

## Calibration of GNSS receivers at AGGO, INTI, and ONBA

Diego Luna<sup>1</sup> , Carla de la Pina<sup>2</sup> , Mariano Caballero<sup>3</sup> , Alfredo Pasquaré<sup>4</sup> , Mauricio Gende<sup>4,5</sup> 

**Abstract** Global Navigation Satellite System (GNSS) receivers are widely used for the comparison of distant clocks in time and frequency metrology. Since the 1980s, they have played a key role in the realization of Coordinated Universal Time (UTC). In this context, the calibration of GNSS receivers is required to ensure time-transfer uncertainties at the level of a few nanoseconds. This work presents calibration results for three GNSS timing stations in Argentina, located at the Argentine–German Geodetic Observatory (AGGO), the Observatorio Naval de Buenos Aires (ONBA), and the Instituto Nacional de Tecnología Industrial (INTI). Measurements were performed using a traveling receiver from the National Institute of Standards and Technology (NIST) during its round trip between NIST and Argentina. The mean values and their calibration uncertainties obtained were those expected for this technique.

**Keywords** GNSS calibration, UTC, time transfer, metrology

### Calibración de receptores GNSS en AGGO, INTI y ONBA

**Resumen** Los receptores del Sistema Global de Navegación por Satélite (GNSS) se utilizan frecuentemente para la comparación de relojes distantes en metrología de tiempo y frecuencia. En particular, desde la década del 80 han desempeñado un papel clave en la realización del Tiempo Universal Coordinado (UTC). En este contexto, la calibración de los receptores GNSS es necesaria para garantizar incertidumbres de transferencia de tiempo del orden de unos pocos nanosegundos. Este trabajo presenta los resultados de la calibración de tres estaciones GNSS de tiempo en Argentina, ubicadas en el Observatorio Argentino–Aleman de Geodesia (AGGO), el Observatorio Naval de Buenos Aires (ONBA) y el Instituto Nacional de Tecnología Industrial (INTI). Las mediciones se realizaron utilizando un receptor itinerante del National Institute of Standards and Technology (NIST, Estados Unidos), durante su recorrido de ida y vuelta entre el NIST y la Argentina. Los valores medios y sus incertidumbres de calibración obtenidos fueron los esperados para esta técnica.

**Palabras clave** Calibración GNSS, UTC, transferencia de tiempo, metrología

## INTRODUCTION

The need for timekeeping originated in ancient societies from the requirement to date events, seasons, and harvests. In modern society, this dependence has intensified considerably, as accurate realizations of time are essential for computing, electronic commerce, financial markets, mobile communications, navigation systems, power distribution networks, and digital authentication.

At present, time can be measured with a relative precision of  $1 \times 10^{-19}$  (Marshall et al., 2025), making it the physical quantity that can be measured with the highest precision.

Although time can be accurately realized locally in independent laboratories, the establishment of a uniform and reliable common time scale requires a coordinated procedure to define a unified time reference. Atomic time scales must therefore be mutually comparable. Historically, this was achieved through the physical transport of clocks or by means of radio signal comparisons. Today, the most accurate and widely used method relies on signals from Global Navigation Satellite Systems (GNSS) (Luna et al., 2017).

International Atomic Time (TAI) and Coordinated Universal Time (UTC) are derived from a combination of data from more than 400 atomic clocks maintained by over 70 timing centres worldwide, each realizing a local time scale denoted UTC(k) (Panfilo & Arias, 2019). The Bureau International des Poids et Mesures (BIPM) coordinates the international network of time links used to compare local

<sup>1</sup> Instituto Nacional de Tecnología Industrial (INTI), Argentina

<sup>2</sup> Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina

<sup>3</sup> Observatorio Naval de Buenos Aires (ONBA), Argentina

<sup>4</sup> Observatorio Argentino–Aleman de Geodesia (AGGO), CONICET–BKG, Argentina

<sup>5</sup> Centro de Investigaciones Geofísicas (CIGEOF), Universidad Nacional de La Plata (UNLP), Argentina

\* Contacto: [luna@inti.gob.ar](mailto:luna@inti.gob.ar)

realizations of UTC and to compute TAI.

Each month, the differences between UTC and the local time scales UTC(k) are published at five-day intervals in BIPM Circular T (Bureau International des Poids et Mesures, [n.d.](#)). At present, all UTC(k) laboratories rely on GNSS-based time-transfer techniques to participate in UTC, and for most laboratories GNSS constitutes the only operational method for time transfer.

To ensure traceability and quantified uncertainty limits in UTC(k) realizations, calibration of the GNSS equipment operated at each participating laboratory is required. Given the large number of GNSS stations involved, it is impractical for the BIPM to organize calibration campaigns with sufficient frequency. Consequently, since 2014 the BIPM and the Regional Metrology Organizations (RMOs) have jointly implemented a distributed calibration scheme for GNSS equipment used in UTC generation (Lewandowski et al., [2006](#); Petit & Defraigne, [2023](#)).

## CALIBRATION FRAMEWORK AND METHODOLOGY

### Involved network

The clock network considered in this work comprises the following national and local realizations of time and frequency:

- **Buenos Aires Naval Observatory (ONBA):** Two cesium atomic clocks, operated under the Argentine Hydrographic Service (SHN), used for the provision of the National Public Service of Official Time.
- **National Institute of Industrial Technology (INTI):** Three cesium atomic clocks employed for the realization, maintenance, and dissemination of the national time and frequency standards.
- **Argentine–German Geodetic Observatory (AGGO):** Three cesium atomic clocks which, together with two hydrogen masers, contribute to the realization of a local time scale, denoted UTC(AGGO), designed to meet the stability and continuity requirements of the observatory's geodetic instrumentation.

The systematic and continuous comparison of the atomic standards operated at ONBA, INTI, and AGGO is essential to reinforce the coherence of the national time and frequency system, introduce metrological redundancy, and ensure controlled levels of accuracy, stability, operational continuity, and traceability to the International System of Units (SI).

