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Estimating the Time Tag Bias of HY-2A Radar Altimeter and Its Application to Dual-frequency Ionosphere Correction

Maofei Jiang\textsuperscript{a,b}, Ke Xu\textsuperscript{a}, Yalong Liu\textsuperscript{c}, and Lei Wang\textsuperscript{a}

\textsuperscript{a}Key Laboratory of Microwave Remote Sensing, National Space Science Center, Chinese Academy of Sciences, Beijing, China; \textsuperscript{b}University of Chinese Academy of Sciences, Beijing, China; \textsuperscript{c}Yantai Marine Environmental Monitoring Center Station, State Oceanic Administration, Yantai, China

\textbf{ABSTRACT}

The sea surface height (SSH) derived from radar altimetry is determined by the distance from the satellite to the sea surface and the altitude of the satellite above a reference ellipsoid. The former is measured by the radar altimeter, while the latter is determined by the precision orbit determination (POD). The clock for the POD equipment is independent from that of the radar altimeter onboard the HY-2A satellite. The time tag bias, which is the bias between the time tags provided by the two independent clocks, can greatly affect the SSH measurement accuracy of HY-2A altimeter. This paper estimates the time tag bias of HY-2A radar altimeter using the crossover differences obtained from the sensor geophysical dataset records (SGDR) from February 2014. We obtained a $-0.61$-ms Ku-band time tag bias and a $-5.61$-ms C-band time tag bias. After we added the time tag bias corrections to the SSH measurements from Ku and C bands, respectively, the means and standard deviations of the global crossover differences can be significantly reduced. We then applied the SSH measurements with the time tag biases corrected to calculate the HY-2A dual-frequency ionosphere correction, significantly improving the accuracy of the HY-2A dual-frequency ionosphere correction.

\textbf{KEYWORDS}

Dual-frequency ionosphere correction; HY-2A; radar altimeter; time tag bias

\textbf{Introduction}

HY-2A (Haiyang-2A) is China’s first ocean dynamic environment satellite, and radar altimeter is one of its main payloads. One of the main objectives of the radar altimeter onboard the HY-2A satellite is to measure the sea surface height. The basic principle of satellite radar altimetry is very simple. The radar altimeter transmits an electromagnetic pulse toward the sea surface and measures the two-way travel time between the satellite and the sea surface. The range between the satellite and the sea surface can be obtained from the two-way travel time. By subtracting this range from the altitude of the satellite above a reference ellipsoid, we can derive the sea surface height, which is the height of the sea surface relative to the reference ellipsoid. The altitude of the satellite is determined by precision orbit determination.
(POD). The two clocks providing the time tags for the POD equipment and the radar altimeter onboard the HY-2A satellite, respectively, are independent of each other. There may be a bias between the time tags provided by the two clocks, and this bias is known as the time tag bias, which can affect the accuracy of the SSH measurement derived from the radar altimeter.

Several spaceborne radar altimeters have been launched during the past few decades. However, there are relatively few published studies on the time tag bias. Schutz et al. (1982) estimated the time tag bias of Seasat altimeter using the crossover differences and the geoid model. The time tag bias of Seasat altimeter Schutz detected is around $-78.1$ ms. Marsh et al. (1982) also estimated the Seasat altimeter time tag bias using the crossover differences and obtained a $-81.0$-ms time tag bias. Scharroo et al. (2000) estimated the time tag biases of the ERS-1 and ERS-2 altimeters and discussed their causes. Naeije et al. (2011) estimated the time tag bias of CryoSat-2 synthetic interferometric radar altimeter (SIRAL) with the low-resolution mode (LRM) data and obtained an $8.2$-ms time tag bias using the sea level anomaly fitting, and an $8.3$-ms time tag bias using the crossover differences. Wang et al. (2013) estimated the time tag bias of HY-2A altimeter using the crossover differences obtained from the interim geophysical data record (IGDR) data from 7 July 2012, to 21 July 2012, and obtained a $-7.3$-ms time tag bias. Bao et al. (2015) reprocessed the HY-2A geophysical data record (GDR) data from 25 May 2013 to 19 October 2013 and obtained a $-0.26$-ms time tag bias using the crossover differences. Wan et al. (2015) estimated the time tag bias of HY-2A altimeter using reconstructive transponder and the HY-2A IGDR data from 9 August 2012 to 20 July 2014. However, their results have not been validated.

