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Transmission delay inconsistency in satellite array antennas cause elevation-dependent pseudorange biases in GNSS signals

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Dear editor,

With the increasing demand for higher-precision positioning by the global navigation satellite system (GNSS), more accurate original measurements are required by the receiver, such as the pseudoranges and carrier phases. However, in recent years, a measurement anomaly has been discovered involving elevation-dependent pseudorange biases in the observations of global positioning system (GPS) and BeiDou navigation satellite system (BDS) satellites. No dependencies of these biases with respect to the observation site, receiver type, or time interval could be identified, which indicates that they are induced by the on-orbit satellites. Although these biases have little effect on single-point positioning, which has limited accuracy requirements, they disrupt precise-point positioning (PPP) applications [1] and the determination of the navigation satellite orbits by the control segment [2], thereby reducing system availability or forcing the satellites to be labeled as unhealthy.

Specifically, with respect to the GPS, where the anomaly was first observed in the SVN49 satellite, the cause is attributed to the internal signal reflection due to the impedance mismatch of newly-introduced payloads, which results in a multipath signal superposed on the primary signal before being fed into the array elements [3,4]. For different elevation angles, the multipath and primary signals are combined differently by the antenna array, thereby making the pseudorange biases elevation-dependent. If a single antenna is used to transmit the signal rather than an array, the internal multipath still generates a pseudorange bias, but it is not elevation-dependent.

Despite the fact that the cause of the SVN49 anomaly has been fully explained and validated, the investigation of this problem involved great cost, including both in-orbit and ground tests. This demonstrates that our understanding of how the satellite antenna array influences the quality of the navigation signal is less than complete. With respect to the BeiDou pseudorange bias anomaly, to the best of our knowledge, the cause has yet to be determined. At the same time, the development of the next-generation GNSS with more signals, wider bandwidths, and more complex modulation modes is underway. To avoid this bias anomaly in the next-generation GNSS, a more general and thorough study of this issue is necessary. Here we focus on this issue. Specifically, we propose a hypothesis for the cause of this anomaly and demonstrate its correctness and effectiveness via theoretical analysis and simulations.

Signal transmission on the satellite. To perform a theoretical analysis, first we must investi-

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gate in detail the navigation signal transmission on the satellite. After being generated by the signal-generation payload, the single-stream signal is fed into a power-dividing and phase-shifting network. Then, the output multi-stream signals are input to each antenna array element for radiation.

The reason an array antenna is used is to achieve antenna pattern shaping. Due to the geometric relationship between the satellite and the Earth, a receiver in different locations on the Earth surface may experience free-space attenuation that differs from that of the satellite. The attenuation is minimal when the satellite is overhead and reaches a maximum when the satellite is on the horizon. To guarantee that the signal reaches the Earth surface with almost uniform power strength, the satellite antenna pattern must dimple toward the Earth center.

This goal is achieved by the beam-forming technique in which a specific amplitude and phase shift are allocated through the network to the signal for each antenna element, which can be denoted by a complex weight value w_i, where i denotes the element index. By tuning the array geometry and $\{w_i, i = 1, 2, \ldots, N\}$, where N is the array element number, the desired radio beam pattern can be obtained.

Ideally, the satellite signal transmission is fully described by w_i. However, non-ideal factors in the transmission links may exist, which are modeled by the frequency response function $G_i(f + f_c)$ corresponding to the i-th antenna element as follows:

$$G_i(f) = \alpha_i + \sum_{k=1}^{M_i} \beta_{i,k} \mathrm{e}^{-\mathrm{j}2\pi f \Delta t_{i,k}}. \tag{1}$$

This model has a similar form to that of the multipath. Parameter α_i is set to 1 if there is a direct signal component that has no transfer time delay in the link. Otherwise, it is set to 0. The parameter M_i denotes the number of multipath signal components. The parameter $\beta_{i,k}$ is a complex value describing the relative gain and phase of the multipath signal component with respect to the direct signal component. The parameter $\Delta t_{i,k}$ is a real value representing the transmission delay of the i-th multipath signal component. By transmission delay inconsistency, we mean that α_i, $\beta_{i,k}$, M_i, and $\Delta t_{i,k}$ differ for each antenna element indexed by i. This inconsistency is our hypothesis regarding the cause of the BeiDou bias anomaly, which we validate through simulation.

Based on the above, the satellite signal transmission can be fully described by the following transfer function:

$$H(f, \theta, \phi) = \sum_{i=1}^{N} A_i(f, \theta, \phi) G_i(f) w_i \mathrm{e}^{\mathrm{j}\Delta\varphi_i(\theta,\phi)}, \tag{2}$$

where $A_i(f, \theta, \phi)$ denotes the in-situ radio pattern for the i-th antenna element [5], and $\Delta\varphi_i(\theta, \phi)$ denotes the phase shift due to the antenna array geometry and the signal transmission direction. We can see that the transfer function depends on the signal direction (θ, ϕ). This transfer function forms the foundation for the theoretical calculation of the pseudorange bias, as shown below.

