HY-2A Altimeter Time Tag Bias Estimation Using Reconstructive Transponder Postprint

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Date: 2016-12-26T00:00:00+00:00

Abstract

Independent clocks provide time tags for the precision orbit determination (POD) equipment and the radar altimeter onboard the HY-2A satellite, and a bias between POD data' time tag and corresponding range observation' s time tag from the HY-2A altimeter exists. The time tag bias contributes a bias in the sea surface height observation due to the nonzero time rate of change of the HY-2A altimeter' s height. A transponder for in-orbit radar altimeter calibration provides an approach to estimate the time tag bias. The altimeter receives the responding signals from the transponder and generates ranges. Pertinent reference ranges are obtained fromthe POD data and the transponder' s coordinate. Using the ranges from the radar altimeter and the reference ranges, the time tag bias between the POD data and the altimeter observations can be estimated. During an in situ HY-2A altimeter calibration campaign using a reconstructive transponder from August 9, 2012, to July 20, 2014, 17 estimations of the altimeter' s time tag bias were obtained. The preliminary results are presented in this letter.

Full Text

Preamble

HY-2A Altimeter Time Tag Bias Estimation Using Reconstructive Transponder

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Abstract—The HY-2A satellite employs independent clocks for its Precision Orbit Determination (POD) equipment and radar altimeter, resulting in a time tag bias between POD data and corresponding altimeter range observations. This time tag bias introduces an error in Sea Surface Height (SSH) measurements due to the non-zero temporal rate of change of the satellite' s altitude. A reconstructive transponder provides an effective approach for estimating this

bias during in-orbit calibration. The altimeter receives responding signals from the transponder and generates range measurements, which are compared with reference ranges derived from POD data and the transponder' s coordinates to estimate the time tag bias. During an in-situ calibration campaign from August 9, 2012 to July 20, 2014, 17 estimations of the altimeter' s time tag bias were obtained, with preliminary results presented herein.

Index Terms–Calibration, altimeter, transponder, time tag bias.

I. Introduction

The China' s marine dynamic environment satellite HY-2A, launched on August 16, 2011, carries a nadir-looking pulse-limited radar altimeter as one of its main payloads [1], [2]. The Sea Surface Height (SSH) product represents a primary output of the HY-2A altimeter. SSH measured by the radar altimeter can be expressed as SSH = H − Ralt, where H is the altimeter altitude above the reference ellipsoid provided by Precise Orbit Determination (POD) data, and Ralt is the one-way range from the radar altimeter. The HY-2 satellite is equipped with a dual-frequency Global Positioning System (GPS) receiver, a Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) receiver, and a Laser Retroreflector Array (LRA), all of which contribute to POD data generation.

At any given time t, the altimeter produces range measurements Ralt(t) while POD equipment generates altitude H(t). The time tag for Ralt(t) originates from the altimeter' s clock, whereas the time tag for H(t) comes from the POD system's clock. A time tag bias tb may exist between these two independent time systems. In the presence of tb, we can assume without loss of generality that the altimeter' s clock produces time tag t = t + tb at actual time t. This timing process is also known as "datation" [3], and time tag bias may alternatively be termed "datation error." The following discussion uses "time tag bias" unless otherwise specified.

Normally, the time rate of change of H, denoted as $\dot{h}$, is non-zero and varies with the satellite' s latitude. Consequently, H(t) H(t). According to [4], [5], the time tag bias introduces a bias ΔH expressed as ΔH = H(t) − H(t) = $\dot{h}tb + \frac{1}{2}\ddot{h}tb^2 + \cdots$, where $\ddot{h}$ represents the acceleration of H. This Taylor series approximation of ΔH is illustrated in Fig. 1 [Figure 1: see original paper], which shows the altitude rate and acceleration of the HY-2A satellite as functions of latitude. The maximum altitude rate is approximately 25 m/s, while the maximum acceleration does not exceed 0.04 m/s^2. Considering the time tag bias of the SEASAT altimeter [4], if tb = 80 ms, the second-order term introduces only a 0.12 mm bias. Given that the nominal uncertainty of HY-2A altimeter SSH measurements is 4 cm, we can safely ignore the $\frac{1}{2}\ddot{h}tb^2$ term and higher-order terms, yielding ΔH = H(t) − H(t) $\dot{h}$tb.

