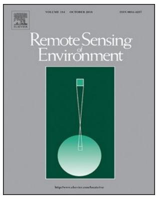
Remote Sensing of Environment 218 (2018) 245–254

Contents lists available at ScienceDirect

Remote Sensing of Environment

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



Improving the precision of sea level data from satellite altimetry with high-frequency and regional sea state bias corrections

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ARTICLE INFO

Keywords:
Satellite altimetry
Sea state bias
Sea level
Retracking

ABSTRACT

The sea state bias (SSB) is a large source of uncertainty in the estimation of sea level from satellite altimetry. It is still unclear to what extent it depends on errors in parameter estimations (numerical source) or to the wave physics (physical source).

By improving the application of this correction we compute 20-Hz sea level anomalies that are about 30% more precise (i.e. less noisy) than the current standards. The improvement is two-fold: first we prove that the SSB correction should be applied directly to the 20-Hz data (12 to 19% noise decrease); secondly, we show that by recomputing a regional SSB model (based on the 20-Hz estimations) even a simple parametric relation is sufficient to further improve the correction (further 15 to 19% noise decrease).

We test our methodology using range, wave height and wind speed estimated with two retrackers applied to Jason-1 waveform data: the MLE4 retracked-data available in the Sensor Geophysical Data Records of the mission and the ALES retracked-data available in the OpenADB repository (https://openadb.dgfi.tum.de/). The regional SSB models are computed parametrically by means of a crossover analysis in the Mediterranean Sea and North Sea.

Correcting the high-rate data for the SSB reduces the correlation between retracked parameters. Regional variations in the proposed models might be due to differences in wave climate and remaining sea-state dependent residual errors. The variations in the empirical model with respect to the retracker used recall the need for a specific SSB correction for any retracker.

This study, while providing a significantly more precise solution to exploit high-rate sea level data, calls for a re-thinking of the SSB correction in both its physical and numerical component, gives robustness to previous theories and provides an immediate improvement for the application of satellite altimetry in the regions of study.

1. Introduction

Satellite altimetry measures the distance between the sea surface and the satellite (range), but this first estimate needs to be corrected for a number of geophysical effects, prior to being used for sea level estimation. The sea state bias (SSB) is among the time-variable corrections that are applied to sea surface height estimates from satellite altimetry. With a mean of 5 cm and a time-variable standard deviation of 2 to 5 cm in the open ocean (Andersen and Scharroo, 2011), it is currently one of the largest sources of uncertainty linked with the altimetric signal (Pires et al., 2016).

Previous studies have usually identified different effects that play a role in the SSB. The first, the Electromagnetic (EM) bias, is strongly dependent on the significant wave height (SWH) in the viewing area of the altimeter, and is due to the different backscattering of troughs and crests of the waves, which causes the EM range (what the altimeter actually measures) to be biased towards the troughs in comparison with the mean sea level (Fu and Cazenave, 2001).

The second contribution is known as "Skewness Bias", which is related to the notion that the algorithms (retrackers) that are used to fit the altimetric waveform assume that the vertical distribution of specular reflectors illuminated by a radar altimeter is Gaussian, while their actual probability density function has a non-zero skewness.

The third contribution, historically called Tracker Bias, is actually a sum of errors related to the way the altimeter tracks the returning echoes. This contribution plays a role in the total SSB correction due to the empirical way in which this is estimated. Despite a few attempts to produce a theoretical description of the EM bias, e.g. Elfouhaily et al. (1999), any SSB correction currently used in the production of sea level data is derived by an empirical method that models this correction by expressing sea level residuals as a function of SWH and wind speed

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https://doi.org/10.1016/j.rse.2018.09.007
Received 27 June 2018; Received in revised form 23 August 2018; Accepted 12 September 2018

estimated by the altimeter itself. More recently, attempts have been made to add a third parameter, namely the mean wave period from a numerical model (Tran et al., 2010a). The empirical nature of the SSB modeling implies that any sea-state dependent error in the residuals will be included in the correction.

Conceptually, only the third term varies with instrument and retracking algorithm, while the first two components should be the same for all Ku-band altimeters. Two fundamental studies have dealt with this contribution. Firstly, Sandwell and Smith (2005) has shown that part of the SSB correction is related to the inherent correlation between arrival time and rise time of the leading edge of the altimetric waveform, from which the physical parameters of SWH and sea level are estimated. Secondly, Zaron and DeCarvalho (2016) developed a correction to decorrelate SWH and sea level estimations based on the analysis of their errors. They derived a correction to be applied to low frequency (LF, i.e. at 1 Hz, corresponding to roughly one measurement every 7 km) data that are already corrected for SSB. Quartly et al. (2016) demonstrated that the correlation of the errors in the estimation process shows up as correlated high frequency (HF, i.e. at 20 Hz for Jason-1, Jason-2 and Jason-3) SWH and SLA estimates within the LF spacing. A term related to issues in the fitting of a waveform cannot be considered as a SSB in a physical sense, since the non-linearities of the ocean waves should not vary at scales smaller than 10 km. Nevertheless, due to the empirical derivation of the SSB models, it does influence any attempt in finding a parametric relation between SLA and SWH. For clarity and in analogy with Zaron and DeCarvalho (2016), we will refer to “retracker-related noise” to discuss the contribution of this term to the total SSB correction.

