# CALIBRA: Mitigating the impact of ionospheric scintillation on Precise Point Positioning in Brazil

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## ABSTRACT

The current increase in solar activity occurs at a time when our reliance on high-precision GNSS applications has reached unprecedented proportions. The perturbations caused in the ionosphere by such solar activity pose a major threat to these applications, in particular in equatorial regions such as Brazil where high exposure to solar-induced disturbances comes with a high reliance on precise GNSS applications in a number of key areas such as in the oil and gas industry. Mitigating the impact of severe ionosphere disturbance on high-precision positioning is the main goal of the FP7 CALIBRA project, which first results are discussed in this paper. We focus on the impact of scintillations, one of the most forthcoming disturbances, on real time precise point positioning (PPP). A simple and effective mitigation approach is discussed and shown to significantly increase the resilience of PPP applications to scintillations.

## INTRODUCTION

GNSS has become essential to governmental and industrial sectors in support of activities such as precision agriculture, offshore operations, land management, construction, mining, as well as safety-critical operations, including those related to maritime, land and air transportation. The perturbations caused in the ionosphere by the current increasing solar activity, corresponding to the impending maximum of cycle 24, pose a major threat to these applications, in particular in equatorial regions where high exposure to solar-induced disturbances comes together with high reliance on high-precision GNSS. Brazil is one of the most affected countries. In particular, ionospheric scintillation is a daily issue impacting both the availability and accuracy of high-precision GNSS-based positioning techniques, such as Real-Time-Kinematic (RTK) and Precise Point Positioning (PPP).

Mitigating the impact of severe scintillation on high-precision positioning is the main goal of CALIBRA, a project funded by the European Commission in the framework of the FP7-GALILEO-2011-GSA activity.

In this paper, we present the first results of the CALIBRA project, with as main focus the assessment of the impact of scintillation on Precise Point Positioning (PPP) and its mitigation. The remainder of this paper is organized as follows. First the context, scope and main objectives of the CALIBRA project are described. Next, we discuss the on-going monitoring of ionospheric scintillation in the region of interest, endeavored in the previous CIGALA project, and the resulting climatology results that are instrumental to assess the threat. Then, we zoom on the impact of scintillation on PPP, exploiting data collected during strong scintillation events. Finally, we discuss simple and effective mitigations at positioning algorithm level.

## THE FP7 CALIBRA PROJECT

CALIBRA (Countering GNSS high Accuracy applications Limitations due to Ionospheric disturbances in BRAzil), a project funded under the Seventh Framework Program (FP7) by the European GNSS Agency (GSA) and coordinated by the Nottingham Geospatial Institute (NGI) at the University of Nottingham, deals with these ionospheric disturbances and their effect on GNSS high accuracy techniques. CALIBRA's partners are the Centre for Atmospheric Research (CAR) at the University of Nova Gorica (UNG) in Slovenia, the Upper Atmospheric Physics group of Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Italy, Septentrio Satellite Navigation NV (SSN) in Belgium, Sao Paulo State University (UNESP) and ConsultGEL (CSG) in Brazil.

CALIBRA builds on the outcomes of the CIGALA project where it was demonstrated that signal tracking under ionospheric scintillation can be effectively mitigated by new algorithms and tracking loop configuration within the receiver signal tracking engine [14]. This is illustrated in Figure 1, which show the achieved loss-of-lock probability as a function of S4 (amplitude scintillation index) and user configurable loop bandwidth. The improved tracking robustness achieved in CIGALA, results in increased availability of the code and phase observables and, consequently, of the position solution (PVT) during moderate to strong scintillation.

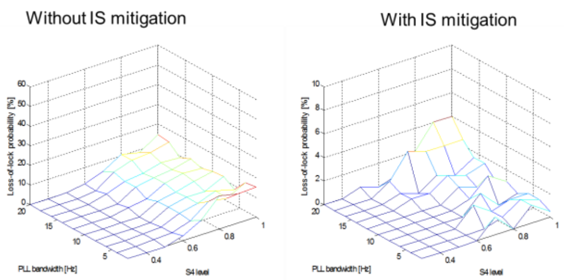


Figure 1 Tracking level mitigation of ionospheric scintillation

CIGALA however also demonstrated that the carrier phase based PVT solution, although available during periods of moderate to strong scintillation thanks to the increased tracking robustness, may be significantly affected, with large error, which in all likelihood is related to the underlying degradation caused by ionospheric scintillation. This is shown in Figure 2, where the time series of the height component of a PPP (Precise Point Positioning) solution is shown during a period of moderate to strong scintillation at a station located in Presidente Prudente in Brazil (22.1ºS, 51.4ºW). The height component is normally the PVT component most affected by the ionosphere.

