}$ is the correction of instrument dependent errors (e.g., biases, drifts, delays).

$\sum R_{atmos}$ accounts for the path delays due to the atmospheric refraction. In particular, there are three main components of the delay and attenuation due to the radiation transfer in the atmosphere: the first originates from dry gases, the main contributor being Oxygen (O_2), the second one from water vapour (H_2O) and the third one from ionospheric electrons.

$\sum R_{surface}$ compensates for the error sources connected with the interaction between the electromagnetic signal and the reflective surface, e.g., sea state bias.

3. Water surface elevation in the open ocean

The estimated range is not directly usable in applications, as users generally want to measure the elevation of the sea surface relative to a reference. Such quantity is called Sea Surface Height (SSH). The reference system adopted in the satellite altimetry context is usually the ellipsoid, which is a rough approximation of the Earth's surface. The computation of SSH requires independent measurements of the satellite orbital trajectory. The distance of the satellite above the ellipsoid, called altitude (H), is determined by the Precise Orbit Determination (POD), a procedure that enables the acquisition of the orbit ephemeris (that is the three-dimensional location of satellite's centre of mass).

Figure 4: Schematic of the satellite radar altimetry system

Fig. 4 shows the satellite altimetry system. The SSH at a given instant is therefore calculated by subtracting the corrected range (R_{corr}) from the satellite altitude (H). The actual shape of the SSH results from different forcings. The Earth rotation, shape and mass distribution contribute to what is called the geoid, i.e. the equipotential gravity surface on which the water would relax if there were no other effects, which varies between –105 and + 85 m with respect to a reference ellipsoid. External forcing from the atmosphere (winds, pressure, solar heating, precipitation) and gravitational effects from the moon and the sun (tides) generate motions of the ocean resulting in a SSH topography that departs a few m from the geoid. By measuring SSH oceanographers can observe the signal due to these processes and in many cases isolate and monitor each process, as explained in detail in Fu and Cazenave (2000).

The satellite-based sea surface elevation differs from a point-wise elevation of the sea surface provided by a traditional shore-based tide gauge at a given location. Compared to in situ measurements of water surface elevations, the computation of satellite-based SSH therefore requires independent measurements of the satellite orbital trajectory and auxiliary information to correct for various effects (instrument errors, atmospheric refractions, perturbations caused by the surface interaction). Moreover, the SSH measurement is an average across the radar footprint (with a radius of 2 to 15 km according to sea state conditions). Some averaging is typical done in the along-track direction of the satellite in order to reduce the noise of individual waveforms.

When the ellipsoid reference is used, the larger signal captured in the sea surface elevation measurements is the geoid. However, for many applications the spatial resolution of the existing geoids is not sufficient. Nevertheless, the geoid is assumed to be constant at our time scales, suggesting focusing only on the variations of the sea surface elevation over time (i.e. the sea surface elevation anomalies). The SSH is therefore often given with reference to a Mean Sea Surface (MSS) and therefore expressed as a sea-level anomaly (SLA) or sea surface height anomaly (SSHA). The MSS can be computed by averaging SSH over several years at a fixed along-track ground point or using models that are based on SSH from all satellite altimetry missions over a given time period (e.g., Schaeffer et al, 2012; Andersen et al., 2015). Then, in practice the MSS is subtracted from SSH to compute SLA as SLA= SSH – MSS with SSH= H - R_{corr}.

Some applications require additional geophysical corrections to remove the signature of other geophysical phenomena. These phenomena include: (1) tides (ocean, solid earth, polar, loading tides) and (2) the ocean's response to the atmospheric pressure at low frequency (inverse barometric correction) and to the wind field at high frequency (dynamic atmospheric correction). These corrections can be done through the use of models. However, in the case of extreme events (e.g., storm surges), the interest is in the actual level the sea reaches, therefore the signals mentioned above are an integral part of the water surface elevation which results from the combined effects of ocean dynamics, tidal effects and atmospheric forcing.

4. Satellite radar altimetry missions

The development of satellite altimetry technology started in the 1970s. Fig. 5 shows the timeline of the historical altimeter missions, including those still operating at the time of writing.

Figure 5: Global satellite altimetry missions: past, now and then (Courtesy: PODAAC)

A total of ten altimeter missions have flown in the past. Generally, altimeter satellites are only operational for a limited number of years. The first altimeter was on-board the Skylab satellite in 1973 and was intended to measure the shape of the Earth (Marsh and Chang, 1976). Geos3 (1975) made measurements sufficiently accurate for geoid studies (Lerch et al. 1979). With Seasat (1978), the potential for ocean studies was shown (Tapley et al., 1982). Unfortunately the mission failed after only three months. The next satellite altimetry mission, Geosat, was launched in 1985 and was the first one to work for several years and produce the first routine ocean product (McConathy and Kilgus, 1987). However, the modern age of satellite radar altimetry with uniterruped global measurements started on 1991, with the first European satellite to carry a radar altimeter, ERS-1 (Andersen et al., 2013). This satellite was designed to have three different orbital configurations, including a 35-day repeat orbit lasting from April