Previous studies on the time tag bias estimation were focused on the SSH measurements from the Ku band. The altimeters onboard Seasat, ERS-1, ERS-2, and CryoSat-2 are all single-frequency altimeters. However, the altimeter onboard HY-2A satellite is a dual-frequency (Ku band and C band) altimeter. The SSH measurement from the C band is vital to calculate the dual-frequency ionosphere correction. This study aims to show how much the Ku-band and C-band time tag biases influence measurements from HY-2A and to obtain a better dual-frequency ionosphere correction by correcting the time tag biases. We used the crossover differences obtained from the reprocessed sensor geophysical dataset records (SGDR) data from February 2014 to estimate the time tag biases. Finally, we obtained a $-0.61$-ms Ku-band time tag bias and a $-5.61$-ms C-band time tag bias. We validated the obtained time tag biases using crossover analysis with the reprocessed SGDR data from January 2014. After we added the time tag bias corrections to the SSH measurements, the means and standard deviations of the crossover differences can be significantly reduced. We then used the SSH measurements with the Ku-band and C-band time tag biases corrected to calculate the HY-2A dual-frequency ionosphere correction and significantly improved the accuracy of the HY-2A dual-frequency ionosphere correction.

**Principle of time tag bias**

At the given time $t$, we can obtain the sea surface height $SSH(t)$ by subtracting the altimeter measured range $h(t)$ from the POD-provided altitude $H(t)$.

$$SSH(t) = H(t) - h(t)$$ (1)
Both $H(t)$ and $SSH(t)$ in (1) are relative to the reference ellipsoid. $h(t)$ contains the range and geophysical corrections:

$$h(t) = h_{\text{range}} + h_{\text{dry}} + h_{\text{wet}} + h_{\text{iono}} + h_{\text{ssb}} + h_{\text{ocean}} + h_{\text{solid}} + h_{\text{pole}} + h_{\text{DAC}}$$  \hspace{1cm} (2)

where $h_{\text{range}}$ is the altimeter measured range between the satellite and the sea surface at the given time $t$. $h_{\text{dry}}$ and $h_{\text{wet}}$ are the dry and wet troposphere corrections, respectively. $h_{\text{iono}}$ is the ionosphere correction and $h_{\text{ssb}}$ is the sea state bias. $h_{\text{ocean}}$ is the geocentric ocean tide correction and $h_{\text{solid}}$ is the solid earth tide correction. $h_{\text{pole}}$ is the pole tide correction and $h_{\text{DAC}}$ is the dynamic atmosphere correction.

For HY-2A altimeter, the time tags of $h(t)$ and $H(t)$ are, respectively, determined by the altimeter’s clock and the POD system’s clock. The time tag bias $t_b$ is the bias between altimeter’s time and the POD system’s time. Assume the POD system’s time is the reference time, the altimeter’s clock provides time tag $t' = t_b + t$ at time $t$. The time tag bias introduces a bias $\Delta H$(Wang et al. 2013; Wan et al. 2015):

$$\Delta H = H(t') - H(t) = \frac{1}{2} \ddot{H} t_b^2 + \cdots$$  \hspace{1cm} (3)

where $\dot{H}$ and $\ddot{H}$ are, respectively, the rate and the acceleration of $H$. Normally, the term $\frac{1}{2} \ddot{H} t_b^2$ and higher-order terms can be neglected,

$$\Delta H = H(t') - H(t) \approx \dot{H} t_b$$  \hspace{1cm} (4)

From (1), (3), and (4), we can obtain

$$H(t) - h(t') = H(t') - h(t') - \dot{H} t_b = SSH(t') - \dot{H} t_b$$  \hspace{1cm} (5)

where $\dot{H} t_b$ is the bias term of SSH.

