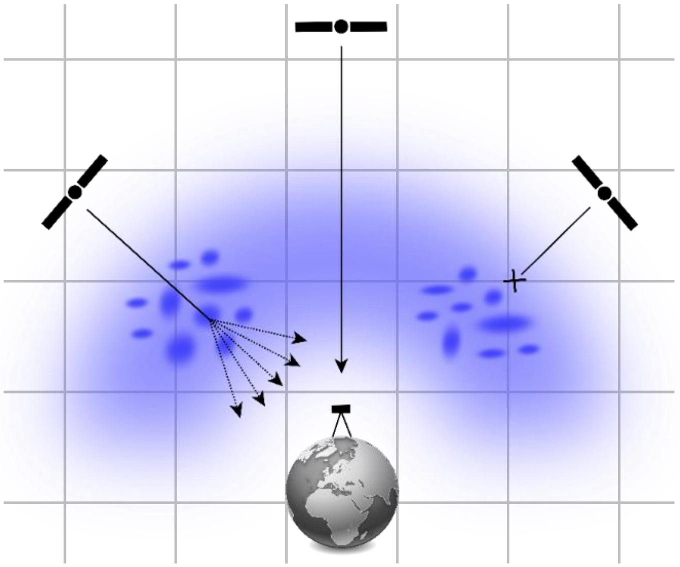
Performances of Absolute GNSS Positioning Algorithms during Equatorial and Polar Ionospheric Scintillations



Matthieu Lonchay

University of Liège, Belgium
Geomatics Unit

Thesis Committee Meeting
Liège, Belgium

13 November 2014

Introduction

Objectives

Research

Conclusion

Discussion

Background

Analysis

Algorithm

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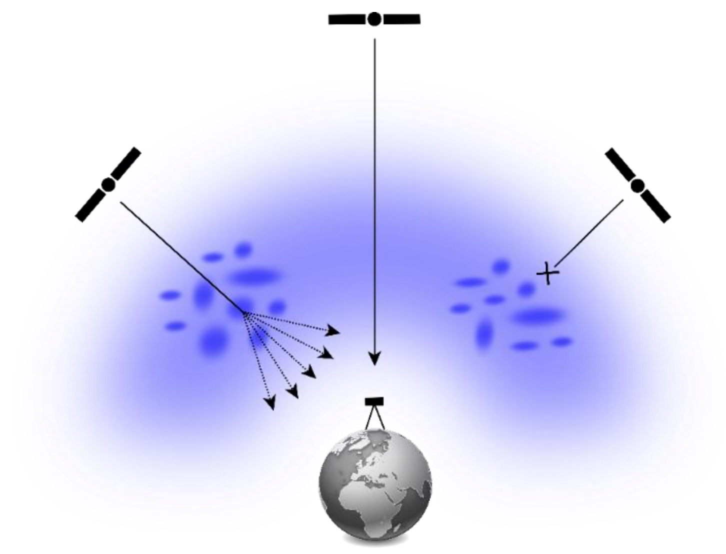
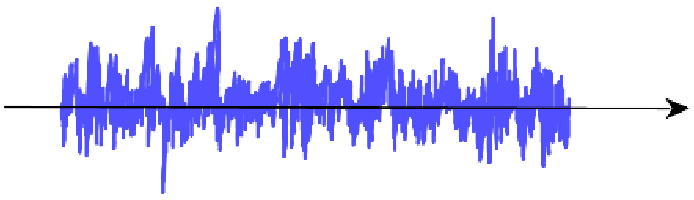
Ionospheric Scintillations are Rapid Fluctuations of the Phase and the Amplitude of Electromagnetic Signals diffracted by the Ionosphere



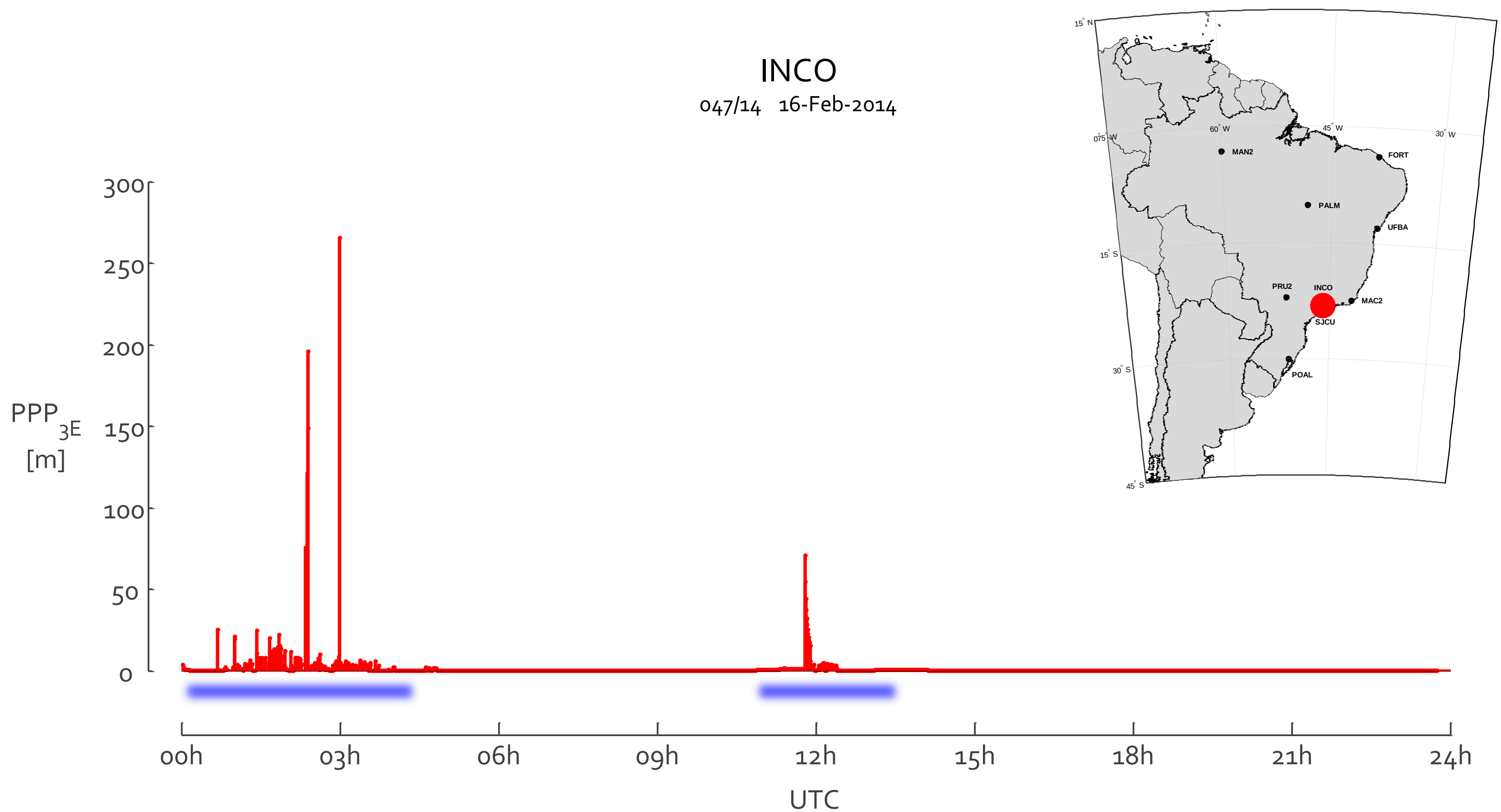


Effects on GNSS Signals Tracking

- Signal Losses
- Noise Measurement
- Cycle Slips
- Weak Geometry

→ Reduced Performances for Positioning

Ionospheric Scintillations limit the performances of GNSS Positioning Algorithms



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My Research aims at improving the Performances of Absolute GNSS Positioning Algorithms (SPP/PPP) in case of Ionospheric Scintillations

1) Analysis

- Descriptive Analysis of Ionospheric Scintillations on GNSS Signals

→ Symptoms

→ M-GNSS + M-Signals

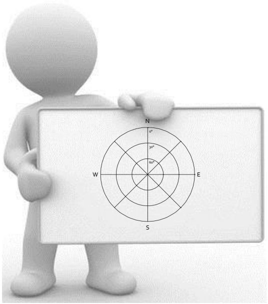
→ Equatorial + Polar Scintillations

→ RINEX vs. ISMR

My Research aims at improving the Performances of Absolute GNSS Positioning Algorithms (SPP/PPP) in case of Ionospheric Scintillations

1) Analysis

- Descriptive Analysis of Ionospheric Scintillations
- Spatial Analysis of Ionospheric Scintillations



Today Meeting:

→ Detection of Spatial Autocorrelation

→ Spatio-Temporal Analysis of Ionospheric Scintillation

→ « Hot Spots » Detection

→ Production of Ionospheric Scintillation Sky Maps

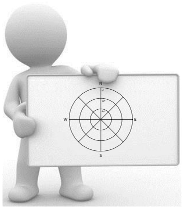
My Research aims at improving the Performances of Absolute GNSS Positioning Algorithms (SPP/PPP) in case of Ionospheric Scintillations

1) Analysis

- Descriptive Analysis of Ionospheric Scintillations
- Spatial Analysis of Ionospheric Scintillations

2) Algorithm

- Spatial Stochastic Modeling
- Spatial Preprocessing Technique



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- Background → Ionosphere, Positioning
- Analysis
- Algorithm

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Introduction

Objectives

Research

- Background → Ionosphere / Positioning
- Analysis
- Algorithm

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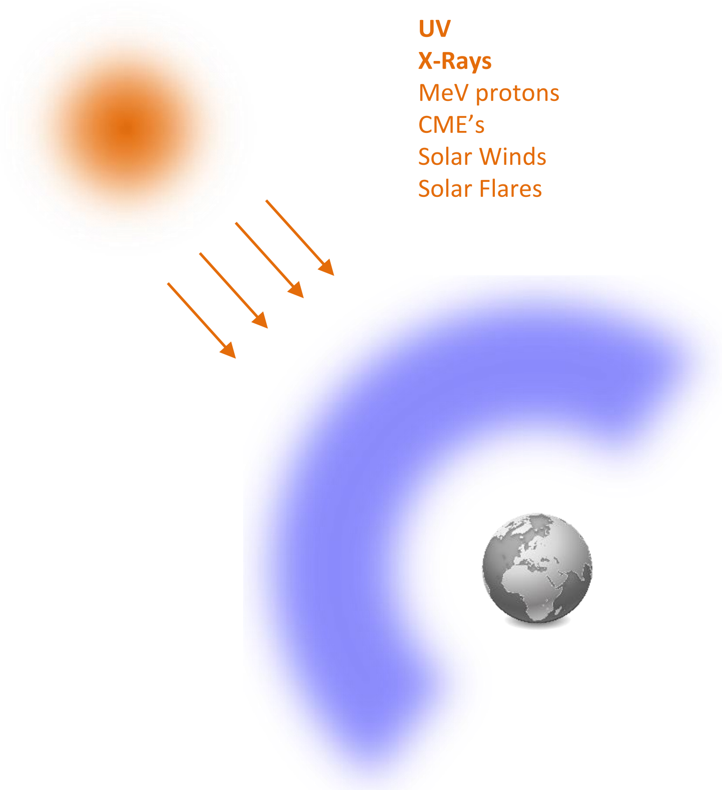
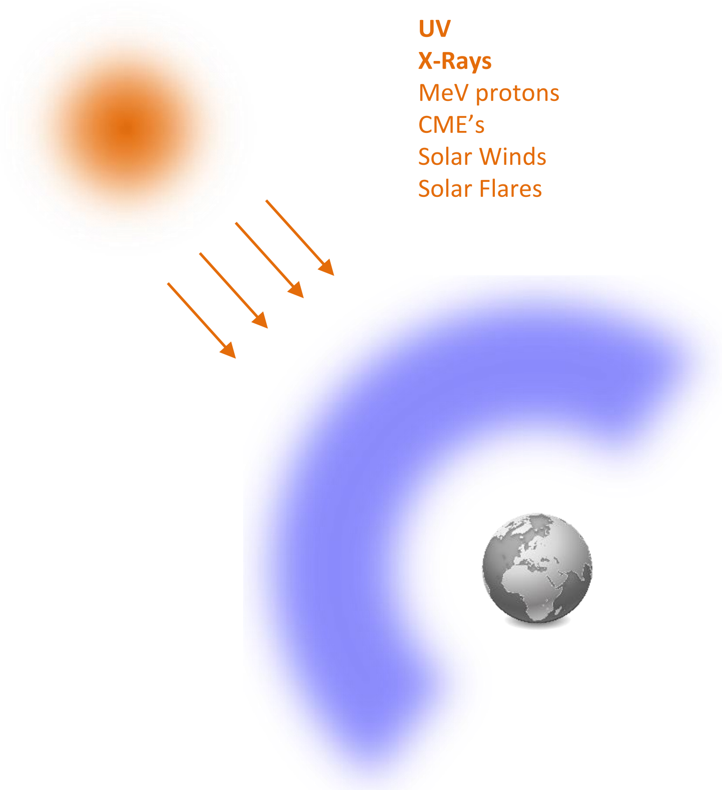
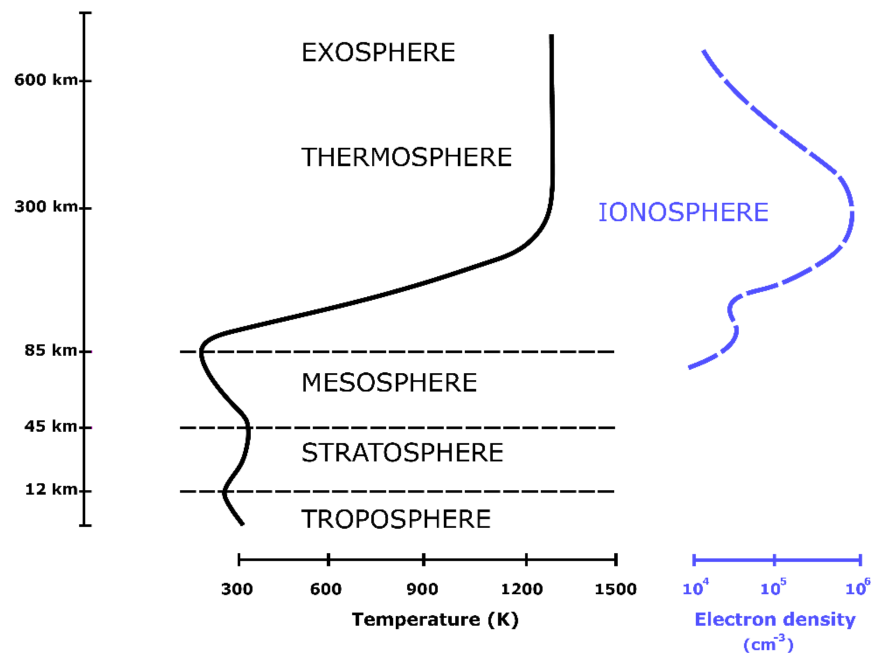
The Ionosphere is a Plasma ionised by Solar Radiations and characterised by an Electron Density highly variable in Space and Time

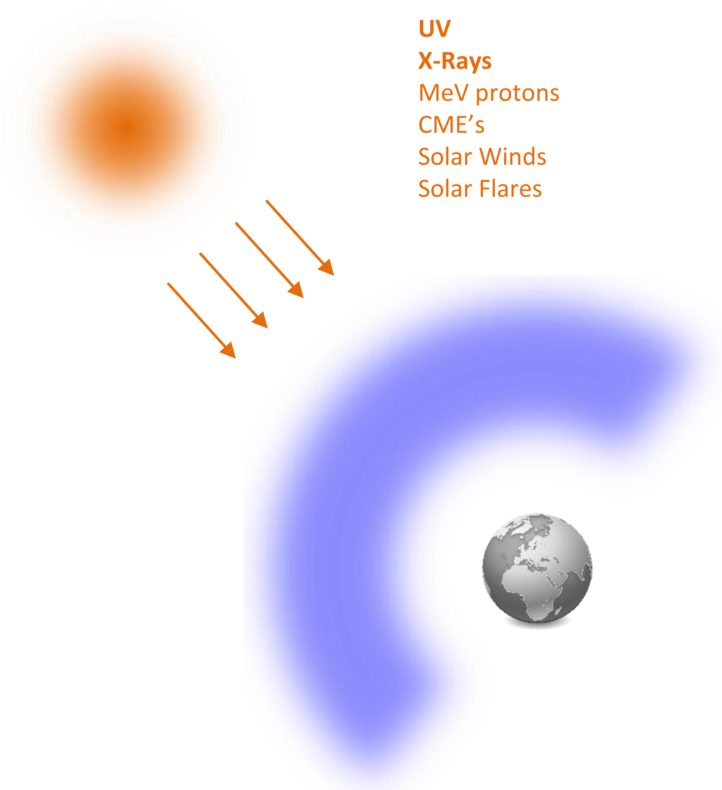


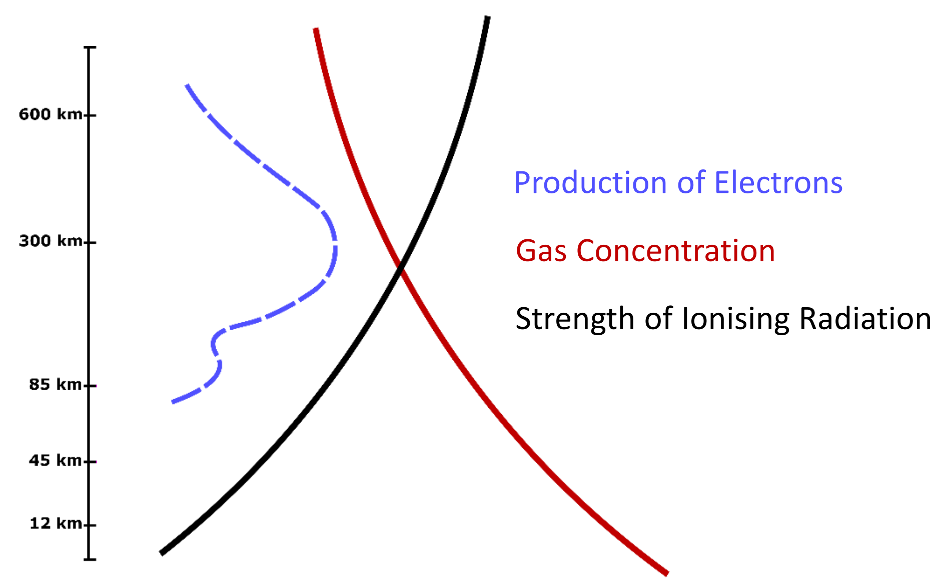
The Earth Atmosphere can be Partitioned in Several Layers Separated by Reversals of the Temperature Gradient





The Vertical Electron Density Profile Results of the Balance between the Gas Concentration and the Strength of Ionising Radiation





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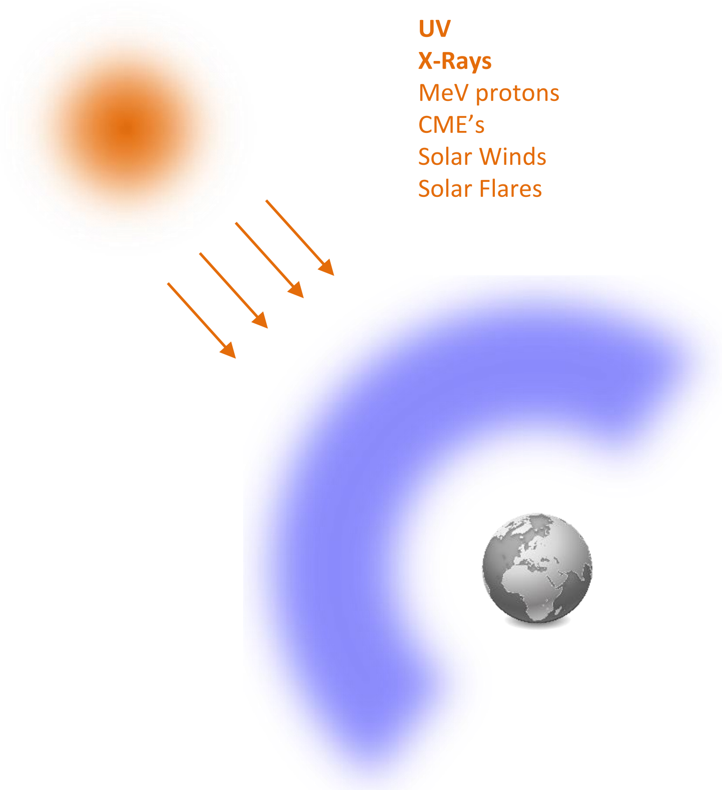
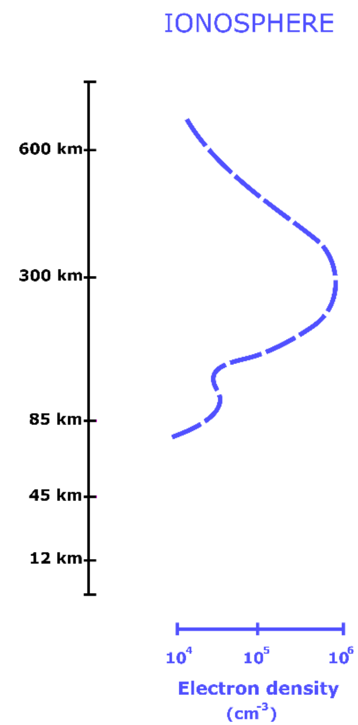
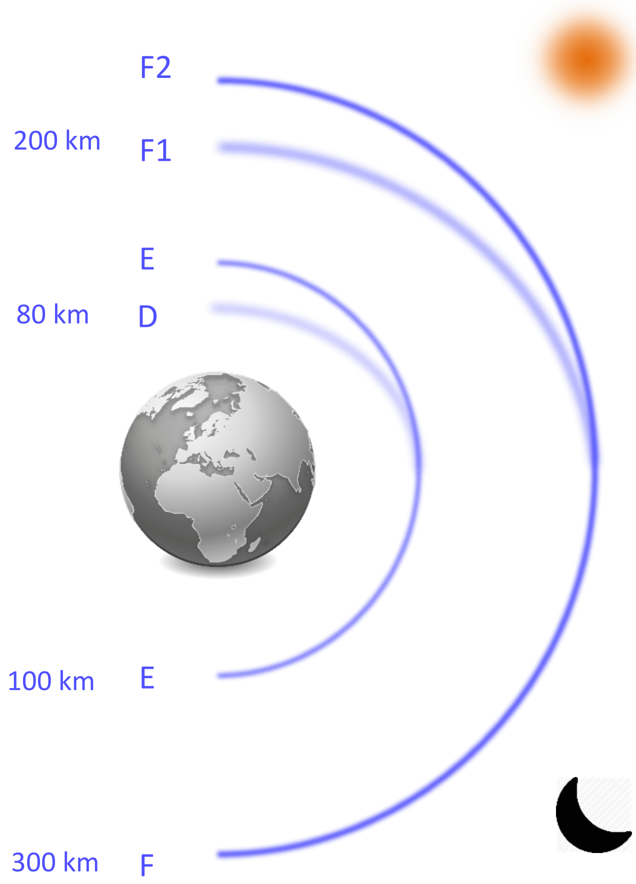


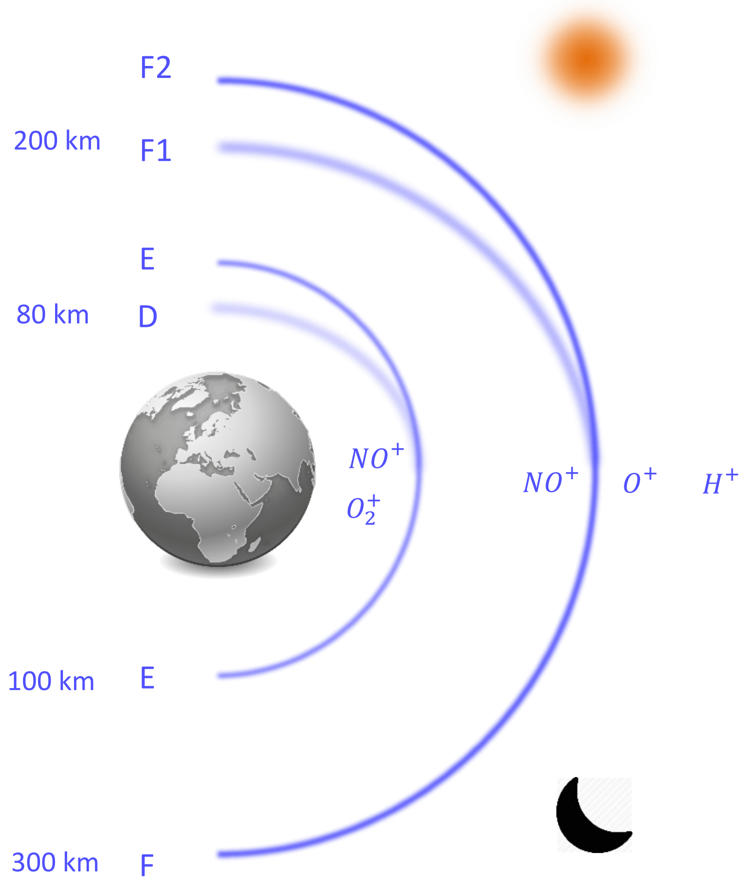


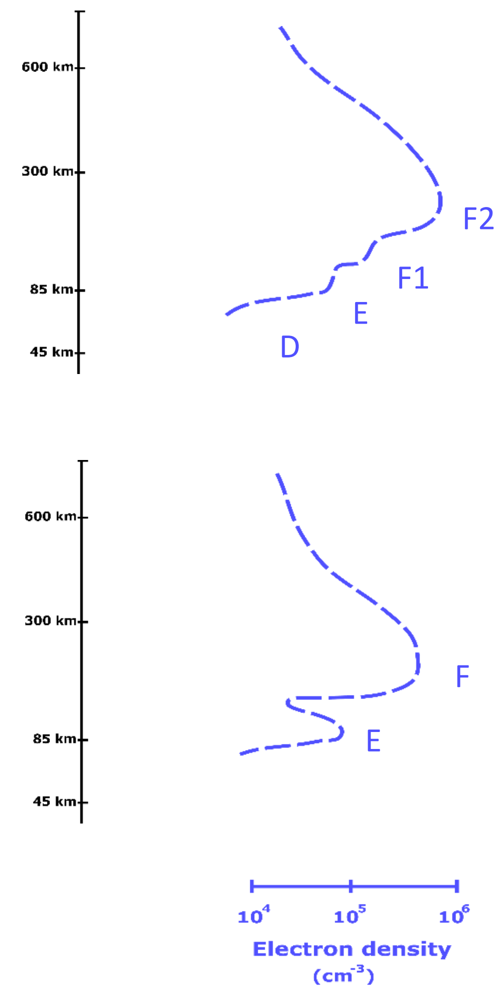
Ionisation Peak

The Ionosphere Structure Exhibits Day-To-Night Variations

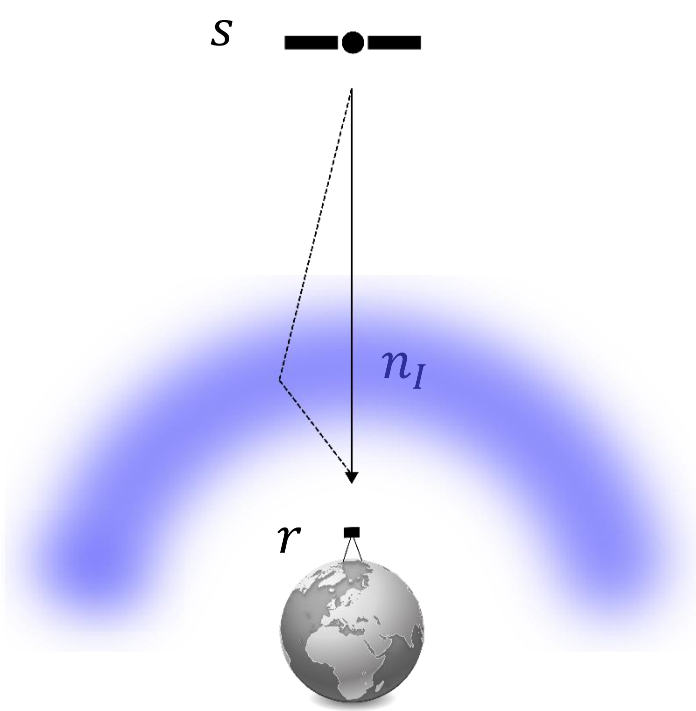


The Multicomponent Earth Atmosphere is partially responsible for the Formation of several Regions in the Ionosphere





The Electron Density of the Ionosphere is responsible for Refraction effects of GNSS radio signals

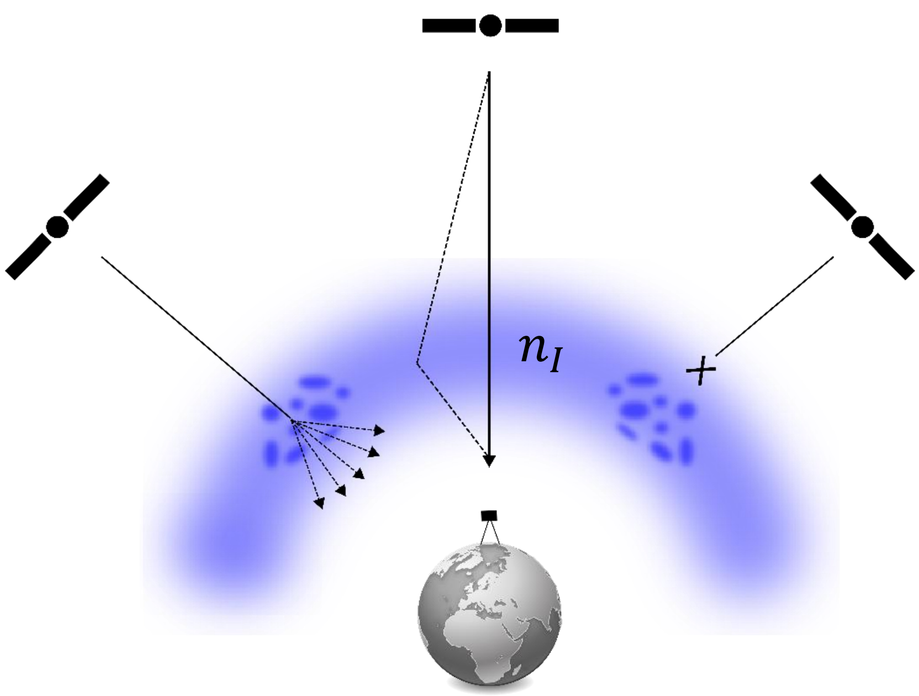


Ionospheric Delay

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

$$I \approx \pm \frac{40.3}{f^2} \int_r^s N_e \, dl = \pm \frac{40.3}{f^2} sTEC$$

Small-Scale Irregularities in the Electron Density of the Ionosphere are responsible for Diffraction effects of GNSS radio signals



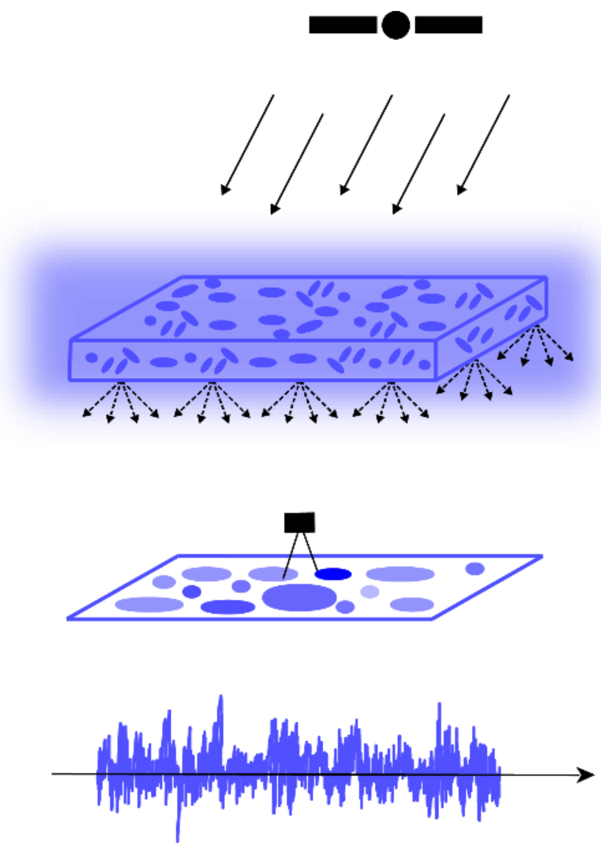
Fluctuation of the GNSS signal phase

$$\sigma_\varphi = \sqrt{\langle \theta^2 \rangle - \langle \theta \rangle^2}$$

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



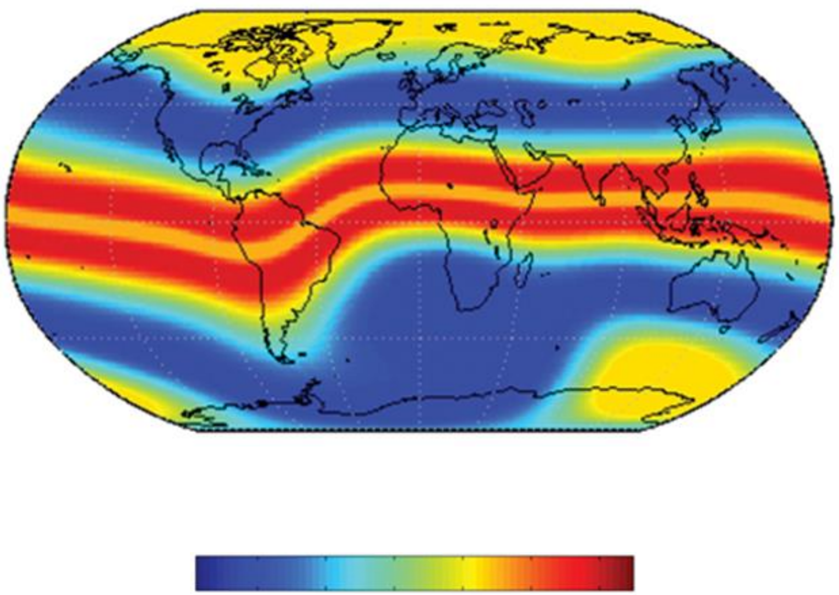
Fluctuation of the GNSS signal phase

$$\sigma_\varphi = \sqrt{\langle \theta^2 \rangle - \langle \theta \rangle^2}$$

Fluctuation of the GNSS signal amplitude

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

Intense Ionospheric Scintillations affect mostly two areas on Earth:
Equatorial and Polar Latitudes



