GNSS Inter-system Time-Offset Estimates and impact on high altitude SSV

Sabrina Ugazio, Brian C. Peters, Kevin Croissant, Gregory Jenkins, Ryan McKnight, and Frank van Graas,
Ohio University

BIOGRAPHIES

Sabrina Ugazio is an Assistant Professor in Electrical Engineering and Computer Science at Ohio University and involved in the Avionics Engineering Center at Ohio University. She received her PhD in Electrical Engineering from Politecnico di Torino, Italy, in 2013. Her research interests include various aspects of GNSS, such as ionospheric measurements, timing, and signal monitoring.

Brian C. Peters received his B.S. in Electrical Engineering from Ohio University in 2019. He is currently is pursuing his master's degree in Electrical Engineering at Ohio University, where he is involved in the Avionics Engineering Center as a member of the CubeSat team.

Gregory Jenkins is pursuing his master's degree in Electrical Engineering at Ohio University. He is involved in the Avionics Engineering Center as a member of the CubeSat team. He received his B.S. in Computer Science and Engineering from Ohio State University in 2019.

Ryan McKnight is pursuing his master's degree in Electrical Engineering at Ohio University, where he is involved in the Avionics Engineering Center as a member of the CubeSat team. He received his B.S in Electrical Engineering from Ohio University in 2019.

Kevin Croissant is involved in the Avionics Engineering Center as a member of the CubeSat team. He is currently pursuing his degree in Computer Engineering at Ohio University.

Frank van Graas holds an endowed Fritz J. and Dolores H. Russ Professorship in Electrical Engineering and Computer Science, and is a Principal Investigator with the Avionics Engineering Center at Ohio University. Dr. Van Graas is a Past President of The Institute of Navigation (1998–1999) and served as the Institute of Navigation (ION) executive branch fellow at the Space Communications and Navigation Office, National Aeronautics and Space Administration, Washington, DC (2009). He is a fellow of the ION (2001) and received the ION Kepler (1996), Thurlow (2002), and Burka (2010) awards, as well as the American Institute of Aeronautics and Astronautics John Ruth Avionics Award (2010). He has been actively involved with navigation and timing research since 1984.

INTRODUCTION

A core aspect of Global Navigation Satellite Systems (GNSSs) is the time scale they use to operate. Since they use independent time scales, inter-system time-offsets are one of the most significant biases to be taken into account in a multi-constellation solution, and in the framework of interoperability. In [1] a performance analysis is presented considering GPS, Galileo, GLONASS and BeiDou, showing inter-system time-offsets on the order of 10 to 100 ns.

While a multi-system solution enables more satellites in view and possibly a better Geometric Dilution of Precision (GDOP), it must be taken into account that any additional constellation involves an additional bias. So, if a single-constellation solution involves four unknowns, including the user's spatial coordinates and the receiver time offset, a multi-system solution exploiting measurements from N_{GNSS} constellations involves $4 + N_{GNSS} - 1$ unknows, where the additional $N_{GNSS} - 1$ unknows are the inter-system time offsets to be estimated. This means that in order to get an improvement with respect to a single-system solution, at least two satellites from any additional constellation must be in view.

In general, on-Earth users have enough satellites in view to get an improvement in GDOP thanks to a multi-GNSS solution. However, this is not always true when the user is in a low-visibility environment. In those cases, a multi-GNSS solution would ideally be

https://doi.org/10.33012/2020.17146

beneficial, providing more satellites in view. On the other hand, the inter-system time-biases may constitute the bottle neck, and actually make the solution unavailable. Different approaches have been proposed to overcome this issue.
The ICG-IGS Joint Trial Project (IGS-IGMA), led by the International Committee on GNSS (ICG) and the International GNSS Service (IGS), includes as long term objectives to "make all performance standard entries for each GNSS openly available" and to "provide a multi-GNSS service performance standard" [2]. The IGS Multi-GNSS Experiment (MGEX) [3-5] has, among its objectives to provide multi-GNSS products, exploit the IGS monitoring station network, and estimate biases and provide standards. In [6], different methods for the estimation of the inter-system biases are evaluated; the measurement model is constrained assuming the inter-system offset as constant over short time intervals, enabling the solution with only four satellites from mixed constellations. Another possible approach is to provide the users with the inter-system time-offset estimates. [7] describes the implementation of the GPS to Galileo Time Offset (GGTO), which is currently broadcast as part of the Galileo message, with an accuracy of 20 ns (95%, initial service target) [8]. However, as analyzed in [6], [9] and detailed in [10], different receivers have different impacts on the inter-system bias, being on the order of 20 ns and therefore comparable with GGTO [11]. This means that in order to exploit the broadcast estimate, inter-system biases due to the receiver must be calibrated or bounded. Discussion on this still open topic, and different possible approaches to address the receiver biases are presented, for example, in [8], [12], [13]. However, some test results show that in poor visibility conditions some users may benefit using the broadcast value of GGTO, even in presence of the inter-system bias due to the receiver effects [14].
While some users with limited satellite visibility may be able to estimate the inter-system bias and keep that estimate for the epoch when the visibility is poorer, some users may have such limited visibility to find this kind of approach unpractical. For instance, users in the high-altitude Space Service Volume (SSV), such as GEO and HEO satellites. This kind of users would possibly get high benefits from interoperable GNSS. Given the increasing number of applications related to the high-altitude SSV, there is a growing interest in providing those SSV users with PVT solution from GNSS [15-20]. Different approaches have been evaluated, including the opportunity of exploiting GNSS sidelobes signals [21], given that some missions, as for instance [22-23], demonstrated navigation performance in the high altuitude SSV exploiting the GNSS sidelobes that greatly exceed the expected performance [24]. How detailed in [24], these results are given to a combination of factor, including that the actual transmitted GPS power exceed the levels from specifications, even if in different ways in different satellite blocks, in particular [22], and that receiver technology allows to track very weak signals. However, transmissions from the antenna side lobes are totally excluded from performance specifications, in terms of power and errors. Therefore, an analysis of side-lobes measurements was conducted, detailed in [24]. As stated in [25], GPS is a critical infrastructure for space navigation, on which space users rely; however, space users are vulnerable to design changes, if service provider does not specify requirements on those performance. Following these guidelines, the Interface Specification document [26] specifies, for GPS block III, the SSV User-Received Signal Levels. However, only the signals main lobes are considered.
Here, the analysis here has been conducted considering only the main lobes of the GNSS signals, considering the minimum performance in terms of main lobe beam-width and minimum radiated transmit power as specified in the performance standard documents, provided by the GNSS service providers and summarized in [27].
Different analyses have been performed to evaluate the availability of GNSS to those users [17], [28]. In this paper, an analysis has been conducted that considers not only the availability in terms of number of satellites in view given a desired received power, as in [28], but also the geometry and the resulting GDOP that a user in the SSV would experience with or without the provision of inter-system time-offset estimates.
The discussion about the user receiver calibration is not further detailed here. For this analysis, it is assumed that the user's receiver has been calibrated, and has a residual bias small enough to satisfy the user's requirements.
This analysis have been performed in the framework of the Bobcat-1 project at Ohio University, to analyze a possible application of inter-constellation time-offsets estimates, which is one of the objectives of the Bobcat-1 project. Bobcat-1 is the first CubeSat being developed in the Avionics Engineering Center (AEC) at Ohio University, Electrical Engineering and Computer Science (EECS) department, in Athens Ohio; Bobcat-1 has been selected for launch through the NASA CubeSat Launch Initiative (CLI), and is expected to be launched in the third quarter of 2020. Figure 1 shows the CubeSat under development at Ohio University. The details of the CubeSat and the mission development are not the focus of this paper.

