Estimation and Evaluation of GNSS Differential Code Bias (DCB) from Spire Global CubeSats

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Abstract

Measurements from low-cost low earth orbit (LEO) CubeSats can provide a great opportunity to improve observations of global ionospheric state. Accurate DCB estimations of GNSS transmitters and LEO CubeSats receivers must be resolved for high-accuracy absolute ionospheric total electron content (TEC) retrieval. In this study, we focus on estimating GPS transmitter and Spire receiver DCB parameters using LEO satellite POD observations collected by 25 Spire Global CubeSats. Results show that (1) the accuracy of GPS transmitter DCBs estimated by low-cost Spire CubeSats observations are comparable to solutions estimated using hundreds of global distributed ground-based GNSS receivers. (2) Spire receiver DCB determination is highly dependent on the ionosphere effective height (IEH) used in the mapping function. We will develop an optimized IEH model for Spire POD DCB determination in future. (3) Spire receiver DCBs in general exhibit consistent behavior during both daytime and nighttime, with no noticeable variations observed on storm days. However, systematic biases in Spire receiver DCB are visually apparent between daytime and nighttime for some sun-synchronous orbit (SSO) Spire CubeSats when crossing the equator in local afternoon. This is due to the low-latitude ionosphere during this period characterized by strong horizontal gradients which challenges the assumption of ionospheric symmetry and reduces DCB estimation accuracy.

1. Introduction

Spaceborne GNSS receivers have been proven to be a powerful tool to retrieve ionosphere TEC. Dual-frequency GNSS signals can be used to determine topside ionosphere TEC between GNSS transmitters and receivers onboard LEO satellites. To obtain accurate TEC estimation using data from low-cost CubeSats, precise knowledge of DCBs from both GNSS satellites and receivers is needed.

While DCBs of GNSS satellites can be obtained from the international GNSS center (IGS), biases associated with LEO CubeSat-based receivers remain largely unexplored. There are two commonly used methods used for LEO satellite DCB determination. The first is the Zero TEC method. It assumes that the ionospheric TEC above a LEO satellite is zero at high latitudes or during nighttime [1, 2]. The second method is the Least square (LSQ) method which assumes simultaneous observations with different elevation angles have the same zenith TEC under the spherical symmetry hypothesis [3, 4]. It is obvious that the parameter configuration (e.g., ionosphere effective height) in mapping function and solar radiance could be important factors that would influence LEO satellite DCB estimation when using LSQ method. In this study, we estimate Spire CubeSat DCB by investigating the influence of IEH and solar radiance (daytime/nighttime) using LSQ method.

From early 2023, Spire Global operates a constellation of more than 150 CubeSats, and over 100 of them perform GNSS radio occultation (RO) measurements. The Spire CubeSat receives and processes dual-frequency GNSS signals entering three antennas: zenith-pointing precise orbit determination (POD), front RO (FRO), and backward RO (BRO) antennas. The POD antenna receives dual-frequency GNSS signals from both high elevation and low/negative elevation. In this study, we focus on estimating Spire POD antenna DCBs and assess their impact on topside TEC retrieval.

2. Methodology

Equation (1) below is used to estimate DCBs using LSQ method based on ionosphere spherical symmetry assumption. Two simultaneous ionosphere slant TEC (sTEC) observations ($sTEC_A$ and $sTEC_B$) at one given epoch are assumed to have the same vertical TEC (vTEC) above the LEO satellite when applying the mapping function.

$$\begin{cases} sTEC_i = \alpha(P_{sm}^i - c\cdot DCB_{Rx} - c\cdot DCB^{Tx,i}) \\ sTEC_A \cdot M(\varepsilon_A) = sTEC_B \cdot M(\varepsilon_B) \\ M(\varepsilon_i) = \dfrac{\sin\varepsilon_i + \sqrt{(R_{ion}/R_{LEO})^2 - \cos^2\varepsilon_i}}{1 + R_{ion}/R_{LEO}} \\ R_{LEO} = R_E + H_{LEO}, \quad R_{ion} = R_{LEO} + H_{ion} \end{cases} \quad (\mathbf{1}).$$