Combining the SSH equation with this approximation, we obtain H(t) − Ralt(t) = H(t) − $\dot{h}$tb − Ralt(t) = SSH(t) − $\dot{h}$tb, where $\dot{h}$tb represents the SSH bias term.

Schutz et al. [4] estimated the SEASAT altimeter' s time tag bias using two independent approaches: (1) altimeter data differencing at crossover points and (2) geoid model fitting, detecting a bias of -78.1 ± 2.0 ms. Marsh et al. [6] similarly employed a crossover-differencing approach, obtaining a bias of -81.0 ± 2.0 ms. Scharroo et al. discussed the causes of time tag biases in ERS-1 and ERS-2 altimeters [7], while Naeije et al. reported on CryoSat-2 Synthetic Interferometric Radar Altimeter (SIRAL) Low Resolution Mode (LRM) data calibration and validation, obtaining an 8.2 ms time tag bias through Sea Level Anomaly (SLA) fitting and an 8.3 ms bias through crossover differencing [8]. Wang et al. processed HY-2A altimeter Interim Geophysical Data Record (IGDR) for cycle 21 (July 7–21, 2012), deriving a -7.3 ms time tag bias via crossover SSH differencing [5]. Bao et al. reprocessed HY-2A altimeter Geophysical Data Record (GDR) data from the National Ocean Satellite Application Center, China (NSOAS), producing a new GDR version with a -0.26 ms time tag bias validated through crossover height differencing [9].

Transponders serve as an effective in-orbit radar altimeter calibration tool and can estimate altimeter time tag bias. A transponder acts as a point target, and its responding signal is free from error sources associated with sea surface dynamics, such as Sea State Bias (SSB), ocean waves, atmospheric loading, currents, and tides [10]. Therefore, utilizing a transponder provides an independent approach for estimating altimeter time tag bias.

Roca et al. reported on CryoSat-2 SIRAL calibration using transponders, demonstrating the feasibility of estimating in-orbit radar altimeter time tag bias [11]. Their work used bent-pipe transponders located at Svalbard and Crete to estimate datation errors in SIRAL-A data products. An experimental HY-2A altimeter calibration campaign employing a reconstructive transponder designed by the National Space Science Center, Chinese Academy of Sciences, has been conducted since March 2012 [12], [13].

Different HY-2A altimeter data products may exhibit different time tag biases depending on parameter definitions, input data, and processing algorithms. Hereinafter, we adopt POD time as the reference time frame, utilizing Level 0 altimeter data and Medium Orbital Ephemerides (MOE) POD data. During calibration, the HY-2A altimeter operates in search mode, processing one out of every four observations and recording corresponding time-domain baseband waveform samples. The range tracker is disabled, and the range window delay Rse is set to a precalculated value exceeding the altimeter' s orbital altitude. By properly setting the reconstructive transponder' s echo signal delay, the transponder' s echo can be captured within the altimeter' s range window without interference from surface echoes.

Fig. 2 [Figure 2: see original paper] illustrates the reconstructive transponder setup.

II. Principle and Algorithm

The reconstructive transponder receives pulses from the altimeter, reconstructs responding pulses, and transmits them back to the altimeter. The transponder’ s coordinates are determined by GPS equipment, enabling derivation of the reference range between the altimeter and transponder from POD data and transponder coordinates. The altimeter receives the transponder’ s responding signal and produces range measurements. Using POD time as the reference, the altimeter’ s time tag bias can be determined from the spatial relationship between the reference range and altimeter range.