1992 until December 1994. ERS-2 was launched on 1995 and operated simultaneously to ERS-1 shifted by 8 km, until ERS-1 was retired, in March 2000 (Andersen et al., 2013). The launch of TOPEX/Poseidon satellite mission in 1992 provided the greatest impetus for radar altimetry research in the 20th century (Fu et al., 1994). Its launch was followed by Jason-1 (2001), Jason-2 (2008) and Jason-3 (2016) over the same ground track pattern (Ménard et al, 2003; Lambin et al., 2010) known now as the ‘reference orbit’. US Navy Geosat Follow-On (known as GFO) was launched in 1998 (Walker and Barry 1997). ESA follow-up satellites were Envisat, launched in 2002 (Resti et al., 2009), CryoSat-2, launched in 2010 (Parrinello et al, 2018) and Sentinel-3 A and B flying since 2016 and 2018, respectively (Donlon et al., 2013). HY-2 (HaiYang, meaning 'ocean' in Chinese) is a marine remote sensing satellite series launched by China in 2011 (Jiang et al, 2012). AltiKa, the altimeter onboard SARAL mission (launched in 2013), is the first and so far the only one to operate in the Ka-band (Verron et al., 2015).

At time of the writing, there are seven altimetry satellites currently in service:

- two satellites, Jason-2 and Jason-3, with a relatively short repeat cycle (10 days), able to observe the same water target frequently but with relatively widely-spaced ground tracks (350 kilometres at the equator). Jason-3 is on the same ‘reference orbit’ as their predecessors, TOPEX/Poseidon (1992-2005), Jason-1 and Jason-2, with Jason-2 that has been shifted after launching Jason-3 on a new orbit, mid-way between its previous tracks, with a 5-day time lag;
- one satellite, CryoSat-2, with an altimeter (SIRAL) capable to work with a Synthetic Aperture Radar (SAR) mode (also known as Delay-Doppler processing mode) to satisfy the scientific requirements for observing the poles and the ice sheets, but also some

coastal and inland water regions with a drifting orbit (revising the same place after 369 days);

- two satellites, Sentinel-3A and -3B, with a longer repeat cycle (27 days) but tighter ground track spacing (around 100 kilometres at the equator) forming a constellation;
- one satellite, HY-2, which was for 2 years on a 14-day orbit with ground track spacing of 315 kilometres at the equator, and has then been moved from its nominal orbit to a drifting (i.e. non-repeat) orbit; and
- one satellite, SARAL, with AltiKa altimeter that had originally covered the old ERS/EnviSat 35-day repeat for more than four years and has then been moved to a drifting orbit.

Table 1: Main characteristics of satellite altimetry missions operating until now and planned for the future

The characteristics of past and present flying altimetric missions are given in the Table 1. The combined global altimetry historical data set begins in the early 1970. However, the older altimeter missions provided water surface elevations with low accuracy. The precise (and uninterrupted) era of altimetry started in 1991 with the launch of TOPEX/Poseidon and ERS-1. Thus, we have a potential situation at today that there is one long-term record since 1992 thanks to TOPEX/Poseidon and Jason 1/2 series that will continue in the same orbit configuration with the Jason-3 mission. At present, in addition to the Jason-3 mission, there are other six missions that provide complementary observations. Along-track resolution can be improved by utilizing new SAR techniques, as explained further in this chapter. SAR altimetry has been firstly tested with CryoSat-2 over selected portions of the ocean, and it is now definitely operational globally with Sentinel-3A&B.

Most satellite altimetry missions (e.g., ERS-1/2, Envisat, TOPEX/Poseidon, Jason-1/2/3, Sentinel-3A & -3B & -3C & -3D) have been designed to fly in repeat orbits for most of the time, which means that the satellite revisits the same geographical location after a certain period. Some missions were moved in drifting orbits for geodesy objectives for some limited periods (e.g., Geosat, ERS-1, Envisat, Jason-2 SARAL/AltiKa). The repeat orbit duration dictates the distance between ground tracks and therefore the cross-track spatial resolution. Table 1 shows that CryoSat-2 has the best cross-track spatial resolution, 7.5 km but at expenses of a 369 days repeat cycle, while at the other end of the spectrum we find TOPEX/Poseidon and Jason series with a wide cross-track spacing (350 km), but much faster repeat (every ~10 days). This series of missions provides, during 10 days, a global coverage but its coarse coverage resolution does not sufficiently sample the coastal zone and also misses several inland water targets. However, a large lake could be crossed several times during a cycle.

An example is Lake Issykul in Kyrgystan. Envisat is passing every 16 days with two ascending and descending tracks. It increases the temporal resolution that is a requirement during flooding. With reference to rivers, for each track crossing the river a water virtual time series can be formed and used. With satellite missions in drifting orbits (e.g., CryoSat-2) it would take 369 days to fly at the same location, so the time series approach cannot be applied. Drifting orbits provide the possibility to observe the same river in more locations at different times, but the changing over time of the river dynamics has to be taken into account. This calls for different usage when in synergy with modelling tools compared from those used for virtual water station time series.

CHAPTER

5. Altimeter processing in the coastal zone and inland waters

Satellite radar altimetry was originally designed for the open ocean domain. As on-board instrumentation and signal processing improved, new applications to coastal zones and to inland water targets became possible and continue to be researched, developed and exploited today. Indeed, the application of satellite radar altimetry to inland waters has the potential to provide a strong contribution to the hydrological sector.

