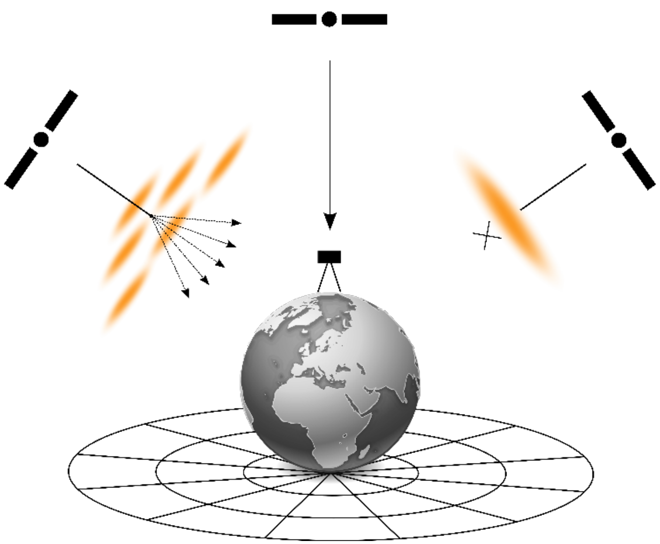
Ingestion of Ionospheric Scintillation Skymaps into GNSS Algorithms



Matthieu Lonchay

PhD Defense

ULiège

Friday 24 May 2019

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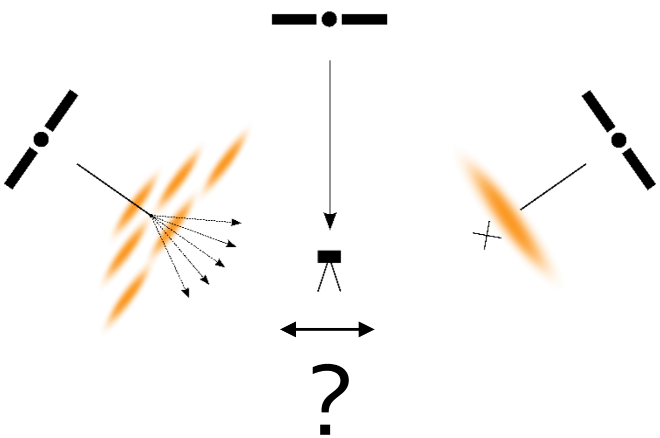

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Analysis

GNSS Algorithms and Ionosphere

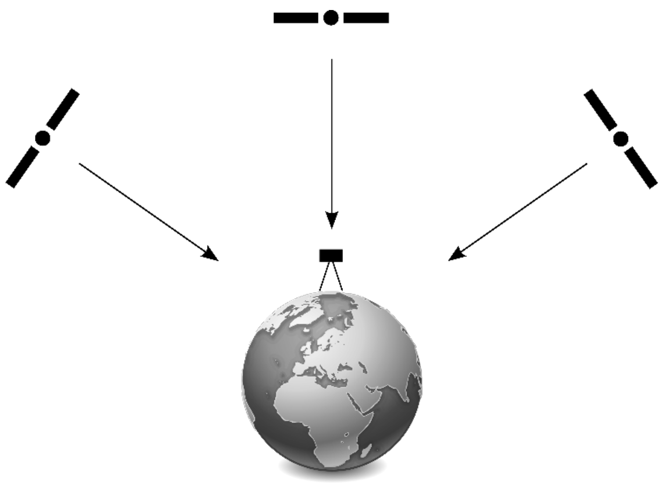
Geostatistics

Ionospheric Scintillation Skymaps

Prototypes

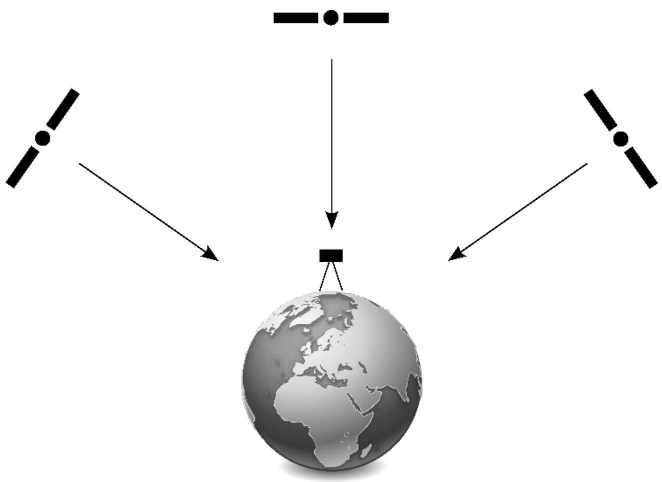
Mitigation Strategies

GNSS positioning is based on the principle of multilateration between a GNSS receiver and several GNSS satellites orbiting the Earth



GNSS positioning is based on the principle of multilateration

GNSS algorithms exploit code pseudorange and carrier phase measurements performed on several frequencies in order to estimate the instantaneous navigation solution of the receiver



GNSS algorithms exploit code pseudorange and carrier phase measurements related to several frequencies

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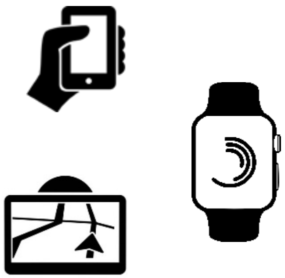
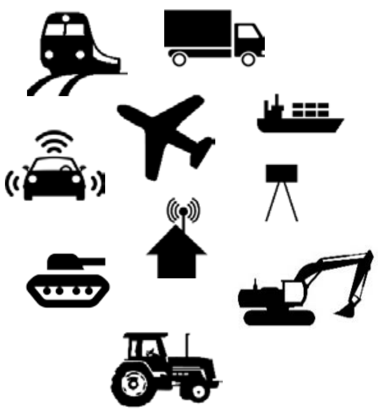


GNSS algorithms exploit code pseudorange and carrier phase measurements related to several frequencies

The Standard Point Positioning (SPP) algorithm is based on single-frequency code pseudorange measurements

- Light implementation
- Least-squares adjustment
- Precision of 5 m-10 m

GNSS algorithms exploit code pseudorange and carrier phase measurements performed on several frequencies in order to estimate the instantaneous navigation solution of the receiver



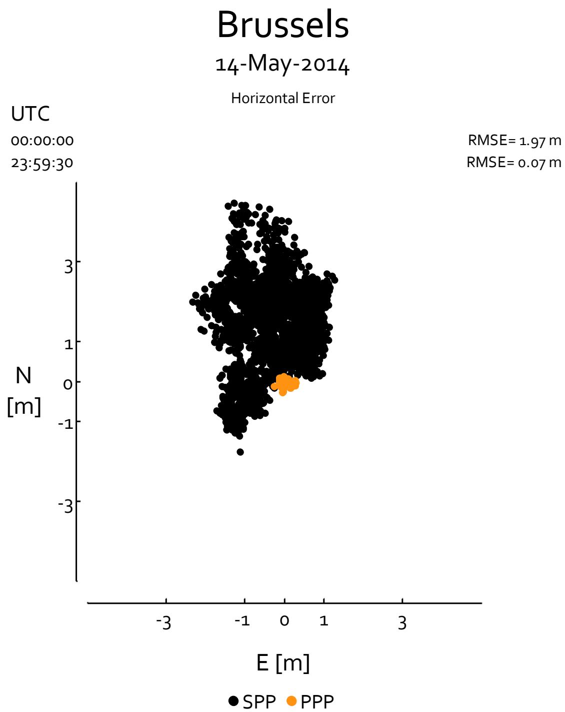
GNSS algorithms exploit code pseudorange and carrier phase measurements related to several frequencies

The Standard Point Positioning (SPP) algorithm is based on single-frequency code pseudorange measurements

The Precise Point Positioning (PPP) algorithm is based on dual-frequency code pseudorange and carrier phase measurements combined with regional and global corrections

- Complex implementation
- Corrections required from a provider
- Kalman filter
- **Initial integer ambiguities to estimate**
- **Centimetre-decimetre precision level**

GNSS algorithms exploit code pseudorange and carrier phase measurements performed on several frequencies in order to estimate the instantaneous navigation solution of the receiver



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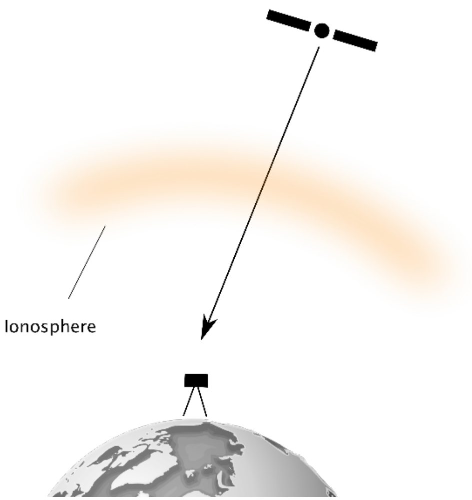
The ionosphere is the part of the upper atmosphere of the Earth where sufficient ionisation can exist to affect the propagation of radio waves



The ionosphere is responsible for refraction effects on GNSS signals which result in delays to be considered in the mathematical model of GNSS algorithms

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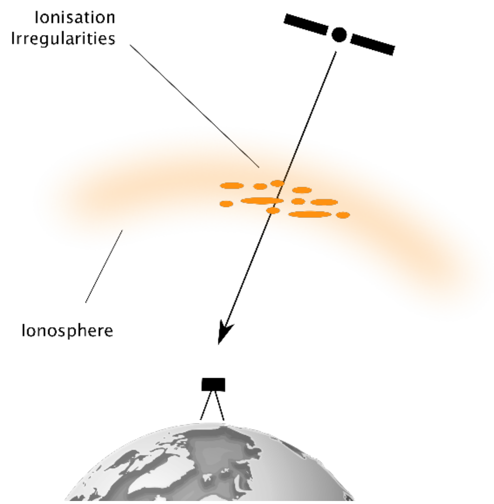

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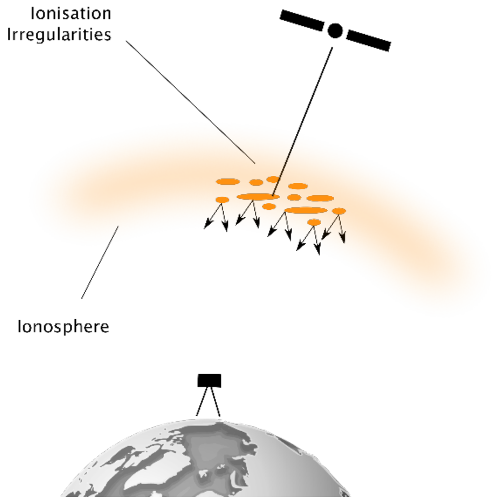

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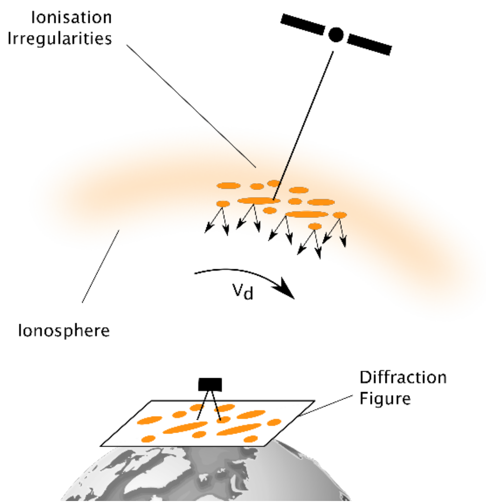
Small-scale irregularities in the ionospheric free-electron density involve diffraction and scattering effects of GNSS signals

Small-scale irregularities in the ionospheric free-electron density cause diffraction and scattering effects on GNSS signals leading to rapid fluctuations of the amplitude and phase of the signals



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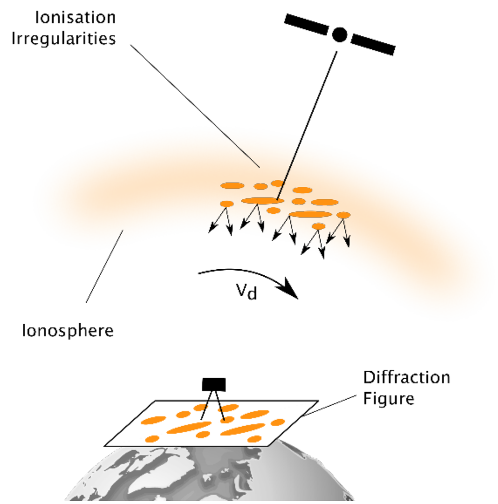
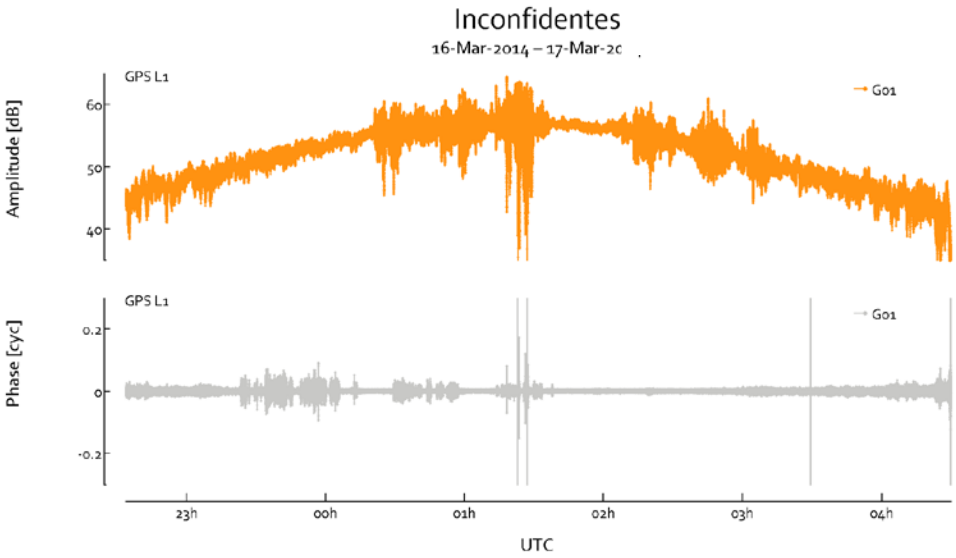
Small-scale irregularities in the ionospheric free-electron density involve diffraction and scattering effects of GNSS signals

Scattered signals reach the receiver via multiple paths resulting in a diffraction pattern with destructive and constructive interferences of the scattered signals

Intense ionospheric scintillations of GNSS signals severely threaten GNSS positioning performances and can make GNSSs totally in inoperable





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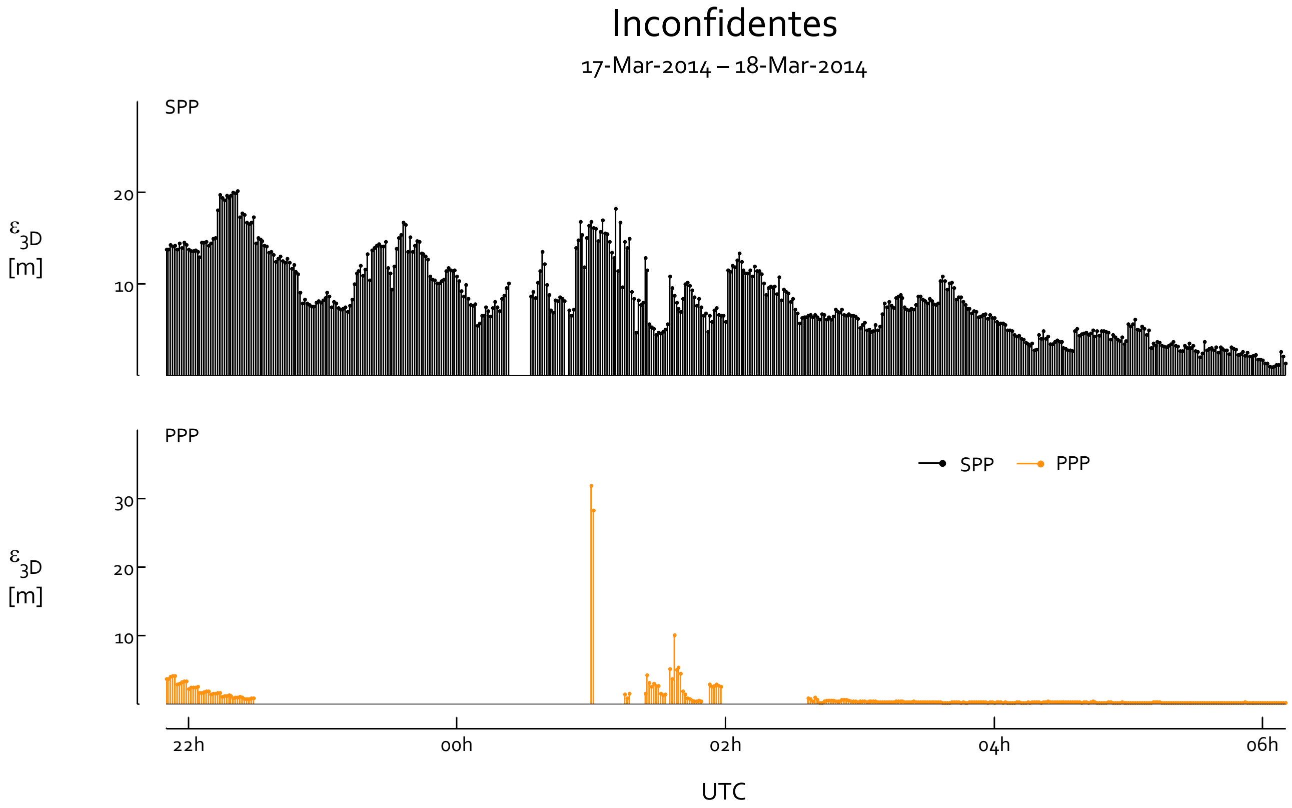