The range between the altimeter and reconstructive transponder can be expressed as a quadratic function of time t:

$$R(t) = (R \ - H) + (Re + H)GM / [2(R \ - H)(Re + R\ )^2]\ t^2$$

where $GM = 3.986 \times 10^{1}$ m^3/s^{2} is a constant, Re is Earth’ s radius, R is the distance between the altimeter and nadir point, and H is the transponder height relative to Earth’ s surface [16]. Without loss of generality, this can be simplified to:

$$R(t) = at^2 + bt + c; a \quad 0$$

where a, b, and c are constants.

Letting POD time be t, we obtain the one-way range from POD data as R(t). The HY-2A altimeter’ s transmit-receive interval is fixed at Δt during calibration. Without considering time tag bias tb, the two-way range from altimeter observations Ra(t) can be expressed as:

$$Ra(t) = Rat(tt) + Rar(tr)$$

where Rat(tt) is the one-way range at signal transmission and Rar(tr) is the one-way range at signal reception. The reception time tr is contained in the altimeter’ s time code. In search mode, the interval between signal transmission and reception is a known constant inta, making tt known. Given POD one-way range R(t) and corresponding time t, reference range parabolas Rrt(tt) at time tt and Rrr(tr) at time tr can be obtained through interpolation:

$$Rrt(tt) = interp(R(t); t; tt)\ Rrr(tr) = interp(R(t); t; tr)$$

Considering range bias BR:

$$Rat(tt) = Rrt(tt) + BR\ Rar(tr) = Rrr(tr) + BR$$

Using these relationships, if no bias exists in altimeter time, we can derive:

$$Ra(ta) = 2at^2a + 2bta + c$$

where ta = t + 1 2 t and c is a constant.

Considering time tag bias tb and letting t = ta + tb, the equation becomes:

$$Ra(t\ ) = 2a(ta + tb)^2 + 2b(ta + tb) + c$$

Let ab, bb, and cb be the fitting parameters of Ra(t). Considering the quadratic form, time tag bias tb can be calculated as:

tb = (bb − 2b) / (4a)

Fig. 3 [Figure 3: see original paper] shows the POD one-way range between the altimeter and transponder, along with the one-way range from HY-2A altimeter observations obtained on August 9, 2012 in Beijing, China.

While direct estimation of tb using the above equation is feasible, an equivalent approach mitigates uncertainty introduced by additive noise w in Ra(t). This alternative method proceeds as follows: Consider the altimeter' s two-way range parabola Ra as the sum of parabolas Rat(tt) and Rar(tr). The residual Ra − Rrt(tt) − Rrr(tr) should theoretically be a line with zero slope. However, if altimeter time contains bias Δt, then t t = tt + Δt and t r = tr + Δt, yielding:

Rrt(t t) = interp(R(t); t; tt + Δt) Rrt(tt) Rrr(t r) = interp(R(t); t; tr + Δt) Rrr(tr)

Consequently:

Ra − Rrt(t t) − Rrr(t r) 2BR

The slope of Ra − Rrt(t t) − Rrr(t r) is no longer zero. We can utilize an auxiliary parameter Δt in interpolation:

Rrt(t t) = interp(R(t); t; tt + Δt + Δt) Rrr(t r) = interp(R(t); t; tr + Δt + Δt)

By adjusting Δt in small steps and recalculating resi = Ra − Rrt(t t) − Rrr(t r), when Δt = −Δt, the slope of resi returns to zero, revealing the time tag bias Δt.

The algorithm proceeds as follows: 1. Obtain t and R(t) from POD data, and tr and Ra from altimeter data. Calculate tt = tr − inta and initialize parameter Δt. 2. Calculate Rrt(t t) and Rrr(t r): Rrt(t t) = interp(R(t); t; tt + Δt) Rrr(t r) = interp(R(t); t; tr + Δt) 3. Calculate residual: resi = Ra − Rrt(t t) − Rrr(t r) 4. If resi' s slope is sufficiently small, stop. Otherwise, adjust Δt by small steps and return to step 2.