As anticipated in Section 2, the radar signal reflected by water targets with surrounding land does not adhere to the typical Brown model, which characterizes open ocean waveforms. The altimeter maintains the received signal inside a fixed-length analysis window by using an onboard pre-tracker. The pre-tracker continuously adjusts the acquisition delay of the received signals, trying to keep the leading edge of the collected waveform (corresponding to the earliest return from water) tied to a nominal tracking point within the time window. A deeper explanation of this aspect can be found in Gommenginger et al., (2011). The presence of non-water targets (e.g., land, artificial structures, etc.) can introduce artifacts in the positioning and shape of the received waveforms. Thus, the signal contamination due to non-water scatterers may happen in the coastal zone and inland waters, resulting in inaccurate range estimations as a consequence.

Classical models for the radar altimeter waveform assume a homogeneous wave field and constant sigma-0. When approaching the coastline it is common to observe variable wave spectrum, variable wind and surfactant streaks, all contributing to the variability of the ocean backscatter. Ignoring such variability leads to errors in range computation, which the retracking algorithms need to mitigate. In standard altimetry products, data in the coastal zone are flagged as bad and left unused. Several dedicated retrackers have been developed to improve altimetry measurements near coasts (e.g., see Gommenginger et al, 2011 for a review), including the latest promising sub-waveform approach (Passaro et al. 2014; Roscher et al., 2017; Peng and Deng, 2018). But, modern altimetry using SAR mode already shows better coastal performance (Dinardo et al. 2018). Many studies also show improvements over inland water targets with the retracking of the waveforms from conventional altimeters (e.g., see recently Yuan et al., 2017; Huang et al., 2018) and from recent altimeters operating in SAR mode (e.g. see recently Villadsen et al., 2016; Moore et al., 2018).

Moreover, the corrections and auxiliary information are not optimized for the coastal zone, neither for inland water applications, and must be revisited in order to enhance accuracy. Another important point is that the combination of coastal morphology and local winds may produce calm water areas that appear to the radar as “bright targets”, as demonstrated in (Gómez-Enri et al., 2010; Scozzari et al., 2012).

Some data sets are already available for usage in the coastal zone and inland waters, currently oriented to big lakes and rivers, for what regards the hydrological applications. Specialised processing chains, including the usage of adaptive retracking scenarios based on machine learning, the usage of dedicated retrackers robust to signal contamination due to land, and the merging of multiple missions, are some of the particular features of the various products and services developed for hydrological applications. Section 6 of this chapter goes deeper into the illustration of these datasets. Like for oceans, hydrological applications imply calibration and validation requirements of needed reference measurements, as mentioned in Bonnefond et al.

(2011) and Crétaux et al. (2011).

The typical representation technique used to visually inspect the acquired data is called "radargram". Similarly to GPR (Ground Penetrating Radar) applications, the radargram for altimetry applications is a 2-D plot representing the reflection amplitudes versus time (or gate number) along the satellite track. In a radargram each waveform is projected onto a 2-D space where the x-axis represents the satellite position (along track) and the y-axis the range bin (or gate); signal amplitudes are represented according to an assigned colormap.

Fig. 6: Example of radargram taken in a descending orbit of Envisat across the Ligurian Sea. A sequence of Brown-shaped returns can be identified between the two dashed red lines.

Fig. 6 shows an example of radargram taken in a descending orbit of Envisat across the Ligurian Sea. A sequence of Brown-shaped returns can be identified between the two dashed red lines. The remaining of the radargram clearly shows the effect of land interference, even when the satellite track is over the sea but close to the coast, like in the proximity of Corsica Island. The ground projection of the satellite orbit is shown in the inset of Fig. 6.

Figure 7: Example of radar echo impacted by presence of land

Land interference as observed in the radargrams is also apparent by analyzing single waveforms. Fig. 7 shows two waveforms derived from the RA-2 altimeter on board Envisat satellite, demonstrating how the radar echoes may be impacted by the presence of land. In this example, the Envisat satellite track is almost perpendicular to the coastline of Make-jima, a small island in Japan (Abileah et al., 2013). The waveform shown in the upper panel was obtained by incoherent averaging of N = 1984 raw waveforms (about one second at Envisat's Pulse Repetition Frequency, PRF). It deviates from Brown's theoretical model, being characterized by a double-peaking feature due to land contamination to the signal.

An improvement is expected by coherent summing and exploitation of Doppler velocity for beam sharpening, like it happens for SAR techniques. In Abileah et al. (2013) the possibility to do coherent sums at relatively low PRF was demonstrated, and a simplified method was proposed, named "zero-Doppler", because it uses only a zero-delay, thus ignoring the off-nadir backscatter. The zero-Doppler velocity method produces a much improved waveform by reducing the land interference (Abileah et al., 2013).

As mentioned in the previous section, CryoSat-2 carries the first radar altimeter (SIRAL) that uses the SAR technique. The SAR altimeter sends a burst of coherent pulses, which are combined (i.e., coherently summed) and organised in Doppler beams by partitioning in Doppler frequency bins. In this way, the surface footprint is split into narrow across-track strips from which sharper returns (waveforms) are obtained. As a result, a higher along-track resolution (~300 m) is achieved (Raney, 1998), leading to the ability of resolving shorter-scale surface features with respect to conventional radar altimetry. In order to ensure coherence of the returned signals, SIRAL operates at a PRF of 17.8 kHz. Following the pathway opened by CryoSat-2, the current Sentinel-3 constellation carries a SAR altimeter (SRAL); also the future Sentinel-6 / Jason-CS mission due for launch after 2020 will be equipped with a SAR altimeter.