Analysis
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Geostatistics
Ionospheric Scintillation Skymaps

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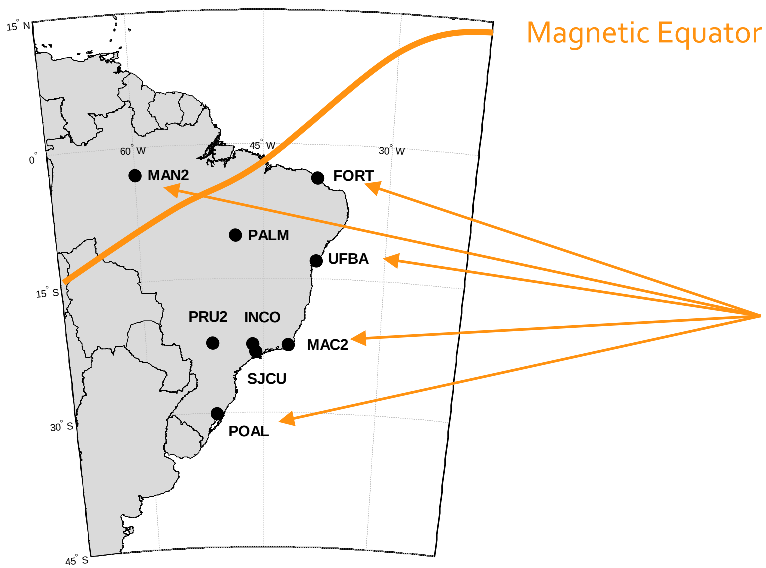
A network of Ionospheric Scintillation Monitoring Receivers (ISMRs) located in Brazil is exploited to generate high-density ionospheric scintillation skyplots



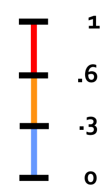
Ionospheric

Scintillation

Monitoring

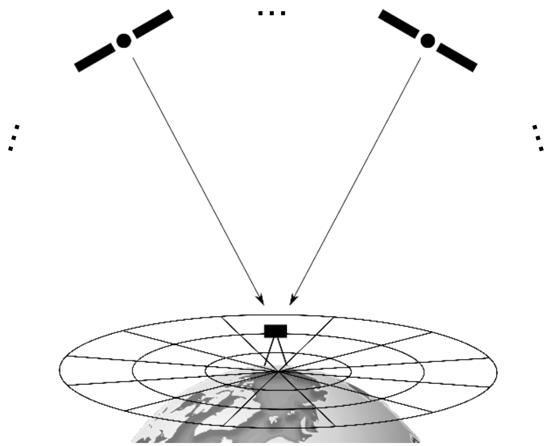
Receiver

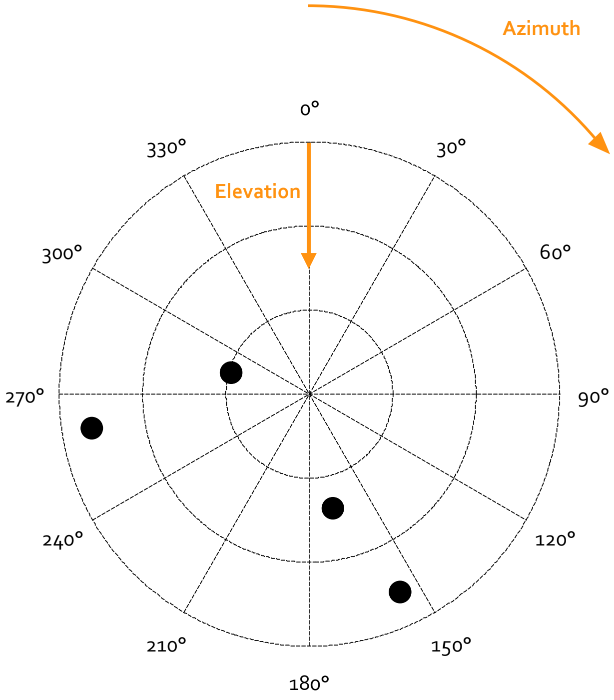
$$S_4 = \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}}$$



Each station of the network is equipped with an ISMR to monitor low-latitude ionospheric scintillations

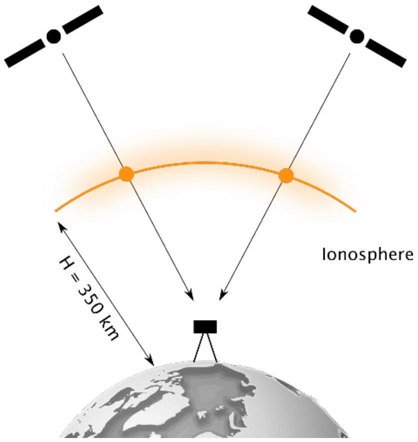
A network of Ionospheric Scintillation Monitoring Receivers (ISMRs) located in Brazil is exploited to generate high-density ionospheric scintillation skyplots





A skyplot is a specific type of map resulting from the projection of the satellite locations from the satellite hemisphere (horizontal coordinates) to a plane centred on the user's location

A network of Ionospheric Scintillation Monitoring Receivers (ISMRs) located in Brazil is exploited to generate high-density ionospheric scintillation skyplots



Ionospheric Pierce Points (IPPs) associated to satellite-receiver lines of sight related to a network of ISMRs can be exploited to generate high-density skyplots

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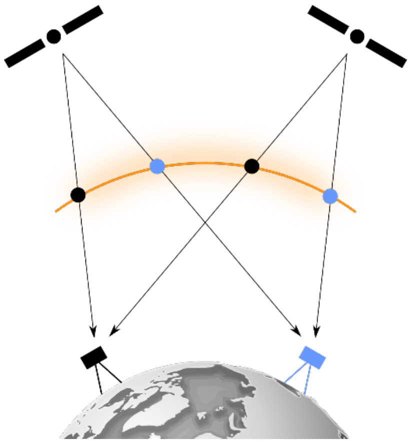

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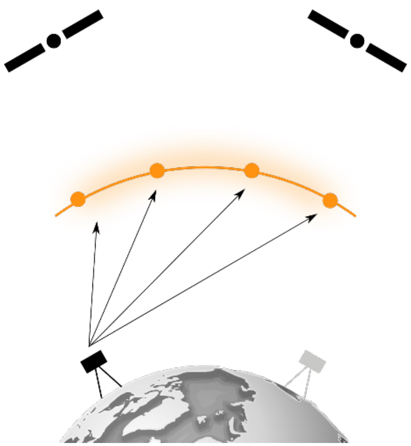
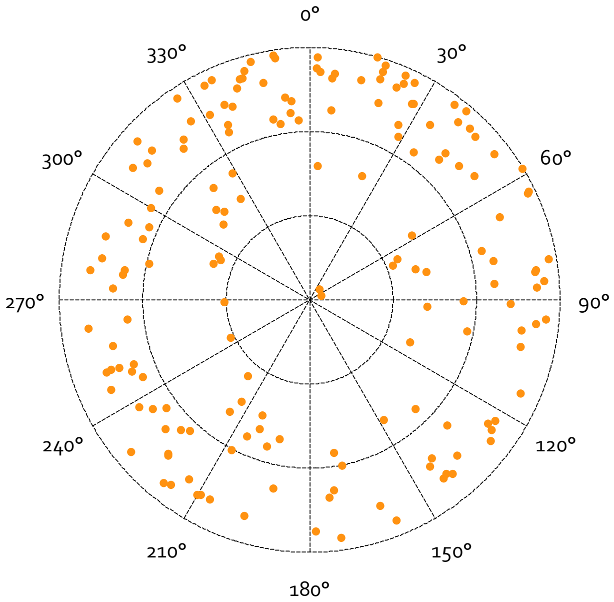




Ionospheric Pierce Points (IPPs) associated to satellite-receiver lines of sight related to a network of ISMRs can be exploited to generate high-density skyplots

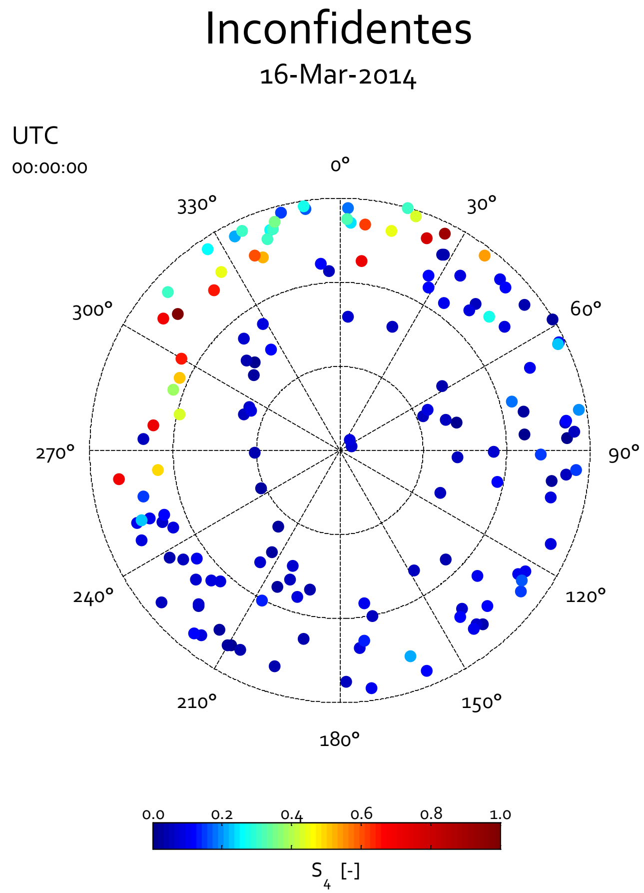
A network of Ionospheric Scintillation Monitoring Receivers (ISMRs) located in Brazil is exploited to generate high-density ionospheric scintillation skyplots

Geometric Component

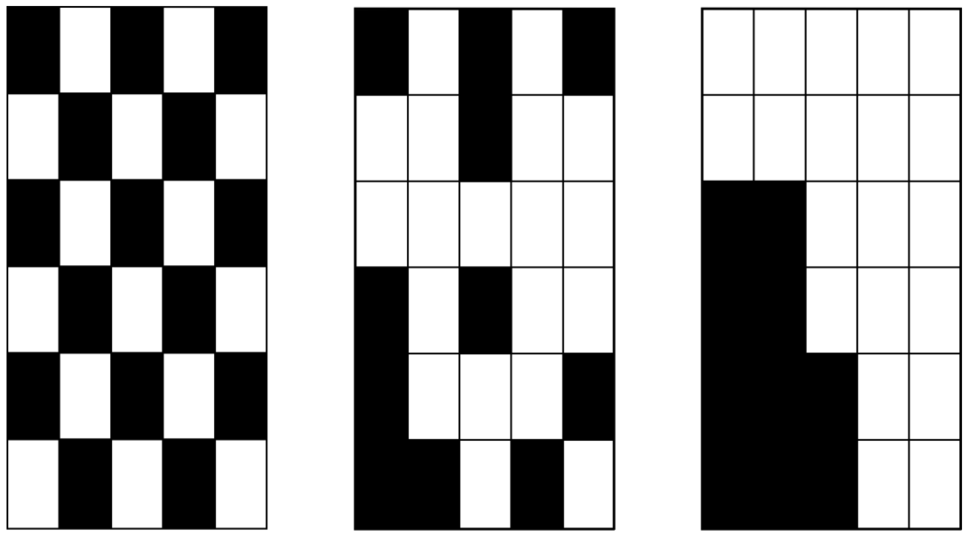
The locations of the IPPs depend on the GNSS orbits and the geographic coordinates of the user's location

Attribute Component

The values of the S_4 index for every IPP depends on the instantaneous state of the ionosphere



Spatial Autocorrelation constitutes a measure of how similar are nearby objects



Negative SAC Neutral SAC Positive SAC

Positive SAC is essential to compute interpolated maps

Detection → Scaling → Tracking

Spatial Autocorrelation indices can be calculated and statistically tested to **detect** the presence of significantly positive spatial autocorrelation in a given scatter plot

Moran's I Index

$$I = \frac{N}{S_0} \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} \, (z_i - \bar{z})(z_j - \bar{z})}{\sum_{i=1}^{N} z_i^2}$$

Geary's C Index

$$C = \frac{(N-1)}{2\, S_0} \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} \, (z_i - z_j)^2}{\sum_{i=1}^{N} (z_i - \bar{z})^2}$$

Getis-Ord General G Statistic

$$G = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} \, z_i \, z_j}{\sum_{i=1}^{N} z_i \, z_j}$$

$$S_0 = \sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij}$$

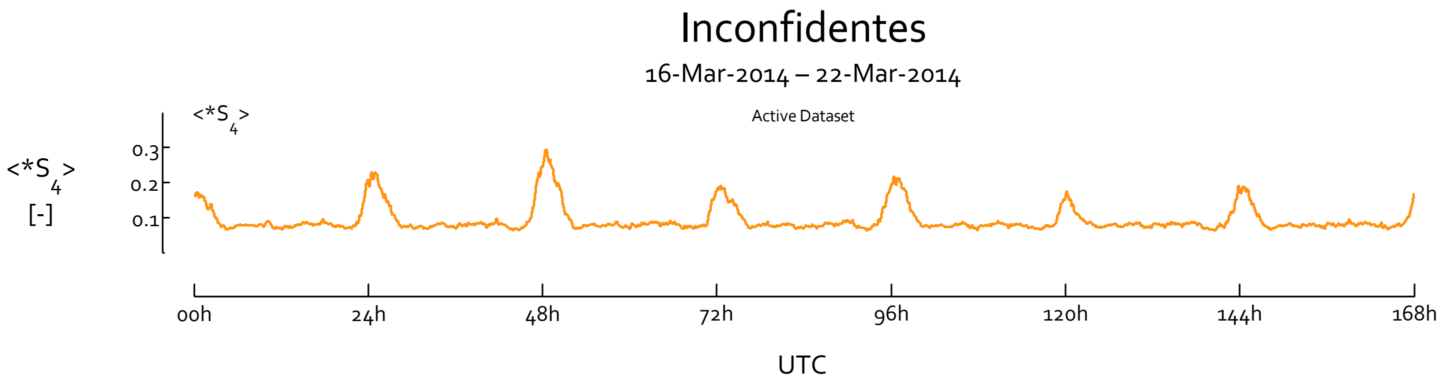
$$w_{ij} = \begin{cases} \frac{1}{d_{ij}^2}, & i \neq j \\ 0, & i = j \end{cases}$$

SAC indices are based on the geometric and attribute components of Ionospheric Scintillation Skyplots

SAC indices consider all possible pairs of entities

SAC indices are based on a weight function based on the interdistance related to each pair of entities

Ionospheric scintillation skyplots show significantly positive spatial autocorrelation during active ionospheric scintillation conditions at the station of Inconfidentes, Brazil



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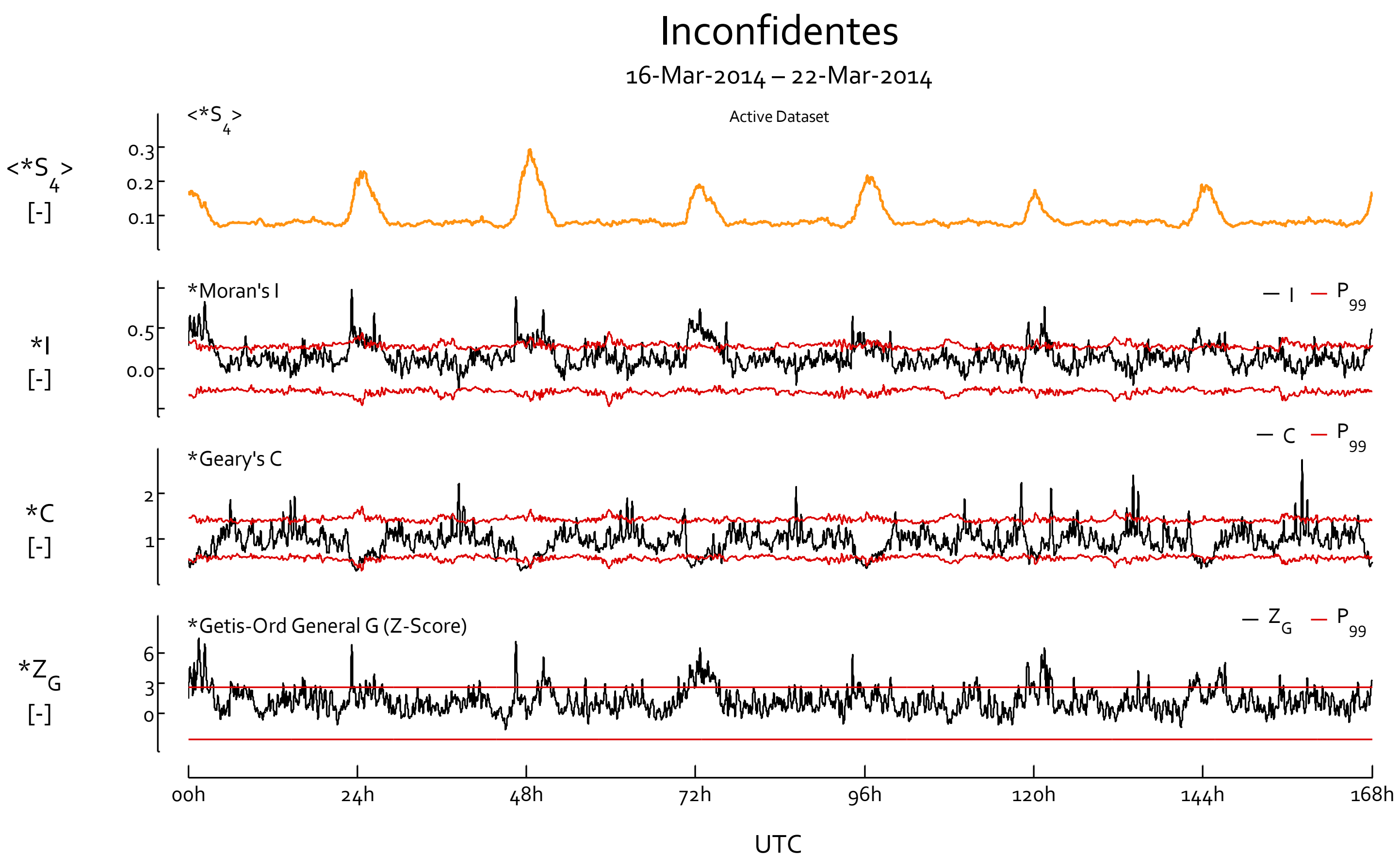