Data

**ERA-interim reanalysis**

We used the ERA-Interim data to calculate the dry and wet troposphere corrections. ERA-Interim is the third global reanalysis project of the European Centre for Medium-Range Weather Forecasts (ECMWF). It is the successor of ERA-40 and provides reanalysis data from 1979 until present. The sea state bias in (2) is calculated using the significant wave height and the wind speed. However, the wind speed in HY-2A SGDR is not reliable (the backscattering coefficient used to derive the wind speed in HY-2A SGDR has not been fully calibrated; after the backscattering coefficient is fully calibrated, the derived wind speed will be better), so we used the wind speed derived from ERA-Interim to calculate the sea state bias for HY-2A altimeter. The data in ERA-Interim are provided in uniform latitude/longitude grids at 00, 06, 12, and 18 UTC every day. The data we used are projected on the grid of $0.25^\circ \times 0.25^\circ$.

**HY-2A altimeter**

HY-2A was launched on 16 August 2011. It is a polar-orbit satellite with an orbit height of 971 km and an inclination of 99.3°. The payloads on HY-2A include a dual-band (13.58 and
5.25 GHz) radar altimeter (RA), a Ku-band microwave scatterometer (SCAT), and a microwave imager (MWI) (Zheng et al. 2014). The RA onboard HY-2A is equipped with a three-channel (18.7, 23.8, and 37 GHz) microwave radiometer to correct the altimeter range measurements for atmospheric range delays induced by water vapor. The repeat cycle of HY-2A is 14 days, which means every location along the HY-2A ground track is measured approximately every 14 days. The SGDR data of HY-2A altimeter are produced by NSOAS (National Ocean Satellite Application Service, China). In this paper, we used two-cycle reprocessed SGDR data from 1 February 2014 to 28 February 2014 to estimate the time tag biases of HY-2A altimeter. We then applied the time tag bias corrections to the data from 1 January 2014 to 31 January 2014 to validate the time tag biases and assess the performance of the improved HY-2A dual-frequency ionosphere correction.

**JASON-2 altimeter**

We used the Jason-2 altimeter data to assess the performance of the SSH measurements and the dual-frequency ionosphere correction derived from HY-2A altimeter. Jason-2, launched in June 2008, is the successor of TOPEX/Poseidon (launched in August 1992) and Jason-1 (launched in December 2001). Jason-2 occupies a non-sun-synchronous orbit at an altitude of 1336 km with an inclination of 66.15°, and the Poseidon-3 radar altimeter is its main payload. Poseidon-3 is a dual-frequency radar altimeter operating at 13.575 GHz (Ku band) and 5.3 GHz (C band). An advanced microwave radiometer (AMR) consisting of three separate channels at 18.7, 23.8, and 34 GHz is onboard Jason-2 for wet troposphere delay correction. The repeat cycle of Jason-2 is about 9.91 days. In this study, we used the version “D” of Jason-2 GDR data from 1 January 2014 to 31 January 2014. The GDR data that we used are obtained from Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO).

**Estimating HY-2A radar altimeter time tag bias**

**Time tag bias estimation method using the crossover differences**

According to Marsh and Williamson (1982), given a time tag bias $t_b$, the sea surface height can be written as

$$SSH = H - h + \dot{h} t_b$$

where $\dot{h}$ is a range measurement rate which is independent of $t_b$.

The crossover point is the intersection of the ascending and descending passes at the same latitude and longitude. We can obtain the crossover difference by subtracting the SSH measurement on the descending pass $SSH^d$ from the SSH measurement on the ascending pass $SSH^a$. The superscripts $a$ and $b$ denote ascending and descending passes, respectively. Therefore, the crossover difference can be written as

$$\Delta SSH = SSH^a - SSH^d$$

Or

$$\Delta SSH = H^a - h^a - H^d + h^d + (\dot{h}^a - \dot{h}^d) t_b$$
The time tag bias $t_b$ can be estimated using the least square method (Marsh and Williamson 1982):

$$
t_b = \frac{\sum_i p_i R_i}{\sum_i p_i^2}
$$

(9)

where for each of the $i$ sea surface height discrepancies

$$
R_i = SSH^a_i - SSH^d_i
$$

(10)

$$
P_i = h^a_i - h^d_i
$$

(11)

Therefore, we can use the SSH differences and the measurement rate differences at the crossover points to estimate the time tag bias. After obtaining the time tag bias using (9), we can correct the time tag bias using (6).

