Satellite Positioning
Performances under Ionospheric Scintillations

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Thesis Committee
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Geomatics Unit, ULg
Introduction
Objectives
Research
Conclusions
Perspectives
The **Ionosphere** is Ionized by Solar Radiation

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

**Introduction – Ionosphere**

![Diagram showing atmospheric layers and solar radiation interaction](image-url)
GNSS Signals are refracted by the Ionosphere

Introduction – Ionosphere

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

\[ l \approx \pm \frac{40.3}{f^2} \int_r^s N_e \, dl = \pm \frac{40.3}{f^2} sTEC \]
GNSS Signals are refracted by the Ionosphere

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

\[ l \approx \pm \frac{40.3}{f^2} \int_{r}^{s} N_e \, dl = \pm \frac{40.3}{f^2} \text{sTEC} \]
GNSS Signals are diffracted by the Ionosphere

- Ionospheric Electron Density Irregularities
- Spatial Variation of the Refraction Index
- Signal Losses
- Signal Diffraction
- Constructive and Destructive Signal Interferences
GNSS Signals are **diffracted** by the Ionosphere

- Ionospheric Electron Density
- Diffraction Pattern
- Received Signal Intensity
Ionospheric Electron Density Irregularities are involved by **Geomagnetic Storms**

*Van Allen radiation belts*
Geomagnetic Storms can be detected by global **Geomagnetic Indices**

Introduction – Ionosphere
Geomagnetic Storms can be detected by global Geomagnetic Indices

Halloween Storm
302/03  29-Oct-2003

Introduction – Ionosphere
Ionospheric Electron Density Irregularities involve GNSS Signal Phase and Amplitude fluctuations.
Ionospheric Scintillation Effects on GNSS Signals are Monitored by Scintillation GNSS Receivers

Ionospheric Scintillation Monitoring Receiver - ISMR

*\[ S_4 = \sqrt{\langle I^2 \rangle - \langle I \rangle^2} \]

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

High Data Rate (≈ 50-100 Hz)
ISMR Files
Space Weather

Specific Observables
- \( S_4 \)
- \( \Phi_60 \)
- ...

Low Data Rate (≈ 0.01 - 1 Hz)
Positioning
RINEX Files

Classic Observables
- C1C
- L1C
- D1C
- S1C
- ...

Introduction – Ionosphere
Ionospheric Scintillations exhibit **Spatial** and **Temporal** Characteristics

- Operating Frequencies
- Geographic Locations
- Local Time
- Season
- Magnetic Activity
- Solar Activity

Introduction – Ionosphere
Ionospheric Scintillations exhibit **Spatial and Temporal Characteristics**

- Large Scale Irregularities ≈ 100 km
- Small Scale Irregularities ≈ 1 – 100 m
- Background Plasma Drift Speed ≈ 50-150 ms⁻¹
- Duration ≈ minutes/hours

Spatiotemporal Variations of Scintillations Intensity
Satellite Positioning is based on **Multilatervation**

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

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

\[ I_{r,k}^s = \frac{40.3}{f^2} \text{sTEC} \]

\[ D_r^s = \sqrt{(X^s - X_r)^2 + (Y^s - Y_r)^2 + (Z^s - Z_r)^2} \]

\[ \varepsilon_{r,k,m}^s \quad \varepsilon_{r,k,\phi}^s \]

\[ N_{r,k}^s \]
The **Standard Point Positioning** is an elementary SF Technique

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

\[ D_r^s = \sqrt{(X_r^s - X_r)^2 + (Y_r^s - Y_r)^2 + (Z_r^s - Z_r)^2} \]

Pseudorange (code) measurements

Single Frequency

Single Point Single Epoch (SPSE) Technique

Real-Time / Post-Processing

Static / Kinematic

Atmospheric Models (Ionosphere and Troposphere)

Broadcast Ephemeris

Least Square Adjustment (LSA) to resolve unknowns
The **Standard Point Positioning** is an elementary SF Technique
The **Precise Point Positioning** is an advanced DF Technique

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

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

- Pseudorange (code) and Carrier-Phase measurements
- Ambiguity Resolution Process
- Dual Frequency
- Real-Time / Post-Processing
- Static / Kinematic
- Strategies against atmospheric effects
- Precise Products: Ephemeris / Code-Phase Delays / Antenna
- Sequential Least Squares Adjustment (Filter)
The **Precise Point Positioning** is an advanced DF Technique

