Receiver-Specific GNSS Inter-System Bias in Low Earth Orbit

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BIOGRAPHY

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ABSTRACT

In this paper, the stability and repeatability of receiver-characteristic inter-system biases (ISBs) is assessed in low Earth orbit (LEO), analyzing the measurements collected by Bobcat-1, the CubeSat developed at Ohio University which completed its mission in April 2022 after 17 months in orbit. GNSS interoperability has been a goal in the past years. The current increasing interest in a number of applications which would benefit from it, such as those involving users in the high-altitude Space Service Volume (SSV), are making the topic more and more crucial. GNSS-to-GNSS time offsets, also referred to as GNSS inter-constellation time offsets or XYTOs, are among the critical parameters for full interoperability. Users with not enough satellites in view to solve for the user XYTOs at the receiver could benefit from estimates provided externally, assuming their receiver-characteristic ISBs being prior calibrated. The results shown in this paper suggest that GNSS-to-GNSS time offset measurement and monitoring exploiting LEO receivers can be feasible, leading to the concept of a master-clock in space.

I. INTRODUCTION

The Bobcat-1 mission's main objective was to test the feasibility and performance of a master-clock in space, to measure and monitor Global Navigation Satellite System (GNSS) inter-system biases (ISBs). The interest related to the ISB is particularly relevant in the context of the interoperable GNSS Space Service Volume (SSV) (United Nations Office for Outer Space Affairs, 2018), which was the target application of the Bobcat-1 mission's study. An assessment of the relevance of interoperability for users in the high-altitude SSV is described in Parker et al. (2018) and Enderle et al. (2018), and further simulations considering the possible benefit of GNSS-to-GNSS time offset estimates are shown in Peters (2021). Bobcat-1 was a 3-unit CubeSat, developed at Ohio University. It deorbited on April 8th 2022, after a 17 month-long successful mission, and the analysis of the data collected during the mission is still ongoing. After a preliminary analysis focusing on the Galileo-to-GPS time offset in Arnett et al. (2022), in this paper an assessment of the inter-constellation time offsets is given considering also BeiDou and GLONASS. Before proceeding, a note shall be made related to nomenclature: in Arnett et al. (2022) the authors used the nomenclature of inter-constellation time offsets. Different nomenclatures can be found in literature, as for example GNSS inter-constellation timescale biases in Bar-Sever et al. (2021). From now on in this paper, GNSS-to-GNSS time offsets (XYTOs or XTO system-time offset) will be used to refer to the system-specific offset as in Sesia et al. (2021) and Carlin et al. (2022); receiver-specific ISBs will be used to refer to receiver-specific biases, as in Carlin et al. (2022). The notation has been recently changed on the RINEX Navigation files. The records in RINEX 2.11 were renamed in version 3.x as TIME SYSTEM CORR, in the header line. In the version 4.x, released in January 2022, it has been further updated, including instead System Time Offset (STO) navigation messages.

GNSS interoperability and consequently the assessment of the GNSS-to-GNSS time offsets has become more and more crucial with the growth of space applications, such as lunar and cislunar missions. As a consequence, very relevant work has been published in the past few years to assess performance and to provide new solutions. Different solutions have been suggested in the past few years and months, including sharing a common GNSS reference time to which the other system timescale corrections may be referred (Sesia et al., 2021). In Sesia et al. (2021) the calibration of the receiver is discussed, as well as comparison with broadcast XYTO values. In Carlin et al. (2022), a precise point positioning (PPP) solution based on broadcast ephemeris (Carlin et al., 2021) is applied for time synchronization and for timescale monitoring. The main reason to perform the GNSS-to-GNSS time offset monitoring from low Earth orbit (LEO) is related to the observability: Bobcat-1, which was deployed from the International Space Station (ISS), had an orbit altitude that started at approximately 415 km with an orbit period of roughly 90 minutes, resulting in about 15 orbits per day. As a consequence, the collected data included measurements from most GNSS satellites multiple times a day. Therefore, a small number of receivers orbiting at LEO could potentially provide an independent monitoring system to the GNSS-to-GNSS time offsets.

II. BOBCAT-1 MISSION

Bobcat-1 was developed at Ohio University's Avionics Engineering Center and 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 ISS on November 5th, 2020, with the primary objective of evaluating the feasibility of GNSS-to-GNSS time offset monitoring from LEO. Additional details about the design and development of Bobcat-1 are available in Croissant et al. (2020).

Bobcat-1 has completed its mission, and deorbited at approximately 2:02 (UTC), April 9th, 2022. Figure 2 shows Bobcat-1's periapsis and apoapsis (and average altitude) since deployment from the ISS on November 5th, 2020, at approximately 415 km above earth, until April 6th, 2022, i.e. three days before the end of the mission. Bobcat-1 was fully operational until just a few minutes before re-entering. The last decoded telemetry beacon from Bobcat-1 was recorded via SatNOGS at an altitude of $109\,\mathrm{km}$ by an amateur ground station (ZR6AIC) located near Johannesburg, South Africa, approximately 10 minutes prior to deorbiting. A summary of the mission is available on the SatNOGS dashboard as shown in Figure 1, at SatNOGS (2023b). In the SatNOGS telemetry dashboard at SatNOGS (2023a), more details on Bobcat-1's telemetry data are provided, throughout its whole lifetime. In total, Bobcat-1 collected and downlinked $656\,\mathrm{MB}$ of data from its NovAtel OEM719 and Qascom QN400 receivers. Over the course of the mission Bobcat-1's firmware was updated 6 times. An update on March 3rd, 2022 added support for simultaneous data collections on both receivers.