where P_{sm}^i is the smoothed geometry-free code measurements after performing carrier-to-code leveling. $sTEC_i$ is the sTEC from GNSS Tx to Spire onboard Rx. $i = A, B$. $DCB^{Tx,i}$ and DCB_{Rx} are GNSS satellite i and Spire POD receiver DCBs, respectively. The DCBs are usually assumed to be constant during a day. $\alpha = \frac{f_1^2 \cdot f_2^2}{40.28(f_2^2 - f_1^2)}$. $M(\varepsilon_i)$ is the Foelsche and Kirchengas (F&K) mapping function for converting sTEC to vTEC [5]. ε_i is elevation angle from Spire CubeSat to GNSS satellite, which is empirically set as 35° in this study to mitigate multipath effects and mapping function errors. R_E and H_{LEO} are Earth radius and Spire CubeSat orbit altitude, respectively. H_{ion} is the IEH above the LEO satellite.

From equation (1), $DCB^{Tx,i}$ and DCB_{Rx} are coupled and cannot be estimated separately because of the rank deficiency issue. We adopt two approaches to estimate Spire receiver DCB_{Rx}. With the first approach, we add a zero-mean constraint for available GNSS satellites, which assumes the sum of all GPS DCB^{Tx} is zero, so that DCB^{Tx} and DCB_{Rx} can be estimated simultaneously using the LSQ approach. In the second approach, we use GNSS satellite DCB products from Chinese Academy Sciences (CAS) to correct DCB_{Rx}, so only Spire receiver DCB_{Rx} need to be estimated.

Moreover, it should be noted that F&K mapping function is based on the height-dependent homogeneous distribution of topside ionosphere. However, this assumption is not always reasonable when considering various ionosphere gradients over daytime/nighttime, and ionosphere altitude distribution. In this study, we investigate the dependency of Spire CubeSat DCB on the IEH (H_{ion}) and examine whether DCB estimation is influenced by daytime and nighttime conditions during high solar activities.

3. Results

Figure 1 presents GPS DCB results estimated using the two approaches discussed above. The GPS satellite DCBs are estimated using approach 1 based on data from 25 Spire CubeSats. These estimated results are labeled as University of Colorado Boulder (UCB) in the figure. For reference and comparison, GPS DCB products from two IGS ionosphere analysis centers, CAS and German Aerospace Center (DLR), are also included, which are determined by using hundreds of ground-based GNSS receivers distributed globally. It is observed from top panel of Figure 1 that the GPS DCB solutions from UCB, CAS, and DLR are in the same magnitudes with very small standard deviations, suggesting the feasibility of GPS DCB estimation using Spire POD observations. The bottom panel shows that the GPS DCB differences among the three different solutions are within 1ns for most GPS satellites. This indicates that GPS DCB stability determined by 25 Spire CubeSats equipped with low-cost, low-power, and low-mass GNSS receivers is comparable to those derived from hundreds of global ground-based GNSS sites.

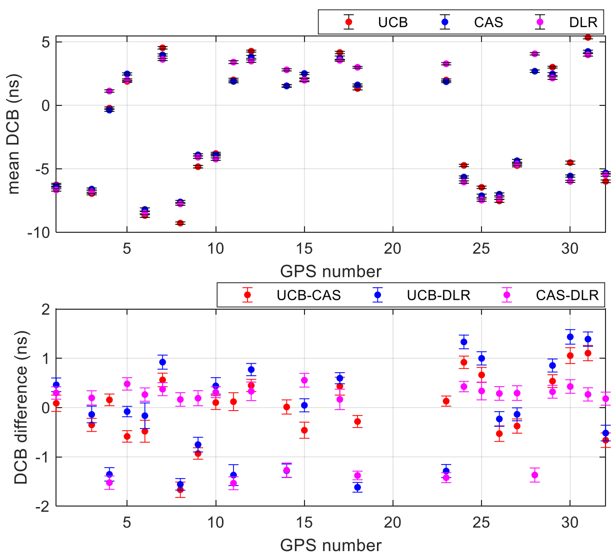

Figure 1. Mean GPS DCB solutions from UCB, CAS and DLR (top panel), and differences among them (bottom panel). UCB indicates GPS DCB estimated using 25 Spire CubeSats observations.