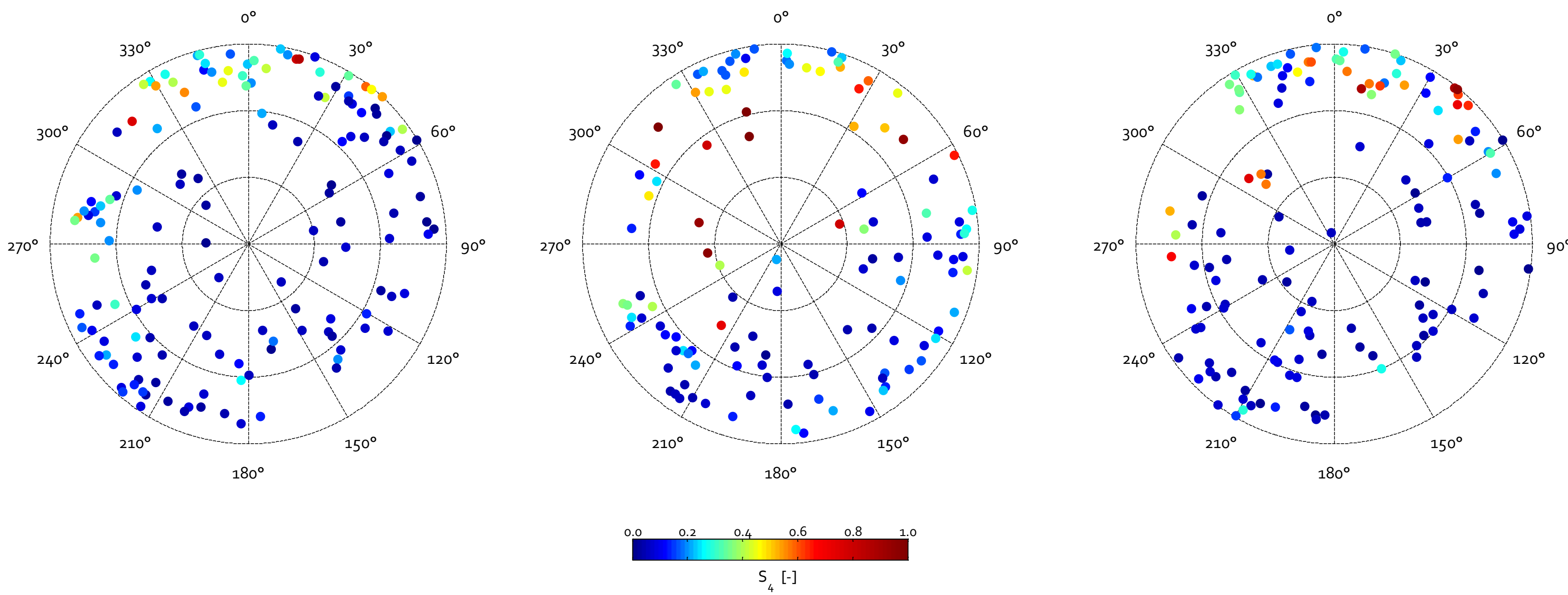
Global SAC Indices have specific characteristics which highlight their complementarity:

Moran:	Global SAC
Geary:	Global index with high sensitivity to Local SAC
Getis-Ord:	Clustering Index

Ionospheric scintillation skyplots show significantly positive spatial autocorrelation during active ionospheric scintillation conditions at the station of Inconfidentes, Brazil

Inconfidentes

16-Mar-2014 – 22-Mar-2014



CS1
Moran's I Index

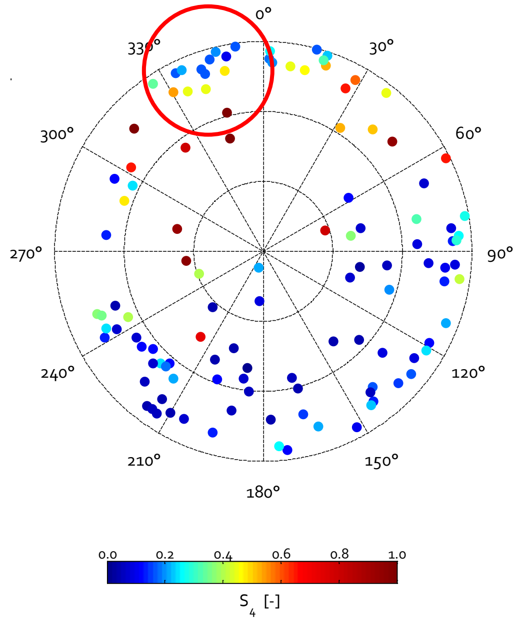
CS2
Geary's C Index

CS3
Getis-Ord General G Statistic

The **tracking** of spatial features impacting the global spatial autocorrelation is performed by exploiting local versions of the spatial autocorrelation indices

Size of the convolution window
20°

Significance level
95%



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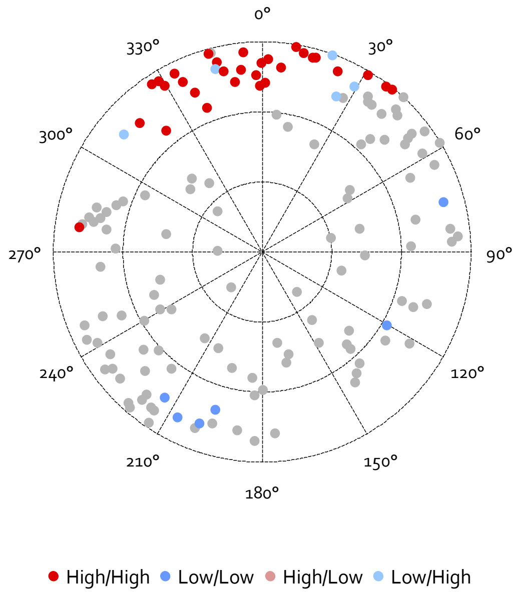
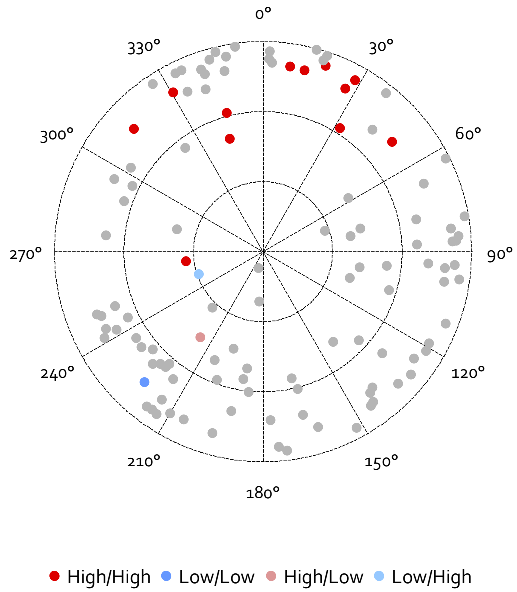
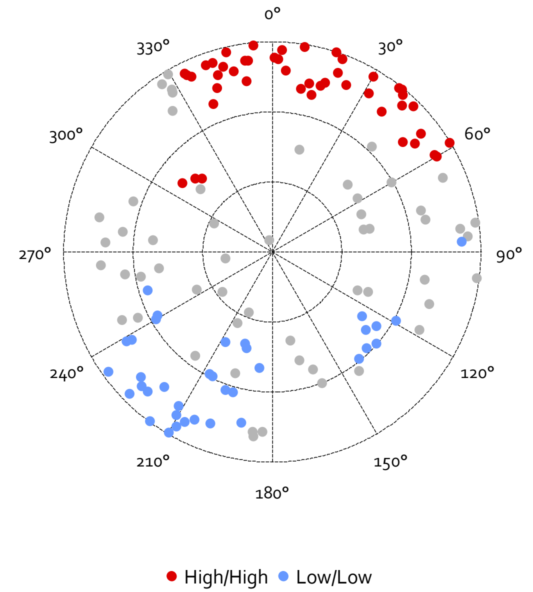


CS1
Moran's I Index

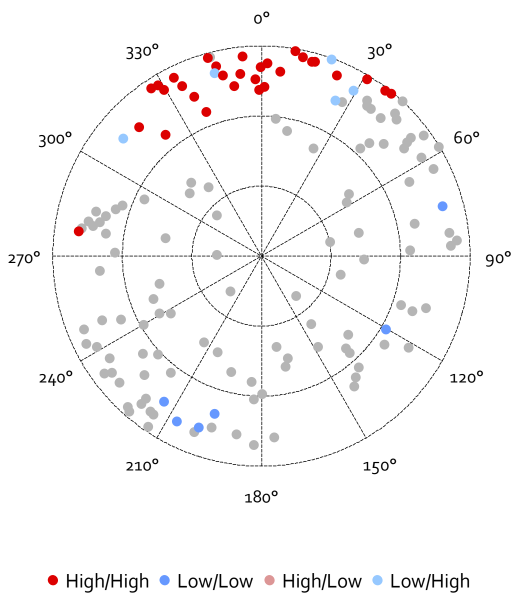


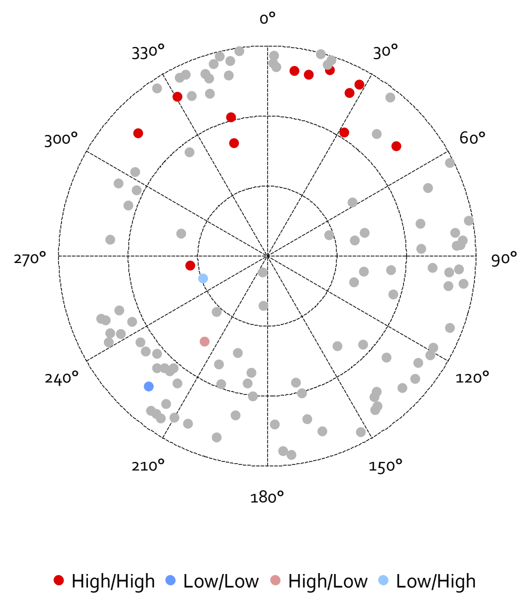
CS2
Geary's C Index



CS3
Getis-Ord Gi* Index

The **tracking** of spatial features impacting the global spatial autocorrelation is performed by exploiting local versions of the spatial autocorrelation indices





$$G_i^*(d_k) = \frac{\sum_{j=1}^{N} w_{ij}\ z_j}{\sum_{j=1}^{N} z_j}$$

$$w_{ij} = \begin{cases} \frac{1}{d_{ij}^2}, & i \neq j \\ 0, & i = j \end{cases}$$

CS1
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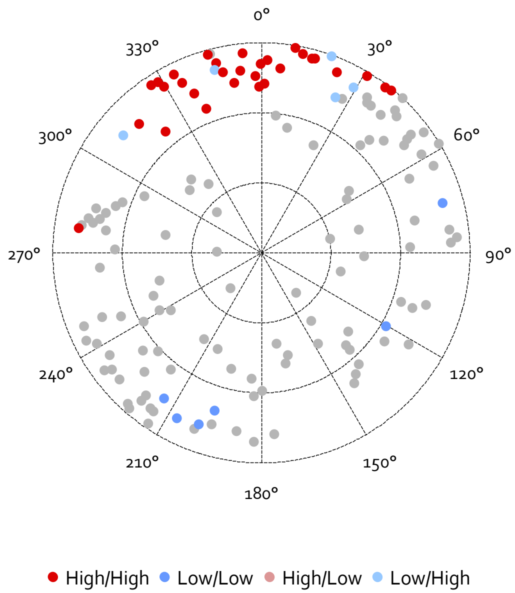

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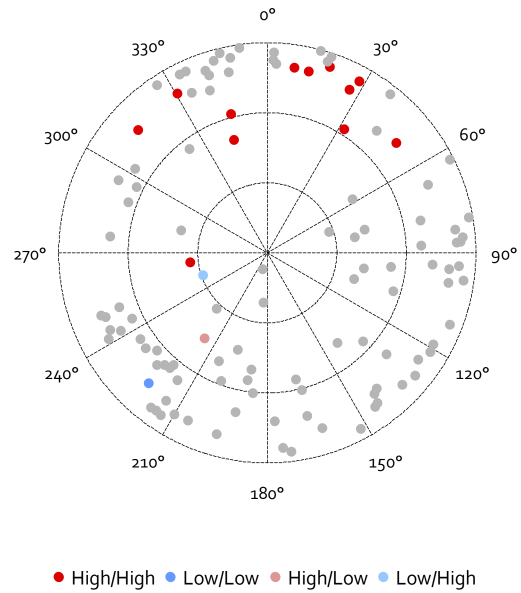
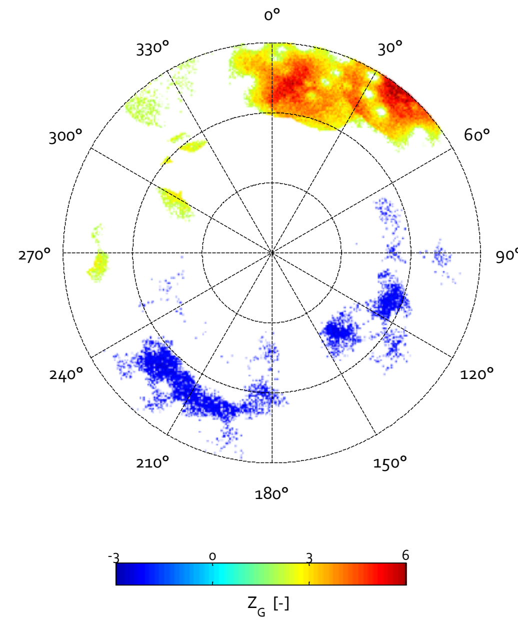
Moran's I Index



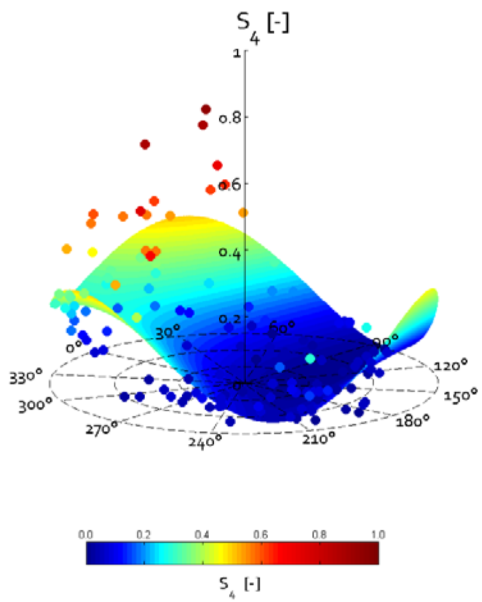
CS2
Geary's C Index

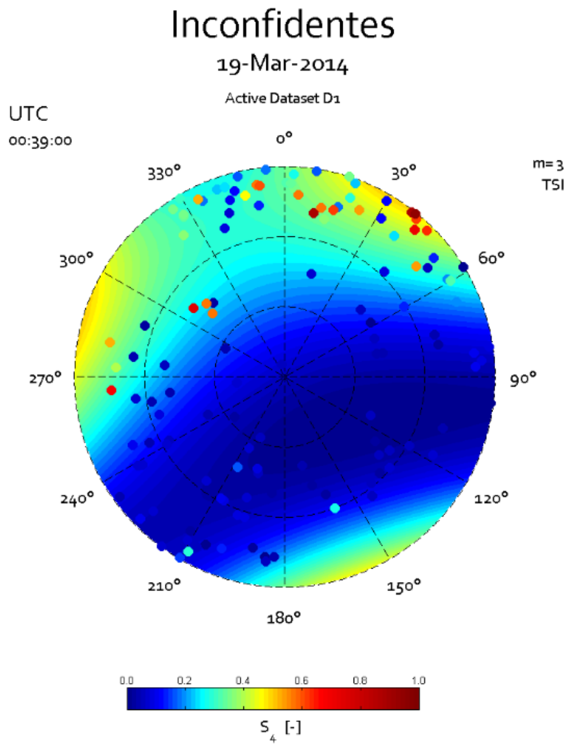


CS3
Getis-Ord Gi* Index

Local and global spatial autocorrelation in ionospheric scintillation skyplots can also be exploited by specific techniques to generate interpolated maps