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

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

Mathematical Model: Ionosphere-Free + Precise Products

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

\[
\phi_{r,IF}^s(t) = D_r^s + T_r^s + c(\Delta t^s - \Delta t_r) + \lambda_{IF} N_{r,IF}^s + M_{r,IF,\phi}^s + \varepsilon_{r,IF,\phi}^s
\]

Stochastic Model

Solution: Sequential Least Square Adjustment (Filter)
The Precise Point Positioning is an advanced DF Technique

Introduction – Positioning
The Precise Point Positioning is highly sensitive to Ionospheric Scintillations Effects
The **Precise Point Positioning** is highly sensitive to Ionospheric Scintillations Effects
Introduction

Objectives

Research

Conclusions

Perspectives
The Project aims to develop new Strategies to mitigate the impact of Ionospheric Scintillations on Satellite Positioning

- Softwares
  - Development of Scintillation Analysis Tools
  - Adaptation of existing softwares
- Analysis
- Stochasticity
- Geometry
- Preprocessing
The Project aims to develop new Strategies to mitigate the impact of Ionospheric Scintillations on Satellite Positioning

- Softwares
- Analysis
  - Statistical Analysis of Scintillation Effects
  - Symptomatic Analysis of Scintillation Effects
- Stochasticity
- Geometry
- Preprocessing
The Project aims to develop new **Strategies** to mitigate the impact of **Ionospheric Scintillations** on **Satellite Positioning**

**Softwares**

**Analysis**

**Stochasticity**

**Geometry**

**Preprocessing**

- **Stochastic Model Improvement**
- **Spatial/Empirical Approach**
- **Correlations Assessment between Observables**
- **Correlations Assessment between Satellites**
- **Validation on SPP and PPP**
- **Validation on different Scintillations Types**
  - Equatorial and Polar Scintillations
  - Weak/Moderate/Intense Scintillations
The Project aims to develop new Strategies to mitigate the impact of Ionospheric Scintillations on Satellite Positioning

Softwares

Analysis

Stochasticity

Geometry

→ Analysis of Geometric Effects of Scintillations

Preprocessing
The Project aims to develop new **Strategies** to mitigate the impact of **Ionospheric Scintillations** on **Satellite Positioning**

- **Softwares**
- **Analysis**

**Stochasticity**

- **Geometry**
- **Preprocessing** → **Validation of a Cycle Slips Treatment Method**
Introduction

Objectives

Research

Conclusions

Perspectives
Introduction

Objectives

Research

Conclusions

Perspectives

Softwares

Analysis

Stochasticity

Geometry

Preprocessing
gLAB is a SPP and PPP Software for Scientific Purposes

ESA/gAGE (UPC)
GNSS Data Processing Tool
GNSS Data Analysis Tool
Support
Multipurpose
Scientific
Professional
Educational
gLAB can be coupled with a Matlab Environment Programming

Data Downloading
SPP and PPP Processing – Parameters?
Data Files Reading
Specific Treatments
Results Visualisations
Graphic Tools: IPP Maps and Skyplots
Introduction

Objectives

Conclusions

Perspectives

Research

Softwares

Analysis

Stochasticity

Geometry

Preprocessing
Ionospheric Scintillation Monitoring Receivers (ISMR) Network

Septentrio and Novatel ISMR

± 2010  
± 2011  ISMR 60"
± 2012  RINEX 30”
Severe Geomagnetic Storms occur under High Solar Activity
Geomagnetic Storms still occur under Moderate Solar Activity
Ionospheric Scintillations occur under Moderate Solar Activity
The **Analysis Strategy** is based on the Selection of 5 typical Days.
The **Analysis Strategy** is based on specific Criteria

<table>
<thead>
<tr>
<th>Multi Station Approach</th>
<th>Single Station Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low/High Magnetic Activity</td>
<td><strong>Occurrence: Measurements and Epochs</strong></td>
</tr>
<tr>
<td>Positioning: SPP and PPP</td>
<td><strong>Geometry: Satellite Number and Dilution of Precision</strong></td>
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The **Analysis Strategy** is based on specific Criteria