Figure 2 shows Spire CubeSat POD DCB results estimated using approach 1 and 2, and comparison with UCAR products. The top panel shows our estimated DCB using these two approaches agree well with the UCAR products. Note that there are significant DCB magnitude differences among these Spire receivers: DCB values for most receivers are around 75~100ns, while others are around 5~10ns. Following our discussion with Dr. Vu Nguyen from Spire Global, the smaller DCB values are expected because the updated STRATOS GNSS receivers (version 2) are now deployed on those Spire CubeSats. Bottom panel shows Spire CubeSat DCB mean differences and standard deviations (STD) between different DCB solutions. Almost all Spire receiver mean DCB differences from the three solutions are limited to -1 to 2ns with similar STD magnitudes (~1ns), except for Spire ID 99, which is comparable to our previous analysis [9]. This indicates similar DCB stabilities for these Spire reivers. The large standard deviation (STD) of Spire ID 99 may be attributed to its lower orbital altitude compared to other Spire CubeSats: Spire ID 99 orbits at approximately 340 km, whereas the others maintain altitudes around 500-550 km.

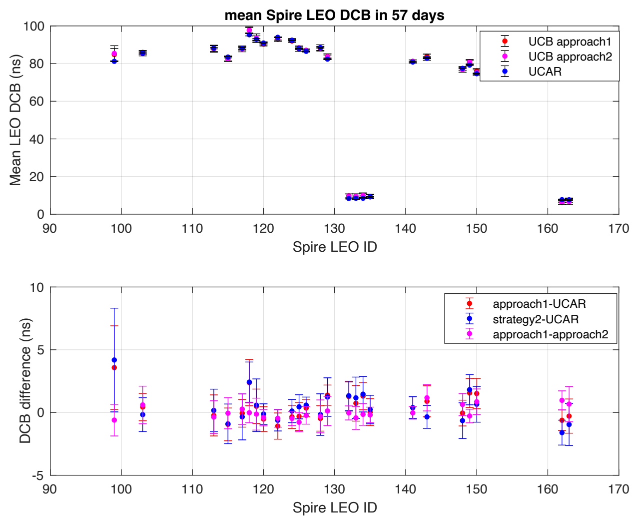

Figure 2. Mean DCB values of Spire CubeSats estimated by UCB approach 1, UCB aproach 2, and UCAR (top panel), and DCB difference among them (bottom panel). H_{ion} in mapping function is set as 4000 km for generating DCB in this plot, which is consistent with the ionosphere effective height used in UCAR product generation.

H_{ion} in the mapping function is set as 4000 km for generating DCB in Figure 2, which is consistent with the ionosphere effective height used in UCAR products generation. According to studies by Yue et al., (2011) [3] and Pedatella et al., (2021) [4], H_{ion} can be selected as several hundreds or thousands of kilometers above the COSMIC satellite orbit altitude without affecting LEO satellites DCB estimation significantly. For COSMIC satellites, 4000km is believed to provide the best performance. However, according to studies by Birch et al. (2002) [6], Zhong et al. (2016) [7], and Wautelet et al.

(2017) [8], the mapping function is sensitive to H_{ion} value which may result in non-ignorable effects on LEO receiver DCB determination. This study investigates the effect of varying H_{ion} on Spire CubeSat DCB retrieval.

Figure 3 shows Spire receiver DCB differences between the UCB and UCAR products when considering various H_{ion} above Spire CubeSat orbits. The DCB difference varies between -5 ns and 1 ns for all Spire CubeSats, except for ID 134 when H_{ion} changes between 1000 km and 5000 km. Moreover, the Spire DCB difference decreases monotonically with increasing H_{ion} from 1000 km to 5000 km. This means that there is a strong dependence of Spire receiver DCB estimation. From Equation (1), Spire receiver DCB and the TEC estimation are closely related. An improper H_{ion} could lead to unreliable LEO satellite receiver DCB estimates and an excessive number of negative TEC values. In our further research, we will develop an optimized IEH model for Spire onboard POD DCB estimations.

