INVESTIGATION OF LOW LATITUDE SCINTILLATIONS IN BRAZIL WITHIN THE CIGALA PROJECT

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ABSTRACT

Ionospheric scintillations are fluctuations in the phase and amplitude of the signals from GNSS satellites occurring when they cross regions of electron density irregularities in the ionosphere. Such disturbances can cause serious degradation on GNSS system performance, including integrity, accuracy and availability. The two indices internationally adopted to characterize ionospheric scintillations are: the amplitude scintillation index, S_4, which is the standard deviation of the received power normalized by its mean value, and the phase scintillation index, σ_Φ, which is the standard deviation of the de-trended carrier phase. At low latitudes scintillations occur very frequently and can be intense. This is because the low latitudes show a characteristic feature of the plasma density, known as the equatorial anomaly, EA, for which a plasma density enhancement is produced and seen as crests on either side of the magnetic equator. It is a region in which the electron density is considerably high and inhomogeneous, producing ionospheric irregularities causing scintillations. The upcoming solar maximum, which is expected to reach its peak around May 2013, occurs at a time when our reliance on high-precision GNSS (such as GPS, GLONASS and the forthcoming GALILEO) has reached unprecedented proportions. Understanding and monitoring of scintillations are essential, so that warnings and forecast information can be made available to GNSS end users, either for global system or local augmentation network administrators in order to guarantee the necessary levels of accuracy, integrity and availability of high precision and/or safety-of-life applications. Especially when facing severe geospatial perturbations, receiver-level mitigations are also needed to minimize adverse effects on satellite signals tracking availability and accuracy. In this context, the challenge of the CIGALA (Concept for Ionospheric scintillation mitiGAtion for professional GNSS in Latin America) project, co-funded by the European GNSS Agency (GSA) through the European 7th Framework Program, is to understand the causes of ionospheric disturbances and model their effects in order to develop novel counter-measure techniques to be implemented in professional multi-frequency GNSS receivers. This paper describes the scientific advancements made within the project to understand and characterize ionospheric scintillation in Brazil by means of historical and new datasets.

1. INTRODUCTION

The Earth’s ionospheric environment currently represents the largest single contributor to the GNSS error budget and abnormal ionospheric conditions can cause serious degradation on GNSS system performance, including integrity, accuracy and availability. Harmful ionospheric effects can therefore impact a wide range of GNSS dependent applications. One such ionospheric phenomenon, known as scintillation, relates to fluctuations in the phase and amplitude of the signals from GNSS satellites when they cross regions of electron density irregularities in the ionosphere [14]. At the GNSS receiver end, scintillation increases the noise level of pseudorange and phase measurements, leading to degradation in positioning accuracy. Strong scintillation is capable of leading to loss of GNSS satellite signal tracking. As strong scintillation events can affect the signals of several satellites simultaneously, positioning availability can be compromised.

Ionospheric phenomena leading to the occurrence of scintillation are latitude and solar cycle dependent [1]. At low latitudes, scintillations occur very frequently and can be intense. This is because the low latitudes show a characteristic feature of the plasma density, known as the Equatorial Anomaly (EA), for which a plasma density enhancement is produced and seen as crests on either side of the magnetic equator. It is a region in which the electron density is considerably high and inhomogeneous, producing ionospheric irregularities causing scintillations. The whole of Latin America and Brazil in particular are located in one of the most greatly affected regions of the Earth, with effects exacerbating during solar maximum, the next predicted around May 2013.

2. CIGALA PROJECT OVERVIEW

Understanding and monitoring of scintillations are essential, so that warnings and forecasts can be made available to GNSS end users. Receiver-level mitigations are also needed to minimize adverse effects on GNSS measurement availability and accuracy, especially in regions such as Brazil. These topics are being addressed by the CIGALA (Concept for Ionospheric scintillation mitiGAtion for professional GNSS in Latin America) project, co-funded by the European GNSS Agency (GSA) through the European 7th Framework Program. The CIGALA team consists of European and Brazilian partners with competences in atmosphere physics, radio wave propagation, signal processing, GNSS receiver hardware and software implementation.

