

***Focusear* passive RF sensor network for space traffic coordination of GEO active satellites**

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Abstract

This paper presents GMV's passive RF ***Focusear*** system for GEO satellite tracking and space traffic coordination. ***Focusear*** is a new satellite tracking sensor network developed by GMV to enhance space safety by accurately predicting GEO satellite orbits. Using Passive Ranging (PR) and Time Difference of Arrival (TDoA) techniques, it tracks over 60 satellites from stations in Spain. ***Focusear*** provides 24/7 real-time reliable data with only 2–3 meter TDoA error, validated against external sources. Its consistent tracking improves orbit accuracy, supports collision avoidance and space traffic coordination, and enables early detection of satellite manoeuvres. The system benefits satellite operators by reducing false alerts and offering backup or primary tracking services, especially when ground antennas are unavailable or outsourced.

Keywords: passive RF, GEO satellite operations

Nomenclature

None

Acronyms/Abbreviations

| | |
|------|-----------------------------|
| GEO | Geostationary |
| RF | Radio-frequency |
| TDoA | Time Difference of Arrival |
| TCA | Time of Closest Approach |
| PoC | Probability of Collision |
| STM | Space Traffic Management |
| SSA | Space Situational Awareness |
| CA | Conjunction Assessment |

1. Introduction

When it comes to space safety, an accurate prediction of satellite position is a key factor to monitor and avoid possible collision risks. Given the huge and highly increasing number of satellites in space, it is essential to develop tracking sensor networks able to observe all the objects orbiting the Earth. This paper describes the operational experience and first results with the ***Focusear*** sensor network recently developed by GMV for satellite tracking, based on the passive ranging (PR) concept, for space traffic coordination purposes of GEO active satellites.

PR sensors can receive the radio signals emitted by GEO active satellites, and by using different stations it is possible to obtain the Time Difference of Arrival (TDoA) to then conduct an orbit determination of the observed satellites. ***Focusear*** is currently composed of three stations in Madrid, Valladolid, and Barcelona (all in Spain), with a 4th antenna being currently under deployment in Southern Spain. Capable to detect signals for satellites emitting in the Ku band, it has visibility of 60+ GEO telecom satellites over the European-African region, including operators such as Hispasat, Eutelsat, Intelsat or Arabsat among others. Performing an orbit determination process for all those GEO active satellites based on the same tracking system is a clear benefit for space traffic coordination, eliminating the impact from the use of different tracking systems owned by different satellite operators, which may be affected by different biases.

Operational results indicate that ***Focusear*** is able to operate continuously (24/7/365) regardless of weather conditions. Comparisons of the observations with the 18th SDS SP catalogue and operational orbits has shown complete consistency of the observations with errors of only 2-3 meters in TDoA measurements. The results have been validated against both external ephemerides of the SP catalogue and operator ephemerides.

During the **Focusear** development process, several issues have been addressed. Firstly, the lack of objects with precise enough ephemerides in GEO has been compensated by introducing a statistical calibration process. The ephemerides of over 20 non-manoeuvred satellites are used together with the **Focusear** observations to determine any possible biases in the TDoA measurements in a consistent manner. Secondly, it has been observed that the publicly available frequencies for some satellites are inconsistent with the derived TDoAs. In other cases, some spurious signals are detected where no signal was expected. For these reasons, a consistency validation process has been implemented to ensure that the derived TDoAs correspond to the expected satellite. As a result of the validation process, the provided data is extremely robust, ensuring the quality of the derived measurements.

The tracking observations generated by **Focusear** have a lot of benefits for satellite operators in general and space safety and traffic coordination applications in particular. They can serve as tracking support for regular operations, enhancing accuracy of orbital estimations, or even act as temporary replacements for periods in which one tracking station is not available, enabling orbit determination. The network can act as the main sensor for a mission too, in cases in which the ground antennae are not property of the operator but contracted as a service. Additionally, the accuracy of the data provided is expected to significantly improve the collision-avoidance (CA) services, by reducing number of false alerts among active satellites. It will also increase the certainty when CA manoeuvres are really needed, even when one of the participants is inactive. Apart from improving the accuracy of the orbits for the operator's satellites, the tracking data can also be used for close encounters which involve an active secondary object. On the one hand, the accuracy of the orbit of the secondary satellite can be enhanced, but more importantly, the immediate acquisition of the observations allows for early detection of manoeuvres, few hours after the manoeuvre execution. Normally this is an issue in collision avoidance applications, as the latency to detect manoeuvres tends to be high in the publicly available data (e.g. SP catalogue), meaning that the active-active encounters are more uncertain.

This paper is structured as follows. Section 2 describes the **Focusear** network at high-level and Section 3 lists the observable objects as of now, while Section 4 describes the procedure followed to calibrate the stations of the network with external information. Moreover, Section 5 focuses on the operational results of the network and Section 6 describes the means to perform the monitoring of the network. Section 7 describes the benefits of such network for collision avoidance and space traffic activities in GEO, and finally, Section 8 draws conclusions from the previous sections.

2. **Focusear** network description

Introduction

GMV's passive ranging network, called **Focusear**, is presented in the following paragraphs. This section is intended to present, not only all the elements of the network, but also the technology.

The concept of **passive ranging** is relatively simple. It is based on measuring the relative time difference of arrival (**Time-Difference-Of-Arrival - TDoA**) of signals emitted by active satellites and received by several distant ground stations illuminated by the radiation pattern of the satellite's antenna (Figure 1).