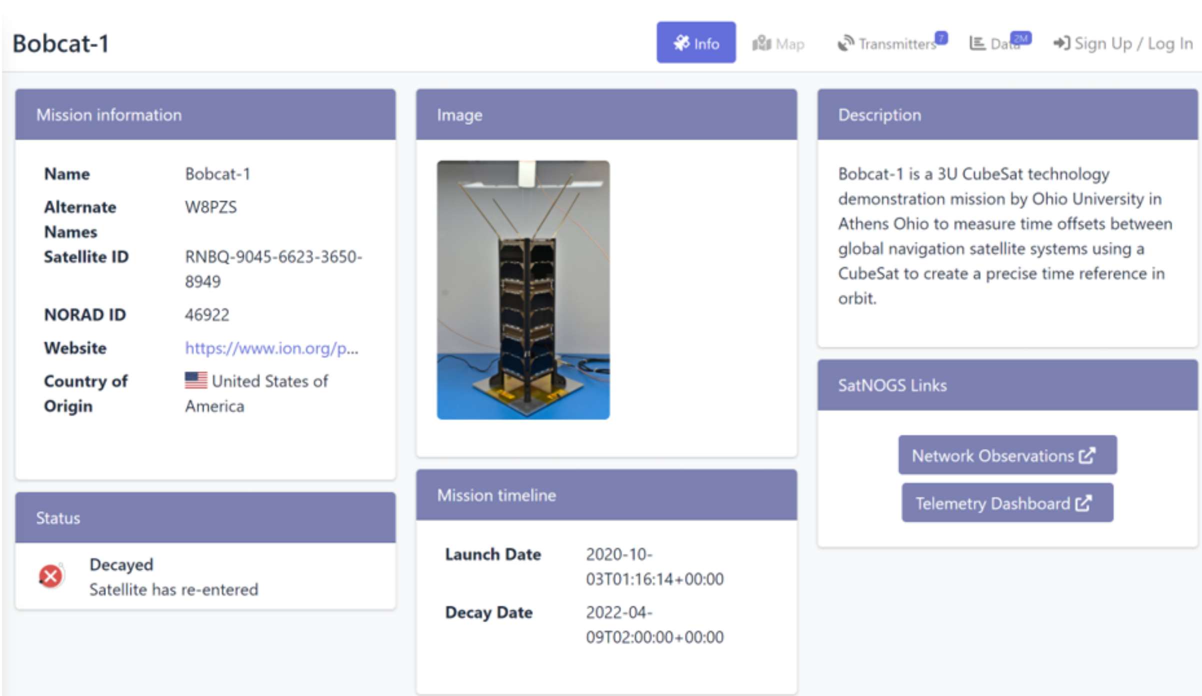

Figure 1: Bobcat-1 mission's summary and timeline as at (SatNOGS, 2023b)

Figure 2: Bobcat-1 periapsis (red), apoapsis (blue), and average altitude (green) since deployment on November 5th, 2020 until April 6th, 2022, three days before the end of the mission.

III. DATA COLLECTION CONFIGURATION

Bobcat-1's mission has the primary objective of measuring GNSS-to-GNSS time offsets. However other side missions and data analysis were enabled (Croissant et al., 2020). With the objective of optimizing the battery consumption as well as the on-board memory and data-link capacity, different collection modes were set. When a data collection was started with a command from the ground station on the roof of the Russ College of Engineering at Ohio University, in Athens Ohio, the desired data collection type was selected. Data collections on Bobcat-1 were configured to automatically end after a certain battery voltage threshold was reached. Figure 3 shows telemetry from Bobcat-1's SatNOGS dashboard: it can be seen that during the first months of mission the threshold was set conservatively at a voltage much higher than the minimum safe mode battery voltage (in red in Figure 3), which limited collection duration to approximately 1-4 hours. Later data collections recorded in the last several months before deorbiting were configured with lower thresholds, closer to the minimum safe mode battery voltage (in red in Figure 3). This enabled continuous data collections with duration up to 24 hours. Figure 4 shows Bobcat-1's ground-track during a data collection for ISB estimation held in February 2022, about 24h long.

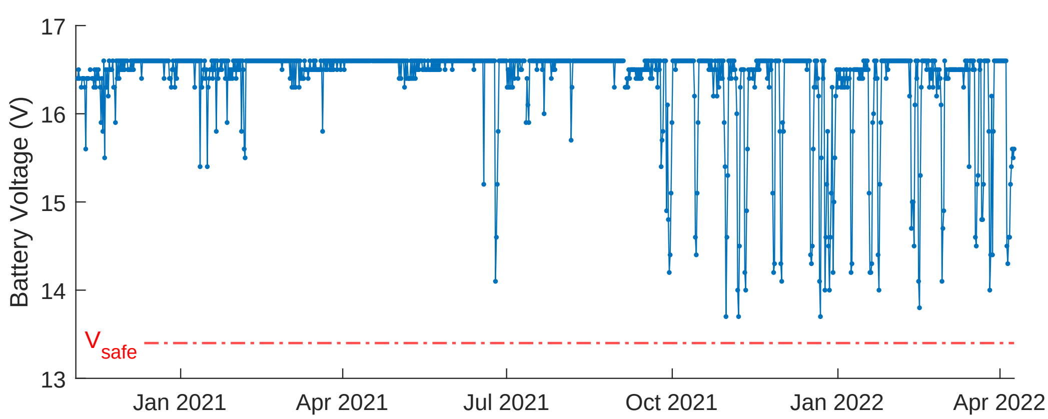

Figure 3: Bobcat-1 battery voltage telemetry throughout the mission. V_{safe} marks the safe mode battery voltage

Data collections for ISB estimation contain (at a minimum), computed pseudorange measurements, carrier phase measurements, and carrier-to-noise ratios from all tracked space vehicles (SVs), along with the GNSS receiver's current best position estimate and samples from its two temperature sensors. Each log is time-tagged by the receiver with the current GPS time and time status reported by the receiver to indicate the certainty of its time estimate (NovAtel, 2022). More details on the mission and payload are available in Croissant et al. (2020).