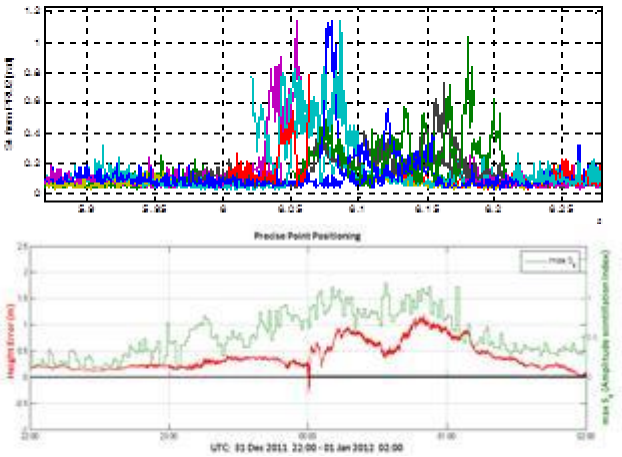

Figure 2 PPP Error during strong scintillation events

The increase in positioning error during scintillation as seen in Figure 2 is a major concern for high precision applications, which may experience accuracy degradation several times over the specification. Resolving this issue is the main goal of CALIBRA with respect to the state of the art. CALIBRA's specific aim is to develop and implement algorithms at receiver level in order to tackle the effects of ionospheric disturbances on high precision phase-based positioning (RTK and PPP). This paper focuses on initial progress in the project with regards to mitigation of scintillation on PPP.

## MONITORING GNSS SCINTILLATION

*The PolaRxS Receiver*

Scintillation effects are characterised by a set of indices, where the most important are the amplitude scintillation index $S_4$ (the standard deviation of the received power normalized by its mean value) and the phase scintillation index $\sigma_\phi$ (the standard deviation of the de-trended carrier phase ). In particular its 60s version, herein termed *Phi60*, is commonly used. Scintillation strength is typically qualified as *weak* ($S_4$<0.25), *moderate* (0.25≤$S_4$<0.6) or *strong* ($S_4$≥0.6).

An ionospheric scintillation monitor (ISM) is expected to measure these quantities next to more commonly used slant Total Electron Count (TEC) and the rate thereof (RTEC). Scintillation indices can effectively be monitored using GNSS signals as originally proposed in [12] and further in [5]. The GNSS signals from the different satellites are exploited to "sample" the ionosphere parameters at the points where they pierce it.

Using GPS only, 4 to 14 points can be sampled depending on time and location. The recent development of additional GNSS constellations (modernized GLONASS, GALILEO, BEIDOU) and the introduction of new civilian signals in the L2 and/or L5 band in each of them significantly increase the observability of the ionospheric parameters in space, time and frequency.

The PolaRxS™ (Figure 3), which specifications were worked out in close collaboration with the project partners, extends the capabilities of state-of-the-art ISM solutions by incorporating a modern triple-frequency receiver engine capable of tracking simultaneously GPS, GLONASS, GALILEO, BEIDOU, SBAS and QZSS signals. The tracking engine, which is coupled with an ultra-low noise OCXO frequency reference (phase standard deviation *Phi60* less than 0.03rad), can generate and store raw high rate data (post-correlation I and Q samples) at up to 100Hz in hourly files which can be processed in real-time or in post-processing to furnish 60s scintillation indices $S_4$ and $\sigma_\phi$, along with other parameters like Total Electron Content (TEC), lock-time and the scintillation spectral parameters *p* (spectral slope of the phase Power Spectral Density, PSD) and *T* (spectral strength of the phase PSD at 1 Hz) for all visible satellites and frequencies. The signals that can be tracked include: GPS L1CA, L1P, L2C, L2P, L5; GLONASS L1CA, L2CA; Galileo E1, E5a, E5b, E5AltBoc; BEIDOU B1, B2; SBAS L1, L5; QZSS L1, L5.