Infrequent Frequent

Operating Frequencies

Geographic Locations

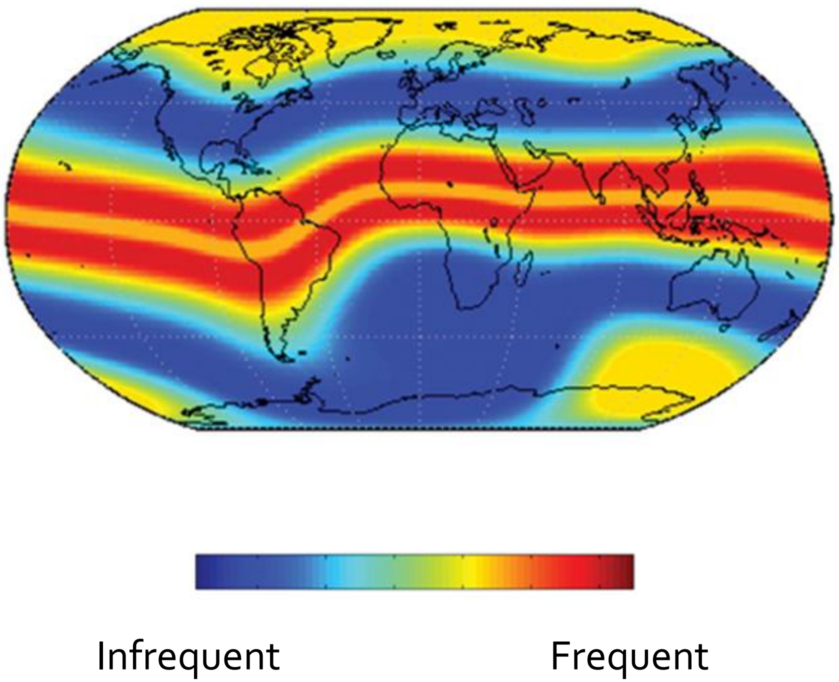
Local Time

Season

Magnetic Activity

Solar Activity

Intense Ionospheric Scintillations affect mostly two areas on Earth:
Equatorial and Polar Latitudes



Large Scale Irregularities
≈ 100 km

Small Scale Irregularities
≈ 1 – 100 m

Background Plasma Drift Speed
≈ 50-150 ms^{-1}

Duration
≈ minutes/hours

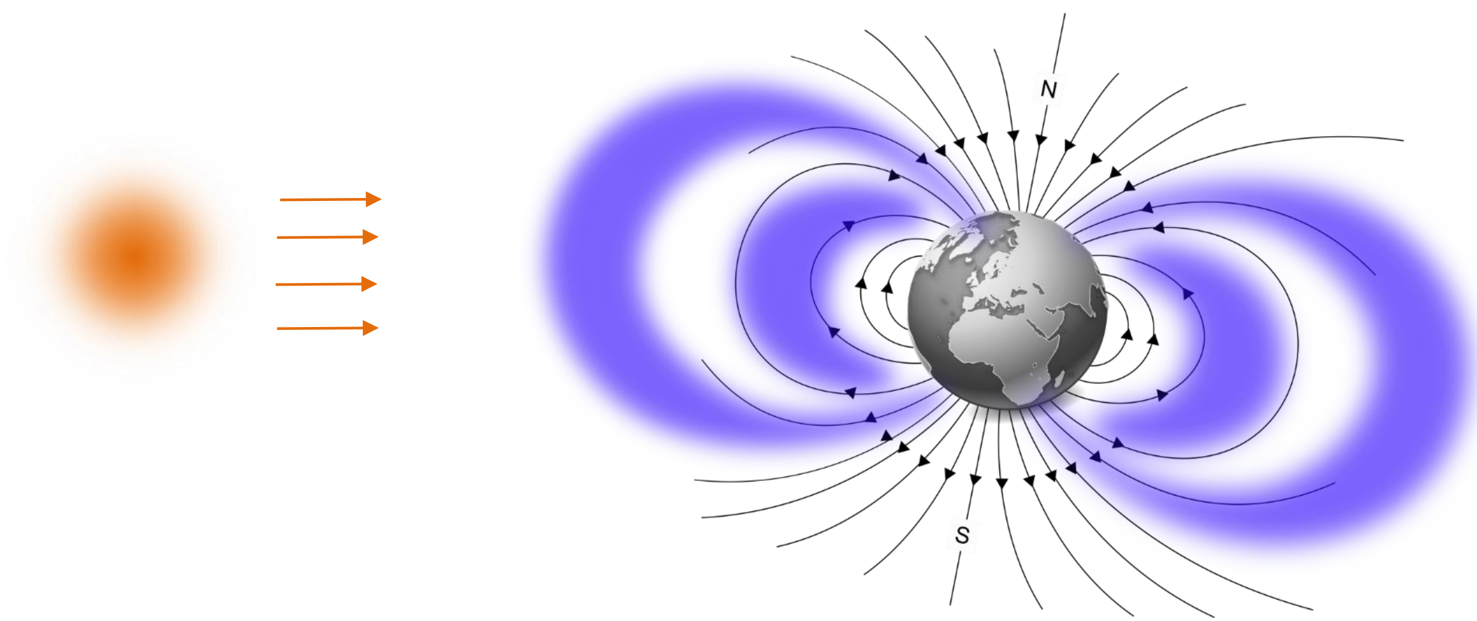
Spatio-Temporal Variations of Scintillations Intensity

Polar and Equatorial Ionospheric Scintillations are generated by different physical process

Polar Scintillations

Geomagnetic Storm

- Polar IS are strongly dependent on the Geomagnetic Activity
- The frequency of Polar IS varies during the 11-year Solar Cycles
- Geomagnetic Planetary Kp-Index [0-9]
- Polar IS can occur at any time during any season



Earth Magnetic Field

Van Allen radiation belts

Polar and Equatorial Ionospheric Scintillations are generated by different physical process

Polar Scintillations

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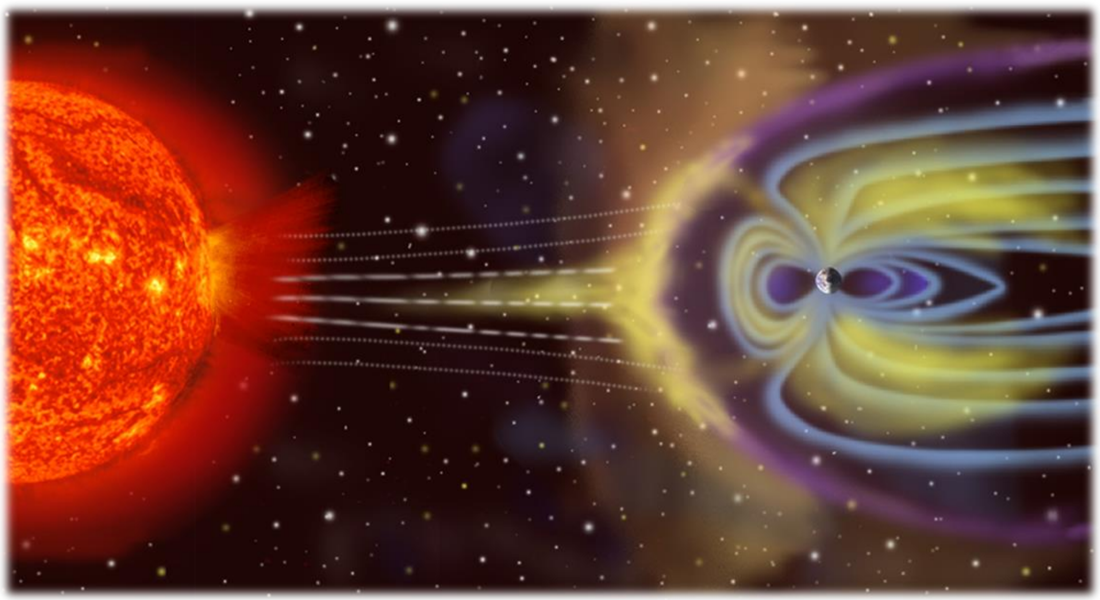

Birth of a Geomagnetic Storm

Polar and Equatorial Ionospheric Scintillations are generated by different physical process

Polar Scintillations

Geomagnetic Storm

- Polar IS are strongly dependent on the Geomagnetic Activity
- The frequency of Polar IS varies during the 11-year Solar Cycles
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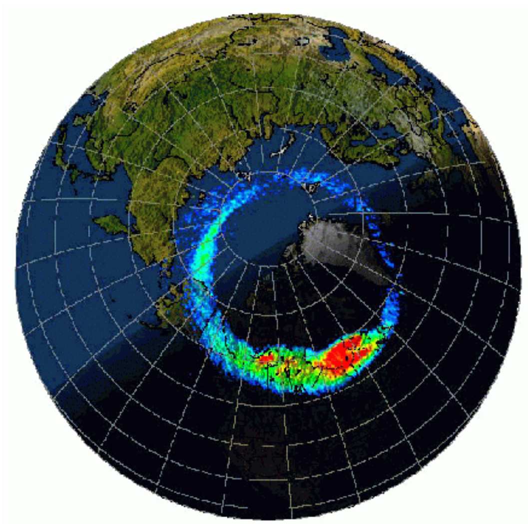
- Polar IS can occur at any time during any season

Aurora Borealis



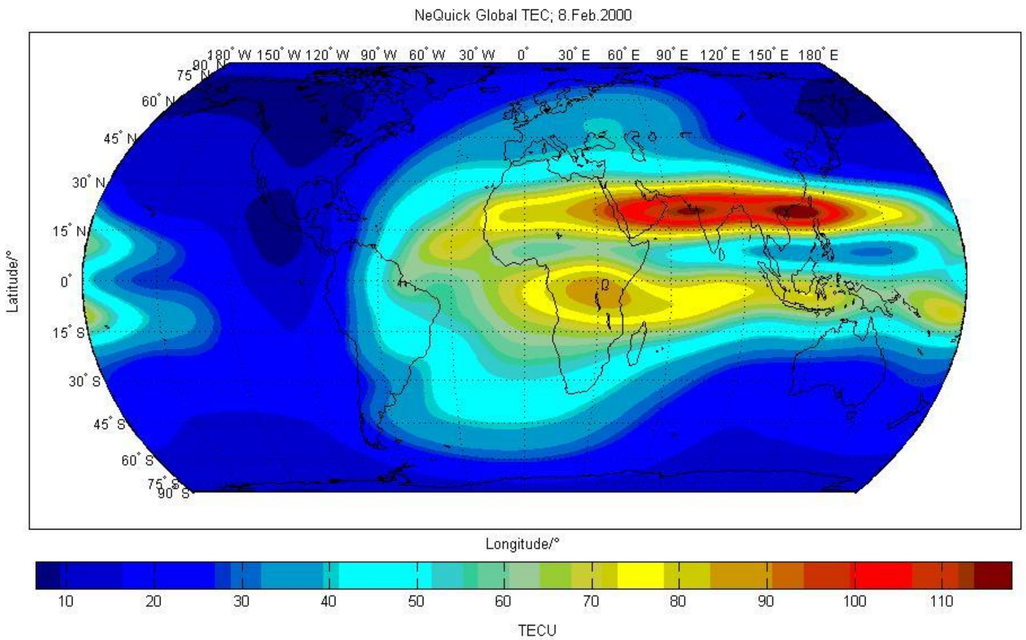
Auroral Oval

Polar and Equatorial Ionospheric Scintillations are generated by different physical process

Equatorial Scintillations

Equatorial Anomaly

- Daily Post-Sunset Irregularities
- Rayleigh-Taylor Instability
- Disturbance Storm Time Index (DST)
- Dense Ionosphere distributed in two bands around the Geomagnetic Equator



Introduction

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Research

- Background
  - Ionosphere
  - Positioning
- Analysis
- Algorithm

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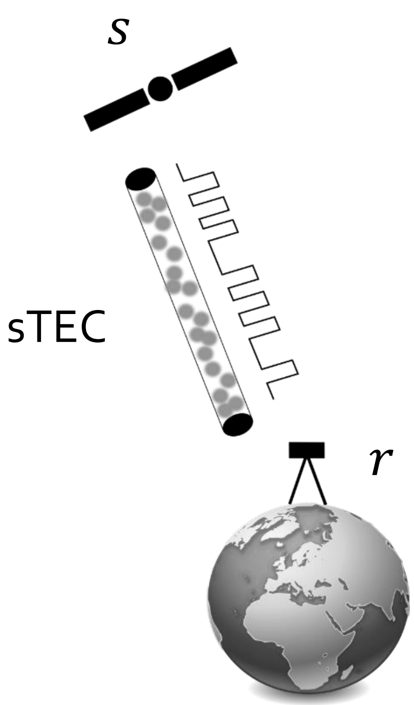
Satellite Positioning is based on Multilateration

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

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

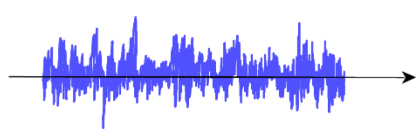


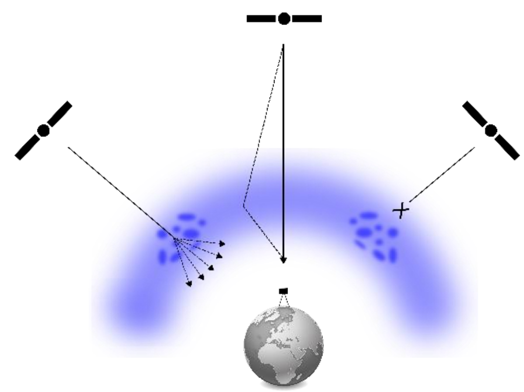
$$D_r^s = \sqrt{(X^s - X_r)^2 + (Y^s - Y_r)^2 + (Z^s - Z_r)^2}$$

$\varepsilon_{r,k,m}^s$ $\varepsilon_{r,k,\phi}^s$

$N_{r,k}^s$

$$I_{r,k}^s = \frac{40.3}{f^2} sTEC$$

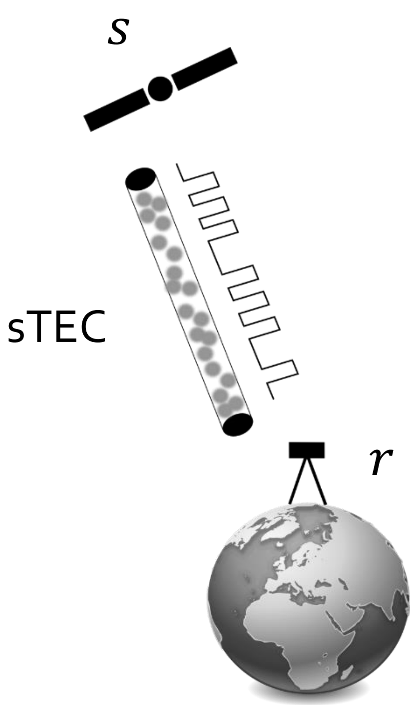




The Standard Point Positioning (SPP) is an Elementary SF Positioning Algorithm

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

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



Pseudorange measurements

Single Frequency

Single Point Single Epoch (SPSE) Technique

Real-Time / Post-Processing

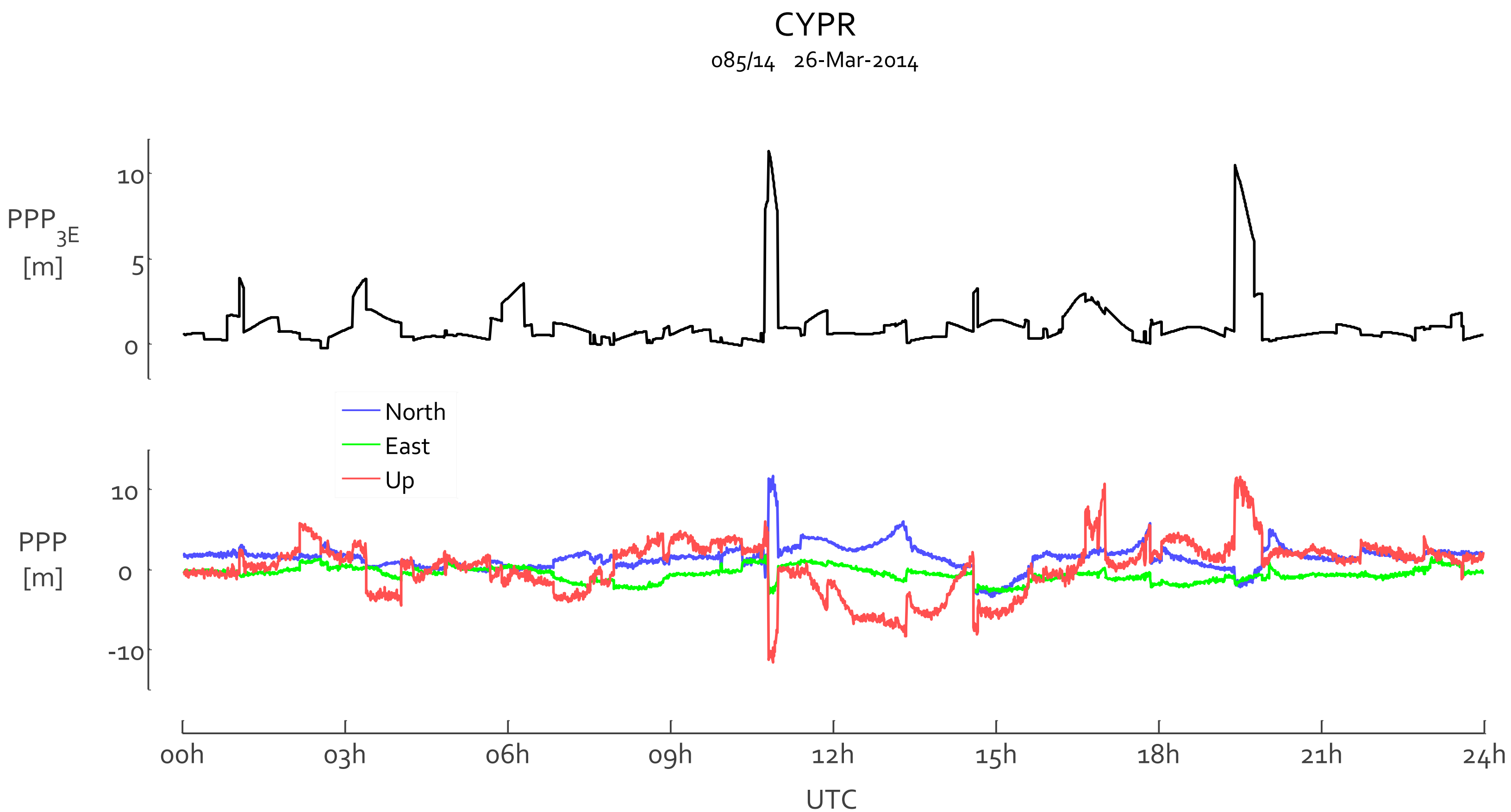
Static / Kinematic

Atmospheric Models (Ionosphere and Troposphere)

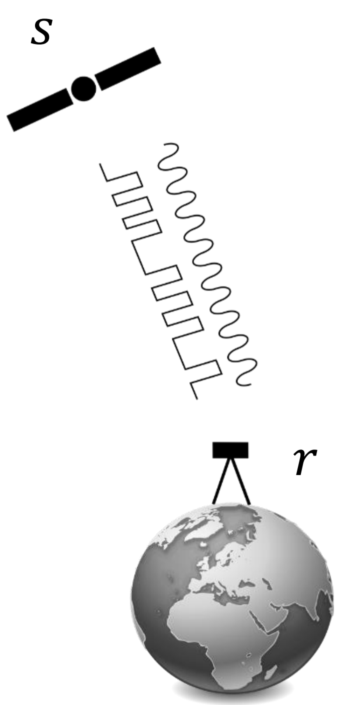
Broadcast Ephemeris

Least Square Adjustement (LSA)

The Standard Point Positioning (SPP) is an Elementary SF Positioning Algorithm



The Precise Point Positioning (PPP) is an Advanced DF Positioning Algorithm



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

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

Pseudorange and Carrier-Phase measurements

Ambiguity Resolution Process

Dual Frequency

Real-Time / Post-Processing

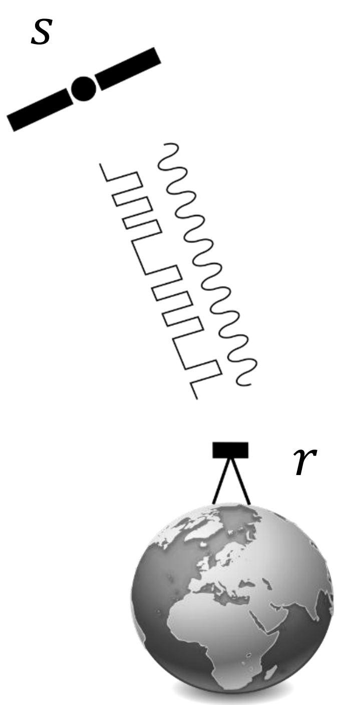
Static / Kinematic

Strategies against atmospheric effects (Ionosphere Free Model)

Precise Products: Ephemeris / Code-Phase Delays / Antenna

Sequential Least Squares Adjustment (Filter)

The Precise Point Positioning (PPP) is an Advanced DF Positioning Algorithm



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

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

Mathematical Model: Ionosphere-Free + Precise Products

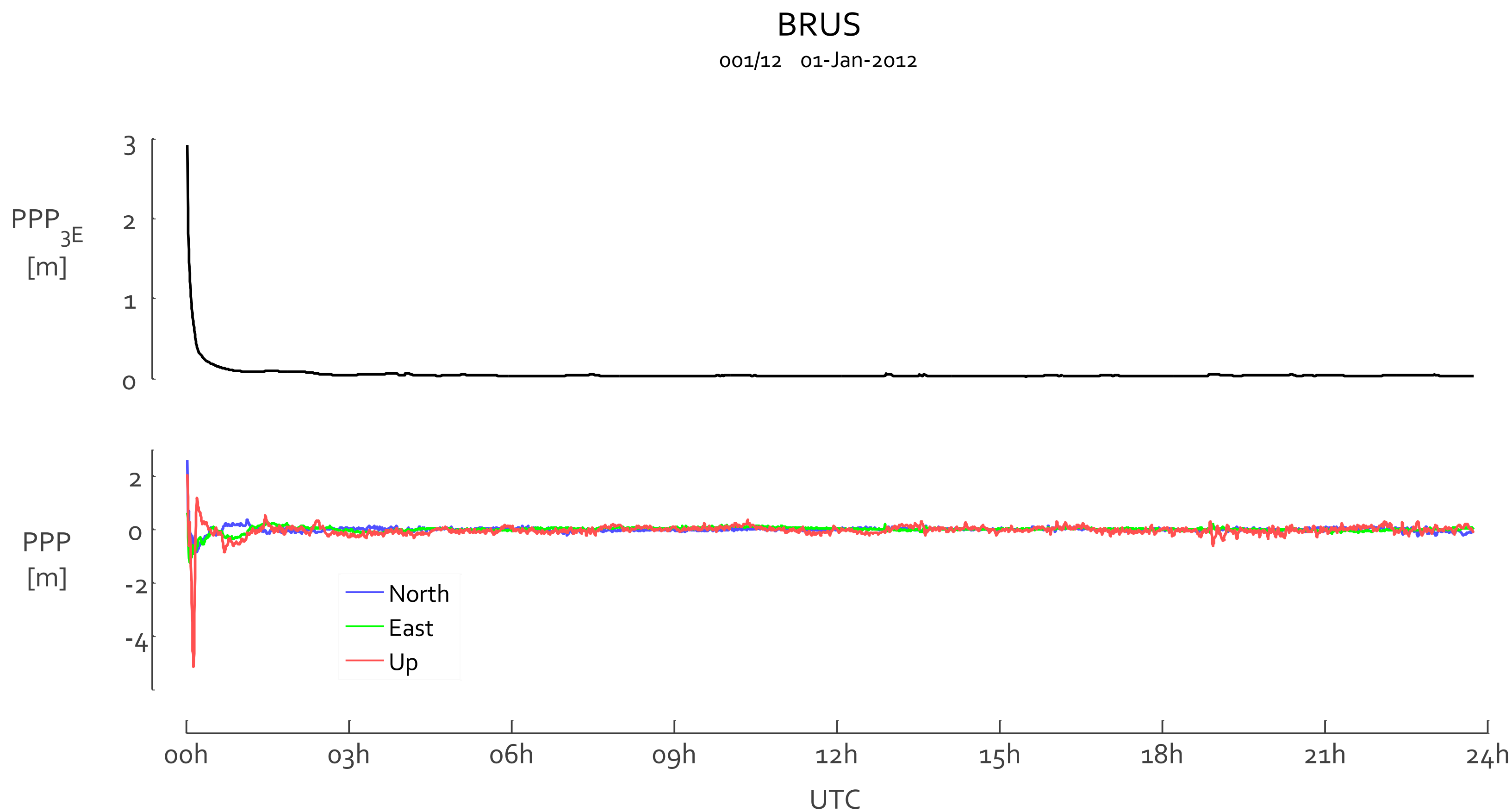
$$P_{r,IF}^s(\mathrm{t}) = \underline{D_r^s} + \underline{T_r^s} + \mathrm{c}\,(\Delta t^s - \underline{\Delta t_r}) + M_{r,IF,m}^s + \varepsilon_{r,IF,m}^s$$

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

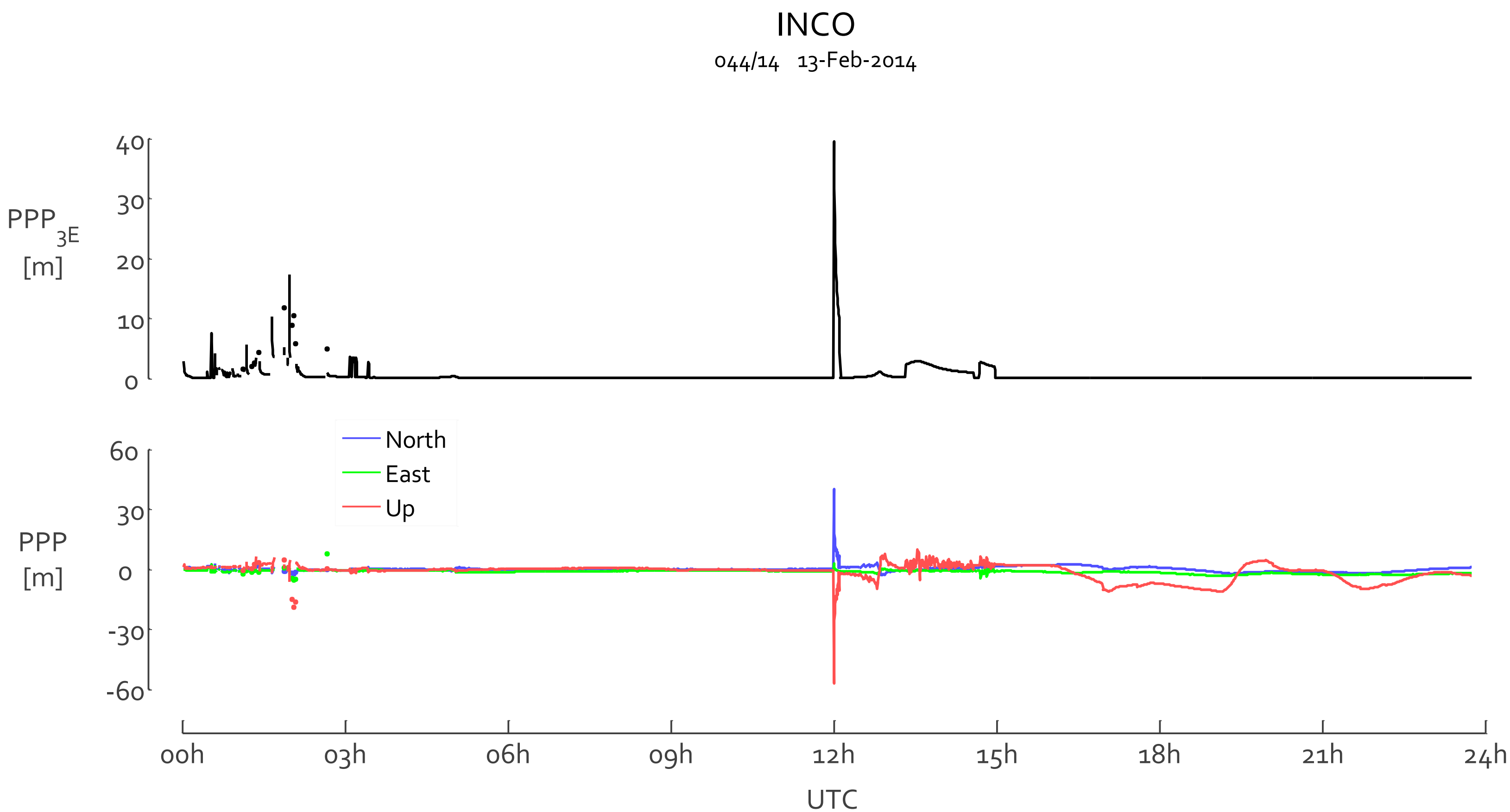
Stochastic Model

Solution: Sequential Least Square Adjustment (Filter)

The Precise Point Positioning (PPP) is an Advanced DF Positioning Algorithm



The Precise Point Positioning (PPP) is highly Sensitive to Ionospheric Scintillations Effects



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- Background
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  - Statistics
  - Spatiality
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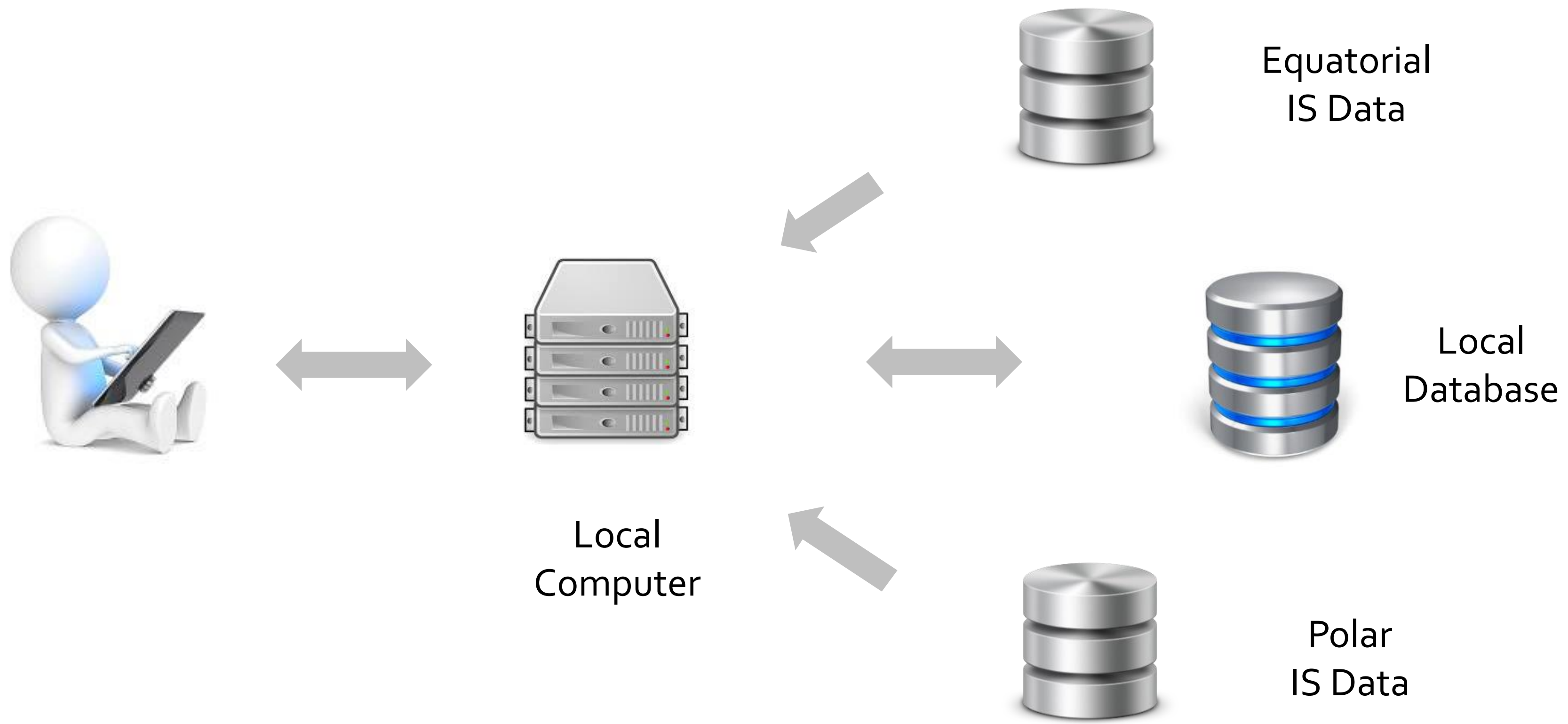
We developped a Matlab Software for Processing GNSS Ionospheric Scintillation Measurements

Acquisition Storage Merging Computation Visualization

O	RINEX Observation
P	RINEX Navigation (M-GNSS)
I	ISMR
J	Jitter
K	Geomagnetic Kp
D	Geomagnetic DST
X	Positioning - SPP
Y	Positioning - PPP
Z	Positioning - POS

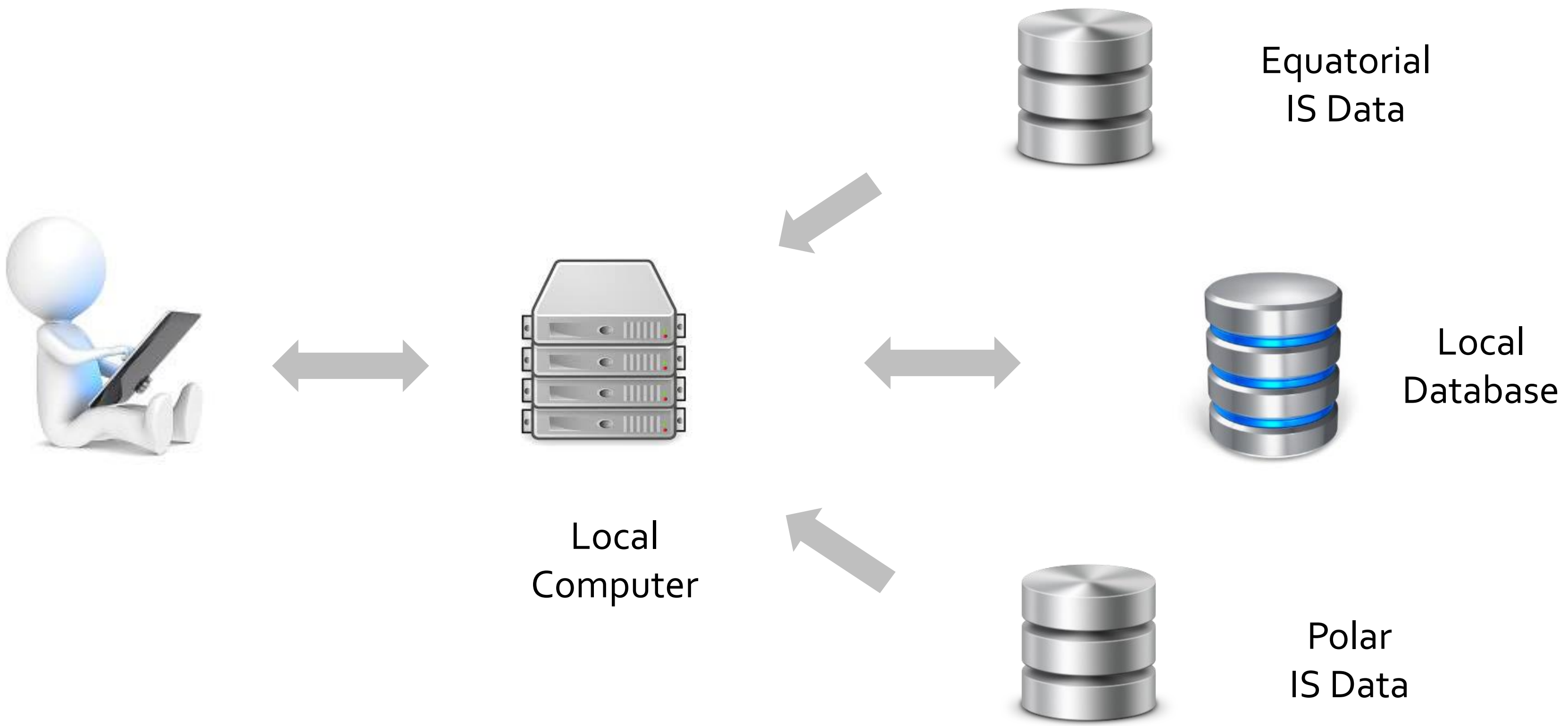
We developped a Matlab Software for Processing GNSS Ionospheric Scintillation Measurements

