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Characterization of multi-GNSS between-receiver differential code biases using zero and short baselines

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Abstract Care should be taken to minimize adverse impact of receiver differential code biases (DCBs) on global navigation satellite system (GNSS)-derived ionospheric parameters. It is therefore of importance to ascertain the intrinsic characteristics of receiver DCBs, preferably in the context of new-generation GNSS. In this contribution, we present a method that enables time-wise retrieval of between-receiver DCBs (BR-DCBs) from dual-frequency, code-only measurements collected by a pair of co-located receivers. This method is applicable to the US GPS as well as to a new set of GNSS constellations including the Chinese BeiDou, the European Galileo and the Japanese QZSS. With the use of this method, we determine the multi-GNSS BR-DCB time-wise estimates covering a time period of up to 2 years (January 2013–March 2015) with a 30-s time resolution for five receiver-pairs (four zero and one short baselines). For the BR-DCB time-wise estimates pertaining to an arbitrary receiver-pair and constellation, we demonstrate their promising intraday stability by means of statistical hypothesis testing. We also find that the BeiDou BR-DCB daily weighted average (DWA) estimates show a dependence on satellite type, in particular for receiver-pairs of mixed types. Finally, we demonstrate that long-term variability in BR-DCB DWA estimates can be closely associated with hardware temperature variations inside the receivers.

Keywords Global navigation satellite system (GNSS) · Total electron content (TEC) · Between-receiver differential code bias (BR-DCB) · BeiDou code inter-satellite-type-bias (ISTB)

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1 Introduction

It has long been recognized that the vertical total electron content (vTEC) parameters determined from global navigation satellite system (GNSS) measurements are quite beneficial to ionospheric studies [1–4]. Since June 1998, the International GNSS Service (IGS) ionosphere working group has started to routinely deliver the global ionosphere maps (GIMs) in support of a wide range of atmospheric and geodetic applications [5–7]. Instead of relying almost exclusively on the US Global Positioning System (GPS), as was often the case throughout the past several decades [8–11], the emergence of new GNSS constellations in recent years would bring unprecedented opportunities for more detailed ionospheric investigations [12–14]. As of this writing, the Chinese BeiDou constellation is comprised of five geostationary orbit (GEO) satellites, five inclined geosynchronous orbit (IGSO) satellites and four medium Earth orbit (MEO) satellites [15]. The ability of the BeiDou constellation to provide positioning, navigation and timing (PNT) services in at least the Asia–Pacific region commenced in December 2012 [16]. The European Galileo has already completed the in-orbit-validation (IOV) phase, and its constellation consists of four operational MEO satellites [17]. The Japanese quasi-zenith satellite system (QZSS) is designed as a regional augmentation system for GPS [18].

The first operational QZSS satellite (IGSO) was launched in September 2010. Two additional IGSO satellites and one GEO satellite will be deployed into the orbit by the late 2010s [19].

The lumped effect of satellite and receiver differential code biases (DCBs) is generally considered a major source of error in determination of vTEC [20]. In fact, satellite DCBs have been found to remain fairly stable over considerable periods of time for different GNSS constellations [21, 22]. This enables us to retrieve the satellite DCB estimates with rather high accuracy, particularly under calm ionospheric conditions [23, 24]. After that, removal of the effect of the satellite DCBs on vTEC determination would become simple and straightforward. For receiver DCBs, however, their variability may be evident even in a comparatively short period of time say 1 d or a couple of hours [25, 26]. One of the main reasons for this is commonly identified as temperature perturbations around the receivers [27]. Hence, handling the short-term temporal variability of receiver DCBs is a very crucial task in order to enhance the reliability of GNSS-derived vTEC parameters.

Up to now, studies that have examined the receiver DCB characteristics using real GNSS data (albeit GPS only) can be classified into two distinct groups. Researchers in the first group have focused their attentions on analyzing the receiver DCB estimates that are by-products of vTEC determination [28–30]. Actually, these estimates with daily time resolution may be subject to severe modeling errors, originating mainly from the imperfection of vTEC mathematical representations. Just for this reason, one might misleadingly assign the ionospheric variability as the primary cause of the receiver DCB estimate variations [28, 31]. Fortunately, this problem is avoidable in the second group of studies as it has completely got rid of the reliance on vTEC modeling process [25, 26, 32]. The basic procedure followed here is to first obtain the ionospheric observables, interpreted as line-of-sight ionospheric delays biased by the satellite and the receiver DCBs, for a pair of co-located receivers using so-called carrier-to-code leveling process [33]. After taking the between-receiver difference of the ionospheric observables, for each satellite it will yield a series of between-receiver DCB (BR-DCB) time-wise estimates. The maximum spread between the BR-DCB time series corresponding to different satellites, which should ideally be zero, is finally treated as a diagnostic measure for inferring the variability of BR-DCB estimates. Nevertheless, this group of studies still has one significant disadvantage, namely that the leveling errors underlying the ionospheric observables that are receiver/antenna dependent may corrupt the BR-DCB time-wise estimates [25].

Without the necessity of vTEC modeling or ionospheric observable formation, we propose in this contribution a time-wise BR-DCB retrieval method employing code-only measurements collected by a zero or short baseline from not only the GPS, but the BeiDou, Galileo and QZSS constellations as well. We take the between-receiver and between-frequency differences of these code measurements so as to minimize the error sources in retrieval of multi-GNSS BR-DCBs. We diagnose the intraday stability of the BR-DCB time-wise estimates for different GNSS constellations and receiver-pairs using the statistical hypothesis testing scheme that takes into account the formal uncertainties of these estimates. Special care has been taken to properly deal with the code inter-satellite-type-biases (ISTBs) when retrieving BeiDou BR-DCBs with our method. Generally, the BeiDou code ISTBs interpreted as the “double-differenced” receiver code biases between two receivers and two BeiDou satellite types are found to be significant for receiver-pairs of mixed types [34]. We are about to investigate the effect of them on the consistency between BeiDou GEO/IGSO/MEO BR-DCB estimates. With the fact that the receiver DCB temperature dependence is likely due to three factors (the antenna, the cable and the receiver hardware) in mind [27], we attempt to discern which one of them is the most influential based on a number of dedicatedly designed experiments.

2 Methods

In a rather compact vector–matrix form, we write the function model of our BR-DCB retrieval method as

$$E\{\boldsymbol{P}(i)\} = \boldsymbol{e}_m b(i), \tag{1}$$

with $E\{\cdot\}$ denoting the expectation operator and where i denotes the epoch index. m equals the total number of satellites that belong to one common GNSS constellation. The $m \times 1$ vector $\boldsymbol{e}_m$ has all 1’s as its entries. The $m \times 1$ vector $\boldsymbol{P}(i)$ contains the between-receiver, between-frequency differenced code measurements, and $b(i)$ is the unknown BR-DCB parameter.

For the entries of the diagonal variance matrix of $\boldsymbol{P}(i)$, we make use of an elevation-dependent weighting

$$D\{\boldsymbol{P}(i)\} = \mathrm{diag}\left\{\frac{4\sigma^2}{\sin^2[\theta^1(i)]} \cdots \frac{4\sigma^2}{\sin^2[\theta^m(i)]}\right\}, \tag{2}$$

in which $D\{\cdot\}$ is the dispersion operator. σ denotes the zenith-referenced undifferenced code standard deviation, and $\theta^s(i)$ is the elevation angle of satellite $s = 1, \ldots, m$ at epoch i.

Assuming that a pair of co-located receivers has collected code measurements from multiple GNSS constellations on at

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