Spatio-Temporal Analysis of Equatorial Ionospheric Scintillations in the Frame of Absolute GNSS Positioning Algorithms

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Spatio-Temporal characteristics of Ionospheric Scintillations may be exploited to build a more effective Stochastic Model.
Introduction

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Conclusions
The **Ionosphere** is a Plasma *ionised* by Solar Radiations and characterised by an electron density highly variable in **Space** and **Time**.

- UV
- X-Rays
- MeV protons
- CME’s
- Solar Winds
- Solar Flares

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![Diagram showing the layers of the atmosphere and the ionosphere](image-url)
The electron density of the Ionosphere is responsible for Refraction effects of GNSS radio signals

Ionospheric Delay

\[ n_I = \frac{c}{v} \approx 1 \pm \frac{40.3}{f^2} N_e \]

\[ l \approx \pm \frac{40.3}{f^2} \int_{r}^{s} N_e \, dl = \pm \frac{40.3}{f^2} sTEC \]
Small-Scale Irregularities in the electron density of the Ionosphere are responsible for Diffraction effects of GNSS radio signals.

Fluctuation of the GNSS signal phase

\[ \sigma_\phi = \sqrt{\langle \theta^2 \rangle - \langle \theta \rangle^2} \]

Fluctuation of the GNSS signal amplitude

\[ S_4 = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle} \]
Ionospheric Scintillations are rapid fluctuations of the signal phase and amplitude due to small-scale irregularities in the electron density of the Ionosphere.

- Fluctuation of the GNSS signal phase
  \[ \sigma_\phi = \sqrt{\langle \theta^2 \rangle - \langle \theta \rangle^2} \]

- Fluctuation of the GNSS signal amplitude
  \[ S_4 = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle} \]
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Our Research focuses on two main Absolute GNSS Positioning Algorithms: the **Standard Point Positioning** (SPP) and the **Precise Point Positioning** (PPP)

\[
P_r^S(t) = D_r^S + T_r^S + I_{r,k,m}^S + c(\Delta t^s - \Delta t_r) + M_{r,k,m}^S + \varepsilon_{r,k,m}^S
\]

\[
\phi_r^S(t) = D_r^S + T_r^S - I_{r,k,\phi}^S + c(\Delta t^s - \Delta t_r) + \lambda_k N_{r,k}^S + M_{r,k,\phi}^S + \varepsilon_{r,k,\phi}^S
\]

\[
P_{r,IF}(t) = D_r^S + T_r^S + c(\Delta t^s - \Delta t_r) + M_{r,IF,m}^S + \varepsilon_{r,IF,m}^S
\]

\[
\phi_{r,IF}(t) = D_r^S + T_r^S + c(\Delta t^s - \Delta t_r) + \lambda_{IF} N_{r,IF}^S + M_{r,IF,\phi}^S + \varepsilon_{r,IF,\phi}^S
\]
The **Precise Point Positioning** is very sensitive to Ionospheric Scintillations which may totally degrade its performances and reliability.

- **Code Pseudorange Noise Measurement**
- **Geometry**
- **Carrier Phase Noise Measurement**
- **Cycle Slips**
- **Loss of lock**
- **Ambiguity Resolution**
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GNSS signal scintillations show signs of Spatio-Temporal Dependence

INCO
047/14 16-Feb-2014

S4 [-]

Phi60 [rad]

UTC
GNSS signal scintillations show signs of **Spatio-Temporal Dependence**
Analysis

GNSS signal scintillations show signs of **Spatio-Temporal Dependence**

INCO
047/14  16-Feb-2014

N
0°
30°
60°

W
E
S

UTC

S4
[-]

00h 01h 02h 03h

Phi60
[rad]
The Ionospheric Scintillation GNSS Survey needs to be densified in order to perform a proper Spatio-Temporal Analyse.
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Spatial Autocorrelation can be detected and quantified by using specific SAC indices

Moran’s I

\[ I = \frac{N}{\Sigma_i \Sigma_j w_{ij}} \frac{\Sigma_i \Sigma_j w_{ij} (v_i - \bar{v})(v_j - \bar{v})}{\Sigma_i (v_i - \bar{v})^2} \]

Geary’s C

\[ C = \frac{(N - 1)}{2 \Sigma_i \Sigma_j w_{ij}} \frac{\Sigma_i \Sigma_j w_{ij} (v_i - v_j)^2}{\Sigma_i (v_i - \bar{v})^2} \]

Hypothesis Test

\[ H_0: \text{The situation is the result of a stationary point process, i.e. there is no significative spatial dependency.} \]
Spatial Autocorrelation can be detected and quantified by using specific SAC indices

Moran’s I

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Geary’s C

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\[ v_{i} = S4_{i} \]

\[ w_{ij} = \frac{1}{d_{ij}} \]

Geary’s C

\[ C = \frac{(N - 1)}{2 \sum_{i} \sum_{j} w_{ij}} \frac{\sum_{i} \sum_{j} w_{ij} (v_{i} - v_{j})^2}{\sum_{i} (v_{i} - \overline{v})^2} \]

Hypothesis Test

Ho: The situation is the result of a stationary point process, i.e. there is no significant spatial dependency.
The **Global Spatial Autocorrelation** inside the data set is **Significative** only during the occurrence of **Ionospheric Scintillations**.
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• We developed a methodology in order to exploit the availability of Multi-GNSS observations from an ISMR Network for the Spatio-Temporal Analysis of Ionospheric Scintillations (based only on GNSS Measurements).

• By using this methodology, we lead a first analysis of the Spatial Dependency of Ionospheric Scintillation Observations. We measured the Spatial Autocorrelation of the $S_4$ observable and showed it was clearly significative but only in the presence of (strong) Ionospheric Scintillations, supporting a possible spatial interpolation at these times.

• We will extend the Spatio-Temporal Analysis to other parameters.

• We will perform a Local Spatial Autocorrelation Test to locate and determine the scale of the detected « hot spots ».

• We will implement specific Spatial Interpolation Techniques to produce a « Scintillation Sky Map ».

• We will integrate the Spatio-Temporal Analysis in the PPP algorithm.
Acknowledgements

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• SPP and PPP Positions were computed by using the gLAB software developed by the gAGE group of the Technical University of Catalonia (UPC).
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