GNSS TIMING MEASUREMENTS FROM A LOW-EARTH ORBITING SATELLITE

Estimating GPS to Galileo Time Offset Using Bobcat-1

BY SABRINA UGAZIO, ZACHARY ARNETT, BRIAN C. PETERS, RYAN MCKNIGHT AND AUSTIN MCKIBBEN

Bobcat-1 was a three-unit CubeSat developed and built at Ohio University's Avionics Engineering Center in Athens, Ohio, and was named after the university's mascot. **FIGURE 1** shows Bobcat-1 with and without its antenna deployed. The satellite was launched to the International Space Station in October 2020 (see **FIGURE 2**) and deployed into low-Earth orbit (LEO) the following month (see **FIGURE 3**). In April 2022, it deorbited and burned up in Earth's atmosphere as planned, after a successful 17-month mission, lasting eight months longer than anticipated. The last signal decoded from Bobcat-1 was received only about 10 minutes before the satellite's demise, from an altitude of about 109 kilometers, by an amateur radio operator (ZR6AIC) near Johannesburg, South Africa, associated with SatNOGS, a global network of amateur satellite-networked open ground stations.

The main mission of the Bobcat-1 CubeSat was to evaluate the feasibility of GNSS-to-GNSS time offset monitoring from LEO. One of the secondary mission objectives was GNSS spectrum monitoring.

In addition, Bobcat-1 also included a side-mission, hosting a software-defined GPS/Galileo receiver developed by the University of Padova and Qascom — an Italian engineering company providing security solutions in satellite navigation and space cybersecurity — to perform its in-space demonstration and testing. This receiver served as a prototype for the receiver soon to be launched on NASA's Lunar GNSS Receiver Experiment (LuGRE) mission.

Communications and control of the satellite utilized the 70-centimeter amateur radio satellite band (435-438 MHz) at a typical data rate of 60 kilobits per second and were primarily conducted using a dedicated ground station on the roof of the engineering building at Ohio University (see **FIGURE 4**). In total, Bobcat-1 collected and downlinked more than 656 megabytes of data during its lifetime. Over the course of the mission, Bobcat-1's firmware was updated in-orbit on six occasions, allowing for minor enhancements to the data collection system.

BACKGROUND: GNSS-TO-GNSS TIME OFFSET

GNSS-to-GNSS time offsets — also referred to as GNSS inter-constellation time offsets, inter-system biases or

FIGURE 1 Bobcat-1, with communications antenna stowed (left) and deployed (right). Bobcat-1 measures approximately 10 x 10 x 30 centimeters.
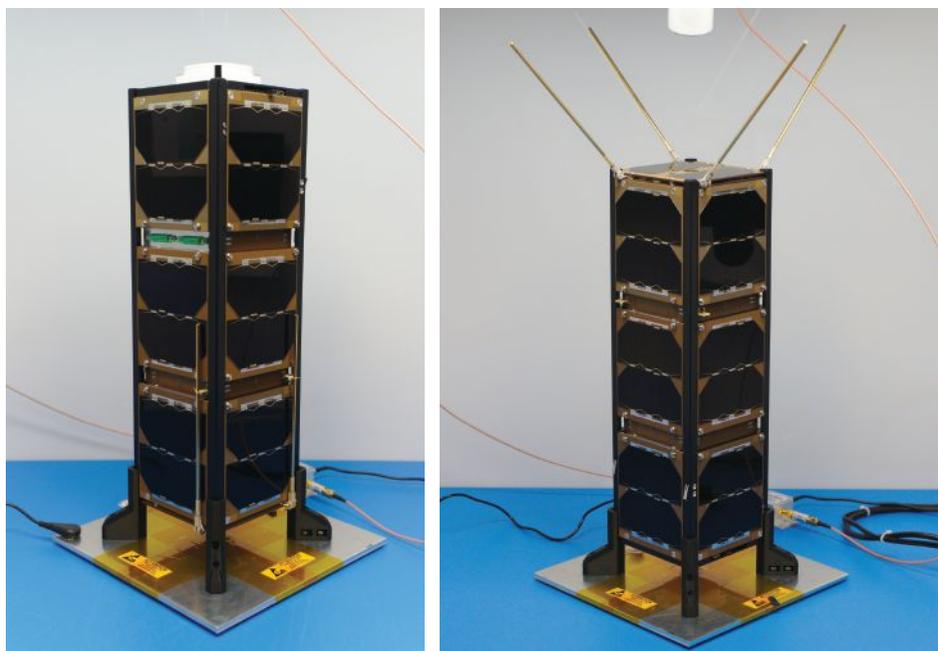
All figures except FIGURE 3 provided by the authors.