The goal of the CIGALA project is to further knowledge on the cause and implications of ionospheric disturbances at low latitudes, model their effects and develop novel countermeasures to be implemented in professional multi-frequency, multi-constellation GNSS receivers. The project includes a wide scale ionospheric measurement and test campaign that is being conducted in Brazil with the support of several local academic and industrial partners. For this purpose, a network of GNSS receivers for scintillation monitoring has been deployed in Brazil. Using archival data and data collected by the CIGALA receiver network, scintillation countermeasures to be implemented at receiver level are being developed. The CIGALA receiver network allows validation of the developed scintillation countermeasures at receiver level.

3. THE GNSS RECEIVER NETWORK IN BRAZIL

3.1. PolaRxS Ionospheric Monitoring Receiver

The two indices internationally adopted to characterize ionospheric scintillations are: the amplitude scintillation index S_4, which is the standard deviation of the received power normalized by its mean value, and the phase scintillation index σ_Φ (in particular its 60 s version, herein termed *Phi60*), which is the standard deviation of the de-trended carrier phase. The CIGALA project involves measuring these and other parameters in Brazil, covering as much as possible the equatorial region around the crests of the Equatorial Anomaly. While in the past, ionospheric monitoring was limited to the GPS L1C/A and L2P signals, the CIGALA monitoring stations are equipped with novel Septentrio PolaRxS receivers [12].

The Septentrio PolaRxS is a multi-frequency multi-constellation GNSS receiver that incorporates a state-of-the-art triple frequency receiver engine that is capable of tracking GPS, GLONASS, Galileo and SBAS signals transmitted on the L1, L2, L5, E5a and E5b carrier frequencies, including GPS L2C and Galileo AltBOC. It has an ultra-low noise OCXO frequency reference with a standard deviation of phase noise (*Phi60*) less than 0.03 radians. The PolaRxS can generate and store raw high rate (correlated I and Q samples) data at 50 Hz in hourly files which can be (post or real-time) processed to provide 60 s scintillation indices S_4 and σ_Φ, 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).

3.2. Network Deployment and Data Repository

The receivers were deployed at selected sites in Brazil based on scientific and also operational characteristics. The aim was to have latitudinal and longitudinal distribution in order to try to register the main events related to the ionosphere that could occur, together with the support of local partners. Additionally, at two sites, Presidente Prudente, and São José dos Campos, both at São Paulo State, two stations where deployed. They are 300 m apart at Pres. Prudente (PPT1 and PPT2) and 10 km from each other at São José dos Campos (SJCI and SJCU). SJCI and SJCU are located in the crest of the Equatorial Anomaly. Such configuration will provide means of testing RTK (Real Time Kinematic) quality around both regions in Brazil. Fig. 1 provides an illustration of the station distribution over the Brazilian territory.

