Estimating the sea state bias of HY-2A radar altimeter by using a three-dimensional nonparametric model (Postprint)

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Abstract

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Full Text

Estimating the Sea State Bias of HY-2A Radar Altimeter Using a Three-Dimensional Nonparametric Model

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ABSTRACT

The sea state bias (SSB) has become the dominant source of error in satellite altimetry. Operational SSB correction models are two-dimensional (2-D) nonparametric models based on wind speed (U) and significant wave height (SWH) that can be directly measured by altimeters. This paper estimates the sea state bias of the HY-2A radar altimeter using a three-dimensional (3-D) nonparametric model based on SWH from HY-2A interim geophysical dataset records (IGDR), U, and mean wave period (MWP) from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis project. The 3-D SSB estimates can increase the explained variance by 1.72 cm^2, or 1.31 cm RMS relative to traditional 2-D SSB estimates based on U and SWH.

Index Terms—HY-2A, radar altimeter, sea state bias, crossover differences, 3-D nonparametric model

1. INTRODUCTION

Sea level rise, primarily caused by global warming, has attracted increasing attention. One of the main purposes of radar altimeters is to measure mean sea level. However, the sea level measured by radar altimeters is lower than the true sea level because wave troughs are better reflectors of radar energy than wave crests. This effect is called the electromagnetic bias (EM bias). Two other sea-state-related biases are the skewness and tracker biases [**?**]. The EM bias together with the skewness bias and tracker bias is generally called the sea state bias (SSB).

Thanks to improvements in precise orbit determination technology and other geophysical corrections, the sea state bias has become the dominant source of error in satellite altimetry. Operational SSB correction models are two-dimensional (2-D) empirical models based on wind speed (U) and significant wave height (SWH) that can be directly measured by altimeters. However, these 2-D SSB models cannot entirely parameterize the range bias variability, and SSB uncertainty may be reduced through improved SSB models that include additional measurable or predictable correlatives [**?**]. This paper estimates the sea state bias of the HY-2A radar altimeter using a 3-D nonparametric model based on U, SWH, and MWP. The model is developed using crossover sea surface height (SSH) differences. Compared with the SSB corrections in HY-2A IGDR and traditional 2-D SSB estimates, the 3-D SSB estimates can greatly reduce the standard deviation (STD) of crossover SSH differences and sea level anomalies (SLAs). The enhancement from 2-D to 3-D SSB estimation is of great significance for improving the precision of HY-2A altimeter products.

2. METHODOLOGY

In this paper, we developed the 3-D SSB model using crossover SSH differences from the HY-2A altimeter.

The sea surface height measurement uncorrected for SSB is denoted as h', which includes the geoid (g), dynamic topography (η), SSB, and some measurement noise (ω). At crossover points, the geoid signal can be eliminated by forming differences between two measurements taken on the ascending arc (index 1) and descending arc (index 2) respectively:

$$h_1' - h_2' = (g_1 - g_2) + (\eta_1 - \eta_2) + (SSB_1 - SSB_2) + (\omega_1 - \omega_2)$$

Assuming the geoid cancels out and the dynamic topography difference and measurement noise can be considered as a single zero-mean noise term ε, the observation equation for the SSH differences can be written as:

$$SSH_1' - SSH_2' = SSB_1 - SSB_2 + \varepsilon$$

Noting that SSB is a function $\phi(U, SWH, MWP) = x$, the observation equation can be written as:

$$y = SSH_1' - SSH_2' = \phi(x_1) - \phi(x_2) + \varepsilon$$

Equation (5) can be solved using a nonparametric estimation method based on kernel smoothing introduced by Gaspar [**?**], [**?**].

3. DATA

The input parameters for the 3-D SSB model are U, SWH, and MWP. While U and SWH are typically obtained from altimeter observations, the wind speed in HY-2A IGDR is not reliable. Therefore, we used wind speed from the ECMWF ERA-Interim reanalysis project. Figure 1 compares U and SWH from ECMWF and Jason-2 GDR. Since Jason-2 altimeter has been fully calibrated, both ECMWF-derived U and SWH show high accuracy compared to Jason-2 GDR data. Figure 2 compares U and SWH from ECMWF and HY-2A IGDR. The root mean square error (RMSE) of differences between ECMWF-derived SWH and HY-2A IGDR-derived SWH is only 0.365 m. Therefore, SWH from HY-2A IGDR can be used to develop the SSB model.

The RMSE of differences between ECMWF-derived U and HY-2A IGDR-derived U is larger than 5 m/s (the backscattering coefficient in HY-2A IGDR has not been fully calibrated; after full calibration, the derived U will be improved). Consequently, we use ECMWF-derived U to estimate the SSB of the HY-2A altimeter.

