The NAVSCIN Project: Towards High-Accuracy Navigation under Scintillation

Adria ROVIRA-GARCIA, José Miguel JUAN, Jaume SANZ, Guillermo GONZÁLEZ-CASADO and Miguel ESCUDERO-ROYO, Spain

Key words: Global Navigation Satellite Navigation, Precise Point Positioning, Ionosphere modeling, Scintillation, Space Weather, Ground Based Augmentation Systems

SUMMARY

The main goal of the Marie Skłodowska-Curie Action (MSCA) titled “High Accuracy Navigation under Scintillation Conditions (NAVSCIN)” is to develop an improved strategy to mitigate scintillation –a particular type of space weather perturbation– tailored for satellite-based navigation techniques, in close collaboration with users and manufacturers of these technologies. Indeed, once the scintillation effect is correctly detected and mitigated, the availability and accuracy of the Global Navigation Satellite Systems (GNSSs) receivers will dramatically improve.

Scintillation is one of the most challenging problems in GNSS. This phenomenon appears when the signal pass through ionospheric irregularities, producing rapid changes on refraction index and, depending on the size of such irregularities, also diffractive effects affecting the signal amplitude and the tracking of the carrier-phase measurements. In this work, we present the results being achieved within NAVSCIN to deal with scintillation effects on GNSS signal, exploiting the evidence that low and high latitudes present different characteristics.

At low-latitude, we observe an increase of the carrier phase noise and a fade on the signal intensity that can produce frequent cycle-slips in the GNSS signal and, in extreme conditions, it can lead to the loss of GNSS signals. The detection of these cycle-slips associated with scintillation condition is a challenging problem for precise navigation. In the current state of the art, these uncorrected discontinuities can produce meters of position error. In contrast, we show that high accuracy is still possible for dual-frequency users, if the cycle-slips are detected in a reliable way.

In high latitude, the size of the ionospheric irregularities is typically larger than the Fresnel scale. Therefore, the main effects are related with the fast change on the refractive index associated to the fast movement of the irregularities (which can reach up to several km/s). Consequently, the main effect on the GNSS signal is a fast fluctuation of the carrier phase, but with a moderate fading in the intensity. Thus, on one hand, this rapid fluctuation of carrier phases is mostly proportional to the inverse squared frequency of the signals, being the effect quite limited (practically null) on the ionosphere-free combination. On the other hand, these fluctuations do not usually produce cycle-slips. These two characteristics make feasible the use of the dual-frequency ionospheric free combination for high accuracy navigation in high latitudes, also during high ionospheric activity.

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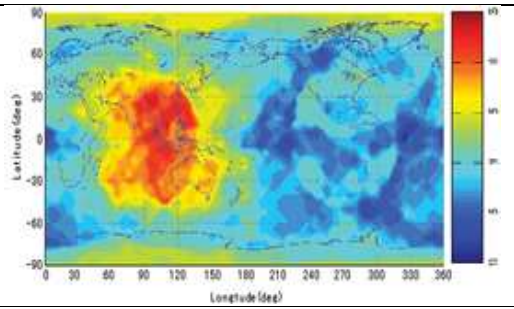
1. INTRODUCTION

The Earth ionosphere is defined as the upper part of the atmosphere (at an altitude comprised between 60 and 2000 km) where ions and free electrons are present in quantities sufficient to affect the propagation of radio waves (IEEE, 1997). Ionospheric disturbances constitute a threat for space-based communication and geolocation by means of the modern Global Navigation Satellite Systems (GNSSs), which includes a heterogeneous community of users equipped with 5 billion GNSS receivers; a number that is expected to grow to 8 billion by 2020 (European GNSS Agency, 2017).

This GNSS' growth is related to an increasing number of GNSS satellite constellations. Two constellations have already declared their Full Operational Capability (FOC). Namely, the Global Positioning System (GPS, US Air Force), completed in 1994; the Global Navigation Satellite System (GLONASS, Russian Federal Space Agency) completed in 1995 (and restored in 2011). Two additional constellations are being completed: the BeiDou Navigation Satellite System (BDS, China National Space Administration) and the Galileo (European Commission). Indeed, Galileo started to provide its services in December 2016 (Bieńkowska, E. 2016). Together, these four GNSSs account for more than 100 satellites.

This fact constitutes an unprecedented frame to improve radio-navigation and ionospheric-sounding techniques, especially in South East Asia (SEA), see *Figure 1*. The Asia-Oceania region is the only area where all of the new GNSS constellations can be observed. This includes Vietnam, where the International Collaboration Centre for Research and Development on Satellite Navigation Technology in South East Asia (NAVIS) is located. NAVIS participates in NAVSCIN as Host Institution in the outgoing phase of the MSCA fellow.