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Ionospheric Scintillations affect a very Small Portion of the Measurements
Ionospheric Scintillations affect a Significant Portion of the Observation Epochs
Ionospheric Scintillations affect a Significant Portion of the Observation Epochs
Ionospheric Scintillations affect a Significant Portion of the Observation Epochs
Ionospheric Scintillations affect a Significant Portion of the Observation Epochs

Results – Analysis
Ionospheric Scintillations affect a Significant Portion of the Observation Epochs
The **Analysis Strategy** is based on specific Criteria

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SPP and PPP Techniques are affected differently by Ionospheric Scintillations Effects

Results – Analysis
SPP and PPP Techniques are affected differently by Ionospheric Scintillations Effects

Brønnøysund
350/12  15-Dec-2012
SPP and PPP Techniques are affected differently by Ionospheric Scintillations Effects

Results – Analysis

- 30 %
+ 380 %
SPP and PPP Techniques are affected differently by Ionospheric Scintillations Effects

Results – Analysis
The **Analysis Strategy** is based on specific Criteria

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Ionospheric Scintillations Decrease the Satellite Geometry
Ionospheric Scintillations Decrease the Satellite Geometry
Ionospheric Scintillations Increase the Dilution of Precision
The **Analysis Strategy** is based on specific Criteria

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High Phi60 values are frequently observed at High Latitudes
Ionospheric Scintillations: a Spatio-Temporal Phenomenon
Ionospheric Scintillations: a Spatio-Temporal Phenomenon
Ionospheric Scintillations: a Spatio-Temporal Phenomenon
Ionospheric Scintillations: a Spatio-Temporal Phenomenon

Results – Analysis

Brønnøysund
130/12  09-Mai-2012  20h00-24h00
The **Analysis Strategy** is based on specific Criteria

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Ionospheric Scintillations involve **Cycle Slips**
Ionospheric Scintillations involve **Cycle Slips**

**Brønnøysund**
287/12  13-Oct-2012

<table>
<thead>
<tr>
<th>KP</th>
<th>00h</th>
<th>03h</th>
<th>06h</th>
<th>09h</th>
<th>12h</th>
<th>15h</th>
<th>18h</th>
<th>21h</th>
<th>24h</th>
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</table>

- **Satellites**: 6/10
- **Cycle Slips**: 4/6  + 186%

Legend:
- < 0.25
- [0.25 - 0.4]
- [0.4 - 0.5]
- > 0.55
The **Analysis Strategy** is based on specific Criteria.

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</table>
High Phi₆₀ values do not seem to be correlated with Noise Measurement

Brønnøysund
287/12  13-Oct-2012
## Analysis: Single Station Approach Summarize

<table>
<thead>
<tr>
<th></th>
<th>Quiet</th>
<th>Intense</th>
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<tbody>
<tr>
<td>Occurrence</td>
<td></td>
<td>Phi60 / S4</td>
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<tr>
<td>Positions</td>
<td></td>
<td>SPP/PPP</td>
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<tr>
<td>Geometry</td>
<td></td>
<td>Main Scintillations Trouble</td>
</tr>
<tr>
<td>Cycle Slips</td>
<td></td>
<td>Cycle Slips Repair</td>
</tr>
<tr>
<td>Locations</td>
<td></td>
<td>Spatial Distribution</td>
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<tr>
<td>Noise</td>
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**Occurrence: Measurements and Epochs**

**Positioning: SPP and PPP**

**Geometry: Satellite Number and Dilution of Precision**

**Spatial Characteristics**

**Cycle Slips**

**Noise Measurement**
Ionospheric Scintillation Monitoring Receivers (ISMR) Network

Septentrio and Novatel ISMR

± 2010 RINEX 30"
± 2011 ISMR 60"
± 2012

Results – Analysis
The Occurrence of Ionospheric Scintillations clearly depends on the **Geographic Latitude**.
The Occurrence of Ionospheric Scintillations clearly depends on the Geographic Latitude.
The Occurrence of Ionospheric Scintillations clearly depends on the Geographic Latitude.
The Occurrence of Ionospheric Scintillations clearly depends on the **Geographic Latitude**
SPP and PPP Techniques are affected differently by Ionospheric Scintillations according to Geographic Latitude
Satellite Geometry Quality is affected differently by Ionospheric Scintillations according to Geographic Latitude
Satellite Geometry Quality is affected differently by Ionospheric Scintillations according to Geographic Latitude.
Ionospheric Scintillations concern only High Latitude Ionospheric Pierce Point
## Analysis: Multi Station Approach Summarize