**Results of HY-2A altimeter time tag bias estimation**

We reprocessed the HY-2A SGDR data derived from NSOAS. Table 1 shows the methods for range and geophysical corrections we used. The GPS-derived global ionosphere maps (GIM) ionosphere model was used to compute the ionosphere correction. The sea sate bias was corrected using the nonparametric models derived from the Jason-2 geophysical dataset records (GDR) data from the year of 2011 (Jiang et al. 2016). The geocentric ocean tide was computed using the GOT4.10c tide model. The solid earth tide was computed with the method described by Cartwright and Tayler (1971) and Cartwright and Edden (1973). The pole tide was computed using the method described by Wahr (1985) and the data from the International Earth Rotation and Reference Systems (IERS). The dynamic atmosphere correction was computed using the dynamic atmosphere correction (DAC) data from AVISO.

The reprocessed HY-2A SGDR data from 1 February 2014 to 28 February 2014 were used to estimate the Ku-band and C-band time tag biases of HY-2A altimeter. We used the spline interpolation to derive the measurements at the crossover points. In order to obtain data with good quality, we only used the data that satisfy four criteria:

1) The time window is less than three days.
2) The water depth is larger than 1000 m.
3) The latitude is between 50°S and 50°N.
4) The SSH difference is less than 20 cm for Ku band and 50 cm for C band.

**Table 1.** Methods for range and geophysical corrections used to reprocess the HY-2A SGDR data.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Model or method</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{dry}$</td>
<td>Dry troposphere correction</td>
<td>ERA-interim</td>
</tr>
<tr>
<td>$h_{wet}$</td>
<td>Wet troposphere correction</td>
<td>ERA-interim</td>
</tr>
<tr>
<td>$h_{iono}$</td>
<td>Ionosphere correction</td>
<td>GIM</td>
</tr>
<tr>
<td>$h_{ssb}$</td>
<td>Sea state bias correction</td>
<td>Nonparametric model</td>
</tr>
<tr>
<td>$h_{ocean}$</td>
<td>Geocentric ocean tide correction</td>
<td>GOT4.10c</td>
</tr>
<tr>
<td>$h_{solid}$</td>
<td>Solid earth tide correction</td>
<td>Cartwright and Edden</td>
</tr>
<tr>
<td>$h_{pole}$</td>
<td>Pole tide correction</td>
<td>Wahr</td>
</tr>
<tr>
<td>$h_{DAC}$</td>
<td>Dynamic atmosphere correction</td>
<td>AVISO</td>
</tr>
</tbody>
</table>
We estimated the time tag biases using (9)–(11), and finally obtained a $-0.61$-ms Ku-band time tag bias and a $-5.61$-ms C-band time tag bias.

Crossover analysis is widely used to assess the performance of the whole altimeter system. For a single mission, the mean of the crossover differences gives the average of the SSH differences between the ascending and descending passes. It should not be significantly different from zero. The standard deviation of the crossover differences conventionally gives an estimate of the overall altimeter system performance (Dorandeu et al. 2004).

We first used in-mission crossover analysis to assess effects of the time tag biases on the SSH measurements. Figures 1 and 2 show the results obtained from the Ku-band measurements. Figure 1 shows the histogram distribution of the global crossover differences before and after the time tag bias is corrected. After the time tag bias is corrected, the mean of the 

![Figure 1](image)