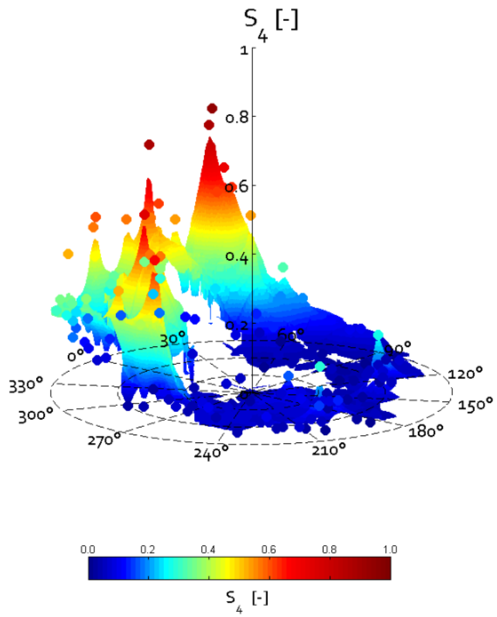
TSI – Trend Surface Interpolation

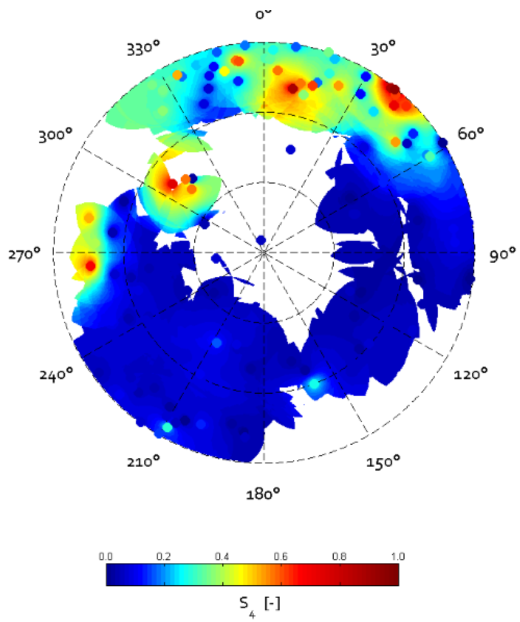




Local and global spatial autocorrelation in ionospheric scintillation skyplots can also be exploited by specific techniques to generate interpolated maps

IDW – Inverse Distance Weighting

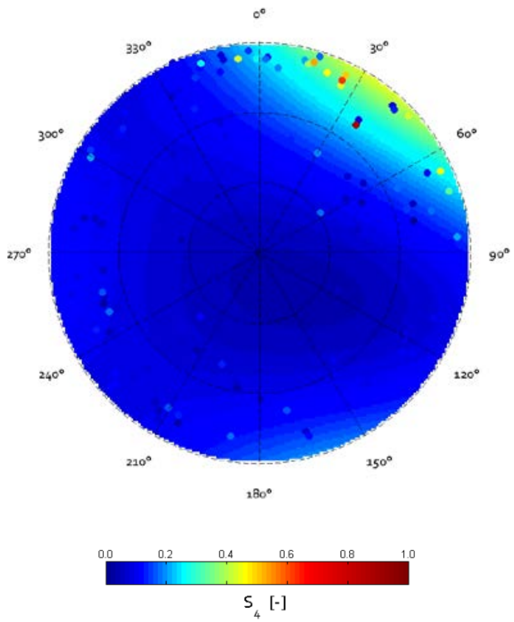




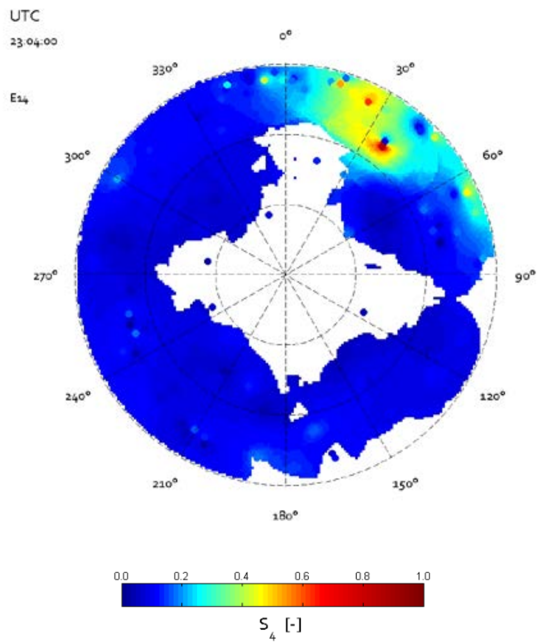
Spatial analysis techniques applied to ionospheric scintillation skyplots can be exploited to generate three types of spatial products / ionospheric scintillation skymaps

Inconfidentes

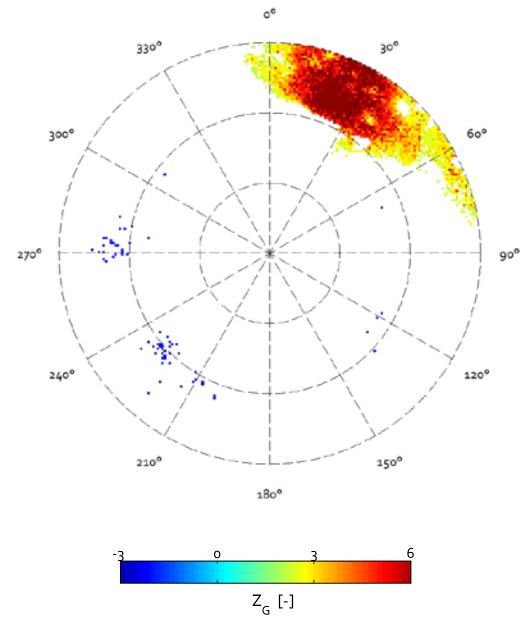
18-Mar-2014 – 19-Mar-2014



TSI skymaps



IDW skymaps



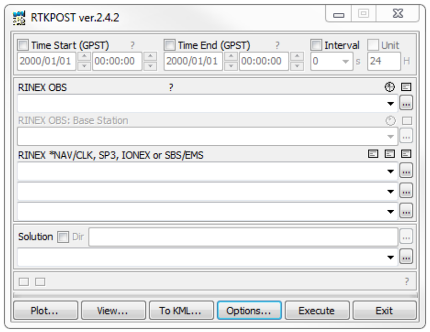
GOS skymaps

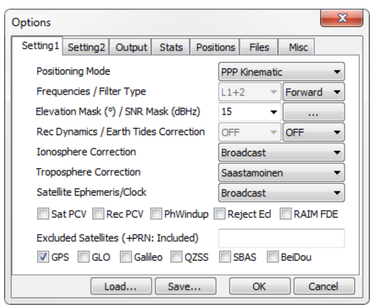
Analysis
GNSS Algorithms and Ionosphere

Geostatistics
Ionospheric Scintillation Skymaps

Prototypes
Mitigation Strategies

The prototyping of mitigation strategies against ionospheric scintillations is grafted to the post-processing GNSS software RTKLIB





RTKLIB

Workspace

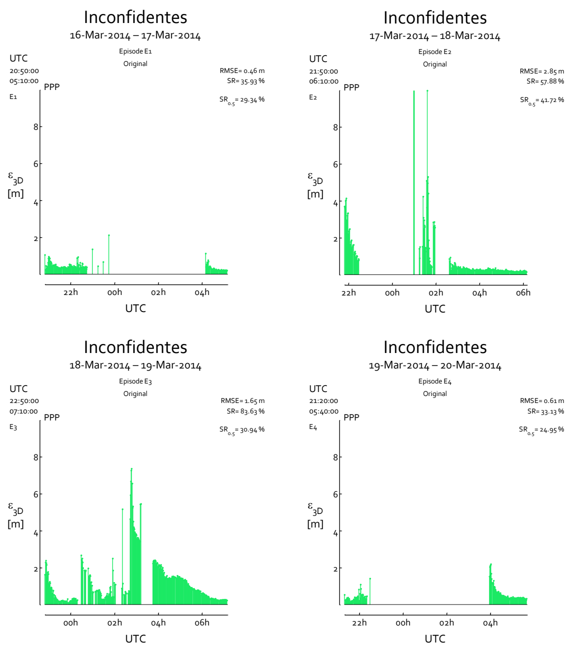
Post-processing GNSS Software RTKLIB

SPP and PPP Algorithms

Multiple Constellations (GPS, GLONASS, Galileo)

Open-Source code (C language)

Mitigation strategies against ionospheric scintillations are benchmarked at the ISMR station of Inconfidentes, Brazil, during four specific 6h-long ionospheric scintillation episodes



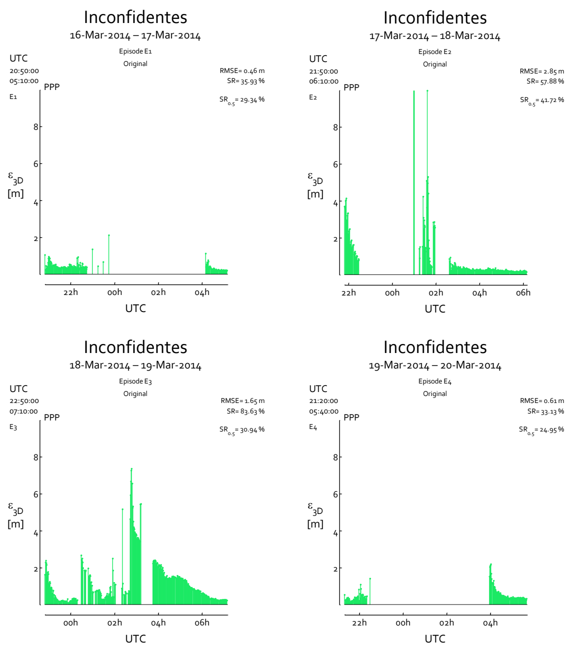
Workspace

Post-processing GNSS Software RTKLIB

ISMR station of Inconfidentes, Brazil

Experimental Episodes E1/E2/E3/E4

The benchmark of the prototype mitigation strategies against ionospheric scintillations requires the definition of several performance criteria



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Post-processing GNSS Software RTKLIB

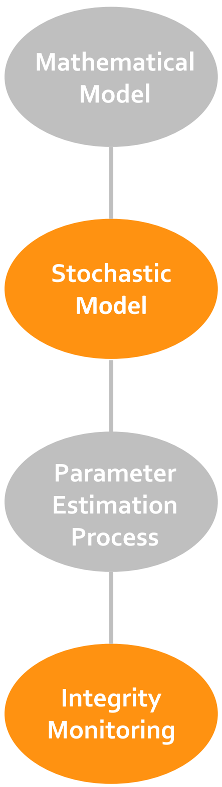
ISMR station of Inconfidentes, Brazil

Experimental Episodes E1/E2/E3/E4

Performance Criteria

- → **Accuracy** — **Root-Mean-Square Error (RMSE)**
- → **Continuity** — **Success Rate (SR)**
- → **Reliability** — **Success Rate for a given accuracy (SR_{XX})**
- **Processing Time**

Prototype mitigation strategies target the stochastic modelling stage and the integrity monitoring stage of the SPP and PPP algorithms



Workspace

Post-processing GNSS Software RTKLIB

ISMR station of Inconfidentes, Brazil

Experimental Episodes E1/E2/E3/E4

Performance Criteria

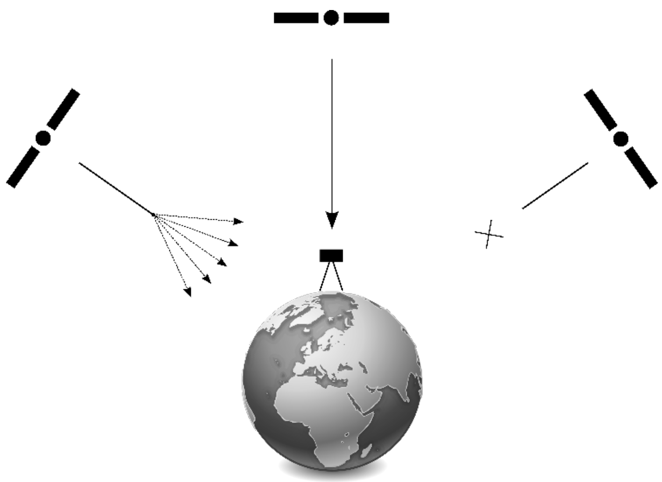
Targets

→ **Stochastic Modelling**

→ **Integrity Monitoring**

→ **SPP/PPP Algorithms**

The stochastic model of the SPP/PPP algorithms is represented by the covariance matrix of the observations which contains information related to the precision of the individual measurements



Covariance Matrix of the Observations

$$Q_{\underline{l}} = \sigma^2 I_m = \begin{bmatrix} {\sigma^1}^2 & & & \\ & {\sigma^2}^2 & & \\ & & \ddots & \\ & & & {\sigma^m}^2 \end{bmatrix}$$

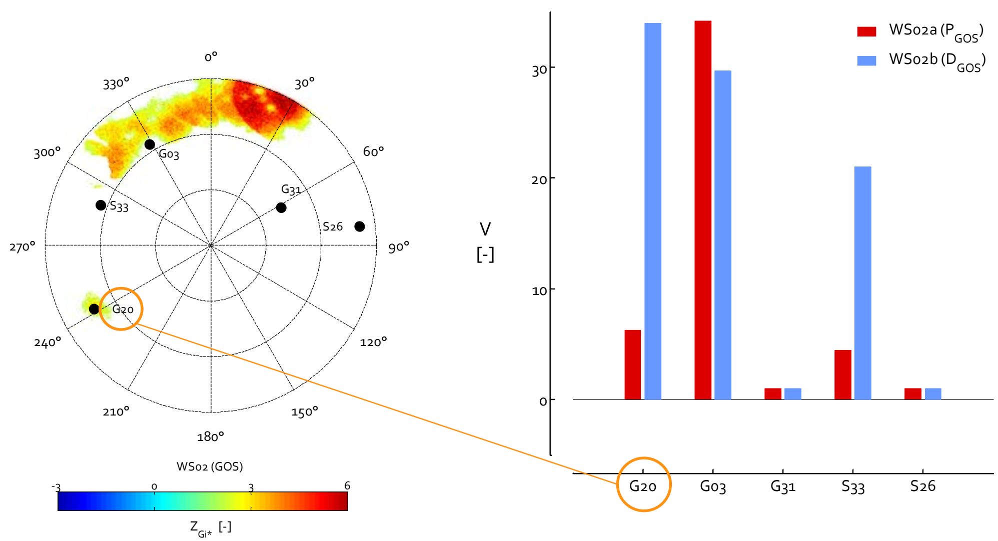
Two approaches are considered to customise the stochastic model of the SPP and PPP Algorithms

Weighting Scheme (WS)

Spatial Masks (SM)

The **Weighting Scheme (WS)** of the stochastic model can be tuned by adjusting calibrated stochastic factors based on ionospheric scintillation skymaps to deweight culprit observations

A Calibration Process based on the actual tracking variance (Conker Model) is exploited in order to defined the variation of the Stochastic Factors according to variables measurable in skymaps



$$\sigma^2 = \left[F_{GNSS}^2\, R^2 \left(a^2 + \frac{b^2}{\sin \eta^s}\right)\right] * V + \cdots$$

Tracking Variance

Stochastic Factor

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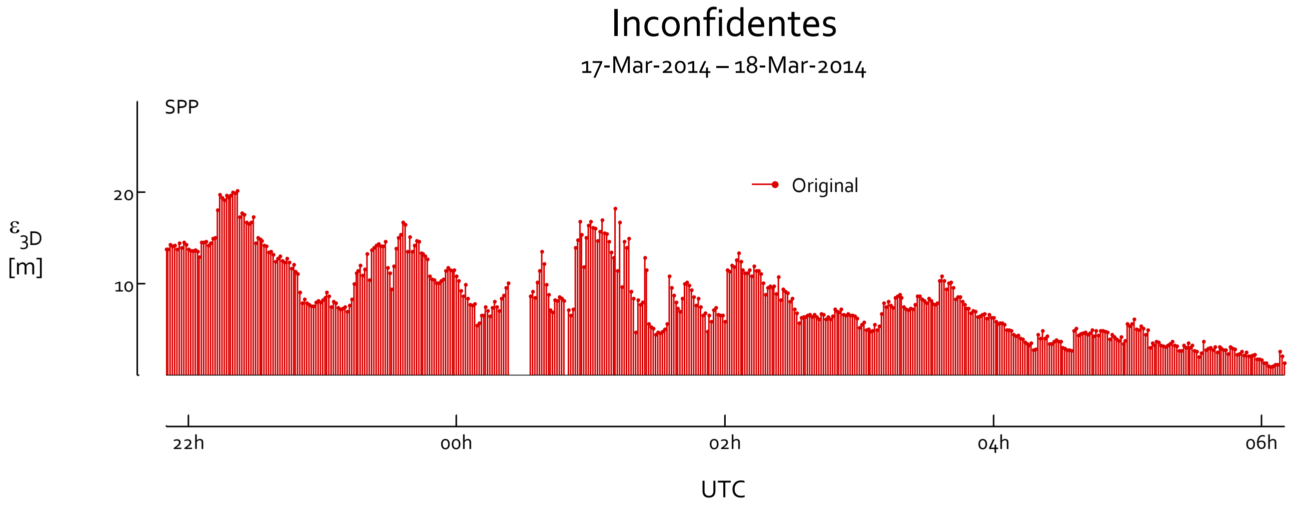

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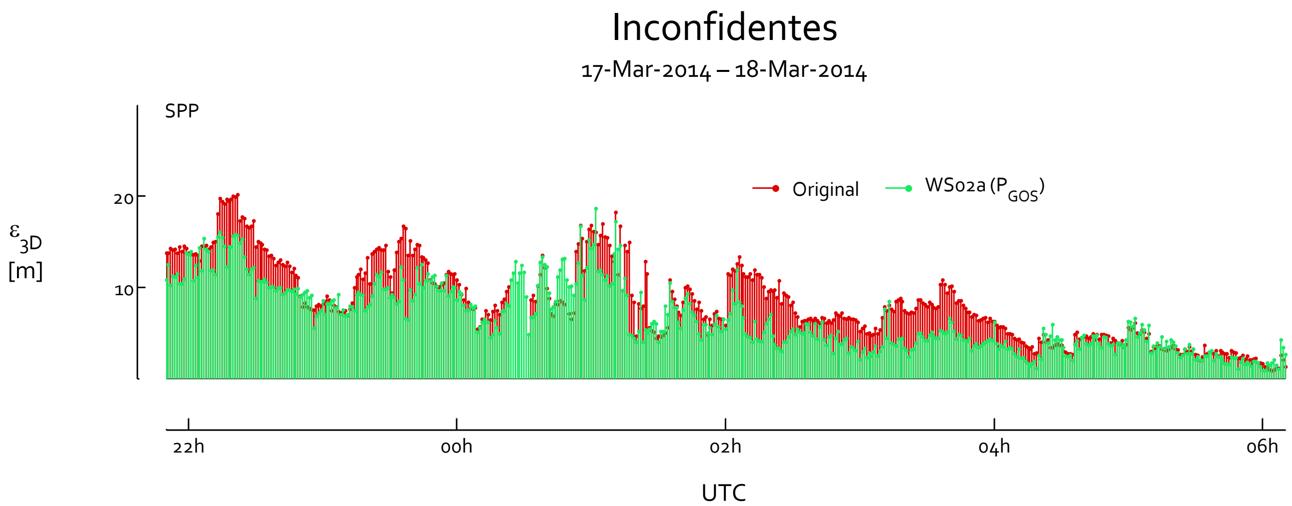