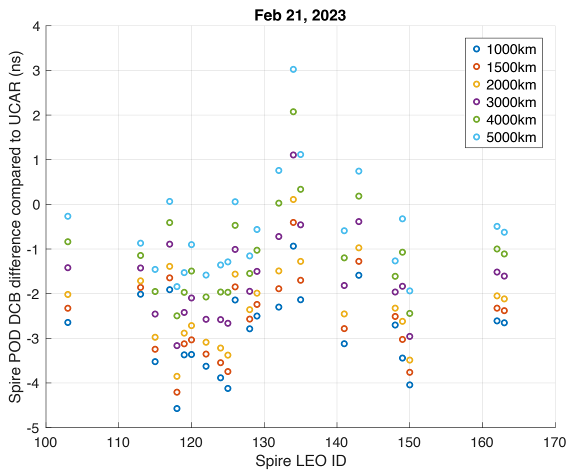

Figure 3. Spire onboard receiver DCB difference between UCB apporaoch 2 and UCAR on February 21, 2023. Various ionosphere effective heights (1000, 1500, 2000, 3000, 4000, and 5000 km) above Spire CubeSat orbit are investigated when estimating LEO receiver DCB using UCB apporaoch 2.

Collocated sTEC from COSMIC-2 satellites are used to evaluate Spire CubeSat-derived sTEC observations, which are empirically selected based on criteria below. For the same tracked GPS satellite at the same epoch, the spatial distance is less than 1.5° in latitude and longitude between Spire and COSMIC-2 satellites. Only sTEC observations for those elevation angles above 45° and LEO satellite altitude differences are within 50 km are used. Each conjunction lasts for only several seconds. We take the median value of the slant TEC difference to determine a single value for the collocated observation. Figure 4 shows collocated sTEC observations (left panel) and histogram of sTEC difference (right panel) observed by 25 Spire CubeSats and six COSMIC-2 satellites during February 21-April 18, 2023. There is a liner correlation with a correlation coefficient of 0.95 for these 356 collocated observations. The mean difference and RMSE are -0.68 and 5.32 TECu, respectively. This large RMSE magnitude could be attributed to several reasons. First, the Nequick-2 TEC estimation used for correction of LEO satellite height difference might not be accurate. Second, the sTEC is obtained during high solar activity period, and the resulting sTEC magnitude is much larger than that from Pedatella et al., (2021). Finally, the H_{ion} value of 4000km may not be an optimal choice for Spire receiver DCB determination. We hope to optimize H_{ion} and provide the best performance.

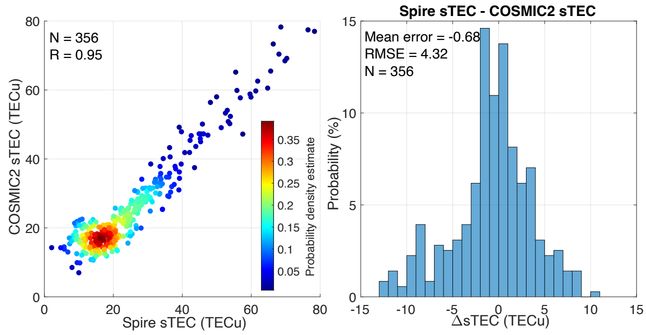

Figure 4. Scatter plot of Spire sTEC observed from 25 Spire CubeSats against collocated COSMIC-2 sTEC (left panel), and histogram of sTEC difference for these collocated events (right panel) during February 21-April 18, 2023. TEC bias due to altitude difference between Spire and COSMIC-2 is corrected by NeQuick-2 model. Ionosphere effective height is 4000km for Spire and COSMIC-2 DCB determination in this plot.