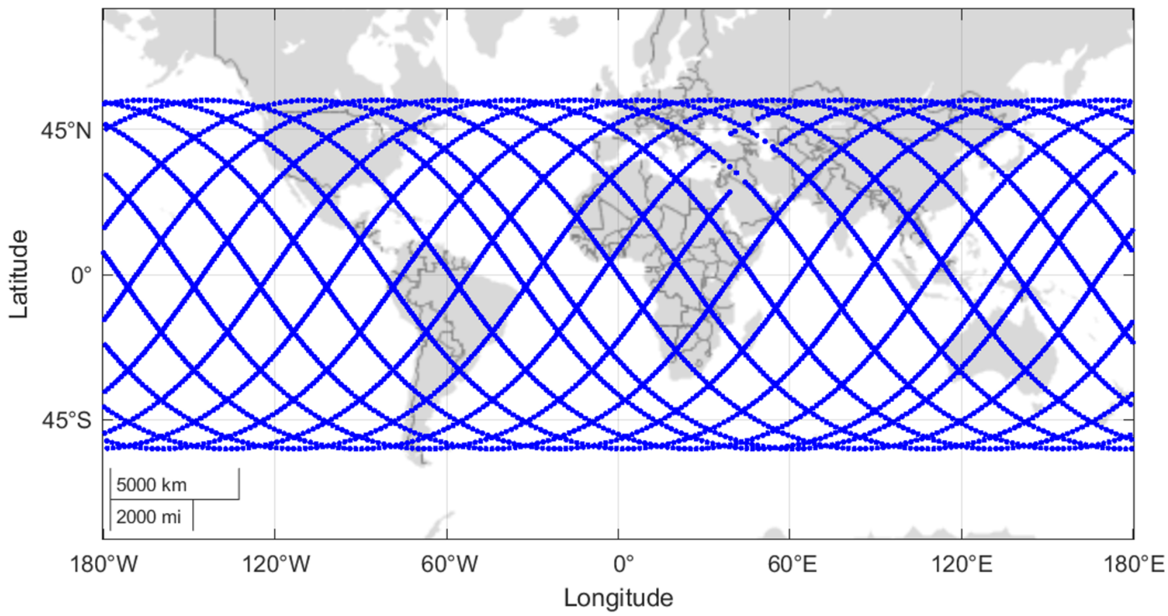

Figure 4: Bobcat-1's ground-track during a continuous data collection for ISB measurement. Approximately 24h long (start time: 27-Feb-2022 12:01:22 UTC, end time: 28-Feb-2022 11:59:22 UTC).

IV. MEASUREMENTS AND ERROR ANALYSIS

Multi-GNSS and multi-frequency pseudorange, carrier phase and Doppler measurements have been collected. However, the results shown in this paper were found considering only pseudorange measurements. Carrier phase measurements were used so far to evaluate multipath and antenna group delay error variations in the measurements (Croissant et al., 2021). The observation model for the k-th satellite's pseudorange and carrier phase measurements can be expressed, respectively, as ρ_k and Φ_k:

$$\rho_k = R_k + I_k + T_k + \varepsilon_P + \tau_k(\theta, \phi) + \Delta t_{\text{RX-SYS}} + \eta_{\rho_k} \quad (1)$$

Where:

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

$$\Phi_k = R_k - I_k + T_k + \varepsilon_P + \tau_k(\theta, \phi) + \frac{\lambda}{2\pi}\phi + \Delta t_{\Phi\text{RX-SYS}} + \eta_{\Phi_k} + N\lambda \quad (2)$$

Where:

R_k	true range,
I_k	ionospheric delay,
T_k	tropospheric delay,
ε_P	satellite orbit error projected onto the line-of-sight,
$\tau_k(\theta, \phi)$	antenna group delay as a function of elevation and azimuth angles,
λ	wavelength,
$\Delta t_{\Phi \text{RX-SYS}}$	receiver-to-system clock offset (for Φ),
η_{Φ_k}	noise and multipath errors (for Φ_k),
N	integer ambiguity number (in this case removed by the receiver)

The measurements collected with Bobcat-1, in space, are not affected by the T_k component, since the tropospheric error is not present in LEO. The multipath error is also in general not present: the only multipath effects are due to reflections on the body of the CubeSat; given the position of the GNSS antenna, on the shortest side of the spacecraft, in the worst case scenario the multipath error would not exceed 10 cm ($\sim 0.3\,\mathrm{ns}$). In general, the multipath error on the CubeSat is negligible and η_{ρ_k} and η_{Φ_k} are mainly noise components. The bias due to the antenna group delay is as well expected to be below 10 cm (Raghuvanshi & van Graas, 2015). In Croissant et al. (2021), the code-minus-carrier (CMC) measurements are analyzed, showing a standard deviation around 10 cm, and 12 cm in the worst case. Broadcast orbit and clock corrections were used here; to accurately calibrate, residual biases shall later be assessed, applying precise orbit and clock corrections.

The ionosphere error shall be discussed. At an altitude of about 400 km, the effect of the ionosphere is still present, though it is smaller than the ionospheric effect on a terrestrial receiver. The F2 layer (Klobuchar, 1996) extends in general at the altitudes 200-1000 km, varying with day/night cycles and other events as for example magnetic storms, with peak between 300 km and 450 km (Limberger et al., 2013; Montenbruck & Gill, 2002). The assessment in this paper was on a pre-calibration analysis. Without a proper calibration of the receiver inter-frequency biases, a double-frequency ionospheric correction would actually result in worse performance, as shown in Croissant et al. (2021). The ionospheric effect was evaluated with dual frequency measurements; satellite inter-frequency corrections were applied, and receiver inter-frequency biases were bounded with laboratory measurements in a controlled environment at different temperatures. Accurate calibration of the residual biases will be needed to effectively apply double-frequency ionospheric corrections. As shown in Croissant et al. (2021), with the ionospheric conditions as at the time of the data collections considered, when high spatial gradients were not visible, for this analysis a cutoff elevation angle of 5 degrees was selected to minimize the the residual ionospheric induced bias. The last bias still to be discussed, affecting the pseudorange (and carrier phase) measurements, is the target of this study: the GNSS-to-GNSS time offset. In Equation 1, $\Delta t_{\text{RX-SYS}}$ is the time bias between the receiver and the system time. If measurements from different systems are used to calculate a multi-GNSS solution, one approach is to define the time offsets $\Delta t_{\text{RX-SYS}}$ between the receiver and each system as:

$$\Delta t_{\text{RX-SYS}} = \Delta t_{\text{RX-SYS}_{\text{REF}}} + \Delta t_{\text{XY}_{\text{USER}}} \tag{3}$$