The RA-2 instrument offers a global archive of Individual Echoes (IEs), i.e., raw waveforms collected at the native sampling rate of 1795 Hz (which is the instrument's PRF). RA-2 worked with a continuous pulse transmission scheme, like it is expected from the upcoming Sentinel-6 mission. In Abileah et al., (2017) it was demonstrated that most rivers and small-to-medium sized lakes exhibit specular echoes, which have a well-defined Doppler evolution and can be processed with the SAR technique for water level estimation.

Figure 8: Example of radar echo impacted in narrow river

The radargram in Fig.8, obtained by a dataset of Envisat IEs, shows the evidence of bright specular echoes when the satellite orbit is crossing a tiny river (about 50 m large) in three distinct points, demonstrating the possibility to detect and range even such relatively small water targets. Such investigation, made by using RA-2 data, supports very much the perspectives of SAR altimetry applications to inland water.

Improvements may also be obtained by working in the Ka-band (shorter wavelength than Ku). The SARAL mission carries AltiKa (see Section 4 of this chapter), the first altimeter operating in such band. The usage of Ka-band enhances the spatial resolution, both in terms of smaller footprint and in terms of narrower range bins, thanks to the larger bandwidth with respect to Ku-band altimeters. These happens at the expense of a higher uncertainty due to the attenuation and propagation delays introduced by the water column in the atmosphere, to which the Ka-band is more sensitive than Ku.

6. Data sets available for usage in the coastal zone and inland waters

Data acquisition from the different altimetry satellites is performed by each space agency. There are four levels (from Level 0 to Level 4) of processed data depending on their processing stage. Space agencies generate a suite of altimeter products. Their availability depends on how long it takes to produce them. Three classes are usually considered: i) products available to users within a few (e.g., 3) hours after data sensing; ii) products available to users after a few (e.g., 3) days; and ii) products available to users after weeks. The main output of Level 2 processing stage is the GDR (Geophysical Data Record) product. It usually exists in different versions, the main difference among them laying in their temporal availability and therefore in the different quality of the corrections (geophysical or engineering calibration) and orbits. The GDR product is normally generated at the rate of 1 Hz (i.e. a record every ~7 km). It usually contains all the altimeter data and connected corrections to compute the SSH or SLA. Some corrections come directly from the altimeter, some from the other on board instruments, or other instruments; others from models, or a combination of all the former. The main output of Level 1 processing stage is the SGDR (Sensor Geophysical Data Record) that users require when they like performing their own retracking. The product is designed to supply both the GDR level output and the waveforms at the rate of 18/20 Hz (i.e. a waveform every ~0.35 km).

Every satellite mission has its own record format of products. Many “off the shelf” products, whether distributed on DVD or available online through FTP, become almost immediately out of date due to the continuous improvement in corrections and processing. Variety of sources of data components, together with improvements in processing, can change in time, giving rise to improved versions becoming available. AVISO for CNES and PO.DAAC for NASA are the official facilities to process and distribute the up-to-dates suite of satellite altimetry products in netCDF format. Both services offer free access to these products in NRT and off-line for light

(L4), advanced (L2, L3) and expert (L1) users.

The above dissemination services have been designed with the open ocean in mind. They remain the source especially for altimetry specialists. Most users may not be aware of, or have access to, the latest updates and most appropriate corrections to use for their application (Snaith et al., 2006). RADS (Radar Altimeter Database System) was the first service in which an user can select and combine altimeter data and models from various external sources 'on the fly' (Scharroo et al., 2012) and recompute the updated SLA. RADS is maintained by Delft Technical University and NOAA. It provides a harmonised, validated and cross-calibrated multi-mission L2/L3 database, including all up-to-dated corrections, auxiliary information, in consistent format, and reference frame common for all altimeter missions. The multi-mission data set is accessible at http://rads.tudelft.nl/rads/rads.shtml .

The use of satellite altimetry in coastal zones and inland waters requires specialized processing that takes into account the typical problems of these regions. The PISTACH (Prototype Innovant de Système de Traitement pour l'Altimétrie Côtière et l'Hydrologie) project generated a product that includes all possible corrections and source data, including values from a number of different retracking scenarios (Mercier et al., 2010). This approach provides a wealth of detailed information for the technical specialist, but results in very large products, which are the domain of the expert. The COASTALT project had a similar approach, generating a product with a range of re-tracking scenarios and possible corrections,
with data only generated for coastal areas (Vignudelli et al., 2011). Only those corrections that can be calculated globally were included in the standard product and users were able to add regional specific corrections to provide a more tailored solution.

A decade of progress in improving processing made possible the availability of experimental and operational products dedicated to the monitoring of coastal and inland waters. Compared to standard products they include higher along track resolution, new/improved retrackers, new/improved corrections, refined pre-processing and/or post-processing,

Table 2: Available altimeter datasets for usage in the coastal zone (adapted from Cipollini et al., 2017). Updated table with links at www.coastalt.eu

Table 2 (adopted from Cipollini et al., 2017) summarizes the main characteristics of the available products for coastal zone. The following section provide more information on some specific products, i.e., CTOH, ALES, COSTA, X-TRACK, PEACHI, GPOD SARvatore, highlighting their main characteristics. A data set with consistent coastal processing for all available missions is not yet available.

