Echo Signal Quality Analysis During HY-2A Radar Altimeter Calibration Campaign Using Reconstructive Transponder Postprint

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

Abstract

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Full Text

Preamble

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Abstract—A reconstructive transponder has been utilized for the in-orbit calibration campaign of the HY-2A radar altimeter since March 2012. The precision of the final calibration result is influenced by the echo signal' s quality within the HY-2A altimeter' s range window. As an indicator of signal quality, echo signal dwell time is analyzed considering its influence on signal quality and its associated uncertainty. In HY-2A altimeter calibration, the echo signal dwell time is determined by radial orbit prediction uncertainty and the real-time signal processing mechanism of the reconstructive transponder. The real-time signal processing mechanism of the reconstructive transponder utilizes some incoming signal samples without transmitting echo signals before responding. Compared with the length of the HY-2A altimeter' s range window, the radial orbit prediction uncertainty is large. Large radial orbit prediction uncertainty and the signal processing mechanism of the reconstructive transponder are the two main factors that limit the echo signal dwell time in HY-2A altimeter calibration. Finally, approaches for increasing echo signal dwell time are briefly proposed.

Index Terms—Altimeter, reconstructive transponder, dwell time, signal quality

I. Introduction

The HY-2A radar altimeter in-orbit range absolute calibration campaign using a reconstructive transponder has been carried out since March 2012. Works on signal processing and utilization of the reconstructive transponder are presented in [**?**]-[**?**]. Bao et al. utilized the HY-2A ultra-stable oscillator (USO) drift calibration data from the calibration campaign using the reconstructive transponder and successfully mitigated the significant sea surface height (SSH) drift that existed in the HY-2A altimeter Interim Geophysical Data Records (IGDR) [**?**].

The basic requirement of a transponder for radar altimeter calibration is sending echo signals into the altimeter's range window. So far, there have been two types of transponders for in-orbit radar altimeter calibration: bent-pipe transponder and reconstructive transponder. The bent-pipe transponder, a type of transponder with relatively simple system structure, has been utilized for in-orbit radar altimeter calibration for more than 20 years. The principle of in-orbit radar altimeter calibration utilizing a transponder and pertinent experimental results have been reported in [**?**]-[**?**]. Up to now, the bent-pipe transponder has been utilized as an operational calibration approach for radar altimeters.

The concept of the reconstructive transponder was proposed by MacDoran et al. as an in-orbit calibration approach for the TOPEX/Poseidon mission [**?**]. Mathews reported prototype research and development work as well as field experiment results of a reconstructive transponder, but difficulty in obtaining permission to transmit signals to the TOPEX/Poseidon satellite prevented further calibration experiments [**?**]. No work about in-orbit radar altimeter calibration using a reconstructive transponder had been reported until the HY-2A altimeter calibration work utilizing a reconstructive transponder.

In altimeter calibration using a transponder, let the ranges from the altimeter observation be $R_a[n]$, $n = 1, 2, ..., N$, the reference ranges from the precision orbit determination (POD) data be $R_0[n]$, $n = 1, 2, ..., N$, and the standard deviation of $R_a[n]$ be σ_a. Then the altimeter' s range bias B_a can be estimated as:

$$B_a = \frac{1}{N}\sum_{n=1}^{N}(R_a[n] - R_0[n]).$$

If the altimeter can receive more echo signal samples, higher precision of final calibration results can be achieved:

$$\sigma_{B_a} = \frac{\sigma_a}{\sqrt{N+M}}, \quad M > 0$$

where σ_{B_a} is the standard deviation of B_a, and $N + M$ corresponds to more echo signal samples in the altimeter' s range window. The σ_a in (2), which is determined by the system features of the radar altimeter and the reconstructive transponder, is regarded as a constant in this paper. The larger the $N + M$, the more signal samples are observed by the altimeter, and the longer the echo signal dwell time in the altimeter' s range window.

Therefore, $N + M$ can be measured by echo signal dwell time. In the HY-2A altimeter calibration campaign, the echo signal dwell time in (2) changed significantly in each calibration and was the main factor affecting σ_{B_a}. In this paper, we take echo signal dwell time as a main indicator of the echo signal quality of the reconstructive transponder. The maximum dwell time can be regarded as constant for a particular in-orbit radar altimetry mission; hence, the causes that reduce echo signal dwell time are important for calibration result improvement.

As will be discussed below, the range between the altimeter and the transponder is a parabolic function of time t; the shape of the range curve in the altimeter' s range window reflects the echo signal dwell time, i.e., a non-ideal range curve indicates a shorter dwell time. Equation (2) applies to both a bent-pipe transponder and a reconstructive transponder. So far, discussion on echo signal dwell time and the shape of the signal curve in altimeter calibration utilizing a bent-pipe transponder has been limited.