Acquisition | Storage | Merging | Computation | Visualization



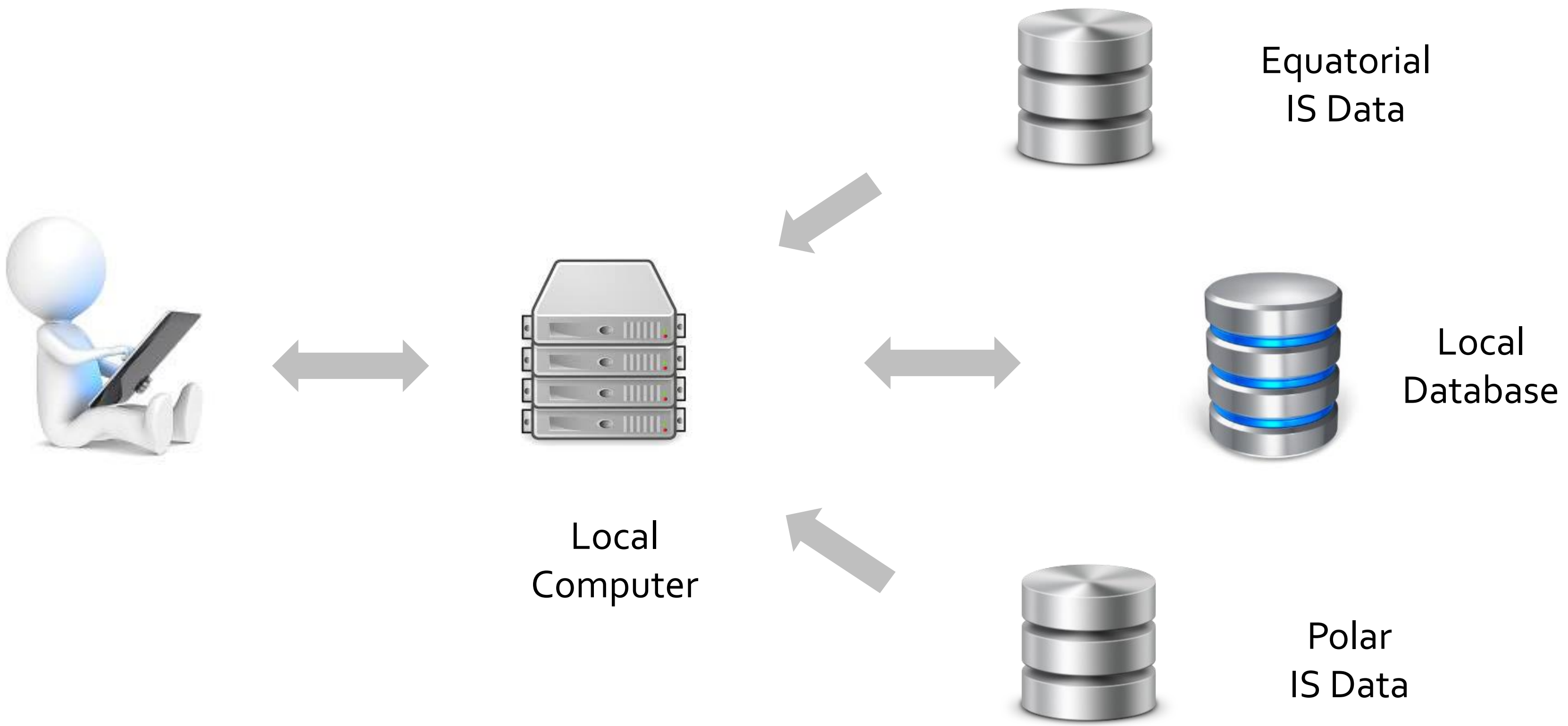
We developped a Matlab Software for Processing GNSS Ionospheric Scintillation Measurements

Acquisition Storage Merging Computation Visualization



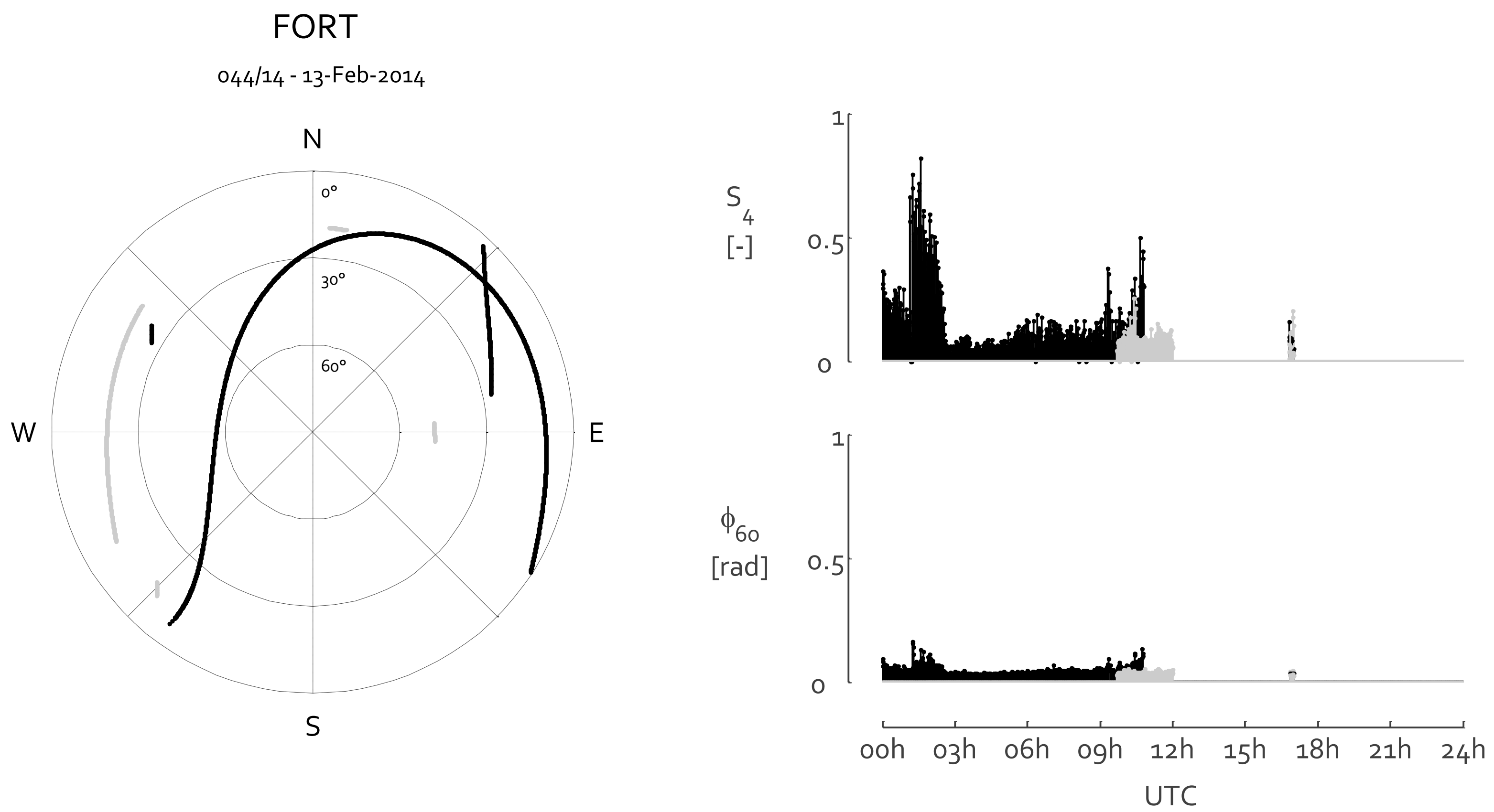
We developped a Matlab Software for Processing GNSS Ionospheric Scintillation Measurements

Acquisition Storage Merging **Computation** Visualization



We developped a Matlab Software for Processing GNSS Ionospheric Scintillation Measurements

Acquisition | Storage | Merging | Computation | Visualization



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Description

Detection

Scale

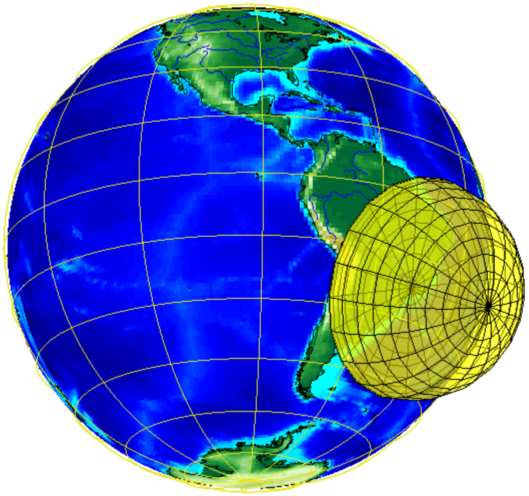
Location

Introduction

Configuration

Spatial Dependency

Interpolation



Description

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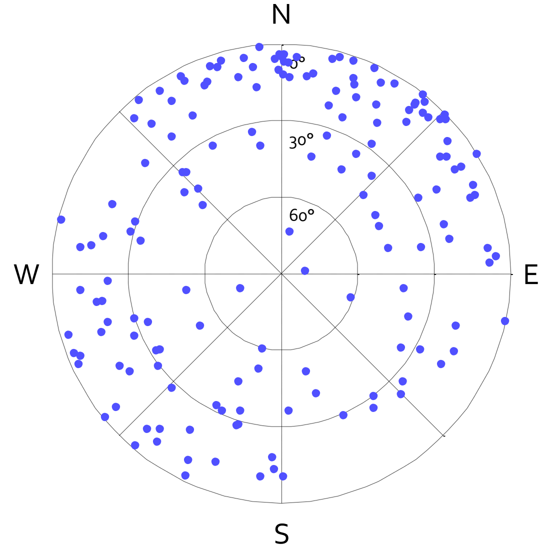
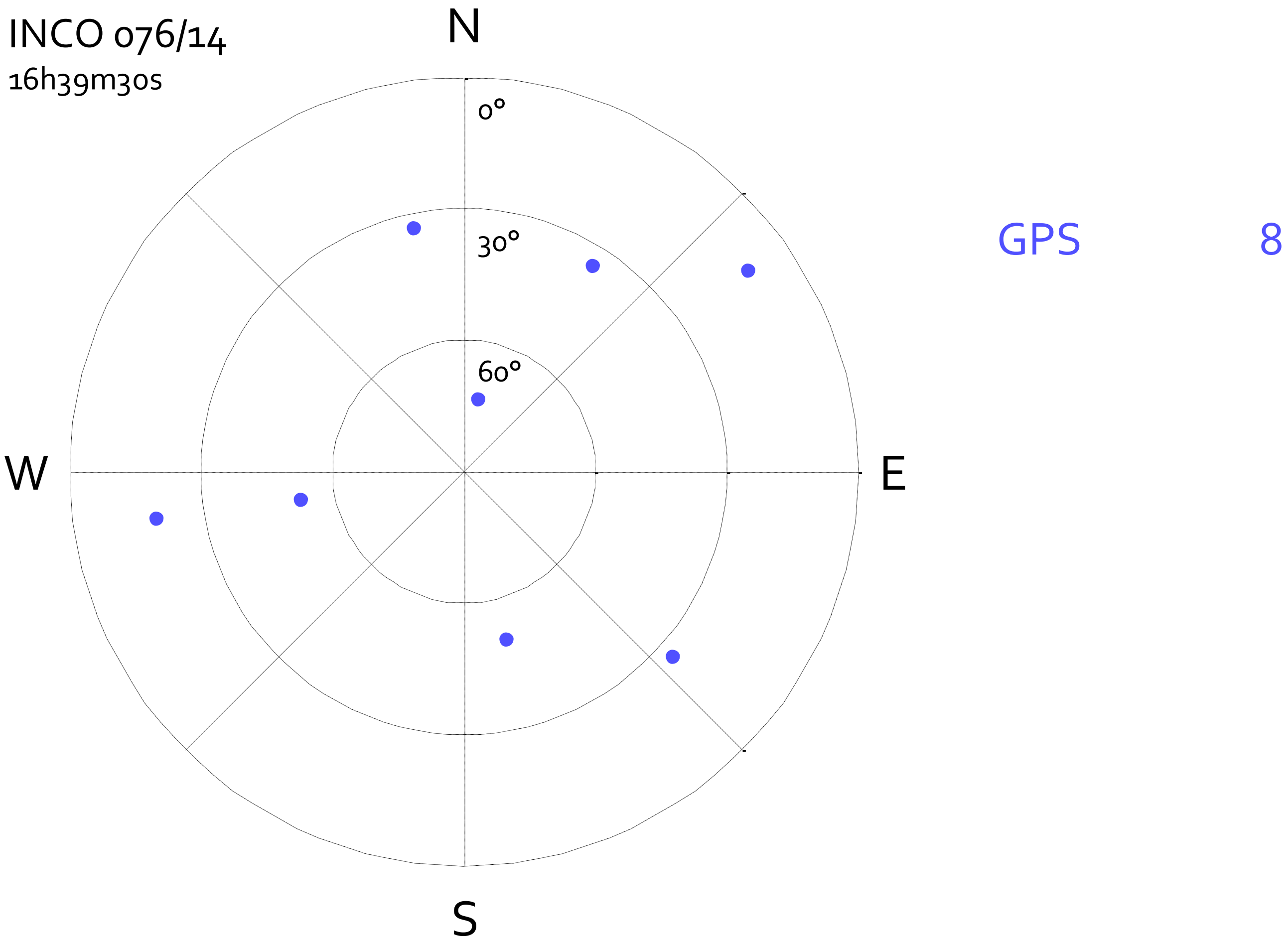


	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●
Interpolation				

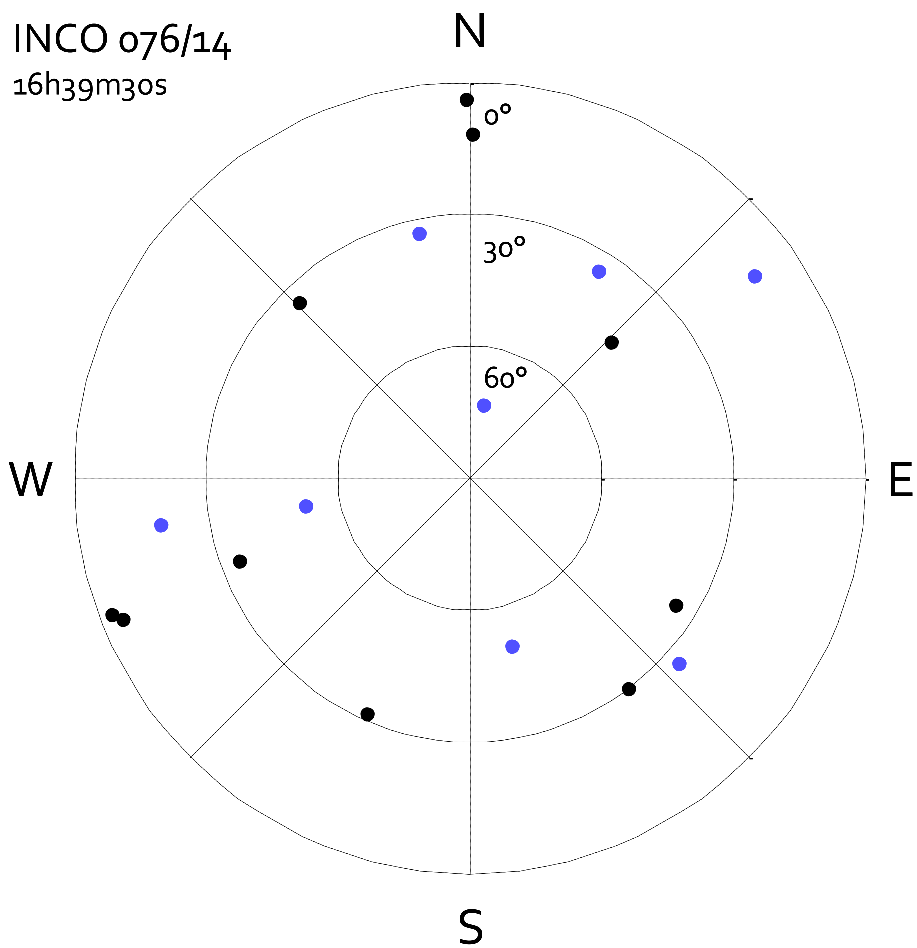
	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●
Interpolation				

The M-GNSS Measurement Skyplot constitute the Experimental Data Field



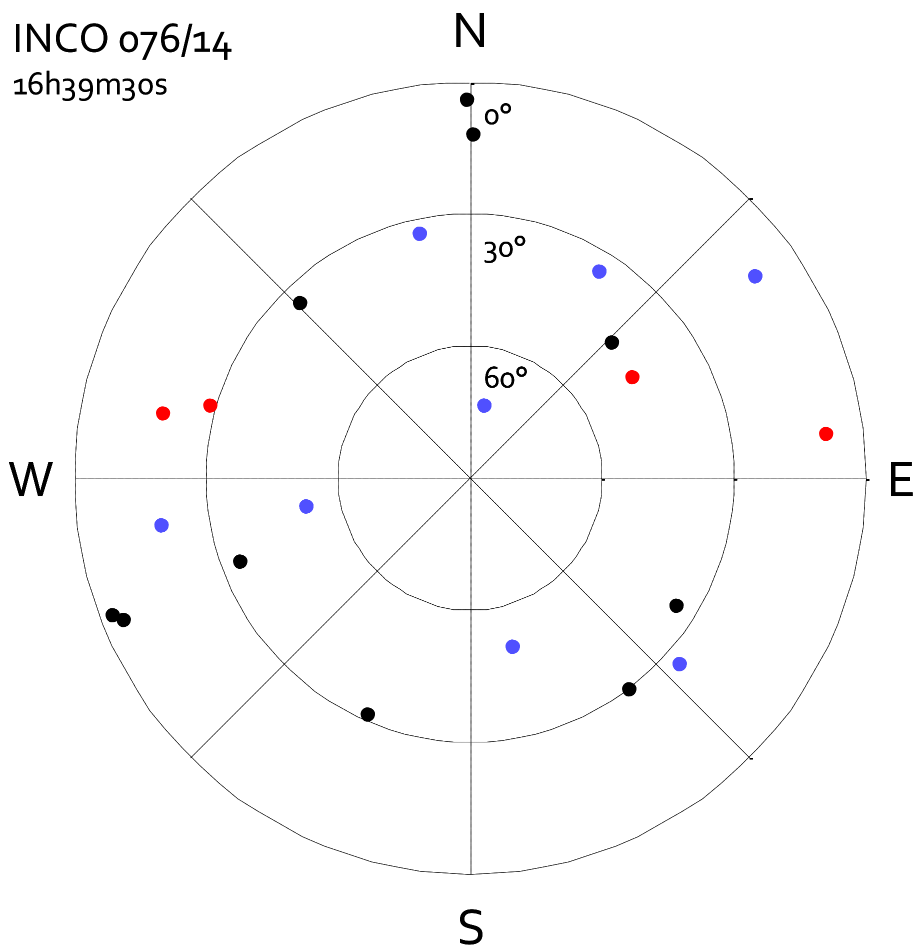
The M-GNSS Measurement Skyplot constitute the Experimental Data Field