*Figure 1*. Histogram distribution of the global Ku-band-measured SSH differences at the crossover points (a) before and (b) after the time tag bias is corrected.
SSH differences is reduced from 1.47 to 0.45 cm, and the standard deviation of the SSH differences is reduced from 5.43 to 5.26 cm. In order to assess the improvements on the northern and southern hemispheres, respectively, we separated the crossovers in the northern hemisphere from the crossovers in the southern hemisphere, and computed the individual distribution for each hemisphere. Figure 2a and c shows the histogram of the SSH differences before and after the time tag bias is corrected in the northern hemisphere, while Figure 2b and d shows the similar results in the southern hemisphere. After the time tag bias is corrected, the mean of the SSH differences in the southern hemisphere is reduced from 2.35 to 0.37 cm, while the mean of the SSH differences in the northern hemisphere is increased from 0.19 to 0.60 cm. The standard deviations of the SSH differences in the both north and southern hemispheres are reduced but not substantially.

The accuracy of the SSH measurements from HY-2A altimeter can also be evaluated by crossover calibration with Jason-2 altimeter. Figure 3 shows the histogram distribution of the global crossover SSH differences between the HY-2A and Jason-2 altimeters before and after the time tag bias is corrected. After the time tag bias of the Ku band is corrected, the mean of the SSH differences between the HY-2A and Jason-2 altimeters does not change significantly, but the standard deviation of the SSH differences is reduced from 5.65 to 5.59 cm. Therefore, the accuracy of the SSH measurements from HY-2A altimeter can be improved after the time tag bias of the Ku band is corrected.

Figure 2. Histogram distribution of the Ku-band-measured SSH differences at the crossover points before (top) and after (bottom) the time tag bias is corrected in the northern (left) and southern (right) hemispheres, respectively.
Figures 4–6 show the results obtained from the C-band measurements. Figure 6 shows the global distribution map of the single-satellite SSH differences before and after the time tag bias is corrected. As shown in Figures 5a, 5b, and 6a, the positive crossover differences are mainly distributed in the southern hemisphere, while the negative values are mainly distributed in the northern hemisphere. There are two peaks in Figure 4a: a negative peak and a positive peak. For HY-2A satellite, $\hat{H}$ in the northern hemisphere is only half of that in the southern hemisphere around $40^\circ$C14S and $40^\circ$C14N (Wan et al. 2015; Wang et al. 2013). From Figure 6a, we can see that a large number of crossovers are distributed in the regions around $40^\circ$S and $40^\circ$N. Moreover, due to the larger extent of the southern hemisphere ocean, containing substantially more data than the northern hemisphere, the mean of the global crossover differences is mostly determined by the mean of crossover differences in the southern hemisphere. Therefore, the positive peak is larger than the negative peak. From Figures 4b

Figure 3. Histogram distribution of the global Ku-band-measured SSH differences between the HY-2A and Jason-2 altimeters at the crossover points (a) before and (b) after the time tag bias is corrected.
and 6b, we can see that there is only one peak and the spatial distribution of crossover differences (i.e. the sign of the difference) is distributed homogeneously within both hemispheres after the time tag bias is corrected. The mean of the global crossover differences is reduced from 11.32 to \(-0.60\) cm, and the standard deviation of the global crossover differences is reduced from 18.02 to 9.47 cm. As shown in Figure 5, the means and standard deviations of the SSH differences in the northern and southern hemispheres are both significantly reduced after the time tag bias is corrected. In the northern hemisphere, the mean of the SSH differences is reduced from \(-5.09\) cm to \(-0.27\) cm, and the standard deviation is reduced from 13.43 to 10.62 cm. In the southern hemisphere, the mean of the SSH differences is reduced from 22.36 to \(-0.82\) cm, and the standard deviation is reduced from 10.88 to 8.61 cm. Therefore, after the time tag bias of the C band is corrected, the accuracy of the SSH measurements from the C band of HY-2A altimeter is improved significantly.

Figure 4. Histogram distribution of the global C-band-measured SSH differences at the crossover points (a) before and (b) after the time tag bias is corrected.
The estimated C-band time tag bias is $-5.61 \text{ ms}$, which is much larger than the estimated Ku-band time tag bias. As shown in (5), the time tag bias $t_b$ can introduce a bias $\Delta t_b$ to the SSH. Therefore, the improvement after time tag bias correction is much larger for the C band compared to the improvement on the Ku band. It is still not very clear why the Ku-band time tag bias is different from the C-band time tag bias. The altimeter instrument design and the data processing method for the lower level product may both create this difference. In the future, we will further study why the time tag bias has a much smaller effect on the Ku band than it has on the C band.

