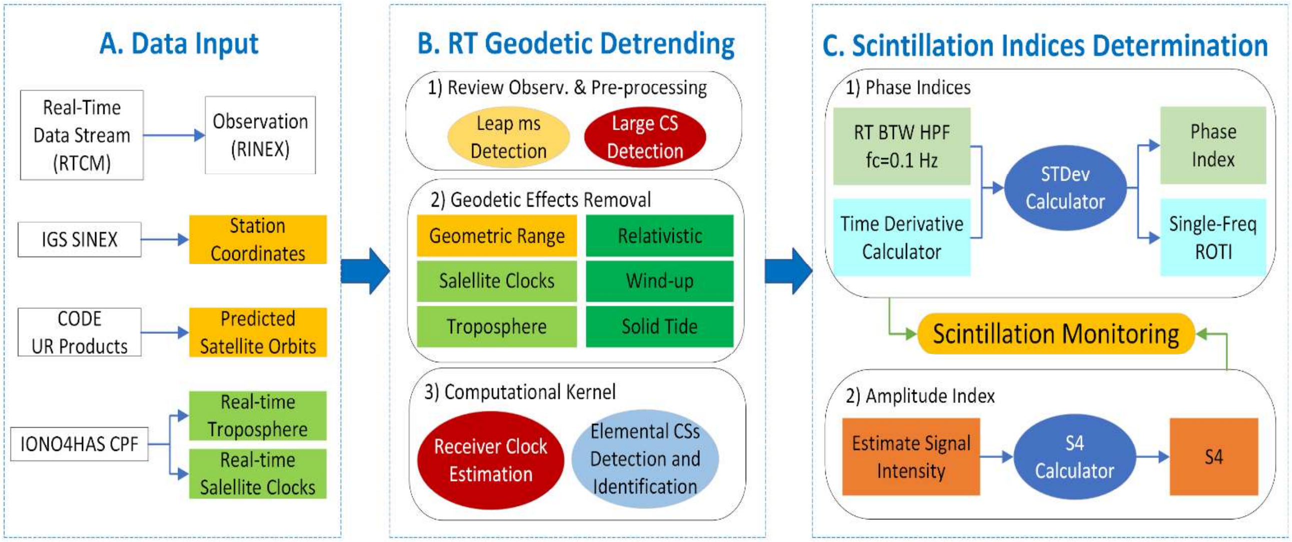

REAL TIME WORLD-WIDE MONITORING OF IONOSPHERIC SCINTILLATION USING GEODETIC RECEIVERS: FROM HIGH END TO LOW-COST RECEIVERS

Executive Summary Report

Early Technology Development
Open Discovery Ideas Channel

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Activity summary:

This activity has demonstrated the feasibility of a real-time (RT) worldwide monitoring of ionospheric scintillation based on GNSS RT data collected from geodetic receivers operating at 1Hz. This monitoring involves an accurate modelling of GNSS signals by means of the geodetic detrending methodology based on precise RT products. Furthermore, the study confirmed the potential for a similar monitoring service using low-cost GNSS receivers, such as the Ublox-F9P and the Septentrio-Mosaic-X5. Incorporating these mass-market receivers into routine scintillation monitoring could significantly reduce the cost of deploying new equipment for this purpose.

The RT scintillation products include amplitude and phase scintillation indices, the Rate of Total Electron Content Index (ROTI) derived from uncombined GNSS signals, and an index related to the performance of the ionosphere-free combination in precise positioning applications. These RT products pave the way for the development of a warning service aimed at mitigating the impact of scintillation on GNSS signals. A roadmap is proposed to guide the full deployment of such a service.

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Purpose of this document

The Executive Summary Report concisely summarizes the findings of the Contract. It is suitable for non-experts in the field and it is appropriate for publication. This document is free of all commercial/confidential information, which should be provided under separate cover if necessary. No copyright nor dissemination restrictions apply.

