Remote Sensing of Environment 201 (2017) 148–164

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

STAR: Spatio-temporal altimeter waveform retracking using sparse representation and conditional random fields

Ribana Roscher*, Bernd Uebbing, Jürgen Kusche

Institute of Geodesy and Geoinformation, University of Bonn, Nußallee 15 + 17, 53115 Bonn, Germany

ARTICLE INFO

Keywords:
Coastal
Oceans
Altimetry
Retracking
Sea surface heights
Conditional random fields
Sparse representation

ABSTRACT

Satellite radar altimetry is one of the most powerful techniques for measuring sea surface height variations, with applications ranging from operational oceanography to climate research. Over open oceans, altimeter return waveforms generally correspond to the Brown model, and by inversion, estimated shape parameters provide mean surface height and wind speed. However, in coastal areas or over inland waters, the waveform shape is often distorted by land influence, resulting in peaks or fast decaying trailing edges. As a result, derived sea surface heights are then less accurate and waveforms need to be reprocessed by sophisticated algorithms. To this end, this work suggests a novel Spatio-Temporal Altimetry Retracking (STAR) technique. We show that STAR enables the derivation of sea surface heights over the open ocean as well as over coastal regions of at least the same quality as compared to existing retracking methods, but for a larger number of cycles and thus retaining more useful data. Novel elements of our method are (a) integrating information from spatially and temporally neighboring waveforms through a conditional random field approach, (b) sub-waveform detection, where relevant sub-waveforms are separated from corrupted or non-relevant parts through a sparse representation approach, and (c) identifying the final best set of sea surfaces heights from multiple likely heights using `Dijkstra's` algorithm. We apply STAR to data from the Jason-1, Jason-2 and Envisat missions for study sites in the Gulf of Trieste, Italy and in the coastal region of the Ganges–Brahmaputra–Meghna estuary, Bangladesh. We compare to several established and recent retracking methods, as well as to tide gauge data. Our experiments suggest that the obtained sea surface heights are significantly less affected by outliers when compared to results obtained by other approaches.

1. Introduction

For several decades, radar altimetry is routinely being used for monitoring sea surface height (SSH) variations. Observed SSHs play a key role in several applications, ranging from operational oceanography (Chelton et al., 2001) and tidal modeling (Savcenko and Bosch, 2008; Wang, 2004) to gravity estimation (Hwang et al., 1998), and they serve as important indicators in climate research. Recently, radar altimetry in coastal zones (Gommenginger et al., 2011) and for inland water bodies (Birkett and Beckley, 2010) has become a topic of increasing interest. However, in both applications one needs to mitigate the potentially significant land influence on the altimeter return signal.

The altimeter instrument on-board a satellite emits a spherically propagating, nadir-directed radar pulse, which is reflected at the surface. Range information can then be inferred from the two-way travel time (Fu and Cazenave, 2001). In addition, the returned signal energy is measured over time, forming an altimeter waveform. It can be shown that over an ideal surface, the return waveform corresponds to the theoretical Brown model (Brown, 1977) and the estimated shape parameters of this model provide information on mean SSH and significant wave height (SWH), while the amplitude strength of the reflected radar pulse can be used to derive wind speed. On board the satellite, the waveform signal is sampled at discrete epochs with a spacing of about 3 ns of two-way travel time, which are generally referred to as range gates (Chelton et al., 1989). Altimeter measurements do not refer to an individual point directly below the satellite, but rather to a footprint with a diameter of several kilometers, depending on SWH and the altitude of the altimetry mission.

As illustrated in Fig. 1, the return waveform over the open ocean consists of three main parts; first, before any return energy from the radar pulse is measured, the waveform contains only thermal noise which is present in all radar systems. As soon as the front of the radar pulse hits the wave crests, the altimeter footprint is defined by a single point and the measured return energy begins to rise. Afterwards, more of the pulse illuminates the surface around the initial point and the footprint becomes a growing circle, which corresponds to rapidly

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.rse.2017.07.024
Received 9 October 2016; Received in revised form 1 July 2017; Accepted 21 July 2017

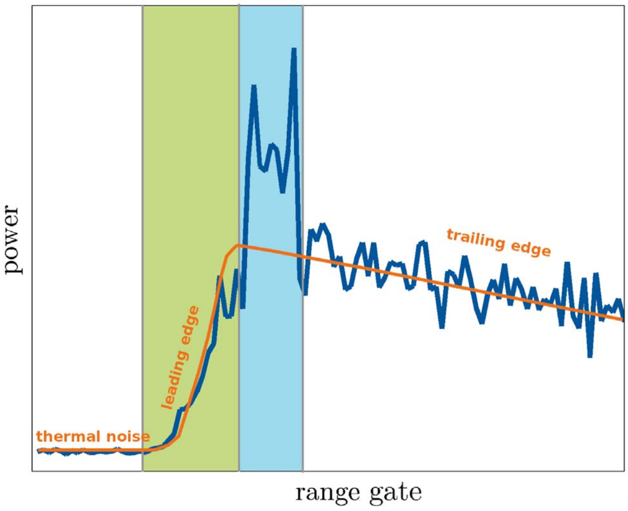

Fig. 1. Waveform with disturbing peak caused by land influences (colored in blue). The relevant part for sea surface height, determined by sub-waveform detection, is illustrated in green. A theoretical waveform model is depicted in orange. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

increasing signal energy in the measured altimeter waveform. The leading edge of the altimeter return waveform is defined between the first energy return from wave crests and the return energy after the radar pulse has reached the wave troughs (Fig. 1). At this point. the area of the footprint circle reaches its maximum, which is defined as the pulse-limited footprint (PLF, Chelton et al., 1989). Afterwards, the circle transforms into an annulus with increasing inner and outer radii, but with a fixed illuminated area. The corresponding signal energy measured outside of the PLF is referred to as trailing edge of the measured waveform (Fig. 1). The slope of the trailing edge can be utilized to derive information on the off-nadir attitude of the altimeter satellite.