Application of HY-2A radar altimeter time tag bias to dual-frequency ionosphere correction

The delay of an electromagnetic pulse through the ionosphere is caused by the ionosphere refraction due to the presence of free electrons in the upper atmosphere. The ionosphere correction is proportional to the total electron content (TEC) in the ionosphere and inversely proportional to the square of the radar frequency (Andersen and Scharroo 2011):

$$\Delta R_{\text{iono}} = -\frac{k \text{TEC}}{f^2}$$

where $k$ is a constant of $0.4025 \text{ m GHz}^2/\text{TECU}$. The TEC unit equals to $10^{16} \text{ electrons / m}^2$. 

Figure 5. Histogram distribution of the C-band-measured SSH differences at the crossover points before (top) and after (bottom) the time tag bias is corrected in the northern (left) and southern (right) hemispheres, respectively.
The dual-frequency altimeter onboard the HY-2A satellite can use the dispersion of the ionosphere to measure the delay at two different frequencies and correct the delay. The range measurements measured by the C-band altimeter are inherently less precise than those measured by the Ku-band altimeter. The ionosphere correction to the Ku-band range can be estimated using the Ku-band and C-band measurements (Imel 1994):

$$\Delta R_{\text{iono,Ku}} = \delta f_{\text{Ku}}[R_{\text{Ku}} + SSB_{\text{Ku}} - (R_{\text{C}} + SSB_{\text{C}})]$$  \hspace{1cm} (13)

$$\delta f_{\text{Ku}} = \frac{f_{\text{C}}^2}{f_{\text{Ku}}^2 - f_{\text{C}}^2}$$  \hspace{1cm} (14)

where $f_{\text{Ku}}$ and $f_{\text{C}}$ are the emitted radar frequencies. $R_{\text{Ku}}$ and $R_{\text{C}}$ are the ranges measured by the Ku-band and C-band altimeters. $SSB_{\text{Ku}}$ and $SSB_{\text{C}}$ are the sea state bias corrections for the Ku band and C band, respectively. For HY-2A altimeter, the Ku-band time tag bias is different from the C-band time tag bias. The two time tag biases can affect $R_{\text{Ku}}$ and $R_{\text{C}}$, and thus affect the dual-frequency ionosphere correction. If the time tag biases are not corrected well, the dual-frequency ionosphere will be of poor quality.

The GPS-derived global maps (GIM) can be interpolated in space and time to altimeter ground track to compute the ionosphere correction using (12). The ionosphere correction estimated using the GIM model has accuracy close to the ionosphere correction derived from the dual-frequency altimeters (Andersen and Scharroo 2011). Therefore, we used the GIM ionosphere correction to validate the dual-frequency ionosphere correction derived from HY-2A altimeter.

Figure 6. Global distribution map of the C-band-measured SSH differences (m) at the crossover points (a) before and (b) after the time tag bias is corrected.
Figure 7. GIM ionosphere correction vs (a) HY-2A dual-frequency ionosphere correction with the time tag bias uncorrected, (b) HY-2A dual-frequency ionosphere correction with the time tag bias corrected, and (c) Jason-2 dual-frequency ionosphere correction.
Figure 7a and b compares the GIM ionosphere correction with the HY-2A dual-frequency ionosphere corrections before and after the time tag biases are corrected, respectively. The ionosphere correction derived from the HY-2A dual-frequency altimeters is very poor when the time tag biases are not corrected. After the time tag biases are corrected, the performance of the HY-2A dual-frequency ionosphere correction is obviously improved. The Jason-2 altimeter is also a dual-frequency altimeter. Figure 7c compares the GIM ionosphere correction with the Jason-2 dual-frequency ionosphere correction. From Figure 7b and c, we can see that the standard deviation of the differences between GIM ionosphere corrections and the HY-2A dual-frequency ionosphere corrections with the time tag biases corrected is 0.755 cm, which is very close to 0.767 cm calculated using the Jason-2 dual-frequency ionosphere corrections. Therefore, the accuracy of HY-2A dual-frequency ionosphere correction is close to that of Jason-2 dual-frequency ionosphere correction. Figure 8 compares the dual-frequency ionosphere corrections between the HY-2A and Jason-2 altimeters at the crossovers of which the time difference is less than one hour. The HY-2A dual-frequency ionosphere correction is consistent with the Jason-2 dual-frequency ionosphere correction. The standard deviation of the differences between the HY-2A and Jason-2 dual-frequency ionosphere corrections is approximately 0.623 cm. There is a bias of approximately 1.667 cm. It is likely that this bias is caused by no calibration for C band yet since launch.