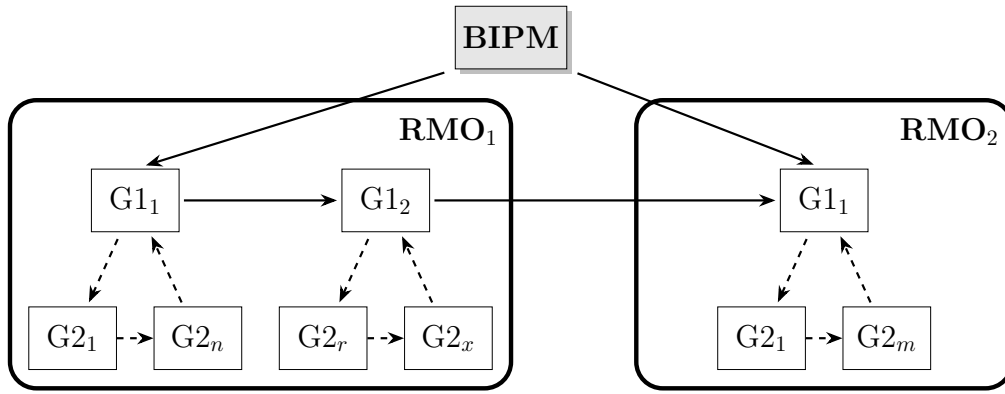
### GNSS calibration scheme

The GNSS calibration scheme coordinated by the BIPM is illustrated in [Figure 1](#). Within each Regional Metrology Organization (RMO), a subset of UTC laboratories is designated as Group 1 (G1). These laboratories are directly calibrated by the BIPM and act as reference systems within their respective regions. The remaining laboratories belong to Group 2 (G2) and participate in calibration campaigns whose reference includes at least one G1 laboratory.

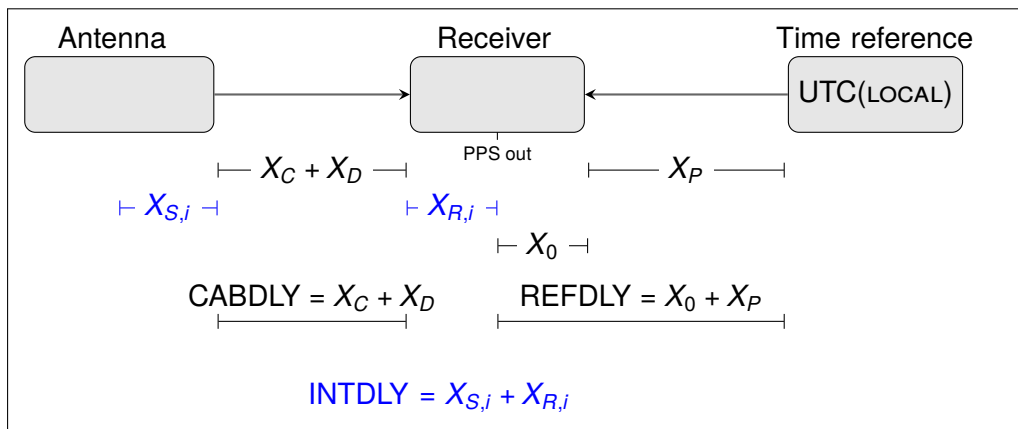
In G2 calibration campaigns, the reference is provided by a participating G1 system, which is measured at both the beginning and the end of the calibration trip. A reference value, typically defined as the average of these two measurements, is transferred to the traveling system and subsequently propagated to the other participating systems. The reports and results of G2 campaigns are submitted to the BIPM for validation, which evaluates the consistency of the measurements and assigns an uncertainty to the calibration results.

### Definition of receiver delays

The calibration of a GNSS time and frequency station requires the determination of several signal delays, schematically illustrated in [Figure 2](#). These delays are defined as follows.



**Figure 1.** Schematic representation of the GNSS calibration organization for UTC generation. G1 and G2 denote Group 1 and Group 2 laboratories, respectively.



**Figure 2.** Definition of delays in a GNSS receiver station.

- **INT DLY:** The sum  $X_{R,i} + X_{S,i}$ , where the subindex  $i$  denotes the observable, representing the internal delay of the receiver and the antenna delay between the antenna phase center and the antenna connector. This delay is frequency dependent.
- **CAB DLY:** The sum  $X_C + X_D$ , corresponding to the delay introduced by the antenna cable and, if present, the splitter and the short cable connecting to the receiver.
- **REF DLY:** The sum  $X_P + X_0$ , corresponding to the delay between the local UTC reference point and the receiver's Pulse Per Second (PPS) input.

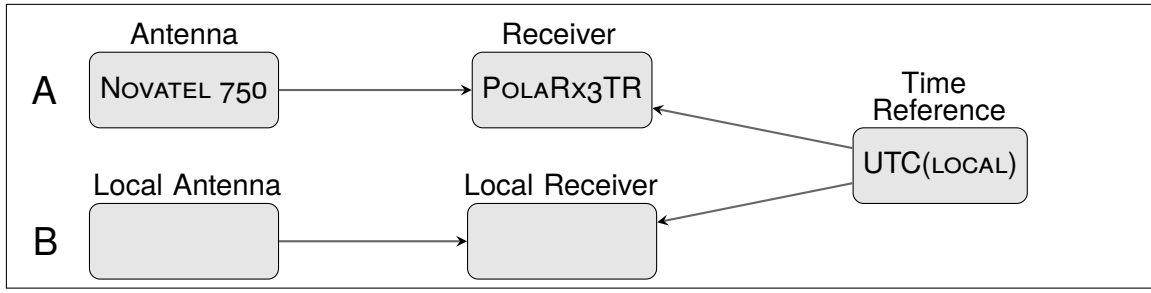
### Common-clock and short-baseline measurements

The internal delay of a GNSS receiver cannot be measured directly and must therefore be determined either by absolute calibration using a GNSS signal simulator or through relative calibration with respect to a reference receiver. In the latter case, a common-clock, short-baseline experiment is performed, as illustrated in Figure 3.