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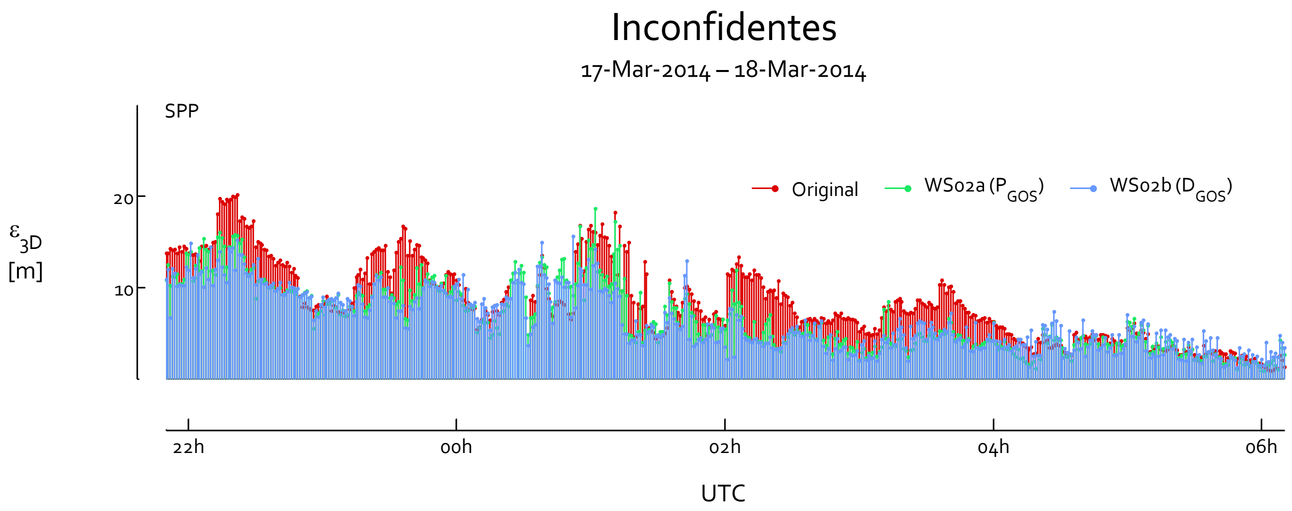

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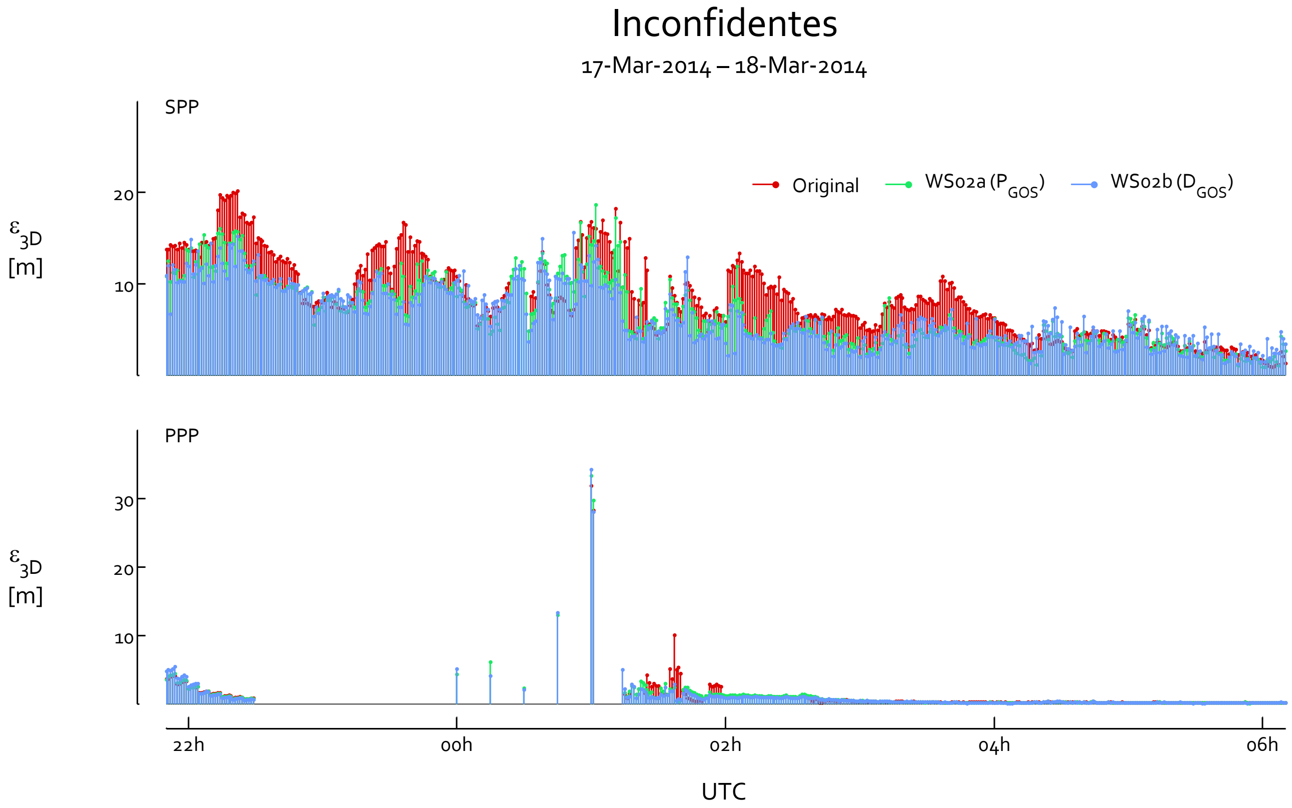
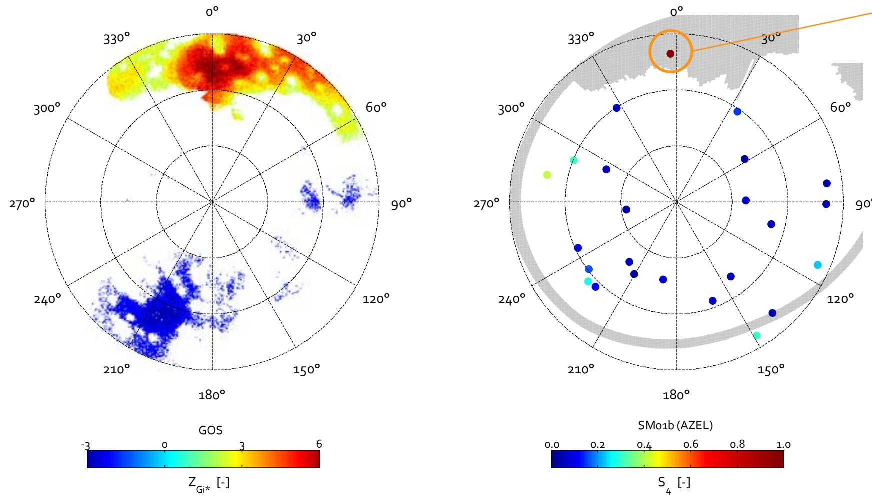


Spatial Masks (SM) are designed according to ionospheric scintillation skymaps in order to exclude potentially culprit observations from the parameter estimation process of the SPP and PPP algorithms

Ionospheric Scintillation Skymaps are exploited to design specific masks based on various criteria.

$$Q_{\underline{l}} = \sigma^2 I_m = \begin{bmatrix} {\sigma^1}^2 & & & \\ & {\sigma^2}^2 & & \\ & & \ddots & \\ & & & {\sigma^m}^2 \end{bmatrix}$$



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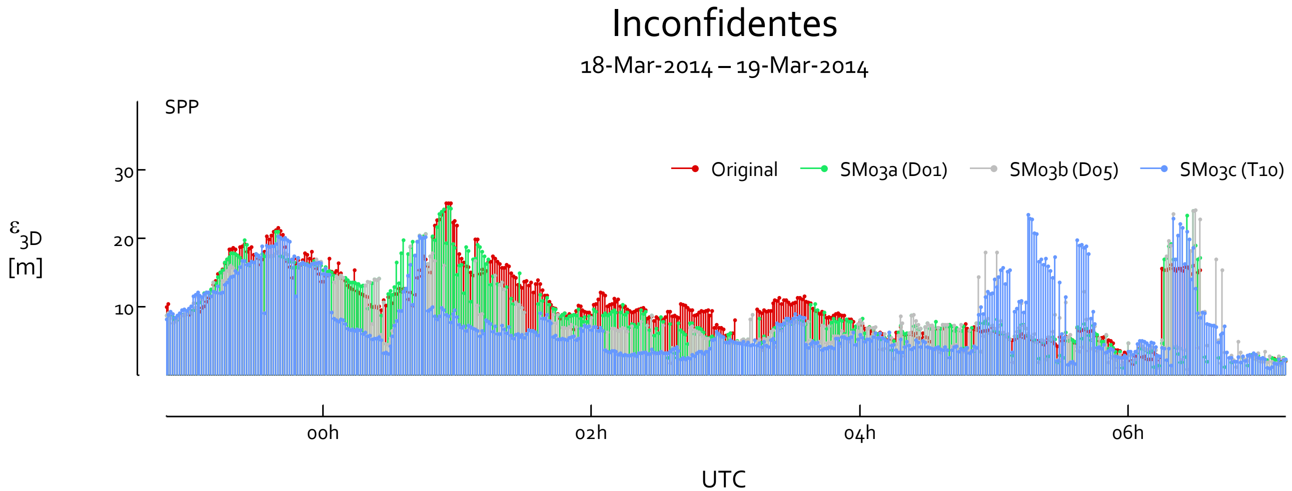

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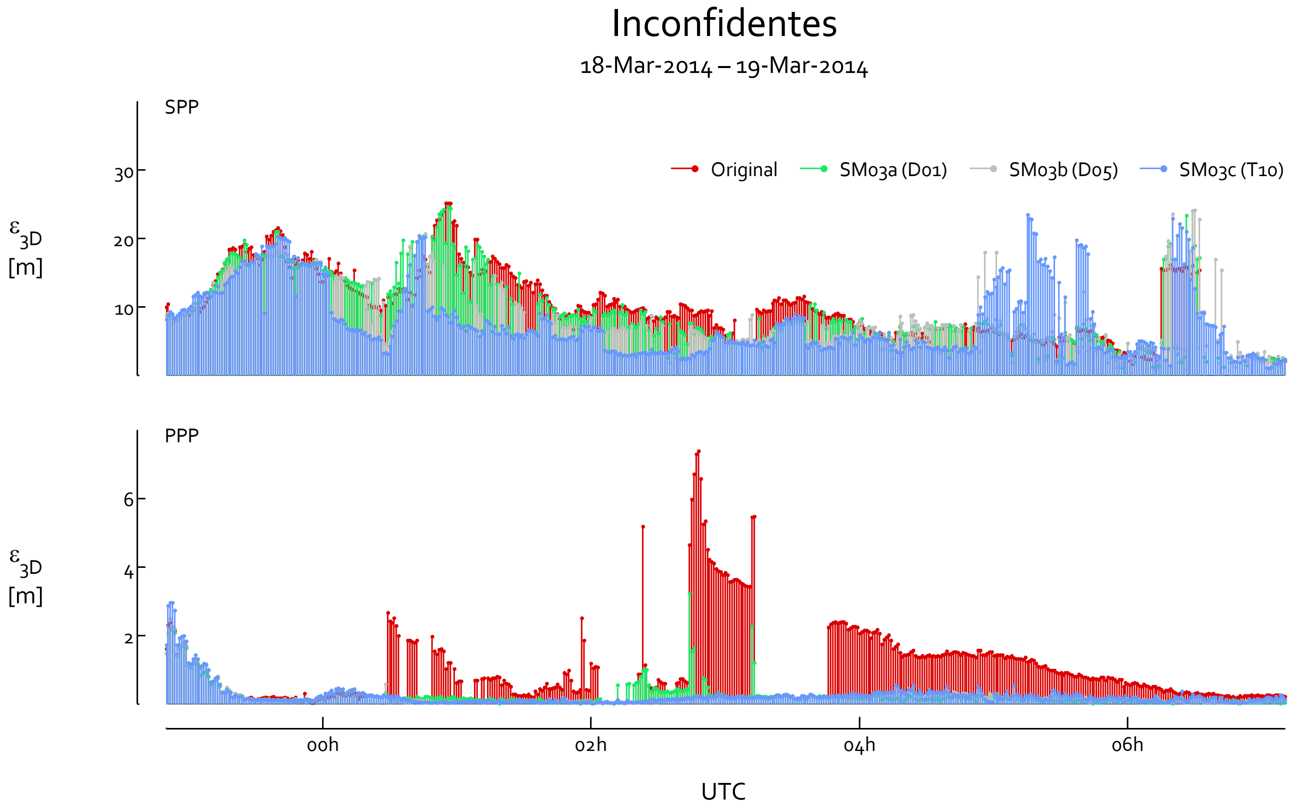
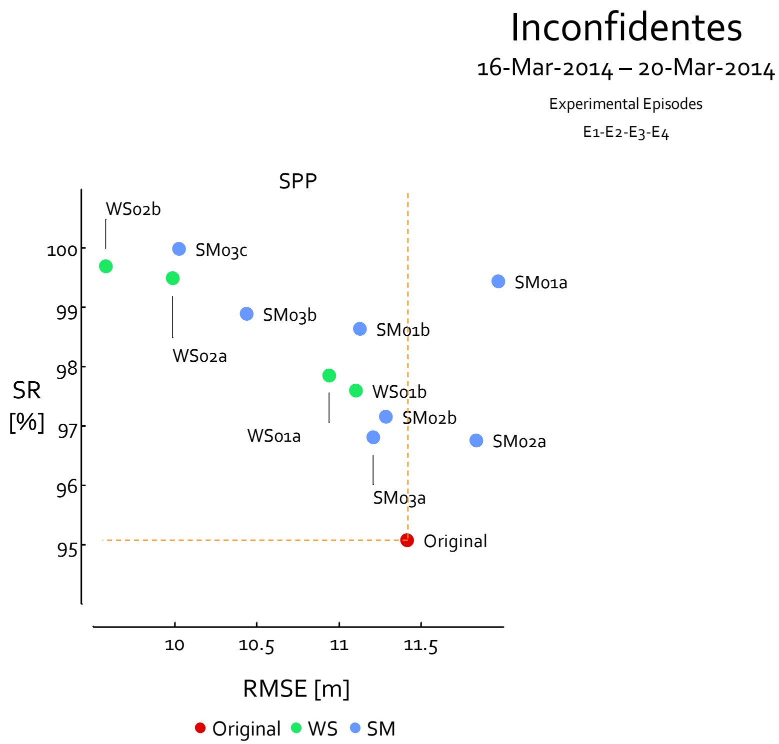
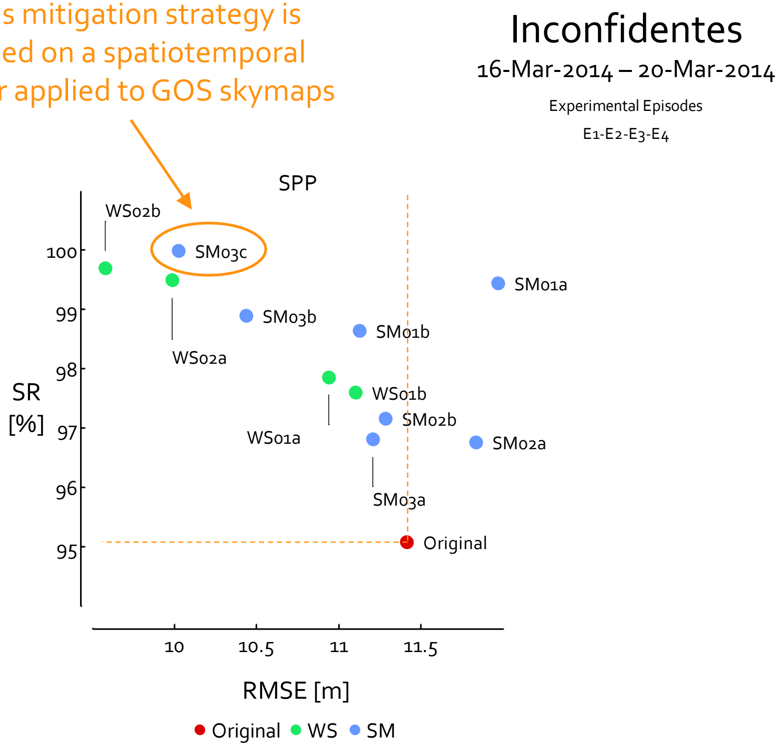


All prototype mitigation strategies increase the continuity of the SPP algorithm with a Success Rate ranging between 95% and 100%



All prototype mitigation strategies increase the continuity of the SPP algorithm with a Success Rate ranging between 95% and 100%

This mitigation strategy is based on a spatiotemporal buffer applied to GOS skymaps



