Receiver Inter-Constellation Time Offset at Low Earth Orbit: An Experiment with Bobcat-1, the Ohio University CubeSat

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BIOGRAPHY

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ABSTRACT

On October 2nd, 2020, Bobcat-1, the Ohio University CubeSat, launched as part of NASA's Educational Launch of Nanosatellites (ELaNa 31), on the Cygnus NG-14 mission. Bobcat-1 was deployed from the International Space Station on November 5th, 2020, with the primary mission of evaluating the in-space performance of inter-constellation time offset determination. The results presented in this paper are related to the Galileo-to-GPS time offset (GGTO), as the first step in validating the feasibility of the work and the applied methods to enable further analysis of other inter-constellation time offsets. Bobcat-1 measurements include GLONASS, BeiDou, and QZSS multi-frequency measurements as well, which will be included in future analysis. This paper will focus on the evaluation of Bobcat-1's receiver inter-constellation time offset, with a particular focus on its stability over time; the value is estimated by comparison with the broadcast inter-constellation time offset. Results obtained so far suggest that the Bobcat-1 offset is within a 2 ns error bound. The estimate above is the result of multiple data collections performed over three months (September 2021–December 2021). The applied estimation techniques are described here, with a focus on the environmental and receiver hardware errors.

I. MOTIVATION

When determining a single-constellation user solution, four unknown parameters must be solved for: the user's spatial coordinates and the receiver-to-system time offset. This means that a minimum of four satellites must be visible to solve for a user solution. If a user has sufficient visibility of satellites from different constellations, a multi-GNSS solution can be determined. However, when calculating a solution using measurements from multiple constellations, an additional unknown is added for each constellation used, e.g., for a user solution using measurements from both GPS and Galileo, five unknowns need to be solved for: the user's spatial coordinates, the receiver-to-GPS time offset, and the receiver-to-GAL time offset. The separate receiver-to-system time offsets are needed due to each Global Navigation Satellite System (GNSS) using its own system time reference. Since each constellation's time scale is independent of the others, the inter-system time offsets between the time scales leads to a prominent bias in a multi-constellation solution. According to a performance analysis performed by Torre et al. [1], inter-system time offsets between GPS, Galileo, GLONASS, and BeiDou are expected to range from 10 to 100 ns. Therefore, in order to calculate a user solution with meter level accuracy, the inter-constellation time offsets must be determined.

As defined in [2], interoperability is “the ability of global and regional navigation satellite systems and augmentations and the services they provide to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system.” The effort towards GNSS interoperability can be seen through projects such as the ICG-IGS Joint Trial Project, led by the International Committee on GNSS (ICG) and the International GNSS Service (IGS), which has set out to “provide a multi-GNSS service performance standard” [3]. The IGS Multi-GNSS Pilot Project (MGEX) plans to openly provide products for all GNSS available, including precise orbit and clock products [4]. GNSS interoperability has become particularly important to users in the high-altitude Space Service Volume (SSV) [5, 6]. Space vehicles (SVs) in altitudes beyond the GNSS satellites located in medium Earth orbit (MEO) have limited visibility of GNSS signals, receiving signals transmitted from the side lobes of GNSS SVs and across Earth’s limb [7]. The performance and availability of position, navigation, and timing (PNT) services are reduced for SSV users when compared to terrestrial users, due to the geometry of visible SVs [5]. Based on the study conducted by Enderle et al. [6], full interoperability between the GNSSs reduces outage times and improves the geometric dilution of precision (GDOP). This would not only provide significant benefits to the PNT services of existing missions, but will enable a number of new mission concepts beyond Earth orbit. In order to achieve interoperability between the GNSS constellations the inter-constellation system time offsets must be determined by, or provided to, the user.

Terrestrial users often have sufficient visibility of multiple SVs from multiple GNSS constellations to solve for the Inter-Constellation Time Offsets (ICTOs). For users in low-visibility environments, especially those at SSV altitudes, there may not be sufficient visibility to solve for the ICTOs, rendering a multi-GNSS solution unviable. However, as shown by the study conducted in [5], if the users were externally provided the ICTO estimates, the multi-GNSS’s PNT availability and performance would increase. In order to make use of an externally provided ICTO estimate, the characteristic receiver biases need to be calibrated or bounded [8–10]. The characteristic receiver inter-system biases are comparable to the inter-system time offsets, on the order of 20 ns according to Defraigne et al. [11].

Inter-constellation time offsets are currently estimated by ground networks of receivers. Galileo currently broadcasts a Galileo-to-GPS time offset estimate, within its navigation message [12]. This estimate is referred to as GAGP within [13] but is often referred to as GGTO, as it will be for the remainder of this paper.