3.1 ERA-Interim Reanalysis

ERA-Interim is the third global reanalysis project produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-Interim provides reanalysis data from 1979 to the present and updates in near real time. The objective of the ERA-Interim project is to prepare for a new global reanalysis project to gradually replace ERA-40. Compared with ERA-40, ERA-Interim has improvements in data assimilation, forecast model, and observing system. A variety of data in uniform latitude/longitude grids can be obtained from ERA-Interim datasets. The mean wave period and wind speed we used are projected on a grid of 0.25° × 0.25°.

3.2 HY-2A Altimeter

The HY-2A satellite was launched on 16 August 2011. HY-2A is a polar-orbit satellite with an orbit height of 971 km. The instruments on HY-2A include a dual-band (13.58 and 5.25 GHz) radar altimeter (RA), a Ku-band radar scatterometer (SCAT), and a microwave imager (MWI). The RA is equipped with a three-channel (18.7, 23.8, and 37 GHz) microwave radiometer for wet troposphere delay correction. In this paper, we used cycles 42-56 of the HY-2A 1-Hz IGDR data to develop the SSB models.

4. RESULTS

4.1 HY-2A SSB Estimates

The 2-D SSB estimates are shown in Figure 3 in the form of 2-D grids with contours given in cm. As shown in Figure 3, the magnitude of the SSB generally increases with increasing SWH. For a given SWH, the magnitude of the SSB first increases with U and then decreases at higher wind speeds.

4.2 Assessment of the 3-D SSB Estimates

We used explained variance to evaluate the 3-D SSB model. Explained variance is the reduction in variance of crossover SSH differences obtained after applying a given SSB correction and serves as a primary criterion for assessing SSB model quality. We first used global data to calculate explained variances. The variances explained by 3-D SSB estimates, 2-D SSB estimates, and the SSB corrections in HY-2A IGDR are 29.95 cm^2, 28.23 cm^2, and 26.47 cm^2, respectively.

The 3-D SSB model based on U, SWH, and MWP is presented as a 3-D lookup table with ranges of 0-30 m/s for U, 0-12 m for SWH, and 0-18 s for MWP. To better represent the 3-D SSB model, we present correction values in the form of 2-D arrays by fixing a third parameter. Contours of SSB values are displayed in cm and shown in Figure 4 [Figure 4: see original paper]. The fixed values are near the mean values to ensure sufficient measurements. In our study, the three fixed values we chose are MWP = 9 s, U = 7.5 m/s, and SWH = 2.5 m, respectively. Figure 4(a) agrees closely with Figure 3. When U and MWP are fixed, the magnitude of the SSB is an increasing function of SWH. In contrast, as seen in Figure 4(b), the magnitude of the SSB is a decreasing function of MWP when U and SWH are fixed. In the data-rich region, there is approximately 4 cm variation versus MWP, with the magnitude of the SSB decreasing as wave period increases. As observed in Figure 4(c), when SWH is fixed, variations with MWP are more obvious than those with U in the data-rich region. For a given U, the magnitude of the SSB is a decreasing function of MWP.

We then binned the crossover data into 10° latitude bands and computed the explained variance in each band. The explained variance relative to the 1D (-3.8% SWH) SSB model is given in Figure 5. The 3-D SSB estimates perform better across most latitude regions, with variance reduced after replacing traditional 2-D SSB estimates with 3-D SSB estimates.

Crossover SSH differences are the primary tool for analyzing overall altimetry system performance, allowing assessment of SSH consistency between ascending and descending passes [**?**]. Figure 6 shows the standard deviation (STD) of crossover SSH differences after using different SSB corrections, with results obtained cycle by cycle. Clearly, the 3-D SSB estimates can greatly reduce the STD of crossover SSH differences.

Along-track analysis is also used to assess altimeter system performance by computing sea level anomalies (SLAs). SLAs are computed along-track by subtracting the mean sea surface (MSS) from instantaneous SSH measurements. SLA variance provides an estimate of system errors [**?**]. Figure 7 shows the STD of SLAs after using different SSB corrections. The STD of SLAs can be reduced using 3-D SSB estimates compared to 2-D SSB estimates and the SSB corrections in HY-2A IGDR data.

5. CONCLUSIONS

This paper estimates the SSB of the HY-2A radar altimeter using a 3-D nonparametric model. Crossover SSH differences are used to develop the SSB model. Compared with traditional 2-D SSB estimates, the 3-D SSB estimates can greatly reduce the STD of crossover SSH differences and SLAs. Therefore, the 3-D SSB estimates can improve the precision of HY-2A altimeter products.

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Note: Figure translations are in progress. See original paper for figures.