The primary objectives of Bobcat-1 are educational on one side, providing Ohio University graduate and undergraduate students with hands-on experience on a spacecraft, and scientific on the other side. The primary experiment that will be carried out by Bobcat-1 is the feasibility and performance study of inter-constellation time-offset estimates from Low Earth Orbit (LEO). Given the growing applications of CubeSat technology, the interest on LEO measurements is growing and different studies have been conducted, as for instance [29]. After the analysis of high altitude SSV performance provided with estimates of inter-system time-offsets, in this paper a discussion is presented on the time-offsets estimate method, outlining methodology, challenges and calibration techniques.

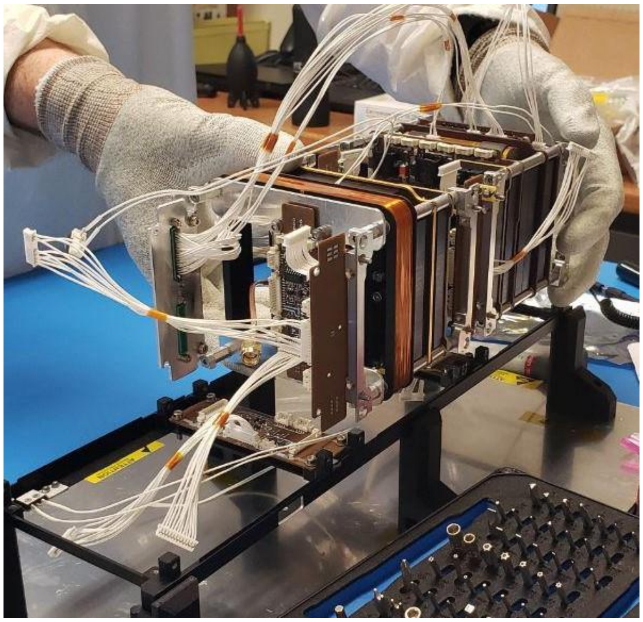 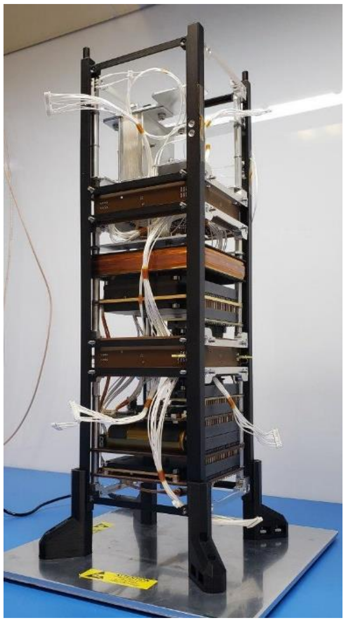

Figure 1: Bobcat-1, the Ohio University CubeSat under development.

GDOP IN THE HIGH ALTITUDE SSV

As discussed in the introduction, GEO and HEO satellite users obtain significant benefits if Inter-Constellation Time-Offset are provided.

Figure 2 shows the geometry between a GEO satellite, with altitude of about 36000 km, and a GNSS satellite in MEO orbit, at altitude of about 20000 km. Given that the target users of GNSS are on-Earth, the GNSS signals are broadcast on Earth with antennas whose main lobe is designed to cover the Earth surface. GEO satellites are able to receive the GNSS signals only when the geometry is favorable and the GNSS satellite is on the other side of the GEO, with respect to Earth, and out of the Earth's shadow, as illustrated in Figure 2.