In this paper, an experiment is presented to evaluate the performance of inter-constellation time offset estimation from a single receiver at Low Earth orbit (LEO). Using a platform in LEO provides several benefits to the networks of ground stations that are currently used to estimate these biases. The first advantage of this approach is visibility of multiple GNSS SVs multiple times per day due to the short orbit period of a SV in LEO. The increased visibility allows for characteristic satellite biases to be averaged out and better observability on the biases of the onboard receiver. Other benefits of this approach include the avoidance and mitigation of error sources that prove difficult to mitigate on Earth, such as the tropospheric delay error and multipath. GNSS orbit and clock errors can be corrected using information provided by ground networks. Another major error source is the characteristic receiver biases onboard the SV in LEO. The focus of this paper is to detail the feasibility study of determining the characteristic receiver Galileo-to-GPS time offset of the receiver onboard Ohio University’s CubeSat, Bobcat-1, currently deployed in LEO.

II. BOBCAT-1 MISSION OVERVIEW

Bobcat-1, shown in Figure 1, was developed at Ohio University’s Avionics Engineering Center and was launched on October 2nd, 2020 as part of the NASA Educational Launch of Nanosatellites initiative (ELaNa 31) on the Cygnus NG-14 mission. Bobcat-1 was deployed from the International Space Station (ISS) on November 5th, 2020, with the primary scientific objective to test the performance of inter-constellation time offset estimation from low Earth orbit. The primary payload onboard Bobcat-1 is a NovAtel OEM719 GNSS receiver, which was selected due to its significant flight heritage and ability to track a wide variety of GNSS signals from GPS, GLONASS, Galileo, BeiDou, and QZSS. The OEM719 receiver is connected to the top-mounted AntCom G5ANT-1.9AS-1-3 patch antenna, which provides coverage across multiple GNSS frequency bands. Additional details about the design and development of Bobcat-1 are available in [14].

Bobcat-1’s initial altitude was approximately 415 km after being deployed from the ISS with the expected life-span of roughly six months. Over a year later, Bobcat-1 has an approximate altitude of 375 km (as of January 10th 2022). Each orbit lasts about 90 minutes, meaning Bobcat-1 performs approximately 15 orbits per day, enabling Bobcat-1 to collect signals from many GNSS satellites multiple times per day, increasing the possibility of averaging out the satellite-related residual biases. The measurements are free from tropospheric errors, while the ionospheric effect is still partially present. A description of the analysis of the remaining error sources, including ionospheric delay, will be provided in Section V.

As of January 10th 2022, 50 data collections composed of 1.1 GB of data, have been completed and downlinked to the ground station located atop Stocker Center, Ohio University, Athens, Ohio, where the data is post-processed. The data downloaded from Bobcat-1 contains the raw measurements from the receiver onboard, including pseudoranges, carrier-phase measurements, and carrier-to-noise ratios. Bobcat-1 is capable of continuously collecting data from the GNSS receiver at a 1 Hz data-rate for approximately 5 orbits. At lower data-rates, e.g., a 20-second sampling period, the data collection time is significantly increased,

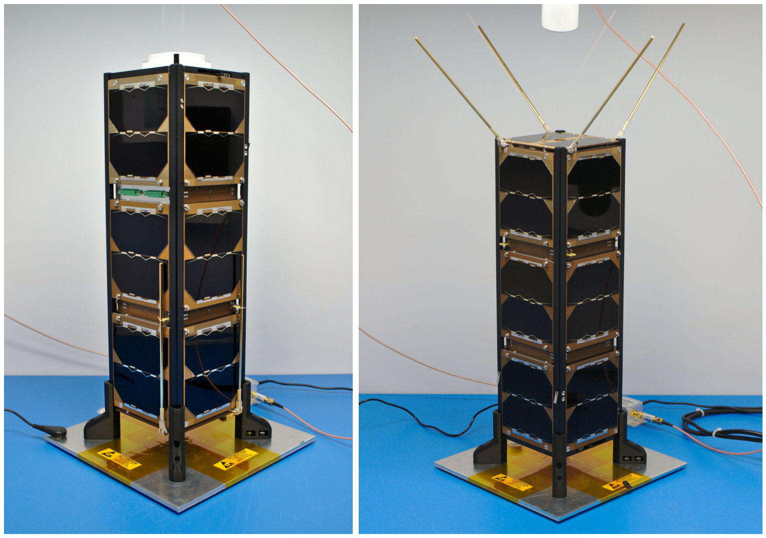


Figure 1: Bobcat-1, with communication antenna stowed (left) and deployed (right).

nearing a full 24 hour period. In [15] some preliminary results from the collected data were shown, and the performance was analyzed quantitatively to evaluate the feasibility of the work. The conclusion in [15] was that the upper bound on the residual errors on the GNSS measurements from Bobcat-1 were low enough to enable accurate evaluation of the inter-constellation time offset.

III. DATA COLLECTION CONFIGURATION

The analysis performed in this paper focuses on four data collections (Collection IDs: 170, 174, 176 and 181) downlinked from Bobcat-1. Although more data collections were run in support of estimating the inter-constellation time offsets, these four collections were chosen due to their length. The details of the duration of each data collection considered in this analysis can be found below in Table 1. These long data collections allow the observability of the stability of our inter-constellation time offset estimate over a period of approximately one day. During these collections, the sampling period was set to 20 seconds in order to reduce the total quantity of data needed to be stored and downlinked. Storage capacity and data downlink limitations do not allow for comparable collection lengths at higher sampling rates.