To analyze algorithm performance, using the quadratic model we can express the reference range as:

$$Rref(t) = R(t) + R(t + \Delta t) = 2a(ta)^2 + 2b(ta) + c$$

Letting w N(0; ^{2}), then:

x(tb) = Ra(t) − Rref(t) + w(t)

A linear expression at ts is obtained through first-order Taylor series approximation:

$$x(tb) \quad [4ats + 2b + 4a(t + \Delta t)]tb - 2a(ts)^2 + w$$

We designate the direct fitting method as Algorithm 1 and the slope-adjustment method as Algorithm 2. With parameters a = 50, b = 0, ts = 9 × 10 ³s, Δt = 4 × 6.48 ³s (corresponding to HY-2A' s search mode recording one out of every four observations), and = 0.05 m, Fig. 4 [Figure 4: see original paper] shows the Cramer-Rao lower bound for tb estimation standard deviation using both algorithms under varying numbers of altimeter observations.

III. Results and Discussion

Fig. 5 [Figure 5: see original paper] presents time tag bias estimates from calibration campaigns conducted between August 9, 2012 (359 days from launch) and July 20, 2014 (1069 days from launch) using the reconstructive transponder, along with corresponding standard deviations calculated from Algorithm 2. Two primary factors reduce estimation quality. First, the HY-2A altimeter operates in search mode during calibration, recording only one out of every four observations, which significantly reduces the number of observations available for curve fitting and increases time tag bias estimation uncertainty. Second, the reconstructive transponder' s internal path delay must be set before each calibration based on orbit prediction. However, orbit prediction errors may be substantial, causing only partial observation of the round-trip parabola and limiting available altimeter observations. Consequently, estimation results derived from highly unreliable altimeter observations are excluded.

The HY-2A satellite' s central electronic system obtains reference time from the GPS receiver and adjusts each payload' s local time, including the radar altimeter, once every S0 seconds (where S0 is variable but does not exceed 8 seconds). Therefore, time tag bias behaviors for both side A and side B should be similar, a conclusion confirmed by Fig. 5.

Wang' s result of −7.3 ms, Bao' s result of −0.26 ms, and our findings all indicate that for a given range measurement, POD system time is t while HY-2A altimeter time is t − Δt, where Δt represents the absolute value of time tag bias. A 10–15 millisecond bias range implies SSH biases of 25–37.5 cm for a vertical velocity of 25 m/s. No time tag bias requirement exists for HY-2A altimeter Level 0 data as a relatively primitive product. However, according to HY-2A altimeter design requirements, time tag bias should not exceed 0.5 milliseconds [17]. Bao' s result of −0.26 ms demonstrates that IGDR data products meet this design requirement.

This work demonstrates the feasibility of radar altimeter time tag bias calibration using a reconstructive transponder. Under current conditions, only HY-2A altimeter Level 0 search mode data can be utilized for this purpose. IGDR and higher-level data derive from HY-2A altimeter tracking mode, which provides only averaged power spectrum data with limited range resolution, leading to low-precision time tag bias estimation. In contrast, HY-2A altimeter search mode provides time-domain baseband signal samples with significantly higher range resolution than tracking mode data.

IV. Conclusion

This work introduces preliminary HY-2A altimeter time tag bias estimation using a reconstructive transponder, marking the first application of this technology for in-orbit radar altimeter time tag bias estimation. As an independent approach, the reconstructive transponder provides a valuable means of time tag bias estimation and serves as an important complement to SSH observation-based methods. Two approaches have been proposed to improve estimation quality: (1) recording more pulses during calibration, and (2) extending the altimeter' s range window to capture more responding signals. The engineering team for the HY-2A altimeter' s successor mission is evaluating these improvements, and the reconstructive transponder is expected to become a more effective tool for altimeter time tag bias estimation if these technical enhancements are implemented.

Acknowledgment

This work is supported by: (1) Centre National d' Etudes Spatiales (CNES) for providing HY-2A satellite POD data; (2) National Satellite Ocean Application Service (NSOAS) for providing HY-2A altimeter IGDR and auxiliary data; and (3) Mrs. Li Lan for paper editing.

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