INCO 076/14
16h39m30s



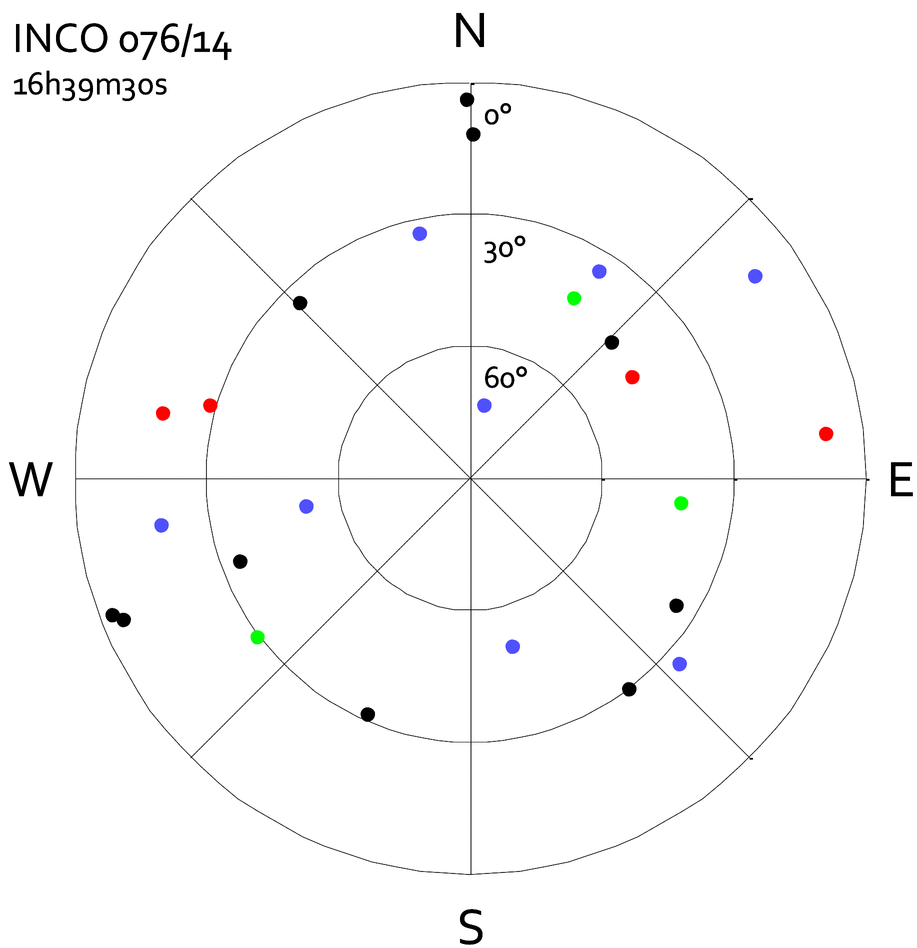
GPS	8
GLONASS	10
	18

The M-GNSS Measurement Skyplot constitute the Experimental Data Field



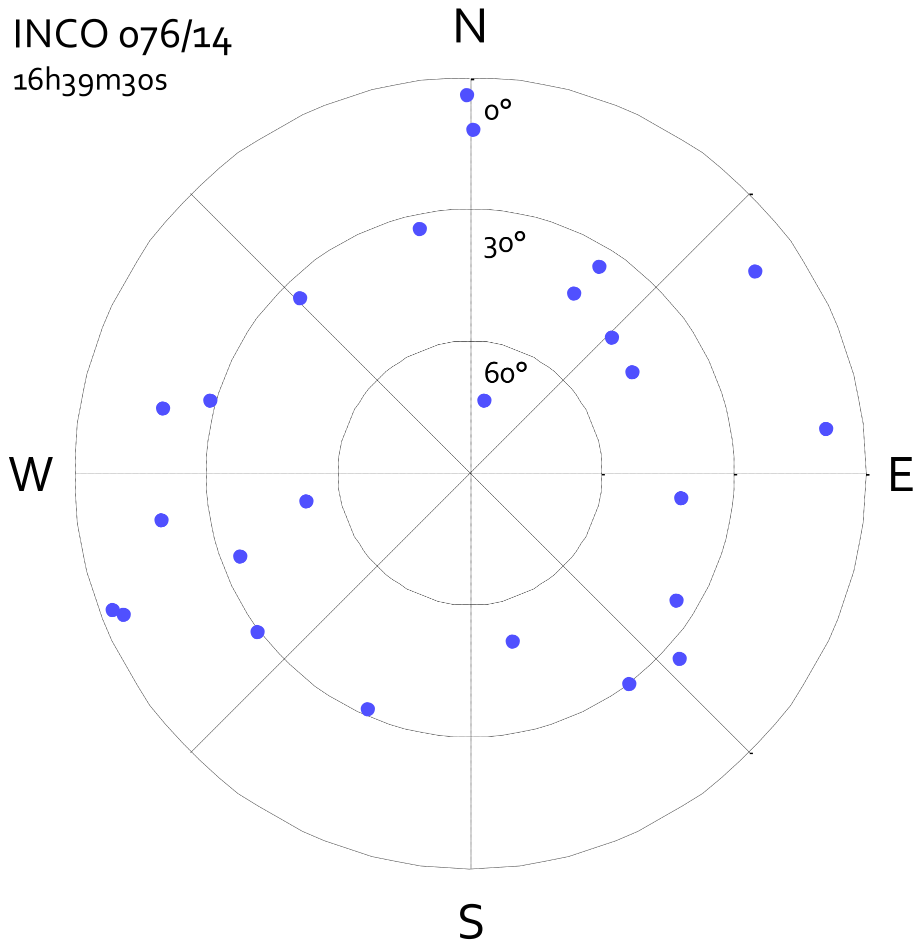
GPS	8
GLONASS	10
SBAS	4
	22

The M-GNSS Measurement Skyplot constitute the Experimental Data Field



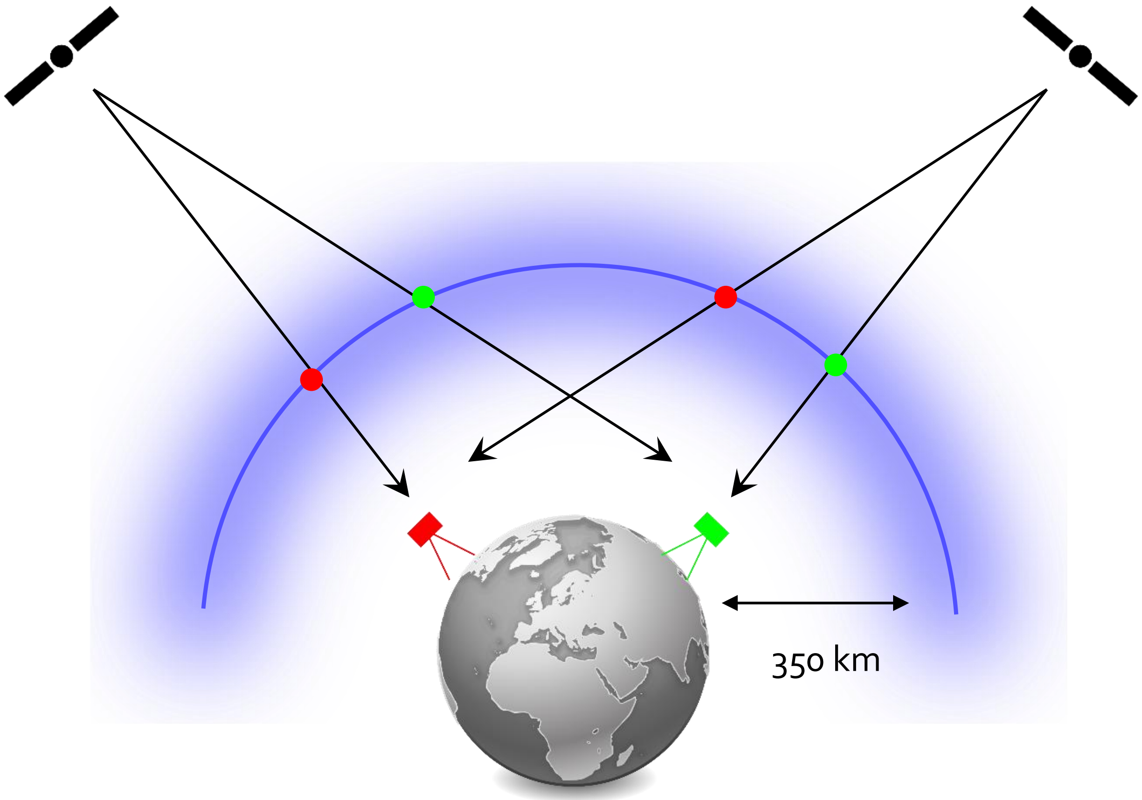
GPS	8
GLONASS	10
SBAS	4
GALILEO	3
	25

The M-GNSS Measurement Skyplot constitute the Experimental Data Field



M-GNSS 25

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

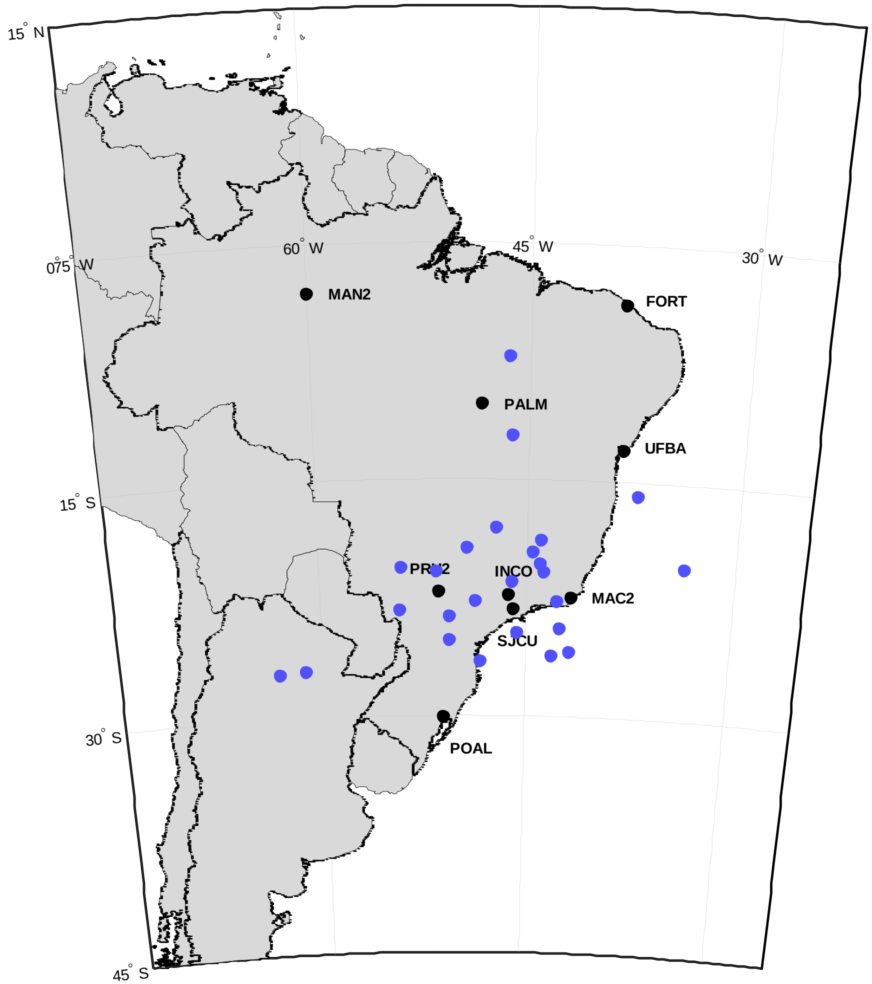


The M-GNSS Measurement Skyplot constitute the Experimental Data Field

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

076/14

16h39m30s

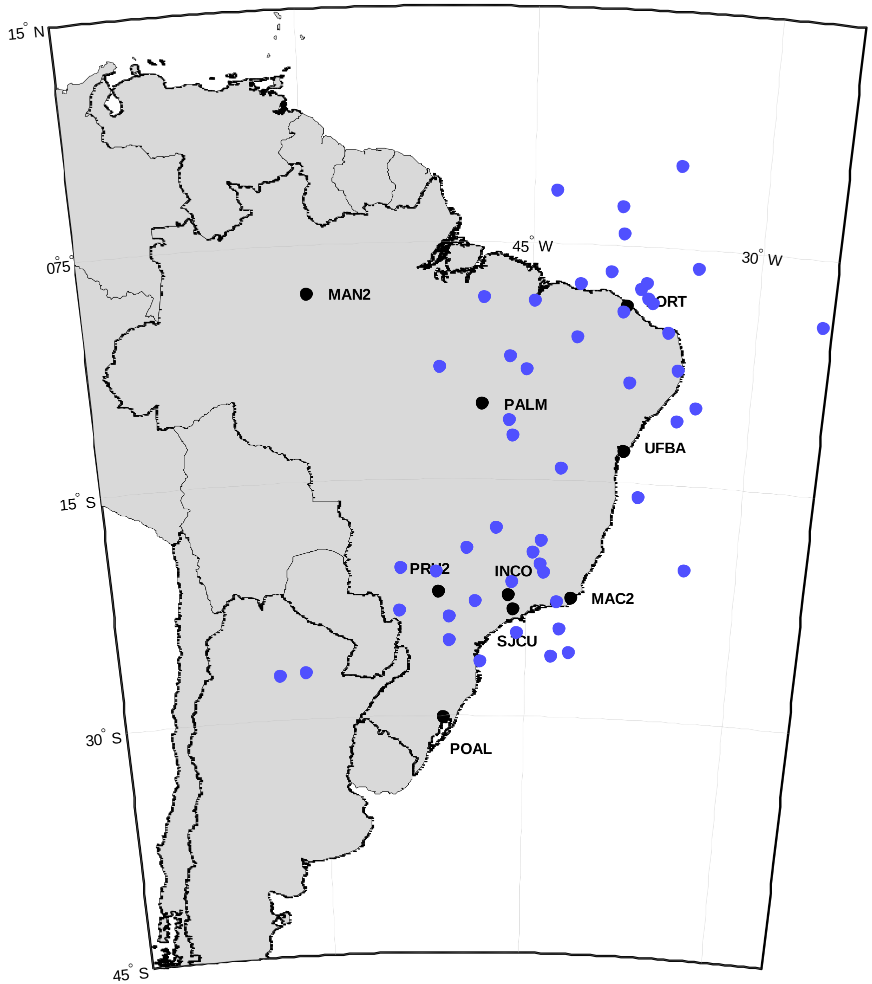


M-GNSS 25

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

076/14

16h39m30s

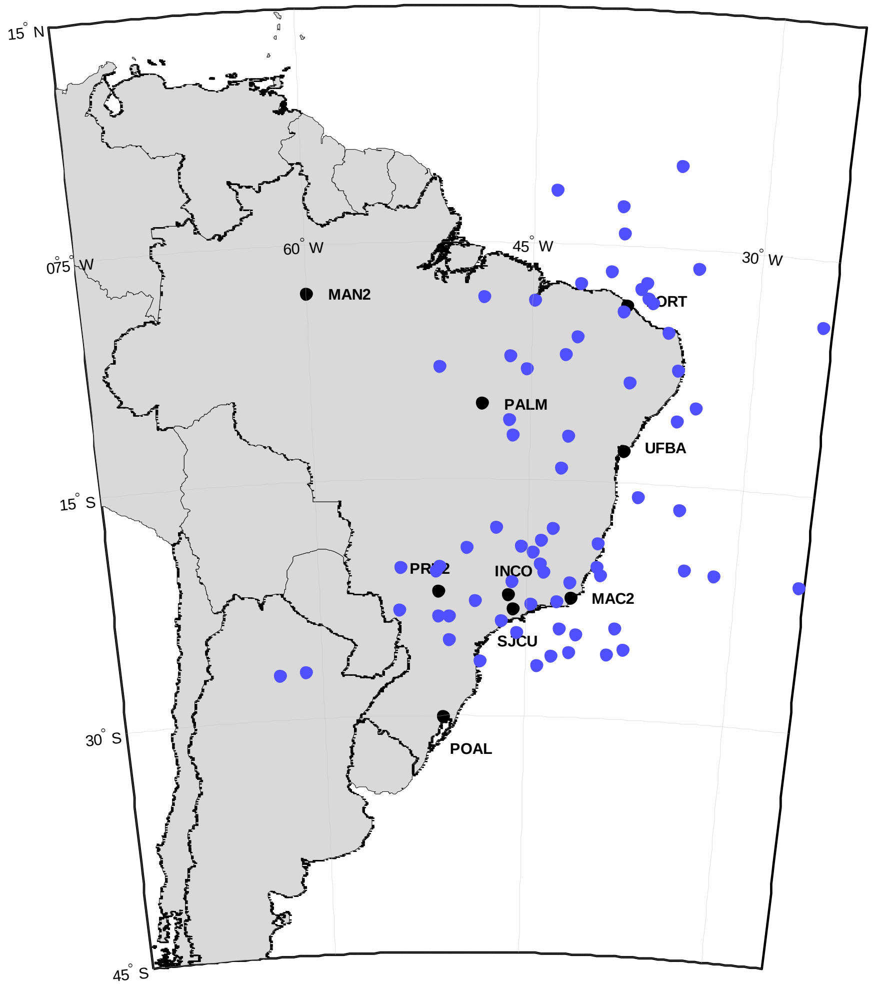


M-GNSS 51

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

076/14

16h39m30s

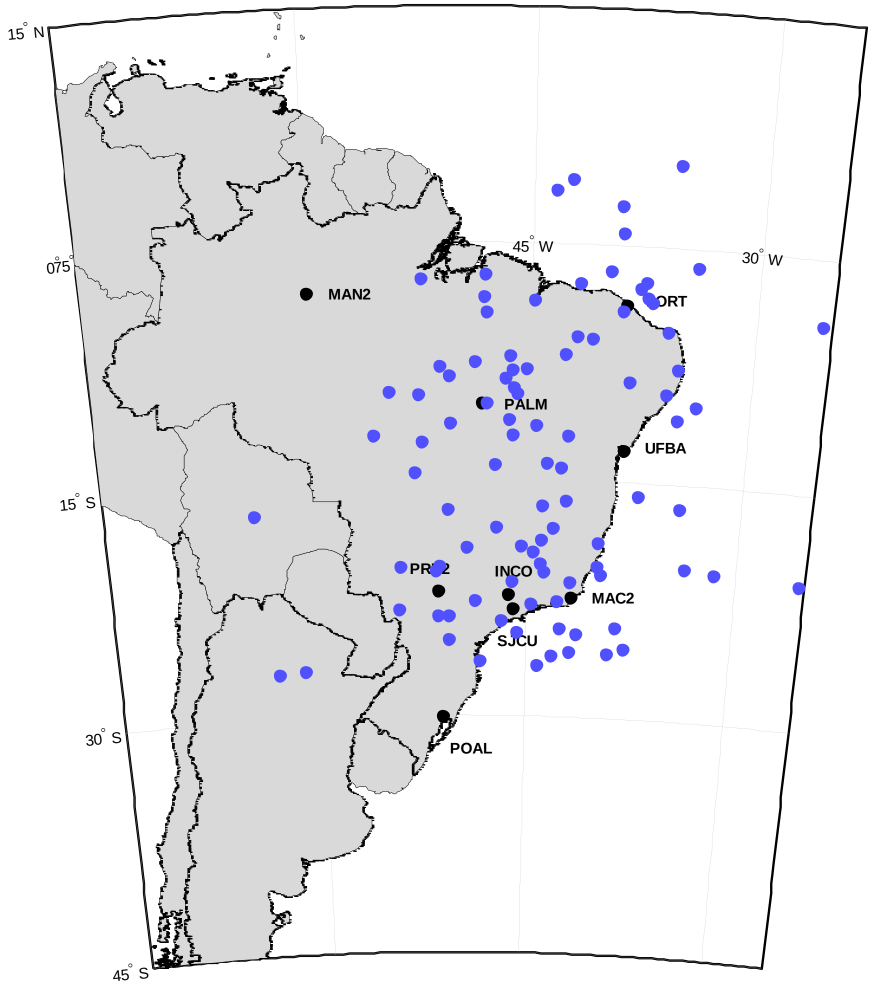


M-GNSS 71

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

076/14

16h39m30s

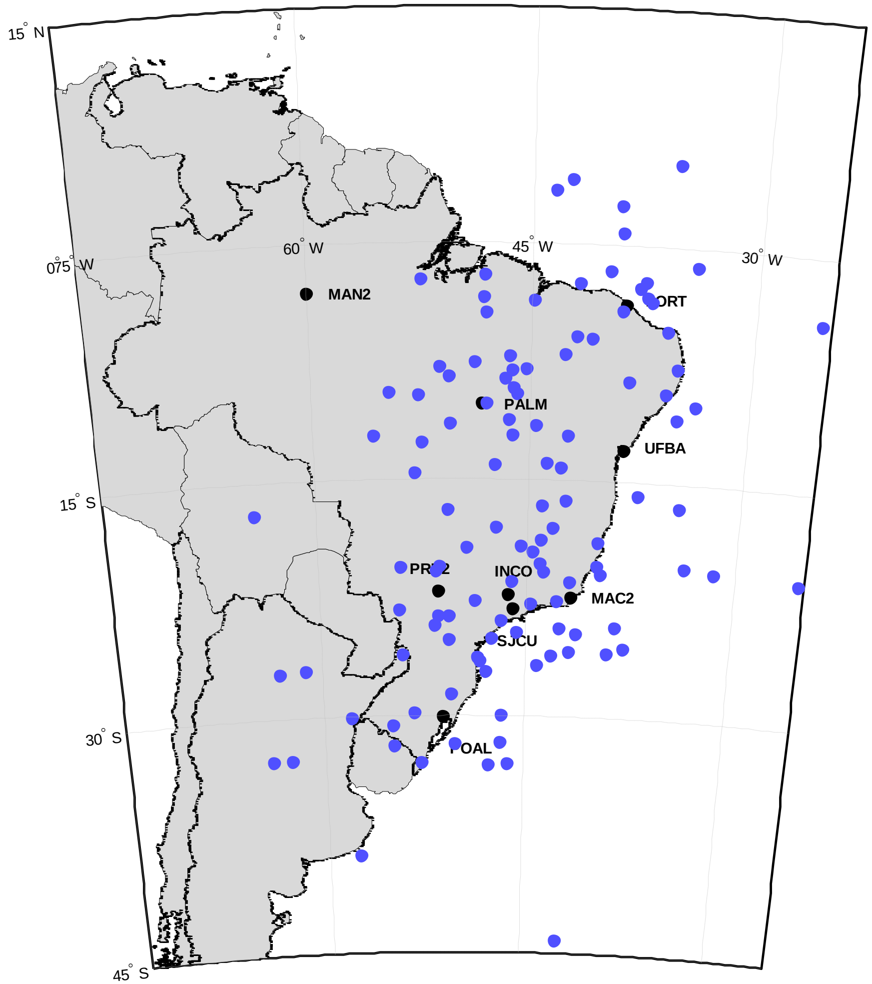


M-GNSS 97

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

076/14

16h39m30s

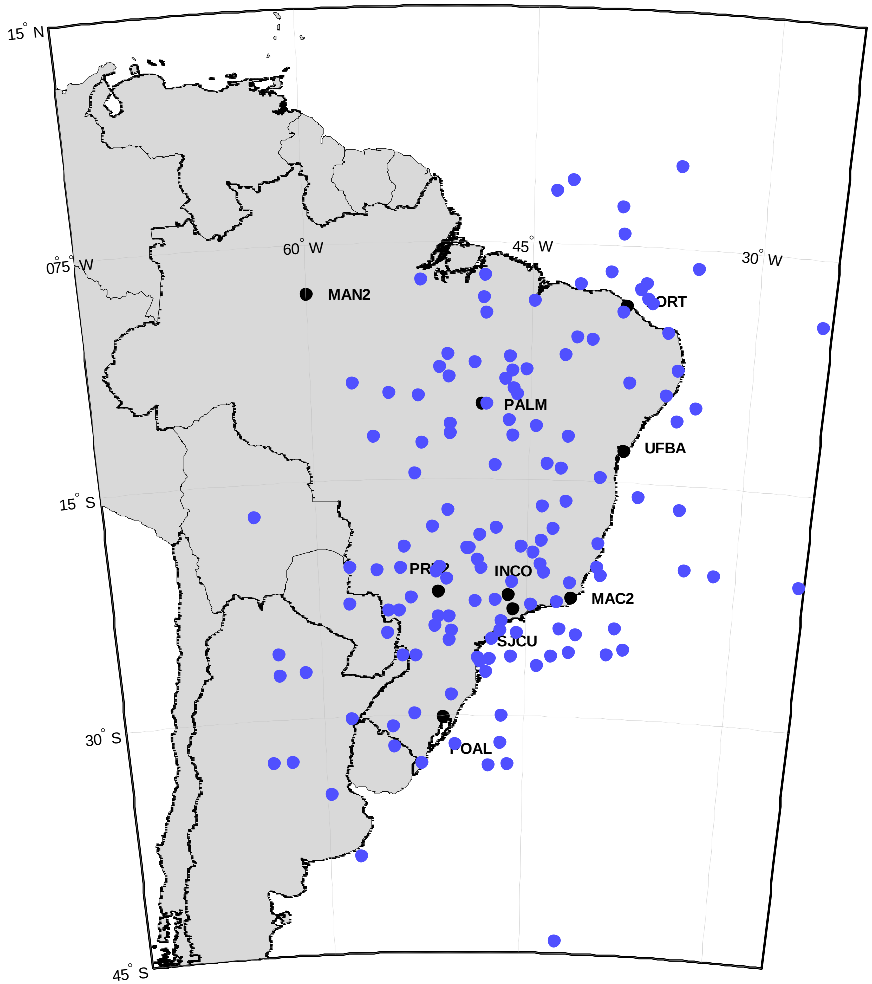


M-GNSS 117

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

076/14

16h39m30s

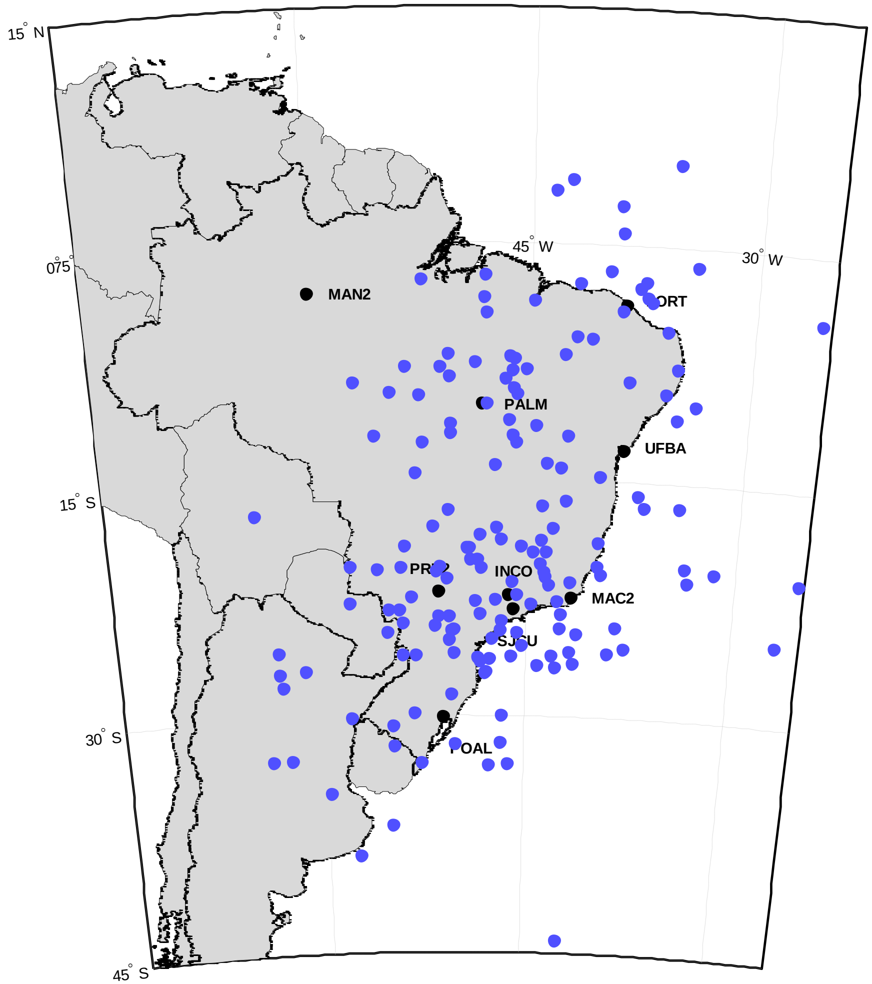


M-GNSS 142

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

076/14

16h39m30s

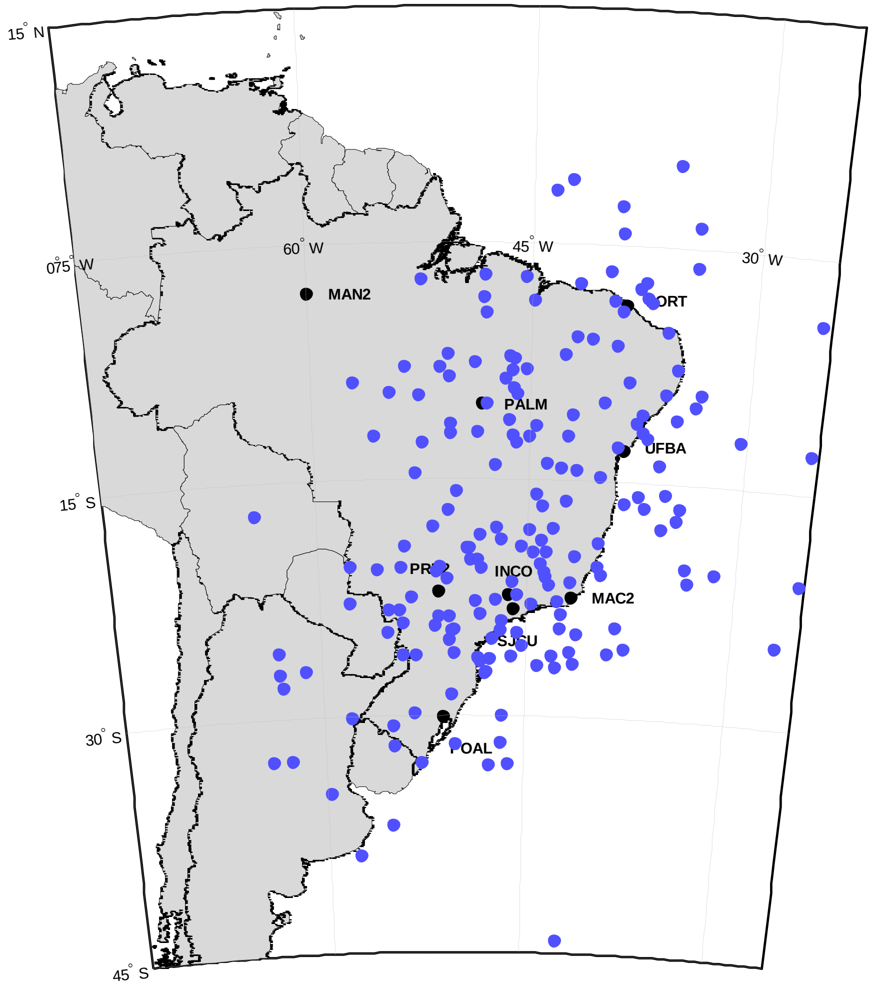


M-GNSS 165

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

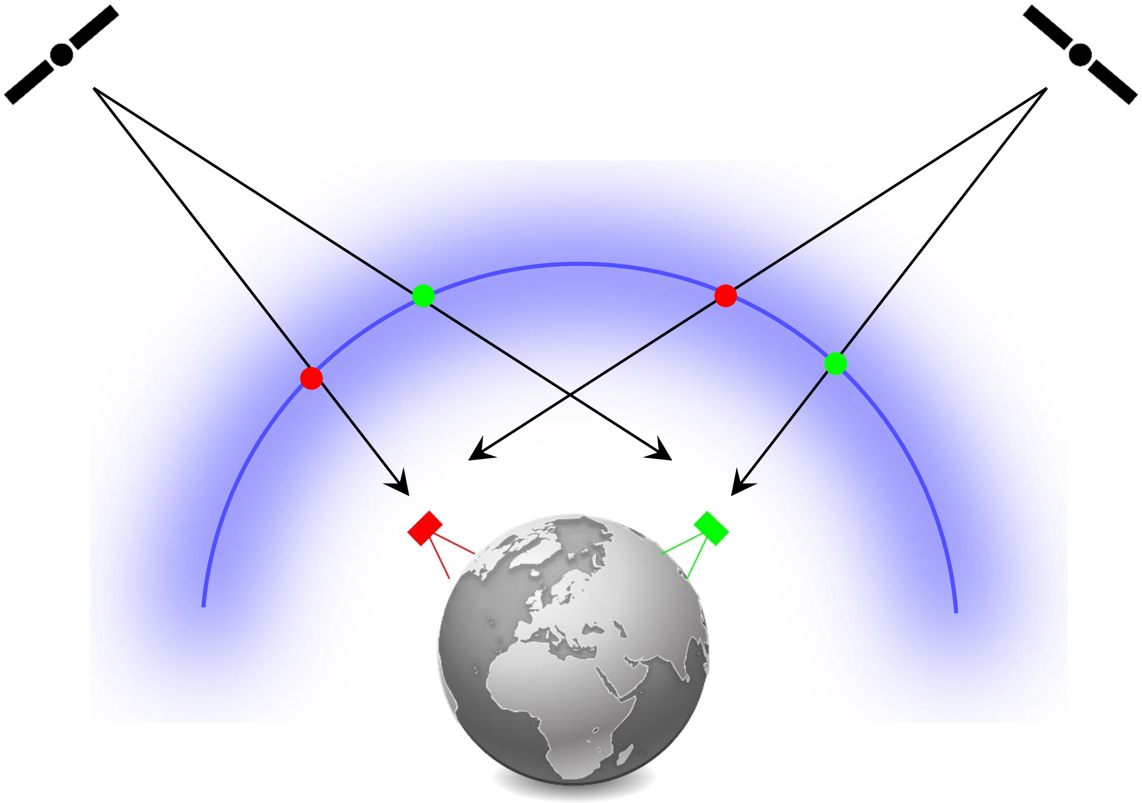
076/14

16h39m30s

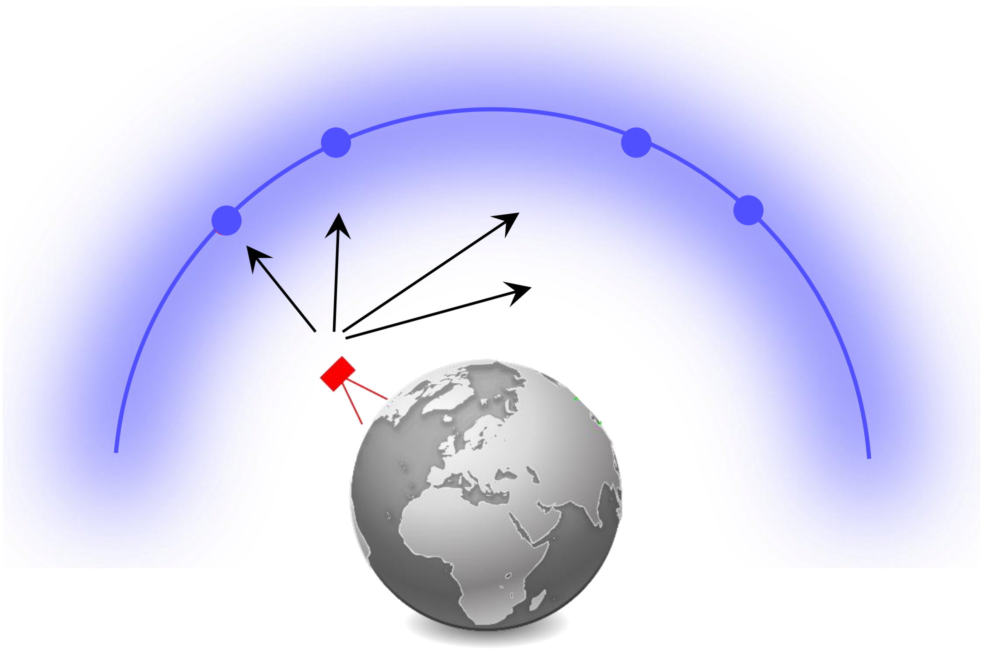


M-GNSS 192

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

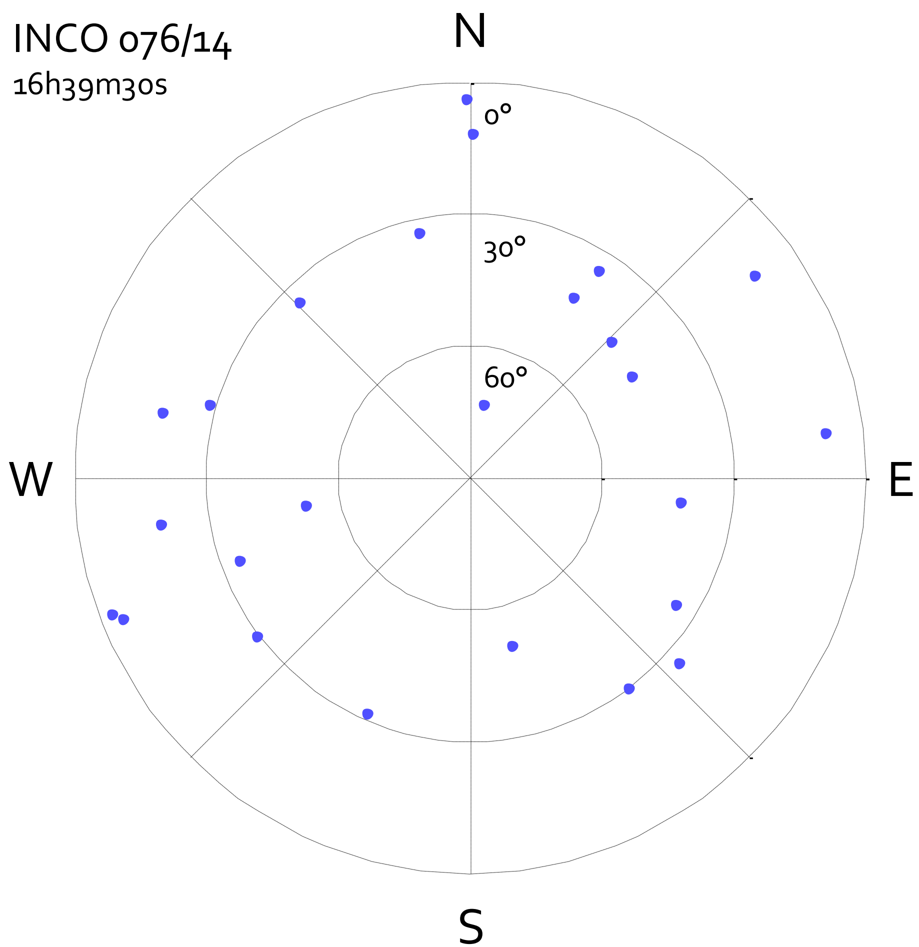


The M-GNSS Measurement Skyplot constitute the Experimental Data Field



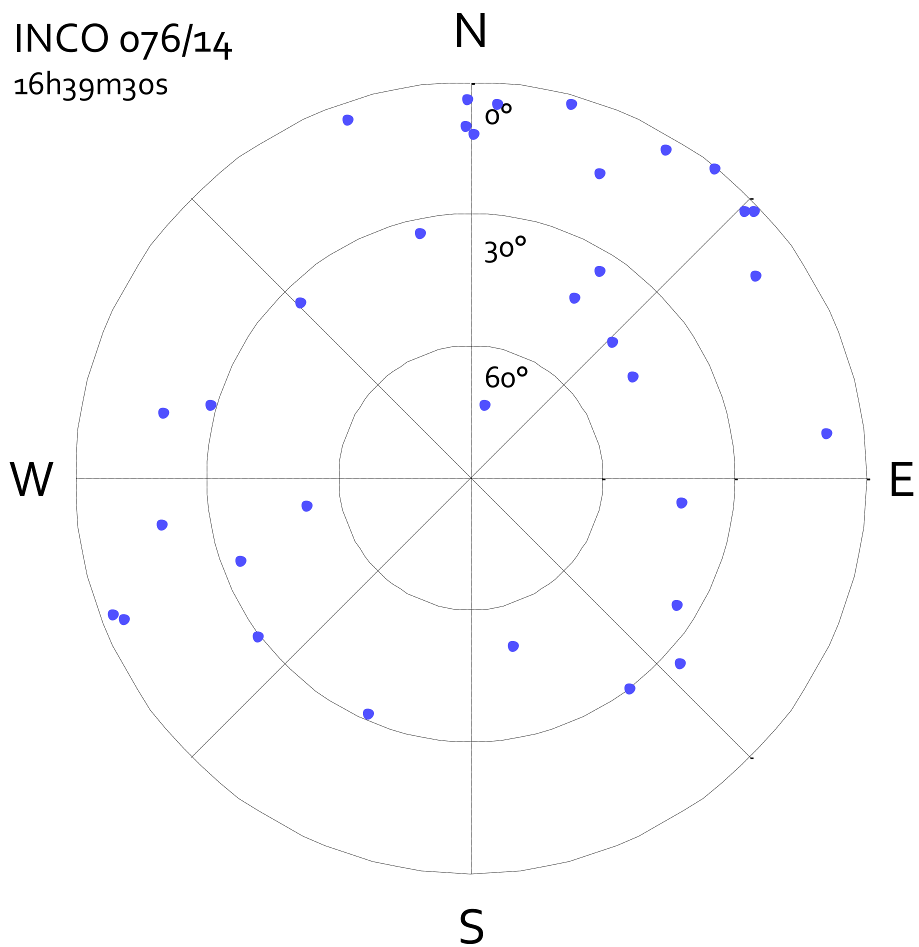
The M-GNSS Measurement Skyplot constitute the Experimental Data Field

INCO 076/14
16h39m30s



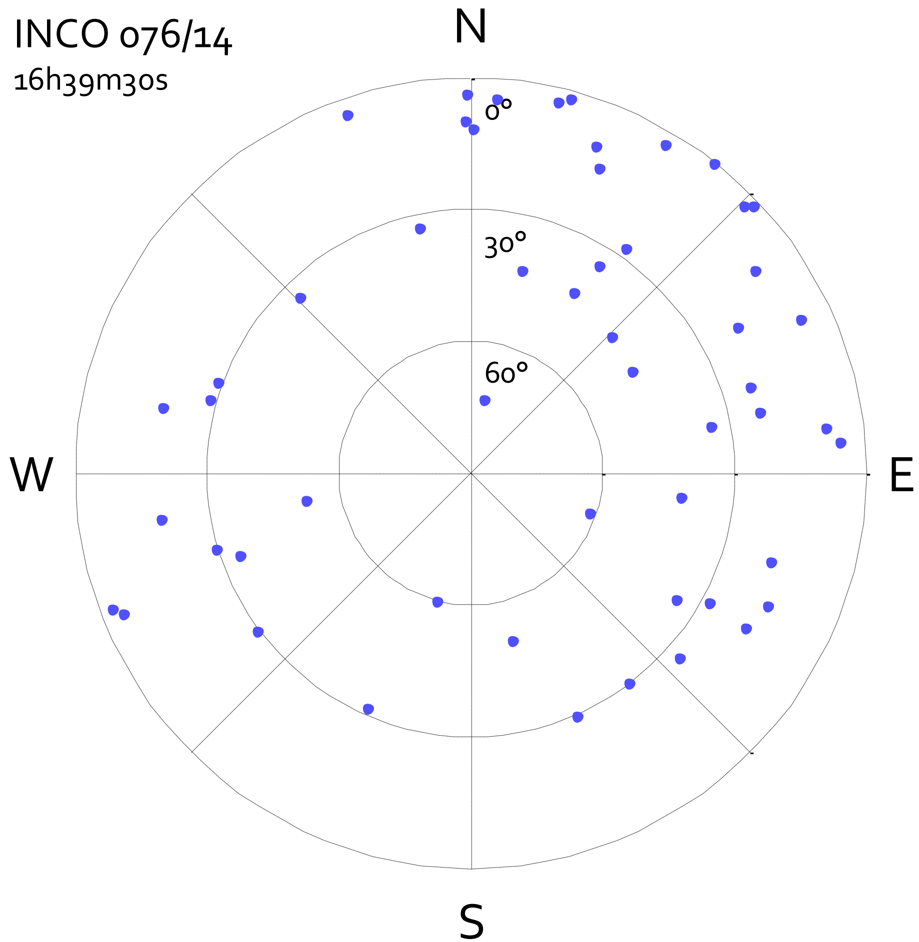
M-GNSS 25

The M-GNSS Measurement Skyplot constitute the Experimental Data Field



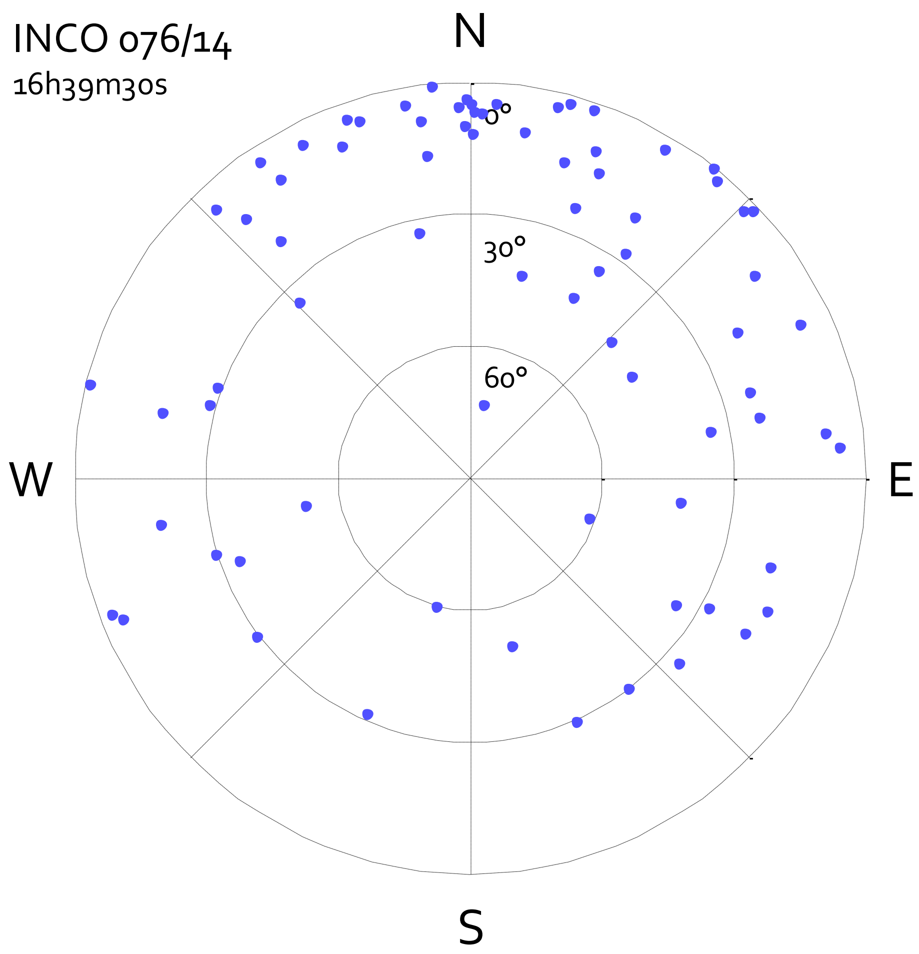
M-GNSS 34

The M-GNSS Measurement Skyplot constitute the Experimental Data Field



M-GNSS 53

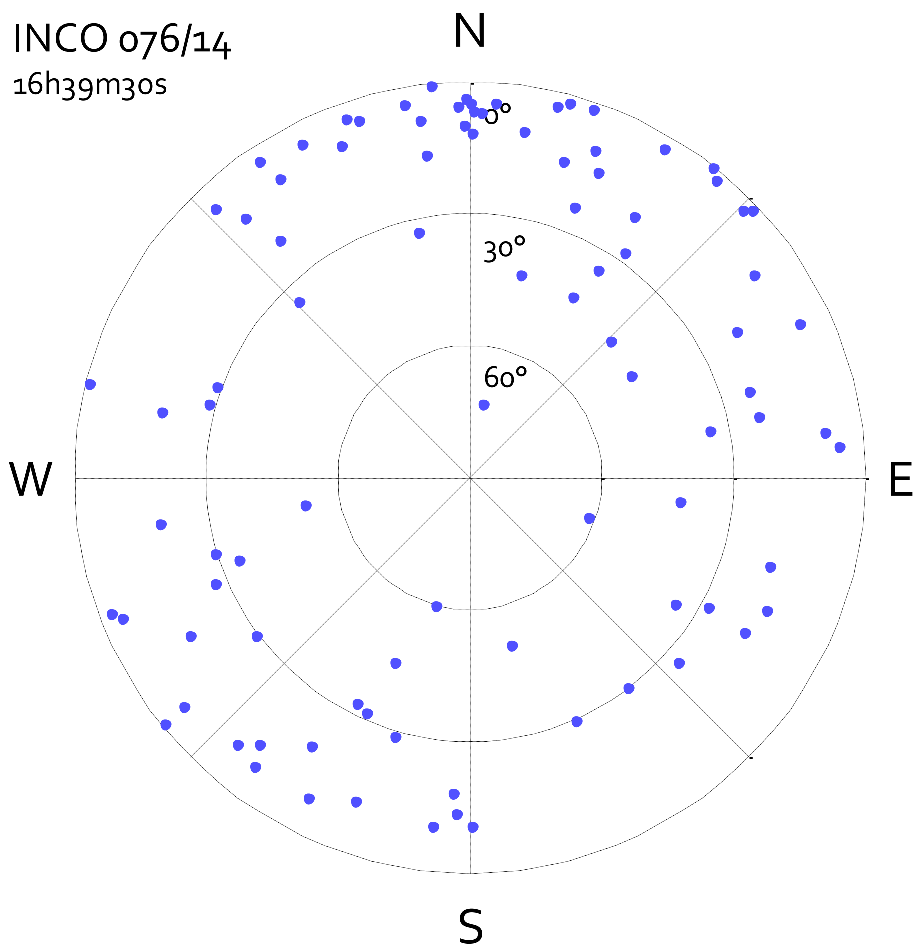
The M-GNSS Measurement Skyplot constitute the Experimental Data Field