Table 1: Data Collection Details

Collection ID	Start Date	Start Time	End Date	End Time	Duration
170	September 28th, 2021	20:11:02 UTC	September 29th, 2021	16:44:22 UTC	20:33:20
174	November 10th, 2021	03:30:42 UTC	November 11th, 2021	01:08:22 UTC	21:37:40
176	November 29th, 2021	23:09:22 UTC	November 30th, 2021	17:36:42 UTC	18:27:20
181	December 26th, 2021	21:50:22 UTC	December 27th 2021	14:10:22 UTC	16:20:20

IV. GGTO ESTIMATE AND GNSS MEASUREMENTS FROM LEO

The focus of this paper is the estimation of the Galileo-to-GPS time offset (GGTO). The data downlinked from Bobcat-1 contains measurements for all GNSS constellations; however, Galileo-to-GPS is currently being used for an initial analysis with plans to estimate time offsets for other GNSS constellations in the future. There are multiple approaches to calculating inter-constellation time offsets, each with slightly different effects in terms of error propagation, as outlined in [5]. One approach is to use a linearized least squares (LLS) estimation method to calculate a position solution and receiver-to-system time offsets. The receiver-to-system time offsets for each constellation can be calculated independently if more than four satellites are visible for each constellation. The inter-constellation time offsets can then be found by taking the difference of the independently calculated receiver-to-system time offsets. Another approach using the LLS estimation method is to implement a multi-GNSS model, which allows for a user position and multi-constellation receiver-to-system time offsets to be calculated, with the minimum number of satellites required being equal to the number of unknown state variables.

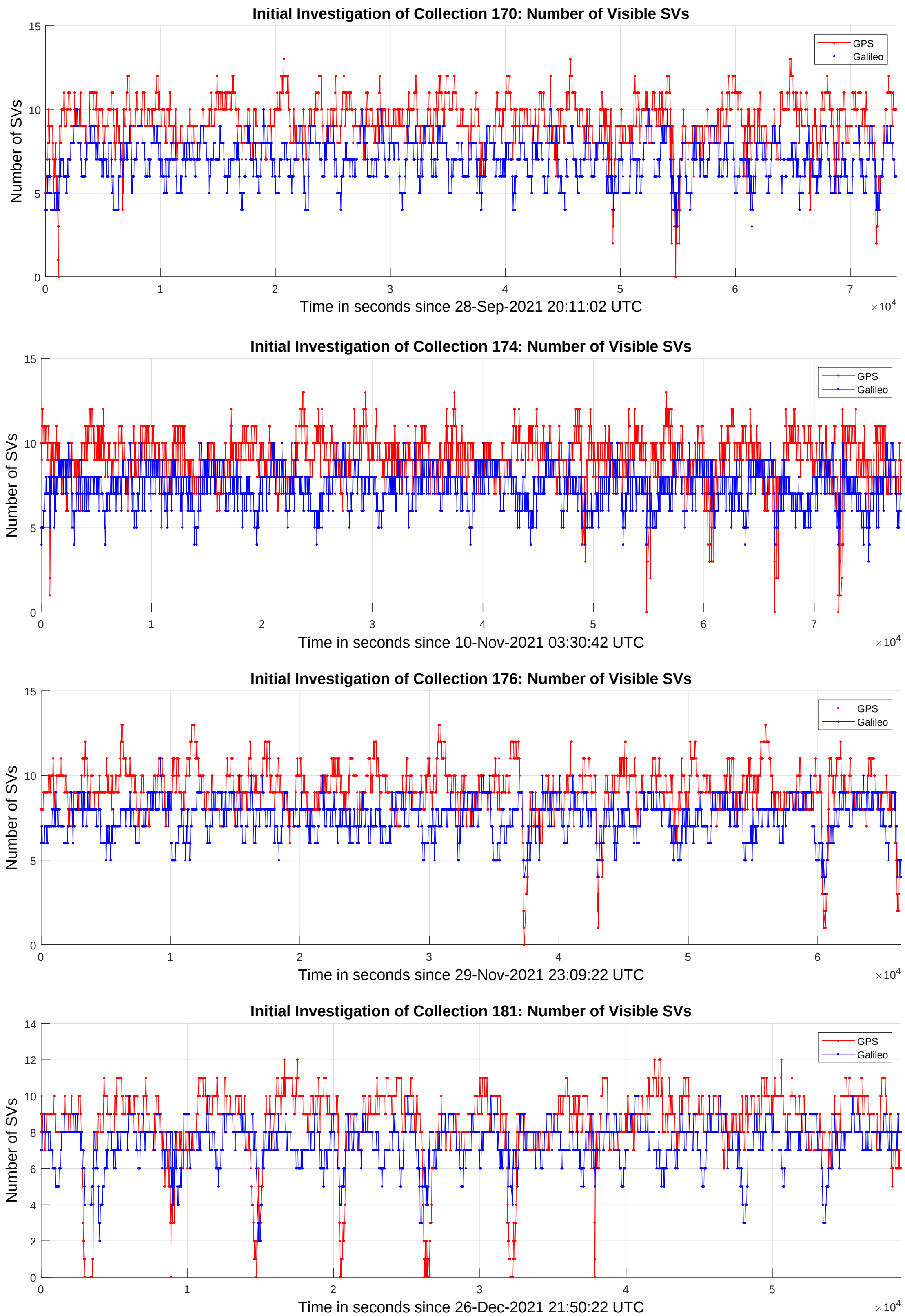


Figure 2: Number of visible SVs for GPS (red) and Galileo (blue) including data points with insufficient visibility.