The CTOH is a French observation service dedicated to satellite altimetry studies (Birol et al., 2017). It maintains homogeneous altimetric databases (L2/L3) for the long-term monitoring of sea level. The reprocessing involves an ad hoc editing strategy of the data records and a careful extrapolation/interpolation of missing or imperfect corrections of the altimetric measurement in the coastal strip.

ALES is a dataset retaining all the fields in the SGDR with the addition of new re-tracked fields (range, SWH and backscatter) from the ALES algorithm (Passaro et al., 2014). It is available along track at a resolution of around 350 m for Envisat, Jason-1, Jason-2 and AltiKa missions in the global coastal strip within 50 km from the coastline (Passaro et al., 2015). COSTA is a post-processed version for particular geographic location (Mediterranean Sea). in which raw data are already corrected and assembled on nominal tracks in the form of SLA time series (Passaro 2017).

X-TRACK has been developed by CTOH for different altimetric missions and regions. It is essentially a standard product at an along track resolution of 7 km, assembled on nominal tracks in the form of SLA time series, that is extended to the coastal zone with an improved editing and post-processing (Birol et al., 2017).

The recent G-POD service called SARvatore (SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation) is a web platform that allows any scientist worldwide to process on-line, on-demand and with a user-selectable configuration both CryoSat-2 and Sentinel-3 data in SAR mode using a dedicated re-tracker for coastal zone and obtaining an along-track data set that is spaced every approximately 350 m (20 Hz) or 87 m (80 Hz) (Dinardo 2014; Dinardo et al., 2015).

As stated previously, due to the processing complexity in inland waters, the know-how is restricted to few expert groups that, however, sponsored by various agencies, now offer water height products derived from the satellite radar altimeters. Water heights are computed as time series over lakes and over rivers at the intersections with the satellite ground tracks (the so-called virtual stations).

The PISTACH product is also available for inland waters, with specific processing, developed by CLS (Satellite Location Collection), in which retracking is based on the classification of typical waveforms occurring in inland water bodies. A number of products have been developed to provide freely accessible water elevation time series for selected targets. There are some products now freely accessible (e.g., River & Lake, Hydroweb, DAHITI, HydroSat) providing water heights over rivers and lakes. There are two additional databases that provide water heights only over lakes (AltWater and G-REALM).

The Rivers and Lake project (http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main) developed by ESA and Montfort University used mainly ERS-2/Envisat (2002-2010) and Jason-2 (2009 to 2011) satellite altimetry to provide historical and Near-Real Time water surface elevations data for a large number of virtual water stations around the world. The waveforms at resolution higher than 1 Hz are processed using the re-tracking expert system reported in Berry et al. (2005), based on different retracking algorithms that are adapted to changes in target type and waveform shape (Berry et al, 1997). Around 750 water targets with 35-day sampling and 57 with 10-day sampling are available (Berry and Wheeler, 2009).

HydroWeb was developed at Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS). The historical data set is accessible at http://ctoh.legos.obs-mip.fr/products/hydroweb. Based on historical and present altimeter data, Hydroweb provides time series over water levels of about 100 lakes and 250 sites on large rivers (Crétaux et al., 2011). Hydroweb is now a fully operational service on the CNES/THEIA Platform at http://hydroweb.theia-land.fr/?lang=en&. The Hydroweb approach is to use standard products and combine different missions that fly over the water target to enhance precision and temporal sampling.

DAHITI (Database for Hydrological Time Series of Inland Waters) is developed by the Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM) and provides virtual station time series from multiple missions over lakes, rivers and reservoirs. The data set is accessible at http://dahiti.dgfi.tum.de/en/. DAHITI uses all the available altimetry missions, including data back to 1992 with TOPEX/Poseidon, with a processing strategy based on an extended outlier detection and a Kalman filtering (Schwatke et al., 2015).

HydroSat is developed by University of Stuttgart, Institute of Geodesy (GIS). It provides water height time series from satellite altimetry over some rivers along with other remotely sensed or derived variables, as surface water extent and discharge (Tourian et al., 2016). The data set is accessible at http://hydrosat.gis.uni-stuttgart.de/php/index.php.

AltWater (Altimetry for inland Water) was developed at DTU space (National Space Institute, Technical University of Denmark) under the FP7 project Land and Ocean Take Up from Sentinel-3 (LOTUS). Currently, the database only contains water heights obtained from CryoSat-2 for a limited number of lakes (Nielsen et al, 2016), but other missions are planned to be added in the future. The main difference consists in the reprocessing of the CryoSat-2 waveforms, which is not performed in the processing chain of the other services. The processing methodology is described in Nielsen et al. (2015). The data set is accessible at http://altwater.dtu.space

G-REALM (Global Reservoirs/Lakes) is developed by the United States Department of Agriculture’s Foreign Agricultural Service (USDA-FAS), in cooperation with NASA and the University of Maryland (Birkett et al., 2017). It provides near-real time data from multiple missions that are utilized to routinely monitor lake and reservoir changes in water surface elevation. The data set is available at https://www.pecad.fas.usda.gov/cropexplorer/global_reservoir/. G-REALM is based on standard retracking algorithms provided in standard products at 18/20 Hz and provides indicators that help to assess quality of the measurements in challenging conditions (e.g., presence of islands in lakes; dry beds, presence of ice, etc.). It keeps the satellite missions separate.