Where $\Delta t_{\text{RX-SYS}_{\text{REF}}}$ is the GNSS-to-GNSS time offset, XYTO, of system Y with respect to system X, and $\Delta t_{\text{XY}_{\text{USER}}}$ is the "user XYTO", as called in Defraigne et al. (2021) and then in Carlin et al. (2021), and can be expressed as:

$$\Delta t_{\text{XY}_{\text{USER}}} = \Delta t_{\text{XY}} + \text{ISB} \tag{4}$$

Where:

Δt_{XY}	GNSS-to-GNSS time offset, XYTO, of system Y with respect to system X
ISB	receiver-specific inter-system bias,

The focus of this paper is to characterize the stability and the repeatability of the receiver-specific ISBs. Indeed, calibrating those biases would enable the accurate measurement of the GNSS-to-GNSS time offsets, XYTO. Since the goal is an accurate measurement of a relative parameter (the bias between each time system and the one chosen as reference), the receiver effects in common among satellites and systems cancel out, including the receiver clock bias.

V. BROADCAST SYSTEM TIME CORRECTIONS

In Arnett et al. (2022), the repeatability of the receiver characteristic ISB was evaluated, considering only the GAL-to-GPS time offset. The analysis was based on comparisons with a reference: the broadcast Galileo-GPS Time-Offset (GGTO). Here the analysis is extended to other ISBs with the same approach, and over a longer observation window. The stability check of uncalibrated receivers by comparison with broadcast values (or, alternatively, with calibrated stations), is mentioned also in Carlin et al. (2021), where an analysis was carried out considering it is stated that with this method different receivers, not calibrated, were consistent within 0.5 ns (GPS, Galileo, BeiDou-3). Broadcast GNSS data, including the system time corrections, are available in the RINEX 3.04 format, for instance at National Aeronautics and Space Administration (2023) and Noll (2010) or "International GNSS Service (IGS)" (2023).

VI. RESULTS

The goal of the analysis described in this paper is assessing the performance in terms of repeatability of the receiver specific ISBs. Five data collections were considered among the longest ones available (approximately between 16 and 24 hours), over a five month span, as summarized in Table 1. GPS, Galileo, BeiDou and GLONASS measurements are used. Single-frequency pseudorange measurements were considered. Ongoing analysis includes all the available measurements of all the systems, at multiple frequencies, as well as carrier phase and Doppler measurement analysis, Additionally, future work includes incorporating shorter collections in the analysis to add more data points and increase the observation time for evaluating the stability.

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
215	February 27th, 2022	12:01:22 UTC	February 28th, 2022	11:59:22 UTC	23:58:00

Figures 5, 7, 8, 9 and 10 show the user XYTO and the broadcast XYTO, in a time span from September 28th, 2021 until February 28th, 2022. The largest variations are mainly due to noise and to the uncalibrated effect of the temperature; indeed, oscillations with a period of about 90 minutes are present on the user XYTO, as well as on the measured receiver's temperature. Figure 6 shows the measured temperature during the data collection started on September 28th, 2021. Note that some broadcast XYTO data were not found, and that is the reason why some plots are missing. Figures 11-13 show the estimated receiver-specific ISBs, filtered through a moving average filter to smooth the effects of the temperature fluctuations over each orbit. The mean value was calculated for each ISB for each data collection, to evaluate the ISB stability over time. For the different data collections, over 5 months, the mean value of each ISB calculated as described in this paper, was stable within 5 ns, and the mean ISBs for every collection appear to be correlated to the corresponding mean temperature. The receiver GAL-to-GPS ISBs estimated in Arnett et al. (2022) was suggesting high dependency with the orbit and the temperature, suggesting that calibration should be possible to 1 ns level or better.

VII. CONCLUSIONS AND FUTURE WORK

The results shown in the previous section appear to be very promising and calibration still needs to be applied to improve this result. The pre-launch measurements done in a controlled environment in a temperature chamber will enable the calibration of the temperature effects on the ISBs; double-frequency ionospheric correction will be applied, corrected for satellite and receiver interfrequeuncy biases (calibrated with the measurements in the temperature chamber, as well). Carrier phase and Doppler measurements should also be used to improve the solution. A PPP solution can be implemented as well. Furthermore, more data collections, even if shorter in duration, shall be considered to assess the ISBs stability over a longer time and with more observation points. However, the pre-calibration receiver-specific ISBs, compared to the broadcast GNSS-to-GNSS time offset show repeatability within 5 ns, after averaging the effects of orbit and temperature. This suggests that calibrated measurements could enable estimate with accuracy 5 ns.

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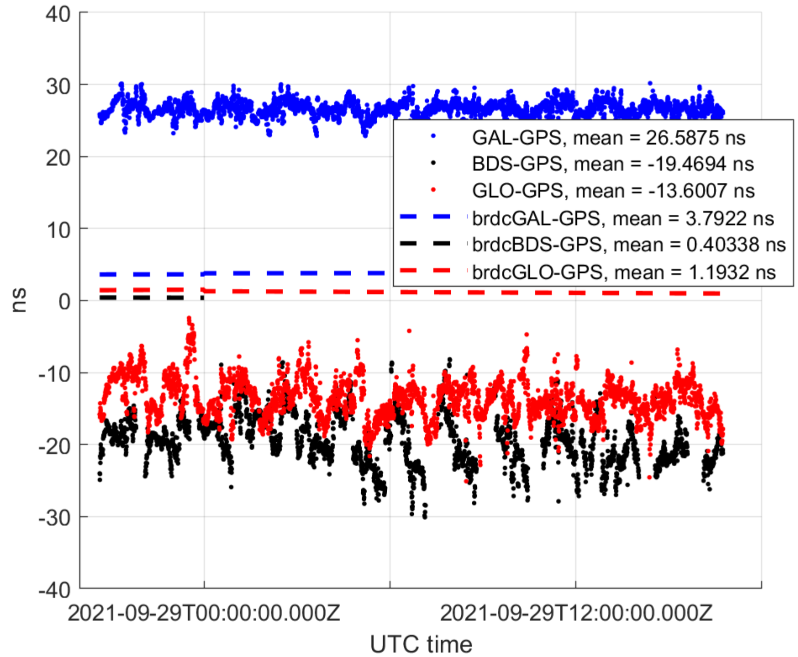