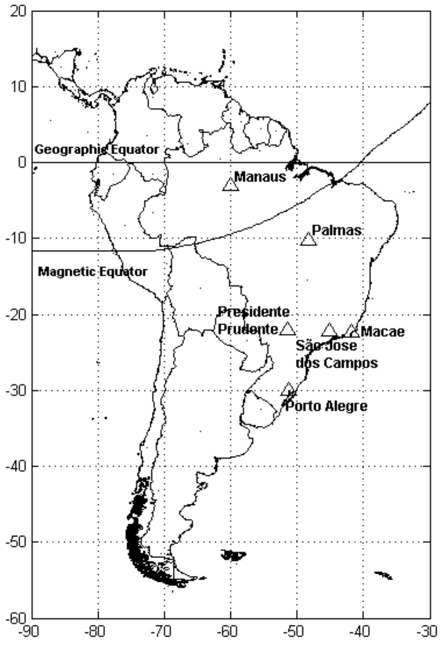

Figure 1. CIGALA stations deployed in Brazil

Each receiver is connected to a computer in order to store data locally, aiming to reduce data loss. A 4 TB hard disk is available at each station. For data storage of all stations, UNESP provided an HP Proliant DL180 G6 - Xeon Quad Core, 8 GB RAM, 2 HD SAS 146 GB RAID 1, Dual Gigabit Ethernet and an HP Modular Smart Array 2000 SAS (MSA 2000), with 2.5 TB (Hot-Plug RAID 5), 7 TB being added. GNU/Linux and virtualization technology was employed. The rack was mounted in an isolated room. Data have been stored and made available to the partners of the project. A mirror of this database is available at INGV in Rome.

4. RESULTS

4.1. WAM Model

The simulation of scintillation effects on trans-ionospheric signals can be accomplished by using in-situ-data based models [5, 11]. The WAM model has originally been realized to reproduce the scintillation climatology over high latitudes [15]. Based on a review of available scintillation models delivered in the frame of CIGALA, it seems that WAM, once tuned to low latitudes, could be the most adequate model within the context of CIGALA. WAM relies on physical principles driving the propagation of radio waves through plasma density irregularities, as well as to the modeling of those irregularities in the ionosphere according to specific helio-geophysical conditions. The model takes into account the strong scintillation by assuming the Rice distribution of the power fluctuations for which the amplitude scintillation index S_4 becomes:

$$S_{42} \sim 1 - \exp(-S_{4w}) \qquad (1)$$

where S_{4w} is the scintillation index derived from the weak scintillation model [11]. The WAM model has been adopted, because it can be easily updated and fine-tuned with low latitudes in-situ data, recently collected or taken from historical archives, such as the Dynamics Explorer 2 plasma density measurements [8]. Besides scintillation indices, WAM also outputs critical spectral parameters such as the spectral strength (T) and slope (p) which are needed for the error analysis and to develop the tracking models. The WAM model makes use of the DE 2 data from the retarding potential analyzer plasma density, covering the period from August 1981 to February 1983, near the solar maximum activity. From in-situ measurements we derive the turbulence strength parameter C_s and the spectral index. In the low latitude formulation of the model realized within CIGALA, the C_s parameter was rescaled to get its value at the height of the maximum electron density provided by the NeQuick model [6]. The NeQuick model is also used to estimate the irregularity layer thickness. To convert the parameters derived from in-situ measurements to the equivalent scintillation index one should rely on the scintillation theory. We used the simplest phase screen approach as described in [10]. Our final results are maps (as function of time and geographic or geomagnetic latitude) sorted according to the K_p geomagnetic activity index and season of different predicted parameters:

- overhead scintillation index S_4;
- overhead scintillation index σ_Φ;
- spectral quantities (T, p, etc.).

4.2. Ground Based Scintillation Climatology using PolaRxS data

The Ground Based Scintillation Climatology (GBSC) technique has been recently developed (see e.g. [4, 13]) as a tool to investigate the physical process involved in ionospheric scintillation, to contribute to mitigation algorithms and as a first step towards the forecasting of Space Weather related events with GNSS receivers. The core of the GBSC are maps of occurrence of the phase (σ_Φ) and amplitude (S_4) scintillation indices. Starting from such quantities, the GBSC method builds maps of the percentage of the occurrence above an arbitrary threshold. The maps at low latitude are currently available in the following two coordinate systems: geographic coordinates (latitude and longitude) and time (universal and/or local). The coordinates refer to the position of the ionospheric piercing point, assumed to be at 350 km. Thresholds for occurrence calculation are chosen in order to distinguish between different scintillation scenarios: for moderate/strong scintillations, typical threshold values are 0.25 radians for σ_Φ and 0.25 for S_4. Scintillation indices can also be projected to the vertical, in order to account for varying geometrical effects and a cut on the elevation angle (20°) is applied to reduce the impact of error sources like multipath, reflections, etc. Fig. 2 shows the maps produced by applying the GBSC technique on data acquired by the CIGALA receivers located at Presidente Prudente (22.S°S, 51.4°W). The threshold for the occurrence calculation is chosen to be 0.25 and maps are in geographic coordinates (left plot) and in latitude vs. universal time (right plot). Data used runs from February to March 2011. The time dependence of the occurrence (right plot) shows that the enhancement of scintillation roughly peaks between 00 and 05 UT, corresponding to 21 and 02 LT, while the map in geographic coordinates (left plot) shows that the enhancement covers the region of the ionosphere pointing towards the magnetic equator. Both plots indicate that the enhancement of scintillation corresponds to the southern crest of the EIA, where post sunset scintillation is more likely to occur.

