Estimation of P2-C2 Biases by Means of Precise Point Positioning

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ABSTRACT

The United States has started a modernization program to provide better service to Global Positioning System (GPS) users, with launches of modernized GPS satellites. The sub-group of these new satellites is called Block IIR-M, where "R" stands for replenishment and "M" for modernized. In this modernization process, GPS has gained a new open civil code (called L2C), centered at the L2 frequency. The first modernized satellite, for which PRN17 was assigned, was launched on 25 September 2005 and the new L2C signal from this satellite has been fully available from 15 December 2005. Even before PRN17 was placed in orbit, the L2C signal became an issue of worldwide interest to the GPS research communities. Currently L2C is being transmitted by three satellites: PRN17, PRN31 and PRN12. Enhanced receivers capable of tracking the modernized GPS signal have been developed and provided by a number of manufacturers. The IGS (International GNSS Service) has organized a network of L2C signal tracking stations which have been established in different places around the world. The role of projects involving the new signal is to analyze its quality, as well as the impact of its use for positioning and navigation.

One of the issues to be considered when dealing with the new signal is the impact of mixing L2C-capable and legacy receivers within a network, or processing data from an L2C-capable receiver with satellite clock values generated using a legacy receiver network. Because hardware delays of receivers and satellites for L2C measurements (called C2 in the RINEX 2.11 standard) might not be necessarily the same of those for P2 (pseudoranges based on semi-codeless L2 P(Y)-code tracking), a bias between P2 and C2 code measurements must be considered when mixing observations from different receiver types. This bias will be called here the P2-C2 bias, using the same standard nomenclature used for P1-C1 biases. Code biases are present in the receiver and the satellite hardware, but in a positioning scenario, receiver code biases are usually absorbed by the receiver clock parameter and do not need to be separately accounted for. In a scenario of network clock (receivers and satellites) estimation using mixed receiver types (e.g.,

legacy and L2C-capable), both receiver and satellite biases have to be considered as parameters in the observational model.

The main goal of this work is to determine and analyze values for the IIR-M satellite P2-C2 biases. Knowing these values allows us to begin using L2C as an observable for positioning, applying satellite clock values computed using P2 as the observable on L2, as in the case of IGS clock products. The dataset used is the data observed by the IGS L2C Test Network, which consisted of 12 receivers at the time the data was collected for this research.

Observation functional and stochastic models have been realized in a precise point positioning package developed at the University of New Brunswick. Inside this package, called GAPS (GPS Analysis and Positioning Software), tools for data analysis were implemented, allowing, among other things, the estimation of code biases. The approach used treats the observations in the same way as a user would do for positioning, thus the impact of satellite biases is the same as for point positioning using IGS products. In this work our approach is validated by comparing our satellite P1-C1 bias estimates with values determined by IGS analysis centers. This validation is required because up until now, no P2-C2 bias estimates have been published with which we could make comparisons. The two scientific contributions of our work are: (1) an approach for PPP-based bias determination, and (2) the first (to our knowledge) publicly available determination of differential P2-C2 bias, which can be used in the future as a reference for further investigations related to P2-C2 satellite biases. Our results show that the differential P2-C2 satellite biases for the three modernized satellites currently in orbit are very similar, with the value likely between plus or minus 0 and 20 cm.

INTRODUCTION

Hardware delay is one of the effects which has to be taken into account when using GPS under certain conditions. These delays can be different for each observable, and for each frequency, which means that depending on the signal which is being used in a given application, accounting for the hardware delays might be an ordinary step to achieve the targeted accuracy. The hardware delay is usually determined in a relative sense, where a given observable and frequency (or frequency combination) is used as standard. Because of this, the values which are determined are usually called biases, because they represent the bias between two observable types, and can be represented in time or length units. One can separate the instrumental biases into two classes: the inter-frequency biases, which are the biases between observables on two or more frequencies; and, the intra-frequency biases, which are the biases between two observables broadcast on the same frequency.

The inter-frequency bias is a matter of interest for estimating ionospheric delays, which requires a comparison between observations on different frequencies. It is also of interest for positioning with single-frequency receivers, because the satellite clocks are usually computed using the ionospheric-delay-free (iono-free) combination and thus the bias between the receiver's observable type and the iono-free observable should be accounted for to allow a correct time transfer and consequently adequate positioning.