For two co-located receivers, A and B, observing the same signals and connected to a common clock, the difference in pseudorange observations for a given signal can be expressed as

$$\text{RAWDIF}_{A-B} = \Delta\text{CABDLY}_{A-B} + \Delta\text{INTDLY}_{A-B} - \Delta\text{REFDLY}_{A-B}, \quad (1)$$

where the numerical value of  $\text{RAWDIF}_{A-B}$  depends on the observable (code and phase of each frequency) (Defraigne & Petit, 2015).



**Figure 3.** Short-baseline common-clock measurement setup.

### Stability analysis

The characterization of time and frequency stability is a central aspect of time metrology, particularly in applications involving the comparison and calibration of clocks and time-transfer equipment. While frequency-domain estimators such as the Allan deviation (ADEV) are widely used to quantify fractional frequency stability, time-domain metrics are often more appropriate when the primary observable is a time or phase difference. In this context, the Time Deviation (TDEV) has become a standard estimator for assessing time stability over a wide range of averaging intervals.

Let  $x(t)$  denote the time (or phase) deviation of a clock or timing signal with respect to a reference. For sampled data with sampling interval  $\tau_0$ , the sequence  $x_n = x(n\tau_0)$  represents the measured time offsets. The Allan variance is defined as:

$$\sigma_y^2(\tau) = \frac{1}{2} \langle (\bar{y}_{n+1} - \bar{y}_n)^2 \rangle = \frac{1}{2\tau^2} \langle (x_{n+2} - 2x_{n+1} + x_n)^2 \rangle \quad (2)$$

where the normalized mean frequency deviation over a period is defined as  $\bar{y}_n = \frac{x_{n+1} - x_n}{\tau}$  and  $\langle \dots \rangle$  denotes the expectation operator (Riehle, 2006).

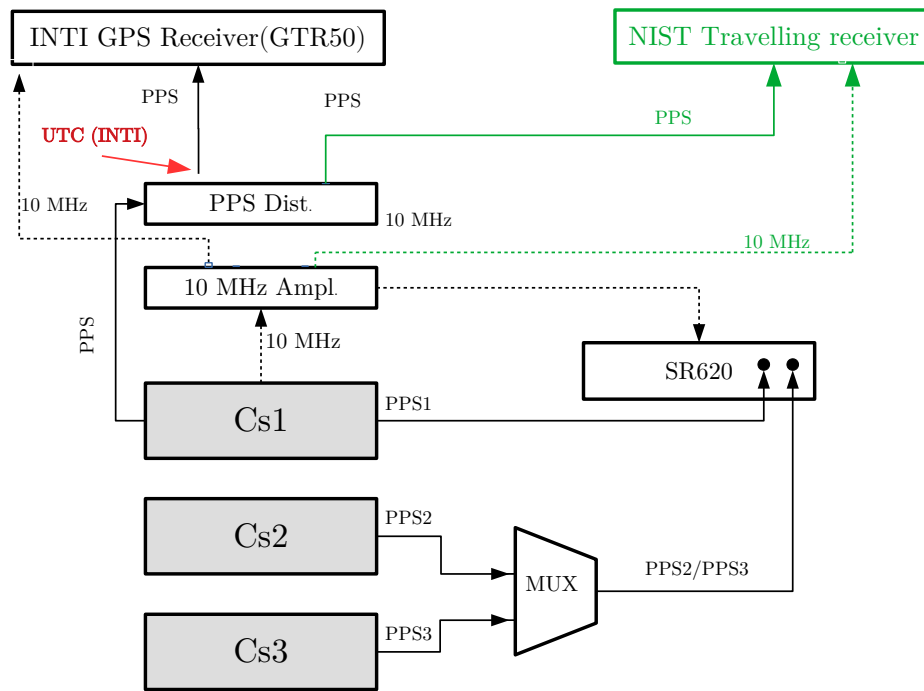
The modified Allan variance (MVAR), is a variable bandwidth modified variant of Allan variance, a measurement of frequency stability in clocks, oscillators and amplifiers. Its main advantage relative to Allan variance is its ability to separate white phase noise from flicker phase noise (Allan & Barnes, 1981; Riehle, 2006). It is defined as:

$$\text{mod } \sigma_y^2(n\tau_0) = \frac{1}{2\tau^2} \left\langle \left[ \frac{1}{n} \sum_{i=0}^{n-1} (x_{i+2n} - 2x_{i+n} + x_i) \right]^2 \right\rangle \quad (3)$$

The Time Deviation (TDEV)  $\sigma_x(\tau)$  for an averaging time  $\tau = n\tau_0$  is defined as (Allan & Barnes, 1981; Stein, 2010):

$$\sigma_x^2(\tau) = \frac{\tau^2}{3} \text{mod } \sigma_y^2(\tau) \quad (4)$$

Because TDEV is expressed in units of time, it is particularly well suited for the evaluation of timing systems, travelling receivers, and calibration links, where sub-nanosecond stability is of primary interest. For this reason, TDEV is widely adopted by timing laboratories and is recommended in international guidelines for the analysis of time-transfer measurements. In this work, TDEV is used as the principal estimator to quantify the stability of the travelling receiver throughout the calibration campaign.



**Figure 4.** Time and frequency distribution scheme for GNSS receiver calibration at INTI.

## EXPERIMENTAL SETUP

### Travelling receiver

The calibration campaign reported in this work was carried out as a G2 exercise, using a reference provided by NIST. The traveling calibration system consisted of a Septentrio PolaRx3eTR PRO GNSS receiver (NB05), a NovAtel pinwheel antenna connected through an LMR-100A antenna cable, a laptop computer, a time interval counter (HP 53132A), and auxiliary cables used for REF DLY measurements.

