HY-2A altimeter time tag bias estimation using reconstructive transponder

Junzhi Wan, Wei Guo, Fei Zhao* and Caiyun Wang

***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 (SSH) observation due to the non-zero 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 work.**

***Index Terms*—Calibration, altimeter, transponder, time tag bias.**

I. INTRODUCTION

THE 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 at August 16, 2011 [1], [2]. The sea surface height (SSH) product is one of the main products of the HY-2A altimeter. SSH measured by the radar altimeter can be written as

$$SSH = H - R_{alt} \tag{1}$$

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-2 satellite carries a dual-frequency Global Positioning System (GPS) receiver, a Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) receiver and a laser retroreflector array (LRA). These equipments are used to produce POD data.

At a given time t, the altimeter produces range measurements $R_{alt}(t)$, and POD equipments 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. Timing process is also known as "datation" [3], and time tag bias can also be called "datation error". The following content utilizes the term "time tag bias" if not specifically stated.

Normally, $\dot{h}$, 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], [5], the time tag bias introduces a bias ΔH:

$$\Delta H = H(t') - H(t) = \dot{h}t_b + \frac{1}{2}\ddot{h}t_b^2 + ... \tag{2}$$

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

$$\Delta H = H(t') - H(t) \approx \dot{h}t_b. \tag{3}$$

From (1) and (3), we obtain

$$\begin{aligned} H(t) - R_{alt}(t') &= H(t') - \dot{h}t_b - R_{alt}(t') \\ &= SSH(t') - \dot{h}t_b \end{aligned} \tag{4}$$

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 $-78.1 \pm 2.0ms$ time tag bias is detected. Marsh *et al.* [6] also used crossover- differencing based approach to analyze time tag bias of the SEASAT altimeter's range observations, and a $-81.0 \pm 2.0ms$ 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 (LRM) data calibration

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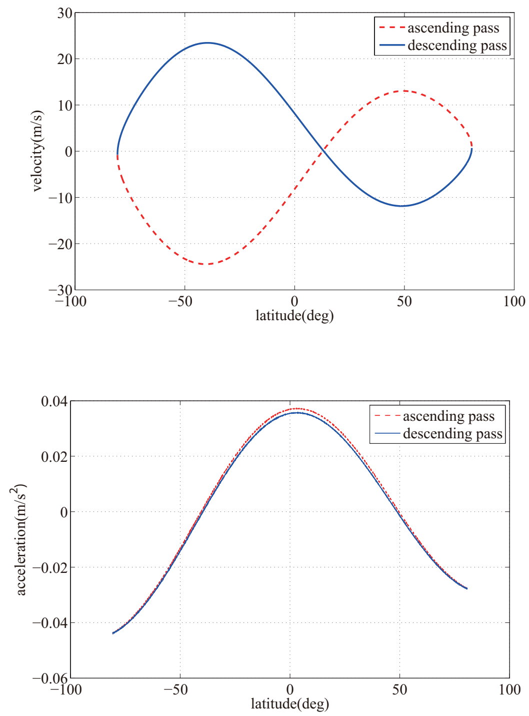

Fig. 1. (a) The altitude rate of the HY-2A satellite and (b) the acceleration of the HY-2A satellite's altitude as a function of latitude.

and validation result. A $8.2ms$ time tag bias was obtained by sea level anomalies (SLA) fitting, and a $8.3ms$ 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 $-7.3ms$ time tag bias by means of crossover SSH differencing [5]. Bao *et al.* reprocessed the HY-2A altimeter geophysical data record (GDR) data from National Ocean Satellite Application Center, China (NSOAS), and obtained a new version GDR data with a $-0.26ms$ time tag bias validated by crossover height differencing [9].