The intra-frequency biases are of interest for two types of applications: network data processing and single receiver data processing. Sometimes receiver networks are formed by receivers of several types, collecting different observable types. Currently, the only intra-frequency bias of wide interest for the GPS community is the P1-C1 bias. P1 and C1 observables have to be mixed in networks formed by non-cross-correlation receivers (which collect P1), non-cross-correlation receivers reporting C1, and cross-correlation receivers (which report only C1 on the L1 frequency). On the single receiver side, the need to account for biases depends on whether this receiver is using the same observables which were used to compute satellite clocks or not.

It is important to mention that the delays and consequently the biases exist for both receivers and satellites. In a positioning scenario, the receiver's biases are usually absorbed by the receiver clock error parameter in the adjustment as long as only one type of observable is being used, thus only the satellite biases have to be taken into account. In the same sense, instrumental biases are not an issue for relative positioning, because they are eliminated together with satellite and receiver clocks in the double-differencing.

Until the end of 2005, only one code was broadcast on frequency L2, the encrypted military P2 code, and for this reason intra-frequency biases have never been an issue on L2. With the launch of the first IIR-M GPS satellites, a second code started to be broadcast on L2, the L2C code (called C2 code in the current RINEX standard), where C stands for civil (thus, an open civil code). Around the same time, many of the GPS receiver manufacturers started to produce and to put on the market receivers capable of tracking the L2C signal, which made this new observable a matter of interest for the GPS community. The International GNSS Service (IGS) organized a network of continuously operating L2C-capable GPS receivers, called the L2C Test Network. These receivers are operated by a number of institutions all over the world.

One of the aspects of the new code which has to be investigated is the bias between itself and the P2 code, which will become necessary for L2C users when a reasonably full modernized satellite constellation is available, to allow positioning based on L2C rather than on P2. In this paper, we are presenting a determination of the P2-C2 satellite biases. This determination was made possible using data from the L2C Test Network, and a technique based on precise point positioning, which itself is another novel aspect of this work.

L2C TEST NETWORK

The L2C Test Network was created in an effort of the IGS to create a pool of data from globally spread L2C-capable receivers. It has been established as voluntary contributors start to submit their data to be stored on the CDDIS (Crustal Dynamics Data Information System) ftp server. L2C Test data can be accessed from <ftp://cddis.gsfc.nasa.gov/gps/data/l2ctest/>.

As of April 2007, the L2C Test Network was composed of 12 GPS receivers. All of them were manufactured by Trimble Navigation Ltd., ten of them being of the model NetRS, and two of them of the model NetR5. Even though it was proposed to use RINEX 2.11 [Gurtner and Estey, 2006] as the standard data file format for the L2C Test Network, which allows the use of L2C as an observable (using the observable code C2), some of the stations (three in total) use RINEX 2.10 format. Table 1 shows the list of stations and data format currently being used by each of them.

Table 1. Current L2C Test Network stations

Station	Latitude (degrees)	Longitude (degrees)	Data Format
BHAO	36.09	128.58	2.11
GANP	49.02	20.19	2.11
HRAC	-25.53	27.41	2.11
KOKC	22.07	-159.39	2.11
MCMC	-77.50	166.40	2.11
NYAC	78.55	11.51	2.11
OURI	-22.95	-49.90	2.10
PGC5	48.38	-123.27	2.11
RIOP	-20.79	-49.36	2.10
ROSA	-22.52	-52.95	2.10
UNAC	40.03	-105.12	2.11
UNB3	45.57	-66.38	2.11

The stations using RINEX 2.10 data format were not used in this investigation for a matter of convenience. The nine used stations are shown in Figure 1.

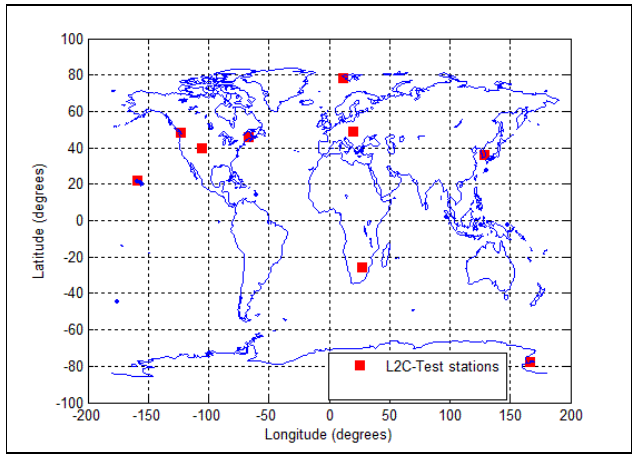

Figure 1. Used stations from the L2C Test Network.