Pseudorange bias calculation. In the receiver, the code phase of the received signal is measured at the peak of the correlation function. Given the complex envelope of the received signal denoted by $\tilde{d}(t)$ and the locally replicated desired signal denoted by $d(t)$, the correlation function can be defined as follows:

$$R_{\tilde{d}d}(\tau) = \int \tilde{d}(t) d(t - \tau) \mathrm{d}t. \tag{3}$$

Theoretically, this function can be calculated by the following equation:

$$R_{\tilde{d}d}(\tau, \theta) = \int H(f, \theta, \phi) \Phi_{dd}(f) \mathrm{e}^{\mathrm{j}2\pi f \tau} \mathrm{d}f, \tag{4}$$

where $\Phi_{dd}(f)$ denotes the power spectral density function (PSDF) of the desired signal [5]. Then, we can write the pseudorange bias as follows:

$$\tau_{\mathrm{bias}}(\theta, \phi) = \arg\max_{\tau} \{|R_{\tilde{d}d}(\tau, \theta, \phi)|\}, \tag{5}$$

$$\rho_{\mathrm{bias}}(\theta, \phi) = c \cdot \tau_{\mathrm{bias}}(\theta, \phi), \tag{6}$$

where c denotes the speed of light and $\rho_{\mathrm{bias}}(\theta, \phi)$ is the final pseudorange bias in meters.

For the binary-phase-shift keying (BPSK) modulation, the PSDF $\Phi_{dd}(f)$ can be given directly by the following:

$$\Phi_{dd}(f) = T_c \mathrm{sinc}^2(\pi T_c f), \tag{7}$$

where T_c denotes the chip rate of the ranging code. The above equations also apply to other kinds of signal modulations.

Simulation validation. Using above bias calculation method, we can obtain the simulated elevation-dependent pseudorange biases using the hypothetical transmssion delay inconsistency model given by $G_i(f)$. The first obstacle encountered is the exact one experienced by the BeiDou satellites, which is not referenced in the literature, including the array geometry and $\{w_i\}$. As an expedience measure, we use the parameters of GPS Block IIR

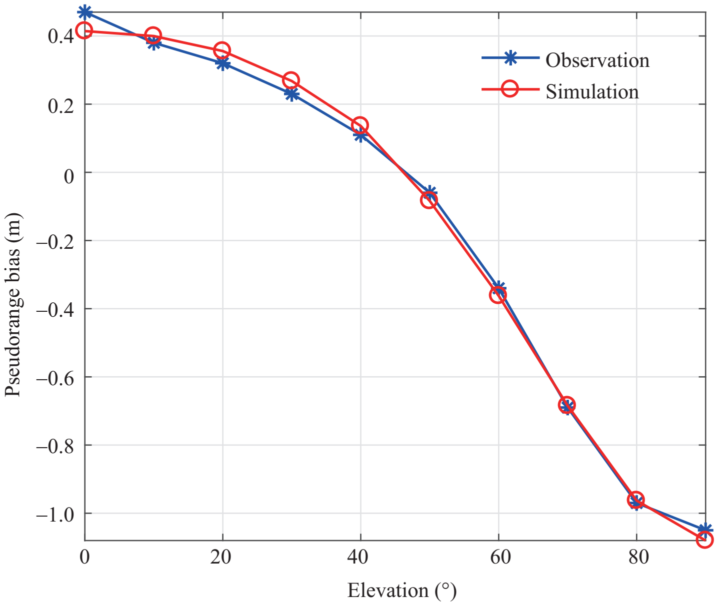

Figure 1 (Color online) Comparison of simulated and observed bias results.

satellites as reference, in which the antenna array geometry is 12-element and arranged in two concentric rings. The simulation results may be less accurate with this replacement, but are still useful in understanding the pseudorange bias. Once the accurate parameters of the BeiDou satellites are known, a similar analysis procedure and simulation can be conducted to obtain more accurate results.

The next issue is that the parameter set $\{\alpha_i, M_i, \beta_{i,k}, \Delta_{i,k}\}$ consists of an infinite number of possible transmission delay inconsistencies. As such, we selected a few typical situations. For example, one typical situation is that the signal corresponding to the antenna elements in the outer ring of the array geometry is delayed with respect to the inner ring by an identical time value. The result is that the parameter space is greatly reduced. By searching in the reduced parameter space, we can find a transmission delay inconsistency when the simulated biases agree very well with the observed biases. Figure 1 shows one set of obtained results. Furthermore, various situations and parameter combinations of this inconsistency model can lead to simulated biases that agree with those observed.

Conclusion. In this article, we showed through mathematical analysis and simulation that the transmission delay inconsistency between different antenna elements can cause elevation-dependent pseudorange bias variations that are similar to those observed, which proves that this non-ideal effect on the satellite is a possible cause of the observed anomaly. Therefore, we recommend that during the manufacturing process of a navigation satellite, special attention should be paid to the transmission delay consistency between different satellite antenna elements to avoid any subsequent elevation-dependent pseudorange biases. In ground tests before launch, we also suggest that the RF signals corresponding to each antenna element be checked to ensure that they have an identical time delay and a minimum of multipath signal components.

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