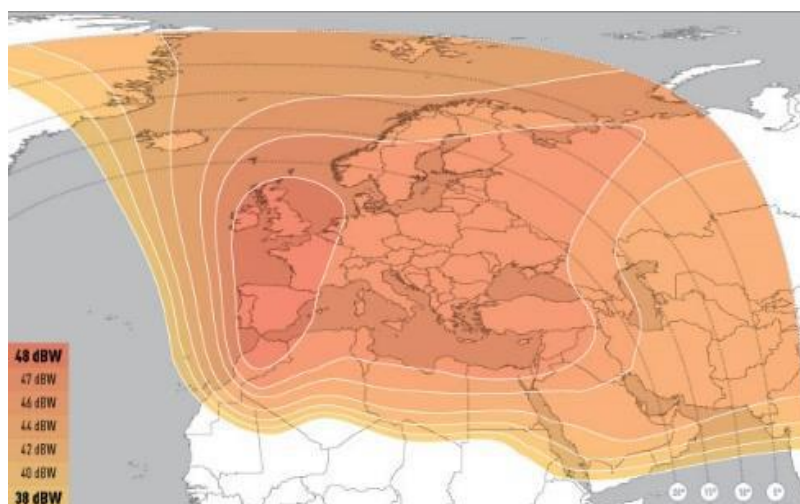


Figure 1: Typical radiation pattern of a Ku band emitting satellites over Europe

The use of these systems is usually limited to satellites in geostationary orbit (GEO) since their emission patterns (mainly in the Ku band) are very extensive, pointing to them is simple from the ground (virtually fixed satellites in space) and their visibility is continuous. However, this technique can also be applied to other orbital regimes (LEO, MEO and HEO) even though the visibility is not continuous, the passes are short, and the pointing is more complex.

The main **reasons** for using passive ranging measurements for orbit determination are the following: it is a completely independent data source from optical systems; it is **autonomous** (it can be a source of data or also of orbits) and **passive** (with a low cost for deployment, operations and maintenance); it is suitable for **24x7 operations** (not affected by day/night or atmospheric conditions) and easy to **automate**; as it will be presented later in this document, the data it provides is highly accurate (~3 metres), high-frequency (1 minute tracks every 1 hour for each satellite), high data rate (observations every ~1 sec in each track), and low-latency (~15 minutes), facilitating **manoeuvre detection** and **accurate orbit determination** for **active satellites**, especially when compared to the alternative of using optical data only for these manoeuvrable objects (particularly, electric propulsion satellites) in the catalogue.

In this way, the **main benefits** of the use of passive ranging for the generation of CA services, particularly in GEO, are (in order of relevance): improvement of the **accuracy** of the orbital information in the active satellites, improvement of the **latency** of the orbital information for the active satellites (being able to quickly detect and estimate the manoeuvres) and improvement of the **robustness** of the system, by having a new source of measurements. All this with a moderate increase in the cost of development, operation, and maintenance of the system, in addition to a reasonably simple integration with CA service providers.

Given the large number of GEO satellites that can be tracked from Spain, having a passive ranging network can be a noticeable **added value for the collision avoidance (CA) services** and lay the foundations for the provision of higher value-added services.

Network architecture

GMV's **Focusear** consists as of now of a network of 3 passive ranging antennae. With **three antennae in Spain**, it gathers signals from active geostationary satellites emitting in the Ku band (10.70 – 12.75 GHz). This signal, without necessity of being decoded, is used to obtain the **Time Difference of Arrival (TDoA)**. The derived TDoAs are the result of the differential measurements obtained between two antennae and, therefore, the three **Focusear** antennae can provide **two simultaneous and independent TDoA** measurements at any time (Figure 2).

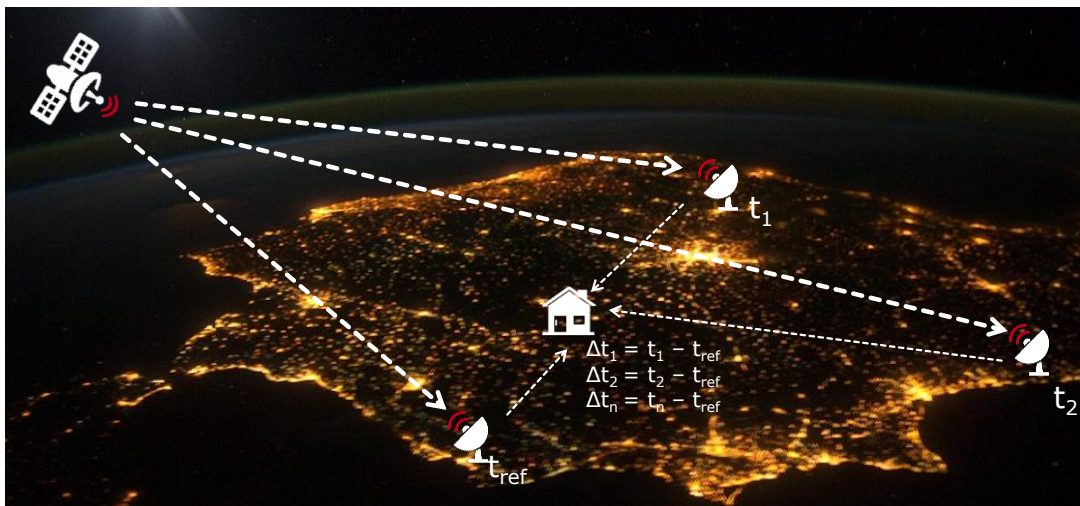


Figure 2: Process of obtaining TDoA data (shown as Δt_i)

The three **Focusear** stations are currently deployed in three of GMV locations: Tres Cantos in Madrid, Boecillo in Valladolid and L'Ametlla del Vallès in Barcelona (**Figure 3** and **Table 1**). All the three stations use equivalent hardware and software to ease its maintenance and operations. In addition, the network can be easily extended with additional antennae in new locations.