Figure 3 Septentrio PolaRxS™

The PolaRxS™ has been tested independently by Septentrio and the University of Nottingham in their respective laboratories for interoperability with already installed ISM equipment such as the GSV4004, which used to be the reference.

Since its release and installation in the CIGALA network in 2010, the PolaRxS has been tested and adopted by an increasing number of groups and installed in networks all around the world.

Another important feature of the PolaRxS is the very low noise floor of the $\sigma_\phi$ measurement. This is illustrated in Figure 4 which depicts the *Phi60* for the L1 frequency obtained during a 24h long simulation using a Spirent GSS8000 GNSS simulator configured to generate perfect GPS signals.

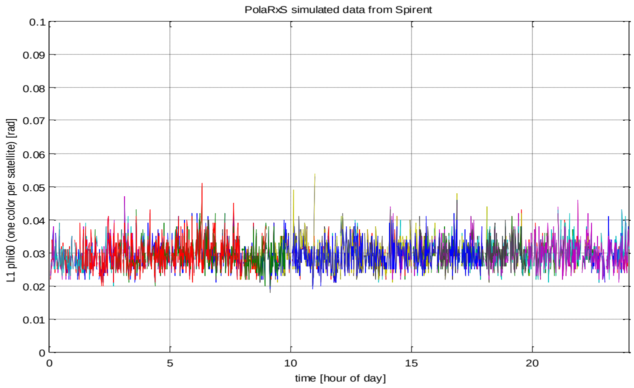


Figure 4 Characterization of the PolaRxS™ noise floor using Spirent GPS simulator

The PolaRxS™ benefits from tracking level scintillation mitigation as described in [14]. This maximizes the availability of code and phase observables, scintillation indices and minimizes the occurrence of cycle slips and loss of lock, even in strong scintillation events.

*The CIGALA/CALIBRA ISM network in Brazil*

During the years of 2011 and 2012, 8 GNSS stations were deployed in strategic locations over the Brazilian territory. Their localization is represented on Figure 5.

Each of those stations is equipped with a Septentrio PolaRxS PRO receiver (Figure 3), capable of logging measurements at a rate up to 100 Hz, a GNSS AERO AT1639 antenna, and PCs with high-end processors and power supply redundancy. In this scope, this network is capable of calculating, sending and storing data in two data mainframes located at Presidente Prudente – SP. Those mainframes run FTP/SSH servers, providing easy access to the collected observations and also an easy environment to work with data analysis tools.

Each one of the CIGALA/CALIBRA stations is monitored by local partners. For instance, in Porto Alegre – RS (POAL receiver) the installation site is in a building inside the Federal University of Rio Grande do Sul (UFRGS), in Palmas – TO (PALM station), the receiver is located at a research site of the Federal Institute of Technology (IFT-TO) and in São José dos Campos – SP (SJCI/SJCE receivers), the equipment is installed in the premise of the National Institute for Spatial Research (INPE) in the Aeronomy department. Figure 5 shows some of the installation sites. This station deployment provides the project with an easy way to control the equipment and to solve issues related to receiver and computer configuration. All the stations have shown more than 90% availabilities in two years of operation.

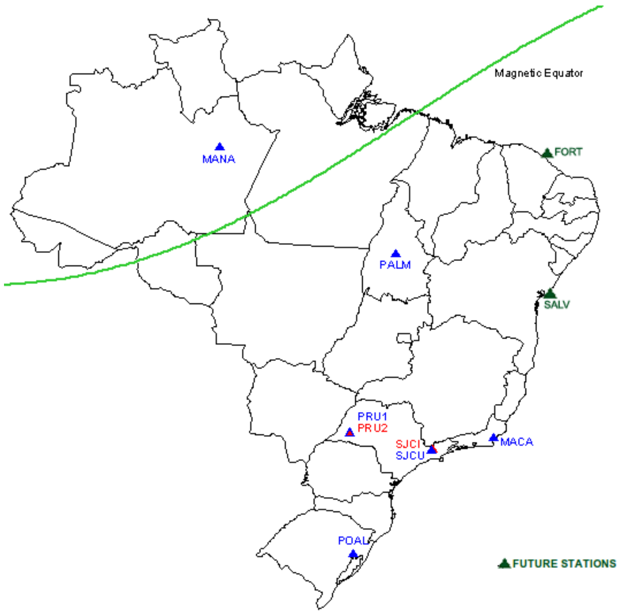


Figure 5 Geographical distribution of the CIGALA ISM Network

Also in the mainframes, besides RAW and ISMR files, a data access tool is running on a PHP/SQL environment, providing a suitable solution to data visualization and filtering. In this system, named ISMR Query Tool[1], the registered user can insert queries to the scintillation database, and get the answer in a chart or in a customizable ASCII file. Figure 6 an example page of ISMR Query Tool.