In [28] an analysis showed the visibility of GNSS satellites from GEO; in this paper a further analysis is presented, and the GNSS solution performance at GEO is characterized in terms of GDOP, comparing a stand-alone solution versus the case when the estimate of the inter-constellation time-offsets are provided to the GEO user.

The scope of this analysis was to evaluate the possible improvement that high elevation users in the SSV could experience if the inter-system time-offset would be available. It must be noted that a key component to allow SSV users to benefit from these estimates is the characterization of the user's receiver, in terms of inter-system bias. Further discussions on the user requirements would be needed if this kind of approach would be chosen.

It must be noted that in some cases a solution seems to be available, if only the number of satellites in view and the received satellite signal power are considered, even though a poor geometry may lead to an impractical solution.

In general, the geometry matrix for a multi-GNSS solution has a number of rows corresponding to the number of satellites in view, and a number of columns corresponding to the unknowns, being the three spatial coordinates, the receiver time-offset and the inter-constellation time-offsets. Different approaches have been considered to address the problem, sometimes suggesting to introduce an absolute time reference. Here the approach will be towards the estimate of the inter-constellation time-offsets focusing on the relative bias between the constellations. In this perspective, any speculation regarding a new absolute time scale is not considered here, and the approach will be to calculate the time-offset of any constellations with respect to one of them selected as reference. For example, in this paper the time-offsets of Galileo, GLONASS and BeiDou are estimated with respect to GPS.

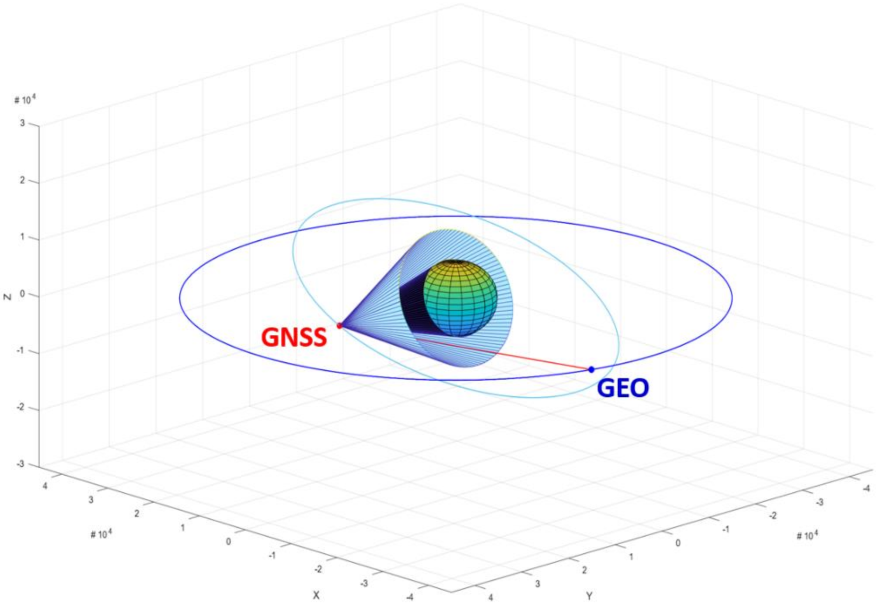

Figure 2: visibility of GNSS satellites from high altitude Space Service Volume (GEO satellite user, altitude ~ 36000 km).

The number of unknowns n_u is $n_u = 4 + N_{GNSS} - 1$, calling N_{GNSS} the number of constellations in view. The pseudorange measurement errors and the unknown position errors and inter-constellation time-offsets are related through the geometry matrix according to the equation:

$$\begin{bmatrix} \Delta\rho_{GPS_1} \\ \vdots \\ \Delta\rho_{GPS_{N_{GPS}}} \\ \Delta\rho_{GLO_1} \\ \vdots \\ \Delta\rho_{GLO_{N_{GLO}}} \\ \Delta\rho_{GAL_1} \\ \vdots \\ \Delta\rho_{GAL_{N_{GAL}}} \\ \Delta\rho_{BDS_1} \\ \vdots \\ \Delta\rho_{BDS_{N_{BDS}}} \end{bmatrix} = H \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta t_{RX} \\ \Delta t_{GLO} \\ \Delta t_{GAL} \\ \Delta t_{BDS} \end{bmatrix} \tag{1}$$

Where $N_{GPS}, N_{GLO}, N_{GAL}, N_{BDS}$ are, respectively, the number of GPS, GLONASS, Galileo and BeiDou satellites in view, Δt_{RX} is the receiver clock bias and $\Delta t_{GLO}, \Delta t_{GAL}, \Delta t_{BDS}$ are respectively the time-offsets of GLONASS, Galileo and BeiDou with respect to GPS. It must be noted that any constellation could be chosen as the reference without changing the concept. In the following simulation results it was convenient to choose GPS as the reference since at every epoch 2 or more GPS satellites were available.
The geometry matrix H in (1) is:

$$H=\begin{bmatrix} h_{x_{GPS_1}} & h_{y_{GPS_1}} & h_{z_{GPS_1}} & 1 & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{x_{GPS_{N_{GPS}}}} & h_{y_{GPS_{N_{GPS}}}} & h_{z_{GPS_{N_{GPS}}}} & 1 & 0 & 0 & 0 \\ h_{x_{GLO_1}} & h_{y_{GLO_1}} & h_{z_{GLO_1}} & 1 & 1 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{x_{GLO_{N_{GLO}}}} & h_{y_{GLO_{N_{GLO}}}} & h_{z_{GLO_{N_{GLO}}}} & 1 & 1 & 0 & 0 \\ h_{x_{GAL_1}} & h_{y_{GAL_1}} & h_{z_{GAL_1}} & 1 & 0 & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{x_{GAL_{N_{GAL}}}} & h_{y_{GAL_{N_{GAL}}}} & h_{z_{GAL_{N_{GAL}}}} & 1 & 0 & 1 & 0 \\ h_{x_{BDS_1}} & h_{y_{BDS_1}} & h_{z_{BDS_1}} & 1 & 0 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{x_{BDS_{N_{BDS}}}} & h_{y_{BDS_{N_{BDS}}}} & h_{z_{BDS_{N_{BDS}}}} & 1 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Where $h_{x_{CON_j}}=\frac{x_{CON_j}-\hat{x}}{\hat{R}_{CON_j}}$, $h_{y_{CON_j}}=\frac{y_{CON_j}-\hat{y}}{\hat{R}_{CON_j}}$, $h_{z_{CON_j}}=\frac{z_{CON_j}-\hat{z}}{\hat{R}_{CON_j}}$ are the elements of H depending on the geometry, i.e. the relative position between the receiver and the j-th satellite of a specified constellation, being the constellation CON either GPS, GLO, GAL or BDS, calling $(\hat{x},\hat{y},\hat{z})$ the estimated user position, (x_j, y_j, z_j) the position of the j-th satellite and $\hat{R}_j$ the j-the satellite-user range. It shall be noted that to solve for the unknown position and biases, an iterative linearization process needs to be performed, while here, to evaluate the GDOP simulated values are used such that the matrix H is known.

While the first three columns are related to the relative position between the GNSS satellites and the receiver, and the forth is the column of ones related to the receiver clock bias, the other columns are related to the inter-constellation time-offsets.

The $(4+(i-1))$-th column is related to the time-offset between GPS and the i-th constellation, and its values are equal to one on the rows corresponding to the measurements from the i-th constellation, and zero elsewhere. Therefore, these columns are sparse, which gives a very easily intuitive mathematical explanation of the reason why the GDOP easily diverges if the inter-constellation time-offsets are unknown and the number of satellites in view is not highly redundant. Any constellations with fewer than 2 satellites in view would not be considered in the solution, given that adding only one observable together with one unknown (the time-offset corresponding to the constellation) will not improve the solution.

The number of unknown inter-constellation time-offsets is equal to $N_{GNSS}-1$, and depending on the geometry at different epochs and the number of satellites in view from different constellations, the number N_{GNSS} may vary. Therefore, the number of columns of H changes dynamically.

The Geometric Dilution of Precision (GDOP) is the trace of the inverse of the matrix resulting from the operation H^TH:

$$GDOP=\sqrt{tr\{(H^TH)^{-1}\}} \quad (3)$$

In general, a constellation is considered only if at least two satellites from that constellation are in view. However, simulation results calculating the GDOP show that, in some cases, even two satellites from a constellation may not be beneficial to the solution calculation, if the geometry is not good.

If the inter-constellation time-offsets are provided to the receiver on board of a high altitude SSV, then the unknowns are simply the user position and clock bias, and the system equations become as usual:

$$
\begin{bmatrix} \Delta\rho_{GPS_1} \\ \vdots \\ \Delta\rho_{GPS_{N_{GPS}}} \\ \Delta\rho_{GLO_1} \\ \vdots \\ \Delta\rho_{GLO_{N_{GLO}}} \\ \Delta\rho_{GAL_1} \\ \vdots \\ \Delta\rho_{GAL_{N_{GAL}}} \\ \Delta\rho_{BDS_1} \\ \vdots \\ \Delta\rho_{BDS_{N_{BDS}}} \end{bmatrix} = H_a \cdot \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta t_{RX} \end{bmatrix} \tag{4}
$$

defining the matrix H_a, where the subscript indicates that the solution is aided since the inter-constellation time-offsets are provided, as:

$$
H_a = \begin{bmatrix} h_{x_{GPS_1}} & h_{y_{GPS_1}} & h_{z_{GPS_1}} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ h_{x_{GPS_{N_{GPS}}}} & h_{y_{GPS_{N_{GPS}}}} & h_{z_{GPS_{N_{GPS}}}} & 1 \\ h_{x_{GLO_1}} & h_{y_{GLO_1}} & h_{z_{GLO_1}} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ h_{x_{GLO_{N_{GLO}}}} & h_{y_{GLO_{N_{GLO}}}} & h_{z_{GLO_{N_{GLO}}}} & 1 \\ h_{x_{GAL_1}} & h_{y_{GAL_1}} & h_{z_{GAL_1}} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ h_{x_{GAL_{N_{GAL}}}} & h_{y_{GAL_{N_{GAL}}}} & h_{z_{GAL_{N_{GAL}}}} & 1 \\ h_{x_{BDS_1}} & h_{y_{BDS_1}} & h_{z_{BDS_1}} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ h_{x_{BDS_{N_{BDS}}}} & h_{y_{BDS_{N_{BDS}}}} & h_{z_{BDS_{N_{BDS}}}} & 1 \end{bmatrix} \tag{5}
$$

where the elements in the first three columns are defined as in (2). It is important to note that in this case any satellite from any constellation can be taken into account and provide information for a Position, Velocity and Time (PVT) solution, even if fewer than two satellites are in view from a certain constellation. The resulting GDOP of the solution becomes

$$
GDOP_a = \sqrt{tr\{(H_a^T H_a)^{-1}\}} \tag{6}
$$

where $\boldsymbol{H_a}$ is the geometry matrix in (5).