All receivers of this network are non-cross-correlation receivers reporting C1, which means the codes available in addition to L2C are C1 and P2.

PRECISE POINT POSITIONING AND GAPS

Precise point positioning (PPP) is a technique in which a single receiver is used for high accuracy positioning. The key to obtaining the best accuracy as possible is the use of a very complete observation model, together with the employment of precise products related to satellite clocks and orbits. GAPS (GPS Analysis and Positioning Software) is a PPP package, which has been developed at University of New Brunswick, with the purpose to make available to the community a research tool for positioning and data analysis. One of the analysis tools created in GAPS is related to code bias estimation, which will be seen in detail in the next section. Introductory information regarding GAPS and PPP can be found in Leandro and Santos [2006]. PPP has been extensively explored by several researchers, such as Zumberge [1997], Kouba and Héroux [2001], Kouba [2003], Gao and Chen [2004], and Tétreault et al. [2005].

PPP-BASED P1-C1 CODE BIAS ESTIMATION

One simple way of estimating code biases is comparing two different codes simultaneously observed by the same receiver. This technique delivers the receiver-satellite differential bias, which means the receiver part of the estimated quantity still has to be eliminated, in order to obtain the satellite bias. Because the biases can be considered as a constant correction for satellite clock error estimates used for positioning, it is desirable that these biases are estimated in a way in which the consistency between biases and clock products is assured. This is usually done, since the differential satellite biases are generally estimated together with the satellite clocks, as it is done for example at the Center for Orbit Determination in Europe (CODE) [CODE, 2007]. In the PPP-based technique, we match this approach by using the clock products for estimating the satellite differential biases, as will be seen later.

In order to estimate code biases a novel technique based on precise point positing was developed inside GAPS. To explain how this technique works, we should start with a simplified pseudorange observation equation, below. The equation assumes that IGS clock products are being used, thus the clocks are referenced to a P1&P2 iono-free combination:

$$P_{if(P1,P2)} = \rho + T + c(dT - dt) + \ldots \\ \ldots + m_{P_{if(P1,P2)}} + e_{P_{if(P1,P2)}} , \tag{1}$$

where:

$P_{if(P1,P2)}$ is the iono-free pseudorange measurement;
T is the neutral atmosphere delay;
c is the speed of light;
dT is the receiver clock offset;
dt is the satellite clock offset;
$m_{P_{if(P1,P2)}}$ is the code multipath, and,
$e_{P_{if(P1,P2)}}$ represents other errors in the measurements.

As one can notice, there are no biases being considered in Equation 1, because the same observation combination as the one used to estimate satellite clocks is being used. In the case of single frequency observations, the satellite bias should be considered, as shown below for the P1 code:

$$P_1 = \rho + T + I + c(dt - dT) + b_{if-P1} + m_{P1} + e_{P1} , \tag{2}$$

where the additional terms are:

P_1 is the P1 pseudorange measurement;
I is the ionospheric delay;
b_{if-P1} is the satellite instrumental bias between P1 code and the P1&P2 iono-free combination (necessary in this equation because we are using IGS iono-free clocks but dealing with L1 frequency measurements);
m_{P1} is the P1 multipath, and,
e_{P1} represents other errors for P1 measurements.

One can notice that an explicit receiver bias term is missing in Equations 1 and 2. This is because, as mentioned before, in a positioning scenario the receiver code biases are absorbed by the receiver clock parameter (dT in Equation 1). If one is using C1 measurements rather than P1 for positioning, the same equation should be used, with the addition of the P1-C1 bias:

$$C_1 = \rho + T + I + c(dt - dT) + b_{if-P1} + b_{P1-C1} + \ldots \\ + m_{C1} + e_{C1} , \tag{3}$$

where b_{P1-C1} is the satellite instrumental bias between P1 code and C1 code. An iono-free observable using C1 and P2 codes would still require the use of the P1-C1 bias, as follows:

$$P_{if(C1,P2)} = \rho + T + c(dt - dT) + \ldots \\ \ldots + \alpha \cdot b_{P1-C1} + m_{P_{if(C1,P2)}} + e_{P_{if(C1,P2)}} , \tag{4}$$

where α the coefficient for L1 in the iono-free combination equation:

$$P_{if(C1,P2)} = \alpha \cdot C1 + \beta \cdot P2 , \tag{5}$$

where α can computed as

$$\alpha = \frac{f_1^{\,2}}{f_1^{\,2} - f_2^{\,2}} , \tag{6}$$

and β can be compute as

$$\beta = \frac{f_2^{\,2}}{f_1^{\,2} - f_2^{\,2}} , \tag{7}$$

Using information related to orbits, clock, atmosphere and receiver position which is inherent to a precise point positioning filter, it is possible to create a pseudo-observable as follows:

$$P'_{if(C1,P2)} = \alpha \cdot b_{P1-C1} + m_{P_{if(C1,P2)}} + e_{P_{if(C1,P2)}} , \tag{8}$$

where $m_{P_{if(C1,P2)}}$ and $e_{P_{if(C1,P2)}}$ are un-modeled parameters, which results in the following simple observation equation:

$$\tilde{P}'_{if(C1,P2)} = \alpha \cdot b_{P1-C1} . \tag{9}$$

In theory, one single observation of one single receiver would then be enough to determine the satellite P1-C1 bias. However, because of the part of the observation which is not modeled (multipath and noise), this is not possible. What would be feasible though is using several observations of a receiver (in other words, a complete arc of a given satellite), which would reduce the effect of the noise. Also, using receivers in different locations (and thus with different multipath patterns) would reduce the effect of the multipath. Using several observations from several receivers requires an adjustment procedure, which might follow the standard least-squares technique:

$$\hat{b} = \left(\underline{A}^t \underline{P}\underline{A}\right)^{-1} \underline{A}^t \underline{P}\underline{l} \ , \qquad (10)$$

where

$\hat{b}$ is the estimate of the bias;
$\underline{A}$ is the design matrix, which, in this case, is a column vector where all elements are α ;
$\underline{l}$ is the vector of observations;
$\underline{P}$ is the weight matrix.

The weights of $\underline{P}$ should vary according to the elevation angle of each observation. Assuming the effect of multipath is less critical for higher elevation angles, an elevation-based weighting scheme should help to reduce the impact of multipath on the bias estimation.

As mentioned earlier, data from nine receivers of the L2C Test Network were used in this work. This dataset was used to estimate satellite differential P1-C1 biases, according to the procedure above. This step is fundamental for this investigation for two reasons: (1) the estimated bias values can be compared with values determined with other techniques, as a validation of the technique based on PPP; and (2) once it was determined that P1-C1 biases determined by other techniques are in accordance with our values, they can be used for P2-C2 bias estimation – this is necessary because there is not a full constellation of modernized satellites available yet. The second reason will be explored in detail in the next section.

Data from the L2C Test Network observed between 1 and 10 January 2007, inclusive, was processed in order to determine the satellite differential P1-C1 and P2-C2 biases. The validation of the estimated P1-C1 biases was done by comparing the values with values determined by CODE for the month of January 2007.

CODE has accounted for P1-C1 code biases since GPS week 1057 (beginning 9 April 2000), by solving for satellite-specific differential (P1-C1) code bias (DCB) parameters as part of the clock estimation procedure. Their approach works as long as a mixture of data of cross-correlation style receivers and modern receivers is processed. At present, between 30 and 40 stations from a total of 80 stations used for the clock estimation may be related to a cross-correlation style receiver providing C1 and P2' code measurements [CODE, 2007]. The P2' code is the code P2 observed by a cross-correlation receiver, and within CODE standard nomenclature it is called X2.

At the beginning of each month, CODE's monthly DCB solutions for the preceding month are computed, automatically archived, and made available. The solution from January 2007 was used in this comparison. Figure 2 shows a comparison of P1-C1 biases determined by CODE and those using GAPS . The blue bars (on the right side of each bar pair) represent the GAPS solution, while the red bars (on the left side of each bar pair) represent the CODE solution.