XYTOs — are among the critical parameters for full GNSS interoperability. Users with poor GNSS visibility, such as high-altitude spacecraft, which operate above the GNSS constellations, often do not have enough satellites in view to enable an accurate solution and can experience high dilution of precision. These users could benefit from XYTO estimates provided externally, assuming their receiver-characteristic inter-system biases (ISBs) are calibrated.

To determine a user solution using measurements from a single GNSS constellation, one must solve for four unknown parameters: 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 applying measurements from multiple constellations, an additional unknown is added for each constellation used. For example, for a user solution incorporating measurements

INNOVATION INSIGHTS

BY RICHARD B. LANGLEY

WHAT IS A CUBESAT? In 1999, professors Jordi Puig-Suari at California Polytechnic State University and Bob Twiggs at Stanford University proposed a design for a miniaturized satellite that would allow students to more easily develop the skills necessary for the design, construction, testing and operation of satellites in low-Earth orbit (LEO). These nanosatellites would be built using standardized modules with a useful volume of 10 × 10 × 10 centimeters (hence the designation cube satellite or CubeSat) with a maximum mass of 2 kilograms. Apparently, the inspiration for the design came from the plastic box used to display "Beanie Babies," a line of small stuffed toys. While a CubeSat can be constructed using one module or unit, termed a 1U design, modules can be stacked together to form sizes of 2U, 3U and so on.

Initially just a suggested form factor, the design was widely adopted by nanosatellite developers and in 2017 the International Organization for Standardization published the ISO 17770:2017 standard to formally define the physical, mechanical, electrical and operational requirements of CubeSats.

While some CubeSats have been launched as secondary payloads on launch vehicles, many have been released into space having been first launched to the International Space Station (ISS) in a cargo resupply vehicle. For example, Nanoracks developed a CubeSat deployer that can house multiple CubeSats. Once on the ISS, the deployer is positioned so that when its forward-facing door is opened, a spring at the back of the deployer pushes the CubeSats into space.

As of January 1, 2024, 2,323 CubeSats have been launched according to a nanosatellite database. Some of these satellites demonstrated new space technologies while others were science investigation missions to study Earth's atmosphere or space weather or astronomical objects or other satellites. Many of these CubeSats, if not most, have been built by universities from around the world. In fact, various space agencies have programs to support the development and launch of CubeSats by students, such as NASA's CubeSat Launch Initiative and the Canadian Space Agency's Canadian CubeSat Project (CCP). As most CubeSats go into LEO, a lot of them have already deorbited. However, while in space, they provided a wealth of data of various kinds and many of the accumulated datasets are still being mined for new results. A nice example of such a dataset is that provided by Bobcat-1, a 3U CubeSat developed by Ohio University. Its mission, in addition to training students in aerospace technologies, was primarily to assess the feasibility of monitoring the time offsets between different GNSS, but also GNSS spectrum monitoring and testing a software-defined GNSS receiver. In this quarter's "Innovation" column, authors from the Bobcat-1 team discuss some of their work on Galileo-to-GPS system time offsets. Go Bobcats!
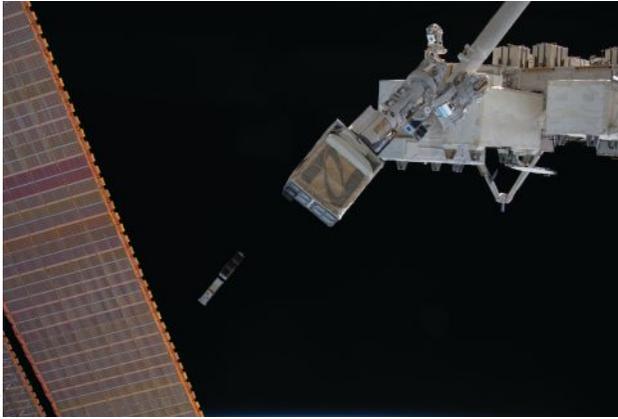
FIGURE 3 Bobcat-1 is deployed into low-Earth orbit by the Nanoracks CubeSat Deployer alongside SPOC, a CubeSat developed by the University of Georgia.