Table 1: *Focusear* stations approximate location

| Antenna Id | Location | Latitude [deg] | Longitude [deg] | Altitude [m] |
|------------|---------------------------------|----------------|-----------------|--------------|
| PRMD | Tres Cantos, Madrid | 40.59 | -3.71 | 710 |
| PRVL | Boecillo, Valladolid | 41.52 | -4.72 | 721 |
| PRBC | L’Ametlla del Vallès, Barcelona | 41.65 | 2.27 | 292 |

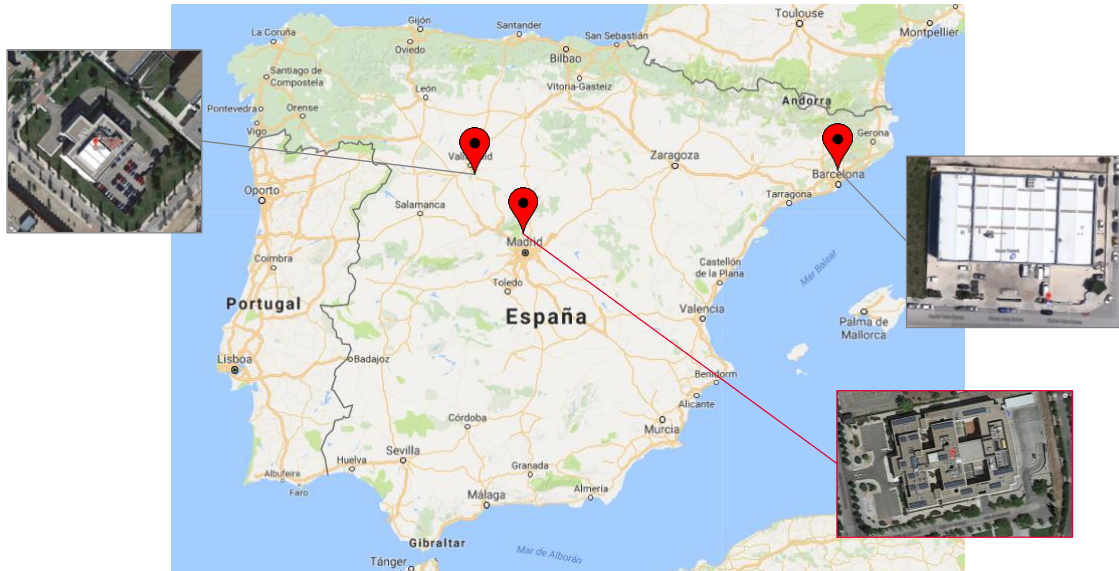


Figure 3: Physical location of the stations in the *Focusear* network

As mentioned above, GMV’s *Focusear* passive ranging system at the moment counts on **3 stations** located in Spain (**Tres Cantos in Madrid, Boecillo in Valladolid, L’Ametlla del Vallès in Barcelona**). The next figure shows the antenna located in Tres Cantos (PRMD), being the other antennae identical to this one.



Figure 4: GMV’s *Focusear* passive ranging antenna in Madrid

3. Observable population

GMV's **Focusear** network is able to observe geostationary satellites emitting in Ku-band, being this frequency band the most common one for telecommunications. All the antennae are required to be within the emitting pattern of the observed satellites and therefore, the observable population is conditioned by the antenna locations and the antenna range of motion in local azimuth and elevation. GMV's **Focusear** network is comprised currently of three antennae located within Spain, as shown in the previous section. Hence, observable satellites need to emit over Spain.

Considering this baseline and the frequency band, 63 satellites are being currently observed. Table 2 shows the **63 satellites** currently observed by **Focusear**, ordered from West to East.

Notice that this is the observable population at the time of writing this proposal. Although it is not frequently the case, some GEO satellites are moved from one slot to another. These large orbital changes can lead to the addition of new satellites in the observable population, as well as to take out some satellites. Also, the launch or decommissioning of any satellite would also obviously lead to the modification of this list. All these modifications, in orbital position or operational status, are monitored by means of different processes.