Figure 1. First frame of an animation depicting the number of navigation satellites (including the global and regional systems) and its worldwide distribution.
The analysis and explanation, available at the link www.multignss.asia/campaign.html, is courtesy of the Multi-GNSS Asia (MGA) initiative.



1.1 Ionospheric Impact

The identification, correction and/or mitigation of the effects of the ionosphere are some of the current challenges for aerospace, aviation and ground-based operations including precise GNSS navigation (Pi et al 2017). Indeed, this need has been formulated as a clear customer requirement (marked “essential”) for the Space Weather segment of the Space Situational Programme (SSA) in European Space Agency (2011).

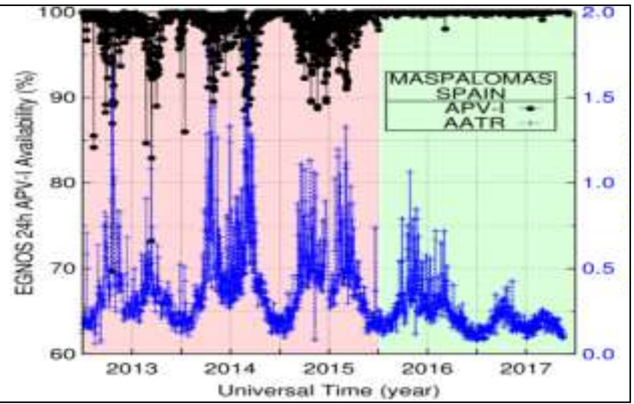
Figure 2 depicts an example of how ionospheric disturbances disrupt operational positioning systems. Namely, the European Geostationary Navigation Overlay System (EGNOS) that has been providing guidance to civil aircraft landings in European airports since 2009. At the same time, it shows that the problem has been mitigated.

The red background depicts severe degradations (down to 70%) of the EGNOS availability (*black dotted line*) for a fault-free receiver situated at the Canary Islands (station MAS1). It was demonstrated that availability deteriorations coincided –almost exactly– with perturbed ionospheric conditions. Namely, with the ionospheric perturbation index named Along Arc TEC Rate (AATR) in Juan et al (2018), see *blue line with plusses*.

The green background highlights the dramatic improvement of the EGNOS availability (almost to 100%), after the last update (July 2015). The EGNOS algorithms improved thanks to the adoption of the AATR index as the metric to define the ionospheric operational conditions (European Commission, 2014). This shows that a correct understanding of the ionosphere is necessary to improve space-based navigation systems.

Figure 2. Impact of ionospheric activity on operational safety-of-life GNSS-based systems.

The European Geostationary Navigation Overlay System (EGNOS) availability used to be deteriorated under perturbed ionospheric conditions



1.2 Ionospheric Scintillation

A particular type of ionospheric perturbation that is currently disturbing navigation systems is called Scintillation (Aarons, 1997). It is related to fluctuations in electromagnetic signals when refracted and/or diffracted during their travel from the satellite to the receiver. Irregularities in the distribution of electrons affect the intensity and phase of GNSS signals along the ray propagation path, traversing the near-Earth space environment.

Two parameters are currently used to characterize the intensity (or amplitude) and the phase scintillation, using specialized Ionospheric Scintillation Monitoring Receivers (ISMRs) capable of sampling GNSS carrier-phase measurements at high-rate (e.g., 50 to 100 Hz):

- The S_4 parameter (Briggs and Parkin 1963) is defined as the normalized standard deviation of the intensity of the GNSS signal. Due to diffractive effects, the amplitude of the signals suffers deep fades (i.e., dramatically decreasing the received power), which can result in a loss of lock (i.e., a reset) between the satellite and the receiver. *Figure 5* shows –with darker colours– that latitudes in Aurora and Equator are most affected.

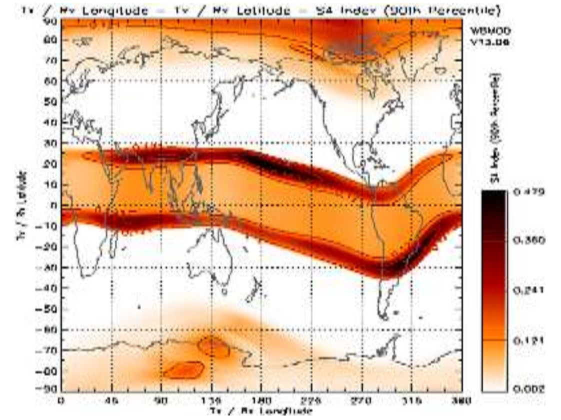


Figure 3. S_4 Scintillation index at GPS L1 frequency (1575.42 MHz).
Prediction using the WideBand MODel (WBMOB) assuming a constant local time (23h) at all longitudes. Image Source: Australian Space Weather Service (SWS).