from both GPS and Galileo, one needs to solve for five unknowns: the user's spatial coordinates, the receiver-to-GPS time offset, and the receiver-to-Galileo time offset. Since each constellation's time scale is independent of the others, the inter-system time offset between the time scales leads to a prominent bias in a multi-constellation solution. Inter-system time offsets between GPS, Galileo, GLONASS, and BeiDou are generally expected to range from 10 to 100 nanoseconds, resulting in 3 to 30 meters of possible positioning error.

System-to-system time offsets are currently estimated by extensive networks of ground stations, such as those used by the International GNSS Service Multi-GNSS Experiment (MGEX). In addition, GNSS service providers often broadcast XYTO estimates in their navigation messages.

So, why would estimating XYTOs from LEO be of interest?

Low-Earth orbit enables high GNSS visibility. The approximately 90-minute orbital period allows for observations from nearly all GNSS satellites multiple times per day. This enables high visibility of multiple satellites from each constellation, in turn enabling high observability of constellation parameters such as XYTOs, leveraging satellite-characteristics errors. In addition, tropospheric errors are absent and multipath is limited and can be bounded based on the CubeSat's dimensions and geometry. Exploiting measurements from LEO could provide additional measurements and independent monitoring of the XYTO estimates provided by ground networks.

However, to estimate system-characteristic XYTOs, the receiver-characteristic biases need to be calibrated. The target is to reach accuracy of approximately 1 nanosecond or possibly lower. Therefore, the error sources need to be evaluated, mitigated, or bounded.

Although the ionospheric effects are lower in LEO than on Earth, they cannot be neglected. Therefore, dual-frequency ionospheric delay estimates must be applied. To do so, the receiver's inter-frequency biases (IFBs), which can introduce errors on the order of nanoseconds, need to be calibrated, as well as the satellite differential code biases (DCBs), orbit and clock errors and receiver antenna group delay. An additional challenge introduced by the LEO environment is the wide range of temperatures to which the receiver is subjected. Over a single orbit, the receiver's temperature can vary from approximately 0 to 50 degrees Celsius. The effects of these temperature variations cause fluctuations in the receiver's IFBs, which need to be evaluated and calibrated. Pre-launch measurements in a controlled environment using a climate chamber and two receivers of the same make and model were used for calibration. We have detailed those measurements elsewhere.

The multipath error can be bounded, as a first approximation, to 10 centimeters (or about 0.3 nanoseconds in equivalent signal delay) due to the dimensions of the CubeSat. However, given the mount of the antenna is on one of the CubeSat's two 10 × 10 centimeter faces, that upper bound is in practice much smaller and the multipath error is mostly negligible.

Finally, the last remaining major error sources to be calibrated are the receiver ISBs. The main goal, to demonstrate the feasibility of LEO-CubeSat-based monitoring of GNSS XYTOs, requires showing the stability (or the repeatability) of the receiver biases in orbit.

DATA COLLECTION

Bobcat-1's primary payload was a NovAtel OEM719, a triple-frequency multi-GNSS receiver, enabling measurements on all frequencies from GPS, GLONASS, Galileo and BeiDou, as well as the regional navigation satellite systems (RNSSs) QZSS and NavIC. The measurements were collected and

FIGURE 4 Bobcat-1's dedicated ground station on the roof of Stocker Center in Athens, Ohio.