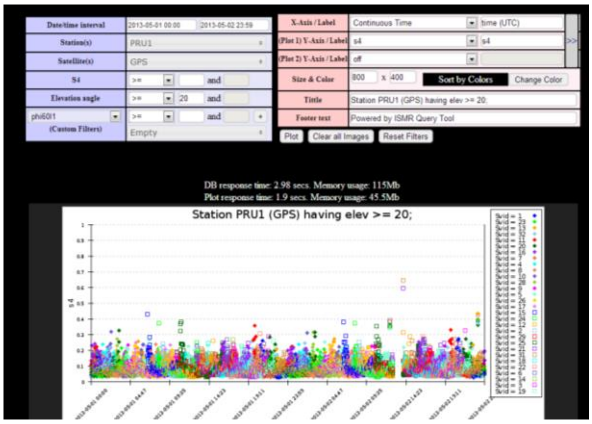


Figure 6 ISMR Query Tool

As the last development of the network, in the beginning of 2013 three new PolaRxS receivers arrived at Unesp, and are ready to be installed to further strengthen geographical coverage. Two places are already defined, as being in Fortaleza – CE and Salvador – BA, both in the northeast region of Brazil and market as green triangles in Figure 5.

More receivers are to come, and more sites are being analyzed to serve the network densification in the context of the CALIBRA project.

[1] Available at http://is-cigala-calibra.fct.unesp.br

**Figure 7 CIGALA ISM sites**

*Ionospheric Scintillation Climatology in Brazil*

Using the ISMR data collected by the CIGALA network during the two last years, the climatology of ionospheric scintillation over the region of interest has been studied, allowing us to assess the risk of disruption of high precision positioning services, in particular PPP.

Only data acquired between 2200 and 0400 UTC has been considered, in order to focus on the post sunset period when the scintillation is more likely to occur (see Figure 8 as example).

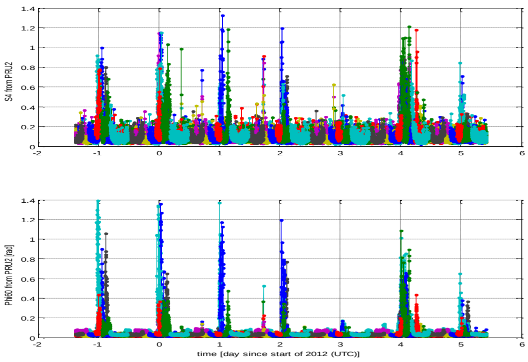

Figure 8 Example of daily scintillation during a period of high solar activity

Analyzing the rate of occurrence of scintillation above a given S4 threshold in the collected data, one can draw a map showing the probability of such scintillation to occur under a given latitude and longitude. Figure 9 depicts such a map for a S4>0.25. It is possible to see the enhancement of scintillation probability under the northern crest of the EIA, mainly covered by the MANA observations. This enhancement is for geographic latitudes greater than 0°N and is localized in a band nearly parallel to the geomagnetic equator (red line). The probability of post-sunset scintillation with S4>0.25 in that area reaches 6%. On the other hand, the southern crest of the EIA shows its effect in terms of amplitude scintillation occurrence in the band of enhanced scintillation nearly parallel to the geomagnetic equator (red line) and reaching a probability of about 16%. The enhancement over POAL is also meaningful and possibly due to the presence of the particle precipitation occurring in the borders of the SAMA [11].

Positioning applications in these regions will be affected quite significantly. Specific impact is discussed further in the next sections.