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 introduce by sea surface dynamics, e.g., sea state bias (SSB), 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 datation error (time tag bias) of SIRAL A's data products are estimated using bent-pipe transponders located at Svalbard and Crete islands [11]. This work demonstrated the feasibility of estimating in orbit radar altimeter's time tag bias using 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 from March 2012 [12], [13](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 echo signal delay of 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, then 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 bias, 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 (MOE) POD data are utilized. HY-2A altimeter operates in search mode during calibration. Under this mode, HY-2A altimeter processes 1 from each of the 4 observations and records corresponding samples of time-domain base band waveform. The range tracker does not work, and the delay of the range window, R_{se}, is set to a precalculated value. R_{se} is higher than orbit height of the altimeter. By properly setting echo signal delay of the reconstructive transponder, echo signal from the reconstructive transponder can be sent into altimeter's range window without interference of echo signal from surface.

Fig. 2. Setting up reconstructive transponder .

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 global position system (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, and the time tag bias of the altimeter can be determined using the spatial relationship between the reference range and the altimeter's range.

R, the range between the altimeter and the reconstructive transponder can be written as a quadratic function of time t:

$$R(t) = (R_0 - H) + \frac{(R_e + H)GM}{2(R_0 - H)(R_e + R_0)^2} t^2 \quad (5)$$

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

$$R(t) = at^2 + bt + c, a \neq 0 \quad (6)$$

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 Δt 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

$$R_a(t_a) = 2at_a^2 + 2bt_a + c' \quad (7)$$

where $t_a = t + \frac{1}{2}\Delta t$ 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

$$R_a(t') = 2a(t_a + t_b)^2 + 2b(t_a + t_b) + c'. \quad (8)$$

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:

$$t_b = \frac{-b_b}{2a_b} - \frac{-b}{2a}. \quad (9)$$

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.

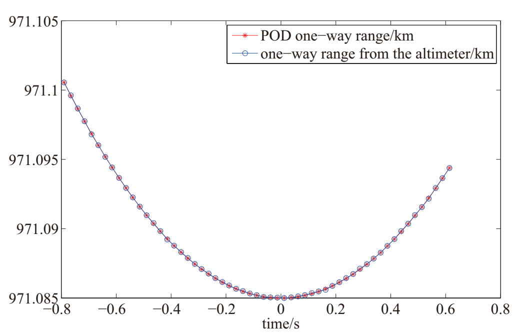

Fig. 3. POD one-way range between the altimeter and the transponder, and the one-way range from the HY-2A altimeter's observation(from experimental calibration on August 9, 2012).

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 below: Take altimeter's two-way range parabola, R_a, as sum of parabolas $R_{at}(t_t)$ and $R_{ar}(t_r)$:

$$R_a = R_{at}(t_t) + R_{ar}(t_r) \quad (10)$$

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

$$\begin{aligned} R_{rt}(t_t) &= interp(R(t), t, t_t) \\ R_{rr}(t_r) &= interp(R(t), t, t_r) \end{aligned} \quad (11)$$

where $interp$ is interpolation operation. Considering the existence of range bias B_R,

$$\begin{aligned} R_{at}(t_t) &= R_{rt}(t_t) + B_R \\ R_{ar}(t_r) &= R_{rr}(t_r) + B_R. \end{aligned} \quad (12)$$

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

$$R_a - R_{rt}(t_t) - R_{rr}(t_r) = 2B_R. \quad (13)$$

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

$$\begin{aligned} R_{rt}(t'_t) &= interp(R(t), t, t_t + \delta t) \neq R_{rt}(t_t) \\ R_{rr}(t'_r) &= interp(R(t), t, t_r + \delta t) \neq R_{rr}(t_r). \end{aligned} \quad (14)$$

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

$$R_a - R_{rt}(t'_t) - R_{rr}(t'_r) \neq 2B_R. \quad (15)$$

The slope of $R_a - R_{rt}(t'_t) - R_{rr}(t'_r)$ is not zero. We can utilize an auxiliary parameter Δt in interpolation:

$$\begin{aligned} R_{rt}(t''_t) &= interp(R(t), t, t_t + \delta t + \Delta t) \\ R_{rr}(t''_r) &= interp(R(t), t, t_r + \delta t + \Delta t). \end{aligned} \quad (16)$$

Adjust Δt by small steps and recalculate

$$resi = R_a - R_{rt}(t''_t) - R_{rr}(t''_r). \quad (17)$$

When $\delta t = -\Delta t$, the slope of $resi$ returns to zero, and time tag bias δt is obtained.