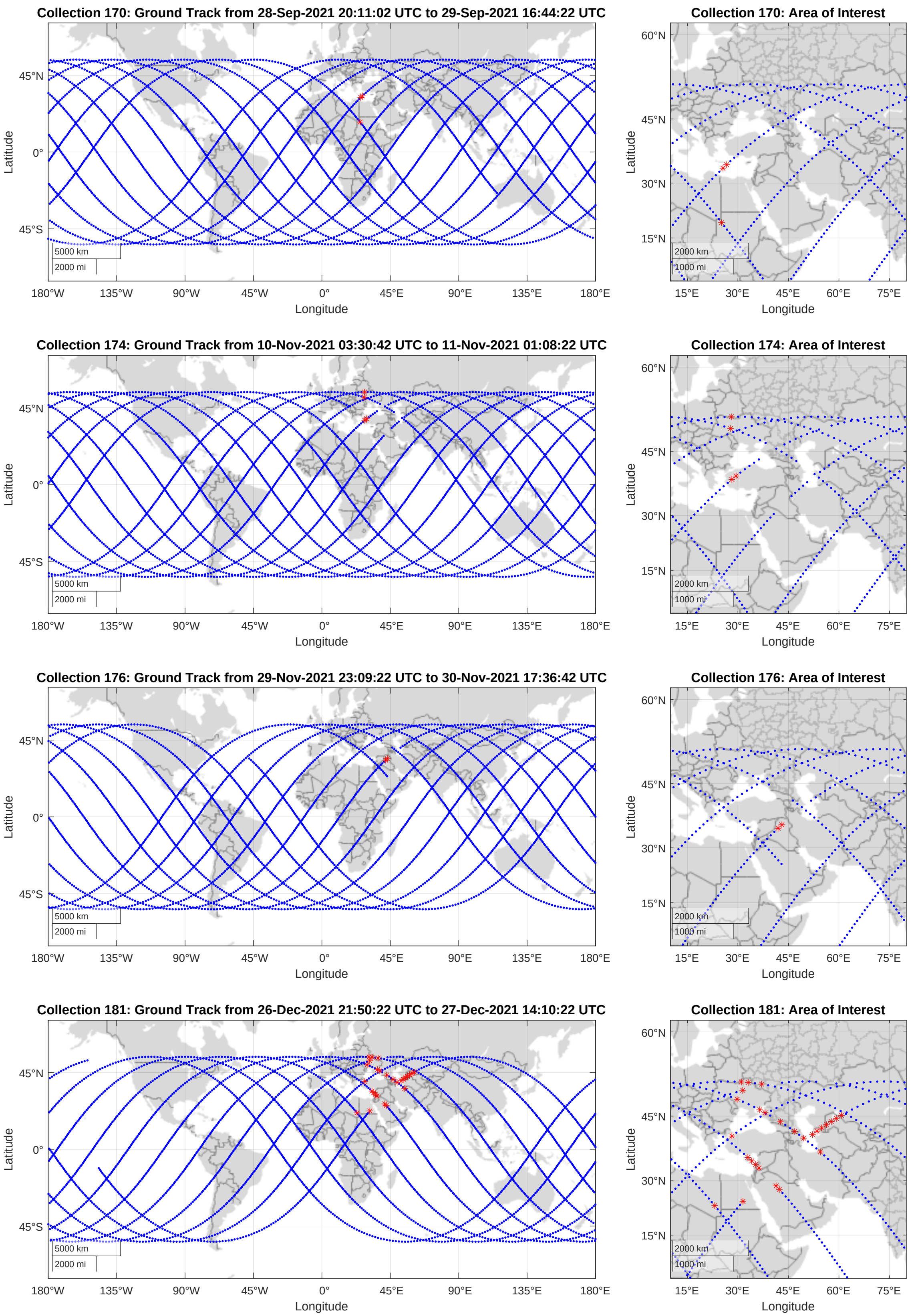


Figure 3: Bobcat-1's ground track during data collections with points of insufficient visibility to estimate GGTO marked in red.

An initial investigation of the downlinked data was conducted in order to determine which approach is best suited for determining the receiver-to-system time offsets (2). As mentioned above, one approach would require at least four visible satellites for both GPS and Galileo. The multi-GNSS model mentioned above would require a minimum of five visible satellites, consisting of a combination of SVs from both GPS and Galileo, in order to solve for the five unknown state variables:

x, y, z	position coordinates,
$t_{\text{RX–GPS}}$	the receiver-to-GPS time offset,
$t_{\text{RX–GAL}}$	the receiver-to-Galileo time offset

If the visible satellites are not a combination of SVs from both constellations, a receiver-to-system time offset cannot be calculated for the missing constellation.