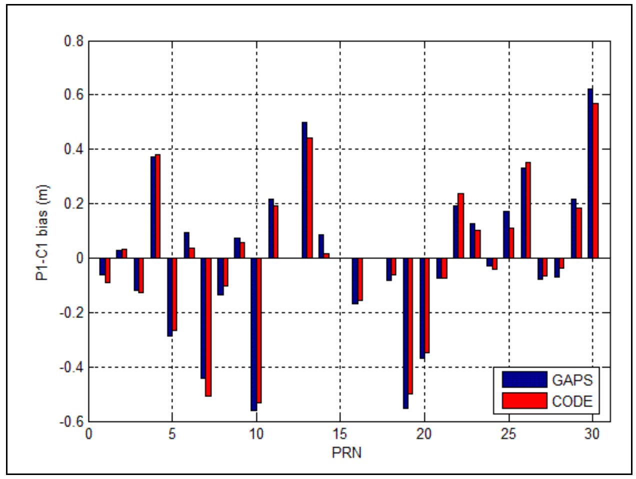

Figure 2. Comparison of satellite differential P1-C1 biases determined by CODE and with GAPS.

As can be seen above, there is reasonable agreement between the two solutions. Differential P1-C1 biases of PRNs 12, 17 and 31 were not estimated because these satellites' data was used for the P2-C2 differential biases estimation, as it will be discussed in the next section. In order to better visualize the differences, Figure 3 shows the differences between them, in the sense GAPS-CODE.

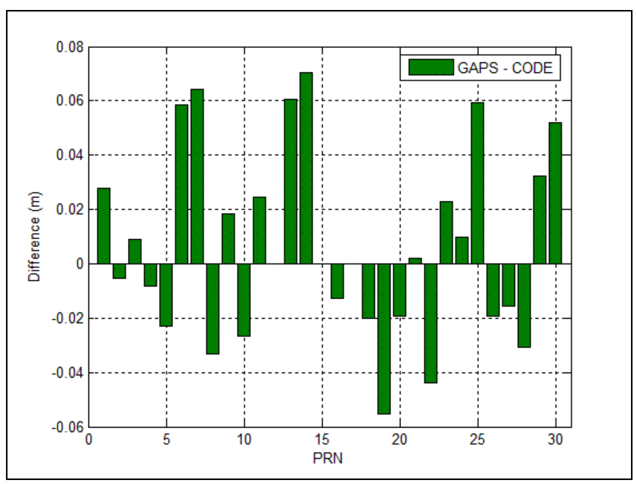

Figure 3. Differences of the satellite differential P1-C1 biases determined by CODE and with GAPS.

The GAPS and CODE differences are summarized with the statistics in Table 2.

Table 2. Statistics of the comparison of P1-C1 bias determinations (GAPS-CODE).

Statistic	*Value (cm)*
Bias	0.74
Standard Deviation	3.63
RMS	3.64
Maximum	7.03
Minimum	-5.52

As can be noticed in the table above, the agreement at one sigma between the two determinations is around 3.6 cm. The maximum difference encountered was around 7 cm, which is also a reasonably small value.

PPP-BASED P2-C2 CODE BIAS ESTIMATION

Following the same procedure used to derive Equation 4, we can now derive the observation equation of the iono-free code combination using C1 and C2 (or L2C) codes:

$$P_{if(C1,C2)} = \rho + T + c(dT - dt) + \alpha \cdot b^{s}{}_{P1-C1} + \ldots \\ + \beta \cdot b^{r}{}_{P2-C2} + \beta \cdot b^{s}{}_{P2-C2}, \qquad (11)$$

where $b^{s}{}_{P1-C1}$ is the satellite P1-C1 bias, $b^{r}{}_{P2-C2}$ is the receiver P2-C2 bias, $b^{s}{}_{P2-C2}$ is the satellite P2-C2 bias and β is one of the coefficients of the iono-free combination, as in Equation 5 – but now using C1 and C2 codes.

The P2-C2 receiver bias term is not absorbed by the receiver clock parameter because L2C observables are available for three satellites only, and the consequence is that we are forced to use the other satellites to be able to provide a PPP solution, which means the receiver clock is absorbing the receiver P1-C1 bias only. We know that only P1-C1 biases are being absorbed by the clock because we actually force that, by giving more weight to legacy satellites than for modernized ones in the PPP solution. The satellite P1-C1 bias is present in this equation simply because no biases were applied to the observations prior to data processing.