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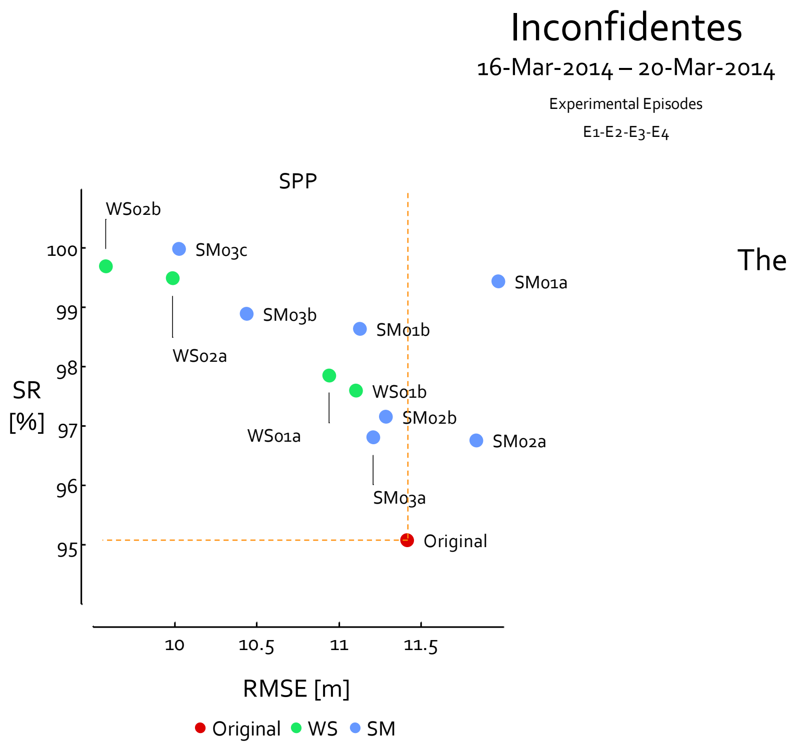
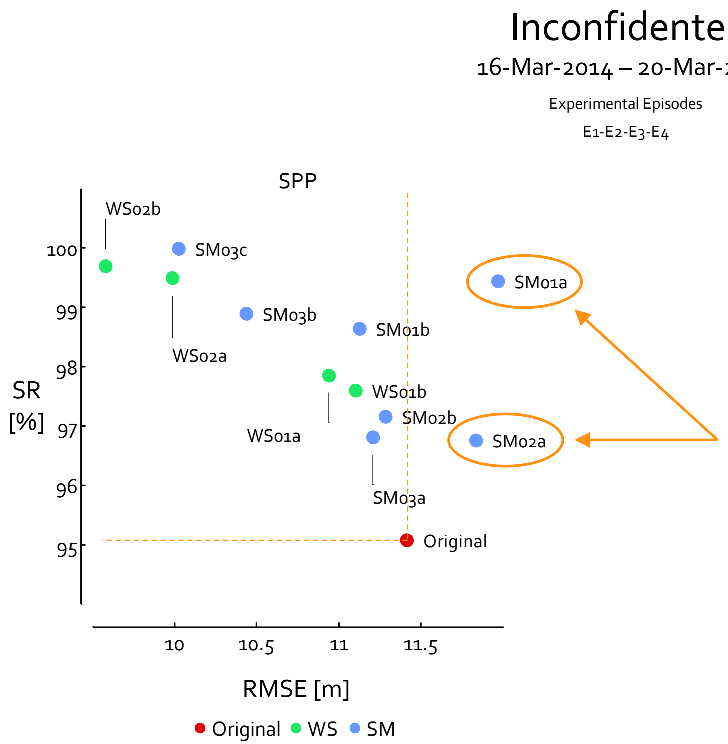


The continuity of the SPP algorithm is always improved

Almost all prototype mitigation strategies increase the accuracy of the SPP algorithm with an RMSE dropping from ~11m down to ~10m



The continuity of the SPP algorithm is always improved

Only those two strategies tend to decrease the accuracy of the SPP algorithm in case of ionospheric scintillations

Almost all prototype mitigation strategies increase the accuracy of the SPP algorithm with an RMSE dropping from ~11m down to ~10m

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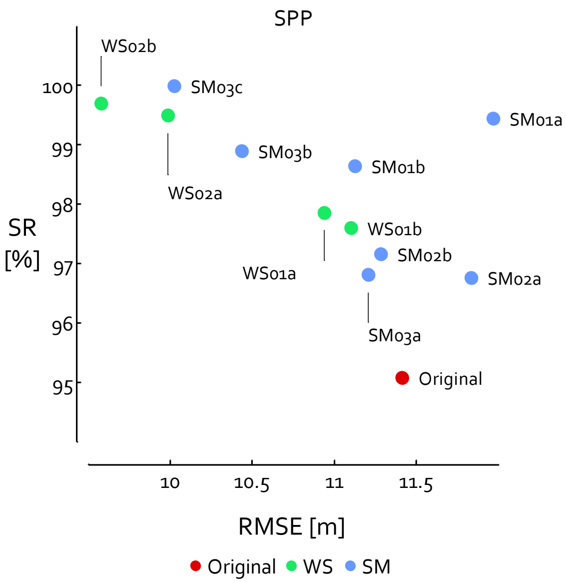
16-Mar-2014 – 20-Mar-2014

Experimental Episodes

E1-E2-E3-E4



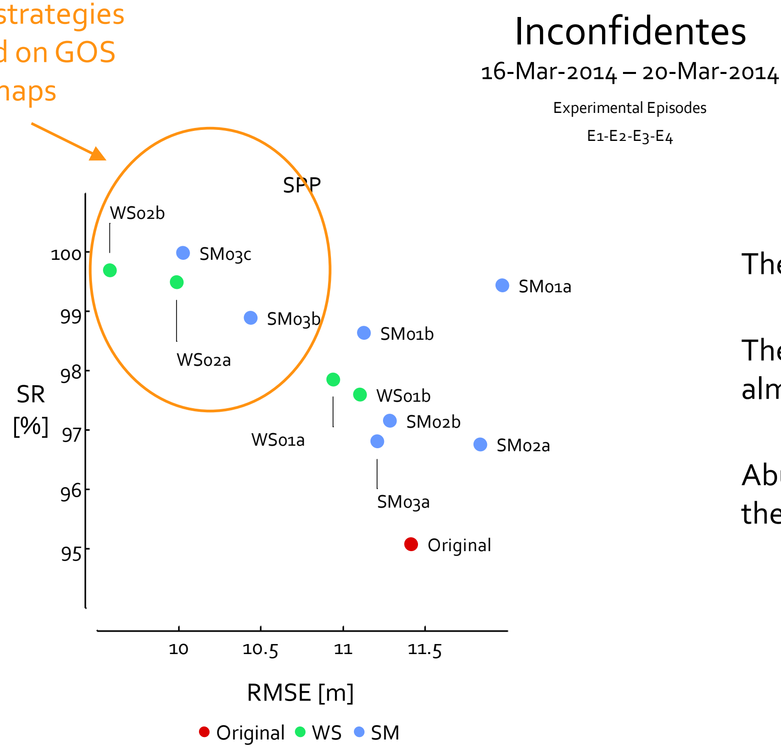
The continuity of the SPP algorithm is always improved

The accuracy of the SPP algorithm is improved by almost all the prototype mitigation strategies

Abusive spatial masks tend to decrease the quality of the satellite geometry

Prototype mitigation strategies based on GOS skymaps provide better performances which indicates a higher suitability of GOS skymaps for GNSS positioning

All those strategies are based on GOS skymaps



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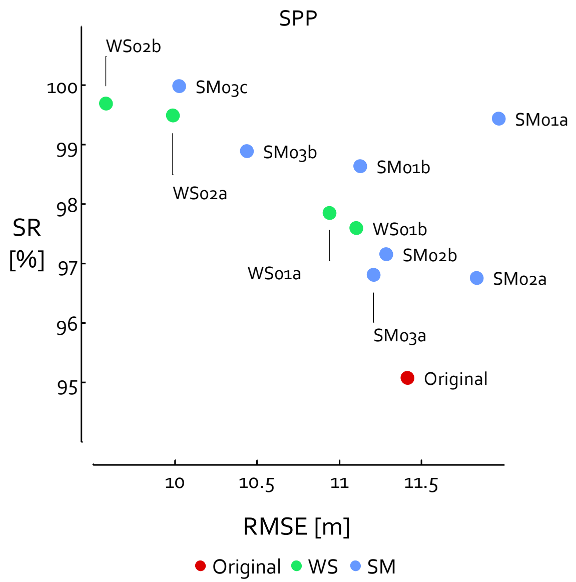


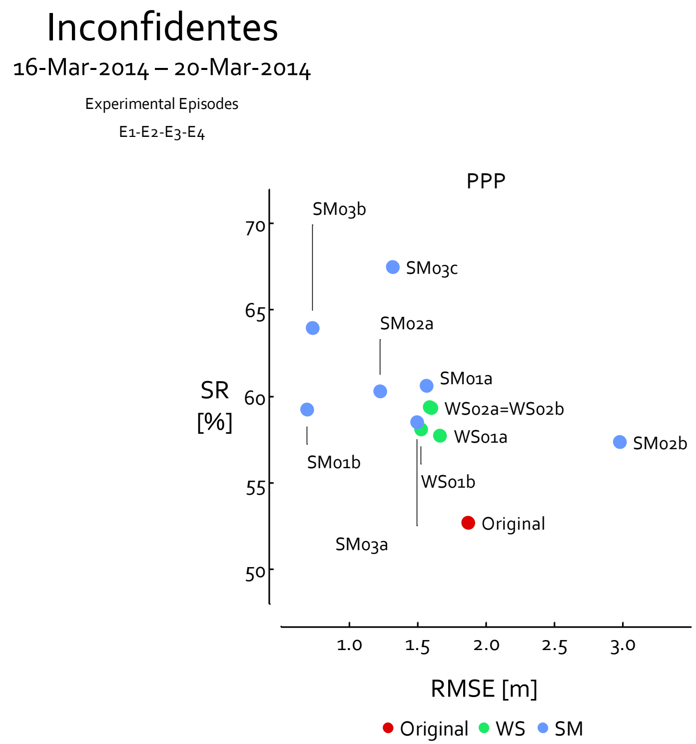
The continuity of the SPP algorithm is always improved

The accuracy of the SPP algorithm is improved by almost all the prototype mitigation strategies

Abusive spatial masks tend to decrease the quality of the satellite geometry

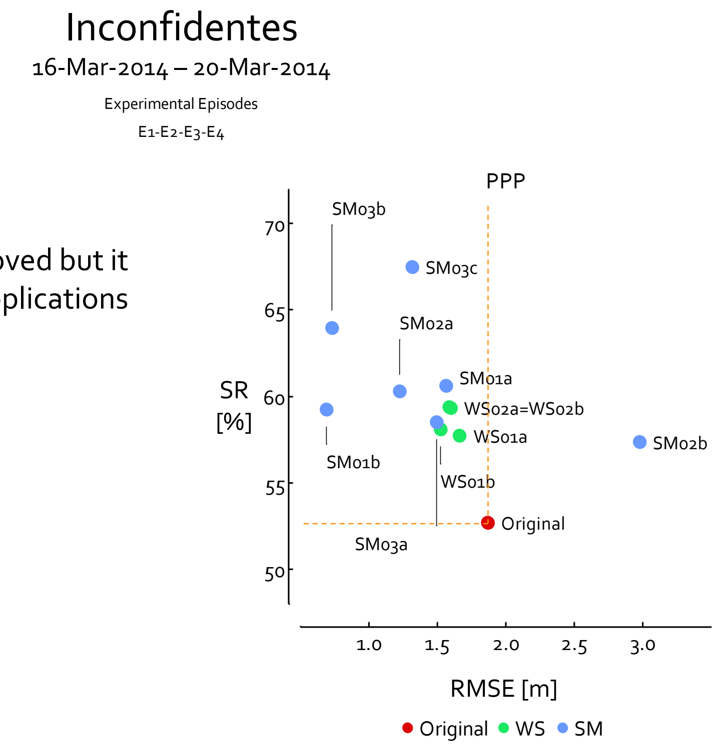
GOS Skymaps provide better results for GNSS positioning in terms of accuracy and continuity

All prototype mitigation strategies increase the continuity of the PPP algorithm with a Success Rate ranging between ~52% and ~68%



All prototype mitigation strategies increase the continuity of the PPP algorithm with a Success Rate ranging between ~52% and ~68%

The continuity of the PPP Algorithm is always improved but it remains too low for demanding applications



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The continuity of the PPP Algorithm is always improved but it remains too low for demanding applications

The accuracy performances of the PPP algorithm are improved but not to the expected level for the PPP algorithm

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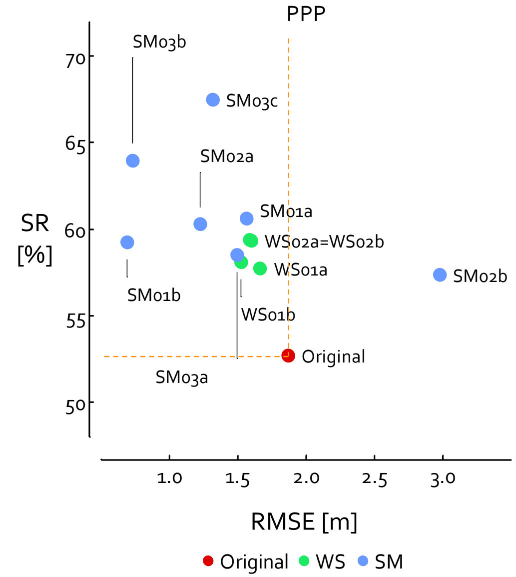
Experimental Episodes

E1-E2-E3-E4



For the PPP algorithm, prototype mitigation strategies based on spatial masks provide better performances than strategies based on the tuning of the weighting scheme

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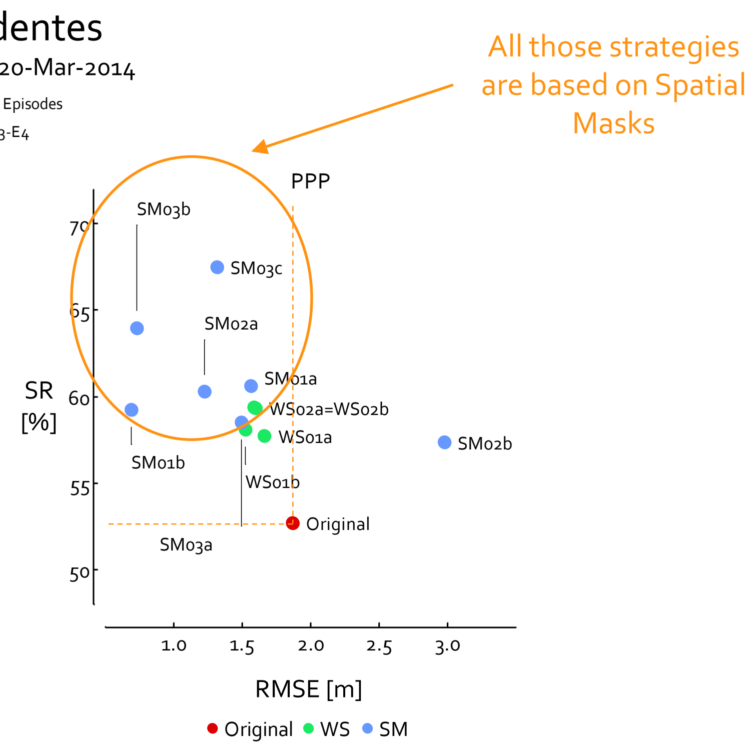

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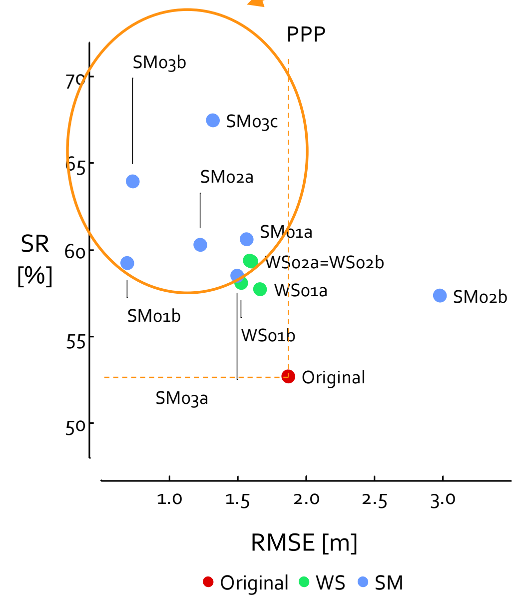
Inconfidentes

16-Mar-2014 – 20-Mar-2014

Experimental Episodes

E1-E2-E3-E4

All those strategies are based on Spatial Masks

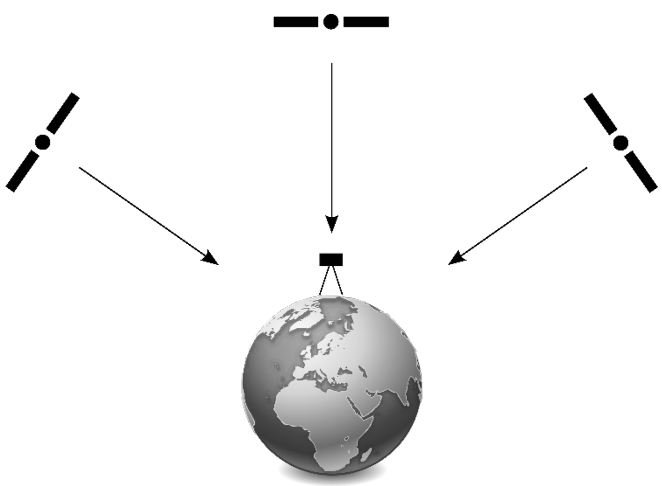


The continuity of the PPP Algorithm is always improved but it remains too low for demanding applications

The accuracy performances of the PPP algorithm are improved but not to the expected level for the PPP algorithm