The initial investigation revealed that the number of visible satellites was almost always sufficient to solve for the five unknown state variables after imposing a 5-degree mask angle on all SVs visible to Bobcat-1. The occasional exception occurs during the collection, and these samples are marked by a red star in Figure 3. These exceptions take place when the number of visible GPS SVs drop to zero or the total number of visible satellites drops below the required five needed to solve for the unknown state variables, which can be seen in Figure 2. These samples will be disregarded as a solution for the five unknown state variables, and thus an estimation of the GGTO is not possible. In the 'Collection 174: Area of Interest' plot in Figure 3, gaps in the data are seen; these gaps occur where the receiver could not calculate a position solution due to the lack of visibility. These drop outs occur seldomly and only last for a few sampling periods at most, leaving only a few samples during the data collections where a solution cannot be calculated. Based on this initial analysis of the data, it was seen that the receiver-to-system time offset estimations could be calculated with fewer exceptions using a multi-constellation LLS estimation method, thus the decision was made to calculate the receiver-to-system time offsets following the method described in [16].

The left side of Equation 1 contains the pseudorange measurement errors, $\Delta\rho_{\text{GPS}_N}$, which are related to the unknown position errors, and receiver-to-system time offsets, $\Delta t_{\text{RX-GPS}}$ and $\Delta t_{\text{RX-GAL}}$ through the measurement matrix, **H**.

$$\begin{bmatrix} \Delta\rho_{\text{GPS}_1} \\ \vdots \\ \Delta\rho_{\text{GPS}_N} \\ \Delta\rho_{\text{GAL}_1} \\ \vdots \\ \Delta\rho_{\text{GAL}_N} \end{bmatrix} = \mathbf{H} \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta t_{\text{RX–GPS}} \\ \Delta t_{\text{RX–GAL}} \end{bmatrix} \tag{1}$$

The first three columns of the measurement matrix contain the relative position between the receiver and the i-th satellite of a specified constellation in the x, y, and z direction, respectively. The number of columns in the measurement matrix is expanded here to five, in order to accommodate both the unknown time offsets between the user receiver and each constellation in the solution. The inter-constellation time offset can then calculated as the difference between the receiver-to-system time offsets, as seen in Equation 3.

$$\mathbf{H} = \begin{bmatrix} h_{x_{\text{GPS}_1}} & h_{y_{\text{GPS}_1}} & h_{z_{\text{GPS}_1}} & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{x_{\text{GPS}_N}} & h_{y_{\text{GPS}_N}} & h_{z_{\text{GPS}_N}} & 1 & 0 \\ h_{x_{\text{GAL}_1}} & h_{y_{\text{GAL}_1}} & h_{z_{\text{GAL}_1}} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{x_{\text{GAL}_N}} & h_{y_{\text{GAL}_N}} & h_{z_{\text{GAL}_N}} & 0 & 1 \end{bmatrix} \tag{2}$$

$$h_{x_{\text{SYS}_i}} = \frac{x_{\text{SYS}_i} - \hat{x}}{\hat{R}_{\text{SYS}_i}}, \qquad h_{y_{\text{SYS}_i}} = \frac{y_{\text{SYS}_i} - \hat{y}}{\hat{R}_{\text{SYS}_i}}, \qquad h_{z_{\text{SYS}_i}} = \frac{z_{\text{SYS}_i} - \hat{z}}{\hat{R}_{\text{SYS}_i}}$$

Where:

$(\hat{x}, \hat{y}, \hat{z})$	is the estimated user coordinates,
$(x_{\text{SYS}_i}, y_{\text{SYS}_i}, z_{\text{SYS}_i})$	is the position of the i-th satellite,
$\hat{R}_{\text{SYS}_i}$	is the range between the GNSS satellite and the user

Thus, the Galileo-to-GPS time offset estimation can be calculated as:

$$\text{GGTO} = \Delta t_{\text{RX–GPS}} - \Delta t_{\text{RX–GAL}} \tag{3}$$

V. ERROR ANALYSIS

In order to produce a high-quality time offset estimation, biases due to the receiver, environment, and SV clocks must be calibrated, mitigated, or bounded. The pseudorange measurements made by the NovAtel OEM719 receiver are affected by a number of impairments, and can be expressed, as in [17].

$$\rho_k = R_k + I_k + T_k + \varepsilon_P + \tau_k(\theta, \phi) + \Delta t_{\text{RX-SYS}} + \eta_k \tag{4}$$

Where:

R_k	is the true range,
I_k	is the ionospheric delay,
T_k	is the tropospheric delay,
ε_P	is the satellite orbit error projected onto the line-of-sight,
$\tau_k(\theta, \phi)$	is the antenna group delay as a function of elevation and azimuth angles,
$\Delta t_{\text{RX-SYS}}$	is the receiver-to-system clock offset,
η_k	represents the noise and multipath errors

It should be noted that in LEO the tropospheric delay T_k is not present. That maximum multipath errors are related to the furthest reflection point from the receiving antenna; in space, these reflections are due only to the body of the spacecraft. Given that the maximum dimension of Bobcat-1 is approximately 30 cm, the maximum multipath error would be bounded to 1 ns. However, given that the reflected signal's power would be lower than the line-of-sight (LOS) signal, the expected maximum error due to multipath would be $\ll 1$ ns, making it negligible given our target.