The G-POD service also allows users to process, on line and on demand, low-level CryoSat-2 and Sentinel-3 Altimetry data products (FBR, Level 1A) in SAR mode up to Level-2 geophysical products with self-customized options that are not available in the default processing of CryoSat-2 and Sentinel-3 Ground Segments (Dinardo 2014; Dinardo et al., 2015). The service is open, free of charge and accessible on line at https://gpod.eo.esa.int/services/CRYOSAT_SARand https://gpod.eo.esa.int/services/Sentinel-3. It provides water surface elevations at the rates of 20 Hz and 80 Hz.

A detailed description of the data processing methods used to generate the altimeter-derived water elevation time series available in the previous databases can be found in the references. The above products may differ for processing approach and applied geophysical corrections.

CHAPTER

7. Improvements in accuracy

Water surface elevations derived from satellite altimetry require to be quantitatively self-consistent and have a certified accuracy and/or precision. Their validation is complicated by the fact that satellite radar altimetry relies on a combination of different types of measurements (range, orbit and corrections). The traditional approach is using a different (independent) dataset, e.g., comparison with different altimetry missions at crossover points or against in situ measurements at close sites. The method to compare satellite altimetry and in situ measurements is not unique and depends on the region and goals of the usage of altimeter data.

Comparisons with in situ water surface elevations can be done in a relative sense, i.e., taking into account the variations over a certain time period. Satellite-based time series near the station are usually constructed and then compared to the time series obtained from the in situ instrument. Comparisons can be done using monthly averaged, daily or near-simultaneous measurements. The frequent in situ observations are generally subsampled to the time of the altimeter overpass.

Extreme events occurring on the ocean and inland waters (e.g., storm surges and flooding) are short-term phenomena, therefore, the near-simultaneous comparison method between satellite altimetry and in situ observations is the more appropriate. The usage requires computing the accuracy of the satellite-based water surface elevations in order to discriminate the anomalous raised value with respect to the background. The relative total altimetric time series would be similar to those observed by the in situ instrument. Because the two time series are generally from spatially separated points, the residual time series will contain differences, which result from the two different locations where the in situ and altimetric data are made.

In fact, the satellite altimeter and in situ station can only overlap by chance. Therefore, the two systems do not necessarily observe the same area. The root-mean-square error (RMSE) is commonly used as an indicator of accuracy. It should decrease in points in close proximity to the station and will indicate if the water surface elevations are within the acceptable threshold, e.g., for assimilation in storm surge models.

Table 3: Accuracy statistics from validation studies in coastal zone using satellite radar altimetry

Table 3 summarizes a list of recent papers aiming at the validation of coastal altimeter products near the coast. The authors generally use three statistical parameters for the comparison against the tide gauges: RMSE, Standard Deviation of the differences (SD) and Correlation Coefficient (R). Comparisons were made in coastal areas all around the world using different satellite missions. RMSE values range between 3.8 cm (Jason-2) and 89 cm (ERS-2) with R between 0.45 (Jason-1) and 0.99 (SARAL/AltiKa, Jason-1, Envisat). The ocean variability at the location of the in-situ instruments and their distance to the tracks justify some of the differences in the observed accuracy. The use of different retracking algorithms, editing strategies, geophysical corrections also play their role.

The retrieval of water surface elevations of inland water targets (lakes, reservoirs and rivers) has a much wider variability of measurement conditions than the coastal zone.

Table 4: Accuracy statistics from validation studies in inland waters using satellite

radar altimetry

Table 4 provides a selection of papers regarding different sites, showing accuracy statistics of water surface elevation products, all generated by satellite radar altimetry. The RMSE estimates vary from few cm (e.g., Lake Vättern) to about a meter (e.g., Zambesi River). The resulting accuracy is certainly influenced by the characteristics of the site. However, the inland water altimetry products are processed by different research groups, using different algorithms (e.g., re-tracking, corrections, editing), so the satellite-based water surface elevations from the various products might have different resolutions, accuracies and errors. Some comparisons of different inland products against water surface elevation measurements in selected sites can be found in Schwatke et al. (2015) and Ricko et al. (2012).

As shown by Abileah et al. (2017), the behavior of water as a reflector is a function of the along track size of the water target. In particular, the size of the water target determines the number of radar echoes returned from the water that can be usefully averaged, to remove speckle. The aperture of the main reflection lobe originating by the illuminated surface determines the length of the satellite track in which the altimeter can collect a strong enough signal for range measurement. By applying basic electromagnetic theory, Abileah et al. (2017) demonstrated that the size of the main lobe first decreases with the increasing size of the water target, then, at some point, the relationship reverses and the lobe width increases with the size of the target, with a turning point at about 100 m in size. Other factors (e.g., water vapor, wind set up, presence of ice, tides, waves) can also impact range and corrections.

8. Case-studies of extreme events

CHAPTER

Extreme events due to meteorological phenomena can produce a rise in the water surface, which can be considerably larger than other background signals. Theoretically, water surface elevations observed by radar altimeters should reflect these transient signals. However, due to the low revisit time there is a low probability of flying over the event at a given location. In addition, abrupt height changes are usually assumed to be associated with erroneous data and are rejected by standard editing methods. Increasing the temporal and spatial coverage by altimetry would require more satellites flying together, with, optimally, coordinated orbital patterns. In the next sections, the potential of satellite altimetry in retrieving surface elevations is showed in presence of strong river discharges and storm surges.