<table>
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<th></th>
<th>Brønnøysund</th>
<th>Cyprus</th>
<th>Lerwick</th>
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Satellite Positioning is Resolving a Problem with several unknowns and equations

Mathematic Model

Stochastic Model

Resolution Process
Satellite Positioning is Resolving a Problem with several unknowns and equations

Mathematic Model

Stochastic Model

Resolution Process

\[
\begin{align*}
P_{r,IF}^s(t) &= D_r^s + T_r^s + \ldots \\
\phi_{r,IF}^s(t) &= D_r^s + T_r^s + \ldots \\
P_{r,IF}^s(t) &= D_r^s + T_r^s + \ldots \\
\phi_{r,IF}^s(t) &= D_r^s + T_r^s + \ldots \\
\ldots
\end{align*}
\]
Satellite Positioning is Resolving a Problem with several unknowns and equations

Mathematic Model

Stochastic Model

Resolution Process →

lsa adjustment
kalman filter
...

Results – Stochasticity
Satellite Positioning is resolving a problem with several unknowns and equations.

Mathematic Model

Stochastic Model

Resolution Process

\[ \Sigma = \begin{pmatrix} \sigma_1^2 & \sigma_{12} & \cdots & \sigma_{1n} \\ \sigma_{21} & \sigma_2^2 & \cdots & \sigma_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{n1} & \sigma_{n2} & \cdots & \sigma_n^2 \end{pmatrix} \]
Satellite Positioning is Resolving a Problem with several *unknowns* and *equations*.

**Mathematic Model**

**Stochastic Model**

**Resolution Process**

\[ \Sigma = \begin{pmatrix} 1 & 0 & \ldots & 0 \\ 0 & 1 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & 1 \end{pmatrix} \]
Satellite Positioning is Resolving a Problem with several unknowns and equations.

Mathematic Model

Stochastic Model

Resolution Process

\[ \Sigma = \begin{pmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_n^2 \end{pmatrix} \]
Satellite Positioning is Resolving a Problem with several unknowns and equations

Mathematic Model

Stochastic Model

Resolution Process

\[ \Sigma = \begin{pmatrix} \sigma_1^2 & \sigma_{12} & \ldots & \sigma_{1n} \\ \sigma_{21} & \sigma_2^2 & \ldots & \sigma_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ \sigma_{n1} & \sigma_{n2} & \ldots & \sigma_n^2 \end{pmatrix} \]

Spatial Approach
Empirical Approach
First Law of Geography...

“Everything is related to everything else, but near things are more related than distant things.”

Waldo Tobler
The «Spatial Strategy» relies on the fact there exists some Spatial Autocorrelation in Scintillations Observations

1. Spatial Autocorrelation Test

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

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

\[ v_i = SIC_i \]
The «Spatial Strategy» relies on the fact there exists some Spatial Autocorrelation in Scintillations Observations.

1. Spatial Autocorrelation Test
The «**Spatial Strategy**» relies on the fact there exists some Spatial Autocorrelation in Scintillations Observations.

1. Spatial Autocorrelation Test
2. Covariance Function

*Description of the Spatial Covariance of a random Variable process*
The «Spatial Strategy» relies on the fact there exists some Spatial Autocorrelation in Scintillations Observations.

1. Spatial Autocorrelation Test
2. Covariance Function
The «Spatial Strategy» relies on the fact there exists some Spatial Autocorrelation in Scintillations Observations

1. Spatial Autocorrelation Test
2. Covariance Function
The «Spatial Strategy» relies on the fact there exists some Spatial Autocorrelation in Scintillations Observations