1. Introduction

The approach proposed in this project is to use dual-frequency multi-constellation geodetic receivers, operating in RT and at 1 Hz (1 second) sampling rate, as a solution to monitor ionospheric scintillation in RT. Hundreds of this type of receivers can be presently found in the wide networks of ground stations already deployed by several institutions. Moreover, there are several services which also are providing in RT the necessary corrections to achieve this purpose. In this way, it is possible to compute in RT standard ionospheric scintillation parameters such as S4, ROTI and σ_{φ}.

The main objectives of this activity were as follows:

- ✓ The proof of concept and subsequent demonstration of the feasibility of a real-time worldwide monitoring of ionospheric scintillation (RT-WMIS) based on:
  1. Global Navigation Satellite System (GNSS) real-time data streams from public networks of geodetic receivers operating at 1Hz.
  2. The accurate modelling of individual GNSS signals by means of the geodetic detrending (GD) methodology.

  For this objective, the real time data products currently available from gAGE/UPC as well as the future products from the Galileo High Accuracy Service (HAS) might be considered and, eventually, other existing similar high-precision services that could be of interest.
- ✓ To analyze the realization of a similar monitoring service using low-cost GNSS receivers (e.g. Ublox-F9P or Septentrio-Mosaic), incorporating the use of mass-market receivers to the RT-WMIS and, ultimately, allowing a significant reduction in the cost of deploying new receivers for scintillation monitoring worldwide.

After demonstrating the previous objectives, the plan was to develop from the RT-WMIS some warning service based on the real-time information of amplitude and phase scintillation indexes and a robust ROTI from individual (uncombined) GNSS signals. At this respect, for this activity it has been proposed a novel approach for computing ROTI from single-frequency signals, which outperforms the classic method based on the use of the geometry free (GF) combination of two GNSS carrier phases.

2. Project Background

Ionospheric scintillation is one of the main effects affecting to the GNSS signals that cannot be totally corrected. Basically, scintillation is due to the presence of ionospheric irregularities that the signal crosses on its path from the transmitting GNSS satellite to the ground receiver.

Scintillation effects are characterized by rapid fluctuations (typically at frequencies greater than 0.1Hz) on the GNSS signals, which degrade the nominal performance of the GNSS products. Depending on the size and velocity of the ionospheric irregularities two types of scintillation can be distinguished: *refractive scintillation*, which affects to GNSS carrier phases and occurs typically at high latitudes, and *diffractive scintillation*, which affects also to the amplitude of the carrier phase signals and typically occurs at low latitudes.

Historically, scintillation monitoring is done through specialized ionospheric scintillation monitoring receivers (ISMRs), which are equipped with very stable clocks to avoid instabilities that could be confused with fast fluctuations produced by scintillation. But the distribution of ISMRs is quite limited, they are sparsely distributed and scarce in many regions of interest. Therefore, considering the local behavior of scintillation, in general it is not possible to monitor scintillation at wider regions and rarely in RT.