For the PPP algorithm, designing spatial masks leads to better positioning performances than tuning the weighting scheme

The integrity monitoring stage of the SPP and PPP algorithms consists in statistically verifying the validity of the computed navigation solution



Statistical Validation Test (RTKLIB)

$$v_r^s = \frac{\left[P_r^s - (\widehat{D}_r^s + c\,\widehat{dt}_r - c\,dt^s + I_r^s + T_r^s)\right]}{\sigma_{P_r^s}}$$

$$\underline{v} = (v_r^1, v_r^2, \ldots, v_r^n)^T$$

$$\frac{\underline{v}^T\, W\, \underline{v}}{\sigma_0^2} < \chi_\alpha^2(n - m - 1)$$

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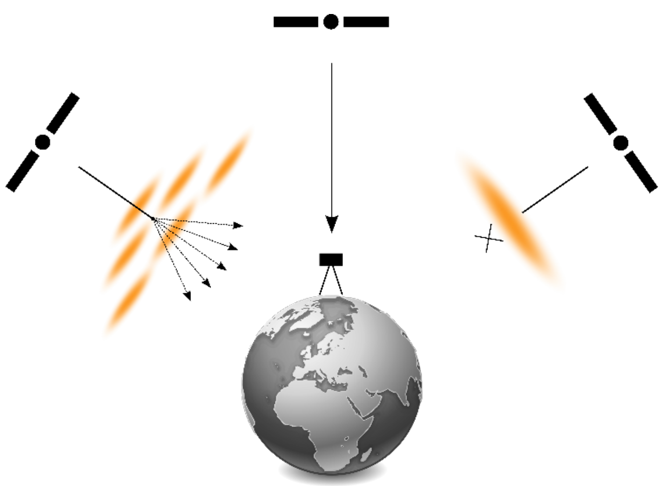

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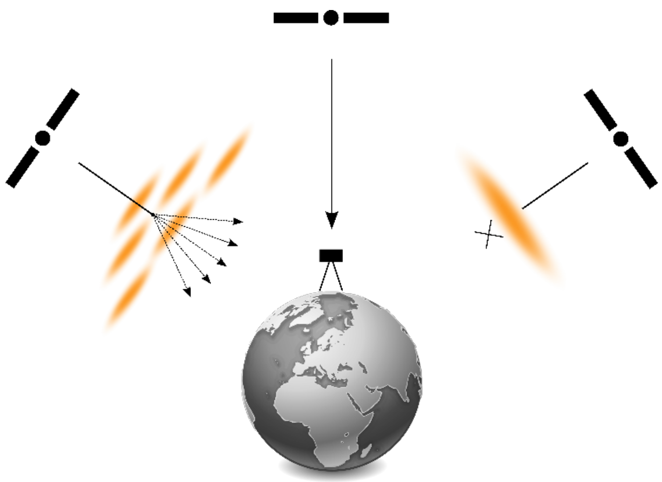

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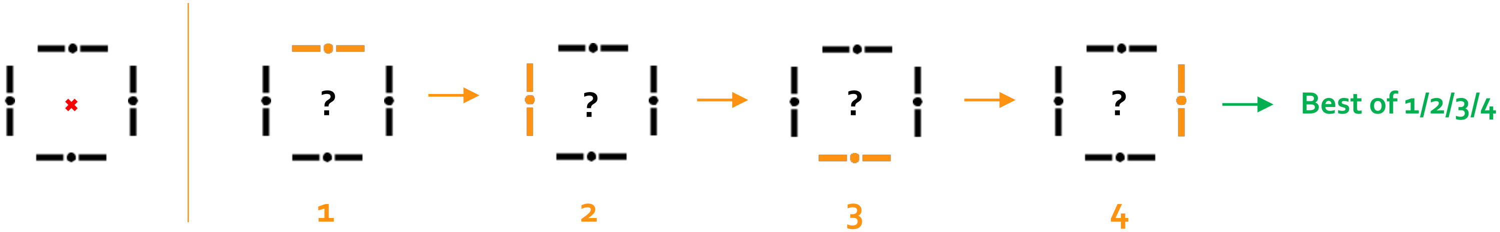
RAIM-FDE

Receiver Autonomous Integrity Monitoring – Fault Detection Exclusion



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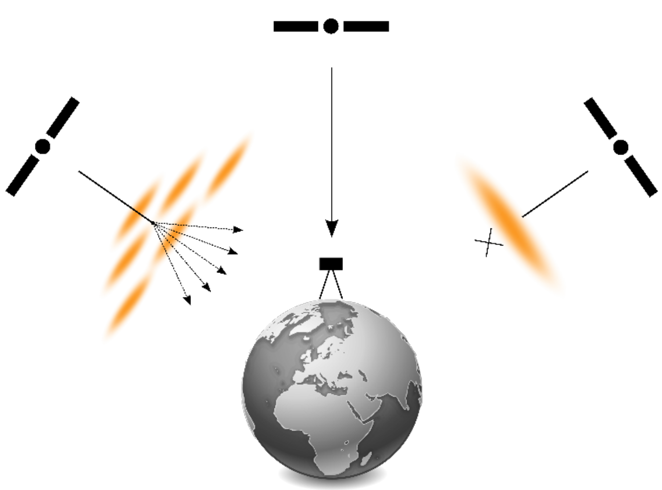


Three Approaches to design prototype mitigation strategies related to the integrity monitoring stage of the SPP and PPP Algorithms.

Original RTKLIB RAIM-FDE Technique (IM00)

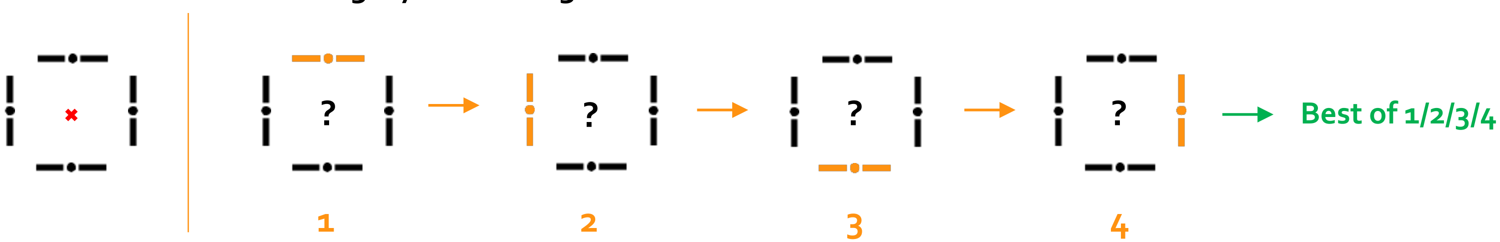
Extended Technique (IM01)

Spatial Technique (IM02)

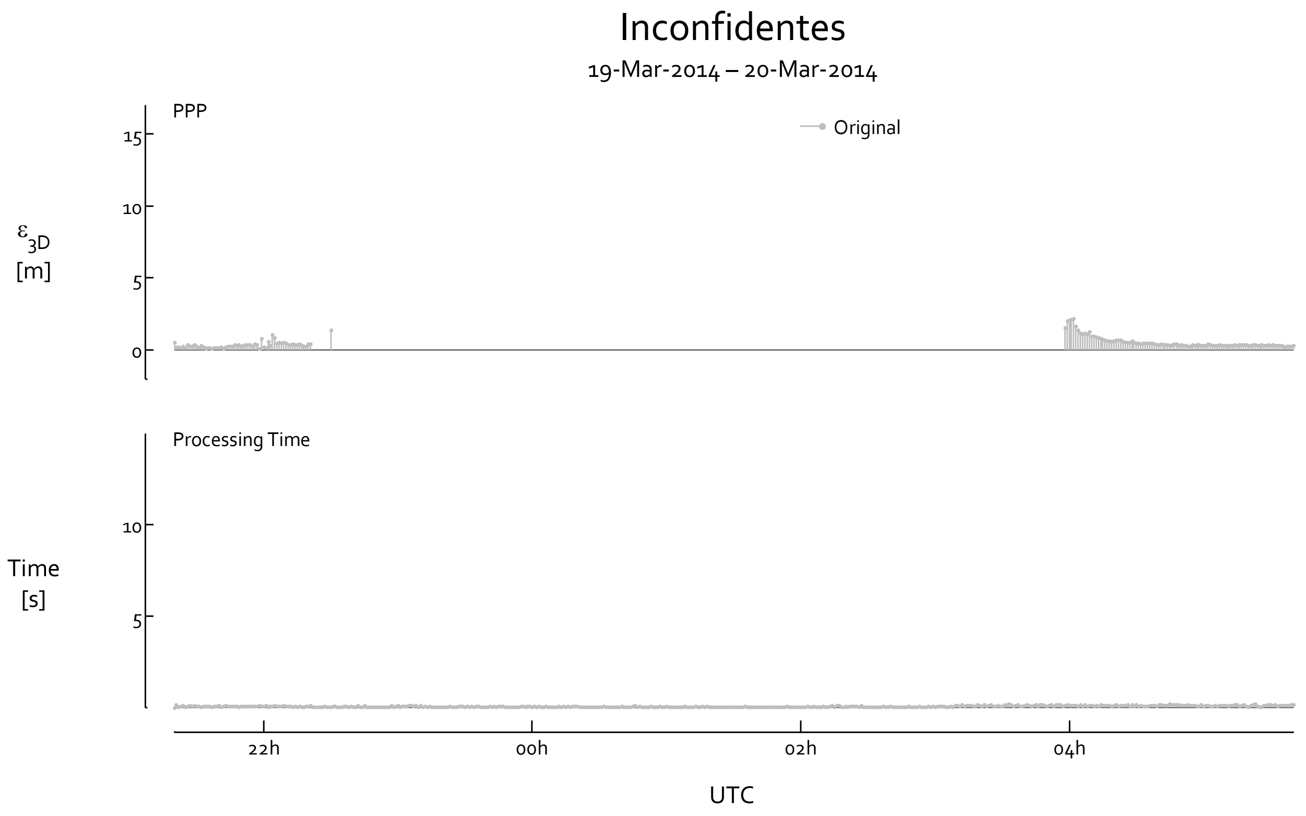
Hybrid Solution (IM03)

RAIM-FDE

Receiver Autonomous Integrity Monitoring – Fault Detection Exclusion



Advanced integrity monitoring is the key towards higher PPP performances in case of ionospheric scintillations but it requires a valid stochastic model



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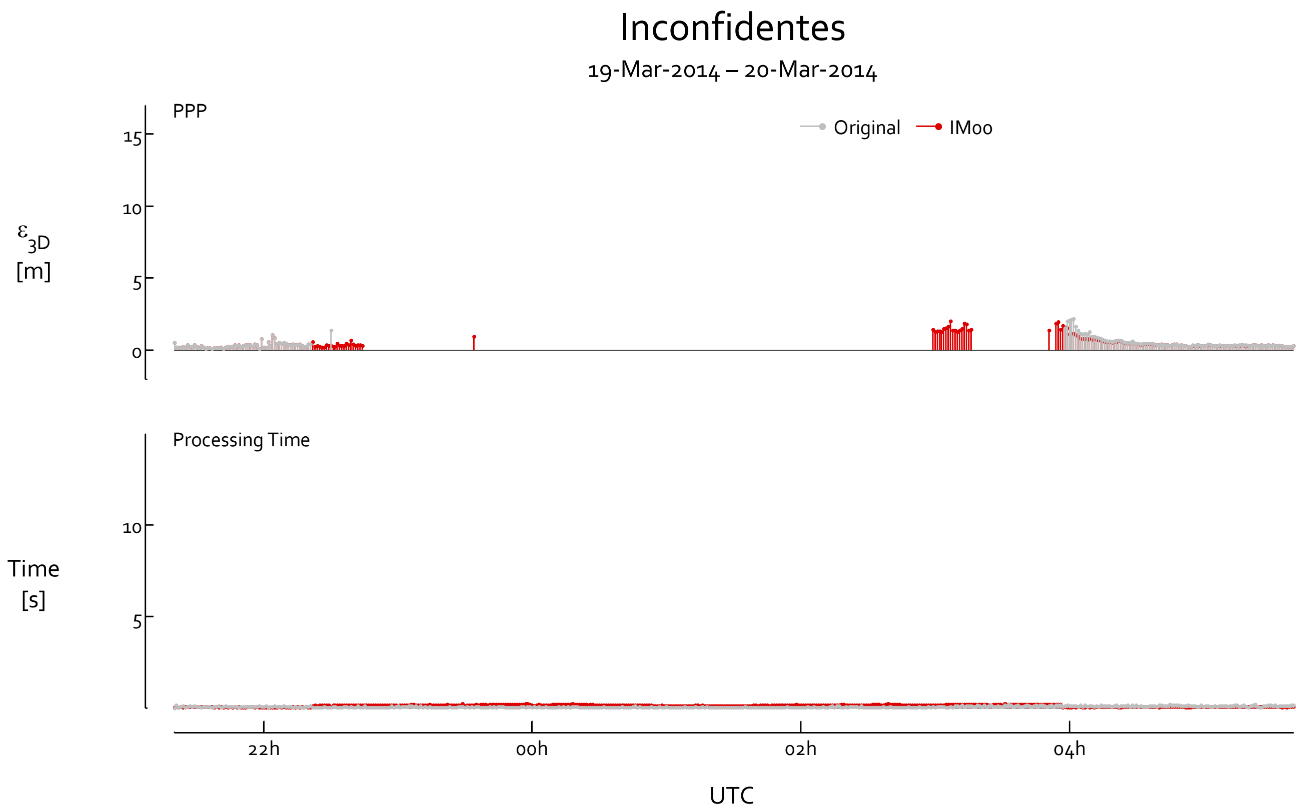

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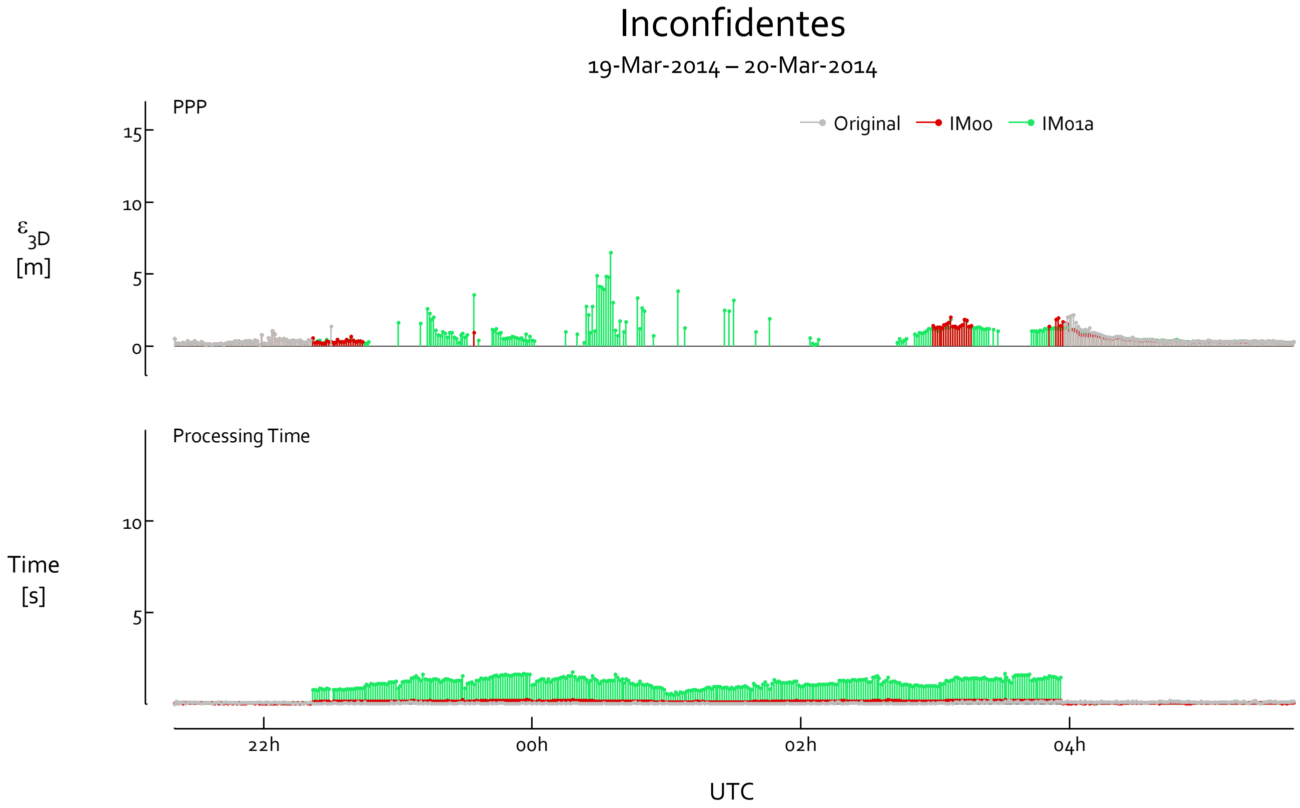