The rest of the paper is organized as follows: In Section II, the distance between the satellite and the reconstructive transponder is modeled as a function of time. Based on this, several possible echo signal curves are shown. Furthermore, actual echo signal dwell times obtained from calibration are presented. In Section III, the differences between the responding mechanisms of a bent-pipe transponder and a reconstructive transponder are discussed, and the real-time signal processing mechanism of the reconstructive transponder is examined as a cause of non-ideal echo signal curves. Radial orbit prediction uncertainty as another cause of non-ideal range parabolas is discussed in Section IV. In Section V, analysis of orbit prediction uncertainty at the Beijing calibration site is presented. Finally, Section VI concludes the paper and proposes possible approaches to obtain more signal samples in the altimeter range window.

II. Dwell Time of Echo Signal

$R(t)$, the distance between the altimeter and the reconstructive transponder, can be modeled as a parabolic function of time t [**?**]:

$$R(t) = (R_0 - (R_e + H))\sqrt{\frac{GM}{(R_e + R_0)^3}}t^2$$

where R_e is the radius of the Earth, R_0 is the height of the altimeter, H is the height of the transponder relative to the Earth' s surface, and $GM = 3.986 \times 10^{14}\mathrm{m}^3\mathrm{s}^{-2}$ is a constant.

During calibration, the HY-2A altimeter operates in search mode that provides a 240-meter-long two-way range window. In an actual HY-2A calibrating overpass at Beijing, $R_0 = 971$ km, $R_e = 6371$ km, $H = 55$ meters, and the theoretical maximum dwell time of $R(t)$ in the HY-2A altimeter' s range window is 4.5 seconds. Reference [**?**] discusses the approach to identifying an error due to varied Doppler effect delays. However, in the discussion of echo signal visibility during calibration, the error from the Doppler effect can be safely ignored.

[Figure 1: see original paper] shows the theoretical range curve with maximum dwell time and other kinds of non-ideal range curves. The maximum dwell time parabola can provide the maximum number of signal samples in the altimeter' s range window and thus minimize σ_{B_a} in (2), but it is almost impossible to obtain in actual calibration. A symmetric parabola with smaller dwell time, an asymmetric parabola with visible apex, and an asymmetric parabola with invisible apex are three kinds of curves that appear in actual calibration data. Both the real-time signal processing mechanism of the reconstructive transponder and radial orbit prediction uncertainty affect the shape of the parabola and will be discussed in detail in the following sections. [Figure 2: see original paper] shows how these two factors affect the curve shape in the altimeter' s range window.

The actual echo signal dwell times in calibration are shown in [Figure 3: see original paper]. It is clear that most calibration results are far from the theoretical maximum dwell time.

III. Real-Time Signal Processing Mechanism and Asymmetric Parabola

A transponder for in-orbit radar altimeter calibration must guarantee a controlled time interval between the incoming signal and the responding signal during calibration. The responding mechanisms of bent-pipe transponders and reconstructive transponders differ significantly. A bent-pipe transponder with central frequency f_c simply amplifies and retransmits any signal with central frequency f_c at any time. Therefore, no matter how weak the incoming signal' s power from the altimeter, it will be captured, amplified, and transmitted to the altimeter by the bent-pipe transponder, although the signal may not be properly processed because of low signal-to-noise ratio (SNR). A bent-pipe transponder does not need to determine whether the signal from the altimeter has arrived.

In contrast, it is necessary for a reconstructive transponder to determine the arrival time of the signal from the altimeter because the reconstruction and transmission of the responding signal must be triggered by the signal from the altimeter during calibration. The reconstructive transponder for HY-2A altimeter in-orbit calibration utilizes a real-time signal processing mechanism to achieve this goal, which contains three sub-mechanisms. During these steps, no responding signal is transmitted:

1. **Low SNR rejection**: Any incoming signal whose SNR is lower than the power threshold of the reconstructive transponder will not be processed.
2. **Repeated confirmation**: If a signal with sufficient power appears, several such signals are analyzed to ensure that the signals from the altimeter have indeed arrived.
3. **Tracking establishment**: After repeated confirmation, precise measurement of incoming signal arrival time requires that several signals are processed to establish stable tracking.

[Figure 4: see original paper] shows how the bent-pipe transponder receives, amplifies, and transmits all incoming signals. [Figure 5: see original paper] shows the process by which a reconstructive transponder begins transmitting signals only after several incoming signals have been processed without transmission for low SNR rejection, repeated confirmation, and tracking establishment. It is certain that the relatively simple signal processing mechanism of a bent-pipe transponder preserves the maximum number of responding signals. Improvements to the signal processing mechanism of the reconstructive transponder for HY-2A altimeter calibration can increase the number of responding signals in the altimeter' s range window, but achieving a responding signal count comparable to a bent-pipe transponder is difficult.