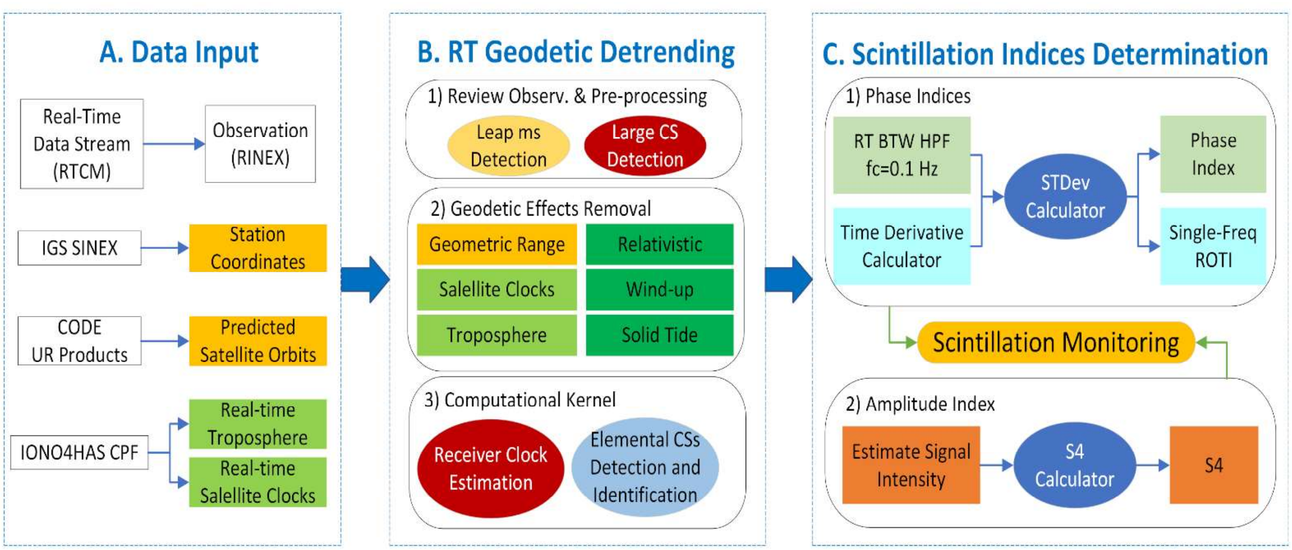
An alternative to the use of ISMR, is to use of conventional geodetic receivers widely deployed around the world by different agencies and providing freely available data sets as sufficiently higher sampling rate (1 Hz) to perform scintillation monitoring.

In recent years gAGE/UPC has developed the geodetic detrending technique (GD), which has been shown to produces ionospheric parameters highly consistent with the outputs from an ISMR. Moreover, the GD outperforms the classic way of monitoring scintillation through the ROTI based in the GF combinations of carrier phases. Some studies have shown the existence of inconsistencies between this dual-frequency ROTI obtained by different models of collocated receivers. To overcome this problem, the GD proposed the use of ROTI calculated from uncombined GNSS measurements, to obtain and index linked to each individual GNSS frequency.

The GD requires the use of 1-Hz GNSS observations and precise GNSS corrections which can be found from several services, some of them operating in RT. Therefore, the challenge for applying GD in RT is to have access to such corrections. The approach followed in the present activity has been to take advantage of the corrections derived from the RT IONO4HAS tool that has been developed by gAGE/UPC under ESA contract (4000128823/19/NL/AS).

3. Methodology

The following diagram illustrates the main steps of the RT-WMIS implementation.



Step A is devoted to download predicted orbits and precise coordinates, which are available in advance, to collect 1-Hz RT data streams received from several broadcasters and for a pre-defined set of ground receivers and, finally, to gather the RT corrections, satellite clocks and receiver zenith tropospheric delays, from the IONO4HAS tool.

Step B is the main part of the processing which is devoted to do the GD of the GNSS signals. For this purpose, rough cycle slips of the carrier phase and fine cycle slips associated to scintillation are detected at the beginning and at the end in this part of the algorithm, respectively. In the middle part, carrier phase signals are corrected from the geodetic effects (satellite clocks, tropospheric delays and other modelled effects), in such a way that it is possible to estimate the receiver clock variation, which is finally subtracted from the signals. In this way, the output of this part of the algorithm is the time series of the ionospheric delays experienced by any of the GNSS signals, separated in continuous arcs of detrended carrier-phase measurements free of cycle slips.

Step C, the last one, starts with the carrier phase signals already corrected from their geodetic effects. Hence, the remaining part in each signal is essentially the ionospheric delay that is used for extracting the ionospheric scintillation parameters. The ROTI and the amplitude scintillation index (S4) are computed directly and the phase scintillation parameter, σ_φ, is calculated after applying a 6^{th}-order Butterworth high-pass filter (HPF) with cut-off frequency of 0.1 Hz to the detrended *L1*-frequency carrier phase.