- The σ_φ parameter (Yeh and Chao-Han, 1982) is defined as the standard deviation of the high-frequency fluctuation of the carrier phase measurements. These fast fluctuations are caused not only by diffraction on the carrier phase, but also by the fast movement (several km/s) of ionospheric irregularities. These rapid changes on the refraction index increase the noise of GNSS signals. If severe, it can also cause a loss of lock of receiver tracking.

1.3 Motivation

Working with ISMRs poses some disadvantages. First, their high sampling-rate generates an enormous, constant amount of output data. In contrast, scintillation only occurs at specific instants: at equatorial locations (during two to five hours after the sunset) and at high-latitude locations (during space weather storms). Because of the large storing capabilities that ISMRs require, their data are not made available to the public. Second, the number of ISMRs is limited to few tens of receivers in the world (see *Figure 4*). This fact limits scintillation studies to those few –sometimes clustered– locations. Worldwide scintillation studies are currently addressed with probabilistic models instead of worldwide observations. This is the case in *Figure 3*, where the colour bar depicts the probability of scintillation occurrence (i.e., not actual observations).

The research that is being carried out in NAVSCIN contributes to change this paradigm. Ironically, ionospheric scintillation studies will benefit from a technique called Precise Point Positioning (PPP) Zumberge et al. (1997), that uses a combination of carrier-phases that eliminates the 99.9% of the ionospheric delay, usually referred as Ionospheric-Free combination (L_{IF}) (Subirana, Zornoza and, Hernández-Pajares 2013).

2. METHODOLOGY

A technique called Geodetic Detrending (GD) has been recently introduced to perform scintillation studies (Juan, et al. 2017). As its name indicates, the GD is composed of two concepts:

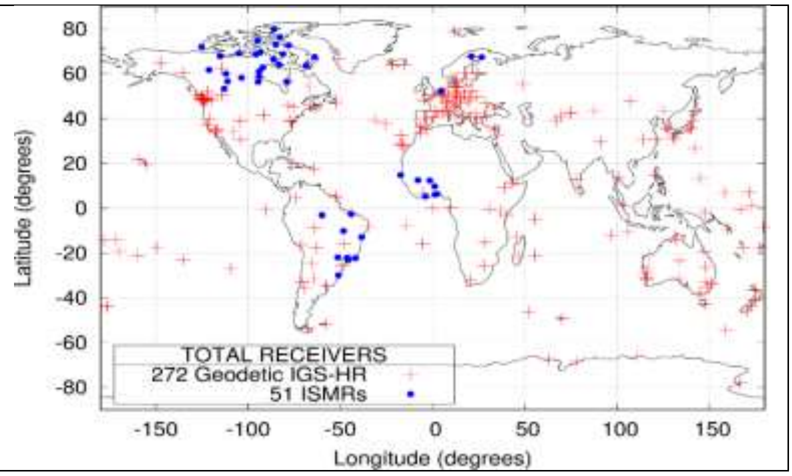
- "Detrending" refers to the removal of slowly-varying effects (i.e., trends) in the GNSS signals, such as the satellite movement, the on-board atomic clock offset, and the tropospheric delay (the atmosphere layer from sea level up to 50 km in height). The trend removal allows studying effects of shorter time-scale –rapid fluctuations– of the signals.
- "Geodetic" refers to the modelling PPP technique used to eliminate the aforementioned effects on the L_{IF}.

Thus, the GD method uses geodetic-grade receivers (i.e., conventional) operating at a low sampling rate (e.g., 1/30 to 1 Hz). This relaxation in the type (and sampling rate) of the receivers allows using 272 permanent stations from the high-rate network of the International GNSS Service (IGS) for worldwide, long-term scintillation studies, see *Figure 4*.

The map depicts the worldwide distribution of geodetic receivers (*red pluses*) that belong to the IGS High-Rate (IGS-HR) network. In contrast, the map also depicts the 51 specialised ISMRs (*blue circles*) from the ESA-MONITOR in Africa and EU, CHAIN in Canada and CIGALA/CALIBRA in South America. Furthermore, many of the ISMRs are currently deployed on a campaign basis (e.g., months), whereas geodetic receivers are available on a permanent basis (i.e., receivers at IGS stations are replaced after years of service).