### Local GNSS stations

The receiver station at INTI is equipped with a Global Positioning System (GPS) dual-frequency GTR50 receiver and a NovAtel GPS-702 antenna. AGGO operates a Septentrio PolaRx5TR GNSS receiver with a Leica LEIAR25.R4 antenna. At ONBA, a single-frequency TTS-2 GPS receiver equipped with a TRC Procom Denmark GPS 2000 antenna was calibrated. All three systems are used as contributing systems for the generation of UTC and for specific applications in each laboratory: Legal Time (ONBA), time and frequency standards (INTI) and fundamental geodetic observations (AGGO).

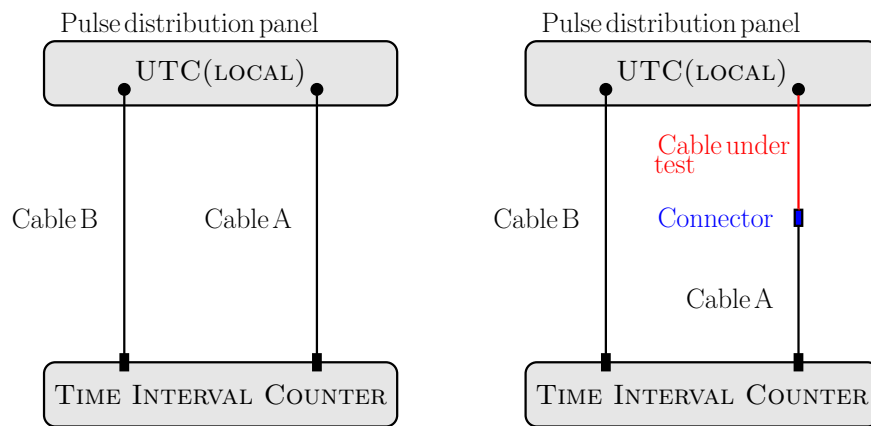
### Time and frequency distribution

Figure 4 illustrates the time and frequency distribution scheme used during the calibration campaign at INTI. The local realization UTC(INTI) provides common 1 PPS and 10 MHz reference signals that are distributed to both the local receiver and the traveling system.

ONBA and AGGO implement time and frequency dissemination systems based on an analogous architecture.

### Cable delay measurements

Cable delays were measured following the procedure recommended by the BIPM, as illustrated in Figure 5. The delay is obtained from the difference between two time interval measurements, after



**Figure 5.** Cable delay measurement following the BIPM procedure. Initial tare measurement is shown on the left, while the configuration including the cable under test is shown on the right. Cable B is connected to channel 1 (start) of the time interval counter, and Cable A is connected to channel 2 (stop).

applying the appropriate corrections (Rovera et al., 2019; Yu et al., 2025).

The first measurement corresponds to a tare. Then the cable under test and a connector must be added to the channel 2 of the time interval counter. The measurement equation for this procedure is

$$\text{Delay} = \text{Delay2} - \text{Delay1} + \text{correction} \quad (5)$$

The correction is the estimated delay introduced by adaptator:  $-0.1$  ns.

A 1 V trigger level is selected on both channels, together with a direct coupling (DC) and a  $50\ \Omega$  impedance. The measurement result is obtained by the mean and standard deviation of 100 measurements. For this number of measurements, the standard deviation of the mean,  $\sigma/\sqrt{100}$ , is one order of magnitude smaller than the resolution of the time interval counter (0.1 ns).

## DATA PROCESSING

Internal delays were derived from common-clock measurements using the median of the delay differences. Uncertainties were evaluated in accordance with the recommendations of the Guide to the Expression of Uncertainty in Measurement (GUM), by combining statistical and systematic contributions.