When the reconstructive transponder receives the HY-2A altimeter' s transmitting signal, it attempts to establish signal tracking. Before stable tracking is established, the reconstructive transponder does not transmit echo signals. When stable tracking is established, the reconstructive transponder begins transmitting echo signals. During the transmitting procedure, a time delay is added to each echo signal to ensure they can be sent into the HY-2A altimeter' s range window. As previously described, a portion of the echo signal parabola is utilized to establish stable tracking, and no responding signal is sent into the range window of the altimeter during this procedure.

Let the altimeter' s tracking height be T, the height of the altimeter be H, the relative height between the reconstructive transponder and the surface of the reference ellipsoid be h, and the time delay of the reconstructive transponder be D_{trans}. T and h are constants at a particular location, and H changes in each calibration overflight. [Figure 6: see original paper] shows the minimum distances between the HY-2A altimeter and the reconstructive transponder during the calibration campaign from August 9, 2012, to December 21, 2015. Therefore, let H be $H(t)$, where t is time. The responding signal can be seen by the altimeter if the following equation holds [**?**]:

$$H(t) = T + 2h - D_{trans}.$$

Before HY-2A altimeter calibration, D_{trans} is derived from (4) and fed to the reconstructive transponder. T and h are precisely known. However, during HY-2A altimeter calibration, the uncertainty of $H(t)$ from orbit prediction is significant compared with the range window length of the altimeter. [Figure 7: see original paper] shows how large $H(t)$ uncertainty affects the shape of the parabola in the altimeter's range window: a larger responding delay of the reconstructive transponder may provide a symmetric parabola, while a smaller one may provide an asymmetric parabola. More discussions about the uncertainty of $H(t)$ can be found in Section V.

IV. Radial Orbit Prediction Error and Shorter Dwell Time

Equation (4), [Figure 1: see original paper], and [Figure 7: see original paper] indicate that the uncertainty of $H(t)$, the orbit height, has significant influence on the echo signal dwell time in the altimeter' s range window. State-of-the-art precise orbit determination approaches provide POD data of the altimetry satellite with no more than 3 cm radial root mean square (RMS) error [**?**]-[**?**]. The radial orbit error of such small magnitude compared with the tens-of-meters-long range window of the radar altimeter does not affect the shape of the signal curve. However, in actual calibration, D_{trans} in (4) must be calculated and fed to the reconstructive transponder before the satellite overflight, and $H(t)$ is provided by orbit prediction data.

In different radar altimeter working modes during calibration, there are different ways to make equation (4) hold:

1. T **is determined by tracking algorithm**: In this case, to send the responding signal into the altimeter' s range window, D_{trans} satisfies $D_{trans} = 2h_r$, where h_r is the distance between the transponder and the surface. The advantage of surface tracking mode calibration is that $H(t)$ is not required before calibration, and the uncertainty of $H(t)$ does not affect the dwell time of the echo signal range curve in the altimeter' s range window. However, the transponder must be placed at a calibration site where the radar altimeter can maintain tracking. Furthermore, changing the internal delay of the bent-pipe transponder by changing hardware components to satisfy (5) is difficult. It is easy for a reconstructive

transponder to change internal delay through digital signal processing.

The Jason-1 Poseidon-2 radar altimeter in-orbit calibration campaign utilizing a bent-pipe transponder at Gavdos Island, Greece, utilized this mode. All attempts to transmit signals into the Jason-1 altimeter’ s range window failed because the altimeter tracked the sea surface at the calibration site and the bent-pipe transponder at the shore was too high relative to the ocean surface [**?**], [**?**]. The reconstructive transponder carried out several experimental calibrations of the HY-2A altimeter utilizing surface tracking mode where the tracking height was determined by the tracking mechanism, but no reliable calibration results were obtained. Keeping the HY-2A altimeter tracking at the calibration site proved difficult, and echo signals from the rough surface interfered with the echo signals from the reconstructive transponder.