Figure 5: GNSS-to-GNSS time offset: User XYTO (measured) compared with broadcast for collection started on September 28th, 2021

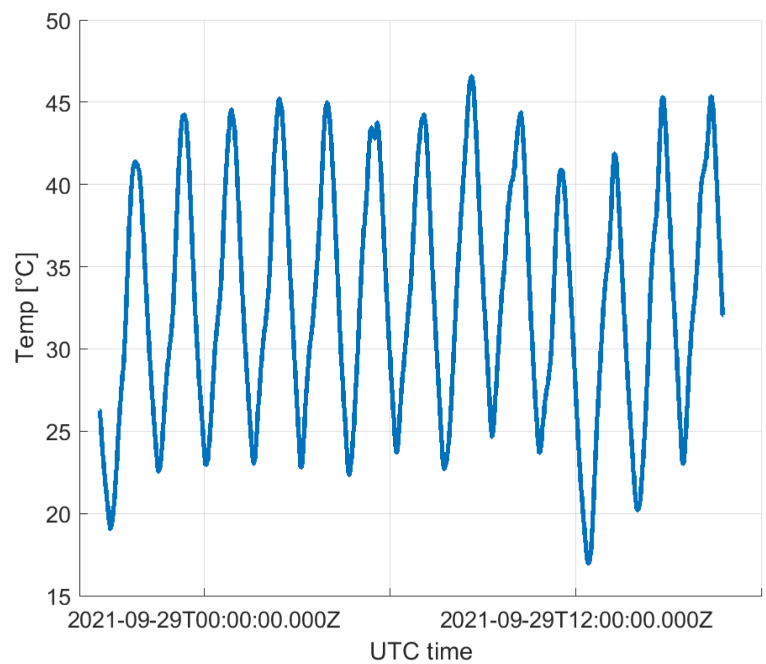

Figure 6: Measured temperature of the on-board receiver, for collection started on September 28th, 2021

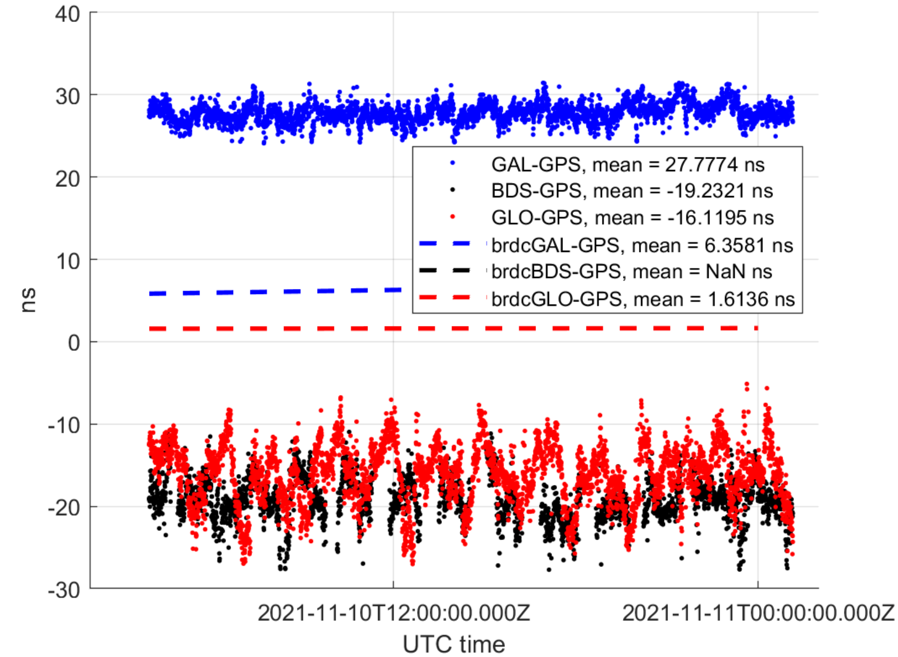

Figure 7: User XYTO (measured) compared with broadcast for collection started on November 10th, 2021

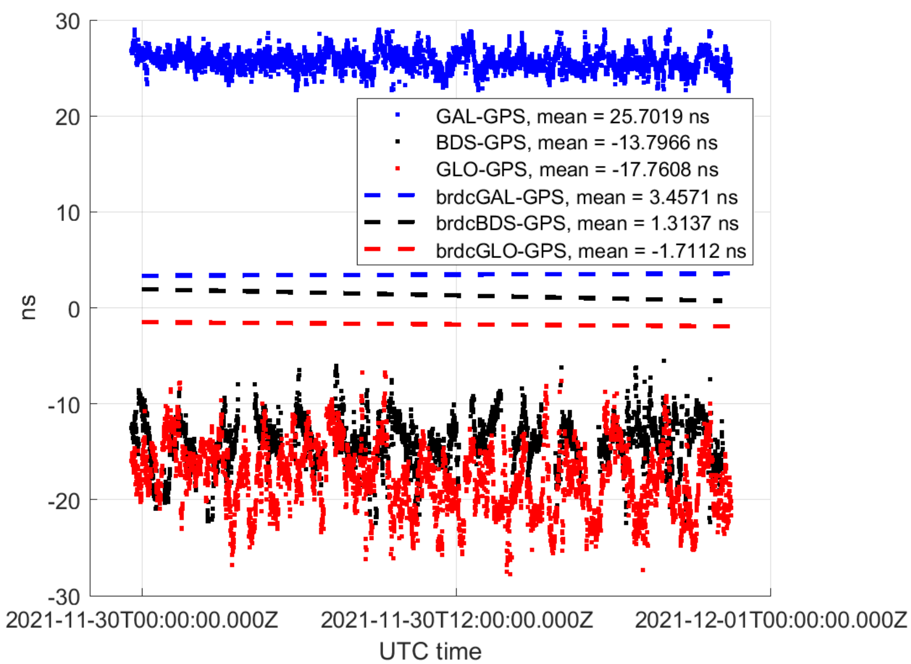

Figure 8: User XYTO (measured) compared with broadcast for collection started on November 29th, 2021