In order to isolate the parameter of interest – the satellite P2-C2 bias, we used a zero-mean condition for each station solution, which eliminates the receiver-dependent part of the bias. The satellite P1-C1 bias was taken care of by removing it using the values provided by CODE for January 2007. CODE's determination can be used here since its consistency with our approach has been checked, as shown in the previous section.

After eliminating the biases which are not of interest for this analysis, it is possible to create the pseudo-observable for the P2-C2 bias, as done for P1-C1, as follows:

$$\tilde{P}'_{if(C1,C2)} = \beta \cdot b_{P2-C2}. \qquad (12)$$

The bias estimate can be computed using the same procedure, by least squares technique, as shown in Equation 10. Figure 4 shows the values obtained for several stations/days (where results for different days and same stations are grouped in the series).

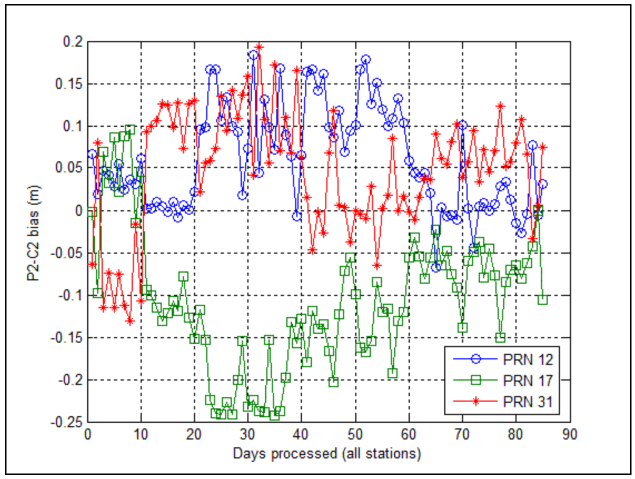

Figure 4. Results of the P2-C2 satellite bias determination for several days and stations.

Table 3 summarizes the results obtained for the satellite P2-C2 biases.

Table 3. P2-C2 satellite biases.

PRN	*Bias* (cm)	*Std. dev.* (cm)
12	6	6.0
17	-11.7	8.1
31	4.7	7.1

Table 3 shows, the range of the determined values is reasonably small if compared to the range of the P1-C1 biases. The values are also reasonably small if compared with their standard deviation. As opposed to what it may look like, it does not mean that the determination is meaningless, or that there are no P2-C2 biases for these satellites. What we believe can be concluded from the numbers above is that the P2-C2 biases of these three satellites are similar, at around the 10 to 20 cm level. Because a zero-mean condition is used (either by directly applying the condition or having receiver biases absorbed by the receiver clock parameter), what has actually been estimated are the differential biases (not the actual instrumental biases), which means we are sensible only to the variation of the biases among the satellites. In this specific case, this variation is reasonably small, and it can be concluded that the P2-C2 biases of these three satellites can be considered the same at around the 10 to 20 cm level.

One way to check if the conclusion that the differential P2-C2 biases of these three satellites are very similar makes sense is looking at the P1-C1 bias values computed by CODE for those same satellites (Table 4).

Table 4. P1-C1 satellite differential biases (from CODE).

PRN	*Bias (cm)*
12	44.3
17	42.0
31	52.6

As can be seen, P1-C1 biases of the three modernized satellites are reasonably similar, a similar characteristic to what we have detected for the P2-C2 biases. We can also see that these values are different from zero, even though small. This happens because they were determined in conjunction with the P1-C1 biases of all satellites, which causes the increase in the range of bias values, as it can be seen in Figure 2.

CONCLUSIONS AND FURTHER WORK

In this work a new technique to estimate satellite differential code biases was presented. A comparison of estimated satellite P1-C1 biases with a monthly CODE solution showed an overall agreement of better than 4 cm. This result validates the new technique.

Satellite P2-C2 differential code biases were also estimated (for PRN12, 17 and 31 modernized satellites). Bias values are reasonably small if compared with their standard deviation, or if compared with the range of P1-C1 biases.

As more modernized satellites are launched, this scenario might change, which means that if new satellites have different values for their P2-C2 biases, the range of the differential biases will increase, forcing the values to be farther from zero, in case a zero-mean condition is used.

For the future, we intend to work on different validation procedures, maybe with different sources and a wider dataset. We will also keep tracking the bias value behaviors as new modernized satellites are launched, as well as tracking the behavior of these values over time.

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