In the empirical estimation of the SSB, the sea level residuals are analyzed by differencing repeat measurements along collinear tracks (Chelton, 1994) or at orbit crossover points (Gaspar et al., 1994), or directly observing the anomalies with respect to the mean sea level (Vandemark et al., 2002). The residuals are modelled with respect to the variables influencing the sea state either in a parametric formulation (Fu and Glazman, 1991; Pires et al., 2016) or non-parametrically solving a large linear system of observation equations for the SSB taken as unknown (Gaspar et al., 2002).

The motivation of this study is three-fold:

1. The SSB correction in the standard products, as any other geophysical correction, is given at LF, rather than at HF. Lately, the attention of the scientific community and particularly the effort to better observe coastal dynamics at a regional scale has moved to the exploitation of HF data (Cipollini et al., 2017b; Birol and Delebecque, 2014). Gómez-Enri et al. (2016) and Passaro et al. (2018) have successfully applied the SSB model of the Envisat and ERS-2 satellite missions to high-rate estimations of SWH and wind speed from the ALES retracker (Passaro et al., 2014), although no SSB-specific consideration was made in analysing the results.
2. Several retrackers alternative to the standards have been proposed in recent years (Cipollini et al., 2017a). It is likely that different retrackers would bring different errors that play a role in the tracker bias. Nevertheless, for none of these alternative methods has a specific SSB correction been derived.
3. Several dedicated altimetry products during recent years provide region-specific processing (Birol et al., 2017; Passaro, 2017). Also the current phase of the European Space Agency's Sea Level Climate Change Initiative project (SL cci) (Quartly et al., 2017; Legeais et al., 2018) is focused on regional sea level analysis. Residual errors in the sea level, which are mirrored in the SSB model estimation, can also be dependent on the region. Since SSB models are estimated globally, regional predominance of certain wind and wave conditions might not be well enough represented in the realization of a global SSB model. An attempt of a regional SSB derivation was the SSB correction proposed for Cryosat-2 mission in the Indonesian Archipelago by Passaro et al. (2016), but comparison was not possible given that there is no official SSB model for that mission.

For these reasons, we aim in this work at computing a high-frequency, regional and retracker-dependent SSB correction in order to improve the performances of HF altimetry data. This is done in two subsequent steps. Firstly, we show that a simple application of the existing SSB model using HF estimations of two different retrackers is sufficient to reduce the SLA noise level in a comparable way to the correction of Zaron and DeCarvalho (2016). Secondly, a new retracker-specific regional parametric SSB model is derived in two test regions.

The novelty compared with previous studies consists in i) an approach to reduce the retracker-related noise starting from HF data rather than the LF of Zaron and DeCarvalho (2016), ii) the adoption of regionally focused corrections as suggested by Tran et al. (2010b) and iii) the provision of a SSB correction for the ALES retracker, which is the algorithm chosen for the current phase of SL cci.

The test regions are defined together with the data sources in Section 2; the methodology for SSB derivation and analysis is described in Section 3; results are presented and discussed in Section 4; the work and its perspectives are finally summarised in Section 5.

2. Data and region of study

In this study HF observations from the Jason-1 mission are used. By choosing this mission, 7 years of data (January 2002 to January 2009) including cycles 1–259 (before the start of the drifting phase) can be exploited and at the same time comparisons can be made with the latest studies focused on SSB (Tran et al., 2010a; Pires et al., 2016). The HF (20 Hz) data were extracted from the DGFI-TUMs Open Altimeter Database (OpenADB: https://openadb.dgfi.tum.de) and are publicly available upon request. The OpenADB contains data from the original Sensor Geophysical Data Records (SGDR Version E) and from the Adaptive Leading Edge Subwaveform (ALES) reprocessing.

The SGDR product provides the orbital altitude, all the necessary corrections to compute the sea level anomaly and the output of the MLE4 retracker (Amarouche et al., 2004; Thibaut et al., 2010): range, SWH and backscatter coefficient. These are also estimated and given as output of ALES (Passaro et al., 2014). We computed the wind speed starting from the backscatter coefficient from the two retrackers using the processing described in Abdalla (2012).

The sea level anomalies (SLA) are derived from the range measurements using exactly the same orbital altitude and corrections (for tides and atmospheric effects), except, of course, the SSB correction, for both SGDR and ALES. Unrealistic estimations are identified using the outlier rejection suggested by Picot et al. (2003). Moreover, since the MLE4 retracker is not optimised for coastal waveforms, data within 20 km of the coast are excluded from the analysis.

The regions of study are the Mediterranean Sea (Med) and the North Sea (NS) and are shown in Fig. 1. These regions have been selected in the context of the SL cci for the high interest in regional sea level dynamics and the relatively abundant in-situ measurements. Moreover, in the context of this study, these choices provide the opportunity to test the results in two areas characterised by different bathymetry, tidal regime and sea state conditions.

3. Methods

3.1. Different SSB corrections used in the study

Three different SSB corrections are applied to derive the SLA in this study:

- 1-Hz SSB is the SSB correction available at LF in the SGDR product. The correction is derived using the methodology described in Gaspar et al. (2002) and Labroue et al. (2004) and updated in Tran et al. (2010a). This methodology adopts a non-parametric estimation: a statistical technique (kernel smoothing) is used to solve a large system of linear equations based on the observations and on a set of weights.