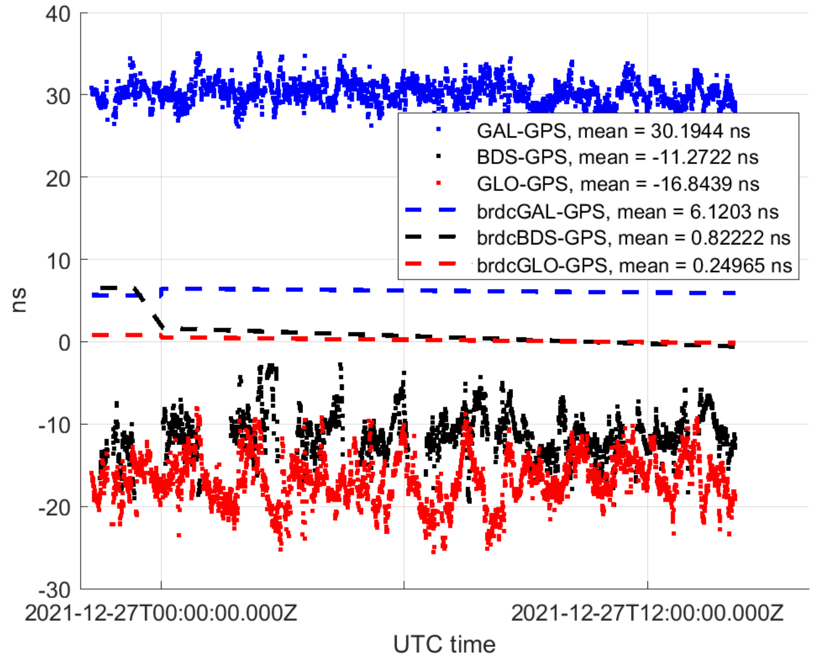

Figure 9: User XYTO (measured) compared with broadcast for collection started on December 26th, 2021

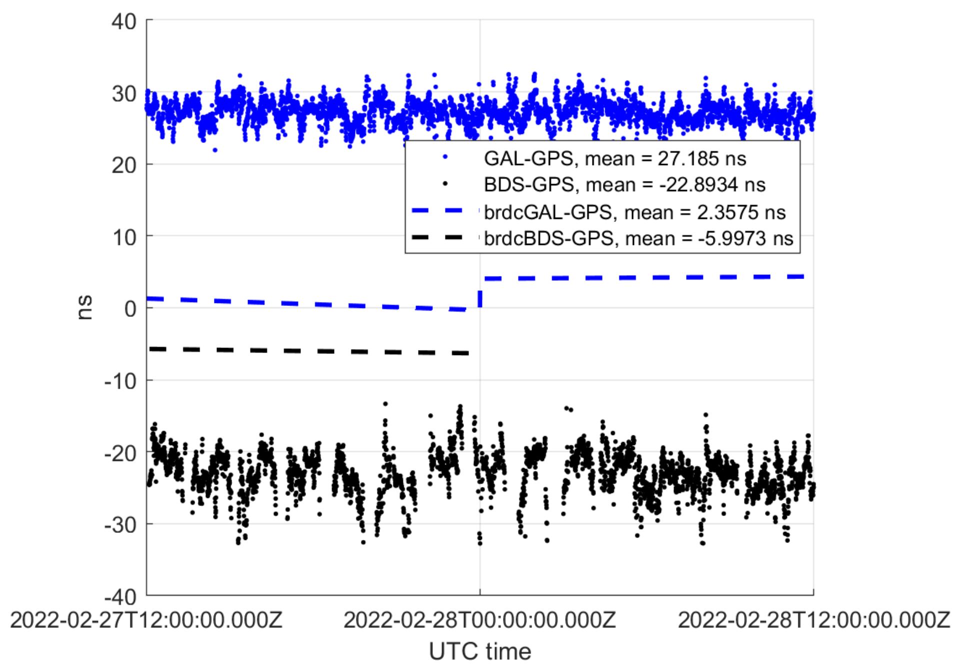

Figure 10: User XYTO (measured) compared with broadcast for collection started on February 27th, 2021

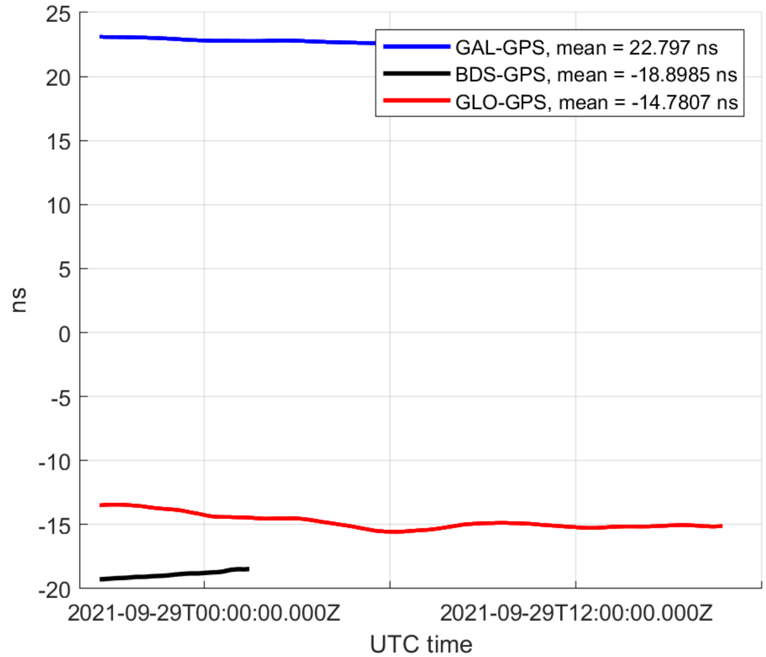

Figure 11: Uncalibrated receiver-specific ISBs (User XYTO - brdc XYTO). Collection started on September 28th, 2021