Table 2: Satellites being observed by *Focusear*

| Cospar | Norad | SpaceTrack Name | Propulsion | Long [deg] | Cospar | Norad | SpaceTrack Name | Propulsion | Long [deg] |
|-----------|-------|----------------------|-------------------|------------|-----------|-------|--------------------|--------------|------------|
| 2009-064A | 36097 | INTELSAT 14 (*) | Chemical | 45.0W | 2010-021A | 36581 | ASTRA 3B | Chemical | 23.5E |
| 2017-007B | 41945 | INTELSAT 32E (*) | Electric | 43.2W | 2012-051A | 38778 | ASTRA 2F | Chemical | 28.2E |
| 2013-026A | 39172 | SES 6 | Chemical | 40.5W | 2013-056A | 39285 | ASTRA 2E | Chemical | 28.2E |
| 2017-006A | 41942 | HISPASAT 36W-1 | Electric | 36.0W | 2014-089A | 40364 | ASTRA 2G | Chemical | 28.2E |
| 2017-041A | 42818 | INTELSAT 35E (*) | Chemical | 34.5W | 2006-032A | 29270 | EUTE HOT BIRD 13B | Chemical | 33.0E |
| 2010-070A | 37264 | HISPASAT 30W-5 | Chemical | 30.0W | 2009-065A | 36101 | EUTE 36B (EUTE W7) | Chemical | 36.0E |
| 2018-023A | 43228 | HISPASAT 30W-6 | Electric | 30.0W | 2017-040A | 42814 | HELLAS-SAT 3 | Chemical | 39.0E |
| 2001-024A | 26824 | INTELSAT 901 (*) | Electric | 27.5W | 2019-007A | 44034 | HELLASSAT4 | Che+Electric | 39.0E |
| 2012-007A | 38087 | SES 4 | Che+Electric | 22.0W | 2009-009A | 34111 | TELSTAR 11N | Che+Electric | 37.5W |
| 2017-059A | 42950 | INTELSAT 37E | Chemical | 18.0W | 2017-078A | 43039 | ALCOMSAT 1 | Unknown | 24.8W |
| 2008-065A | 33459 | EUTE HOT BIRD 13C | Chemical | 12.5W | 2015-068A | 41036 | TELSTAR 12V | Chemical | 15.0W |
| 2015-039B | 40875 | EUTE 8 WEST B | Chemical | 8.0W | 2015-048A | 40895 | EXPRESS AM-8 | Unknown | 14.0W |
| 2011-051A | 37816 | EUTE 7 WEST A (AB 7) | Chemical | 7.0W | 2009-007A | 33595 | EXPRESS AM-44 | Electric | 11.0W |
| 2019-067A | 44624 | EUTE 5W B | Chemical | 5.0W | 2014-046A | 40107 | ASIASAT 8 | Chemical | 4.0W |
| 2004-022A | 28358 | INTELSAT 1002 (*) | Electric | 1.0W | 2015-010A | 40424 | ABS 3A | Electric | 3.0W |
| 2008-006A | 32487 | THOR 5 | Chemical | 1.0W | 2017-038A | 42801 | BULGARIASAT-1 | Chemical | 2.0E |
| 2009-058B | 36033 | THOR 6 | Chemical | 1.0W | 2010-037B | 36831 | RASCOM QAF 1R | Chemical | 3.0E |
| 2014-030A | 39773 | EUTE 3B | Chemical | 3.0E | 2018-090A | 43700 | ES'HAIL 2 | Unknown | 25.5E |
| 2007-057A | 32299 | ASTRA 4A (SIRIUS 4) | Chemical | 5.0E | 2013-044A | 39233 | ES'HAIL 1 | Unknown | 25.5E |
| 2013-022A | 39163 | EUTE 7B (EUTE 3D) | Chemical | 7.0E | 2006-051A | 29526 | ARABSAT 4B | Chemical | 26.0E |
| 2019-034B | 44334 | EUTE 7C | Electric | 7.0E | 2010-025A | 36592 | ARABSAT 5B | Chemical | 26.0E |
| 2016-005A | 41310 | EUTE 9B | Chemical | 9.0E | 2023-075A | 56757 | ARABSAT 7B | Electric | 26.0E |
| 2022-157A | 54259 | EUTELSAT 10B | Electric | 10.0E | 2010-032B | 36745 | ARABSAT 5A | Chemical | 30.5E |
| 2006-007B | 28946 | EUTELSAT HOTBIRD 13E | Chemical | 13.0E | 2008-030B | 33056 | TURKSAT 3A | Chemical | 42.0E |
| 2022-134A | 54048 | HOTBIRD 13F | Electric | 13.0E | 2014-007A | 39522 | TURKSAT 4A | Chemical | 42.0E |
| 2022-146A | 54225 | HOTBIRD 13G | Electric | 13.0E | 2021-126A | 50212 | TURKSAT 5B | Electric | 43.3E |
| 2011-057A | 37836 | EUTE 16A (EUTE W3C) | Chemical | 16.0E | 2018-074A | 43632 | INTELSAT 38 | Unknown | 45.0E |
| 2006-012A | 29055 | ASTRA 1KR | Chemical | 19.2E | 2015-023A | 40277 | EXPRESS AM-6 | Chemical | 52.0E |
| 2007-016A | 31306 | ASTRA 1L | Chemical | 19.2E | 2024-115A | 60086 | ASTRA 1P (SES-24) | Chemical | 19.24E |
| 2008-057A | 33436 | ASTRA 1M | Chemical+Electric | 19.2E | 2010-037A | 36830 | NILESAT 201 | Chemical | 7.0W |
| 2011-041A | 37775 | ASTRA 1N | Chemical+Electric | 19.2E | 2019-021A | 44186 | ARABSAT 6A | Chemical | 30.5E |
| 2012-062B | 38992 | EUTE 21B | Chemical | 21.5E | | | | | |

It is important to highlight that from a design point of view the system is ready to observe GEO satellites with non-zero inclination. In fact, among the objects observed and listed above there is one such satellites that is routinely observed by the network (EXPRESS AM-44 with 1.3 deg inclination)

It is also important to mention that the satellites above are also observed during orbit control manoeuvres, as long as they keep on emitting during such manoeuvres, which is normally the case. It is expected that the observation accuracy remains the same during those orbit-control manoeuvres. Finally, it is worth mentioning that the list of objects observed by the network is adjusted dynamically, considering newly launched or decommissioned satellites.