M-GNSS 76

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

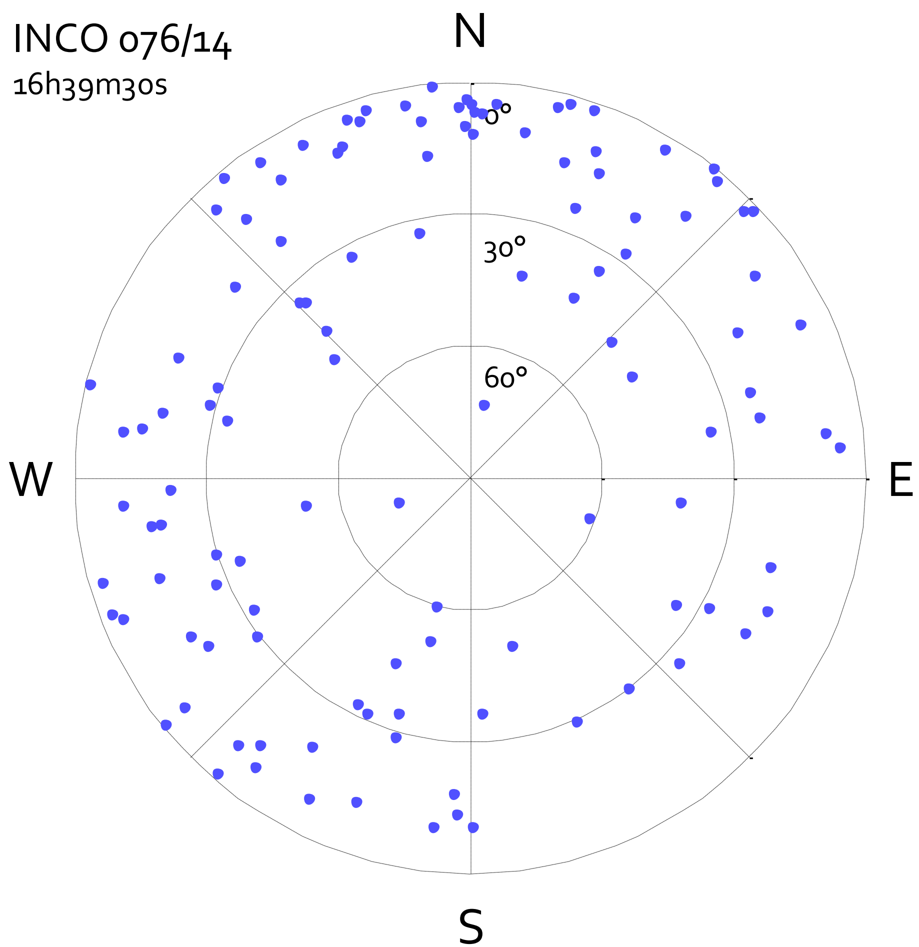
INCO 076/14
16h39m30s



M-GNSS 93

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

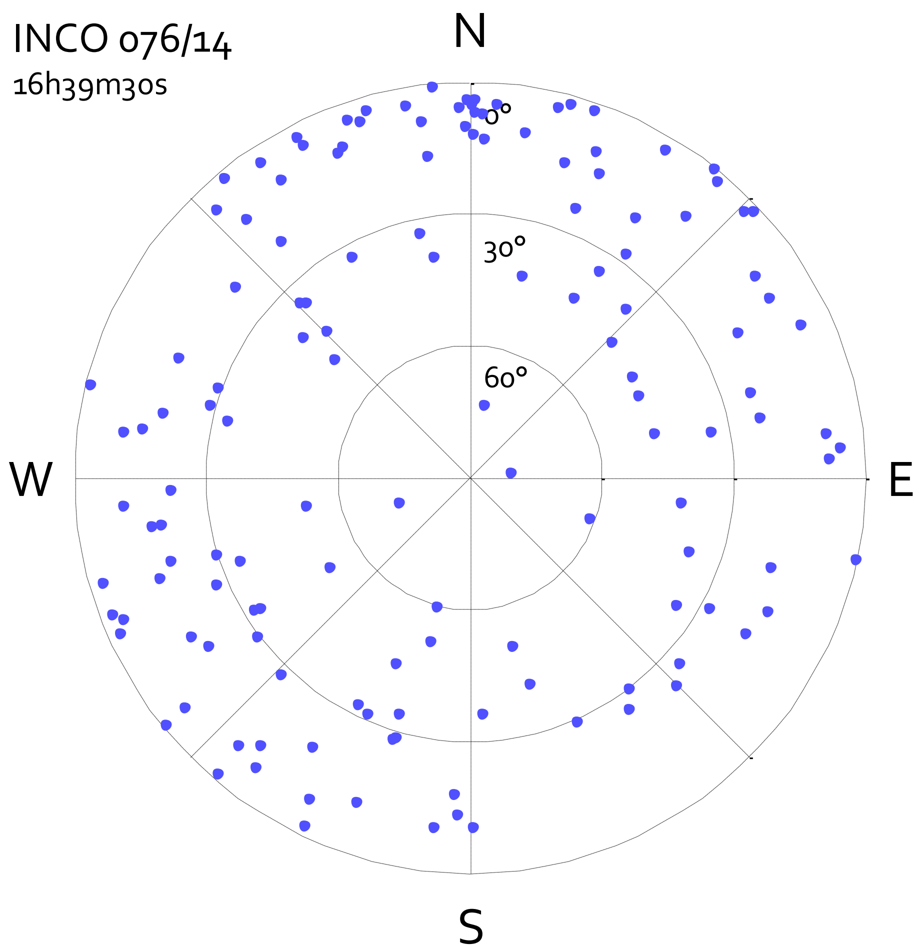
INCO 076/14
16h39m30s



M-GNSS 118

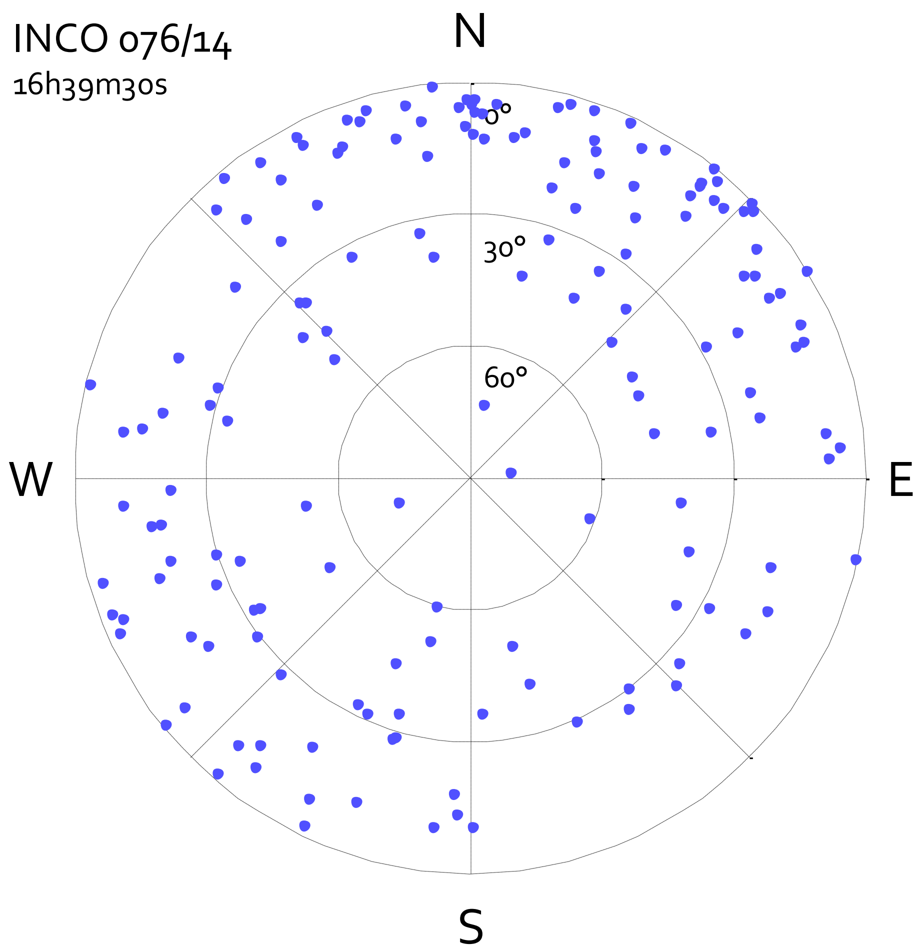
The M-GNSS Measurement Skyplot constitute the Experimental Data Field

INCO 076/14
16h39m30s



M-GNSS 141

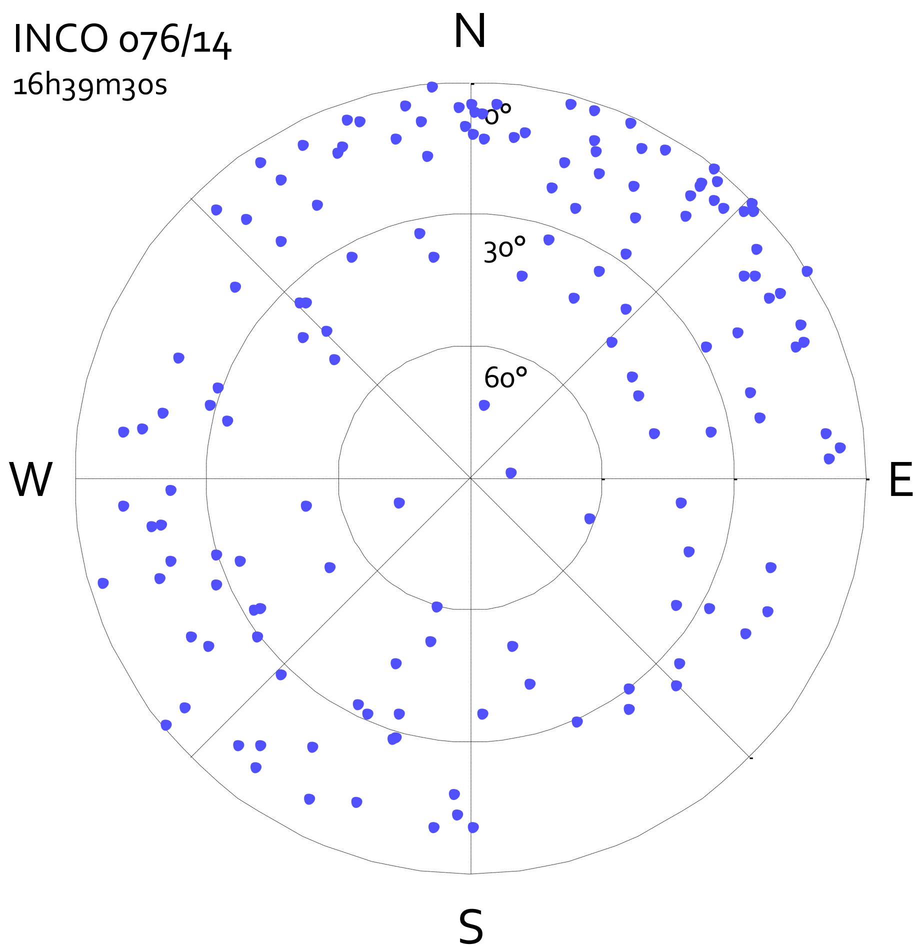
The M-GNSS Measurement Skyplot constitute the Experimental Data Field



M-GNSS 163

The M-GNSS Measurement Skyplot constitute the Experimental Data Field

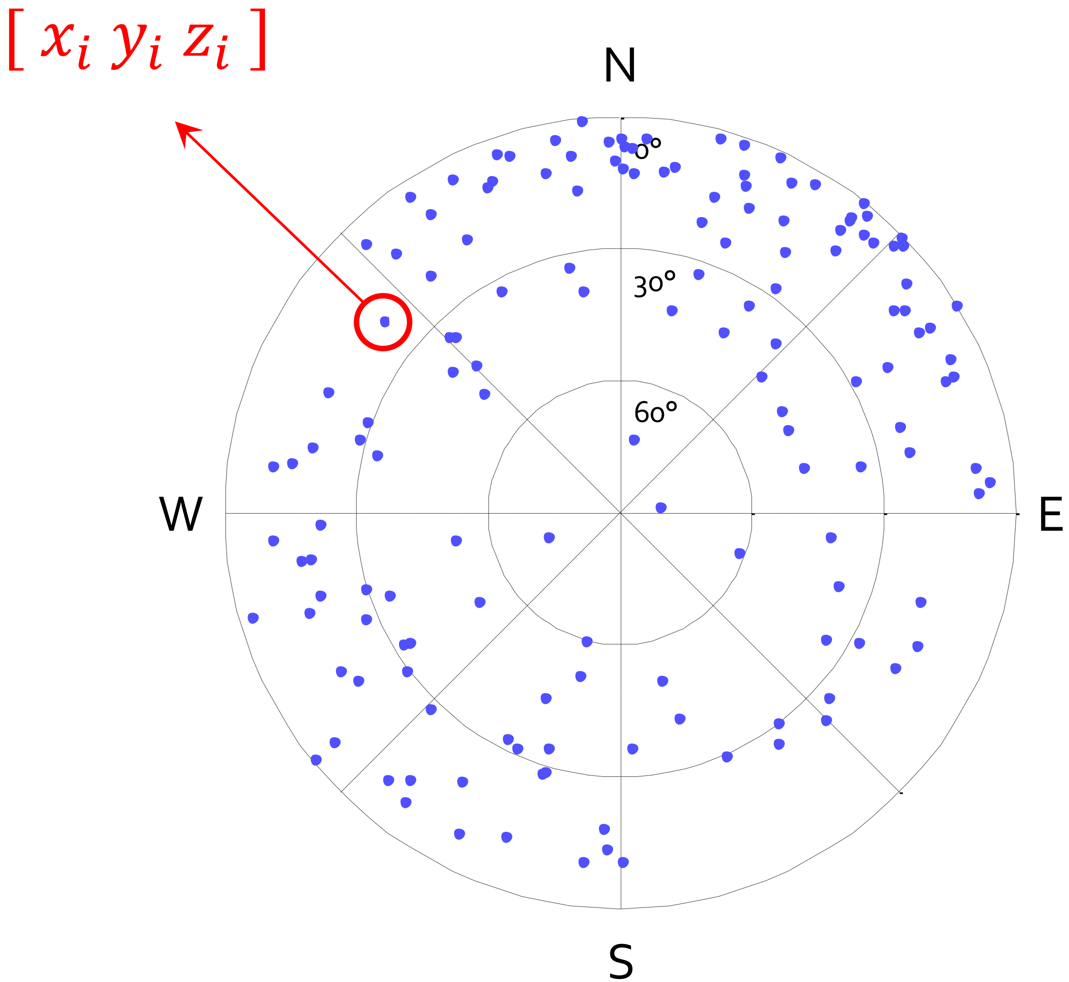
INCO 076/14
16h39m30s

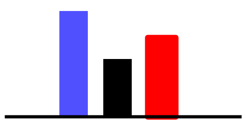


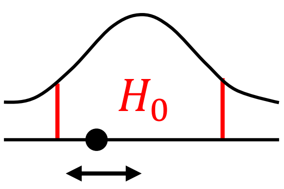
M-GNSS 150

Mask: 5°

Spatial Analysis Techniques involve Descriptive and Inferential Statistics







$Z = f(x_i\ y_i\ z_i)$

$\forall i = 1, 2, \ldots N$

	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●
Interpolation				

Descriptive Statistics is based on 3 Types of Indicators

Central Tendency

INCO

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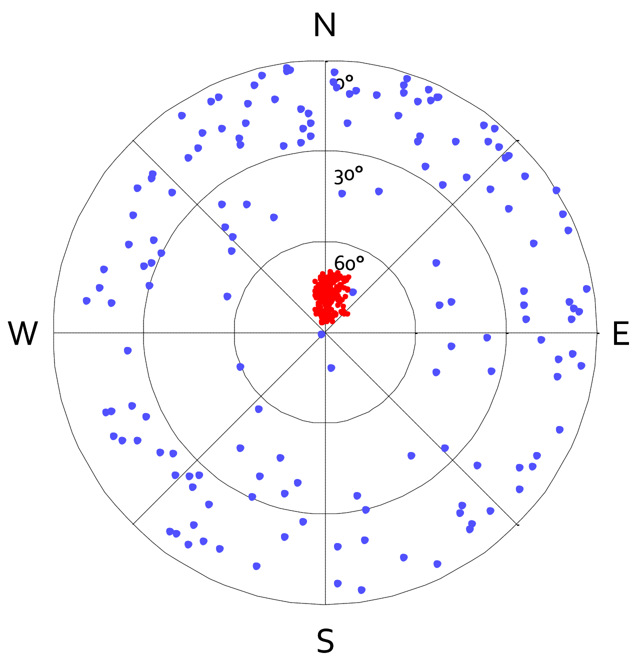

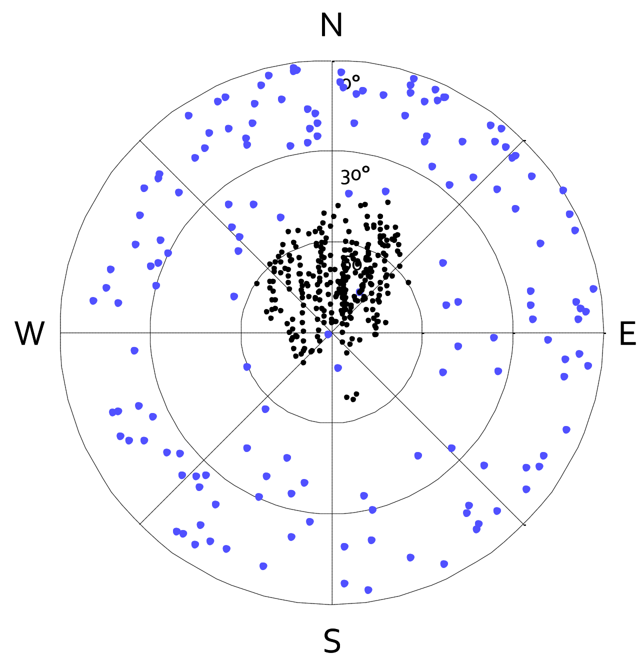

Barycentre

$$X_G = \frac{1}{N}\sum x_i \qquad Y_G = \frac{1}{N}\sum y_i$$

Minimum Distance Point

$$M_D = \sum_i d_{ij}$$

Descriptive Statistics is based on 3 Types of Indicators

Dispersion

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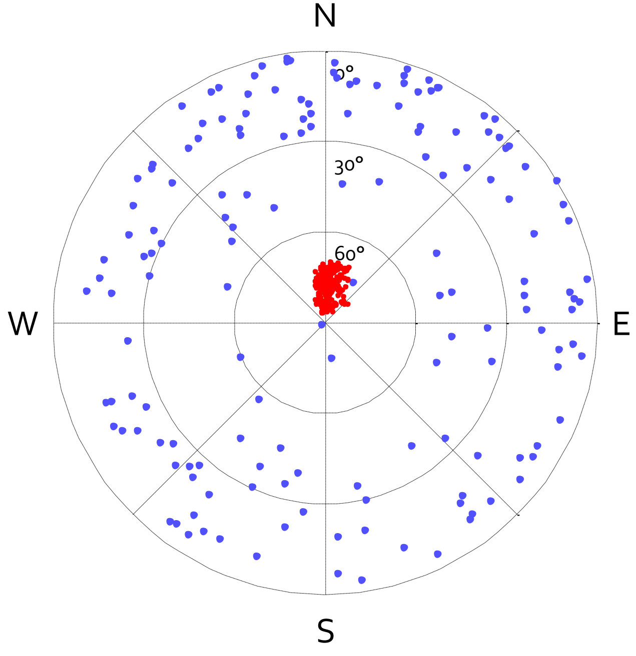
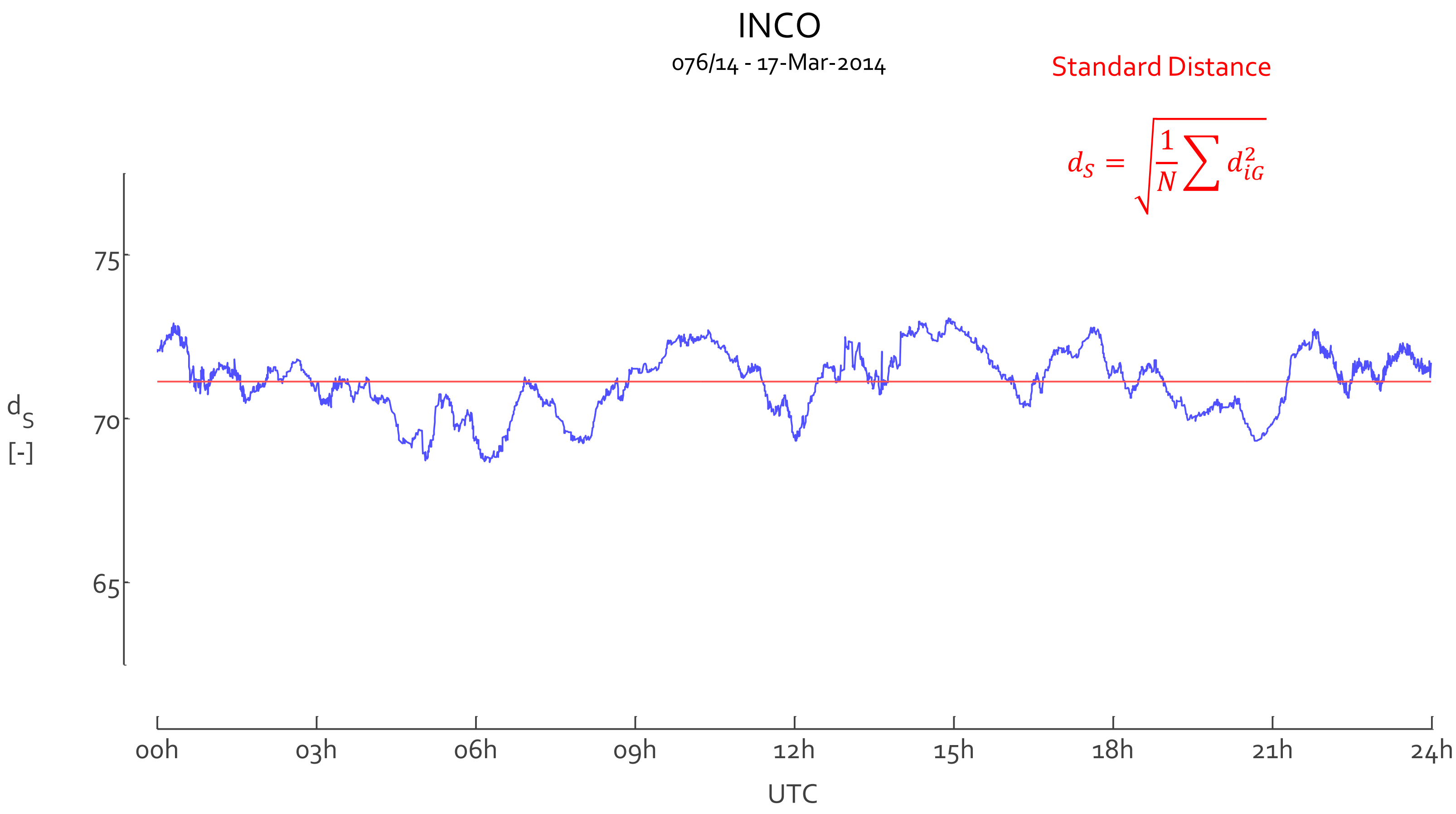


Standard Distance

$$d_S = \sqrt{\frac{1}{N}\sum d_{iG}^2}$$

Descriptive Statistics is based on 3 Types of Indicators

Dispersion



Descriptive Statistics is based on 3 Types of Indicators

Assymetry

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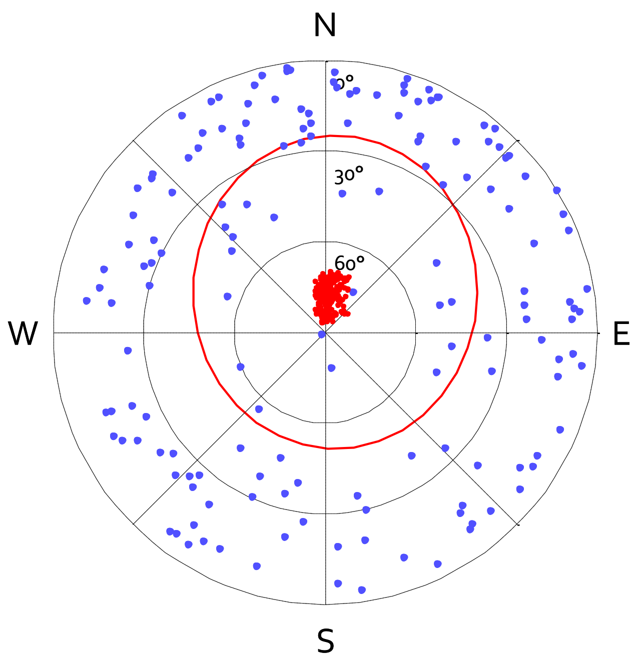


Standard Deviation Ellipse

$$\theta = \text{atan}\left(G(\underline{x}, \underline{y})\right)$$

$$S_x = \sqrt{\frac{1}{N-2}\left[\sum_i (x_i - \overline{x})\cos(\theta) - (x_i - \overline{x})\sin(\theta)\right]^2}$$

$$S_y = \sqrt{\frac{1}{N-2}\left[\sum_i (x_i - \overline{x})\sin(\theta) - (x_i - \overline{x})\cos(\theta)\right]^2}$$

Description
Detection
Scale
Location

Introduction

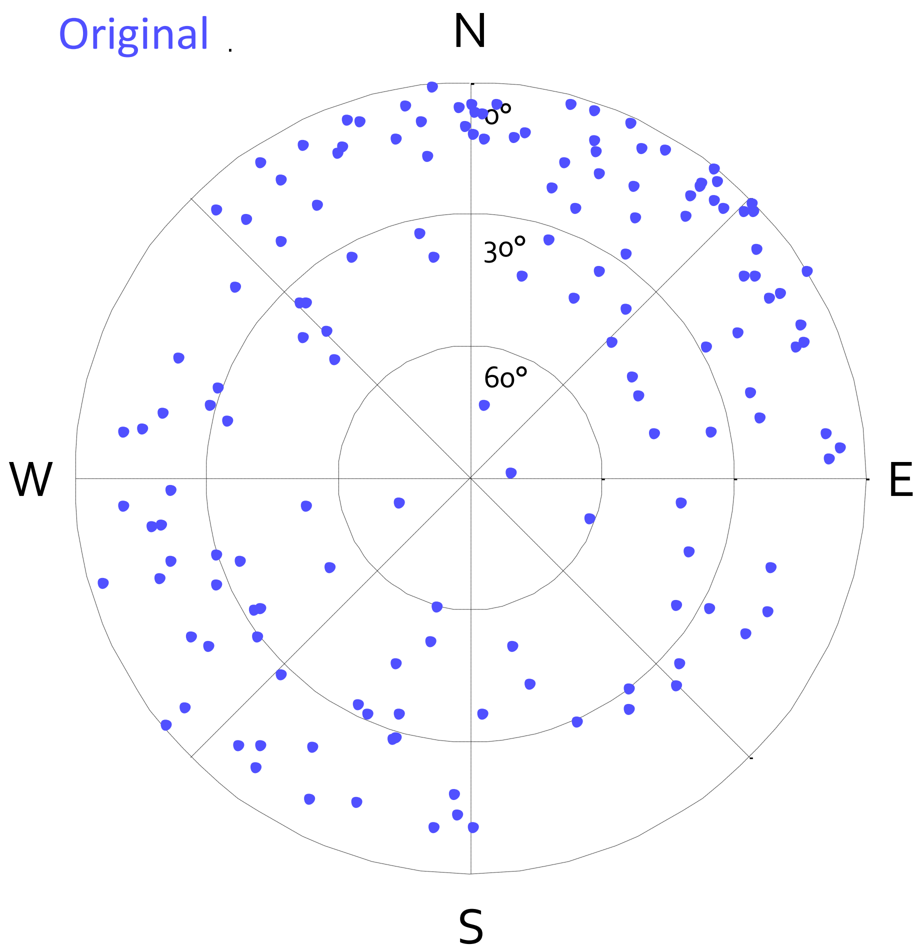
Configuration

Spatial Dependency

Interpolation

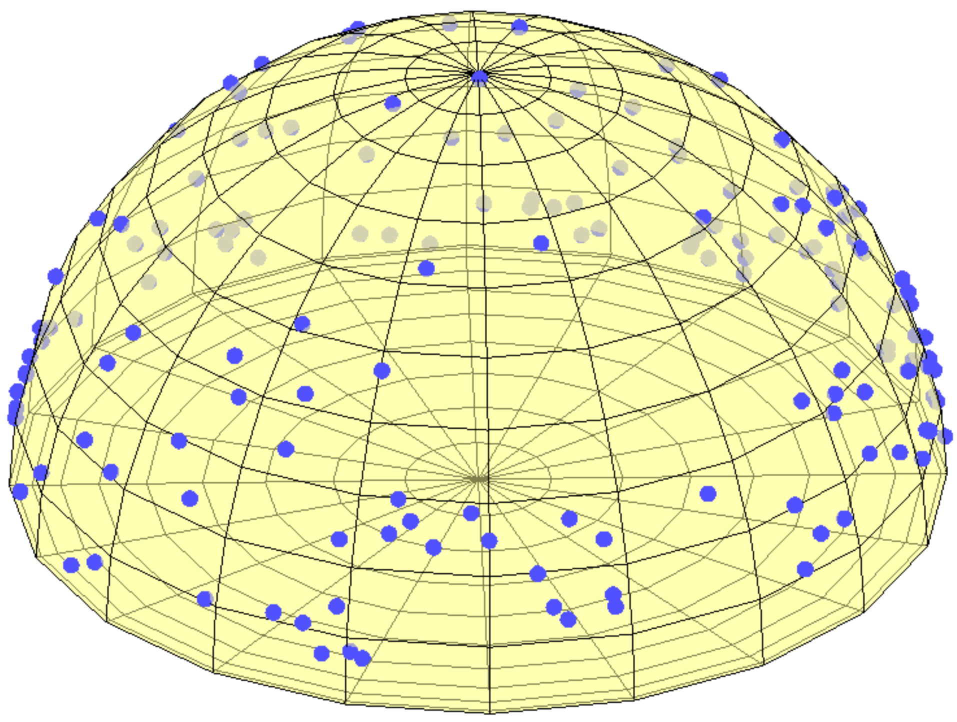
The Data Set is not a Point Pattern Sampled by a Random or Systematic Method

Original



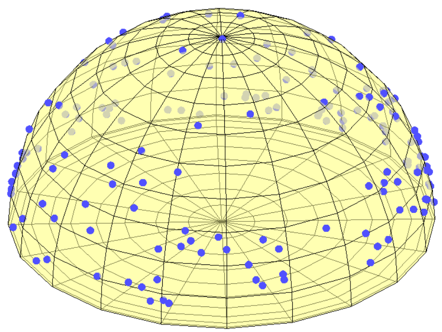
The Data Set is not a Point Pattern Sampled by a Random or Systematic Method

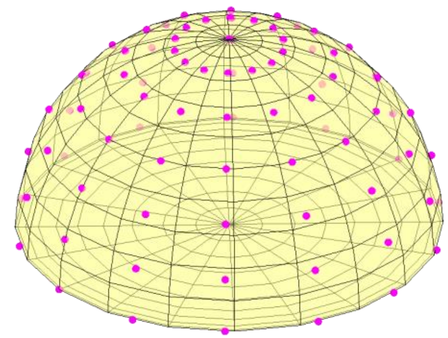
Original



The Data Set is not a Point Pattern Sampled by a Random or Systematic Method

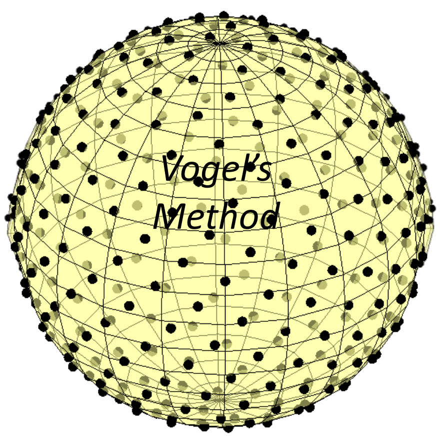
Original

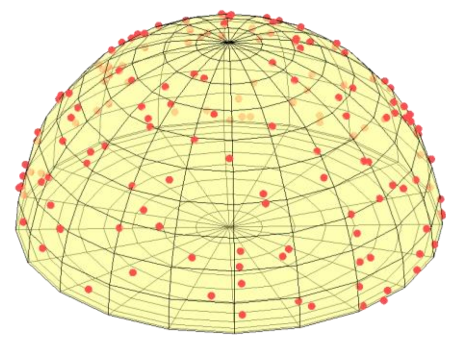




Intuitive

Systematic

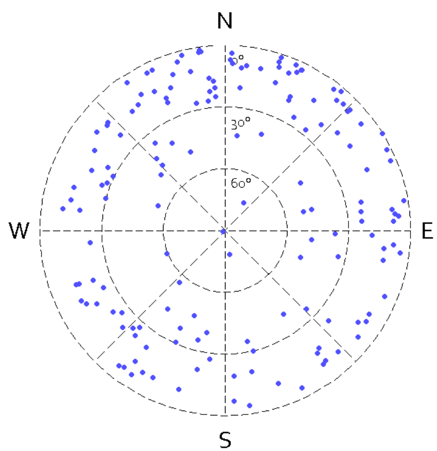


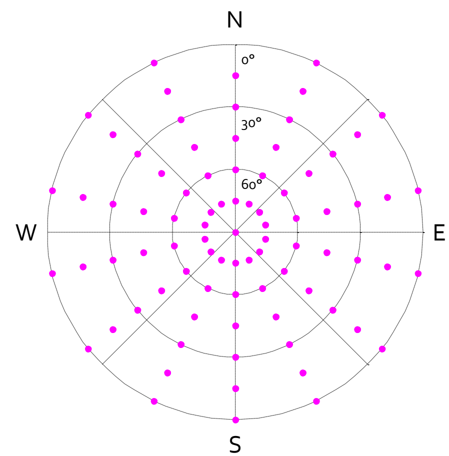


Random

The Data Set is not a Point Pattern Sampled by a Random or Systematic Method

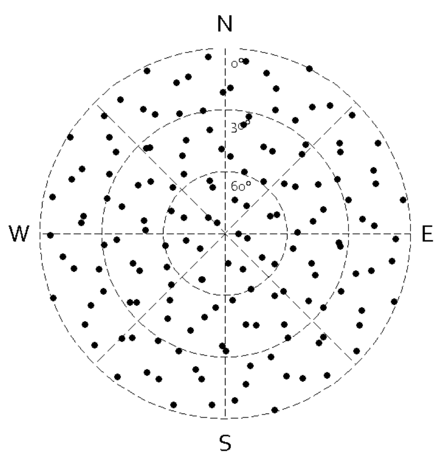
Original

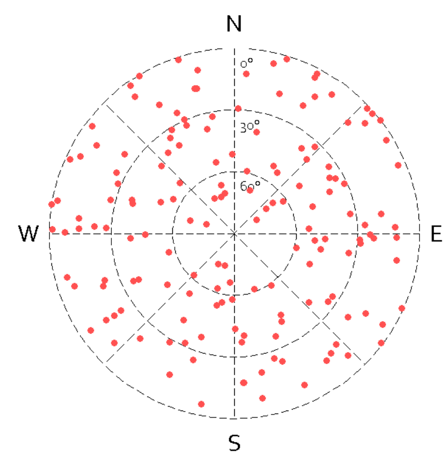




Intuitive

Systematic





Random

Is the Experimental Data Set Spatially Clustered or Scattered?