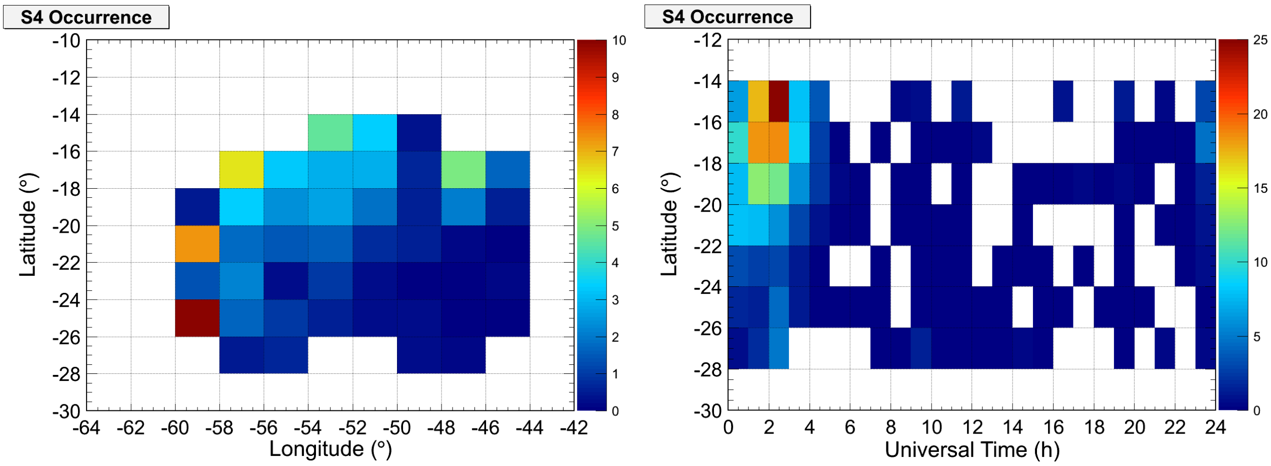

Figure 2. Maps of the percentage of occurrence of S_4 above 0.25 in geographic coordinates (left) and in latitude vs. universal time (right) obtained combining the information acquired by PRU1 and PRU2 receivers between February and March 2011.