4. Calibration process and results

The term **calibration** usually refers to the procedures required to measure and determine any biases in sensor measurements. In the case of SST, the calibration process may involve determining timing and/or positioning biases by comparing the observed measurements with the precise ephemeris of a predefined list of objects. This calibration process provides not only any possible biases in the data, but also the accuracy of the observations. For this reason, the calibration process may also be **used to assess the quality of the measurements** provided by an SST sensor.

The location of the sensor, the visibility of the objects and the accuracy of their ephemerides determine the objects to be used for calibration. Once the calibration objects are selected, the calibration process usually requires comparing the obtained calibration measurements with the object ephemerides to determine the biases in the measurements.

In the case of **passive ranging sensors**, the objects suitable for calibration are further constrained by the high accuracy of the passive ranging data and the need to observe satellites emitting at specific frequency bands. Only those objects with precise ephemerides available and emitting in the same frequency bands as the passive ranging sensors to calibrate are suitable to be used for calibration purposes. For this reason, the list of objects suitable for calibration of passive ranging sensors is usually quite limited. In the case of **Focusear**, there are no suitable satellites in the GEO regime that can provide precise enough ephemerides to perform the calibration process as presented above. Therefore, a **statistical calibration procedure** is used for GMV's **Focusear**.

The statistical calibration procedure can be used when the ephemerides available for the calibration objects have a larger uncertainty than the measurements provided by the sensor. The calibration of the sensor may be then achieved by statistically computing the residuals of a larger list of suitable satellites. This list can be dynamic and is usually determined from several non-maneuvring objects during the calibration period. Therefore, the statistical calibration process requires a **preliminary step to determine list of non-maneuvring satellites**. This is done by analysing the ephemerides in a reference catalogue (e.g., the SP Catalogue in our case) and determining whether any given object has manoeuvred in the previous days to the calibration period. This manoeuvre detection is performed by comparing successive SP ephemeris (up to 4-5 days) and using the RMS of those orbital differences to detect which objects have manoeuvred. This is done by detecting in which dates the RMS of orbital differences is higher than a predefined threshold. The sample used for calibration should be larger than the few satellites usually used for calibration of other sensors. These objects can be a subset of the objects usually observed in operations. **Focusear typically uses a list of 10-15 operational non-maneuvring satellites for its statistical calibration**. It is thanks to the large number of satellites used that the statistical calibration process allows estimating calibration parameters (i.e. time bias) from non-precise orbits, as the high-number of orbits uses reduces the estimation error considerably. Once the list of satellites suitable for calibration is selected, the measurements provided by the sensor are compared with those expected for the calibration satellites for periods of 24 hours. Since the ephemerides provided by the satellites are less precise than the measurements provided by the passive ranging sensors, the combination of the residuals of the entire list of satellites is used to **determine a mean (or median) bias of the sensor**. In the case of **Focusear**, this statistical calibration is used to determine any time biases in its TDoA measurements.

The following results correspond to a calibration process performed in October and November 2023.

As a first step, all the satellites with manoeuvres in the previous 4 days were removed from the process. This is done because the orbital information for geostationary satellites in the SP catalogue is obtained from telescopes data (only provided during nights and not every night due to several limiting conditions, including weather) only and the manoeuvre detection latency can be then up to 4-5 days.

In this first step, **Focusear** measurements obtained on 21st October 2023 for the pair of antennae PRMD-PRVL (Madrid and Valladolid) were used. Initially, a set of 16 satellites out of 59 were considered since no manoeuvre was detected for them in the previous 4 days in the SP catalogue. The set of tracks used in the calibration comprised the whole 24 hours period. For the observed population, as described in a previous section, one track per hour for each satellite with 50 measurements per track (one measurement per second) is obtained. This gives an average of 1400 measurements per satellite.

Figure 5 shows the results of this step of the calibration. In this first calibration, several satellites are identified as outliers for a second calibration since their SP orbits were not aligned with their current orbital status, according to the measurements noise. Some of the outliers can be observed with large sinusoidal signals in the residuals in the figure below.

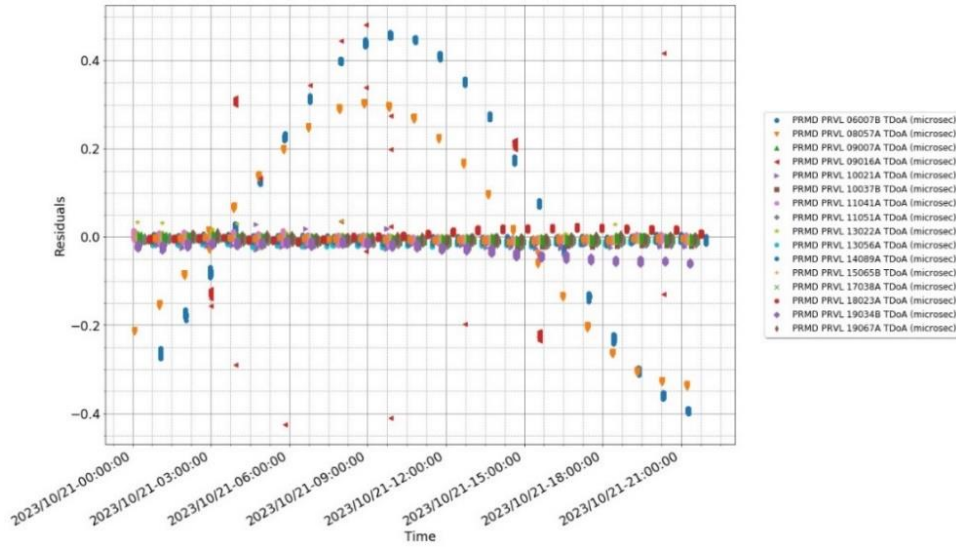


Figure 5: *Focusear* calibration results (step 1)

In the second step of the calibration, those outlier satellites were removed, and 11 satellites were considered. Figure 6 shows the results of this second step. As the figure shows, the vast majority of the satellites are within the same residuals range. In Table 3, the RMS of the residuals and the time-bias estimated for the PRVL antenna with respect to PRMD are shown. Although this calibration has been done manually executing the different processes involved, the process is nowadays automatically performed by the system.