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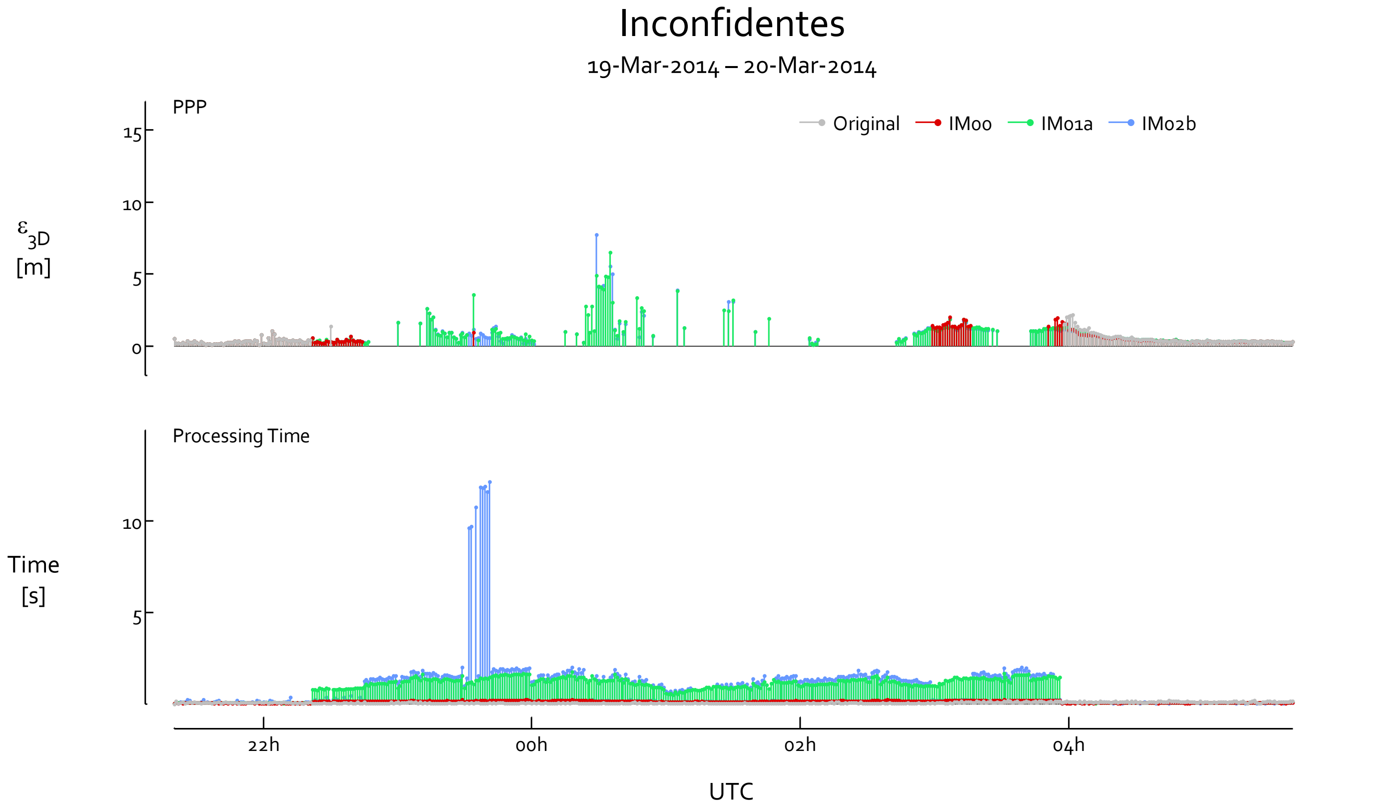

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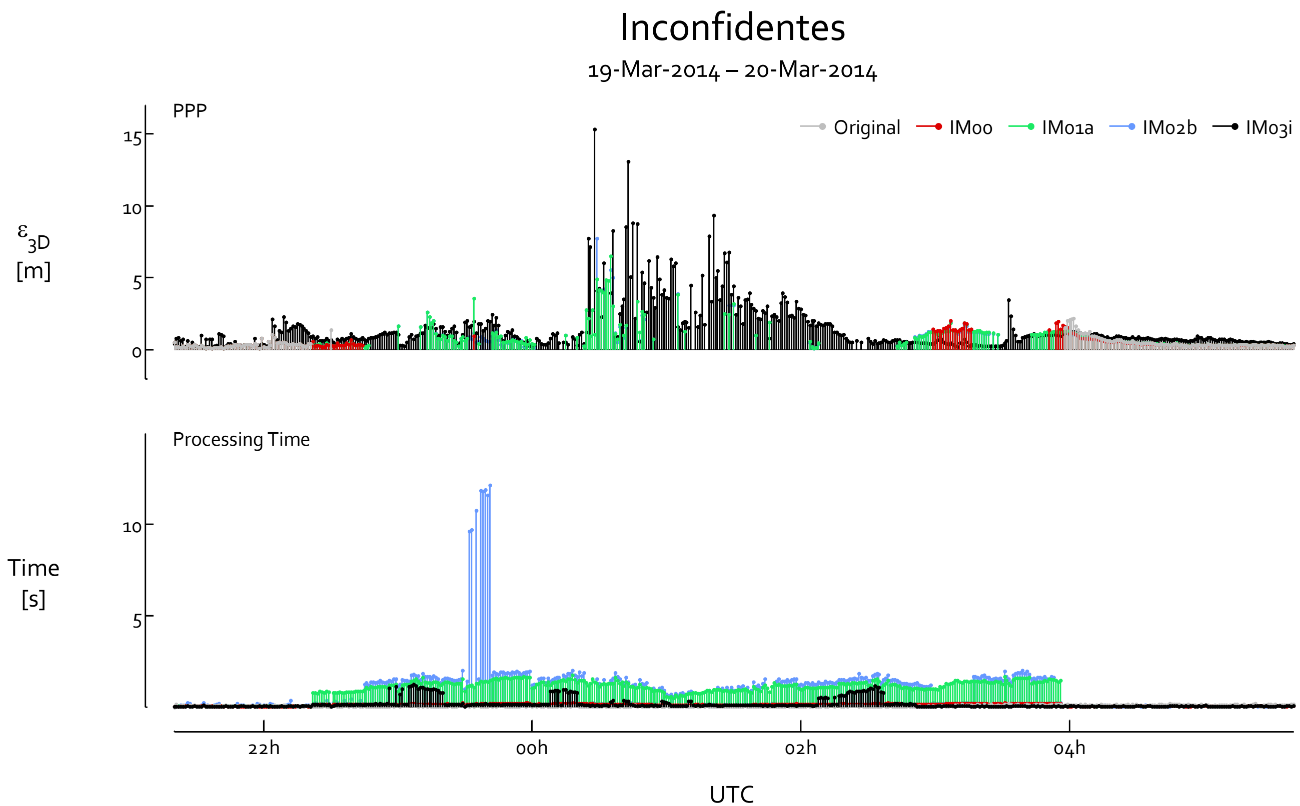

Hybrid prototype mitigation strategies targeting both the stochastic modelling and the integrity monitoring stages lead to the highest results for the SPP and PPP algorithms

Inconfidentes

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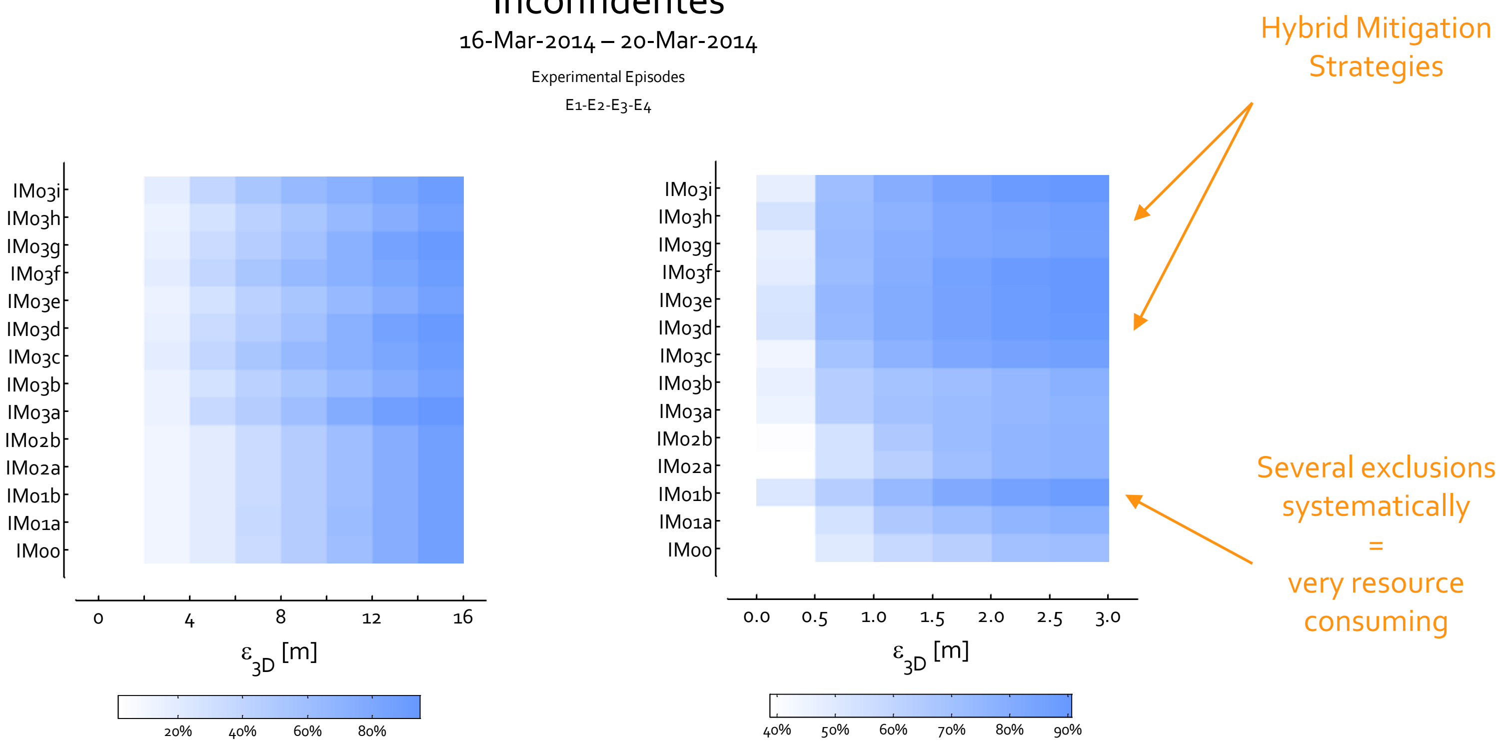
E1-E2-E3-E4



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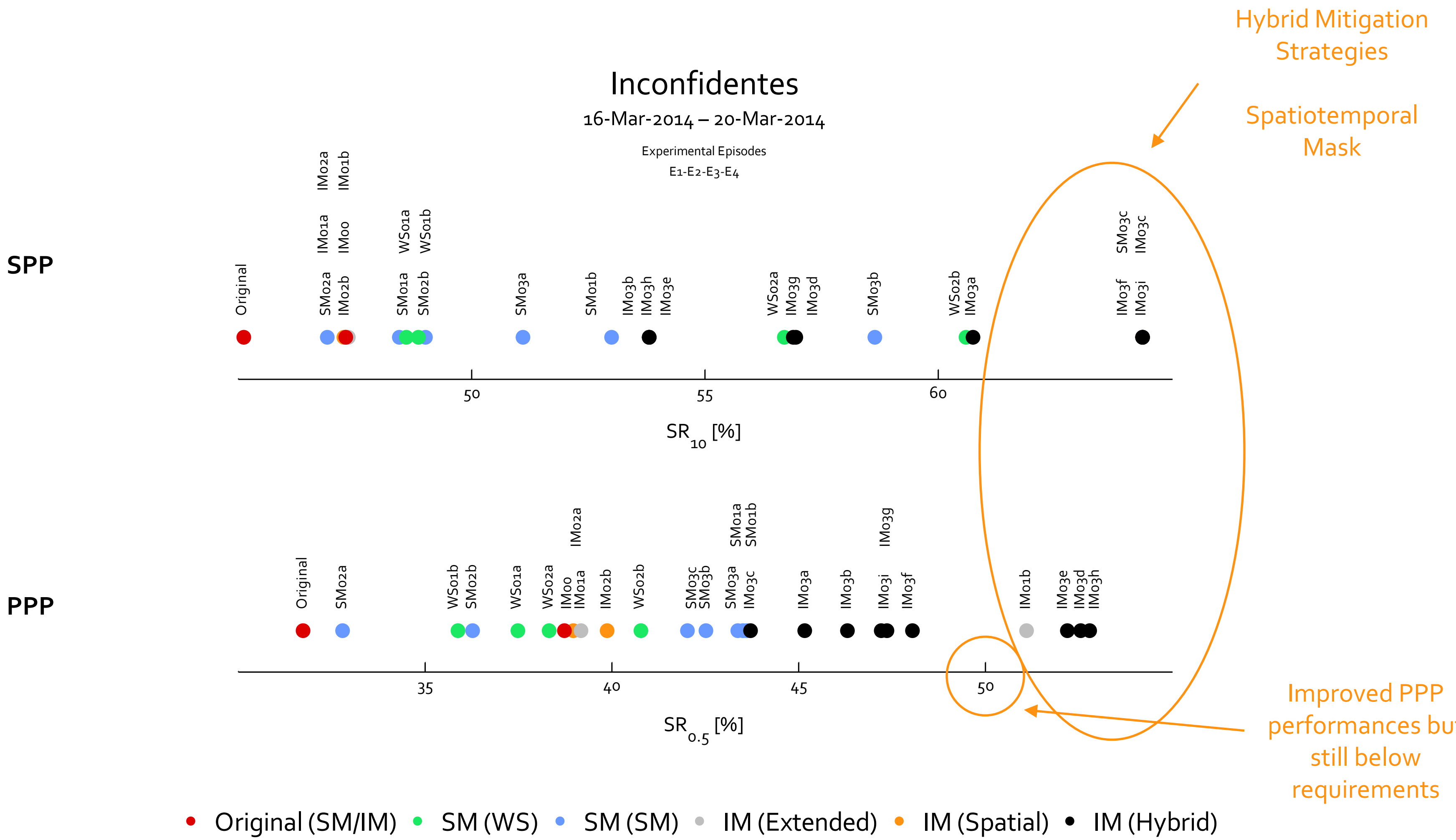


Analysis
GNSS Algorithms and Ionosphere

Geostatistics
Ionospheric Scintillation Skymaps

Prototypes
Mitigation Strategies

Spatial analysis techniques are applicable to GNSS/ISMR measurements collected in a network of stations located near the magnetic equator in order to produce real-time ionospheric scintillation skymaps (H1)

- Detection, scaling and tracking of spatial autocorrelation

- Real-time ionospheric scintillation skymaps

Mitigation strategies based on real-time ionospheric scintillation skymaps improve the performances of the SPP and PPP algorithms in case of low-latitude ionospheric scintillations (H2)

- General improvement of the accuracy, continuity and reliability of the SPP and PPP algorithms

- Higher reliability of the GOS skymaps

- SPP performances improved by tuning the weighting scheme of the stochastic model
- PPP performances improved by applying spatial masks

- Integrity monitoring can bring the performances to the next level in case of ionospheric scintillations

- Hybrid mitigation strategies are very powerful

- PPP performances remain below requirements during intense ionospheric scintillations at low latitudes
  $SR_{0.5}$ = 55% max and at the cost of a heavy computational load

...this research approach constitutes an encouraging breakthrough but there is still room for improvement!

Perspectives exist to extend this research further and reach even better performances for GNSS positioning in case of ionospheric scintillations

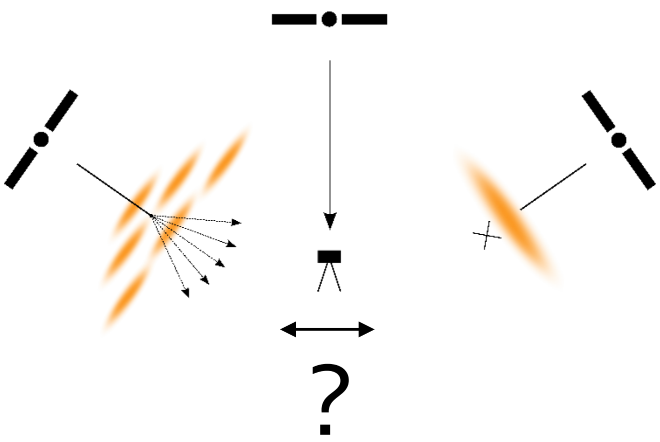
- High-density ionospheric scintillation skymaps (space + time)
    - Alternative variables to measure the impact of ionospheric scintillations on GNSS signals
    - Multiple GNSS constellations
    - High-density GNSS/ISMR networks
    - Smartphone-based crowdsourcing

- Advanced RAIM-FDE technology combined with adaptive exclusion process (pre-processing) and stochastic model
    - GOS skymaps
    - Individual testing
    - Phase/Code/Doppler validation tests
    - Adaptive computational load

- High-latitude ionospheric scintillations

- Application of the approach in other harsh tracking environment (jamming, multipath, etc.)

Ingestion of Ionospheric Scintillation Skymaps into GNSS Algorithms



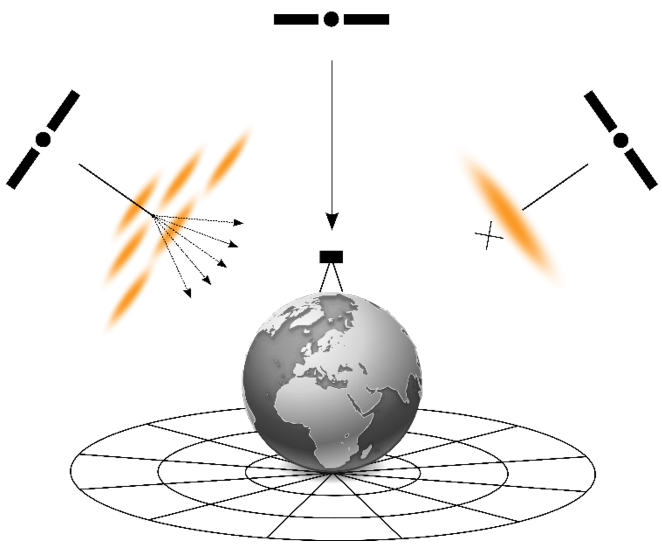
Matthieu Lonchay

PhD Defense

ULiège

Friday 24 May 2019

Ingestion of Ionospheric Scintillation Skymaps into GNSS Algorithms



Matthieu Lonchay

M.Lonchay@alumni.uliege.be

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