Figure 4. Distribution of ISMRs (blue circles) vs the geodetic-grade receivers (red pluses) types.

NAVSCIN proposes to use geodetic conventional receivers, instead of the IMSR receivers.



The first step within NAVSCIN is to improve the GD technique in order to use the satellite orbits and clocks available in real-time. Until present, the GD has only been performed with accurate post-process products (available with two to 15 days of latency). Therefore, NAVSCIN uses the PPP technique to precisely model actual GNSS measurements. Then, long-term GD time series are being computed to identify the relation between the formation of scintillation, and the interplanetary medium.

The second step of the research method focuses on the study of discontinuities, the so-called "cycle-slips", on the geodetically de-trended carrier-phase measurements. The characterisation targets the understanding the frequency of the occurrences, the dependency on the receiver type and on the configuration of the tracking loops, among other factors.

The third step consists of correcting cycle-slips on the carrier-phase measurements. The methodology takes advantage of the fact that the magnitude of the jumps is proportional to the wavelength of the signal (see *Figure 5*). Therefore, an algorithm is being developed to compute the necessary number of integer wavelengths to obtain a continuous signal without cycle-slips.

Using these corrected carrier-phase measurements, the fourth (and final) step is the computation of the Position Velocity and Time (PVT) of the user with the PPP technique, in order to achieve a decimetre level of accuracy, or better. In case the method does not correct the cycle-slip with the exact number of wavelengths, the estimation of the carrier-phase ambiguities will be reset within the navigation filter. A further mitigation technique is foreseen through the computation and analysis of the post-fit residuals after obtaining the user PVT.

3. RESULTS

Figure 5 evidences how scintillation misleads the tracking loops of a permanent receiver of geodetic grade. The example station is located in Seychelles (IGS code SEY1) for the GPS satellite 26. Data collection belongs to 2014, the last Solar Cycle maximum, where the ionospheric effects are most intense.

The green background depicts the nominal tracking condition (i.e., without scintillation), where it can be observed that GD technique is effectively capable to eliminate all trends in the GNSS signal. In particular, to the aforementioned ionosphere-free combination of dual-frequency measurements.

In contrast, the red background indicates the epochs when the receiver is affected by scintillation. The deterioration is observed as sudden jumps in the measurements (*pluses*) recorded by the receiver. The accuracy at the level of few centimetres of the GD technique allows the identification of several cycle-slips (the jumps of 48 and 38 cm) in the frequencies involved in the L_{IF} combination (L1 and L2).

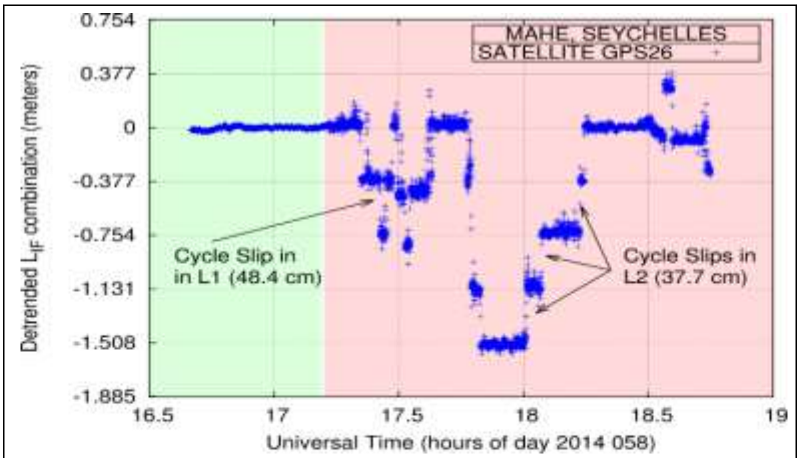


Figure 5. Cycle-slips on actual GNSS carrier-phase measurements caused by ionospheric scintillation.

In the course of NAVSCIN project, it will be explored the possibility to apply the GD method to individual frequencies, instead of usual combinations involving L1 and a second lower frequency (where cycle-slips are most likely to happen). It is of great interest for the scientific community and policy makers, the characterisation of scintillation effects on each individual frequency, to determine potential vulnerabilities of legacy and modern GNSS signals.

In terms of evaluating the impact of scintillation on the users of space based navigation systems, we have processed the observation data from a permanent receiver (geodetic grade) located in Sweden (IGS station KIRU) with the PPP technique in kinematic mode. That is, estimating the coordinates without taking advantage that the receiver is not moving during the data collection. *Figure 6* depicts the 3D errors; the deviation of the obtained coordinates in the navigation filter with respect to the surveyed coordinates of the station.

