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

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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’s 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 from the 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.

Index Terms—Altimeter, calibration, time tag bias, transponder.

I. INTRODUCTION

China’s marine dynamic environment satellite HY-2A, with a nadir-looking pulse-limited radar altimeter onboard as one of its main payloads, was launched on August 16, 2011 [1], [2]. The sea surface height (SSH) product is one of the main products of the HY-2A altimeter. The SSH measured by the radar altimeter can be written as

\[ SSH = H - R_{alt} \]  

(1)

where \( H \) is the altimeter altitude above the reference ellipsoid provided by the precise orbit determination (POD) data and \( R_{alt} \) is the one-way range from the radar altimeter. The HY-2A satellite carries a dual-frequency Global Positioning System (GPS) receiver, a Doppler Orbitography and Radiopositioning Integrated by Satellite receiver, and a laser retroreflector array. These pieces of equipment are used to produce POD data.

At a given time \( t \), the altimeter produces range measurements \( R_{alt}(t) \), and the POD equipment produces altitude \( H(t) \). The time tag of \( R_{alt}(t) \) comes from the altimeter’s clock, and the time tag of \( H(t) \) comes from the POD system’s clock. However, there may be a time tag bias \( t_b \) between the altimeter’s time and the POD system’s time. In the case of the presence of \( t_b \), without loss of generality, we assume that the altimeter’s clock produces time tag \( t' = t + t_b \) at time \( t \). The timing process is also known as “datation” [3], and the time tag bias can also be called “datation error.” The following content utilizes the term “time tag bias” if not specifically stated.

Normally, \( h \), the time rate of change of \( H \), is not zero and varies as the latitude of the satellite changes. Therefore, \( H(t) \neq H(t') \). According to [4] and [5], the time tag bias introduces a bias \( \Delta H \)

\[ \Delta H = H(t') - H(t) = \dot{h}t_b + \frac{1}{2}\ddot{h}t_b^2 + \cdots \]  

(2)

where \( \dot{h} \) is the acceleration of \( H \). Equation (2) is a Taylor series approximation of \( \Delta H \). Fig. 1(a) and (b) shows the altitude rate and the acceleration of the HY-2A satellite as a function of latitude, respectively. The HY-2A satellite’s maximum altitude rate is about 25 m/s, and the maximum value of \( \dot{h} \) is no more than 0.04 m/s². Considering the time tag bias of the Seasat altimeter [4], let \( t_b = 80 \) ms; then, the term \((1/2)\dot{h}t_b^2 \) only introduces a 0.12-mm bias. The nominal uncertainty of the HY-2A altimeter’s SSH measurement is 4 cm; then, we can safely ignore the \((1/2)\dot{h}t_b^2 \) term and higher order terms and get

\[ \Delta H = H(t') - H(t) \approx \dot{h}t_b. \]  

(3)

From (1) and (3), we obtain

\[ H(t) - R_{alt}(t') = H(t') - \dot{h}t_b - R_{alt}(t') = SSH(t') - \dot{h}t_b \]  

(4)

where \( \dot{h}t_b \) is the bias term of SSH.

Schutz et al. [4] estimated the time tag bias of the Seasat altimeter’s range observations with two independent approaches: 1) altimeter data differencing at crossover and 2) using geoid model. A \(-78.1 \pm 2.0\)-ms time tag bias was detected. Marsh et al. [6] also used a crossover-differencing-based approach to analyze the time tag bias of the Seasat altimeter’s range observations, and a \(-81.0 \pm 2.0\)-ms time tag bias was obtained. Scharroo et al. discussed the causes of the time tag biases of the ERS-1 and ERS-2 altimeters [7]. Naeije et al. reported
the Cryosat-2 synthetic interferometric radar altimeter (SIRAL) low-resolution mode data calibration and validation result. An 8.2-ms time tag bias was obtained by sea level anomaly fitting, and an 8.3-ms time tag bias was obtained by the crossover differencing approach [8]. Wang et al. processed the HY-2A altimeter interim geophysical data record (IGDR) for cycle number 21 from July 7, 2012, to July 21, 2012, and obtained a $-7.3$-ms time tag bias by means of crossover SSH differencing [5]. Bao et al. reproccessed the HY-2A altimeter geophysical data record (GDR) data from the National Ocean Satellite Application Center, China (NSOAS), and obtained new version GDR data with a $-0.26$-ms time tag bias validated by crossover height differencing [9].