In general, the ionospheric effect is still present in LEO, though it is smaller than the ionospheric effect seen by a terrestrial user. Bobcat-1's altitude, from about 415 km at deployment, is approximately located in the region of the ionosphere known as the F2-region [18]. However, a minimum solar activity has been observed, which corresponds to a minimum value of the earth's atmosphere thickness, and thus the ionosphere's thickness [19]. The impact of the ionospheric effect has been evaluated using dual frequency measurements and applying satellite inter-frequency corrections. The receiver inter-frequency bias has been evaluated and bounded in the lab, in different temperature conditions. It should be noted that in usual conditions, when the ionosphere does not present high spatial gradients, neglected ionospheric errors mainly affect the clock estimates, and if a sufficient number of satellites are in view, that impact is comparable on both the GNSS constellations considered (here GPS and Galileo). Given these conditions, for our scope neglecting the ionospheric effect while selecting an elevation mask angle larger than zero gave a more accurate result than introducing a double frequency ionospheric correction as shown in Figure 4. Further analysis will be done to consider a multi-frequency approach to mitigate the ionospheric effect.

Comparing the position residuals with and without ionospheric corrections applied, it can be seen in Figure 4 that the ionospheric correction adds noise to the solution without a noticeable improvement in terms of residual bias. Other biases that are neglected here will be addressed in future work, such as satellite orbit error and antenna group delay.

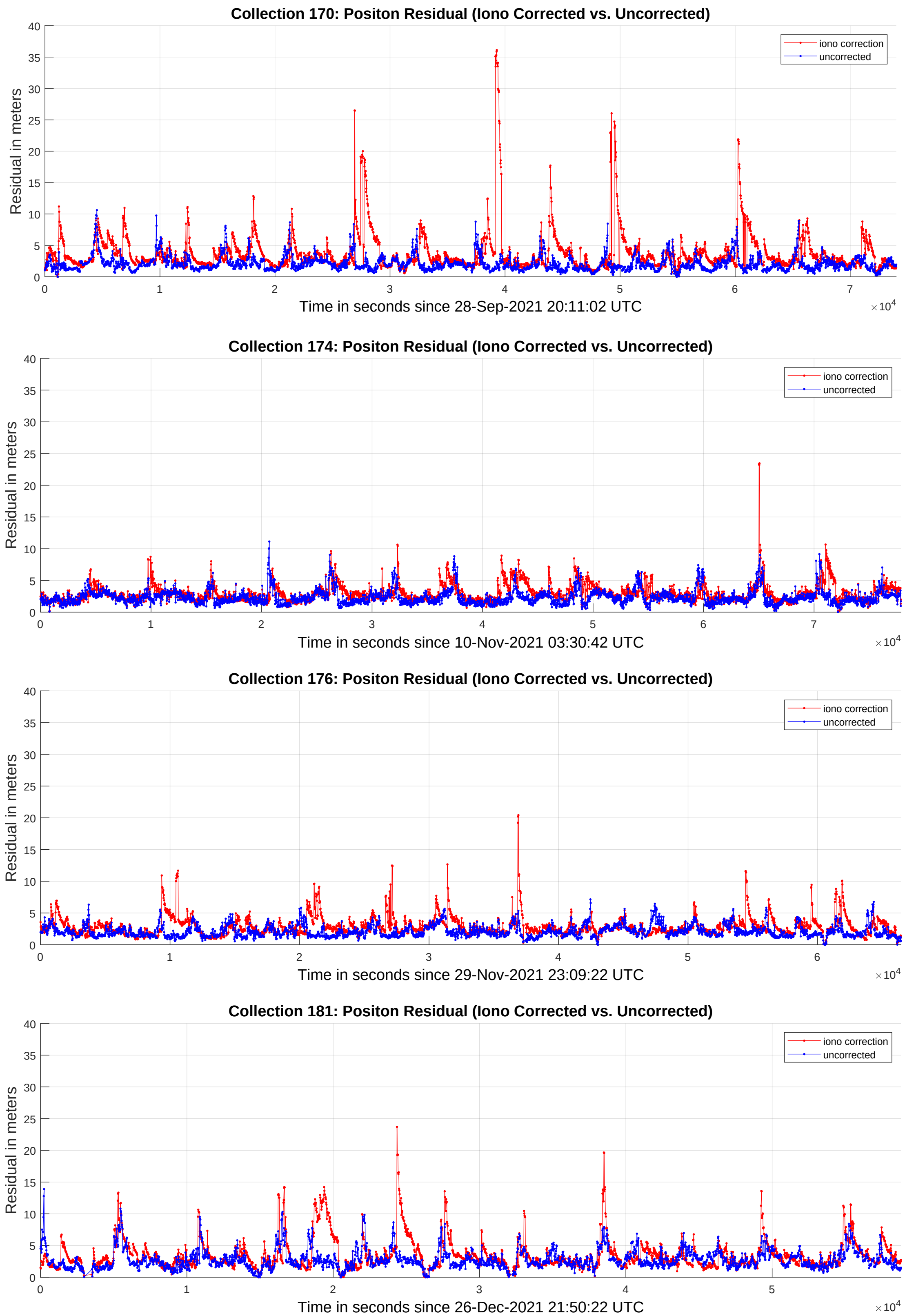


Figure 4: Comparing the position residuals with (red) and without (blue) ionospheric corrections applied for each data collection.