The 50%-point on the leading edge corresponds to the mean sea level between wave crests and wave troughs, and thus represents the reference point for the range measurement. An algorithm on board of the satellite tries to position this point inside a pre-defined range window at a fixed tracking range gate (31 for Jason-2, Quartly et al., 2001). This range window consists of a fixed number of range gates, covering about 50 m depending on the satellite mission, and it is positioned by the onboard tracker based on prior information on the range. However, positioning is not always perfect and the 50%-point is not located exactly at the tracking gate. Consequently, this requires a ground-based reprocessing of the altimeter waveforms transmitted back to Earth, a procedure which is called retracking. Over the open ocean, the shape of the waveform will be close to the theoretical Brown model with the 50%-point being only slightly shifted from the tracking gate position, and this can be easily corrected using an ocean model retracker (Brown, 1977; Deng, 2003; Hayne, 1980). For ice surfaces where the waveform signal often contains two leading edges due to the radar signal partly penetrating through the upper snow layer, specialized retracking algorithms have been developed (Martin et al., 1983). However, in coastal areas the waveform shape is typically disturbed by land influences in the altimeter footprint, resulting in peaks or fast decaying trailing edges.

These deviations of coastal waveforms from the Brown model lead conventional ocean retrackers to generate diverging or strongly biased estimates of SSH, as land-induced peaks propagate along the trailing edge towards the leading edge while the altimeter ground track approaches the coast (Lee et al., 2010). In order to mitigate the land influences on the waveform shape, various tailored approaches have been proposed. As an example for methods that seek to model the entire waveform, (Halimi et al., 2013) combined a 3-parameter Brown ocean model with a modeled asymmetric peak to account for land influences. A different approach for dealing with the influence of peaks on the retracked estimates is to first partition the waveform in a pre-processing step; i.e. to identify relevant parts of the waveform, such as the leading edge, but also possible peaks. For example, (Hwang et al., 2006) first identify relevant sub-waveforms and then apply a threshold retracking algorithm to each of the sub-waveforms, which leads to multiple equally likely SSH estimates at each location from which the final estimate is chosen based on comparison to a-priori height information. In this way, peaks that appear outside of the relevant sub-waveforms are ignored. Recently, for retracking SSHs over inland water bodies, (Uebbing et al., 2015) combined the sub-waveform approach from (Hwang et al., 2006) and the waveform model from (Halimi et al., 2013) to suppress land-induced peaks on the trailing edge, but also to account for possible peaks close to the leading edge of the waveform. This could be shown to lead to improved lake heights compared to conventional methods. In a different approach, (Passaro et al., 2014) suggested a two-step procedure, similar to a previously published approach by Sandwell and Smith (2005), where in the first step all 3 parameters (amplitude, range and SWH) are estimated. In the second iteration they fixed the SWH to a mean value derived from the first step and re-estimated the amplitude and range correction, since SWH estimations are strongly correlated to the range correction. This leads to improved SSHs closer to the coast.

Here, we introduce a novel method for the analysis of sea surface heights from altimetric waveforms, which will utilize spatial information from neighboring range gates within one waveform, as well as temporal information from neighboring waveforms along the altimeter track. This Spatio-Temporal Altimetry Retracker (STAR) can be applied to altimetry data over the open ocean, as well as in coastal areas. Our contributions are twofold: First, our analysis includes a novel sub-waveform detection scheme, which to our knowledge for the first time integrates spatial as well as temporal information. This differs from the conventional sub-waveform detection algorithm (Hwang et al., 2006) in that we partition the entire waveform into separate sub-waveforms, instead of identifying possible, disjointed leading edges. Second, in order to be largely independent of the choice of tuning (or 'hyper') parameters within the sub-waveform detection scheme, we derive multiple sub-waveform partitionings by varying the weight w between unary and binary terms of the conditional random field. This leads to a range of partitionings of the entire waveform, and subsequently to a point cloud of equally likely SSHs at each measurement position, each of which is estimated using a 3-parameter ocean model (Halimi et al., 2013). We then employ `Dijkstra` algorithm (Dijkstra, 1959) to find reasonably smooth SSHs, without resorting to fitting.

Our sub-waveform detection scheme uses a sparse representation (SR) approach, where the return power at all range gates within one particular sub-waveform is modeled by a weighted linear combination of a single common set of basis waveforms, which are derived from synthetic Brown waveforms. The concept of SR has been applied to many areas of signal analysis (Wright et al., 2010), but this study appears to be the first which uses it on radar altimetry.

SSHs and other sea surface conditions such as wave height are neither independent along tracks, nor between neighboring tracks Sandwell and Smith (1997). Spatial information has been used in the analysis, for example, by Maus et al. (1998) through simultaneously processing of a sequence of waveforms for tracking of travel times, or Halimi et al. (2016) for a smooth estimation of altimetric parameters. This means, the integration of spatial information can be carried out in different parts of the analysis. The latter two approaches, for example, integrate spatial information about neighboring waveform to develop improved estimation algorithms for retracking. Here, we integrate spatio-temporal information by means of a conditional random field (CRF, Lafferty et al., 2001): to this end, we introduce spatial relations between the return power at range gates of temporally neighboring