2. T **is determined by an approach independent of surface tracking**: In this case, it is necessary to obtain $H(t)$ before calibration. In HY-2A altimeter calibration, variation of the range between the satellite and the transponder in each calibration is significant compared with the range window length of the radar altimeter. As [Figure 6: see original paper] shows, the range of minimum distance between the HY-2A satellite and the reconstructive transponder is from 971 km to 972 km, while the two-way range window length of the HY-2A altimeter during calibration is 240 meters. Internal delay adjustment of a bent-pipe transponder by component replacement before each satellite overflight is difficult, and no report about the utilization of this approach in calibration has been seen. Altimeter tracker height adjustment and reconstructive transponder internal delay adjustment are two approaches to compensating for orbit height variation. [Figure 8: see original paper] briefly shows the relationship between these two approaches.
    a) **Altimeter tracker range adjustment**: In this case, before each calibration, $H(t)$, h, and D_{trans} are constant. T is obtained from (4). Setting T by ground command is a traditional approach that has been used for several altimetry mission calibration campaigns using bent-pipe transponders [**?**], [**?**], [**?**]. Another approach is DIODE/DEM (DORIS Immediate Orbit on-board Determination/Digital Elevation Model) mode of the DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) system. DIODE is a real-time orbit determination mode that can provide orbit data with about 5 cm radial component RMS [**?**]. In DIODE/DEM mode, DIODE provides $H(t)$, and DEM provides h; then T is obtained from (4) and fed to the altimeter before the calibration overflight. DIODE/DEM mode was implemented on the Jason-2 mission for the first time as an experimental mode [**?**]. DIODE/DEM mode has been proven effective during the Jason-2 calibration campaign carried out at Gavdos Island, Greece, utilizing a bent-pipe transponder [**?**] and provided orbit determination data with less than one centimeter accuracy on

the radial component [?]. There is no report about the influence on the echo signal range curve introduced by the uncertainty of $H(t)$ in calibration campaigns of other radar altimetry missions.

b) **Reconstructive transponder internal time delay adjustment**: In this case, the altimeter tracker height T is the same for each calibration, h is a known constant, and D_{trans} is calculated and fed to the reconstructive transponder before calibration. HY-2A altimeter calibration using a reconstructive transponder adopted this approach for the first time. The uncertainty of $H(t)$ from the POD data during HY-2A altimeter calibration is discussed in Section V.

V. Analysis of Orbit Prediction Uncertainty at Calibration Site

The HY-2A altimeter operates in search mode during calibration. In this mode, the HY-2A altimeter' s tracker range is fixed at a preset value T. There is $T > H(t)$ to eliminate reflection from the Earth' s surface. If there is a bias in $H(t)$, according to (4), the ideal echo signal range curve in the HY-2A altimeter' s range window cannot be obtained. The uncertainty of $H(t)$ at Beijing is discussed below.

The calibration sessions at Beijing were from March 2012 to March 2015, and a new experimental calibration session at Mudanjiang, Heilongjiang Province, China, began in March 2015. [Figure 9: see original paper] shows the location of the calibration site. The Beijing site is far from the descending pass, and all calibrations were carried out on the ascending pass.

We define $\hat{R}_m$ as the minimum distance between the altimeter and the reconstructive transponder from orbit prediction, and R_m as the minimum distance from POD. The calibration site is near the sub-track position of the satellite; hence, the assumption $R_m = H(t)$ is used here. We define $BR = R_m - \hat{R}_m$, where BR is the bias between R_m and $\hat{R}_m$.

It is preferable for reconstructive transponder calibration if BR is predictable. If $BR[n]$ at day n is known, then $BR[m]$, $m > n$, can be estimated with acceptably small uncertainty compared with the length of the altimeter' s range window. [Figure 10: see original paper] shows BR sequences at the Beijing calibration site. More than two years of BR observations at Beijing show that it is highly unpredictable. Therefore, only limited calibrations at Beijing met a BR with relatively small bias. As [Figure 10: see original paper] shows, there is only 1 BR observation in 26 BR observations whose absolute value is less than 5 meters. There are only 11 BR observations in 26 BR observations whose absolute values are less than 60 meters, which are the limits of the HY-2A altimeter' s range window. Both the cause of the unpredictable behavior of BR and effective approaches for mitigating the uncertainty of BR at the Beijing site need further investigation.

VI. Conclusion

The reconstructive transponder provides a novel approach to calibrate the in-orbit radar altimeter. However, significant uncertainty of orbit prediction and the real-time signal processing mechanism of the reconstructive transponder limit the number of echo signals in the HY-2A altimeter' s range window. Reduction of orbit prediction uncertainty is a straightforward way to provide more echo signal samples. Improvement of the signal processing mechanism to reduce time consumption before transmitting is also under development.

Acknowledgment

This work was supported by: 1) CNES AVISO and OSTM/Jason-2 GDR data, which were produced and distributed by Aviso (http://www.aviso.altimetry.fr/), as part of the Ssalto ground processing segment; 2) National Satellite Ocean Application Service (NSOAS) for providing assistance during experimental calibration, the HY-2A altimeter IGDR, and auxiliary data.

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