Table 3: *Focusear* time-bias and RMS results (step 2)

| Time-bias [ns] | RMS [ns] |
|----------------|----------|
| -70.56 | 6.0 |

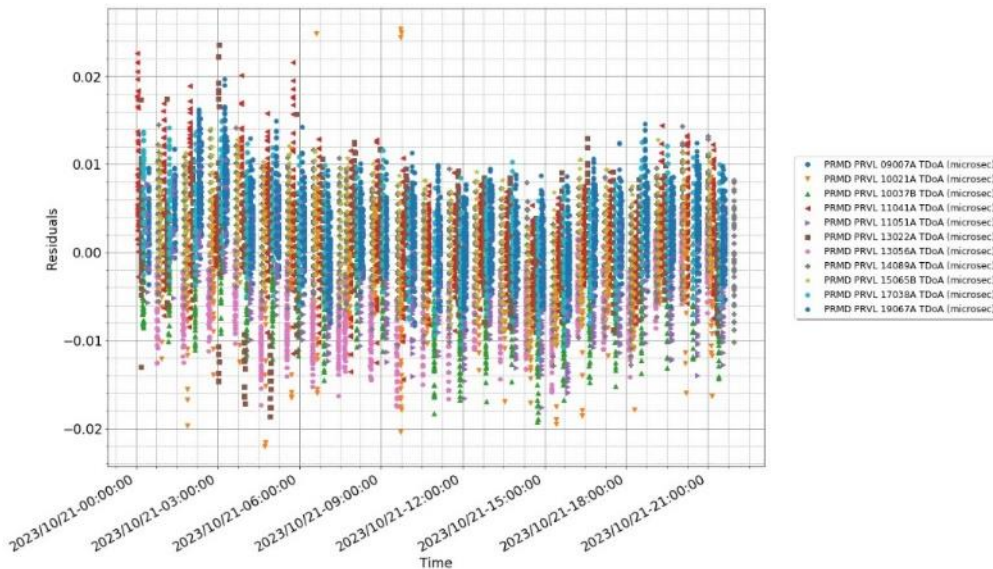


Figure 6: *Focusear* calibration results (step 2)

As mentioned before, these results have been obtained using measurements of a **24 hour period** and considering **11 satellites**, resulting in more than **15000 observations**. These numbers are compliant with the self-imposed rules for the calibration campaign, in terms of number of measurements and number of objects. Besides, the noise of the measurements (**6.0 ns**) is also highly precise, since 6.0 ns of RMS is **equivalent to around 2 meters of accuracy**.

5. Operational results

The **Focusear** system is designed to operate fully autonomously. A daily operation plan is automatically generated with all the objects (usually over 60 satellites) to be followed by each antenna. The plan contains the position, polarization, detection frequency and expected delay in the arrival of the signal for each satellite. Each antenna, that can operate fully independently of the other components in the system, receives the plan and automatically overrides any previous schedule being executed. An entire week is covered by each generated plan, so that even in the case of failure in the scheduling system, the antennas would still be able to continue their operations.

The custom-made GMV software at each station automatically configures all the different devices required to track each satellite in the received plan, according to the received parameters. Once the hardware is properly configured, the raw signal is recorded and stored to be later processed by a centralized server that correlates the different signals acquired by the three antennas.

The usual mode of operation is to follow each satellite in the plan, from east to west, for an entire minute before moving to the next object in the list. This plan can be adapted to the different behaviours of the satellites, depending on their propulsion system (e.g., chemical vs electrical) or whether they are manoeuvring. The antennas operate continuously 24/7 all the days of the year. As a result, over 1400 tracks for each one of the two baselines, with 50 measurements per track, are currently generated every day. Therefore, around 140 000 daily measurements are generated by the current system composed of three antennas. The number of daily measurements is expected to increase by 50% with the addition of the fourth antenna, reaching over 4000 tracks per day.

The continuous monitoring of the tracked population and the high degree of automation allows a fast detection of any possible manoeuvres. For that, the processing server retrieves the signals from the different antennas and correlates them (Figure 7), being capable to provide the resulting TDoA measurements with a timeliness of 15-20 minutes. This has been validated during the operational period, by continuously providing validated data to the EUSST.