The RT-WMIS implementation is currently processing 47 receivers in low and high latitudes. The specific GNSS measurements used are the L1C and L2W RINEX observations from GPS and E1 and E5a frequencies from Galileo.

The final products obtained during the RT processing include the following indexes:

- S4 from each individual GNSS signal.
- ROTI from each individual GNSS signal. The uncombined and the GF ROTI are calculated.
- σ_φ from the L1/E1 frequency and a similar index for the ionosphere-free combination of the two frequencies processed in GPS or Galileo.

4. Key Findings

RT-WMIS started to work on April 14^{th} of 2023 with a reduced set of 11 receivers and, after several upgrades, a stabilized version is working since the day 060 of 2024 with a total number of 47 receivers worldwide distributed, mostly in regions of interest from the point of view of ionospheric scintillation.

The validation of the RT-WMIS outputs has been done by comparing the results with:

Results from geodetic receivers processed off-line.

This type of reference data refers to the scintillation parameters that are calculated by means of the so-called post-process geodetic detrending method (ppGD), that was originally developed and tested in previous research studies. In this case, the reference results were compared against the results from the same receivers after processing with the RT-WMIS software the RINEX files obtained from RT data.

Outputs from ISMRs.

This type of reference data refers to values of the scintillation parameters S4 and σ_φ that are directly obtained from the output of the ISMR and are based on high-frequency GNSS observations (50 Hz sampling frequency typically). This output was compared to the corresponding values from the RT-WMIS tool for a geodetic receiver nearby to the reference ISMR.

Two ISMRs were considered for the validation study because they were found to be closely located to corresponding geodetic receivers from the RT-WMIS network. One ISMR belongs to the CHAIN network (marker name CHUC), at high latitude in North America. It has a baseline distance of nearly 100 m with the geodetic receiver CHUR in the RT network. A second ISMR from the Australian Space Weather Service network (AUSWS), marker name DWNI, was identified, close to the geodetic receiver DARW.

Two periods of time were considered to perform the validation study of the RT-WMIS proof of concept:

I. From DOY 102 to DOY 130 (excluding DOY 103) in 2023. This was a continuous time period of 27 days from DOY 104 to 130 plus DOY 102, yielding a total of 28 days. In this period, reference data from ISMRs and geodetic receivers was used.

II. From DOY 70 (10th March) to DOY 99 (9th April) in 2024. A period of 30 consecutive days around the March equinox in a year of maximum solar activity in current solar cycle (SC). In this period, only the reference data from ISMR CHUC was used.

Comparing with ppGD results used as reference data, overall consistency in S4 and $ROTI_{L1}$ was achieved by the RT-WMIS implementation. In general, the differences in S4 are well below 0.1. The differences in the $ROTI_{L1}$ are typically lower than 3-4 TECU/min. In both cases the differences are similar to the residual noise of the indexes after the processing.

One key finding of this validation study is that the σ_φ index is strongly affected by the specific procedure used to perform the high-pass filtering. The HPF used by the ppGD, the RT tool and the ISMR are different, in this has a relevant impact on the validation results. However, it has been demonstrated that, for example, the ppGD and the RT results become fully compatible when the same HPF is used in the two approaches.

In the case of the high latitude ISMR (CHUC), the results of the RT tool show good consistency in the S4 and the σ_φ indexes in the two time periods analysed. However, it was observed that the validation based on a Septentrio geodetic receiver in 2024 versus the ISMR (also from Septentrio), yields better results in the S4 and phase scintillation indexes than the validation in 2023 based on a geodetic receiver from TPS.

The comparison with the ISMR DWNI in a low latitude region has faced a difficulty, in the side of the ISMR, that impedes a reliable validation. Indeed, large fluctuations in the ISMR internal clock have been identified in several days during the validation period in 2023. When those fluctuations do not appear in a given day, the results show overall consistency between the RT tool and the ISMR output for the σ_φ index.