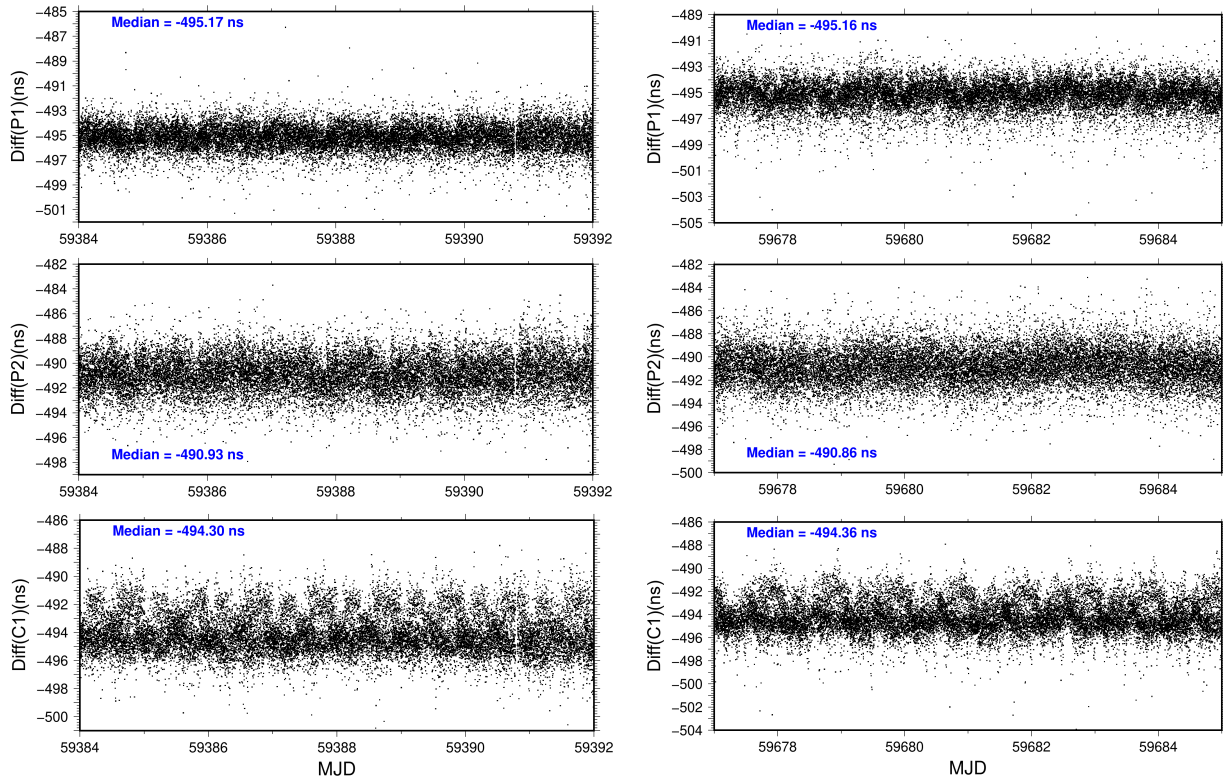
## RESULTS AND DISCUSSION

### Initial and closure measurements of the travelling receiver

The travelling receiver was compared against the NIST standard receiver at the beginning and at the end of the calibration campaign. Figure 6 presents the P1, P2, and C1 pseudorange differences between travelling and standard receiver observed at both epochs of the calibration. The medians obtained at the beginning and at the end of the campaign agree within 0.1 ns, indicating stable receiver performance throughout the calibration exercise (see median values in the blue insets).

### Measurements at the visited laboratories

Short-baseline and common-clock measurements were performed at INTI and AGGO, using the local and the travelling receivers. Results in Figure 7 show the C1, P1, and P2 code differences between measurements performed with the travelling receiver and those obtained with the local receivers at AGGO (left column) and INTI (right column), as a function of MJD. Each panel includes the median



**Figure 6.** P1, P2 and C1 differences at the beginning (left, MJD 59384 to 59392) and end (right, MJD 59677 to 59685) of the calibration. MJD denotes Modified Julian Date. The medians differ by less than 0.1 ns, with median values in blue insets.

value of the corresponding series.

For AGGO (left column), the C1, P1, and P2 differences remain highly stable over the observation interval. In contrast, although at INTI the overall offsets remain well defined, the time series display a more pronounced short-term structure. These features suggest the presence of short-term variability or environmental and instrumental effects influencing the measurements during the campaign. Considering that the results obtained at INTI exhibit a periodic-like modulation, this behavior may be attributed to a daily perturbation. One possible explanation is related to temperature variations, which can affect the travelling receiver and the INTI receiver differently, since both devices are manufactured by different vendors and therefore may present distinct thermal sensitivities. In contrast, this effect is not observed with the receiver at AGGO, which is the same model as the travelling receiver. Another possible explanation is the presence of multipath noise, which depends on the antenna environment and installation conditions. Since the geometry between the satellites and the surrounding reflective surfaces changes periodically with the sidereal day, multipath effects can introduce quasi-periodic perturbations in the measurements (Pereira et al., 2025; Yeh et al., 2007).

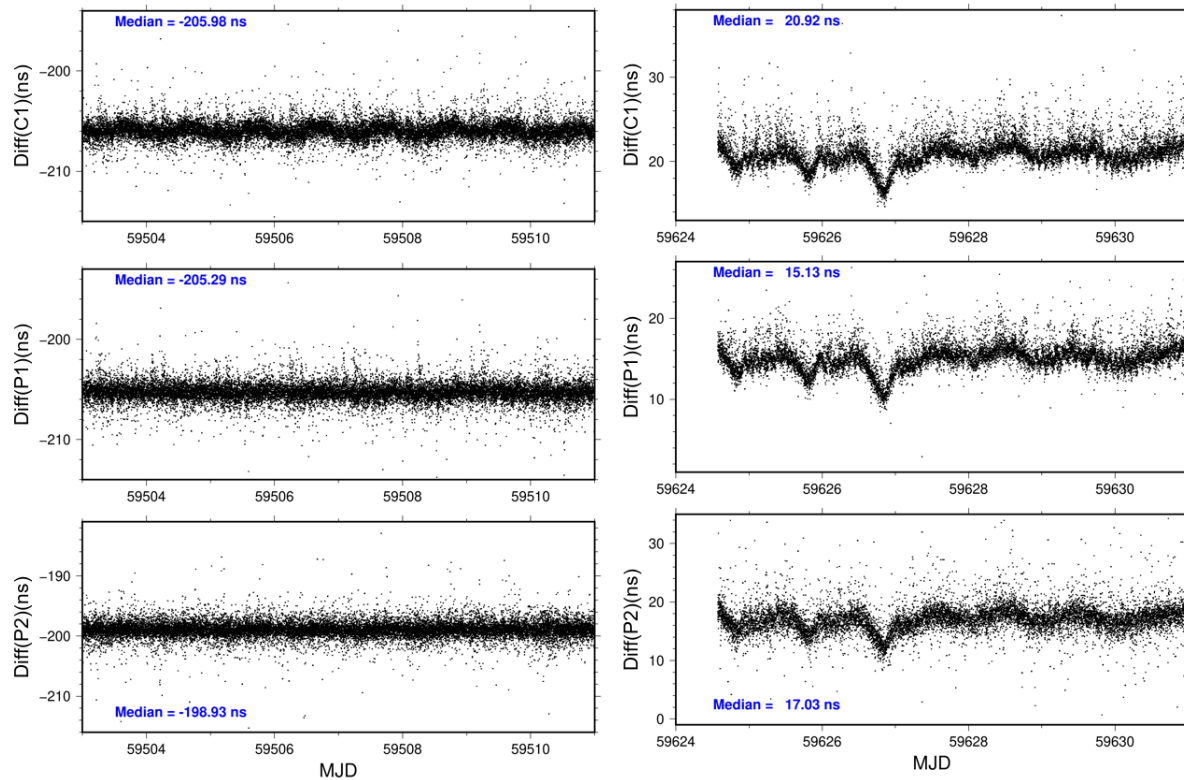
The same measurement as in Figure 7 was performed at ONBA, but with a single frequency receiver. C1 results are shown in Figure 8.

The results from Figure 7 and Figure 8 correspond to the  $RAWDIF_{A-B}$  values defined in equation 1. The computations were performed using the `dclrinex` software.

The code solves for the baseline between the phase centers of the two antennas from L1 and L2 phase differences.