8.1 Strong river discharges as observed by satellite SAR altimetry

The effect of heavy freshwater discharges in river estuaries is of interest in the altimetry community. It represents the transition zone between inland waters and coastal zones. Fresh waters from rivers reduce the salinity levels in the ocean surface adjacent to the river mouth and hence might give a bulge in sea level (González-Ortegón and Drake, 2013; González Ortegón et al., 2010; Navarro et al., 2012). An example of the capabilities of CryoSat-2 SRAL (in SAR mode) to measure this bulge is presented here. The study area is located in the eastern continental shelf of the Gulf of Cadiz (south-western Iberian Peninsula) close to the estuary of the Guadalquivir River. The time period analysed was from 7 December 2010 to 17 January 2011. During that period the river was in extreme conditions with daily averages of water discharges larger than 400 m^3/s (Diez-Minguito et al., 2012). The analysis of CryoSat-2 tracks available in the adjacent shelf of the estuary showed one descending track (absolute orbit #3884: 1 January 2011). The availability of optical RGB MODIS images (Terra) (from AERONET: http://lance-modis.eosdis.nasa.gov/imagery/subsets/?project=aeronet) gave only one cloud-free image (04-01-2011).

Figure 9: a) Heavy river discharges in the estuary mouth of the Guadalquivir River (Spain); b) RGB MODIS image (Terra) 4 January 2011 and example of CryoSat-2 track flying on 1 January 2011 near estuary; c) Along track water surface elevations relative to a Mean Sea Surface from CryoSat-2 passages around the peak discharge

Fig. 9a shows the daily average of water discharges during the extreme event. Fig. 9b presents the RGB MODIS image showing the turbidity plume due to the heavy fresh water river discharge. The surrounding area is characterised by a diffuse plume due to the mixture of the discharged water with the surrounding waters. The profile of the along-track 20 Hz SLA is presented in Fig. 9c. SLA data were smoothed with a running mean of five 20 Hz measurements. A clear bulge of about 15 cm is clearly seen in the SLA profile over the continental shelf. The analysis of the same track at different 369-day cycles under no extreme conditions of water discharges is shown in Fig. 9a. The smoothed SLA profiles confirmed that the bulging shape was observed only during the event of heavy river discharge (1 January 2011). More details of the response of CryoSat-2 SLA 20 Hz measurements during heavy river fresh water discharge can be found in Gómez-Enri et al. (2017). Daily gridded maps of SLA from multi-mission satellites were also used to analyse the sea level response to river discharge in Gómez-Enri et al. (2015).

8.2 Storm surges as observed by satellite altimetry

Satellite altimetry is not routinely used for storm surge services yet, although a possible inclusion was strongly recommended by Cipollini et al. (2010). A review of the available literature shows that there are open questions on how to use these data. Some studies demonstrated the capability of satellite altimetry of observing and studying storm surge features, e.g., during Hurricane Katrina (Scharroo et al. 2005), Hurricane Sandy (Lillibridge et al., 2013), Hurricane Igor (Han et al, 2012), Cyclone Xaver (Fenoglio et al., 2015), Hurricane Isaac (Han et al., 2017), Typhoon Seth (Li et al., 2018). Some assimilation experiments indicate that the improvement compared to tide gauges is rather limited as a consequence of getting good quality near-real time data (e.g., Philippart and Gebrrada 2002). Other investigations suggest that altimeter data could become beneficial if used in the initialization phase (e.g., Peng and Xie, 2006) or for validation of storm surge model outputs (e.g., Høyer and Bøvith 2004). European Space Agency (ESA) through the eSurge Venice Project supported the usage of satellite altimetry to improve storm surge simulations through data assimilation in the Adriatic Sea and around Venice (De Biasio et al., 2016; De Biasio et al., 2017).

Figure 10: Along track total water surface elevations (inclusive of tides and wind/pressure effects) relative to a Mean Sea Surface from satellite altimetry overpasses around the storm surge event of 31 October 2004. Data from CTOH database at http://ctoh.legos.obs-mip.fr/

An example is given in Figure 10, which shows the satellite overpasses (Jason-1 and Envisat) crossing the Adriatic Sea around the storm surge of 31st October 2004. The signature of the surge is clearly evident in the Jason 1 overpass on 30th October 2004. This figure is just an example of how the other altimeter tracks can be eventually used to correct the model results (Bajo et al., 2017).

CHAPTER

9. Future satellite radar altimetry missions in support of coastal zone and inland waters

With the advent of the along-track Delay-Doppler (SAR) processing, first implemented in CryoSat-2, and now in Sentinel-3A & -3B, more accurate surface elevations from satellite radar altimetry are anticipated for coastal and inland waters. The future satellite altimetry missions are expected to increase capabilities and coverage and represent a great opportunity to stimulate further exploitation of altimeter in coastal and inland water targets. A number of satellite missions are planned (Fig. 6), in particular: Sentinel-6 (to be launched 2020), Sentinel-3C & -3D (2021~2023, to replace Sentinel-3A & -3B), SWOT (2021).