Figure 9 shows the histogram distribution of the global SSH differences using the GIM ionosphere correction and the HY-2A dual-frequency ionosphere corrections. After the HY-2A dual-frequency ionosphere corrections are calculated using range measurements with the time tag bias corrected, the standard deviation of the crossover differences is significantly reduced from 5.67 to 5.14 cm. Compared with the GIM ionosphere correction, the HY-2A dual-frequency ionosphere correction with the time tag bias corrected reduces the standard deviation of the SSH differences from 5.21 to 5.14 cm. Figure 10 shows the histogram distribution of the SSH differences between HY-2A and Jason-2 altimeters. Like the results in Figure 9, after the HY-2A dual-frequency ionosphere corrections are calculated using range measurements with the time tag bias corrected, the standard deviation of the crossover differences is significantly reduced from 5.67 to 5.14 cm.
Figure 9. Histogram distribution of the Ku-band-measured SSH differences at the crossover points. (a) Using GIM ionosphere correction. (b) Using dual-frequency ionosphere correction with the time tag bias uncorrected. (c) Using dual-frequency ionosphere correction with the time tag bias corrected.
Figure 10. Histogram distribution of the SSH differences between HY-2A and Jason-2 altimeters with (a) GIM ionosphere correction, (b) dual-frequency ionosphere correction with the time tag bias uncorrected, and (c) dual-frequency ionosphere correction with the time tag bias corrected.
measurements with the time tag bias corrected, the standard deviation of the SSH differences between HY-2A and Jason-2 altimeters is reduced from 5.64 to 5.50 cm. Compared with the GIM ionosphere correction, the HY-2A dual-frequency ionosphere correction with the time tag bias corrected also reduces the standard deviation of the SSH differences between HY-2A and Jason-2 altimeters slightly. Therefore, the HY-2A dual-frequency ionosphere correction with the time tag bias corrected can improve the accuracy of the SSH measurements from HY-2A altimeter with respect to the GIM ionosphere correction and the HY-2A dual-frequency ionosphere correction with the time tag bias uncorrected.

**Summary and conclusion**

This paper estimates the time tag bias of HY-2A altimeter using the crossover differences and improves the HY-2A dual-frequency ionosphere correction by correcting the time tag biases of the Ku and C bands. We reprocessed the HY-2A SGDR data and obtained a $-0.61$-ms Ku-band time tag bias and a $-5.61$-ms C-band time tag bias. After the time tag biases are corrected, both the means and the standard deviations of the Ku-band or C-band crossover differences can be reduced. Due to the larger C-band time tag bias, the improvement after time tag bias correction is much larger for the C band compared to the improvement on the Ku-band. The time tag bias estimations were then applied to calculate the HY-2A dual-frequency ionosphere correction. The accuracy of the dual-frequency ionosphere correction can be improved after the Ku-band and C-band time tag biases are both corrected. The accuracy of the SSH measurements from HY-2A altimeter is also evaluated by the crossover calibration with Jason-2 altimeter. The HY-2A dual-frequency ionosphere correction with the time tag bias corrected can improve the accuracy of the SSH measurements from HY-2A altimeter.

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**ORCID**

Maofei Jiang [http://orcid.org/0000-0002-4688-6260](http://orcid.org/0000-0002-4688-6260)

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