Single-Linkage Clustering

INCO

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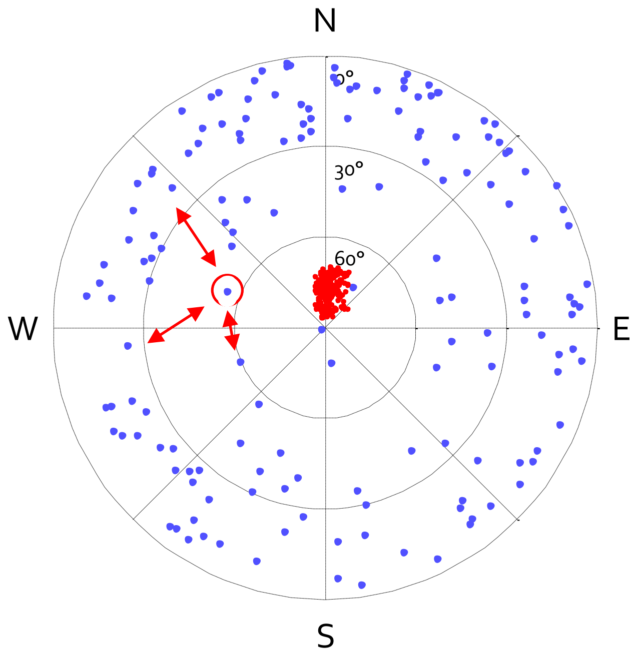

Mean Distance to the Nearest Neighbor (NN)

$$\overline{d_1} = \frac{1}{N}\sum_i d_{i1}$$

Theoretical Model

$$E[d_1] = \frac{1}{2}\sqrt{\frac{S}{N}} \qquad V[d_1] = \frac{0.26136}{\sqrt{\frac{N^2}{S}}}$$

Statistics

$$R = \frac{\overline{d_1}}{E[d_1]} \qquad \varepsilon = \frac{\left|\overline{d_1} - E[d_1]\right|}{V[d_1]}$$

Is the Experimental Data Set Spatially Clustered or Scattered?

Single-Linkage Clustering

INCO

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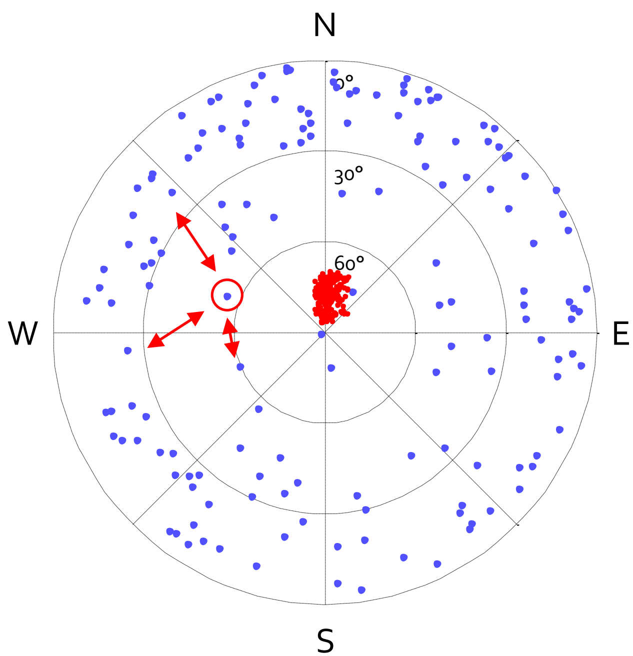
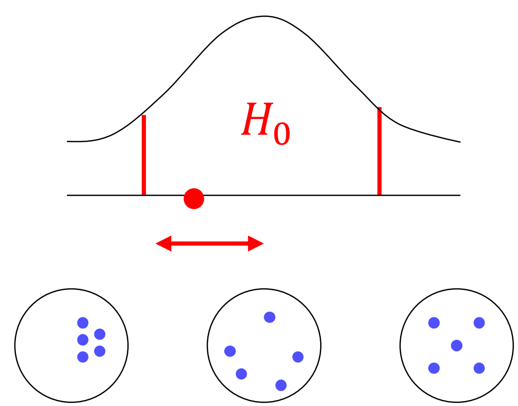


Mean Distance to the Nearest Neighbor (NN)

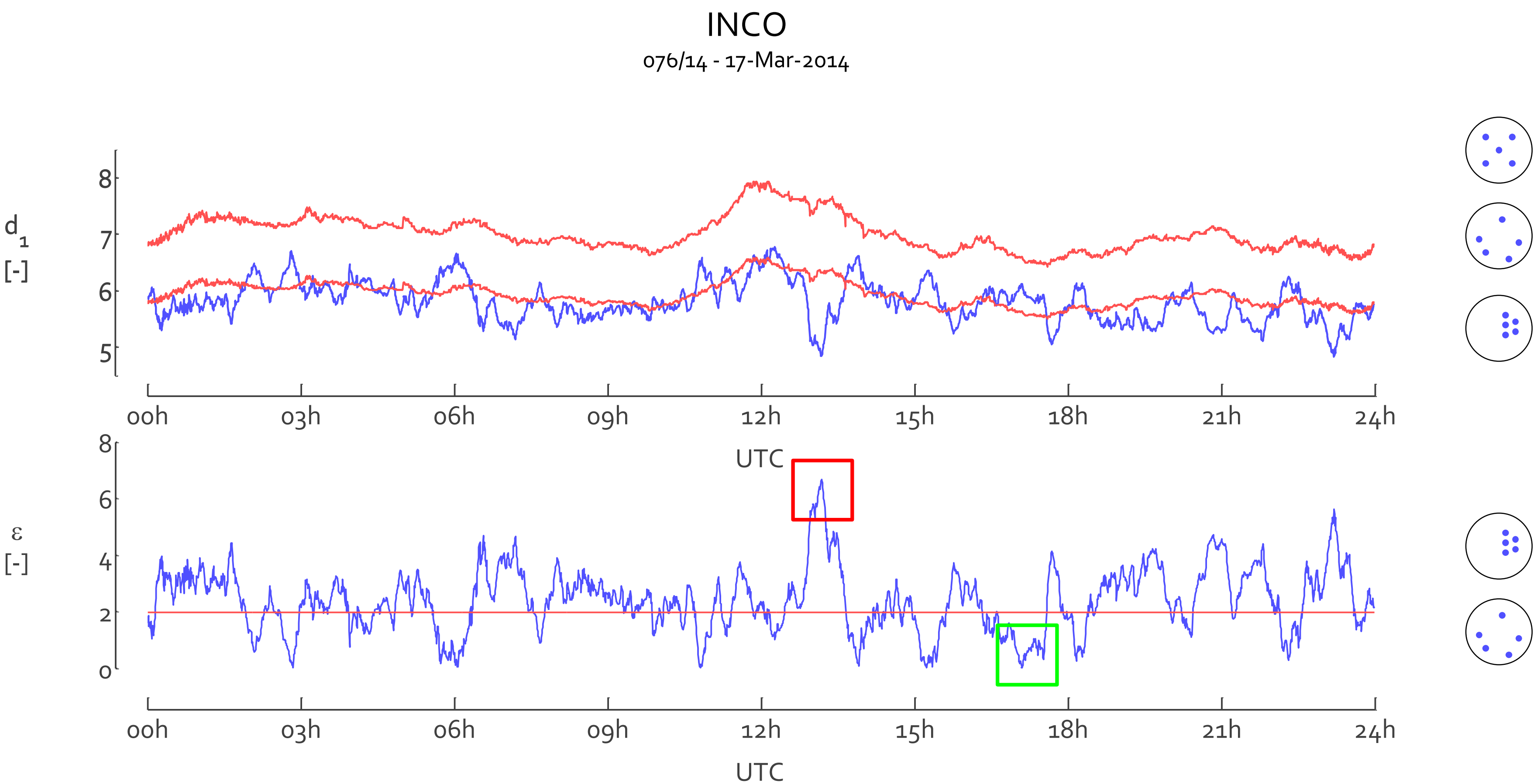
$$\overline{d_1} = \frac{1}{N} \sum_i d_{i1}$$

Statistics

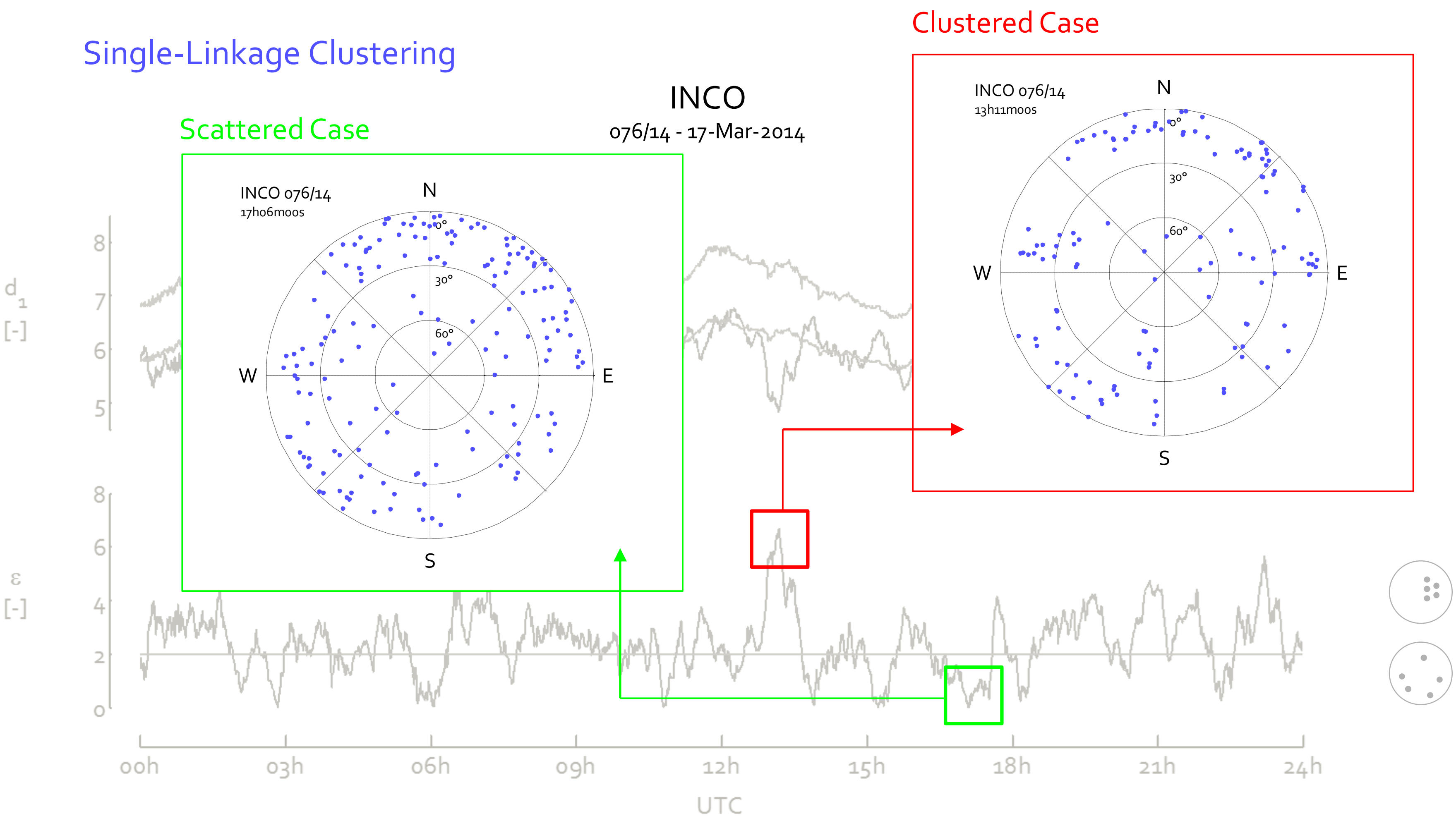


The Clustering Level of the Data Set is Frequently Significant

Single-Linkage Clustering



The Clustering Level of the Data Set is Frequently Significant



	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●
Interpolation				

What is the Scale of the Detected Clusters?

Ripley's K Function

INCO

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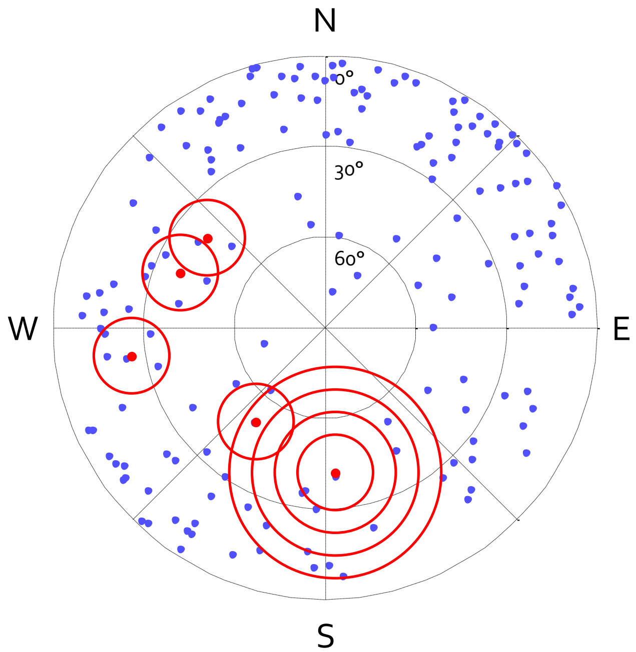

Ripley's K and Besag's L Functions

$$K_{d_p} = \frac{S}{N(N-1)} \sum_i \sum_j k_{ij}$$

$$L_{d_p} = \sqrt{\frac{K_{d_p}}{\pi} - d_p}$$

$$E[L_{d_p}] = ?$$

$$V[L_{d_p}] = ?$$

Monte-Carlo Simulations

What is the Scale of the Detected Clusters?

Ripley's K Function

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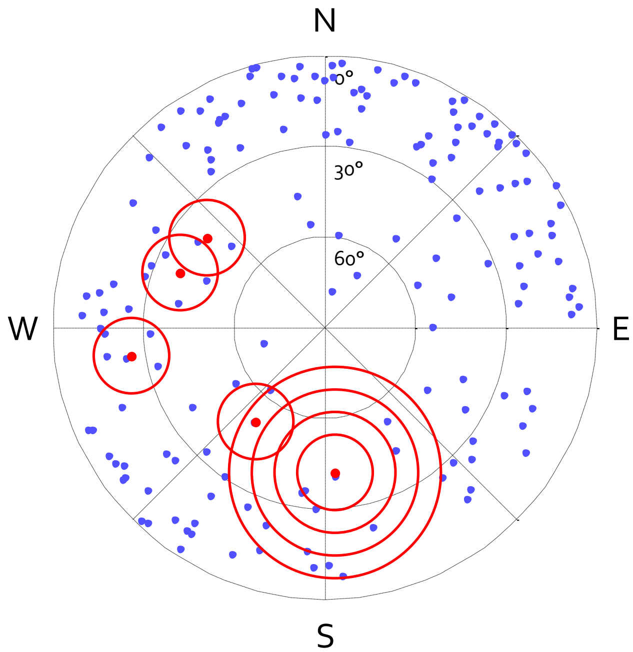
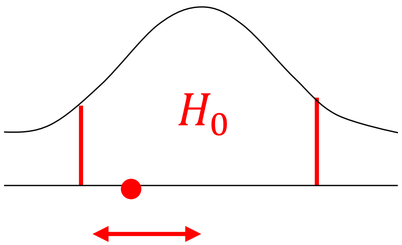


Ripley's K and Besag's L Functions

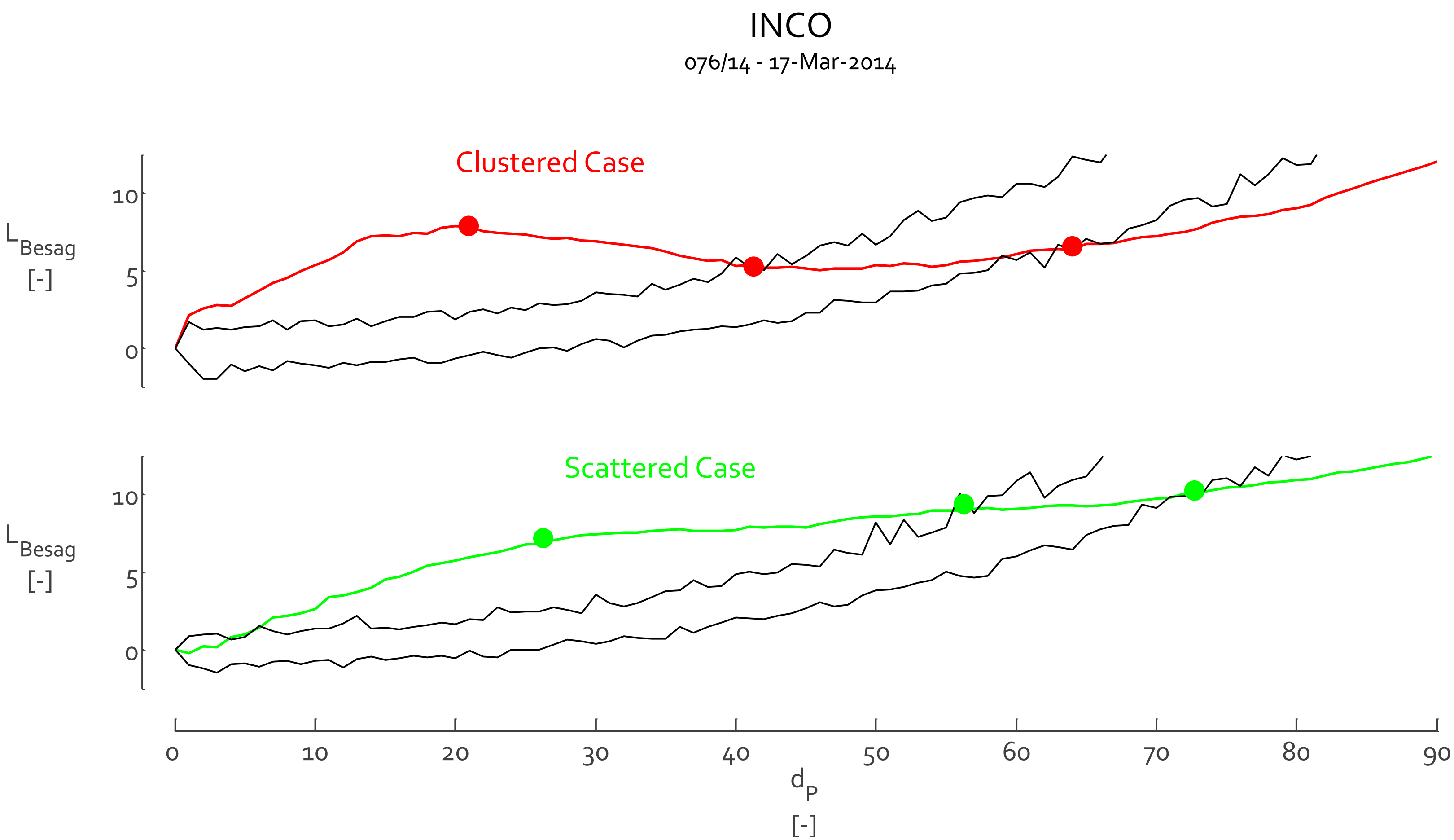
$$K_{d_p} = \frac{S}{N(N-1)} \sum_i \sum_j k_{ij}$$

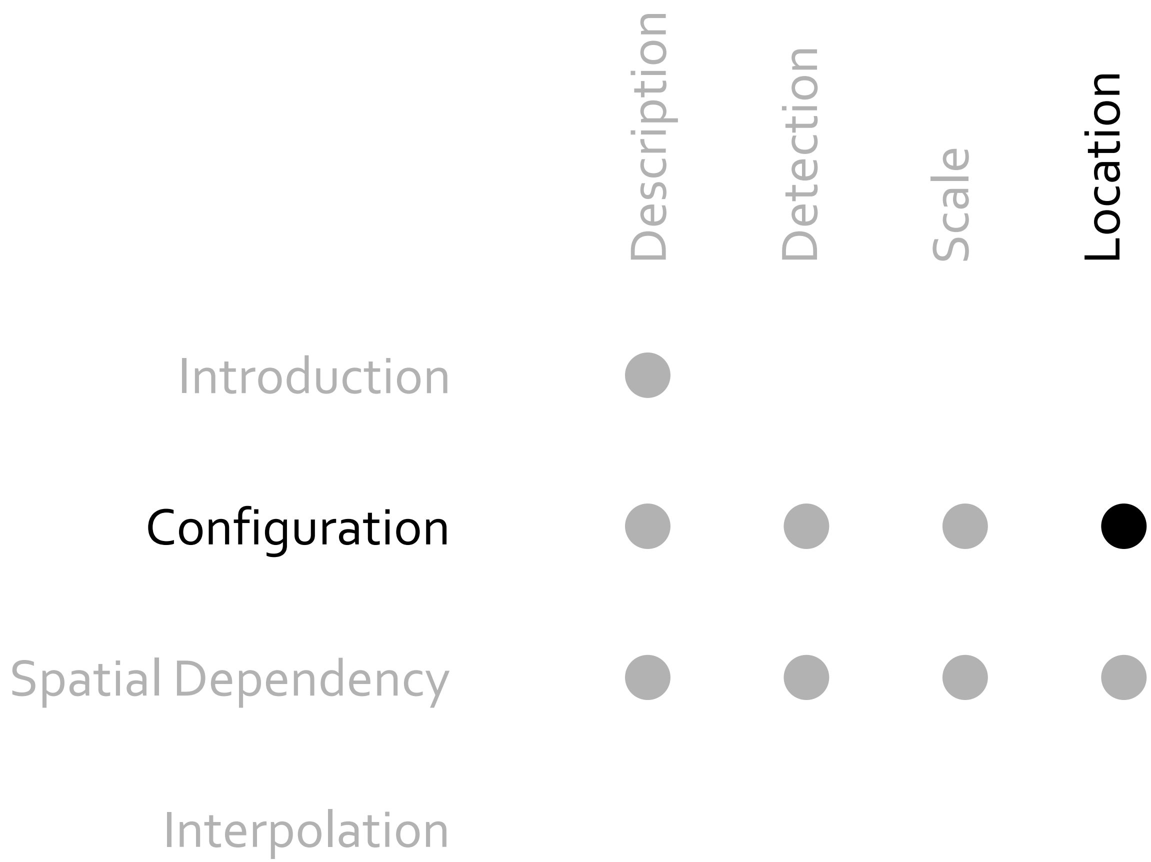
$$L_{d_p} = \sqrt{\frac{K_{d_p}}{\pi}} - d_p$$



What is the Scale of the Detected Clusters?

Ripley's K Function




Description
Detection
Scale
Location
Introduction
Configuration
Spatial Dependency
Interpolation

Where are located the Clusters?

INCO

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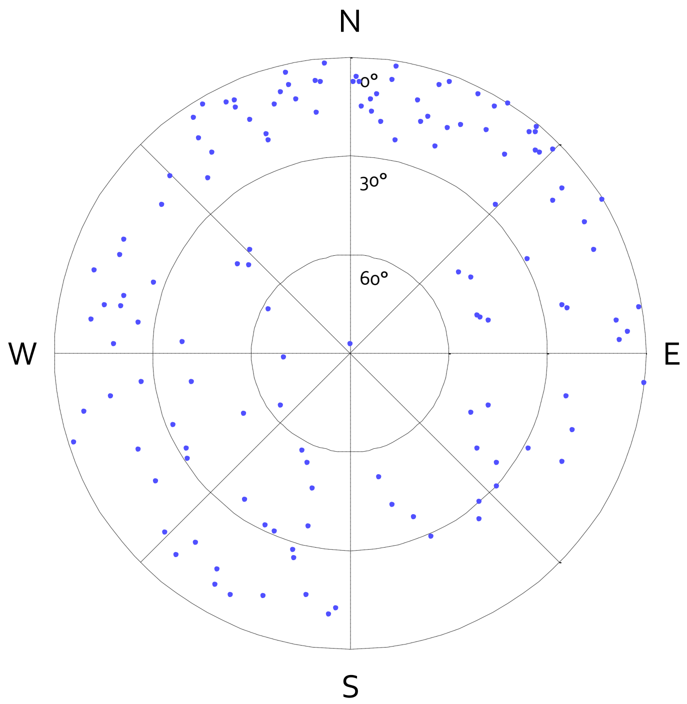
Experimental Sectorization



Where are located the Clusters?

INCO

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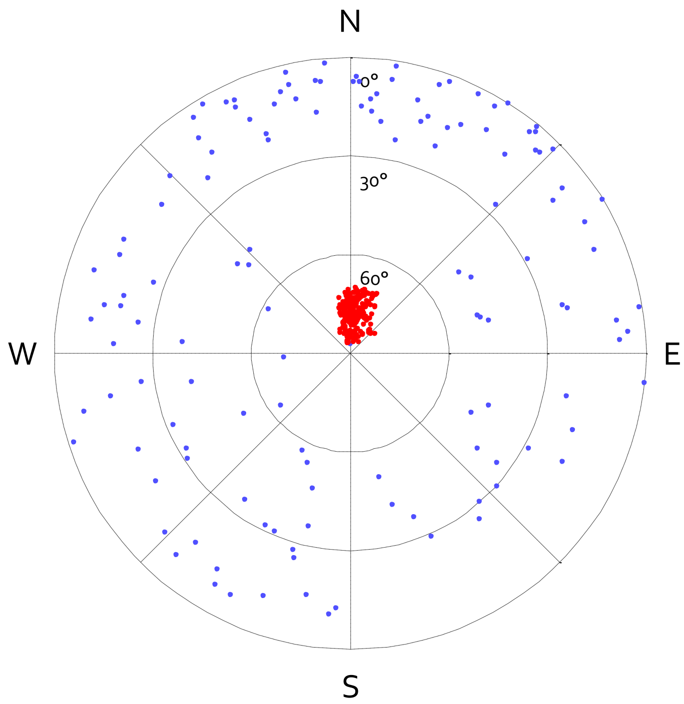
Experimental Sectorization

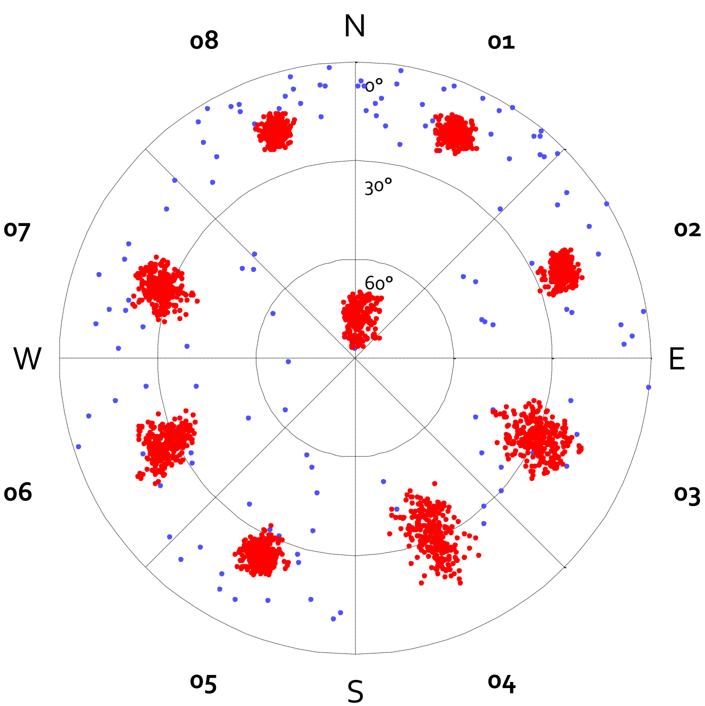


Where are located the Clusters?

INCO

076/14 - 17-Mar-2014

Experimental Sectorization

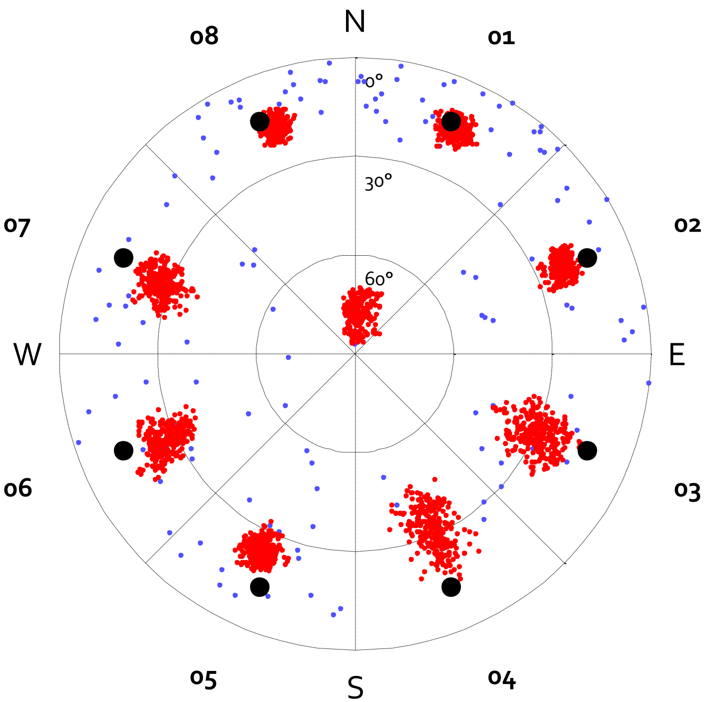


Where are located the Clusters?

INCO

076/14 - 17-Mar-2014

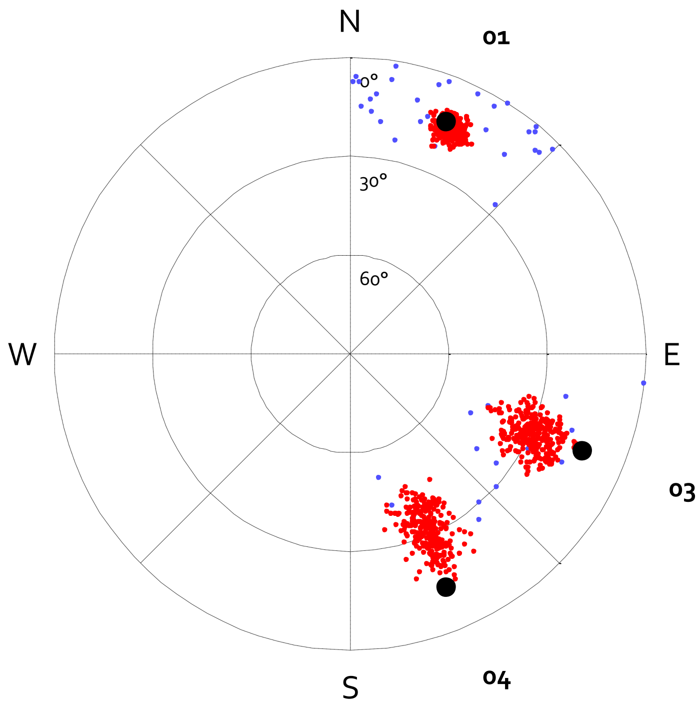
Experimental Sectorization



Where are located the Clusters?

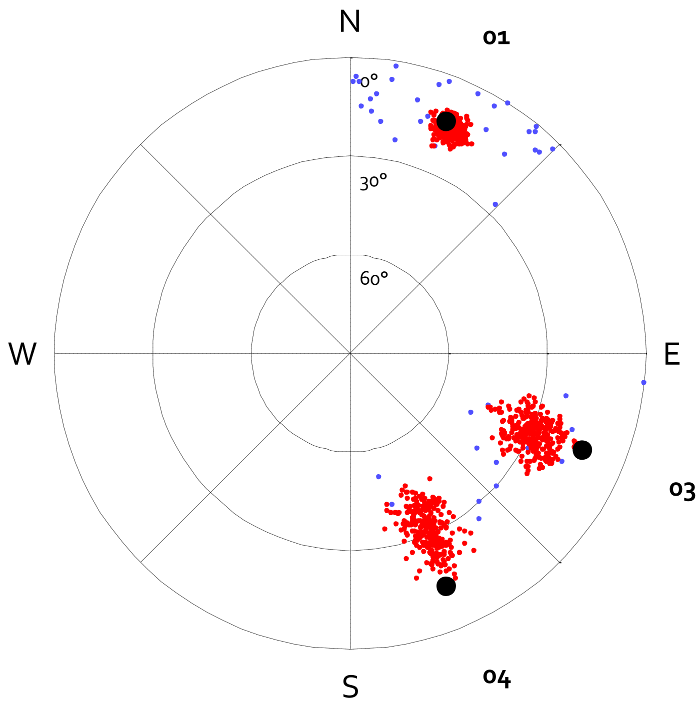
INCO
076/14 - 17-Mar-2014

Experimental Sectorization



Where are located the Clusters?

Experimental Sectorization



INCO

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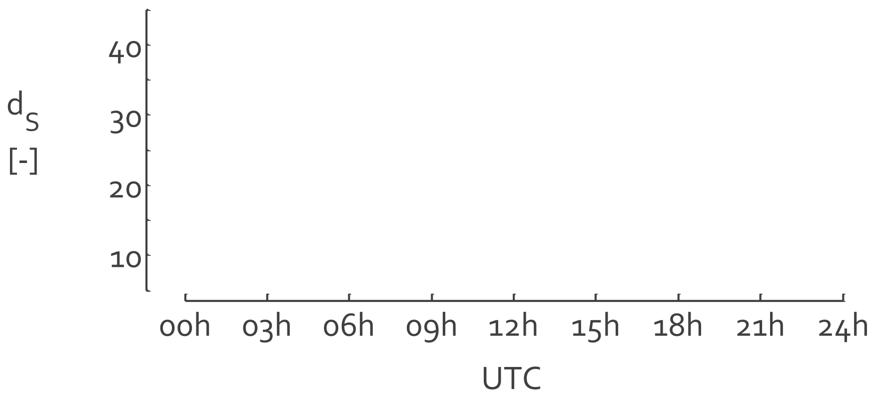

Where are located the Clusters?