We also analyzed Spire CubeSat DCB estimates during both nighttime and daytime, including storm days. Nighttime is defined as when a Spire CubeSat is in Earth's shadow without direct sunlight exposure in the Earth-centered initial (ECI) coordinate frame; otherwise, it is classified as daytime. Figure 5 shows six selected Spire CubeSats DCB time series using observations from nighttime (light blue) and daytime (light red) during February 21-April 18, 2023, respectively. The left column showed that the Spire CubeSat DCB during nighttime agrees well with those during daytime, and related STD is stabilized around 1-2 ns without significant variations during these days. This result indicates the Spire CubeSat DCB estimation is not influenced by daytime and nighttime conditions. However, there are systematic biases for those DCB values shown in the right column, with the DCB differences ranging from 4 to 7 ns. For example, nighttime DCB magnitude is consistently larger than that of the daytime DCB. The systematic biases shown for Spire CubeSats (103, 143 and 150) are due to their sun-synchronous orbit (SSO) type with local time ascending/descending node (LTAN, LTDN) near early afternoon. The LTAN for Spire CubeSat 103 is 15:05, and LTDN for 143 and 150 is 13:30. These Spire CubeSats cross the equator in the early afternoon where ionosphere has larger horizontal gradients. This challenges the assumption of a spherically symmetric ionosphere used in the F&K mapping function, leading to reduced accuracy in DCB estimation. We will further evaluate the potential impact of nighttime/daytime DCB accuracy from these

SSO Spire CubeSats on topside TEC estimation in future study.

The blue/red dots in each panel represent nighttime/daytime DCB distributions during geomagnetic storm days (Feb 27-28 and Mar 23-24, 2023). When compared to those quiet-day DCB distributions, no noticeable differences are observed on storm days. This suggests that reliable Spire CubeSat DCB estimation can still be achieved using observations from geomagnetic storm periods.

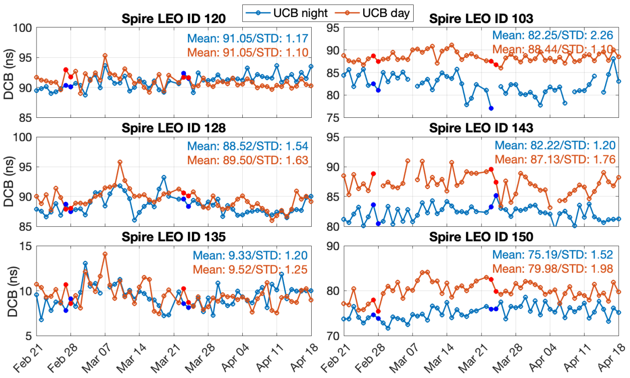

Figure 5. Spire onboard receiver DCB time series for nighttime (light blue) and daytime (light red) during February 21-April 18, 2023. Mean error and STD are illustrated at the top-right corner of each panel. Blue/dots in each panel represent nighttime/daytime DCB distributions during geomagnetic storm days (Feb 27-28 and Mar 23-24).

4. Summary

We estimate GPS transmitter DCB and Spire CubeSat POD receiver DCB using observations collected by 25 Spire CubeSats during February 21-April 18, 2023. Results show that:

(1) GPS transmitter DCB using Spire observations agrees well with solutions from DLR/CAS products. This indicates GPS DCB determined by low-cost CubeSats is comparable to those estimated by hundreds of global ground-based high-end GNSS receivers.

(2) Spire CubeSat DCB variations estimated by two different approaches are very close to UCAR products when the same ionosphere effective height (4000 km) is used in the F&K mapping function. Good agreements can also be observed when comparing collocated absolute sTEC between Spire and COSMIC-2 satellites. However, Spire receiver DCB determination is highly sensitive to ionosphere effective height, which is different from results concluded by Yue et al., (2011) [3] and Pedatella et al., (2021) [4] using COSMIC data. We will develop an optimized IEH model for Spire POD DCB determination in future work.

(3) Receiver DCBs for most Spire CubeSats during nighttime agree well with those during daytime, and no noticeable differences are observed during storm days. However, systematic Spire receiver DCB biases ranging from 4 to 7 ns are visually apparent between daytime and nighttime for some SSO Spire CubeSats when crossing the equator in the local afternoon. This is likely due to ionosphere gradient at low latitudes during local afternoon. The presence of a larger gradient challenges the ionospheric symmetric assumption and leads to reduced accuracy in DCB estimation.

5. Acknowledgements

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