1. Spatial Autocorrelation Test
2. Covariance Function
3. RNX vs. ISMR

Variable?
Time Correlation?
Multi-receiver?
Mapping Function?
Scintillation Level?
Time Sampling?
Polar / Equatorial Scintillations?
The « **Empirical Strategy** relies on Observations whatever their Locations

\[
\Sigma_t = \begin{pmatrix}
\sigma_1^2 & \sigma_{12} & \ldots & \sigma_{1n} \\
\sigma_{21} & \sigma_2^2 & \ldots & \sigma_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\sigma_{n1} & \sigma_{n2} & \ldots & \sigma_n^2
\end{pmatrix}
\]
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Preprocessing
Ionospheric Scintillation involve Satellite Signal Losses

\[ \sigma_{POS} = DOP \times \sigma_p \]
Ionospheric Scintillation increase the Dilution of Precision

Results – Geometry

Brønnøysund
287/12 13-Oct-2012

KP
Satellites
PDOP

9 satellites
9 satellites

< 0.25
[ 0.25 – 0.4 [ [ 0.4 – 0.55 [ > 0.55
The Dilution of Precision depends on the amount and the Spatial Distribution of Tracked Satellites

PDOP = 10.79

PDOP = 2.58
A Conical Satellite Geometry drives the DOP to Infinite Values

\[ x = -(A^T PA)^{-1} A^T PW \]
\[ \sum_{\chi} = (A^T A)^{-1} \sigma_p^2 = N^{-1} \sigma_p^2 = Q_\chi \sigma_p^2 \]

\[ \sigma_{POS} = DOP \times \sigma_p \]

\[ Q_\chi = N^{-1} = (A^T A)^{-1} \]

Any linear dependence?
A Conical Satellite Geometry drives the DOP to Infinite Values
A Conical Satellite Geometry drives the DOP to Infinite Values

PDOP = 10.79

PDOP = 2.58
A Conical Satellite Geometry drives the DOP to Infinite Values

PDOP = 4.39
A Conical Satellite Geometry drives the DOP to Infinite Values

PDOP = 152.05
Cycle Slip Detection/Repair is a real need for Precise Positioning Technique

\[
\phi_r^S(t) = D_r^S + T_r^S - I_{r,k,\phi}^S + c(\Delta t^S - \Delta t_r) + \lambda_k N_{r,k}^S + M_{r,k,\phi}^S + \varepsilon_{r,k,\phi}^S
\]
The availability of Three Frequencies makes the CS Detection more efficient.

Validation of the Detection under IS
Development of a Correction Method
Adaptation to PPP
Observable Noise Assessment could help to define the Stochastic Model (« Empirical Strategy »)

![Graph showing time differencing and polynomial fitting](image-url)
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Softwares

Analysis

$\quad Symptomatic\ Analysis\ for\ a\ HL\ Station$

Methodology

Equatorial Scintillations?

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**Stochasticity** → *Spatial / Empirical Strategies*

Geometry

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Softwares

Analysis

**Stochasticity**

Geometry

Preprocessing

→ *Illustration of Geometric Problems*
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Preprocessing \(\rightarrow\)  
*CS Detection Method*  
*Validation of CS Detection for IS*  
*Development of CS Repair Technique*
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**Perspectives**

**Introduction**

**State of the Art**

**Analysis**
- Versioning
- Python learning
- C learning
- Global Approach
- Global Design
- Adapations
- Stochastic Model
- Preprocessing
- Mathematic Model
- Weigthing Scheme
- Automatisation
- Stoch. Matlab Module
- Matlab routines
- Matlab mapping TB
- Matlab exe
- GIS software

**Stochasticity**
- Spatial Approach
  - ACS Study (Index)
  - ACS Study (covar.)
  - Corr. Observables
  - Index (RXN)
  - Spatial Interpolation
  - Covariance
- Empirical Approach
  - Filter Construction
- Tests

**Preprocessing**
- CS Detection
  - TQ DF+TF
  - Filter Parameters
  - Validation DF+TF

**Geometry**
- Conical Theory
- M-GNSS
- Validation?

**Conclusions**

**Timeline**
- Jun13
- Jul13
- Aug13
- Sep13
- Oct13
- Nov13
- Dec13
- Jan14
- Feb14
- Mar14
- Apr14
- May14
- Jun14
- Jul14
- Aug14
- Sep14

- **Analysis**
- **Preprocessing**
- **Geometry**
- **Softwares**

- **Publication**
- **Conference**
- **Finalization**

- Short Stay in Nottingham?
Satellite Positioning
Performances under Ionospheric Scintillations

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