INCO

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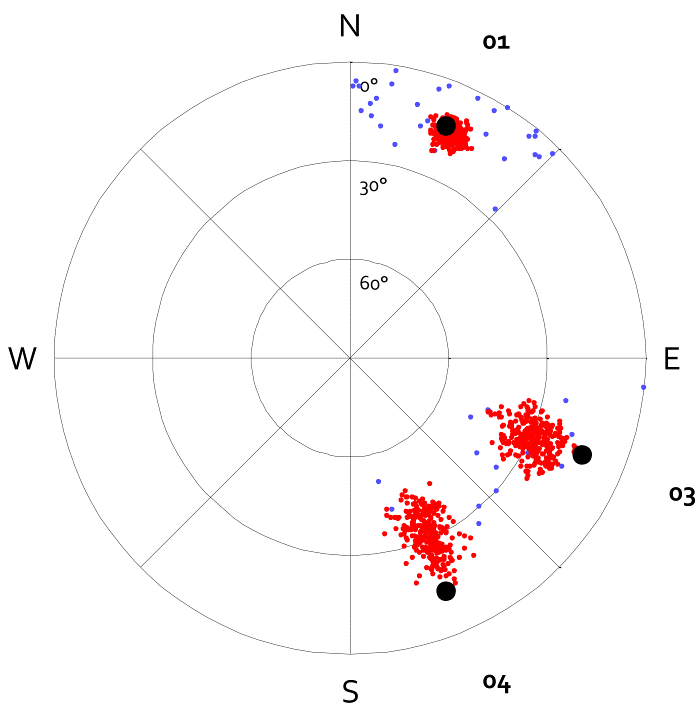
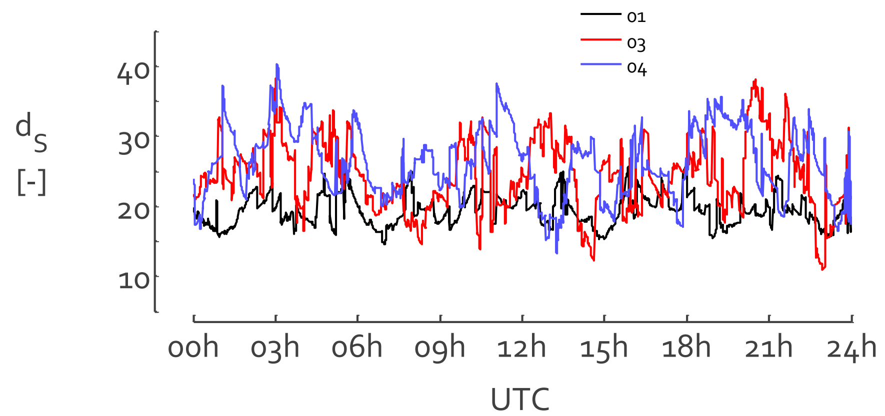
Experimental Sectorization



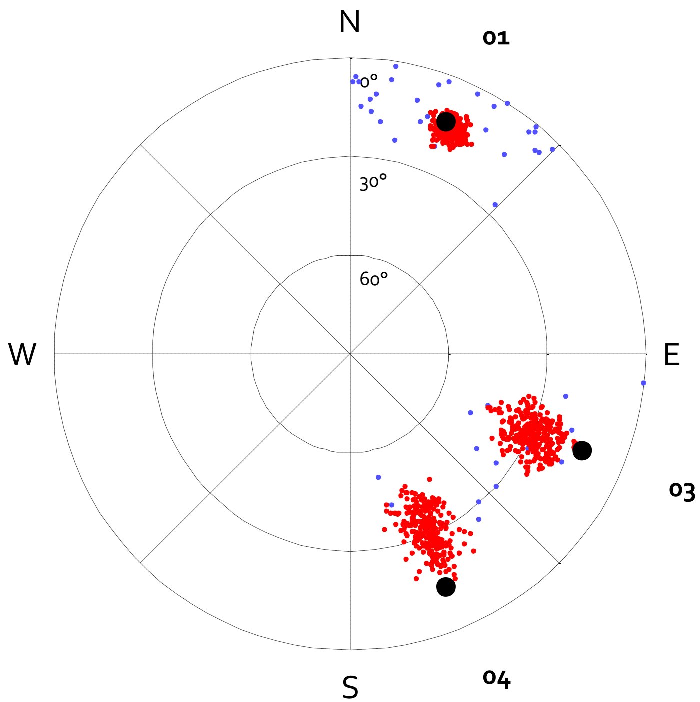


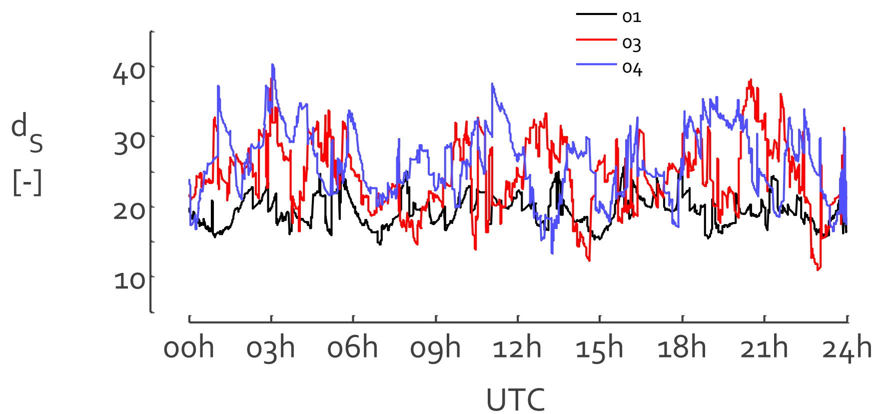
Where are located the Clusters?

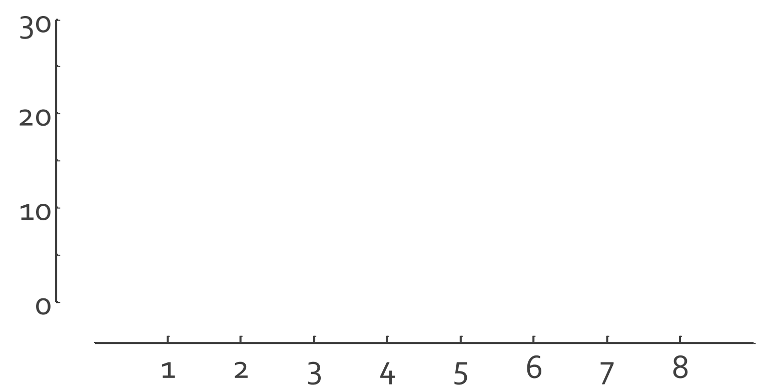
INCO

076/14 - 17-Mar-2014

Experimental Sectorization





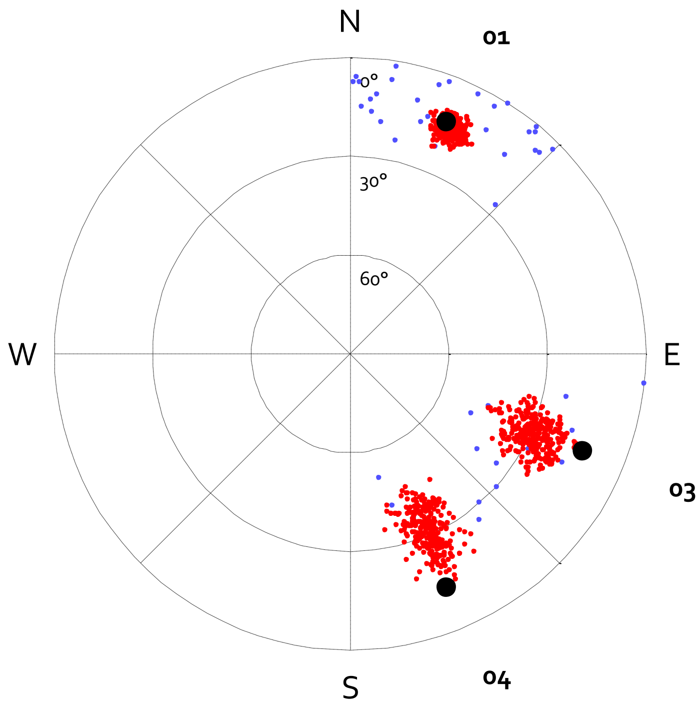


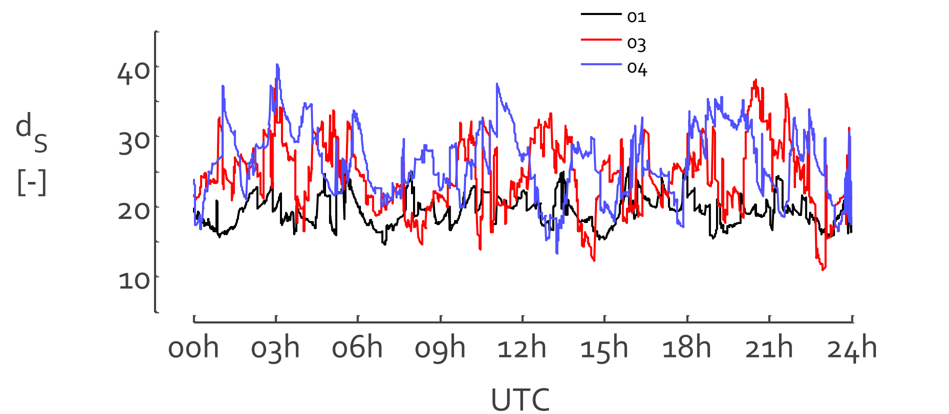
Where are located the Clusters?

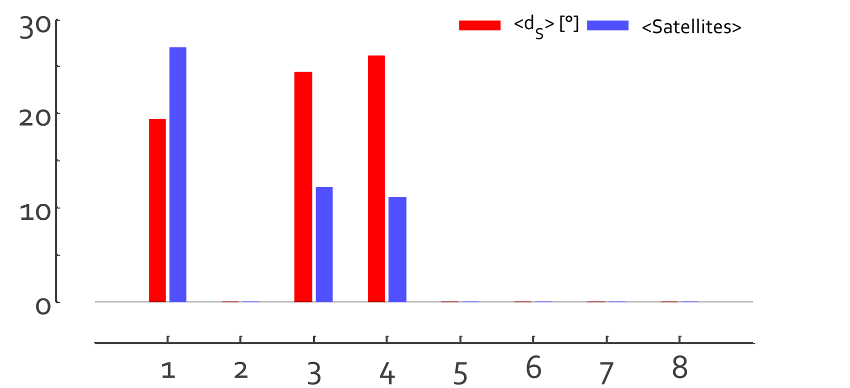
INCO

076/14 - 17-Mar-2014

Experimental Sectorization





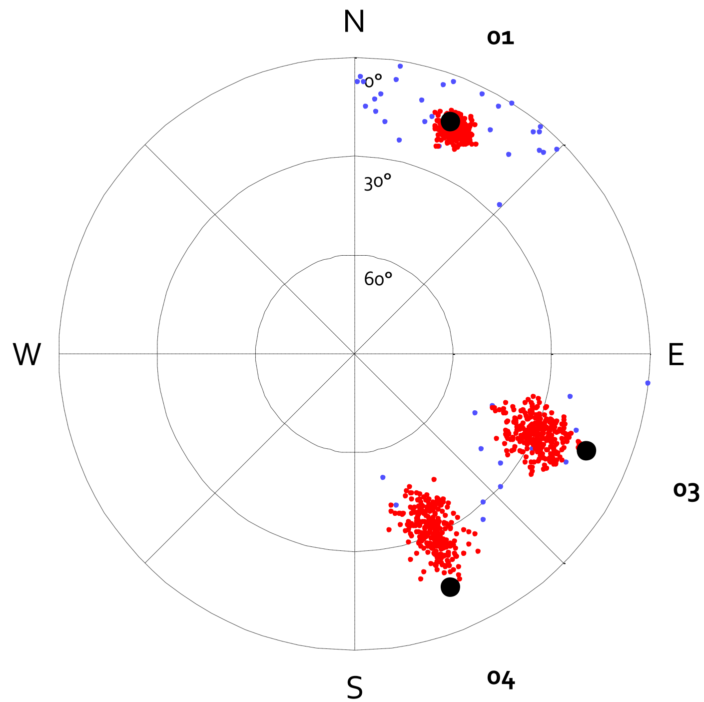


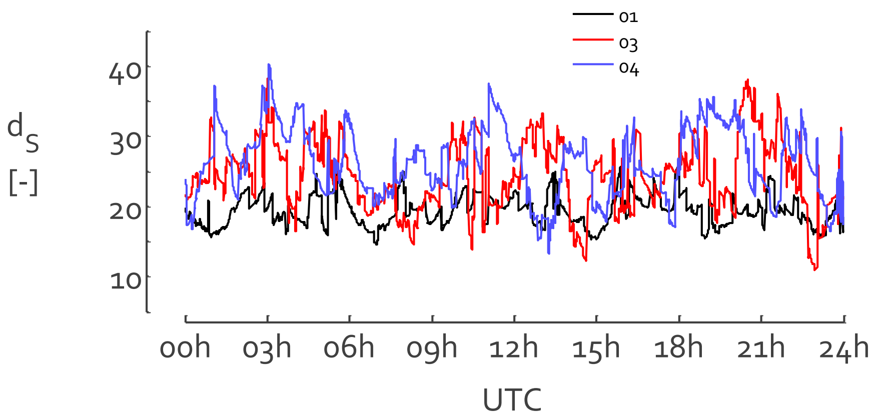
Where are located the Clusters?

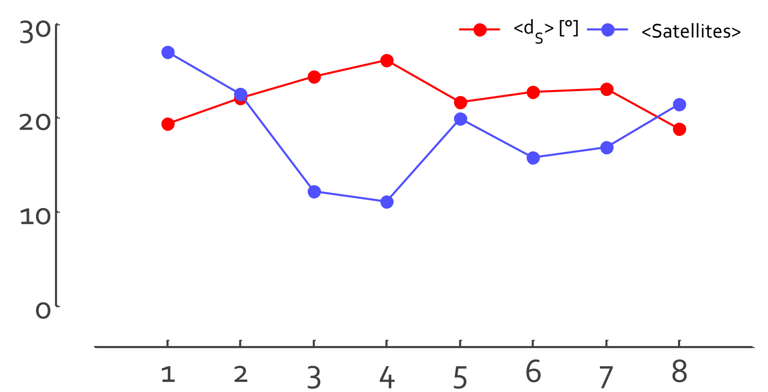
INCO

076/14 - 17-Mar-2014

Experimental Sectorization

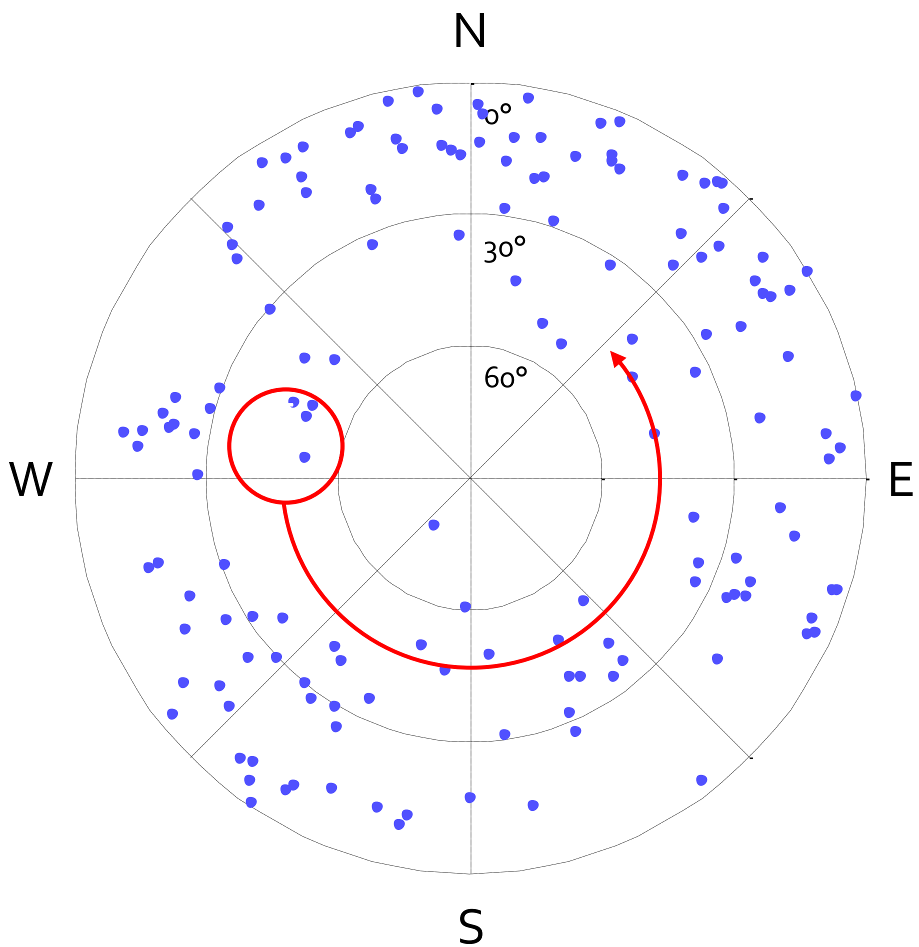






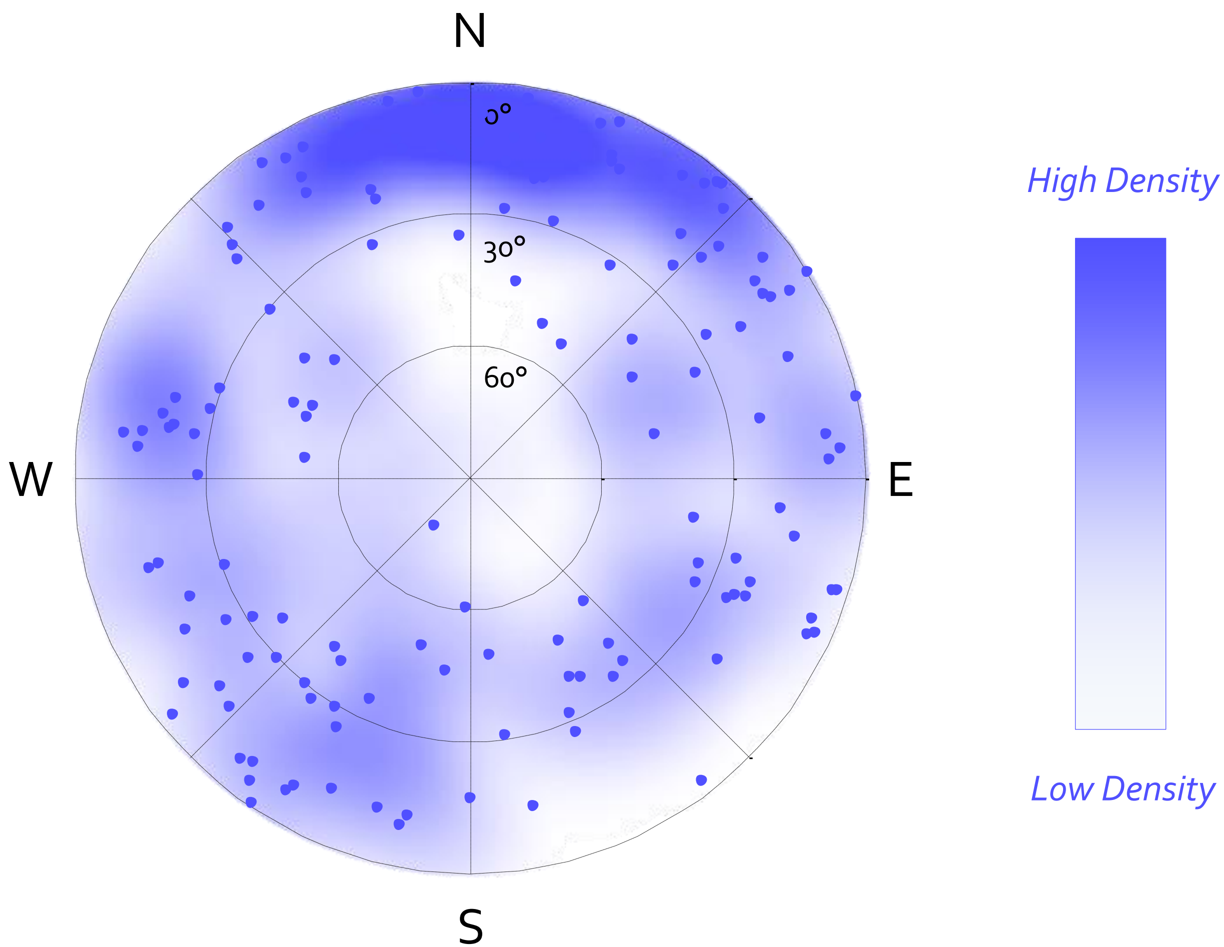
Where are located the Clusters?

Heat Map



Where are located the Clusters?

Heat Map



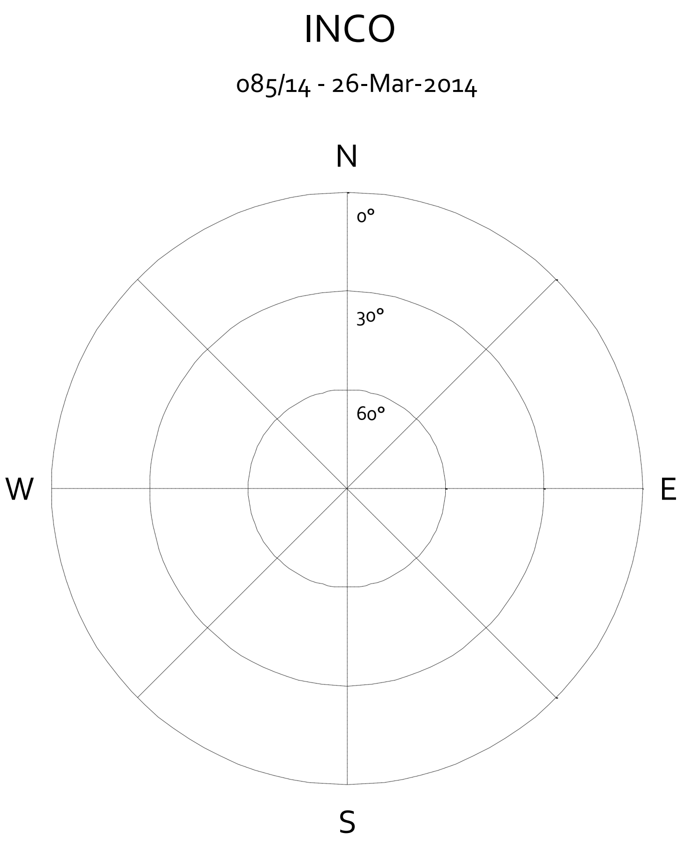
	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●
Interpolation				

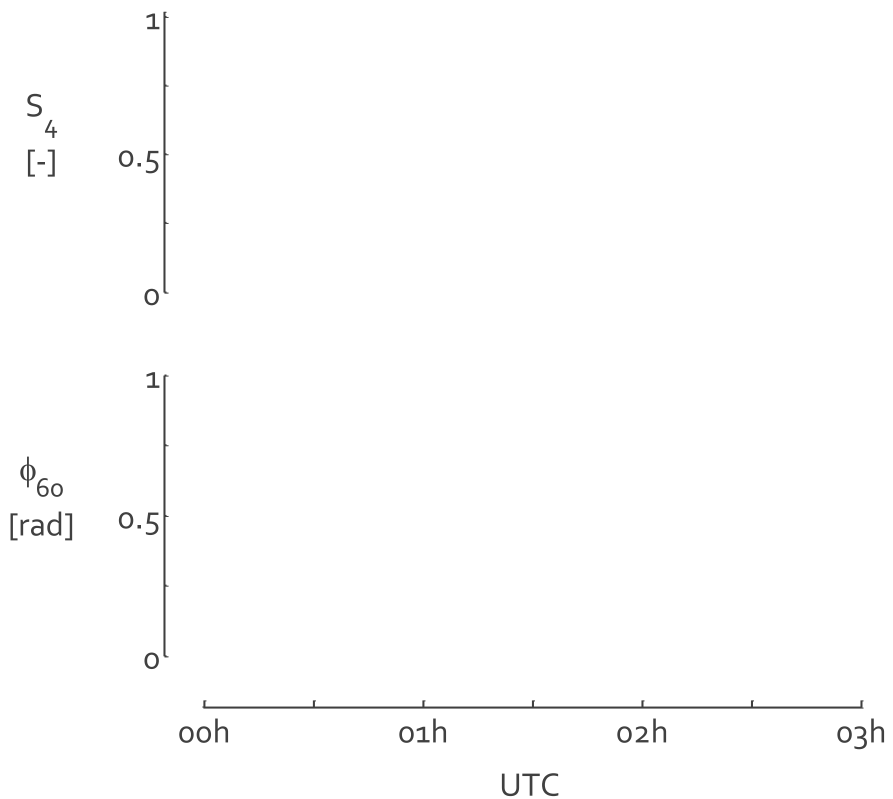
First Law of Geography…

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

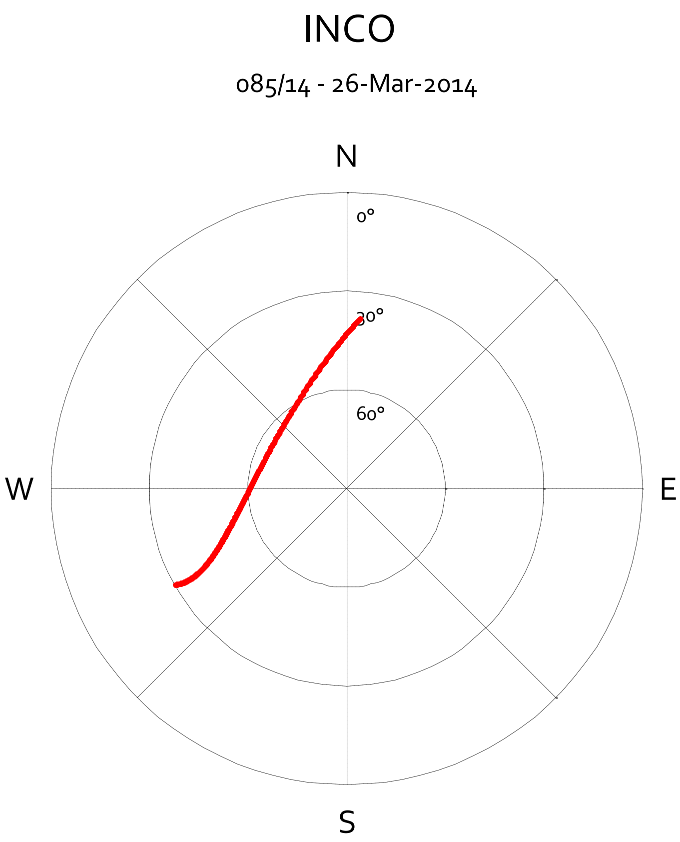
Waldo Tobler

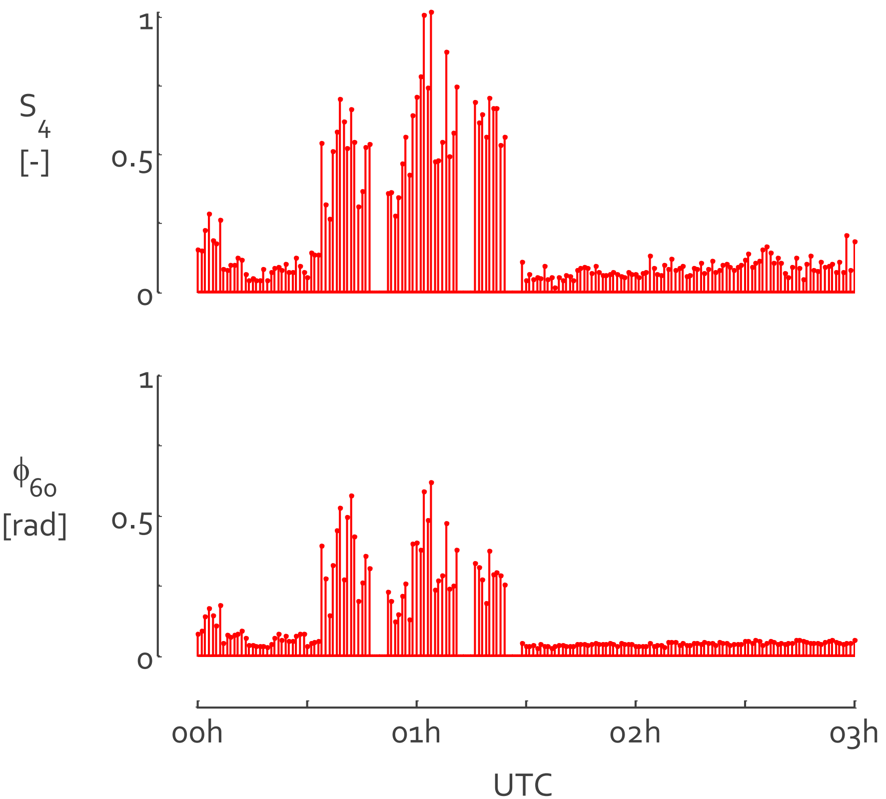
GNSS Signals Scintillations show Signs of Spatial Dependence



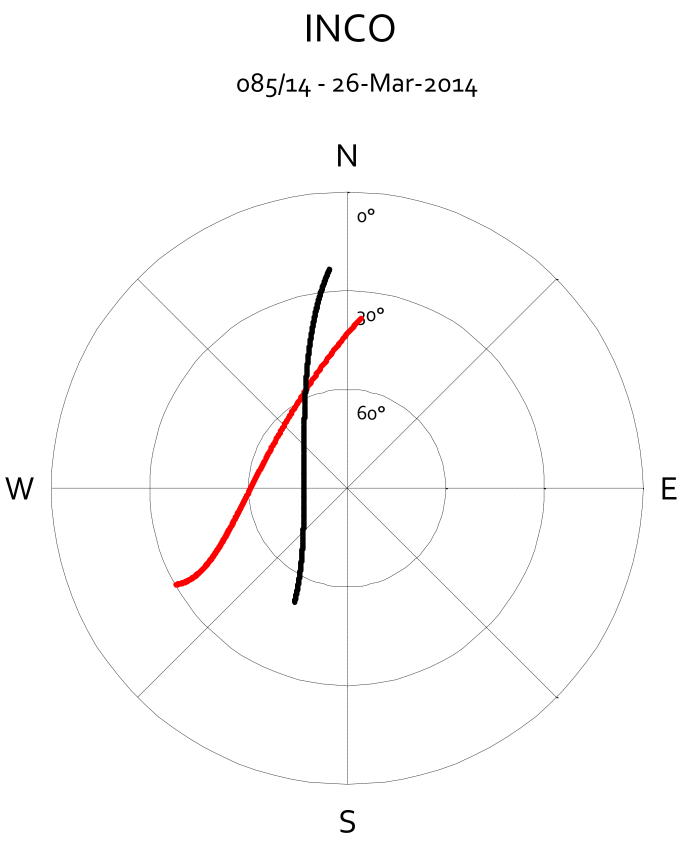


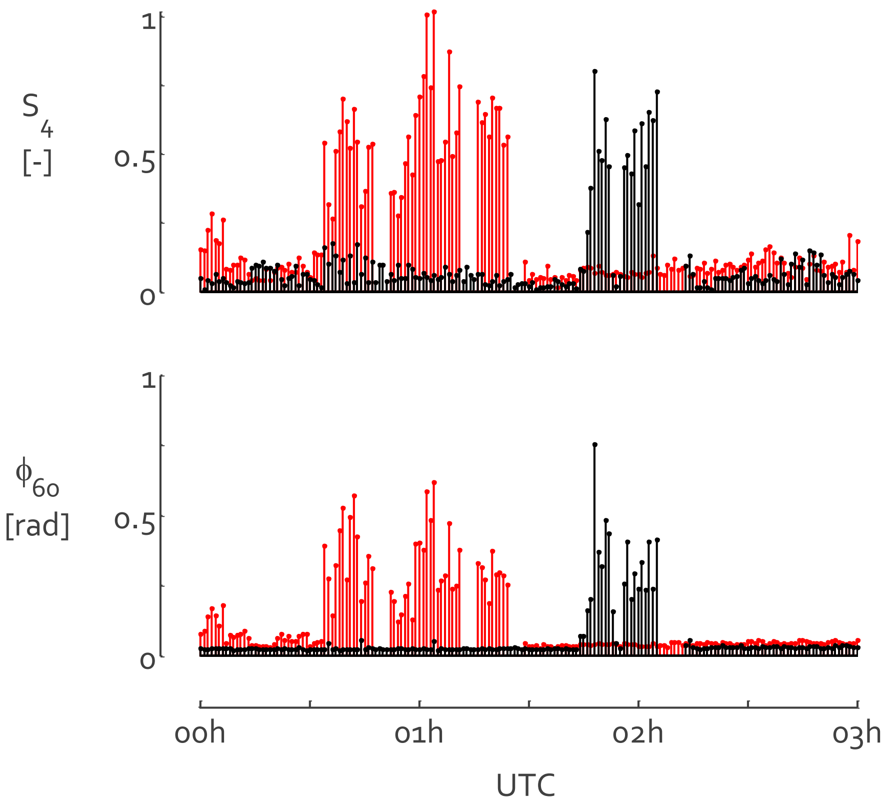
GNSS Signals Scintillations show Signs of Spatial Dependence