The transponder, as an in-orbit radar altimeter calibration approach, can also be used to estimate the time tag bias of the altimeter. The transponder can be taken as a point target, and its responding signal is free from the error sources introduced by sea surface dynamics, e.g., sea state bias, ocean waves, atmospheric loading, currents, and tides [10]. Therefore, it is feasible to utilize the transponder as an independent approach to estimate the altimeter’s time tag bias.

Roca et al. gave a brief report about the Cryosat-2 SIRAL calibration work with transponder, and the datation error (time tag bias) of SIRAL A’s data products is estimated using bent-pipe transponders located at the Svalbard and Crete islands [11]. This work demonstrated the feasibility of estimating the in-orbit radar altimeter’s time tag bias using the transponder.

An experimental HY-2A altimeter calibration campaign, which utilized a reconstructive transponder designed by the National Space Science Center, Chinese Academy of Sciences, has been carried out in March 2012 [12], [13] (Fig. 2). The HY-2A altimeter’s time tag bias, as a part of the calibration result, was analyzed.

The bent-pipe transponder receives the signal from the altimeter, amplifies it, and then transmits it to the altimeter. The structure of the bent-pipe transponder is simple, but the echo signal delay of the bent-pipe transponder is determined by the microwave component and is hard to be changed. The reconstructive transponder processes the signal from the altimeter and obtains signal characteristics, and then, it reconstructs an echo signal and transmits it to the altimeter. The echo signal delay of the reconstructive transponder can be easily adjusted by digital signal processing but at a cost of complex system structure. MacDoran et al. proposed an active transponder for altimetry calibration (ATAC) and built a prototype [14], [15]. ATAC and our reconstructive transponder are the same in principle, but so far, any in-orbit radar altimetry mission calibration using ATAC has not been reported.

Different HY-2A altimeter’s data products may have different time tag biases, depending on parameter definition, input data, and processing algorithm of the input data. Hereinafter, we take the POD time as a reference time. The level 0 data of the HY-2A altimeter and the medium orbital ephemerides POD data are utilized. The HY-2A altimeter operates in search mode during calibration. Under this mode, the HY-2A altimeter processes one from each of the four observations and records the corresponding samples of the time-domain baseband waveform. The range tracker does not work, and the delay of the range window $R_{\text{sw}}$ is set to a precalculated value. $R_{\text{sw}}$ is higher than the orbit height of the altimeter. By properly setting the echo signal delay of the reconstructive transponder, the echo signal from the reconstructive transponder can be sent into the altimeter’s range window without interference of the echo signal from the surface.

II. PRINCIPLE AND ALGORITHM

The reconstructive transponder receives the pulse from the altimeter, reconstructs a responding pulse, and transmits it to
the altimeter. The coordinate of the transponder is determined by the GPS equipment, and the reference range between the altimeter and the transponder can be derived from the POD data and the transponder’s coordinate. The altimeter receives the responding signal from the transponder and produces the altimeter’s range. Taking the POD time as a reference time, the time tag bias of the altimeter can be determined using the spatial relationship between the reference range and the altimeter’s range.

\[ R(t) = (R_0 - H) + \frac{(R_e + H)GM}{2(R_0 - H)(R_e + R_0)^2}t^2 \]

where \( GM = 3.986 \times 10^{14} \text{ m}^3\text{s}^{-2} \) is a constant, \( R_e \) is the radius of the Earth, \( R_0 \) is the distance between the altimeter and nadir point, and \( H \) is the height of the transponder relative to the Earth’s surface [16]. Without loss of generality, (5) can be simplified to

\[ R(t) = at^2 + bt + c, \quad a \neq 0 \]

where \( a, b, \) and \( c \) are constants.

Let the POD time be \( t \); then, we obtain \( R(t) \), the one-way range from the POD data, as (6). The HY-2A altimeter’s transmitting–receiving interval is set at a fixed interval \( \Delta t \) during calibration. Without considering the time tag bias \( t_b \), \( R_a(t) \), the two-way range from the altimeter’s observation, can be written as

\[ R_a(t_a) = 2at^2 + 2bt_a + c' \]

where \( t_a = t + (1/2)\Delta t \) and \( c' \) is a constant.