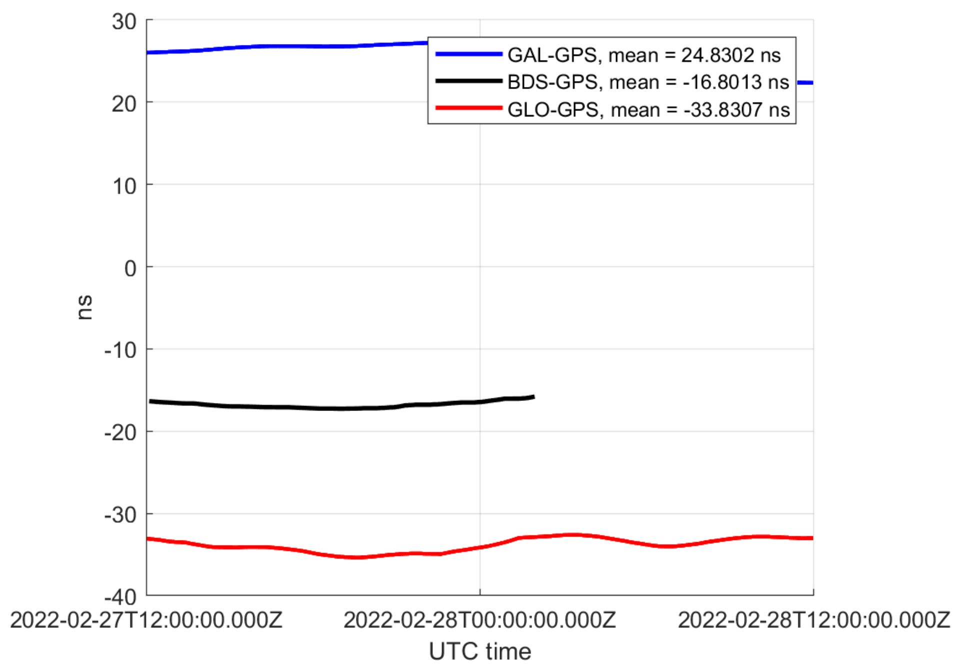

Figure 12: Uncalibrated receiver-specific ISBs (User XYTO - brdc XYTO). Collection started on November 10th, 2021

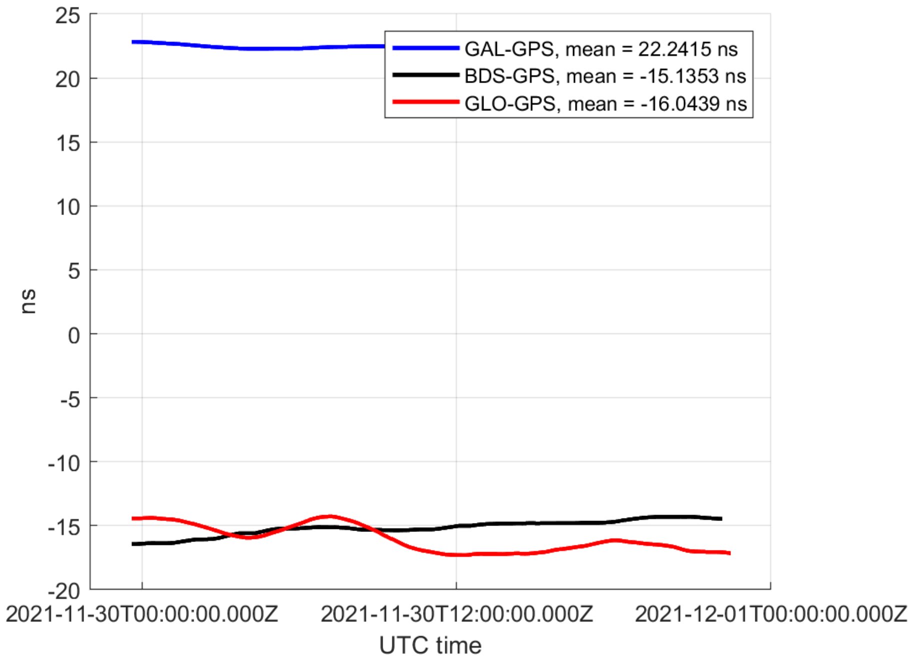

Figure 13: Uncalibrated receiver-specific ISBs (User XYTO - brdc XYTO). Collection started on November 29th, 2021

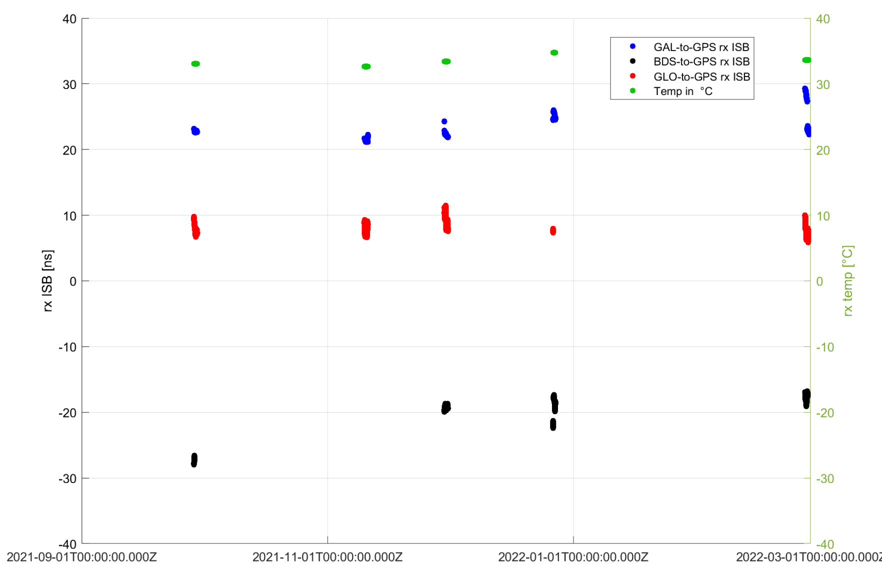

Figure 14: Receiver-specific ISBs estimated during five data collections, filtered, and receiver measured temperature.