The Sentinel-6 mission program (also known as Jason Continuity of Service (Jason-CS)) consists of two identical satellites (Sentinel-6A and Sentinel-6B), each one with a nominal lifetime of 5.5 years and a planned overlap of at least 6 months. The satellites will fly in the same orbit as its predecessors (TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3) to continue the fundamental climatic record. Sentinel-6 will be operating in SAR mode everywhere (Scharroo et al., 2016). The Sentinel-6 missions will also maintain the quality of products from its predecessor Jason-3 mission. The next decade will see also the launch of Sentinel-3 C/D that will follow-up Sentinel-3 A&B to guarantee the continuity of water level measurements for the operational needs of Copernicus program (ESA 2017).

An important aspect of Sentinel-6 to highlight is the continuous high-rate pulse mode, like Envisat IEs but at a higher rate than its predecessor. The advantage of IEs is that complex waveforms can be coherently summed (Zero-Doppler, see Section 5) around the nadir crossing point of a narrow water body. Coherent averaging increases the accuracy of level estimation

(Abileah et al., 2017).

CryoSat-2 and Sentinel-3 transmit pulses only 1/3 of the time and wait 2/3 of the time for pulses to be received (Scharroo et al., 2016). The Individual Echoes produced by the Envisat RA-2 platform (Resti et al. 1999) represent now the only currently available dataset for the experimentation of continuous coherent processing on real data.

SWOT is a research mission under a joint effort between the US National Aeronautics and Space Administration (NASA), the French Space Agency (CNES), the Canadian Space Agency and the United Kingdom Space Agency, that is scheduled for launch in 2021 (Rodriguez et al., 2017; Rodriguez 2016). The primary instrument on SWOT is a Ka-band radar interferometer (KaRIn) (Fjortoft et al., 2014). KaRIn will illuminate the surface with two 50 km swaths and separated by a 20 km nadir gap. Inside each swath, the intrinsic pixel resolution will vary from 10 m to 60 m in the across-track direction and will be at best around 2 m along-track (Chevalier et al., 2017). The SWOT revisiting time is ~21 days, during which sites will be observed 2-4 times at irregular intervals, depending on the location latitude (Biancamaria et al., 2016). For the first time, SWOT brings together both hydrology and oceanography communities, and will extend the satellite-based record of water levels into coastal environments, at land-ocean interface (e.g., estuarine regions) and over inland water targets (e.g., rivers, lakes, reservoirs). While SWOT is not designed to monitor the fast temporal changes of extreme events (e.g., storm surges, flash floods, etc.), the swath coverage and its resolution will permit to better characterize the spatial structure of their dynamics when they occur within the swath. SWOT data, regardless of latency, will be valuable for post event re-analysis as well as model calibration and development (Hossain et al., 2017).

It is expected that advances in technology (e.g., reflectometry) or emerging concepts (CubeSats and miniaturization) will provide new complementary capabilities of collecting water surface elevations. For example, a novel approach that uses wideband signal of opportunity (SoOp) in a bistatic radar configuration is considered to address issues in coastal altimetry (Shah and Garrison, 2017). Small satellite designs were already proposed (Kilgus et al. 1989; Zheng 1999; Richard et al., 2008). A CubeSat concept for ocean altimetry was proposed by Stacy (2012) and also considered by the US Navy (Mroczek and Jacobs, 2015). At present there are still technical challenges to measure water heights with the previous approaches, however, the potential benefits would be substantial.

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Figures

Figure 1: Map of tide gauge stations with water surface elevations in the GESLA-2 dataset. Data from Woodworth et al., 2017).

Figure 2: Distribution of stations measuring water surface elevations produced by University of Texas at Austin, Center for Research in Water Resources (UT CRWR). Data available at Esri ArcGIS Online web map viewer (http://bit.ly/19fUSPY) from different data producers of inland water surface elevations, e.g., GRDC (yellow and violet) and USGS (blue) in US; CONAGUA in Mexico and ISPRA in Italy (green); HRC in New Zealand (cyan); INDRHI in Dominican Republic (red).

Figure 3: Example of 18 Hz Envisat RA-2 ocean signal (black) and best-fitting signal after retracking (red) (adapted from from Gomez-Enri et al. 2009)

Figure 4: Schematic of the satellite radar altimetry system

Figure 5: Global satellite altimetry missions: past, now and then (Courtesy: PODAAC)

Figure 6: Example of radargram taken in a descending orbit of Envisat across the Ligurian Sea. A sequence of Brown-shaped returns can be identified between the two dashed red lines.

Figure 7: Example of radar echo impacted by presence of land

Figure 8: Example of radar echo impacted in narrow river

Figure 9: a) Heavy river discharges in the estuary mouth of the Guadalquivir River (Spain); b) RGB MODIS image (Terra) 4 January 2011 and example of CryoSat-2 track flying on 1 January 2011 near estuary; c) Along track water surface elevations relative to a Mean Sea Surface from CryoSat-2 passages around the peak discharge

Figure 10: Along track total water surface elevations (inclusive of tides and wind/pressure effects) relative to a Mean Sea Surface from satellite altimetry overpasses around the storm surge event of 31 October 2004. Data from CTOH database at http://ctoh.legos.obs-mip.fr/

Tables

Table 1: Main characteristics of satellite altimetry missions operating until now and planned