Collection ID	Start Date	Start Time	End Date	End Time	Duration
170	September 28, 2021	20:11:02 UTC	September 29, 2021	16:44:22 UTC	20:33:20
174	November 10, 2021	03:30:42 UTC	November 11, 2021	01:08:22 UTC	21:37:40
176	November 29, 2021	23:09:22 UTC	November 30, 2021	17:36:42 UTC	18:27:20
181	December 26, 2021	21:50:22 UTC	December 27, 2021	14:10:22 UTC	16:20:20
215	February 27, 2022	12:01:22 UTC	February 28, 2022	11:59:22 UTC	23:58:00

TABLE 1 Summary of data collections discussed in this article.

downloaded, for post-processing purposes.

Pseudorange and carrier-phase measurements, as well as carrier-to-noise-density ratio estimates, were collected, together with the receiver's position and velocity estimates, and other parameters such as the temperature measured by the two sensors embedded in the receiver. In limited instances, power spectral density measurements and in-phase and quadrature (I/Q) component samples were collected to support the secondary mission, GNSS spectrum monitoring. The limited downlink capacity of the satellite constrained these measurements to short time intervals.

The goal of the mission is to estimate the XYTOs for all the GNSS constellations. However, in this article only the Galileo-to-GPS time offset (GGTO) is considered. The Galileo Performance Reports published by the European Union Agency for the Space Programme (EUSPA) provide information on the accuracy of the GGTO broadcast parameters, which are typically within approximately 3 nanoseconds of the true GGTO. Therefore, the broadcast GGTO provides a point of comparison and reference for Bobcat-1's estimates.

A summary of the data collections considered in this work is provided in **TABLE 1**. These data collections are among the longest recorded by Bobcat-1. As an example, **FIGURE 5** shows Bobcat-1's data collection for February 27, 2022. It should be noticed that data collections were initiated from the control station at Ohio University when the CubeSat was in view, and each data collection would start only when the satellite's battery voltage was above a defined threshold. The collection would stop safely if a minimum voltage threshold was reached. The data sets collected during the first months of the mission had durations limited to one to four hours, since the minimum battery voltage threshold was set conservatively. However, as the mission continued, data collections recorded in the last several months before deorbiting were configured with lower thresholds, enabling continuous data collections with durations of up to 24 hours. During the longer data collections, the sampling period was set to 20 seconds to reduce the total quantity of data stored and downlinked. The work described here focuses on a select few data collections that span a period of five months between September 28, 2021, and February 27, 2022.

The data contain multi-frequency measurements from all systems, with an average of 180 observations made per sample. The maximum number of observations at once was 217. While multi-frequency measurements were collected from all constellations, this analysis only uses single-frequency measurements from two constellations: GPS L1 C/A and Galileo E1C.