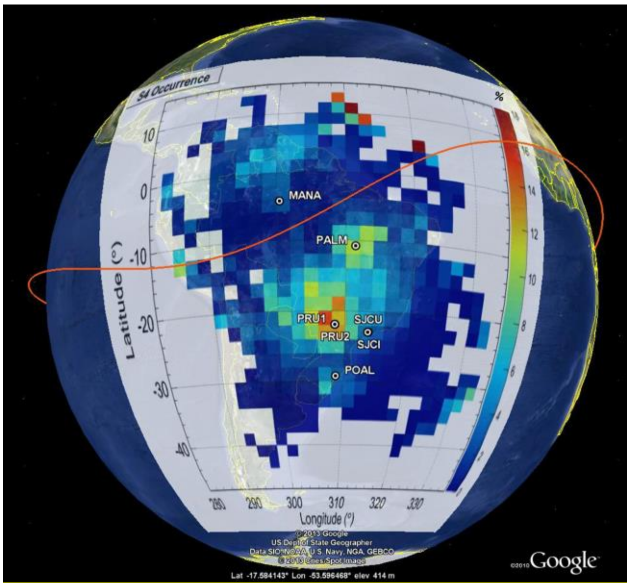

Figure 9. Probabilities of $S_4$>0.25 over the Brazilian territory during post sunset period (2200 to 0400 UTC).

**IMPACT OF IONOSPHERIC SCINTILLATION ON PRECISE POINT POSITIONING**

Being non-differentiated and based on an iono-free combination, one would expect PPP not to be affected by ionospheric delays provided that the delays obey the standard $1/f^2$ rule and that no cycle slip occurs. As it turns out, this is not the case during scintillations. Figure 2 depicts the PPP error measured at station PRU1 during a strong scintillation event. The height error reaches more than 1m (compared to 12cm nominal) at periods when 3 satellites show S4 between 0.6 and 1.

To investigate the effect of scintillation on the GNSS measurements used for PPP, we compared the instantaneous signal power and carrier phase of GPS L1 and L2 signals during strong scintillations. It has been observed that, although the time series of the amplitude for the L1 and L2 signals are correlated, the perturbations caused by scintillations do not occur simultaneously on both frequencies. Figure 10 illustrates the delay between L1 and L2 deep fades and the effect of these fades on the carrier phase. The figure shows real data measured for PRN15 at station PRU1. The upper panel shows the instantaneous signal amplitude and the lower panel shows the difference between L1-C/A and L2C carrier phase observables. Four occurrences of so-called "canonical fades" [9] consisting of deep fades associated with half-cycle phase jumps (about 10cm) are clearly visible and are marked by the red lines. In the case shown in Figure 10, the L2 fades are first to occur, shortly followed by the L1 fades.

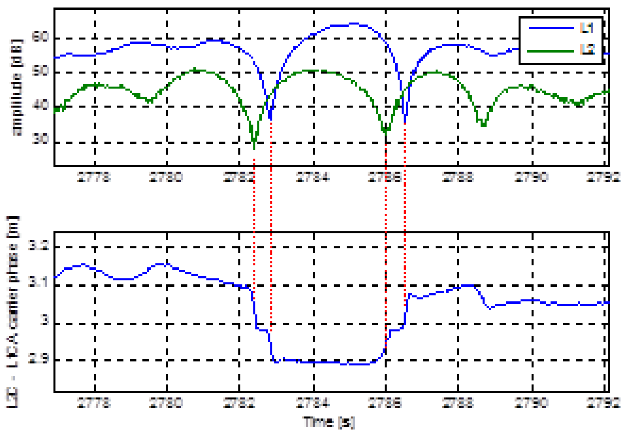


Figure 10 Evolution of signal power and of carrier phase on L1 and L2 frequencies during a scintillation event.

This actually means that the scintillations on L1 and L2 physically occur at different times, the time difference being a fraction of a second. In Figure 10, the L2 fade occurred before the L1 fade, but the value and the sign of the time difference vary from case to case. Figure 11, for example, shows a case where the L1 fade occurred before the L2 fade.

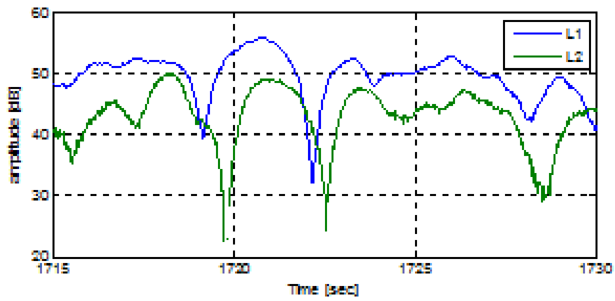


Figure 11 Another example of signal power on L1 and L2 frequencies during a scintillation event

One possible mechanism that could explain the time delay between the L1 and L2 fades is related to the ray path bending of GNSS signals due to the beam refraction in ionosphere coupled with the movement of "ionospheric bubbles". Due to the different path curvature of the L1 and L2 signals, the trajectories of L1 and L2 signals are spatially separated and travelling small-scale disturbances, which cause scintillation, may 'hit' the L1 beam a little later or a little earlier than the L2 beam.