GDOP IN THE HIGH ALTITUDE SSV: SIMULATION RESULTS

Simulations were performed, considering a GEO satellite at an altitude of 36000 km and different longitudes and by simulating the GNSS orbits using Two-Line Element (TLE) data from [30]. The GDOP was calculated for different cases, and some results are shown in the following. Figures 3, 4, and 5 show simulation results for GEO longitude 0, 30 and 120 degrees, respectively. In blue the GDOP in the case of a stand-alone receiver is shown, where the Time-Offsets needs to be estimated, while in red is the GDOP in the case of an aided receiver, when the time-offsets are provided to the GEO user from an external source.

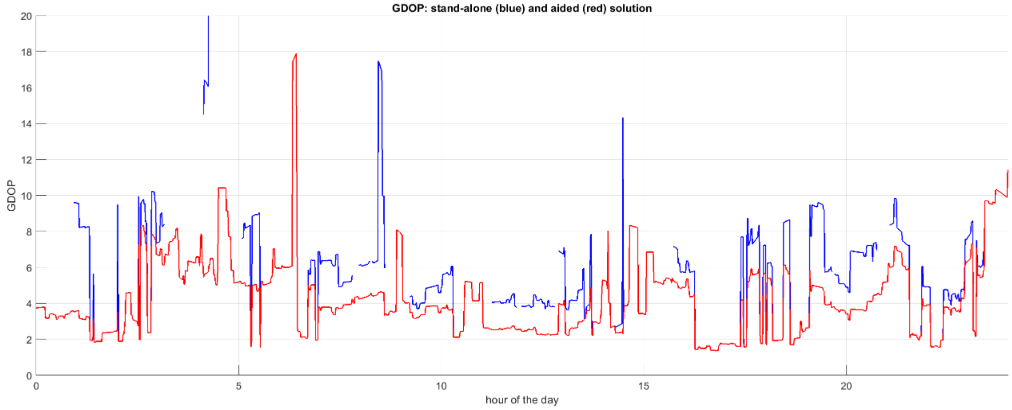

Figure 3: GNSS GDOP for GEO satellite at longitude 0°: comparison between stand-alone solution (blue) and aided solution (red), when the Inter-constellation Time-Offsets are provided. It can be seen how the provided time-offsets highly contribute in improving not only the solution availability but also the GDOP.

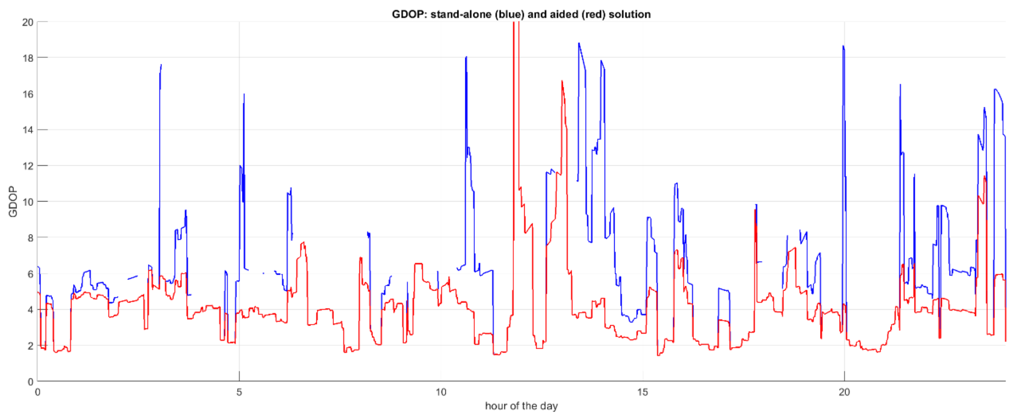

Figure 4: GNSS GDOP for GEO satellite at longitude 30°: comparison between stand-alone solution (blue) and aided solution (red), when the Inter-constellation Time-Offsets are provided. It can be seen how the provided time-offsets highly contribute in improving not only the solution availability but also the GDOP.

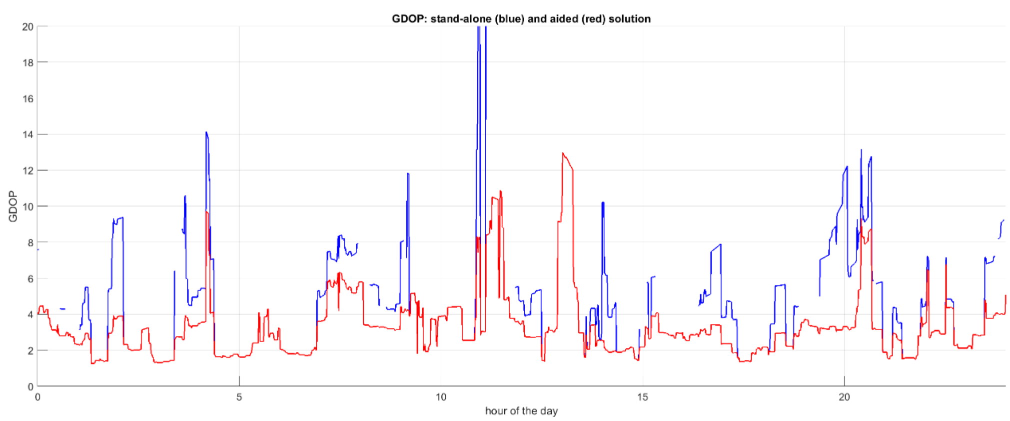

Figure 5: GNSS GDOP for GEO satellite at longitude 120°: comparison between stand-alone solution (blue) and aided solution (red), when the Inter-constellation Time-Offsets are provided. It can be seen how the provided time-offsets highly contribute in improving not only the solution availability but also the GDOP.