RESULTS

There are two simple approaches to calculating inter-constellation time offsets: one involves computing multiple single-constellation user solutions, and the other involves a single multi-constellation user solution. Each approach has slightly different effects in terms of error propagation. In the first approach, the XYTOs can be calculated by taking the difference of the independently calculated receiver-to-system time
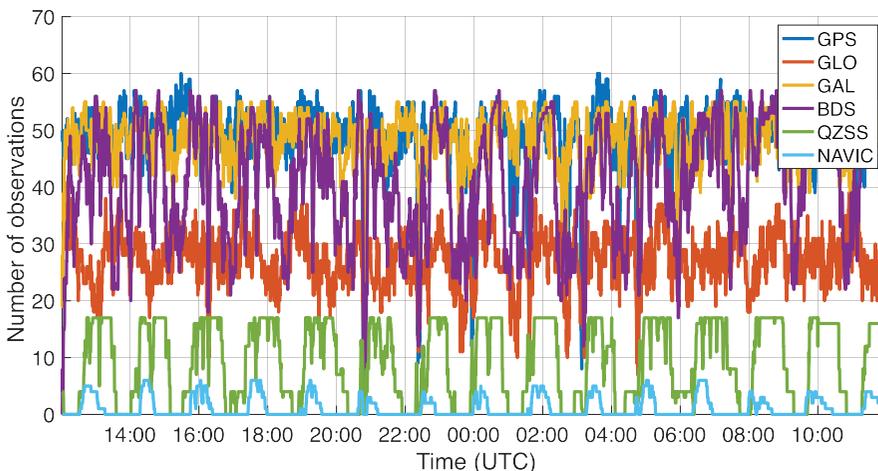
FIGURE 5 Number of observations recorded by Bobcat-1 from each GNSS constellation during a data collection started on February 27, 2022.
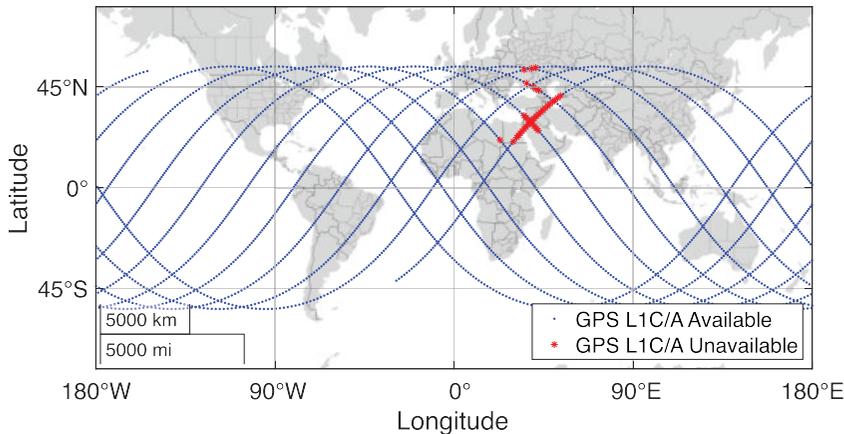
FIGURE 6 Bobcat-1's ground track during a data collection for XYTOs estimation held in February 2022, approximately 24-hours long. Note that the blue dots correspond to the positions (latitude and longitude) of Bobcat-1. The red stars indicate that even if the position was calculated thanks to a multi-frequency and multi-GNSS solution, GPS L1 C/A measurements were not available. Analysis of the carrier-to-noise-density ratio measurements and comparison with the available spectrum measurements showed that in correspondence to those positions interference was present.

FIGURE 7 shows (in blue) the GGTO estimate using Bobcat-1 measurements (data collection 181, started on December 27, 2021, and lasted about 10 orbits). The plotted values are the estimate of the system-to-system bias (GGTO) from which the receiver-specific ISB (Galileo-to-GPS) has not yet been removed. The oscillations visible in the unfiltered GGTO estimates are the result of temperature effects on the receiver. They can be mitigated by applying the calibrations made during pre-launch climate chamber testing, though for this analysis the estimates are simply filtered using a moving average (shown in black in the figure). Note that the abrupt change in the broadcast GGTO about 21 hours after the collection start corresponds to the start of a new day in UTC time, when a new estimate of the broadcast GGTO parameters was provided.

In FIGURE 8, the difference between the Bobcat-1 estimate of the GGTO and the broadcast GGTO is plotted (raw, in blue, and filtered with a moving average, in black). This is an estimate of the Bobcat-1 receiver's Galileo-to-GPS ISB, which needs to be stable and repeatable in orbit, to enable accurate estimates of the true GGTO. As Figure 8 indicates, the receiver ISB shows stability even before calibration, showing periodical variations mainly due to temperature changes over the orbit.

TABLE 2 summarizes some results over a five-month period. Only the longest data collections were considered, but the

offsets. This method requires at least four satellites from each constellation to be visible. In the second approach, all the receiver-to-system time offsets for all constellations involved in the solution are solved simultaneously. This reduces the number of measurements required per-constellation, with the minimum number of measurements needed being equal to the number of unknown state variables.