### Cable delays

The delays in the cables were measured at each visited laboratory, following the method recommended by the BIPM and explained previously. The results are shown in table Table 1.



**Figure 7.** C1, P1, and P2 differences between measurements performed with the travelling receiver and those obtained with the receiver at AGGO (left column) and at INTI (right column).

**Table 1.** Cable delays measured in each laboratory of the local receivers. The values of the travelling receiver were measured at NIST.

| Quantity    | Travelling receiver | AGGO               | ONBA        | INTI              |
|-------------|---------------------|--------------------|-------------|-------------------|
| REFDLY (ns) | 65.9                | 12.3               | 48.9        | 8.0               |
| CABDLY (ns) | 275.5               | 201.7              | 160.4       | 129.3             |
| Cable model | LMR 100A            | EcoFlex 10 LowLoss | LMR 195 PVC | BELDEN VENLO H155 |

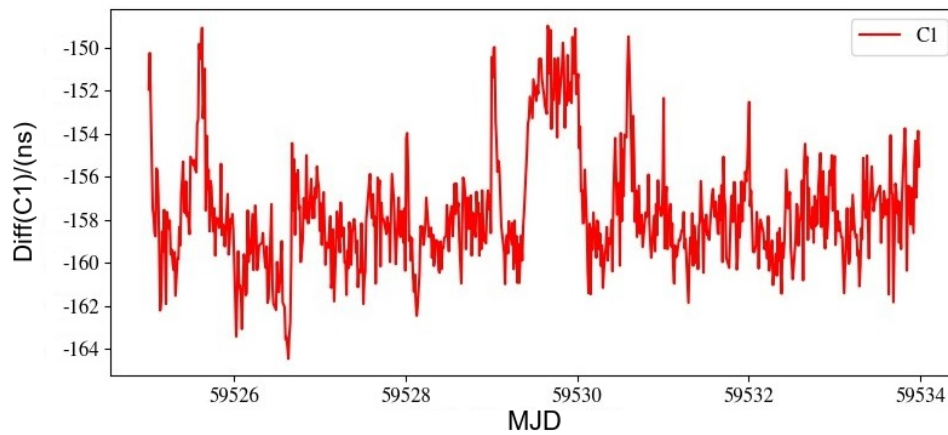
## Noise evaluation of the measurements

Figure 9 shows the TDEV of the measurements obtained at AGGO and INTI. The computation of the stability was performed using the *dclrinex* software.

For C1 (top row), the AGGO link exhibits a monotonic decrease of TDEV with increasing  $\tau$ , reaching a minimum at intermediate averaging times, which indicates effective averaging of short-term noise processes. In contrast, the INTI link displays a more pronounced U-shaped behaviour, with a minimum around  $\tau \sim 10^3$ – $10^4$  s and increasing TDEV at longer averaging times, suggesting the contribution of slower stochastic processes or residual systematic effects.

For P1 (middle row), both links show a general reduction of TDEV as  $\tau$  increases, consistent with the dominance of white phase or white frequency noise at short averaging times. The AGGO results approach the low  $10^{-11}$  s level at long  $\tau$ , while the INTI data present a clearer minimum followed by an increase, indicating the onset of long-term instability.

For P2 (bottom row), a similar trend is observed. The AGGO link shows a steady decrease toward the  $10^{-11}$  s range, whereas the INTI link exhibits a distinct minimum around  $\tau \sim 10^3$  s, followed by increasing TDEV for larger  $\tau$ . This behaviour is characteristic of a transition from short-term noise averaging to long-term correlated noise processes.



**Figure 8.** *C1 differences between measurements performed with the travelling receiver and those obtained with the receiver at ONBA.*

**Table 2.** *Uncertainty assigned for each station.*

| Quantity                             | Uncertainty type | AGGO (ns) | ONBA (ns) | INTI (ns) |
|--------------------------------------|------------------|-----------|-----------|-----------|
| RAWDIFF (P1) <sub>travel–local</sub> | A                | 0.20      | –         | 0.30      |
| RAWDIFF (P2) <sub>travel–local</sub> | A                | 0.10      | –         | 0.30      |
| RAWDIFF (C1) <sub>travel–local</sub> | A                | 0.10      | 1.10      | 0.30      |
| Traveling antenna position           | B                | 0.05      | 0.05      | 0.05      |
| Local antenna position               | B                | 0.05      | 0.05      | 0.05      |
| Travelling multipath                 | B                | 0.20      | 0.20      | 0.20      |
| Local multipath                      | B                | 0.20      | 0.20      | 0.20      |
| REFDLY <sub>travel</sub>             | B                | 0.10      | 0.10      | 0.10      |
| REFDLY <sub>local</sub>              | B                | 0.10      | 0.10      | 0.10      |
| CABDLY <sub>travel</sub>             | B                | 0.10      | 0.10      | 0.10      |
| CABDLY <sub>local</sub>              | B                | 0.10      | 0.10      | 0.10      |
| Misclosure                           | B                | 0.10      | 0.10      | 0.10      |

Overall, the results demonstrate consistency between the travelling receiver and both local receivers at short and intermediate averaging times, while the behaviour at longer  $\tau$  reveals site-dependent long-term stability characteristics of the respective measurement systems.