VI. RESULTS

In this section, results from the four data collections discussed in Sections III are shown. The Bobcat-1 estimated GGTO, computed using the method described in Section IV, is compared with the broadcast GGTO. The broadcast GGTO is calculated according to Equation 5, as in [13], applying the broadcast parameters A_{0G} and A_{1G}, also available in the archive of broadcast ephemerides in NASA's Crustal Dynamics Data Information System (CDDIS) [20].

$$\Delta t_{\text{Systems}} = t_{\text{GAL}} - t_{\text{GPS}} = A_{0G} + A_{1G}(TOW - t_{0G} + 604800 \times (WN - WN_{0G})) \tag{5}$$

Where:

A_{0G}	is the constant term of the offset,
A_{1G}	is the rate of change of the offset,
TOW	is the time-of-week in seconds,
t_{0G}	is the GGTO data reference frame,
WN	is the Galileo System Time week number,
WN_{0G}	is the GGTO data reference week number

Figure 5 shows the stability of the Bobcat-1 GGTO estimate, with respect to the broadcast GGTO. The plots shown in Figure 5(a) show the Bobcat-1 GGTO estimates in blue, as well as a filtered version in red (computed using a 100-point moving average filter), compared against the broadcast GGTO in black. The plots shown in Figure 5(b) show the difference between Bobcat-1's GGTO estimate, both unfiltered and filtered, and the broadcast GGTO, i.e., the characteristic receiver GGTO. The mean of both the Bobcat-1 GGTO estimate and the broadcast GGTO estimate, as well as the standard deviation of the Bobcat-1 estimate, can be found in Table 2. The mean residual receiver bias was then estimated by subtracting the mean of the broadcast GGTO from the mean of the Bobcat-1 GGTO estimate. The stability of the characteristic receiver bias can be seen in column 4 of Table 2, which shows that the residual bias, due to the receiver GGTO and other residual impairments, is stable and repeatable within 1.5 ns. Table 3 shows the average residual receiver GGTO for the NovAtel OEM719 onboard Bobcat-1 for the four data collections used in this experiment. The maximum deviation was calculated by subtracting the mean residual receiver bias, 22.635 ns, from each of the residual receiver offsets in Table 2.