Because the fades are not synchronous between L1 and L2, the iono-free combination cannot remove the associated ranging errors and these errors are directly translated into noise in the PPP solution.

Moreover, because the deep fades can be associated with sudden phase changes, they are likely to cause cycle slips. The presence of cycle slips is evidenced in Figure 11, which shows the L1-L2 phase difference compared to the L2-L1 pseudorange difference over the whole duration of a scintillation event. In the absence of cycle slips, these two quantities should remain parallel. As shown in the lower panel of the figure, this is not the case: the L1-L2 phase has a bias of about 1m with respect to the L2-L1 code after the scintillation. Such cycle slips also contribute to a significant degradation of the PPP accuracy.

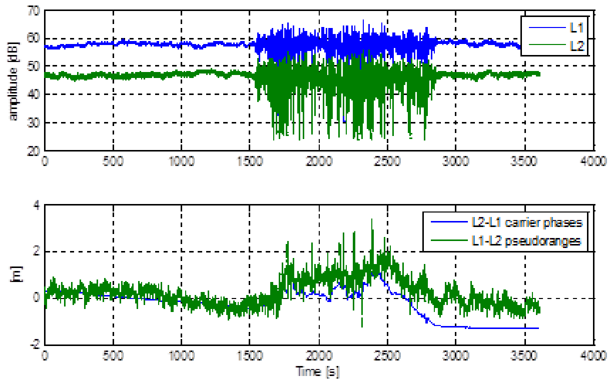


Figure 12 Cycle slips caused by the scintillation. Upper panel shows the L1 and L2 amplitude, where the scintillation time interval is clearly visible. Lower panel illustrates the code-phase divergence due to the cycle slipping during scintillations.

## MITIGATING IMPACT OF SCINTILLATION ON PPP

In order to investigate possible mitigation at positioning level, the phase residuals for the satellites affected by scintillation were analyzed. Figure 13 shows that such residuals are significantly higher during the scintillation periods, indicating that traditional receiver autonomous integrity monitoring (RAIM) methods may be effective at detecting and removing the scintillating satellites from the positioning solution.

This was confirmed by the analysis of the so-called w-test values where $w_i$, is defined as the residual $\boldsymbol{\varepsilon_i}$ normalized with its estimated standard deviation $\boldsymbol{\sigma_i}$. Such values are typically compared in magnitude with a threshold $\boldsymbol{k_\propto^{1/2}}$ prescribed by the probability of false alarm:

$$-k_\propto^{1/2} < w_i = \frac{\varepsilon_i}{\sigma_i} < +k_\propto^{1/2}$$

Most of the time the $\boldsymbol{w_i}$ is within the threshold (as in the above formula), so the w-test is passed and the measurement is used in the solution. If the w-test fails, the measurement is treated as an outlier and is excluded from the solution.

Figure 14 depicts the w-test value for the affected satellites during the scintillation period in question. A threshold of 10 is sufficient to exclude the affected satellites.