Considering the time tag bias \( t_b \) and (7), let \( t' = t_a + t_b \), and (7) can be written as

\[ R_a(t') = 2a(t_a + t_b)^2 + 2b(t_a + t_b) + c'. \]

Let \( a_b, b_b, \) and \( c_b \) be the fitting parameters of \( R_a(t') \); considering (6), the time tag bias \( t_b \) can be calculated using the following expression:

\[ t_b = \frac{-b_b}{2a_b} - \frac{b}{2a}. \]

Fig. 3 shows the POD one-way range between the altimeter and the transponder, and the range from the HY-2A altimeter’s observation obtained on August 9, 2012, in Beijing, China.

Estimating \( t_b \) using (9) directly is feasible. Furthermore, an equivalent approach is used to mitigate the estimating uncertainty introduced by the additive noise \( w \) in \( R_a(t') \).

This approach can be described as follows: take the altimeter’s two-way range parabola \( R_a \) as the sum of parabolas \( R_{at}(t) \) and \( R_{ar}(t) \):

\[ R_a = R_{at}(t) + R_{ar}(t) \]

where \( R_{at}(t) \) is the one-way range when the altimeter transmits a signal and \( R_{ar}(t) \) is the one-way range when the altimeter receives a signal. \( t \) is contained in altimeter’s time code. In the search mode, the interval between signal transmitting and receiving is a known constant \( int_a \), so \( t \) is known. Because we have POD one-way range \( R(t) \) and corresponding time \( t \), the reference range parabolas \( R_{rt}(t) \) at time \( t \) and \( R_{rr}(t) \) at time \( t \) can be obtained using interpolation:

\[ R_{rt}(t) = \text{interp}(R(t), t, t) \]

\[ R_{rr}(t) = \text{interp}(R(t), t, t) \]

where interp is the interpolation operation. Considering the existence of range bias \( B_R \)

\[ R_{at}(t) = R_{at}(t) + B_R \]

\[ R_{ar}(t) = R_{ar}(t) + B_R. \]

Using (10) and (12), if there is no bias in altimeter’s time, then

\[ R_a - R_{rt}(t) - R_{rr}(t) = 2B_R. \]

The residual of \( R_a - R_{rt}(t) - R_{rr}(t) \) should be a line with zero slope. However, if the altimeter’s time contains bias \( \delta t \), \( t'_t = t + \delta t \) and \( t'_r = t + \delta t \), we obtain \( R_{rt}(t') \) and \( R_{rr}(t') \) using interpolation:

\[ R_{rt}(t') = \text{interp}(R(t), t, t + \delta t) \neq R_{rt}(t) \]

\[ R_{rr}(t') = \text{interp}(R(t), t, t + \delta t) \neq R_{rr}(t). \]

As a result, using (10) and (14)

\[ R_a - R_{rt}(t') - R_{rr}(t') \neq 2B_R. \]

The slope of \( R_a - R_{rt}(t') - R_{rr}(t') \) is not zero. We can utilize an auxiliary parameter \( \Delta t \) in interpolation

\[ R_{rt}(t') = \text{interp}(R(t), t, t + \delta t + \Delta t) \]

\[ R_{rr}(t') = \text{interp}(R(t), t, t + \delta t + \Delta t). \]

Adjust \( \Delta t \) by small steps, and recalculate

\[ \text{resi} = R_a - R_{rt}(t'_r) - R_{rr}(t'_r). \]
When $\delta t = -\Delta t$, the slope of resi returns to zero, and time tag bias $\delta t$ is obtained.

The algorithm steps are listed as follows.

1. Obtain $t$ and $R(t)$ from POD data and $t_r$ and $R_a$ from altimeter data. $t_s = t_r - \text{int}_r$. Initialize parameter $\Delta t$.
2. Calculate $R_{rt}(t'_r)$ and $R_{rr}(t'_r)$:
   \[ R_{rt}(t'_r) = \text{interp}(R(t), t, t_r + \Delta t) \]
   \[ R_{rr}(t'_r) = \text{interp}(R(t), t, t_r + \Delta t). \]
3. Calculate resi:
   \[ \text{resi} = R_a - R_{rt}(t'_r) - R_{rr}(t'_r). \]
4. If the slope of resi is small enough, stop. Otherwise, adjust $\Delta t$ by small steps, and return to 2).