Algorithm steps are listed below:

$\langle 1 \rangle$ Obtain t and $R(t)$ from POD data, and t_r and R_a from altimeter data. $t_t = t_r - int_a$. Initialize parameter Δt.

$\langle 2 \rangle$ Calculate $R_{rt}(t'_t)$ and $R_{rr}(t'_r)$:

$$\begin{aligned} R_{rt}(t'_t) &= interp(R(t), t, t_t + \Delta t) \\ R_{rr}(t'_r) &= interp(R(t), t, t_r + \Delta t). \end{aligned}$$

$\langle 3 \rangle$ Calculate $resi$:

$$resi = R_a - R_{rt}(t'_t) - R_{rr}(t'_r). \quad (18)$$

$\langle 4 \rangle$ If the slope of $resi$ is small enough, stop. Otherwise, adjust Δt by small steps, and return to $\langle 2 \rangle$.

To analyse this algorithm's performance, using (6), we can get

$$\begin{aligned} R_{ref}(t') &= R(t) + R(t+\Delta t) \\ &= 2a(t_a)^2 + 2b(t_a) + c'. \end{aligned} \tag{19}$$

Let $w \sim N(0, \sigma^2)$, then

$$x(t_b) = R_a(t') - R_{ref}(t') + w(t'). \tag{20}$$

Linear expression of (20) at t_s is obtained by one-order Taylor-series approximation:

$$x(t_b) \approx [4at_s + 2b + 4a(t' + \frac{1}{2}\Delta t)]t_b - 2a(t_s)^2 + w. \tag{21}$$

We call (9) algorithm 1, and (21) algorithm 2. Let $a = 50$, $b = 0$, $ts = 9 \times 10^{-3}s$, $\Delta t = 4 \times 6.48^{-3}s$(HY-2A altimeter records 1 from each of the 4 observations in search mode), $\sigma = 0.05m$, 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.

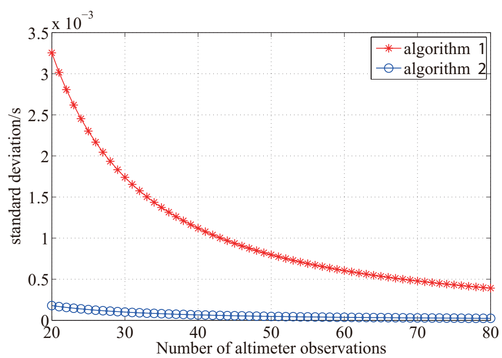

Fig. 4. Cramer-Rao lower bound for the standard deviation of t_b estimation using (9) and (21).

III. Results and Discussion

Fig. 5 shows the time tag bias from 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 1 from each of the 4 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 obtained from highly unreliable altimeter' observation is excluded.

The HY-2A satellite onboard central electronic system gets 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 seconds). Therefore, the behaviors of both side A and side B's time tag bias should be similar, and this inference is confirmed by Fig. 5.

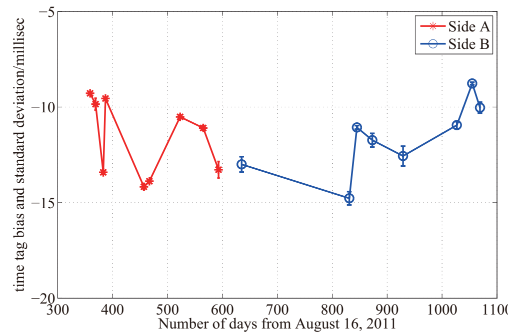

Fig. 5. time tag bias and the standard deviation of each measurement.

Wang's $-7.3ms$, Bao's $-0.26ms$ 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 $t - \delta t$. δt is the absolute value of time tag bias.

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

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

IV. Conclusion

The preliminary HY-2A altimeter's time tag bias estimation work using a reconstructive transponder is introduced in this work. 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 records 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 above can be implemented.

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