4.3. Tracking Model

Weak-to-moderate levels of scintillation cause the receiver PLL to lock onto a wrong phase while still tracking the signals. This causes degradation in the carrier phase measurements, which degrade the positioning accuracy. This can be dealt with by suitable error modelling algorithms, using approaches such as that proposed in [2], where for moderate levels of scintillations, the formula suggested in [7] can be applied to estimate the variance of the tracking error. However, strong scintillation may cause a complete loss of signal lock, as the tracking loops are not able to extract the required information from the affected satellite signals. This means that robust adaptive tracking techniques have to be used, otherwise the affected satellites may be potentially excluded from the solution with detrimental consequences to positioning accuracy. To avoid this, advanced tracking techniques need to be developed to minimise the probability of loss of lock. Based on what is accessible for the research (not commercially protected) in the scope of the CIGALA project at the Phase Locked Loop (PLL) level and considering the capabilities already built in the PolaRxS receiver, a proposed receiver tracking model was devised based on 'tables' representing optimal combinations of PLL parameters for each of the GNSS signals (namely, GPS L1C/A, L2C, L5 and Galileo L1) corresponding to moderate to strong levels of scintillation. To construct these 'tables', simulations were carried out where scintillation effects were introduced to modify the GNSS signals generated by the Spirent^{TM} GSS8000 GNSS signal simulator. For this exercise these perturbations were extracted from open sky data recorded at Presidente Prudente in Brazil on 16 February 2011, for subsequent introduction in the Spirent simulator. Results were presented in [3], where these tables are discussed in detail. Here we show only some results from the tracking of this simulated data by the PolaRxS receiver. Fig. 3 shows the temporal variations in the scintillation indices (S_4 and *Phi60*), lock time on the carrier phase, PLL jitter estimated using [7] and the standard deviation of the phase error estimated from the *I* and *Q* signal components, provided by the PolaRxS receiver for the different signals from two typical satellites, GPS satellite PRN 06 and Galileo satellite 07, respectively.

From the figure, when comparing the tracking error estimated by the theoretical model from [7] with that estimated from the *I* and *Q* signal components, the latter seems to represent a more robust approach for the jitter estimation, in particular not limited by the severity of the scintillation events.