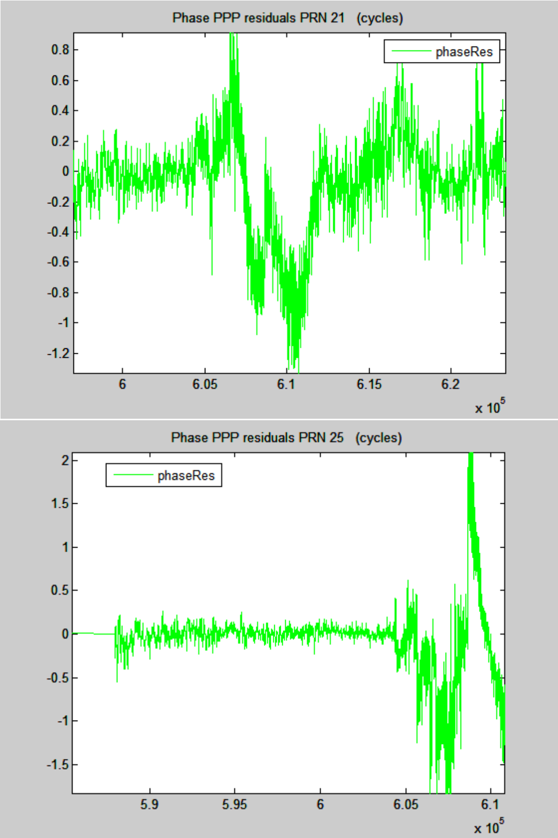


Figure 13 Phase residuals for satellites affected by scintillation

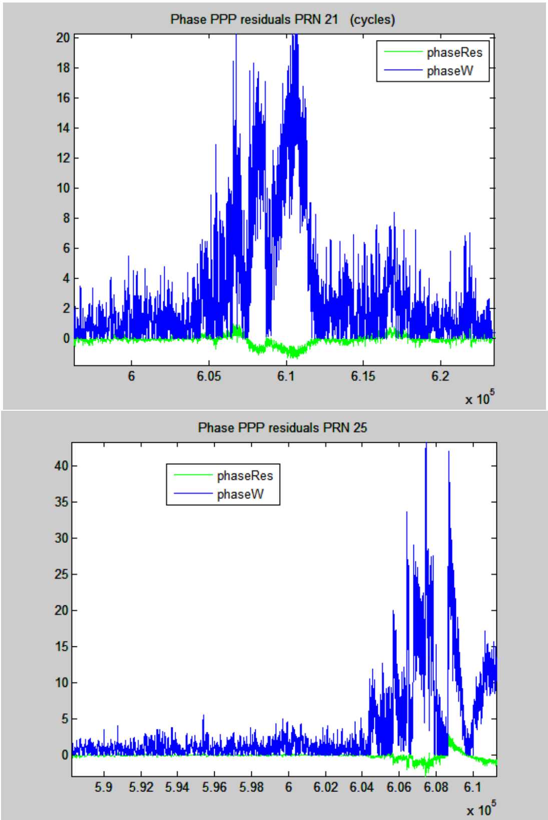


Figure 14 w-test values (blue) and phase residuals (green) for the satellites affected by scintillation

The proposed detection and exclusion method has been prototyped and the measurements reprocessed. As illustrated in Figure 15, the method is effective at restoring the PPP accuracy within its nominal specification during the whole scintillation event.

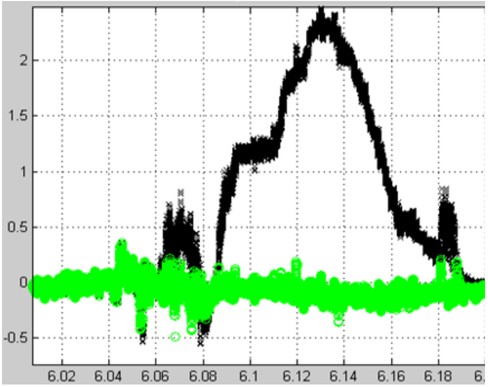


**Figure 15. PPP solution with w-test-based integrity monitoring**

## CONCLUSION

The perturbations in the ionosphere resulting from the increasing solar activity pose a major threat to high precision GNSS applications in equatorial regions. This is particularly the case in Brazil where high exposure to solar-induced disturbances comes with a high reliance on precise GNSS applications in a number of key areas such as in the oil and gas industry.

In this paper, we reviewed the first results of the FP7 CALIBRA project, which principal aim is to mitigate the impact of severe ionosphere disturbance on high-precision positioning.

Capitalizing on the asset of previous CIGALA project, notably the ISM network and data archive, the climatology of ionospheric scintillation, the most forthcoming disturbances, was discussed, highlighting the regions most exposed to degradations due to scintillation.

Further, we discussed the impact of said scintillations to Precise Point Positioning solutions. It has been found that scintillations cause a disturbance of the iono-free phase observables, which ripple down to the positioning solution with error up to 1m (10x the nominal specification).

Finally, a first mitigation approach, making use of standard RAIM procedures based on statistical tests of residuals, was discussed and demonstrated to significantly increase the resilience of PPP applications to scintillations.


## ACKNOWLEDGEMENT

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