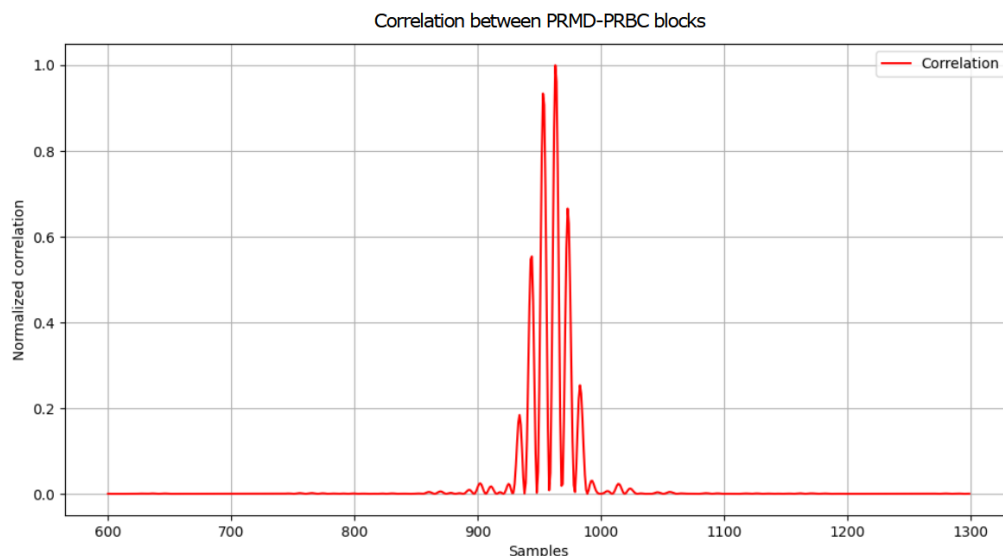


Figure 7: Correlation resulting from combining two of the signals obtained by two different antennas in the *Focusear* network.

Since the start of the operational phase in October 2024, the entire system, composed by the three antennas and the processing server, has been continuously providing valid data for over 97% of the time. During the relatively short operational period, several relevant changes in the tracked population of satellites have been detected. Operationally, the changes in the satellite population are usually detected due to an interruption in the tracked frequency or an important change in the expected satellite position. The two most recent detected movements in GEO are the change in longitude of Intelsat 905 (COSPAR 2002-027A) in February 2025 and of AsiaSat-8 / AMOS-7 (COSPAR 2014-046A) in March 2025.

Ensuring the robustness and continuity of the operations is crucial to provide a reliable system. Being at the GMV premises, the antennas use an UPS to continue operating, even in the case of power cuts. The communications network is also highly reliable with little-to-no downtimes. In addition, the system is designed to recover from any communication error by either resubmitting a failed plan to the antennas, as well as recovering any acquired signal that could have been lost due to a network outage.

With the addition of the fourth antenna, the robustness of the system is being further improved, with a redundant processing system, capable to submit plans and process antenna measurements even in the case of a failure in the nominal system. An additional improvement in the system is the capability to automatically change to an alternative tracking frequency in case that the emission in the nominal frequency is interrupted. Given the differential nature of the TDoA measurements, two antennas are needed to provide a measurement, being one of the two antennas used as reference. The system is also being improved to automatically change the reference antenna, providing a new baseline when needed.

6. System monitoring

As mentioned above, frequency changes, no emission detection or bad signal reception in fringe cases, need to be analysed to ensure the quality of data. To improve the **robustness** and have real-time knowledge of the **Focusbear** system status, a monitoring system has been developed before data sharing. This monitoring system primarily has two functions: to determine whether the data generated in each track meets the minimum quality level established, and to produce daily reports on the system's behaviour to indicate whether the set KPIs have been met. These daily results are also used as previous information for the executions to ensure continuity of data for all given objects.

This monitoring system enhances the global quality of data shared, establishing different types of filters to make decisions about the data produced. Each time data is generated by the correlation process, it is compared with its corresponding SP ephemeris to obtain residuals. Based on this comparison of the data concerning the reference orbit, error information about the labelled object can be given. There is a trade-off where the residual information of the measured data is far away from the reference orbit, but it is high enough to suggest that the difference is not related to an object's manoeuvre (i.e. due signal recorded frequency of a contiguous object).

Furthermore, this residual information is daily stored **to ensure continuity** for the analysis of each object. In case the object hasn't been observed during a period, even though data is generated with good results at border cases, the data is rejected to avoid bad labelling of objects by close ones.

In addition to the comparison with reference ephemeris, the data is expected to be nearly constant for each track duration, with a small variation between observations. In view of the preceding remarks, standard deviation analysis of data has been computed for each slot to avoid noisy measurements at certain executions. This filter permits us **to detect** nearly real-time **frequency changes** of the data **and stop emission cases** and avoid noise sharing. There is a relation between the signal-to-noise ratio of the receiving signal and the standard deviation of the data, and in small signal level cases, observations could be rejected due to high noise level.

This monitoring system, currently used at the processing server, also checks the connectivity with all station servers continuously to alert the operators to synchronization delay for the station raw data before the correlation process in case of extended periods. Besides, daily monitoring of the generated plan has been produced, showing coverage percentage of the plan with the real raw data recorded and number and history of the raw data rejected before the correlation process, as well as the information if the antenna has stopped at any time during the day. The monitoring system has been used by operators for daily tasks at the **Focusbear** system and facilitates integration of new frequencies and discharging or adding new objects based on the results of daily reports without interfering with the operational status of the system.

Tracks that have been selected are stored at an external server in charge of the user interface. This process has also been monitored, as well as the sharing system. Data for each client is stored in different folders to permit analysis and control data status for each user individually. Monitoring process at the external server has been done to oversee all processes up to the delivery of data to the user and ensure that the data sharing is accurate. In case of a connection loss, this system can retry the upload when the connection becomes available again, as well as users can download directly the data already validated by the monitoring system if the loss of connection persists for extended periods.