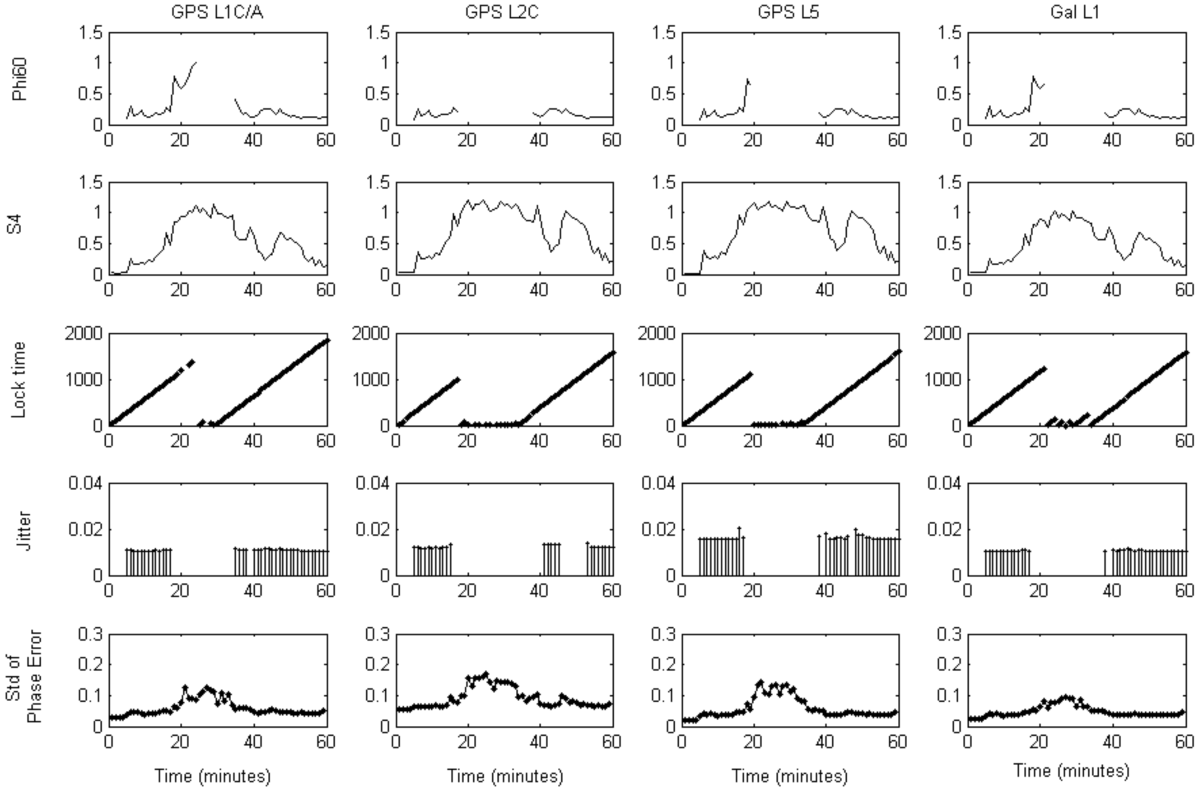

Figure 3. Time variation in the scintillation indices S_4 and Phi60, lock time on carrier phase, jitter (variance in radians squared) estimated from [7] and the standard deviation of the phase error estimated from the I and Q components (in radians) for the signals GPS L1C/A (left panel), GPS L2C (second panel from left), GPS L5 (third panel from left) from GPS satellite PRN 06 and Galileo L1 signal (right panel) from Galileo satellite 07

4.4. Receiver Advancement

As part of the CIGALA project, Phase Locked Loop (PLL) performance under scintillation conditions was investigated using the Cornell Scintillation Model (CSM) [9]. The CSM is a statistical model which generates time series of signal amplitude and phase perturbations, based on the S_4 parameter and the channel decorrelation time in seconds τ_0. The generated scintillation amplitude and phase time series were fed into a representative Matlab model of the tracking loop implemented in the PolaRxS receiver.

It was found that, in case of medium to severe scintillations, the probability of loss-of-lock could be significantly reduced by optimising the lock detector. The lock detector monitors the lock status of the loop and forces signal tracking to stop when the lock conditions are not met. The lock detector was too prudent in the sense that, in case of scintillation, it occurred that loss of lock was declared while tracking could have continued without the loop diverging (a so-called false alarm). The lock detector was optimised and applied to the PolaRxS receivers for further validation in real-life conditions.

5. FINAL REMARKS

GNSS applications are strongly affected by ionospheric scintillation in the Latin American region, causing loss of money and profitability to companies and users. The CIGALA project aims to further knowledge on the cause and implications of ionospheric disturbances at low latitudes, model their effects and develop novel countermeasures to be implemented in professional multi-frequency, multi-constellation GNSS receivers. Countermeasures at GNSS receiver level aim to provide robustness against scintillation effects, allowing the receiver to maintain its performance even in high ionospheric scintillation environments.

As part of the CIGALA project, the WAM model was updated and fine-tuned to reproduce scintillation climatology over low latitudes. In addition, based on data from the PolaRxS receivers deployed in Brazil, the GBSC technique was used to produce maps of the probability of the scintillation indices exceeding a fixed threshold. For the investigation of tracking models, perturbations were extracted from GNSS data recorded at Presidente Prudente for subsequent introduction in a Spirent GNSS signal simulator. The tracking error estimated by the theoretical model was compared with that estimated from the *I* and *Q* data logged by a PolaRxS receiver tracking the simulated GNSS signal. The latter seemed to represent a more robust approach for the jitter estimation, not limited by the severity of the scintillation events. PLL performance under scintillation conditions has also been investigated using the CSM model. Time series generated by the CSM model were fed into a Matlab model of the PolaRxS tracking loop. This resulted in tracking loop adaptations which significantly reduce the probability of loss of lock under scintillation conditions.

Current applications, like precision agriculture, geodesy and cartography, offshore applications, civil aviation etc., are expected to benefit from the knowledge and the technological improvements at the GNSS receiver level developed in the frame of CIGALA project. Most affected local GNSS users are to be involved in the assessment of the threat and countermeasures in order to promote greater awareness of the problem and solutions proposed by European manufacturers.

6. ACKNOWLEDGMENT

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