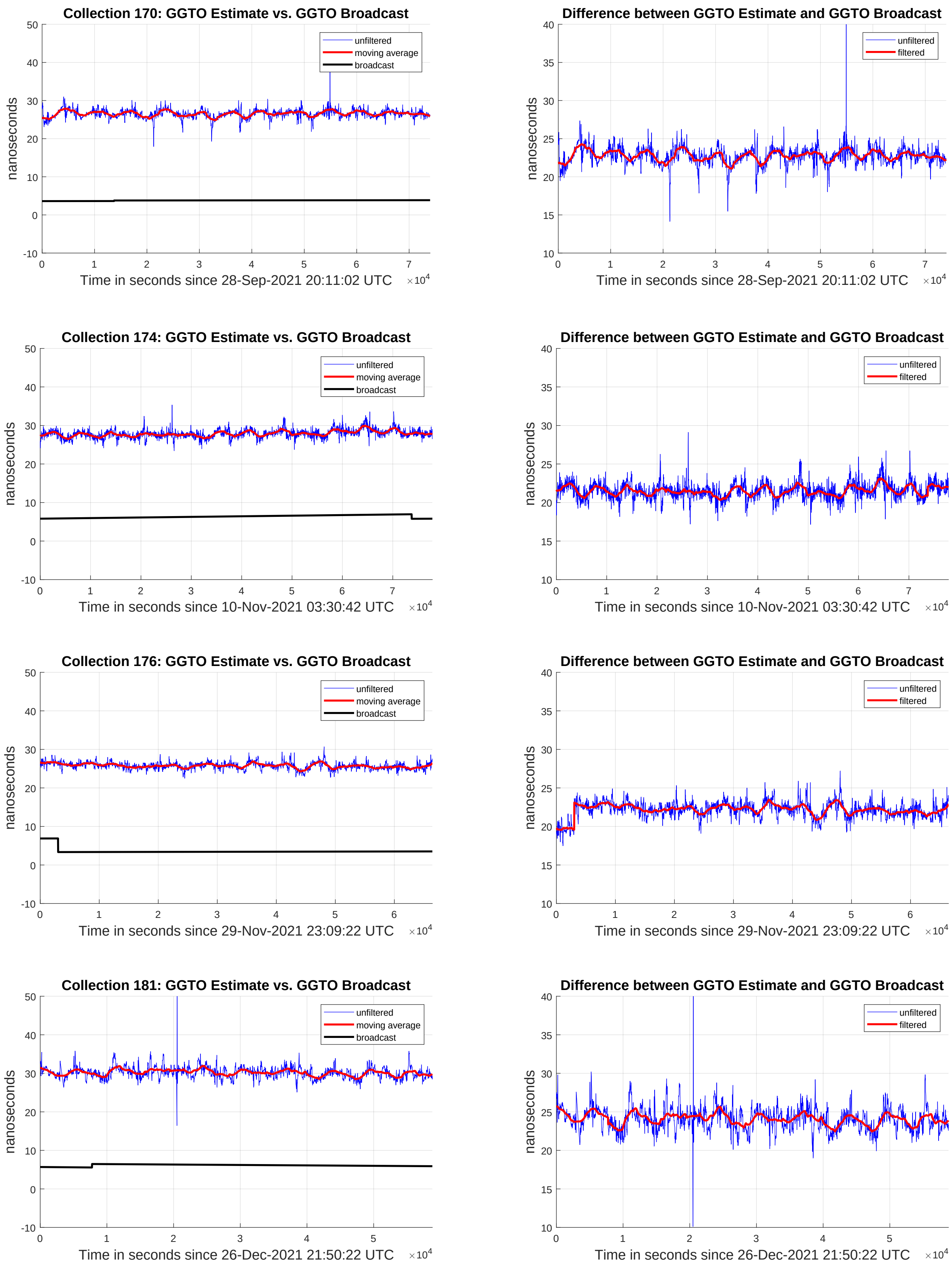
It must be noted that while the mean value of the receiver's GGTO shows a small variance, oscillations of magnitude in the order of 5 ns peak-to-peak are observed. However, when looking at the onboard receiver temperature, oscillations with the same period are observed. Therefore, the oscillations seen on the Bobcat-1 GGTO estimates are highly correlated to the orbit and solar exposure. The relationship between temperature and receiver bias is consistent with the observations made when the receiver was tested in a controlled temperature chamber in laboratory-controlled environment before launch. While in this paper the main goal was to evaluate the stability of the receiver GGTO at LEO and evaluate the impact of environmental impairments, future work will address in detail the correlation between the receiver's GGTO and the residual impairments, including the receiver's temperature, in order to calibrate it.

Table 2: Statistics of Bobcat-1's GGTO Estimation and the Broadcast GGTO for each data collection

Collection ID	Mean GAL-to-GPS offset, Bobcat-1 estimate	Mean Broadcast GAL-to-GPS offset (GAGP or GGTO)	Mean residual Bobcat-1 receiver GAL-to-GPS offset	Standard deviation of GAL-to-GPS offset, Bobcat-1 estimate
170	26.55 ns	3.79 ns	22.76 ns	1.19 ns
174	27.87 ns	6.35 ns	21.52 ns	1.10 ns
176	25.76 ns	3.59 ns	22.16 ns	0.92 ns
181	30.20 ns	6.11 ns	24.10 ns	1.59 ns

Table 3: Statistics considering Collections 170, 174, 176 and 181

Mean residual Bobcat-1 receiver GAL-to-GPS offset	Maximum deviation of GAL-to-GPS offset, Bobcat-1 estimate
22.635 ns	1.465 ns



(a) GGTO Estimate from Bobcat-1 (blue) and a filtered estimate (red) alongside the Broadcast GGTO (black)

(b) The difference between the Bobcat-1 GGTO Estimate and the Broadcast GGTO, i.e., the characteristic receiver GGTO

Figure 5: Comparison of the Bobcat-1 GGTO Estimate and the Broadcast GGTO

VII. CONCLUSIONS AND FUTURE WORK

In this paper, results of four 15+ hour data collections spanning a period of three months are compared, the difference between the broadcast GGTO and the GGTO estimate calculated using data from Bobcat-1 appears to be stable within 1.5 ns. Observing the in-orbit data and comparing it with the data collected previously in a controlled environment in the lab, a high correlation is observed between the bias change over time and the measured receiver temperature. The mitigation of this effect will enable stability of our receiver characteristic GGTO estimate to within 1 ns. These experimental results suggest that a few LEO multi-GNSS receivers could enable a possible way to monitor in semi-real time the estimated GGTO, providing some redundancy and diversity to the ground-network-based estimation system.

Future work includes further investigation of the residual biases, as well as collecting more data with hopes of collection durations surpassing a full 24 hours. Collecting as much data as possible before Bobcat-1's deorbit will allow for more insight on the repeatability of the receiver characteristic GGTO. The focus will then be to address in detail the main hardware components affected by the temperature change, in combination with the data previously collected in the lab. Following the modeling and mitigation of residual impairments, such as temperature effect, antenna group delay, and satellite orbits, the next step will be to consider the inter-constellation time offset between all the GNSS constellations.

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