Beside the development of a tool for monitoring ionospheric scintillation in RT, one of the tasks of RT-WMIS was to asses whether the GD technique is able to be applied to low cost receivers (i.e. receivers with a cost around several hundreds of euros). This was done using several receivers placed in Barcelona, at gAGE/UPC premises and five additional UBLOX FP9 receivers located at low latitude regions in Africa and South America.

The results in the σ_φ parameter confirmed the feasibility of these receivers for measuring phase scintillation when scintillation is above of 0.1 rad. Something similar happens with the S4 parameter, where there is the handicap of the C/N0 resolution that makes that the low-cost receiver UBLOX FP9 requires a slightly larger threshold to detect scintillation reliably based on the S4 index. It has been found that S4 greater than 0.2 is sufficient in the UBLOX to consider a robust scintillation detection. Finally, the feasibility study has confirmed that the magnitude of scintillation indexes derived from the UBLOX measurements in low latitudes are similar to the values achieved by geodetic receivers processed in RT and located in surrounding regions. This was demonstrated in several regions, East and West Africa and South America.

Finally, one of the main findings of RT-WMIS has been the demonstration of the possibility of computing ROTI using data collected at one single frequency (for instance, ROTI at L1), instead the classic way based on building the GF combination of carrier phases. In this sense, we have shown that results obtained with ROTI at L1 are much more consistent than the ones from the classic way of computing ROTI. Using this capability, we have done a study for 10 receivers in different locations during 2024, characterizing the climatology of scintillation in different regions of the world during a year of maximum solar activity.

5. Conclusion

The RT-WMIS has been operational since April 14th 2023 onwards. Running continuously since then, with nearly 20 months of results accumulated. This has ensured a sufficiently long time period and a large amount of results to perform experimentation campaigns and analysis of the scintillation monitoring products. Moreover, some proposed improvements for a future upgraded version of the RT tool have emerged from that feedback.

From this experience, the main conclusion of the present activity has been the demonstration of the feasibility of an RT worldwide monitoring of ionospheric scintillation based on GNSS RT data streams from public networks of geodetic receivers operating at 1Hz. This achievement has been accomplished as planned, using RT data products currently available from gAGE/UPC.

Moreover, the realization of a similar monitoring service based on low-cost GNSS receivers like the Ublox-F9P or the Septentrio-Mosaic-X5 has been demonstrated to be feasible. Once RT data from such devices is available, it will be possible to incorporate the use of these mass-market receivers into the RT monitoring of scintillation, ultimately allowing a significant reduction in the cost of deploying new receivers for scintillation monitoring worldwide.

In parallel to the previous objectives, several monitoring tools were implemented. They can be considered as preliminary elements for developing, from the RT-WMIS, some warning service based on the scintillation indexes produced by the RT tool. These RT products include the amplitude and phase scintillation indexes, a robust ROTI from individual (uncombined) GNSS signals and a ionosphere-free index with potential use for monitoring the performance of the ionosphere-free combination used in precise positioning applications.

The demonstrated feasibility of the RT-WMIS allows to eventually provide warnings, with a low latency, about local/regional environments highly affected by scintillation or large perturbations in the ionosphere. It also allows to report information about the frequency of occurrence of scintillation or other related events affecting GNSS signals, like frequent cycle slips of a few centimeters linked to scintillation.

6. Future Work

It has been demonstrated the capability of extracting scintillation information in RT from tens of geodetic receivers distributed worldwide, and even from additional low-cost receivers that could be placed in areas of interest. Therefore, future work would be oriented to the development of a system targeted for providing a world-wide scintillation monitoring service with public access to interested users. Additionally, this system would provide concise information in the form of issued messages or visual plots about the intensity and levels of scintillation activity in different regions of the world.

In order to develop such a global system, it would be necessary to perform further research and improvements that enhance the performance of the current RT-WMIS implementation developed under this activity. Particularly to ensure the reliability of the products used for geodetic corrections. In this sense, a roadmap has been proposed in the final report for the adoption of this successfully demonstrated technology achievement.

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