To analyze this algorithm’s performance, using (6), we can get
\[ R_{ref}(t') = R(t) + R(t + \Delta t) = 2a(t_a)^2 + 2b(t_a) + c'. \] (19)

Let $w \sim N(0, \sigma^2)$; then
\[ x(t_b) = R_a(t') - R_{ref}(t') + w(t'). \] (20)

The linear expression of (20) at $t_s$ is obtained by one-order Taylor-series approximation:
\[ x(t_b) \approx 4at_s + 2b + 4a \left( t' + \frac{1}{2} \Delta t \right) t_b - 2a(t_a)^2 + w. \] (21)

We call (9) algorithm 1 and (21) algorithm 2. Let $a = 50$, $b = 0$, $t_s = 9 \times 10^{-3}$ s, $\Delta t = 4 \times 6.48 \times 10^{-3}$ s (the HY-2A altimeter records one from each of the four observations in search mode), and $\sigma = 0.05$ m, and Fig. 4 shows the Cramer–Rao lower bound for the standard deviation of $t_b$ estimation using (9) and (21) under different numbers of altimeter observations.

**Fig. 4.** Cramer–Rao lower bound for the standard deviation of $t_b$ estimation using (9) and (21).

III. RESULTS AND DISCUSSION

Fig. 5 shows the time tag bias from the calibration work from August 9, 2012 (359 days), to July 20, 2014 (1069 days), with the reconstructive transponder and corresponding standard deviations from (21). Two factors reduce the quality of the estimating results. First, the HY-2A altimeter operates in search mode during calibration and records one from each of the four observations; therefore, the number of HY-2A’s observations that can be used in curve fitting is significantly reduced, and the uncertainty of time tag bias estimation increases. Second, it is necessary to set the internal path delay of the reconstructive transponder before each calibration according to the orbit prediction. However, orbit prediction error may be so large that only part of the round-trip parabola is observed by the altimeter, and the number of available HY-2A altimeter’s observations is limited. Therefore, the estimating results that were obtained from highly unreliable altimeter observation are excluded.

The HY-2A satellite onboard the central electronic system gets the reference time from the GPS receiver and adjusts the local time of each payload, including the radar altimeter, once every $S_0$ seconds ($S_0$ is variable but no more than 8 s). Therefore, the behaviors of both side A and side B’s time tag biases should be similar, and this inference is confirmed by Fig. 5.

Wang’s $-7.3$ ms, Bao’s $-0.26$ ms, and our result all mean that, for a given range measurement, the time from the POD system is $t$ and the time from the HY-2A altimeter is $t - \delta t$. $\delta t$ is the absolute value of the time tag bias.

The range of 10–15 ms implies 25–37.5-cm SSH biases for a vertical velocity of 25 m/s. There is no time tag bias requirement for the HY-2A altimeter level 0 data as a relatively primitive data product. According to the HY-2A altimeter design requirement, the time tag bias should be no more than 0.5 ms [17]. Bao’s result of $-0.26$ ms means that the IGDR data product meets the design requirement of 0.5 ms.

Our work aims to show the feasibility of radar altimeter time tag bias calibration using a reconstructive transponder. Under the present conditions, only the HY-2A altimeter level 0 search mode data can be used for this purpose. The IGDR and higher level data are from the HY-2A altimeter tracking mode. The HY-2A altimeter tracking mode only provides averaged power spectrum data with limited range solution, and the low range spectrum data with limited range solution, and the low range...
solution leads to an estimation of time tag bias with low precision. The HY-2A altimeter search mode provides time-domain baseband signal samples, and its range solution is significantly higher than the tracking mode data’s range resolution.

IV. CONCLUSION

The preliminary HY-2A altimeter’s time tag bias estimation work using a reconstructive transponder has been introduced in this letter. This is the first time that the reconstructive transponder is used to estimate the in-orbit radar altimeter’s time tag bias. As an independent approach, the reconstructive transponder approach provides a valuable mean of time tag bias estimation and is an important complement to the approaches using SSH observations. Two approaches have been proposed to improve the quality of the time tag bias estimation. First, the altimeter will record more pulses during calibration. Second, it is preferable to lengthen the altimeter’s range window to record more responding signal. The engineering group of the HY-2A altimeter’s successor mission has been evaluating these approaches, and the reconstructive transponder is expected to become a more effective approach for altimeter’s time tag bias estimation if these technical improvements mentioned previously can be implemented.

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REFERENCES