It can be seen how often the GDOP experiences very large and impractical values when aid is not provided, even if a GNSS constellations is considered for the solution only if it is improving the performance. The simulation result shows a dramatic improvement in the performance that can be roughly quantified as an improvement in the GDOP of about 40% on average. However, the estimate does not even consider the dramatic improvement in those cases when the GDOP would tend to infinite, if the Time-Offsets are not provided, corresponding to the missing spots in the blue plots in figures 3 to 5. A more detailed quantitative performance analysis can be derived from Table 1, which provides a numerical comparison in terms of availability and GDOP between the stand alone and the aided GNSS solutions, at GEO orbit at different longitudes. The availability of single constellation solutions is also compared. The first column specifies the GEO longitude, while columns 2 through 5 show the availability of the single-constellation solution, calculated considering simply when four satellites from a constellation are in view and providing enough signal power. The column GNSS stand-alone and GNSS aided indicate the percentage of time when the GNSS solution was available, considering as unavailable those epochs when the GDOP assumes unpractical values and diverges towards infinite. The last column shows the improvement in availability considering these two parameters. Note that the aided solution has an availability of 100%. The average GDOP is also calculated both in the stand alone and in the aided case, considering only the epochs when also the stand-alone GDOP assumes finite values. Even when the stand-alone solution provides a practical solution, its GDOP is highly improved with an aided solution, showing improvements on the order of 30-35%.

GEO longitude (deg.)	GPS	GLO	GAL	BDS	GNSS stand-alone	GNSS aided	average GDOP stand-alone	average GDOP aided	Improvement in availability
0°	15.2%	16.3%	3.05%	85.1%	69.0%	100%	5.1	3.5	44.9%
30°	11.2%	23.5%	8.5%	55.9%	73.2%	100%	5.6	3.6	36.6%
120°	14.7%	20.4%	5.9%	50.7%	75.0%	100%	4.5	2.9	33.3%

Table 1: solution comparison between single constellation versus GNSS stand-alone and GNSS aided solution (inter-constellation time-offsets provided) for a GEO satellite, in terms of availability only (single constellation) and in terms of finite GDOP availability. A comparison of the average GDOP is done between stand-alone and aided GNSS solutions, considering only the epochs when the stand-alone solution provides a finite GDOP. Different longitudes are considered for the GEO satellite.

INTER-CONSTELLATION TIME-OFFSET ESTIMATES

In order to accurately estimate the inter-constellation time-offsets on the order of tens of a nanosecond (target as stated in [8]), the impairments due to receiver, environment, and single satellite effects must be properly evaluated, calibrated, mitigated or bounded. The in-space measurements from the CubeSat will enable some advantages, in particular, the low altitude orbit will enable data from all the GNSS satellites multiple times a day, providing favorable visibility. Figure 6 shows the GDOP during a day in LEO orbit. The CubeSat orbit was simulated using the TLEs of the International Space Station, since Bobcat-1 will be launched to the International Space Station (ISS), orbiting at an altitude of about 408 km, and deployed from there. Therefore the CubeSat orbit will be slightly lower than the ISS', however for the scope of this analysis the approximation gives a valuable result providing an estimate of the expected GDOP at LEO orbit. Another important advantage of using measurements from a GNSS receiver on-board of a CubeSat is that the environment will be nearly multipath-free, and will not experience tropospheric delay errors. The Bobcat-1 GNSS antenna is currently under test to characterize its radiation pattern when mounted on the CubeSat, and characterize and bound the multipath-related bias, as well as the antenna group-delay.

The main challenges are related to the estimation of all the remaining measurements impairments which result in biases on the time-offset estimates. GPS Precise Point Positioning (PPP) trajectory, expected to have accuracy in the order of 0.1 m [21] is applied, exploiting rapid/predicted clock and orbit corrections from the International GNSS Service (IGS); satellite inter-frequency and intra-frequency biases (Differential Code Biases), are corrected exploiting ground network estimates [31], [32].This is feasible thanks to the stability of these biases, on the order of sub-nanosecond over one month [5],[33]. Abrupt errors that may occur due to hardware on board of the GNSS satellite switching will need to be detected [34].

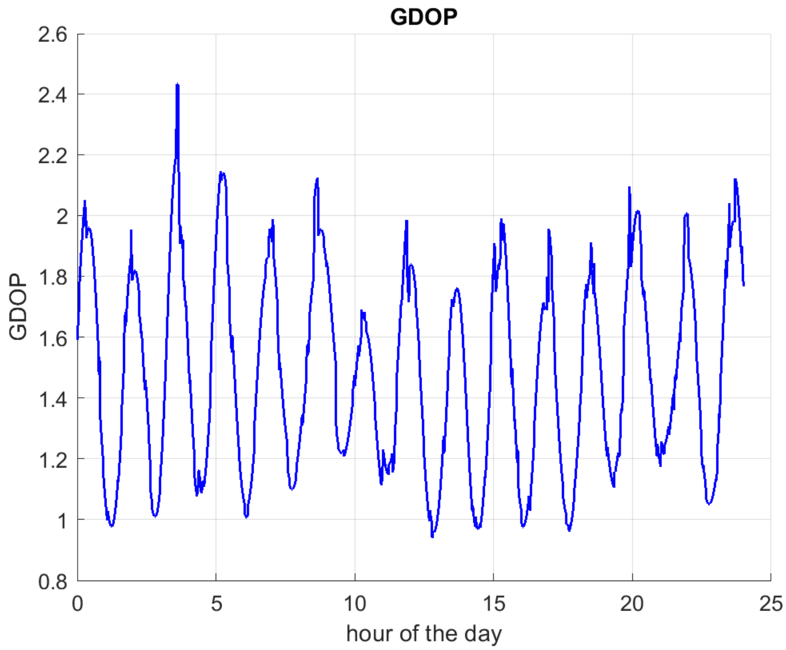

Figure 6: GDOP during one day, at LEO orbit (altitude ≈ 408 km).