In general, the latter method improves the XYTOs' solution availability since the receiver-to-system time offsets for each system can be calculated with even fewer than four measurements from each system. For each sample point, the user solution was determined using this method, and the GGTO estimate was calculated by taking the difference of the receiver-to-GPS time offset and the receiver-to-Galileo time offset. This method allows the XYTO to be estimated by the receiver even when visibility is degraded. For example, as shown in FIGURE 6, Bobcat-1's data collections are affected by interference, mostly on GPS L1, in some regions. Points where interference was believed to be present are marked by red stars on Bobcat-1's ground track shown in the figure, specifically denoting points where the number of tracked GPS L1 C/A signals drops below four. For each sample point, the user solution was determined using the method discussed above, and the GGTO estimate was calculated by taking the difference of the receiver-to-GPS time offset and the receiver-to-Galileo time offset.

FIGURE 7 Broadcast GGTO (red) compared to Bobcat-1 Galileo-GPS time offset estimate, before calibration (blue) and filtered estimate (black). The results are related to data collection 181, started on December 27, 2021, which lasted about 16 hours (more than 10 orbits). The estimates' variations, on the order of ±5 nanoseconds, are mainly due to temperature effects during the orbit and here are simply represented with a moving average.
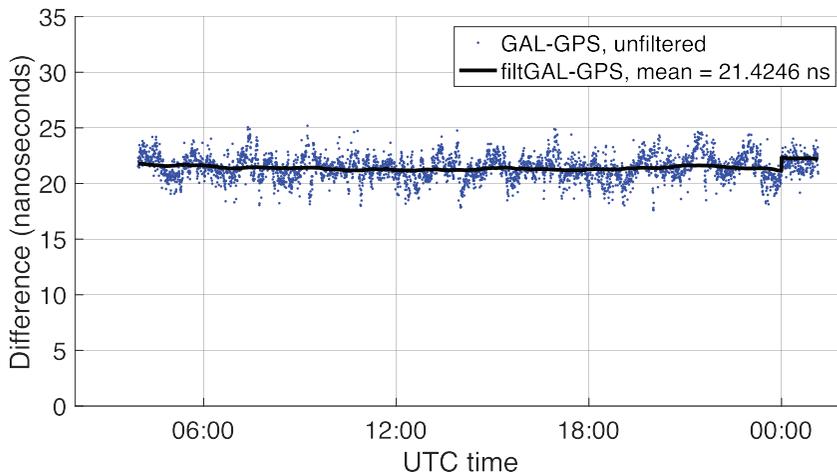
FIGURE 8 Difference between Bobcat-1 estimate and GGTO. The residual is mainly an estimate of the receiver inter-system bias that even pre-calibration shows to be stable in orbit as shown in Table 2.

Collection ID	Mean Galileo-to-GPS offset, Bobcat-1 estimate	Mean Broadcast GGTO (or GAGP)	Mean estimated Bobcat-1 Galileo-to-GPS ISB	SD of Galileo-to-GPS offset, Bobcat-1 estimate
170	26.55	3.79	22.76	1.19
174	27.87	6.35	21.52	1.10
176	25.76	3.59	22.16	0.92
181	30.20	6.11	24.10	1.59
215	27.97	4.89	23.08	1.38

TABLE 2 Bobcat-1 Galileo-to-GPS time offset vs broadcast GGTO, for different data collections over about five months. All figures in columns two through five are in nanoseconds.

shorter ones are also under analysis to provide a longer and denser observation window. From the data in Table 2, the Bobcat-1 receiver's mean Galileo-to-GPS ISB, estimated by comparison with the broadcast GGTO, shows a standard deviation, pre-calibration, of less than 1.5 nanoseconds over five months. Considering that the accuracy on the broadcast GGTO is expected to be ≤ 3 nanoseconds, this estimate of the receiver ISB shows that its stability over time may enable accurate XYTO monitoring from LEO.

The implementation of the receiver bias calibration, including the temperature effects, will refine this result. The final test will include assessing the performance of the calculated system XYTO, utilizing it in the solution of another receiver previously calibrated and at a known location.

CONCLUSIONS

Results of five 15+ hour data collections spanning a period of five 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 nanoseconds. Observing the in-orbit data and comparing it with the data collected previously in a controlled environment in the laboratory, 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 nanosecond. These experimental results suggest that a few multi-GNSS receivers in LEO could provide a method to monitor XYTOs in near real time, providing redundancy and diversity to the ground-network-based estimation system.

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