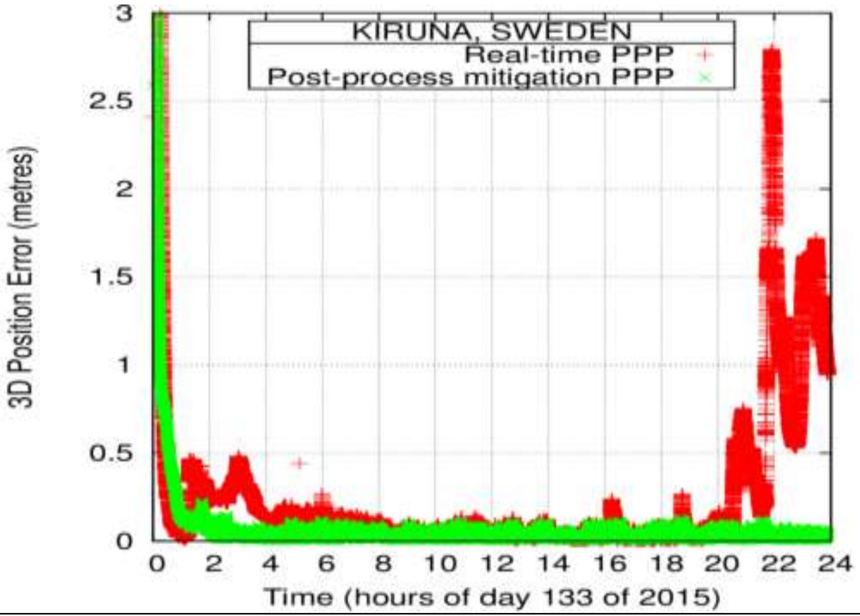
It can be observed how the nominal accuracy, at the level of the decimetre, is reached after a convergence time of about one hour. This is the typical performance of a kinematic PPP solution that can be expected when using a geodetic antenna and receiver and in a controlled environment (low multipath from the surrounding).

In contrast, towards the end of the day, the navigation solution is degraded to several metres because of the presence of scintillation (*red pluses*). This deterioration is not acceptable for those applications that target, at most, few decimetres of accuracy.

The accuracy of PPP can be maintained when the effects of scintillation are correctly detected and mitigated (*green crosses*). However, it must be noted that in the depicted example, mitigation has been performed in post-process. The challenge remains, and that is what NAVSCIN targets, to develop the identification and mitigation techniques that are suitable for real-time operation.

Figure 6. Impact of scintillation on the accuracy of precise GNSS-based navigation.

The NAVSCIN project works towards the high-accuracy navigation under Scintillation.



4. CONCLUSION

The main goal of NAVSCIN project is to develop an improved strategy to mitigate scintillation, tailored for GNSS-based applications, in close collaboration with users and manufacturers of these technologies. Indeed, when the scintillation problem is correctly detected and mitigated, the availability and accuracy of GNSS navigation under scintillation will dramatically improve.

The activities within NAVSCIN contribute to improve our understanding regarding the physical processes resulting in the formation of scintillation, and consequently to identify the drivers in the interplanetary medium, the magnetosphere and the atmosphere. NAVSCIN's improved methodology will support, for the first time, the real-time identification, correction and/or mitigation of scintillation in GNSS receivers.

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BIOGRAPHICAL NOTES

Adrià Rovira-Garcia is a post-doctoral researcher at UPC with a Marie Sklodowska Curie Individual Fellow titled "High Accuracy Navigation under Scintillation Conditions (NAVSCIN)". He co-authors 11 papers in peer-reviewed journals, two book chapters and over 25 works in meeting proceedings, with one best presentation award from the US Institute of Navigation and one Outstanding Poster Award from the European Geosciences Union.

José Miguel Juan is with the Department of Physics (UPC) and member of gAGE since 1988. He has published over 70 papers in peer-reviewed journals and more than 200 works in Meeting proceedings related with GNSS, with four best paper awards from the US Institute of Navigation. He is a coauthor of five patents on GNSS and four books on GNSS Data Processing.

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Dr. Miguel Escudero Royo is with the Department of Mathematics (UPC) since 1982 and member of gAGE since 2007. He received his Degree in Mathematics in 1976, from the University of Barcelona, and his PhD in Mathematics in 1987, the Technical University of Catalonia (UPC) in Barcelona, Spain. Hi is also PhD in Philosophy by the University of Barcelona, 1997.

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