Given the orbit altitude of the CubeSat (~400 km), the ionospheric dispersion cannot be ignored and needs to be compensated: dual/triple frequency measurements will be exploited; in addition, those measurements can be combined with the ionospheric gradient algorithm [35] to estimate the inter-frequency receiver bias and take it apart from the ionospheric measurement. An important bias effect is due to the receiver inter-frequency biases, which need to be taken apart from the ionosphere delay measurements. Given that the temperature has impact possibly causing changes in the receiver related biases [36], the receiver offset is calibrated in the lab using different estimation techniques and measurements, exploiting the temperature chamber available at Ohio University, in order to take into account the effect of the temperature on the biases.

CONCLUSIONS AND FUTURE WORK

In this paper, the benefits that a user in the high elevation SSV would experience if provided with GNSS Inter-Constellation Time-Offsets has been evaluated in terms of GDOP, and availability improvement through simulation. The simulations have been performed considering only the main lobe of GNSS signals, and GEO users; further analysis would be necessary to assess the performance for HEO users. The impact of the estimated accuracy, as well as the requirements for the user receiver calibration are not discussed in this paper, and could be the topic of future analyses. The simulation results show that with the provided GNSS Inter-Constellation Time-Offsets, a practical solution is available continuously, providing an improvement in terms of availability of about 35% compared to no time-offset aiding. In addition, the average GDOP would be on the order of 3 to 3.5, against an average of 5 (when not infinite) in the stand-alone case. Bobcat-1, the Ohio University CubeSat, is an educational project that will enable GNSS-related scientific studies, including the analysis of feasibility of in-space estimates of time offsets.

ACKNOWLEDGMENTS

The authors would like to acknowledge NASA Glenn Research Center and Ohio University for supporting the Bobcat-1 CubeSat project.

REFERENCES

1. Dalla Torre, A., Caporali, A., 2015. An analysis of intersystem biases for multiGNSS positioning. GPS Solut. 19 (2), 297–307, DOI 10.1007/s10291-014- 0388-2
2. https://www.gps.gov/governance/advisory/meetings/2018-12/craddock.pdf
3. http://mgex.igs.org/
4. Montenbruck O. et al (2017) The Multi-GNSS experiment (MGEX) of the international GNSS service (IGS)—achievements, prospects and challenges. Adv Space Res 59(7):1671–1697. https://doi.org/10.1016/j.asr.2017.01.011
5. Oliver Montenbruck, Peter Steigenberger, Lars Prange, Zhiguo Deng, Qile Zhao, Felix Perosanz, Ignacio Romero, Carey Noll, Andrea Stürze, Georg Weber, Ralf Schmid, Ken MacLeod, Stefan Schaer, The Multi-GNSS Experiment (MGEX) of the International GNSS Service (IGS) – Achievements, prospects and challenges, Advances in Space Research, Volume 59, Issue 7, 1 April 2017, Pages 1671-1697, ISSN 0273-1177, http://dx.doi.org/10.1016/j.asr.2017.01.011.
6. C. Gioia, S. Gaglione and D. Borio, "Inter-system Bias: Stability and impact on multi-constellation positioning," *2015 IEEE Metrology for Aerospace (MetroAeroSpace)*, Benevento, 2015, pp. 103-108. doi: 10.1109/MetroAeroSpace.2015.7180635
7. J. H. Hahn and E. D. Powers, "Implementation of the GPS to Galileo time offset (GGTO)," *Proceedings of the 2005 IEEE International Frequency Control Symposium and Exposition, 2005.*, Vancouver, BC, 2005, pp. 5 pp.-. doi: 10.1109/FREQ.2005.1573899
8. https://www.unoosa.org/documents/pdf/icg/2017/wgd/wgd4-2-2.pdf
9. Odijk, D., Teunissen, P.J.G. Characterization of between-receiver GPS-Galileo inter-system biases and their effect on mixed ambiguity resolution. GPS Solut 17, 521–533 (2013). https://doi.org/10.1007/s10291-012-0298-0
10. Hauschild, A., Montenbruck, O. A study on the dependency of GNSS pseudorange biases on correlator spacing. GPS Solut 20, 159–171 (2016). https://doi.org/10.1007/s10291-014-0426-0
11. Defraigne, P., Aerts, W., Cerretto, G., Signorile, G., Cantoni, E., Sesia, I., Tavella, P., Cernigliaro, A., Samperi, A., Sleewaegen, J., 2013. Advances on the use of Galileo signals in time metrology: Calibrated time transfer and estimation of UTC and GGTO using a combined commercial GPS-Galileo receiver. In: Proc. 45th PTTI Systems and Applications Meeting, Bellevue, WA. pp. 256–262
12. https://www.ngs.noaa.gov/IGSWorkshop2008/docs/IGS_workshop-Gao_June_02_2008.pdf
13. J-M Sleewaegen, "New GNSS signals: how to deal with a plethora of observables?", IGS Bias Workshop, January 2012, http://www.biasws2012.unibe.ch/pdf/bws12_2.3.1.pdf
14. http://www.unoosa.org/documents/pdf/icg/2019/icg14/WGS/icg14_wgs_21.pdf
15. Bauer, F.H., Moreau, M.C., Dahle-Melsaether, M.E., Petrofski, W.P., Stanton, B.J., Thomason, S., Harris, G.A, Sena, R.P., Temple, L. Parker, III, "The GPS Space Service Volume," *Proceedings of the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2006)*, Fort Worth, TX, September 2006, pp. 2503-2514.
16. Bauer, F. H., "GPS Space Service Volume (SSV) Ensuring Consistent Utility Across GPS Design Builds for Space Users", Presented at the 15th PNT Advisory Board Meeting, June 11, 2015.
17. Enderle, Werner, Gini, Francesco, Boomkamp, Henno, Parker, Joel J.K., Ashman, Benjamin W., Welch, Bryan W., Koch, Mick, Sands, O. Scott, "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), Miami, Florida, September 2018, pp. 1191-1207. https://doi.org/10.33012/2018.15966
18. Parker, Joel J. K., Bauer, Frank H., Ashman, Benjamin W., Miller, James J., Enderle, Werner, Blonski, Daniel, "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), Miami, Florida, September 2018, pp. 1246-1256.
19. United Nations, Office for Outer Space Affairs, "Global Navigation Satellite Systems, Education Curriculum," ST/SPACE/59, New York, December 2012; available at http://www.unoosa.org/res/oosadoc/data/documents/2012/stspace/stspace59_0_html/st_space_59E.pdf
20. "NASA Proposed Updates to ICG SSV Booklet", 11 June 2019 Vienna, Austria UN ICG WG-B Space Users Subgroup Meeting Joel J. K. Parker, Frank H. Bauer, James J. Miller https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20190027250.pdf
21. Teunissen PJG and Montenbruck O (Eds.) (2017) Springer Handbook of Global Navigation Satellite Systems, Springer International Publishing, ISBN 978-3-319-42926-7
22. Moreau, Michael C., Davis, Edward P., Carpenter, J. Russell, Kelbel, David, Davis, George W., Axelrad, Penina, "Results from the GPS Flight Experiment on the High Earth Orbit AMSAT OSCAR-40 Spacecraft," *Proceedings of the 15th International*

Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2002), Portland, OR, September 2002, pp. 122-133.

23. Winkler, S., Ramsey, G., Frey, C., Chapel, J., Chu, D., Freesland, D., Krimchansky, A., and Concha, M., "GPS Receiver On-Orbit Performance for the GOES-R Spacecraft," in 10th International ESA Conference on Guidance, Navigation & Control Systems, Salzburg; Austria, 2017
24. Donaldson, Jennifer E., Parker, Joel J. K., Moreau, Michael C., Highsmith, Dolan E., Martzen, Philip, "Characterization of On-Orbit GPS Transmit Antenna Patterns for Space Users," *Proceedings of the 31st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2018)*, Miami, Florida, September 2018, pp. 1208-1245. https://doi.org/10.33012/2018.15967
25. Michael C. Moreau. "GPS Space Service Volume; Increasing the Utility of GPS for Space Users", 16 October 2008, https://www.gps.gov/governance/advisory/meetings/2008-10/
26. https://www.gps.gov/technical/icwg/IS-GPS-200K.pdf
27. SSV Booklet: ICG Working Group-B (WG-B), The Interoperable GNSS Space Service Volume, Booklet, 2018
28. Ugazio, Sabrina, Croissant, Kevin, Peters, Brian Casey, van Graas, Frank, "Bobcat-1: The Ohio University CubeSat for Inter-Constellation Time Offset Determination," *Proceedings of the ION 2019 Pacific PNT Meeting*, Honolulu, Hawaii, April 2019, pp. 318-325. https://doi.org/10.33012/2019.16808
29. Peiyuan Zhou, Zhixi Nie, Yan Xiang, Jin Wang, Lan Du, Yang Gao, Differential code bias estimation based on uncombined PPP with LEO onboard GPS observations, Advances in Space Research, Volume 65, Issue 1, 2020, Pages 541-551, ISSN 0273-1177, https://doi.org/10.1016/j.asr.2019.10.005.
30. http://celestrak.com/NORAD/elements/
31. https://www.aiub.unibe.ch/research/code___analysis_center/differential_code_biases_dcb/index_eng.html
32. https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/gnss_differential_code_bias_product.html
33. Montenbruck, O., Hauschild, A. and Steigenberger, P. (2014), Differential Code Bias Estimation using Multi-GNSS Observations and Global Ionosphere Maps. J Inst Navig, 61: 191-201. doi:10.1002/navi.64
34. Ramesh, Rakesh Kashyap Hassana, Ugazio, Sabrina, van Graas, Frank, "Keynote: Characterization of GPS Satellite Anomalies for SVN 63 (PRN 1) Using a Dish Antenna," *Proceedings of the ION 2017 Pacific PNT Meeting*, Honolulu, Hawaii, May 2017, pp. 167-182.
35. Chen C., "Detection of ionospheric spatial gradients", 2010 https://etd.ohiolink.edu/!etd.send_file?accession=ohiou1276028997&disposition=inline
36. Coster, A., Williams, J., Weatherwax, A., Rideout, W., and Herne, D. (2013), Accuracy of GPS total electron content: GPS receiver bias temperature dependence, Radio Sci., 48, 190–196, doi:10.1002/rds.20011.