7. Contribution to CA services

Considering the space environment is a finite resource, it is important to remark the necessity of an effective Space Traffic Management (STM) to ensure the safe and efficient operations of space objects by minimizing the risk of collisions and preventing the increase of space debris. As part of STM, Space Situational Awareness (SSA) refers to the continuous monitoring and analysis of the space environment. One of the main pillars of this monitoring is the early detection of close approaches between in-orbit assets, also known as Conjunction Assessment (CA) service.

Conjunction Assessment (CA) services reliability directly depends on the accuracy of the orbit information used for the close approach detection given that small uncertainties in orbital data can lead to large positional errors over time, significantly affecting the accuracy of collision risk predictions.

Focusear is interesting from the CA service point of view because it provides measurements with high accuracy, at a high rate on a 24x7 basis without weather limitations. All these features not only benefit the OD accuracy itself but also allow for a quicker manoeuvre detection and estimation, that is key for an accurate OD in case of active GEO satellites that are continuously performing manoeuvres to keep their slot in the GEO belt.

Manoeuvre detection timeline highly depends on the nature of measurements used for that purpose. Using passive ranging data, manoeuvres can be detected between 6-8 hours after their execution, depending on the direction (North-South of East-West) and delta-V (higher for chemical than electrical propelled satellites). On the contrary, using telescopes observations, this detection time can increase up to 2-3 days after the manoeuvre for chemical satellites. This means that during this period, any conjunction detected by a CA Service provider would not be reliable enough to properly design a mitigation action (if needed). When considering electrical propelled satellites that are continuously performing small delta-V manoeuvres (up to several manoeuvres per day), this detection time can exponentially increase if only telescope measurements are used. In the worst-case scenario, if the satellite performs daily manoeuvres it can lead to never have an accurate enough orbit to provide a reliable CA service.

The benefit of using **Focusear** measurements for CA service is not only measured on its accuracy for OD and manoeuvre detection. The high rate of measurements provision would lead to have newer and more precise orbits faster, especially after manoeuvres, turning the service more flexible and agile. This is essential in the last days before the time of closest approach (TCA) when satellite operators design avoidance mitigation actions by implementing collision avoidance manoeuvres or by adjusting the station-keeping manoeuvres already planned.

The CA service is based on the early detection of close approaches between in-orbit assets and the risk evaluation of those encounters, based on geometric and probability thresholds. For the risk evaluation, the probability of collision (PoC) at the time of closest approach (TCA) is a commonly used parameter. It highly depends on the covariance of both objects involved in the conjunction at the TCA [1]. For this computation, the covariance needs to be propagated considering that the perturbing forces and the inability of analytical models to exactly describe these forces make the uncertainty to grow in time. Thus, a lower initial uncertainty would yield a more realistic close encounter and PoC computation, potentially leading to the reduction of false alarms. Typically, position of GEO satellites is determined by using telescope measurements and uncertainties are of a few hundred of meters. This is mainly due to the lower accuracy of telescopes measurements and that those can only measure GEO satellites during night periods, without possibility to observe them during daylight. Using **Focusear** measurements, uncertainties of the order of ten meters can be obtained.

Focusear can contribute to CA service provision in two different ways. On one hand, **Focusear** can share its measurements in almost real-time and a third-party CA service provider will benefit from the high rate and accuracy of this data using it on its own OD processes. This is the current contribution that **Focusear** is making to the EUSST Partnership, in which the OD process is on the EUSST side. Considering the system configuration mentioned in the sections above, **Focusear** generates around 1440 TDMs for 63 active GEO satellites per day. Each TDM contains between 53 and 55 TDoA measurements for each one of the station links of **Focusear**.

On the other hand, **Focusear** as operational system will have autonomous capability to perform the OD process itself when the fourth antenna is fully deployed and operationally ready. This OD process first accounts for the manoeuvre detection and estimation, not only in terms of delta-V but also in terms of the epoch of execution. Following this second approach, **Focusear** would maintain a catalogue of orbits based only on its own measurements. The accuracy and quality of this catalogue would be monitored by comparing the orbits with an external source as the Special Perturbation Catalogue published by the 19th SDS. This catalogue of orbits could be directly used as input for CA services such as **Focusoc**.

As demonstrated in [2], the use of passive ranging measurements improves the level of uncertainty in the position of objects. Therefore, the evolution of PoC is improved and the number of false alarms detected decreases considerably.

Although it is not a common approach, sometimes GEO active satellites are moved to a different slot within the GEO belt. The capability of **Focusear** to track satellites based on their telemetry signal (TM) can be used to provide CA service during these relocation processes during which payload signals are usually switched off to avoid interfere with other active GEO satellites. Moreover, this additional contribution to the CA service can be extended to launch and early orbit phases, especially for electrical propelled satellites, that can take up to six months during which the satellite is continuously manoeuvring from the injection point (where the launcher separates the satellite) and their final orbit. During all this phase, satellites usually transmit only telemetry signal. Although this kind of service has not been neither tested nor validated, **Focusear** is able to obtain TDoA measurements based on TM signal and the antennae mounts allow for track non-purely GEO satellites.

8. Contribution to CA services

This paper has presented GMV's passive RF **Focusear** system for GEO satellite tracking and space traffic coordination covering the following aspects with promising operational results: **Focusear** network high-level description, list of the observable objects as of now, calibration process, operational results, monitoring and use of the network for collision avoidance and space traffic management.

References

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