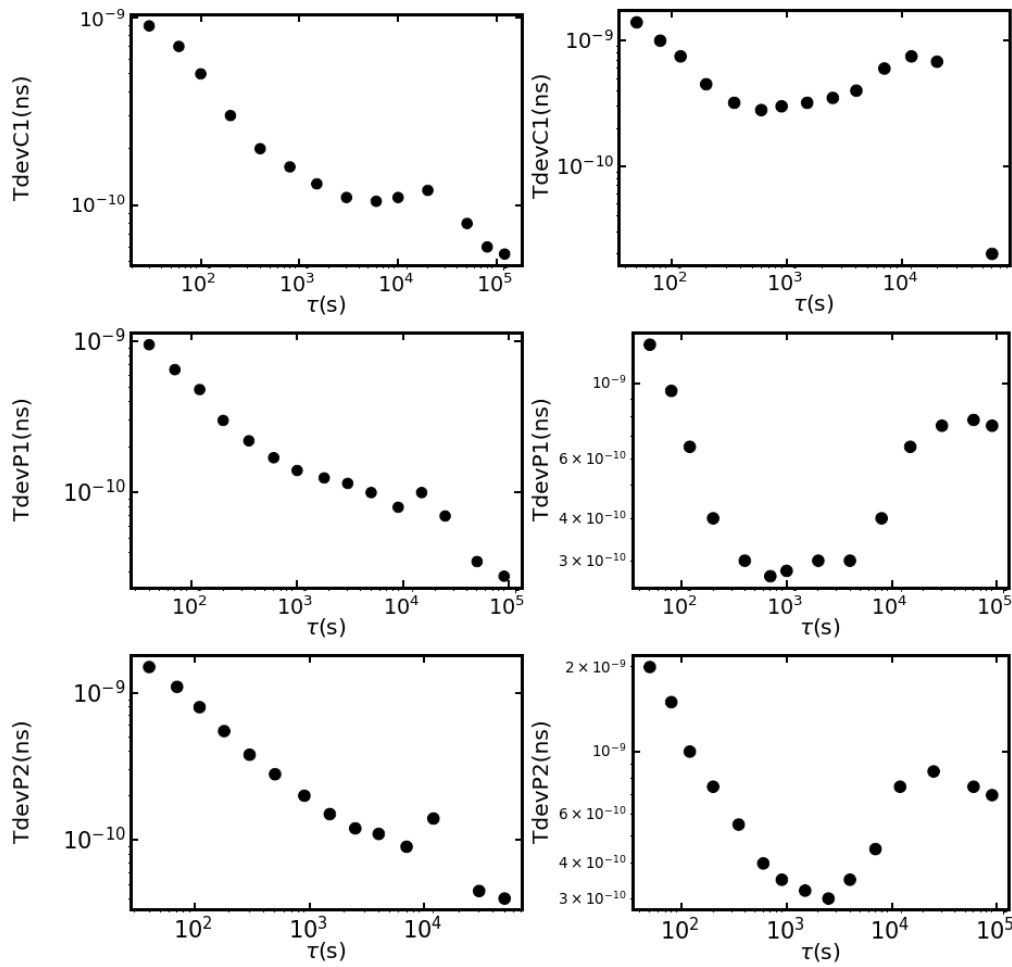
Figure 10 shows the TDEV of the measurements obtained at ONBA. Here, no decrease of TDEV at short integration times is noted.

The BIPM guidelines recommend adopting the TDEV value at an averaging time of one day ( $\tau = 86\,400\text{ s}$ ). In instances where the computed stability is below 0.1 ns, a conservative floor value of 0.1 ns is assigned to the statistical uncertainty.

### Uncertainty evaluation

Uncertainty components were classified in accordance with the GUM as Type A and Type B uncertainties. Type A uncertainties were evaluated by statistical analysis of repeated observations (i.e. TDEV), whereas Type B uncertainties were assessed by means other than statistical methods (Joint Committee for Guides in Metrology, 2008), using manufacturer specifications, previous measurement results, and reference data. All uncertainty components were expressed as standard uncertainties and combined to obtain the combined standard uncertainty associated with the measurand.

TDEV values are extracted at an averaged time of one day.



**Figure 9.** Time deviation (TDEV) of the C1, P1 and P2 differences between measurements performed with the travelling receiver and the AGGO local receiver (left) and INTI local receiver (right).

The items *travelling antenna position* and *local antenna position* account for errors in the differential position. They are conservatively estimated to be 3 cm (100 ps) to account for possible sub-nominal behavior of the baseline determination occasionally observed in the `dclrinex` software.

Multipath uncertainties are assigned to local and travelling antennas. These contributions are difficult to estimate and 0.2 ns is conventionally used, following a discussion in the working group on GNSS of the Consultative Committee for Time and Frequency (CCTF) in 2017 (Kamatham, 2018; Rovera et al., 2018).

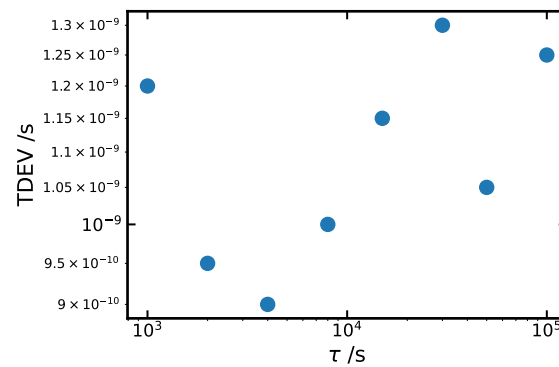
The misclosure value correspond to the difference in the travelling receiver and the NIST reference, at the beginning and end of the exercise.

### Internal delays

Table 3 summarizes the measured internal delays (INTDLY) of the GNSS receivers involved in the calibration, expressed in nanoseconds. They were obtained from the values in Table 2 and equation 1. Uncertainties are expressed with a coverage factor  $k = 1$ , corresponding to a confidence level of approximately 68% under the assumption of a normal distribution (Joint Committee for Guides in Metrology, 2008).

The combined standard uncertainties obtained in this calibration campaign meet the BIPM requirements for GNSS-based UTC links and are on the order of a few nanoseconds (Petit & Panfilio, 2024).

Overall, the calibration results show good consistency among the participating laboratories. Dual-



**Figure 10.** Time deviation (TDEV) of the C1 differences between measurements performed with the travelling receiver and the ONBA local receiver.