REFERENCES

Arnett, Z., McKnight, R., Ugazio, S., & van Graas, F. (2022). Receiver inter-constellation time offset at low Earth orbit: An experiment with Bobcat-1, the Ohio University CubeSat. *Proceedings of the 2022 International Technical Meeting (ION ITM 2022)*, 844–855. https://doi.org/10.33012/2022.18176

Bar-Sever, Y., Meyer, R., Muthuraman, K., & Biacs, Z. (2021). Monitoring and performance assessment of gnss inter-constellation timescale biases. *Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation*, 1903–1916. https://doi.org/10.33012/2021.17983

Carlin, L., Hauschild, A., & Montenbruck, O. (2021). Precise point positioning with gps and galileo broadcast ephemerides. *GPS Solutions*, *25*. https://doi.org/10.1007/s10291-021-01111-4

Carlin, L., Montenbruck, O., Furthner, J., & Hauschild, A. (2022). UTC and GNSS system time access using PPP with broadcast ephemerides. *GPS Solutions*, *26*(4). https://doi.org/10.1007/s10291-022-01326-z

Croissant, K., Jenkins, G., McKnight, R., Peters, B. C., Ugazio, S., & van Graas, F. (2020). Design and mission planning of Bobcat-1, the Ohio University CubeSat. *Proceedings of the 33rd International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2020)*, 1383–1393. https://doi.org/10.33012/2020.17649

Croissant, K., Jenkins, G., McKnight, R., Peters, B. C., Ugazio, S., & van Graas, F. (2021). Bobcat-1, the Ohio University CubeSat: Preliminary data analysis. *Proceedings of the 2021 International Technical Meeting of The Institute of Navigation*, 625–636. https://doi.org/10.33012/2021.17854

Defraigne, P., Pinat, E., & Bertrand, B. (2021). Impact of Galileo-to-GPS-time-offset accuracy on multi-GNSS positioning and timing. *GPS Solutions*, *25*(2). https://doi.org/10.1007/s10291-021-01090-6

Enderle, W., Gini, F., Boomkamp, H., Parker, J. J., Ashman, B. W., Welch, B. W., Koch, M., & Sands, O. (2018). Space user visibility benefits of the multi-GNSS space service volume: An internationally-coordinated, global and mission-specific analysis. *Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018)*, 1191–1207. https://doi.org/10.33012/2018.15966

International GNSS Service (IGS). (2023). https://igs.org/

Klobuchar, J. A. (1996). *Ionospheric effects on GPS* (B. W. Parkinson & J. J. Spilker Jr., Eds.; Vol. 1). American Institute of Aeronautics; Astronautics, Inc.

Limberger, M., Liang, W., Schmidt, M., Dettmering, D., & Hugentobler, U. (2013). Regional representation of f2 chapman parameters based on electron density profiles. *Annales Geophysicae*, *31*(12), 2215–2227. https://doi.org/10.5194/angeo-31-2215-2013

Montenbruck, O., & Gill, E. (2002). Ionospheric correction for GPS tracking of LEO satellites. *Journal of Navigation*, *55*(2), 293–304. https://doi.org/10.1017/s0373463302001789

National Aeronautics and Space Administration. (2023). *CDDIS – NASA's archive of space geodesy data*. Retrieved February 1, 2023, from https://cddis.nasa.gov/archive/gnss/data/daily/

Noll, C. E. (2010). The crustal dynamics data information system: A resource to support scientific analysis using space geodesy. *Advances in Space Research*, *45*(12), 1421–1440. https://doi.org/10.1016/j.asr.2010.01.018

NovAtel. (2022). *OEM7 commands and logs reference manual v22*. Retrieved February 1, 2023, from https://docs.novatel.com/OEM7/Content/PDFs/OEM7_Commands_Logs_Manual.pdf

Parker, J. J. K., Bauer, F. H., Ashman, B. W., Miller, J. J., Enderle, W., & Blonski, D. (2018). Development of an interoperable GNSS space service volume. *Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018)*, 1246–1256. https://doi.org/10.33012/2018.15968

Peters, B. C. (2021). *GNSS inter-constellation time offset determination in low Earth orbit* (Master's thesis). Ohio University.

Raghuvanshi, A., & van Graas, F. (2015). Characterization of airborne antenna group delay biases as a function of arrival angle for aircraft precision approach operations. *Proceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015)*, 3681–3686.

SatNOGS. (2023a). Bobcat-1 – Grafana. Retrieved February 1, 2023, from https://dashboard.satnogs.org/d/BFU00FHMz/bobcat-1?orgId=1

SatNOGS. (2023b). *SatNOGS DB – Bobcat-1*. Retrieved February 1, 2023, from https://db.satnogs.org/satellite/RNBQ-9045-6623-3650-8949

Sesia, I., Signorile, G., Thai, T. T., Defraigne, P., & Tavella, P. (2021). GNSS-to-GNSS time offsets: Study on the broadcast of a common reference time. *GPS Solutions*, *25*(2). https://doi.org/10.1007/s10291-020-01082-y

United Nations Office for Outer Space Affairs. (2018). The interoperable global navigation satellite systems space service volume. (ST/SPACE/75). Retrieved November 21, 2022, from https://digitallibrary.un.org/record/3829212/files/st_space_75E.pdf