**Table 3.** Measured internal delays (INTDLY) of the station GNSS receivers.

| Receiver | Model     | INTDLY(P1)<br>(ns) | INTDLY(C1)<br>(ns) | INTDLY(P2)<br>(ns) |
|----------|-----------|--------------------|--------------------|--------------------|
| AGGO     | PolaRx5TR | $30.1 \pm 0.4$     | $31.9 \pm 0.4$     | $28.3 \pm 0.4$     |
| ONBA     | TTS-2     | —                  | $73.7 \pm 1.2$     | —                  |
| INTI     | GTR50     | $-38.0 \pm 0.5$    | $-37.3 \pm 0.5$    | $-23.0 \pm 0.5$    |

frequency receivers exhibit lower uncertainties compared to single-frequency systems due to their capability to almost completely mitigate ionospheric delay effects through the ionosphere-free frequency combination, which is essential for achieving the highest accuracies when GNSS receivers are separated by more than a few tens of kilometers. The results confirm the suitability of the calibrated stations for their participation in UTC.

## CONCLUSIONS

A GNSS calibration campaign involving the AGGO, INTI, and ONBA timing stations was successfully carried out using a NIST traveling receiver. The internal delays of the local receivers were determined with uncertainties at the nanosecond level, ensuring traceability to UTC. All three stations achieved calibration uncertainties at the nanosecond level, meeting BIPM requirements for UTC participation. The traveling receiver showed excellent consistency, with pre- and post-campaign medians agreeing within 0.1 ns. Highly stable C1, P1, and P2 differences were measured at AGGO, while INTI exhibited a short-term variability with a periodic modulation, likely due to temperature sensitivity or multipath effects.

The results are compliant with BIPM requirements and support the continued use of these stations in GNSS-based time transfer.

**Acknowledgments** The authors gratefully acknowledge Dr. Bijunath Patla (NIST) for providing computational and numerical support that contributed to the analysis presented in this work.

## REFERENCES

- Allan, D. W., & Barnes, J. A. (1981). A modified “Allan variance” with increased oscillator characterization ability. *Proceedings of the 35th Annual Frequency Control Symposium*, 470–475. <https://doi.org/10.1109/FREQ.1981.200514>
- Bureau International des Poids et Mesures. (n.d.). *Circular T*. Retrieved August 18, 2026, from <https://www.bipm.org/en/time-ftp/circular-t>

- Defraigne, P., & Petit, G. (2015). CGGTTS-Version 2E: An extended standard for GNSS time transfer. *Metrologia*, 52(6), G1. <https://doi.org/10.1088/0026-1394/52/6/G1>
- Joint Committee for Guides in Metrology. (2008). *Evaluation of measurement data: Guide to the expression of uncertainty in measurement* (JCGM 100:2008(E)). <https://doi.org/10.59161/JCGM100-2008E>
- Kamatham, Y. (2018). Estimation, analysis and prediction of multipath error for static GNSS applications. *2018 Conference on Signal Processing and Communication Engineering Systems (SPACES)*, 62–65. <https://doi.org/10.1109/SPACES.2018.8316317>
- Lewandowski, W., Matsakis, D., Panfilo, G., & Tavella, P. (2006). The evaluation of uncertainties in [UTC–UTC(k)]. *Metrologia*, 43(3), 278–286. <https://doi.org/10.1088/0026-1394/43/3/010>
- Luna, D., Pérez, D., Cifuentes, A., & Gómez, D. (2017). Three-cornered hat method via GPS common-view comparisons. *IEEE Transactions on Instrumentation and Measurement*, 66(8), 2143–2147. <https://doi.org/10.1109/TIM.2017.2684918>
- Marshall, M. C., Rodriguez Castillo, D. A., Arthur-Dworschack, W. J., Aeppli, A., Kim, K., Lee, D., Warfield, W., Hinrichs, J., Nardelli, N. V., Fortier, T. M., Ye, J., Leibbrandt, D. R., & Hume, D. B. (2025). High-stability single-ion clock with  $5.5 \times 10^{-19}$  systematic uncertainty. *Physical Review Letters*, 135(3), 033201. <https://doi.org/10.1103/hb3c-dk28>
- Panfilo, G., & Arias, F. (2019). The Coordinated Universal Time (UTC). *Metrologia*, 56(4), 042001. <https://doi.org/10.1088/1681-7575/ab1e68>
- Pereira, P. M. C., da Silva, H. D. M., & Lima, C. M. G. S. (2025). Advancements in multipath mitigation for GNSS receivers: Review of channel estimation techniques. *Space: Science & Technology*, 5, 0278. <https://doi.org/10.34133/space.0278>
- Petit, G., & Defraigne, P. (2023). Calibration of GNSS stations for UTC. *Metrologia*, 60(2), 025009. <https://doi.org/10.1088/1681-7575/acbd52>
- Petit, G., & Panfilo, G. (2024). Discussion on the calculation of the uncertainties of [UTC–UTC(k)]. *Metrologia*, 61(4), 045005. <https://doi.org/10.1088/1681-7575/ad59ac>
- Riehle, F. (2006). *Frequency standards: Basics and applications*. Wiley.
- Rovera, G. D., Abgrall, M., Urich, P., Defraigne, P., & Bertrand, B. (2018). GNSS antenna multipath effects. *2018 European Frequency and Time Forum (EFTF)*, 208–212. <https://doi.org/10.1109/EFTF.2018.8409034>
- Rovera, G. D., Siccaldi, M., Römisch, S., & Abgrall, M. (2019). Time delay measurements: Estimation of the error budget. *Metrologia*, 56(3), 035004. <https://doi.org/10.1088/1681-7575/ab14bb>
- Stein, S. R. (2010). The Allan variance—challenges and opportunities. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 57(3), 540–547. <https://doi.org/10.1109/TUFFC.2010.1445>
- Yeh, T.-K., Wang, C.-S., Chao, B. F., Chen, C. S., & Lee, C. W. (2007). Automatic data-quality monitoring for continuous GPS tracking stations in Taiwan. *Metrologia*, 44(5), 393–401. <https://doi.org/10.1088/0026-1394/44/5/016>
- Yu, T., Liang, K., He, Z., Liao, H., & Wang, J. (2025). Coaxial cable delay measurement with different methods: Analyzing influential factors and quantifying numerical effects. *Measurement Science and Technology*, 36(1), 015002. <https://doi.org/10.1088/1361-6501/ad801f>