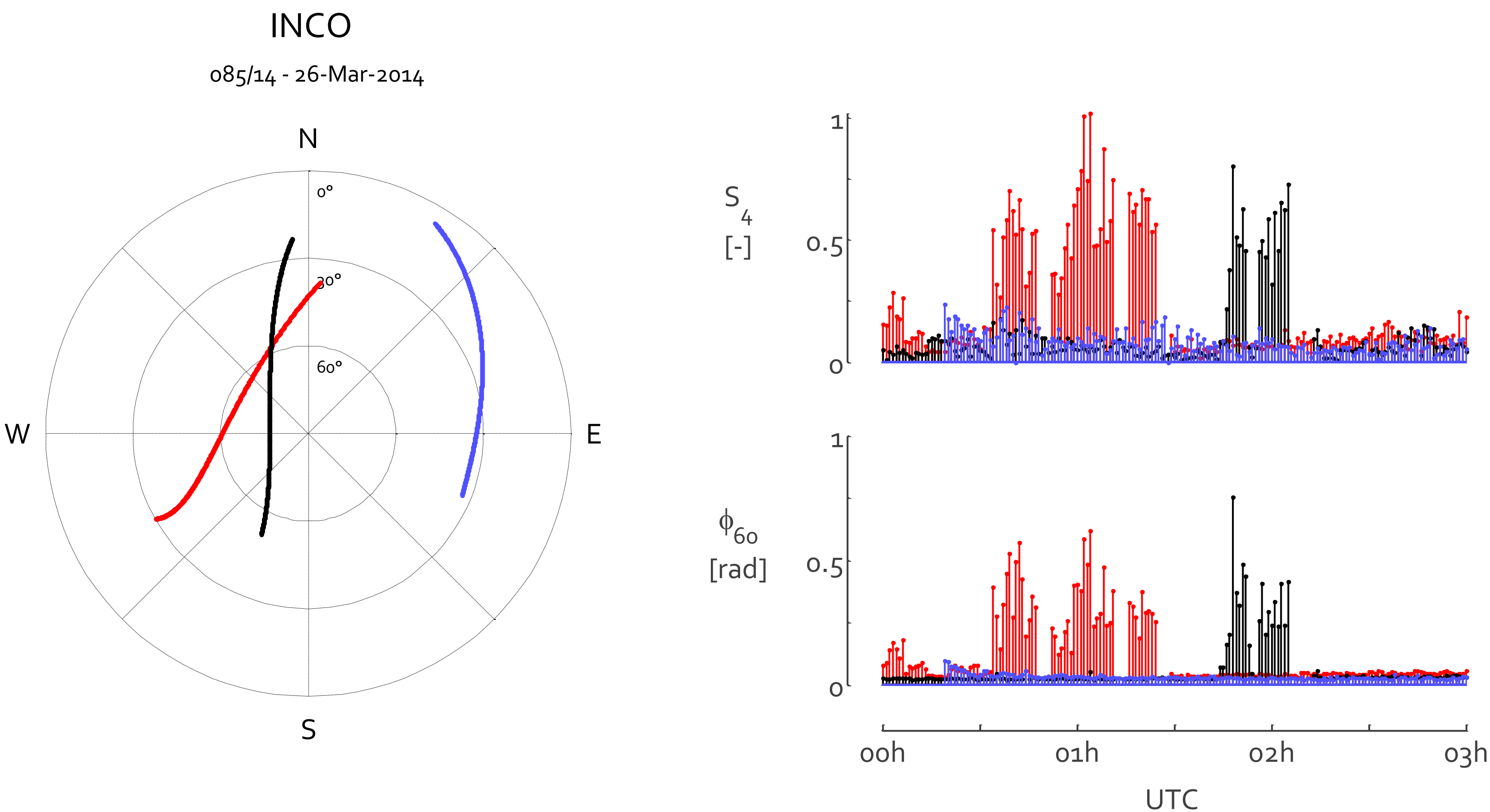


GNSS Signals Scintillations show Signs of Spatial Dependence

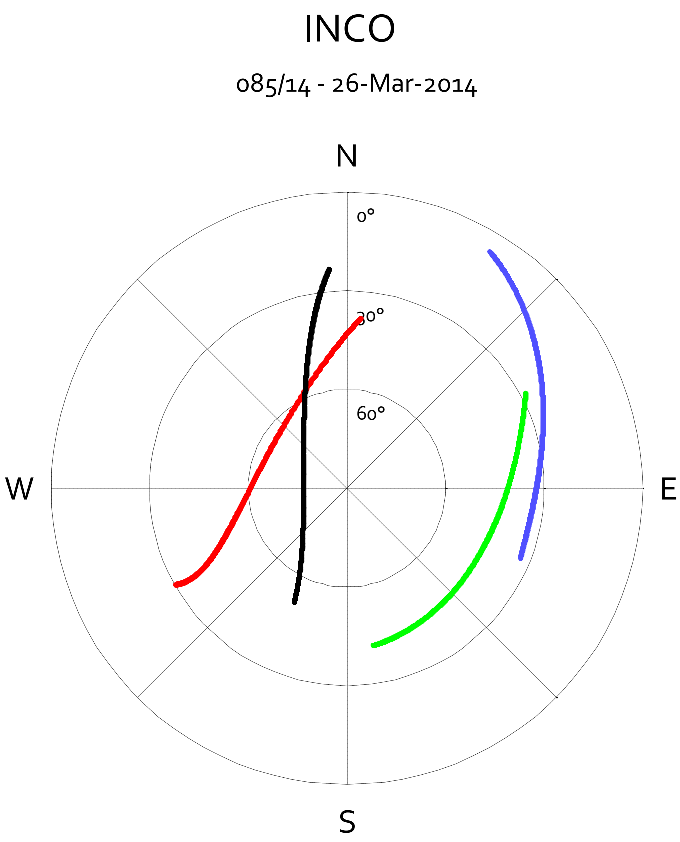


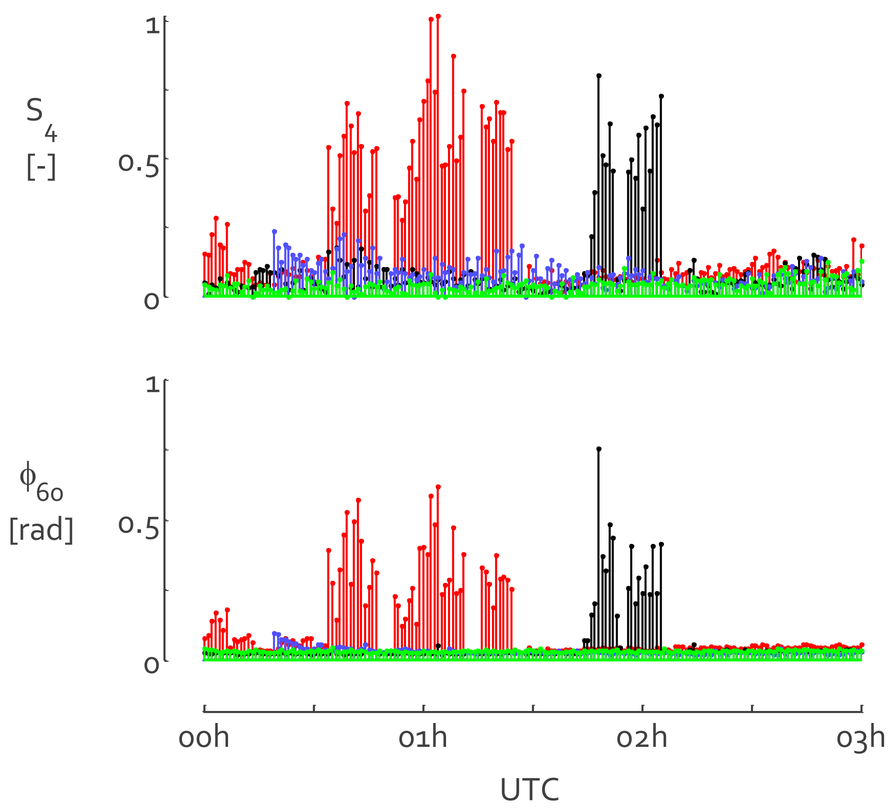


GNSS Signals Scintillations show Signs of Spatial Dependence

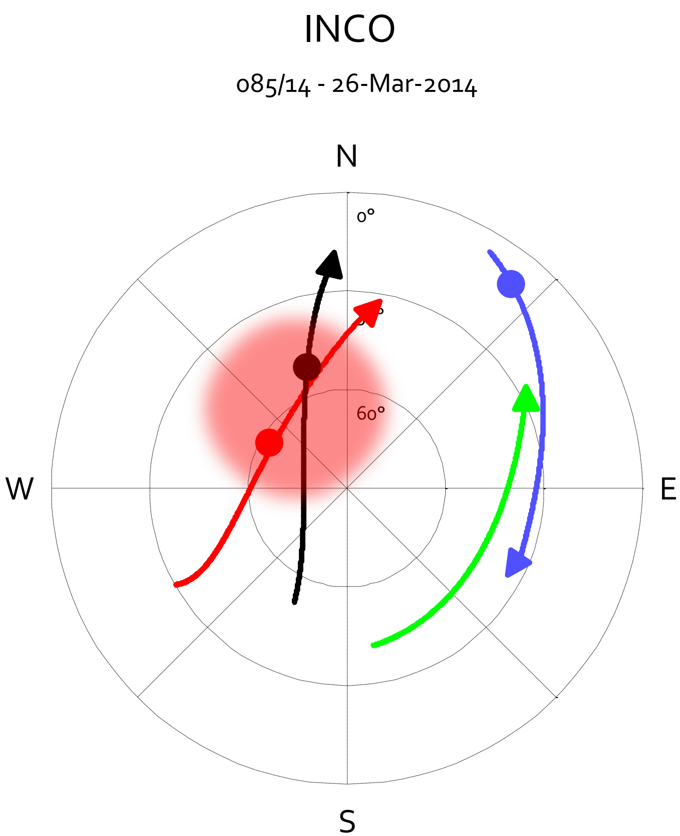


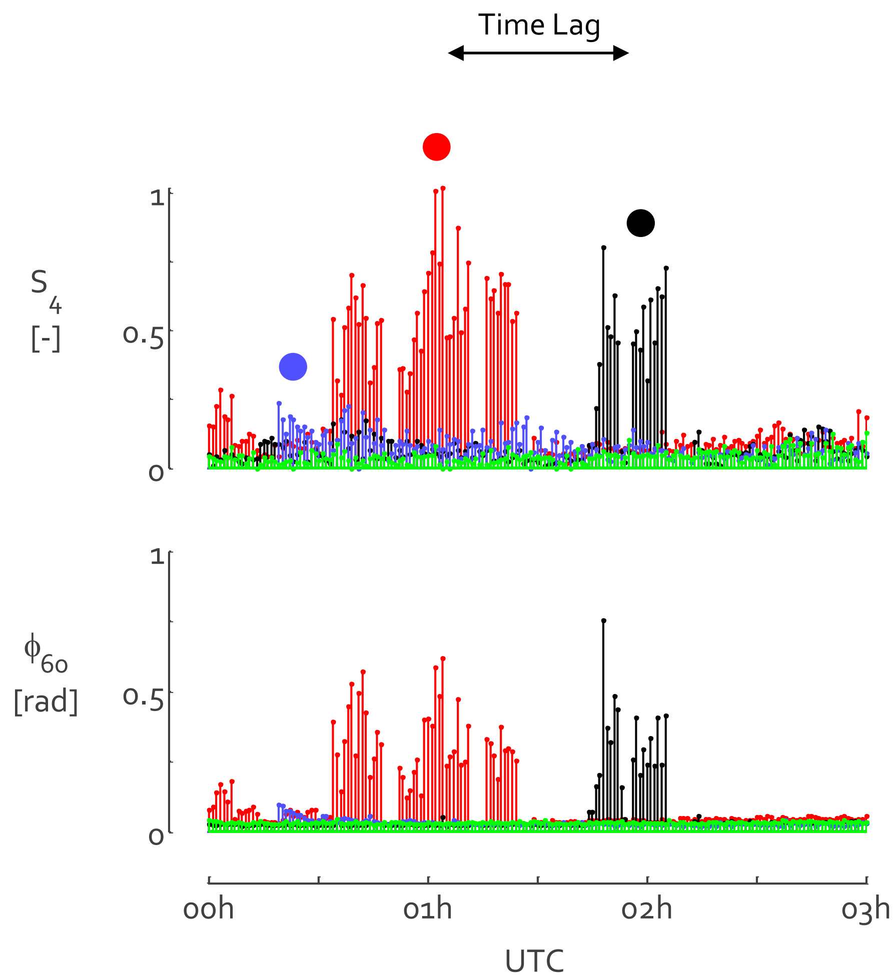
GNSS Signals Scintillations show Signs of Spatial Dependence





GNSS Signals Scintillations show Signs of Spatial Dependence





Description

Detection

Scale

Location

Introduction

Configuration

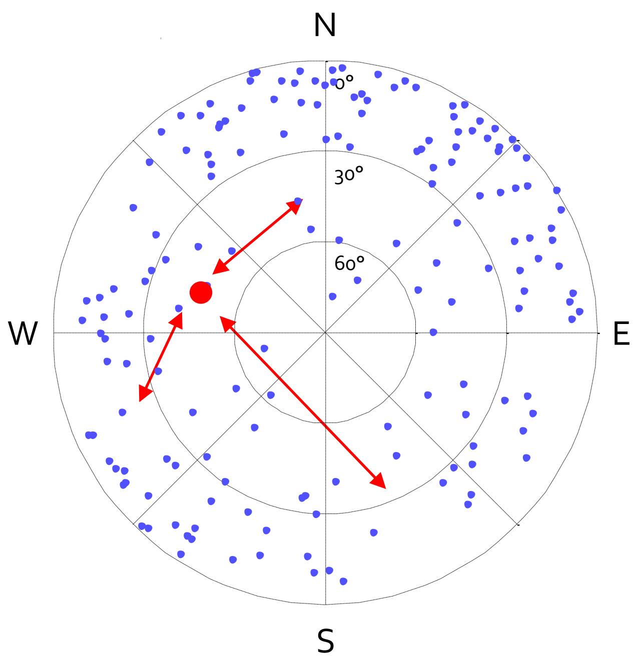
Spatial Dependency

Interpolation

Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency

Moran's I Index

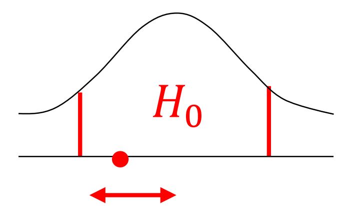
$$I = \frac{N}{\Sigma_i \Sigma_j w_{ij}} \frac{\Sigma_i \Sigma_j w_{ij} (v_i - \bar{v})(v_j - \bar{v})}{\Sigma_i (v_i - \bar{v})^2}$$

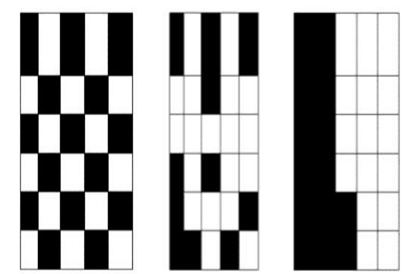


$$v_i = S4_i$$

$$w_{ij} = \frac{1}{d_{ij}^2}$$

$$\forall i \neq j$$





$$E[I] = 0$$

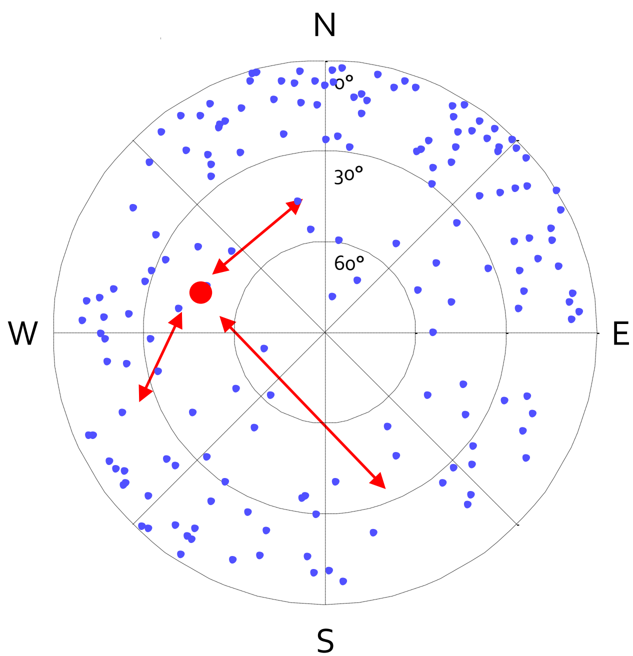
$$V[I] = \ldots$$

$I < 0$ $I \approx 0$ $I > 0$

Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency

Geary's C Index

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



$$v_i = S4_i$$

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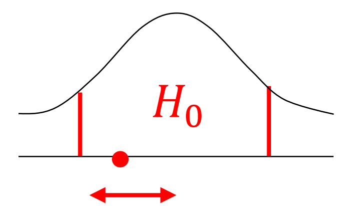
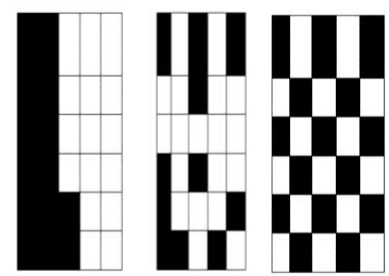
$$\forall i \neq j$$





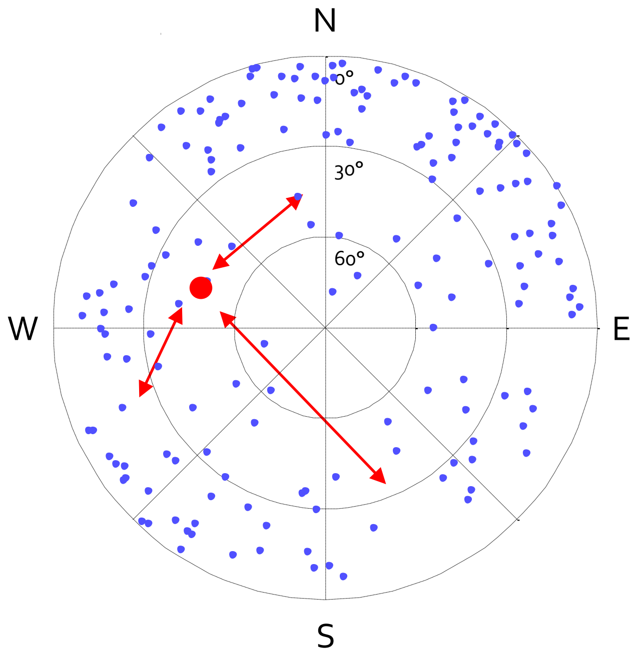
$$E[I] = 1$$

$$V[I] = \ldots$$

$$C < 1 \quad C \approx 1 \quad C > 1$$

Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency

The Geometry of the Survey and the Ionospheric Activity evolve according to Time

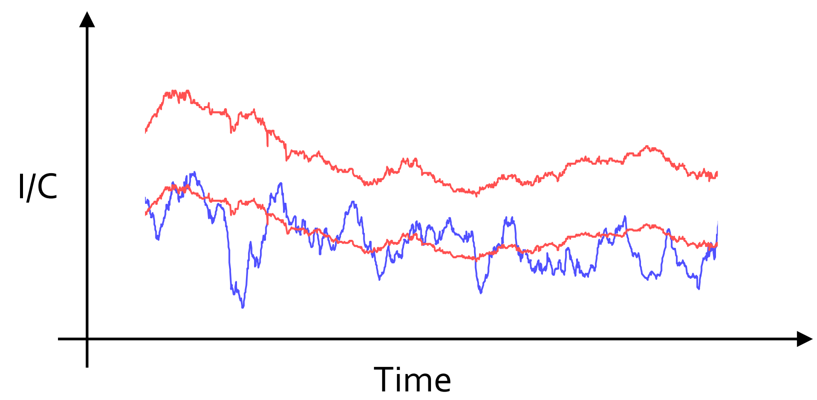


Moran's I

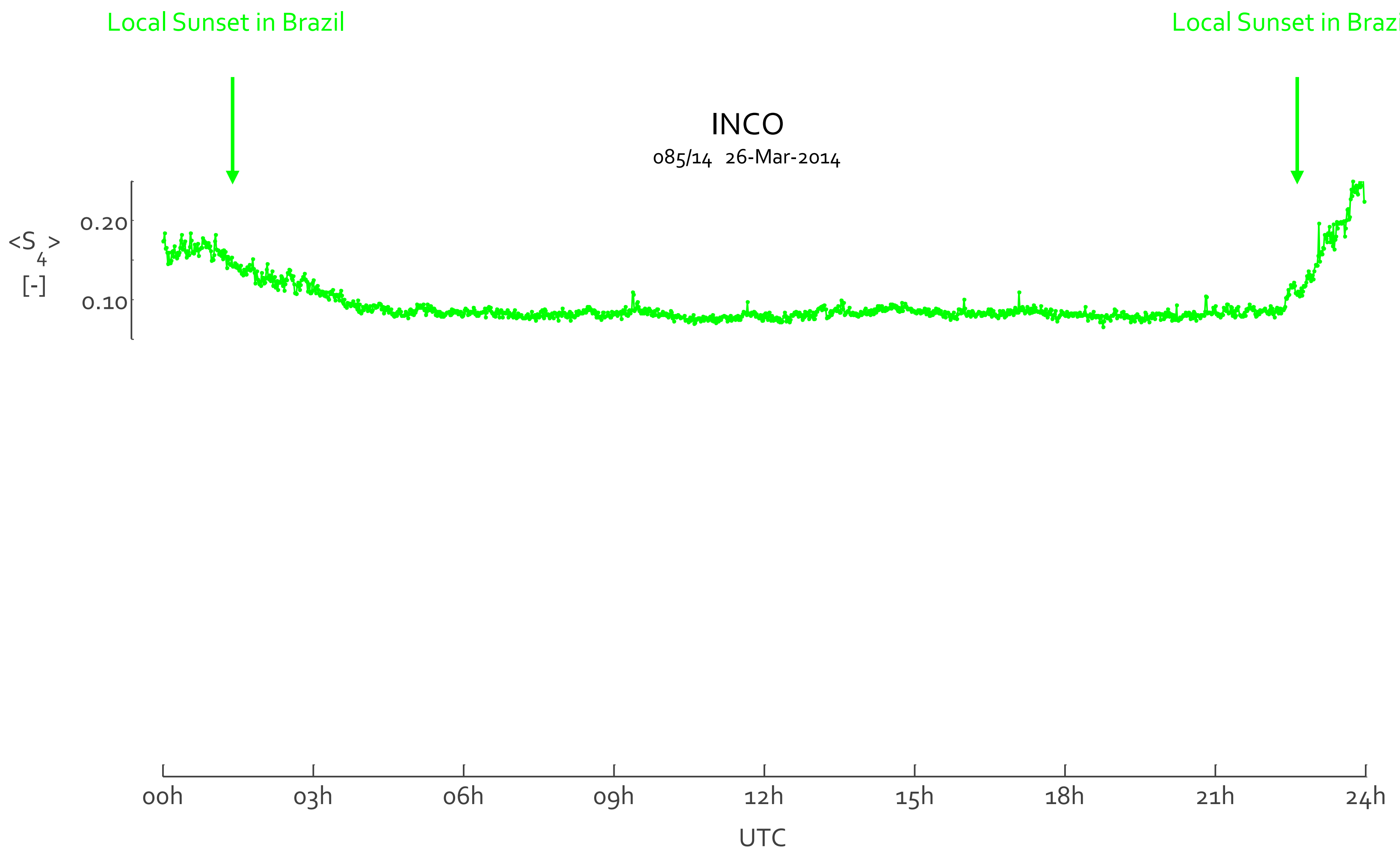
$$I = \frac{N}{\Sigma_i \Sigma_j w_{ij}} \frac{\Sigma_i \Sigma_j w_{ij} (v_i - \bar{v})(v_j - \bar{v})}{\Sigma_i (v_i - \bar{v})^2}$$

Geary's C

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



Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency



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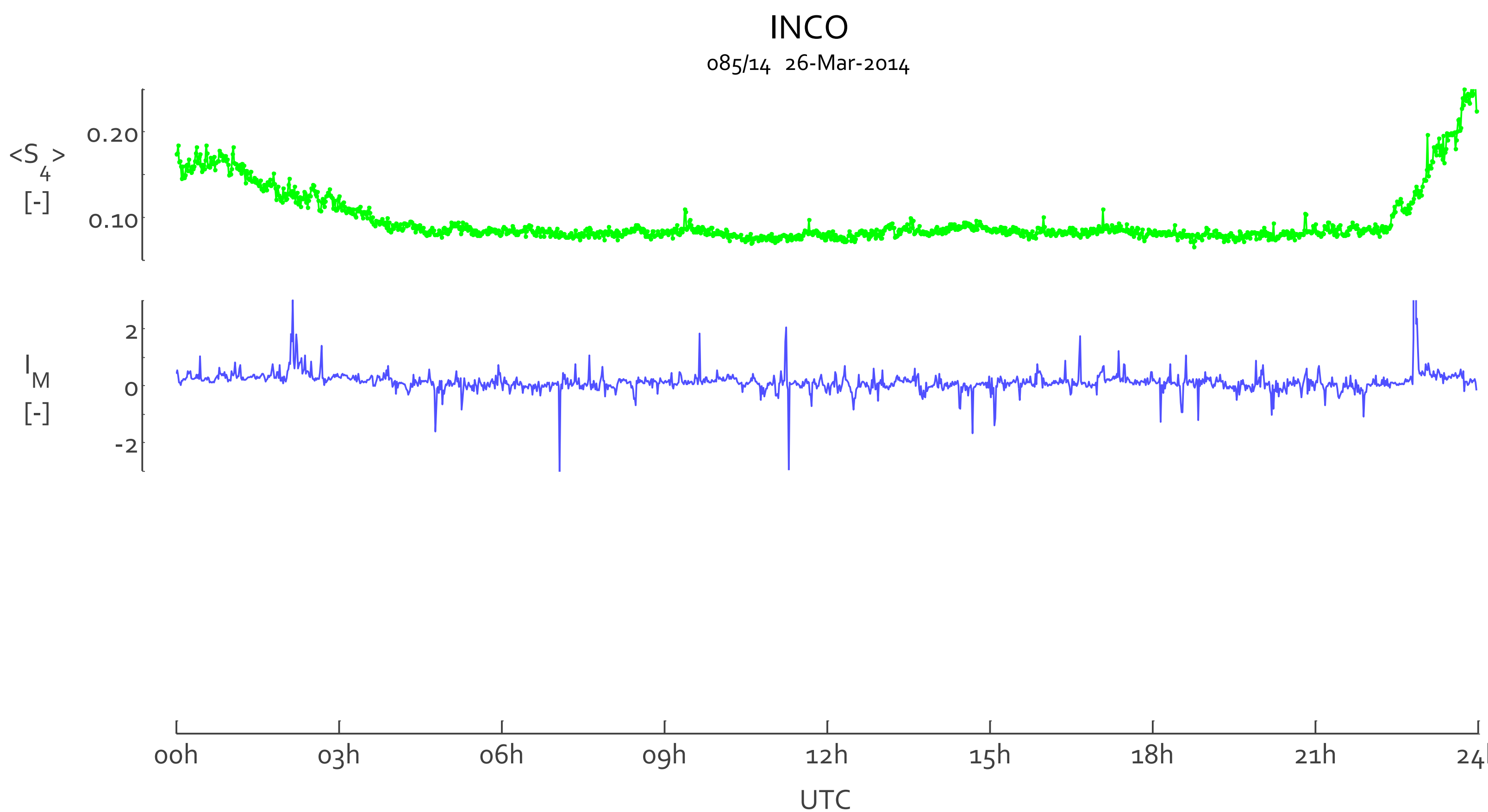
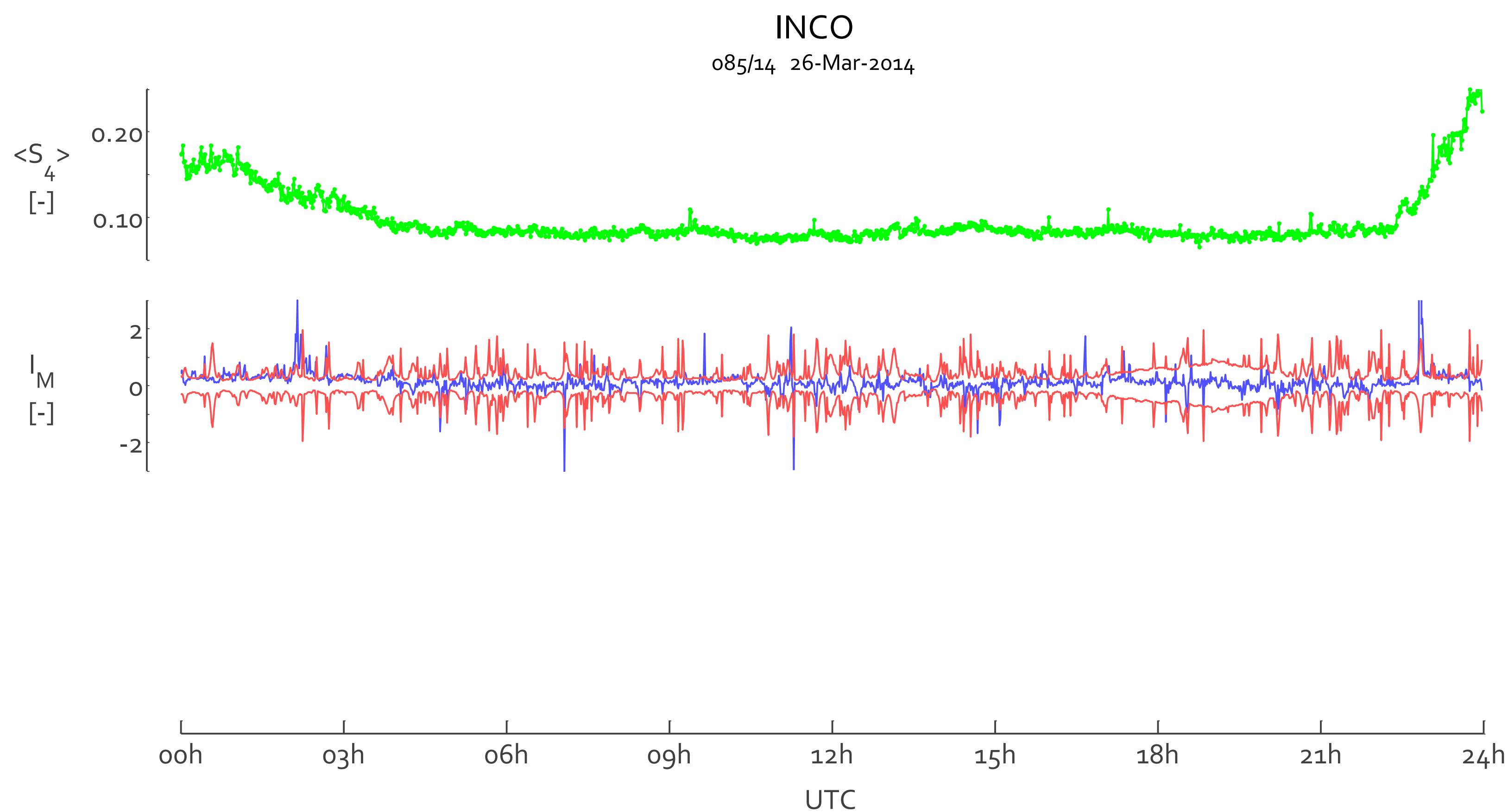


Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency



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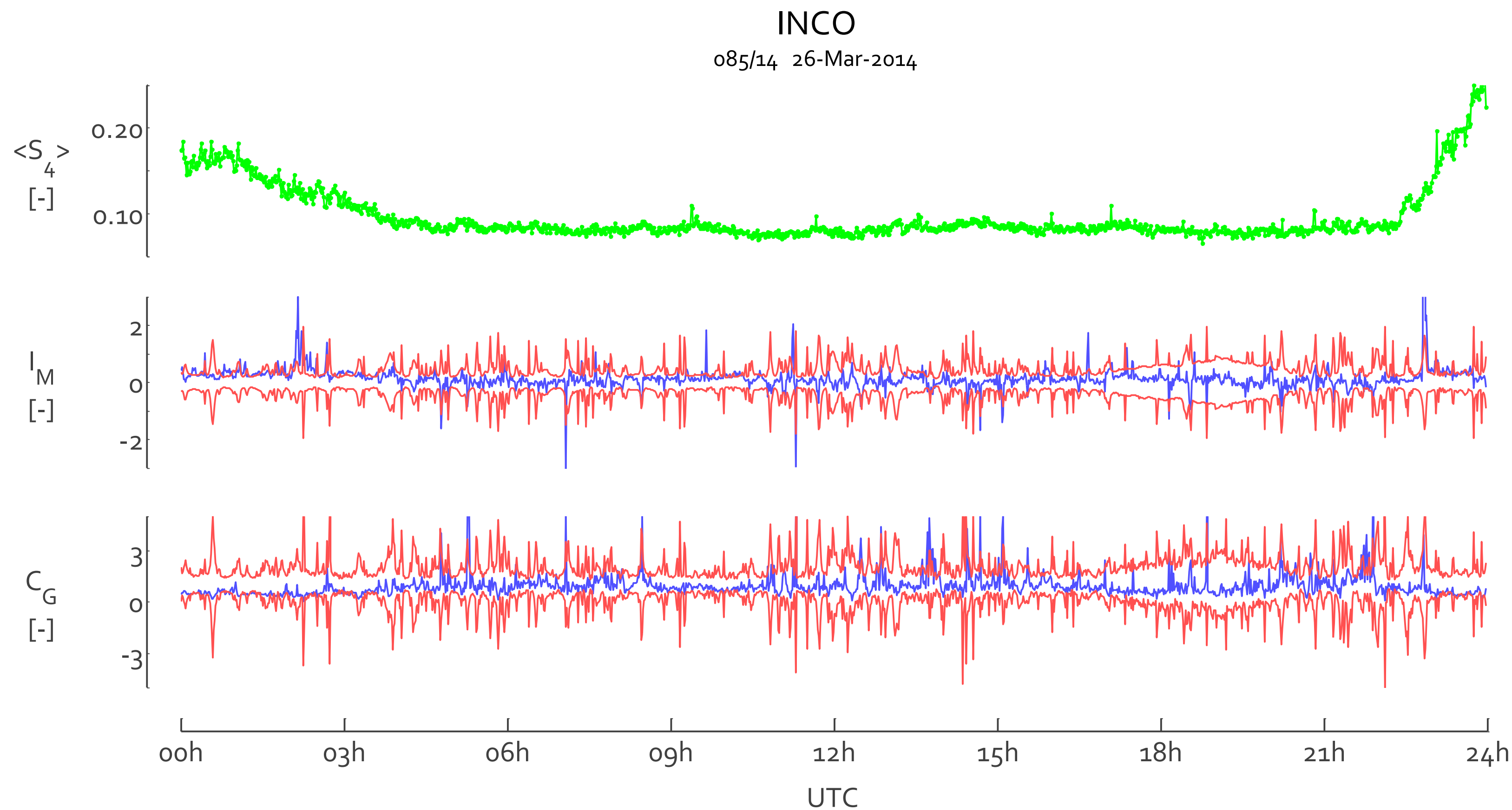

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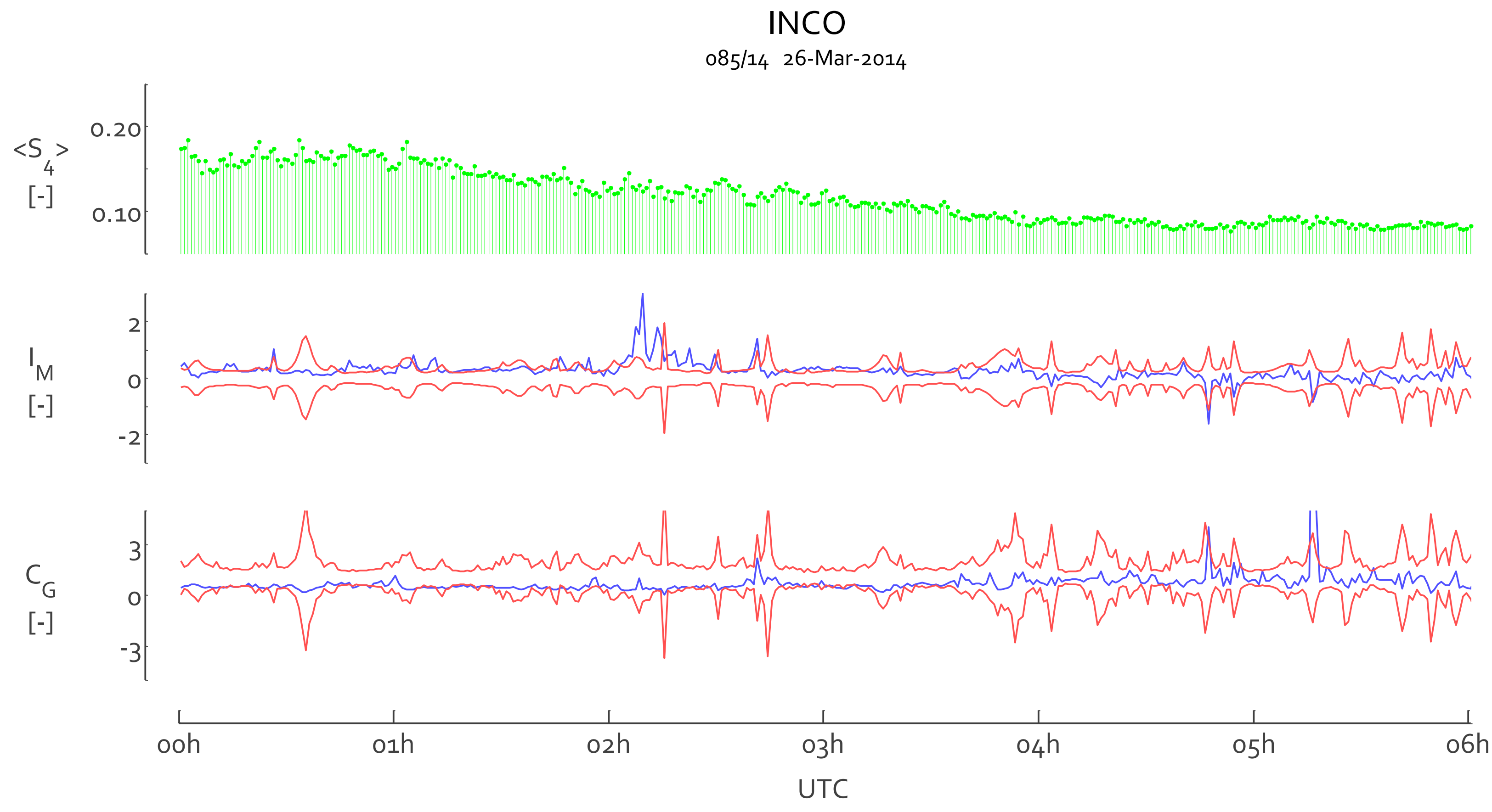

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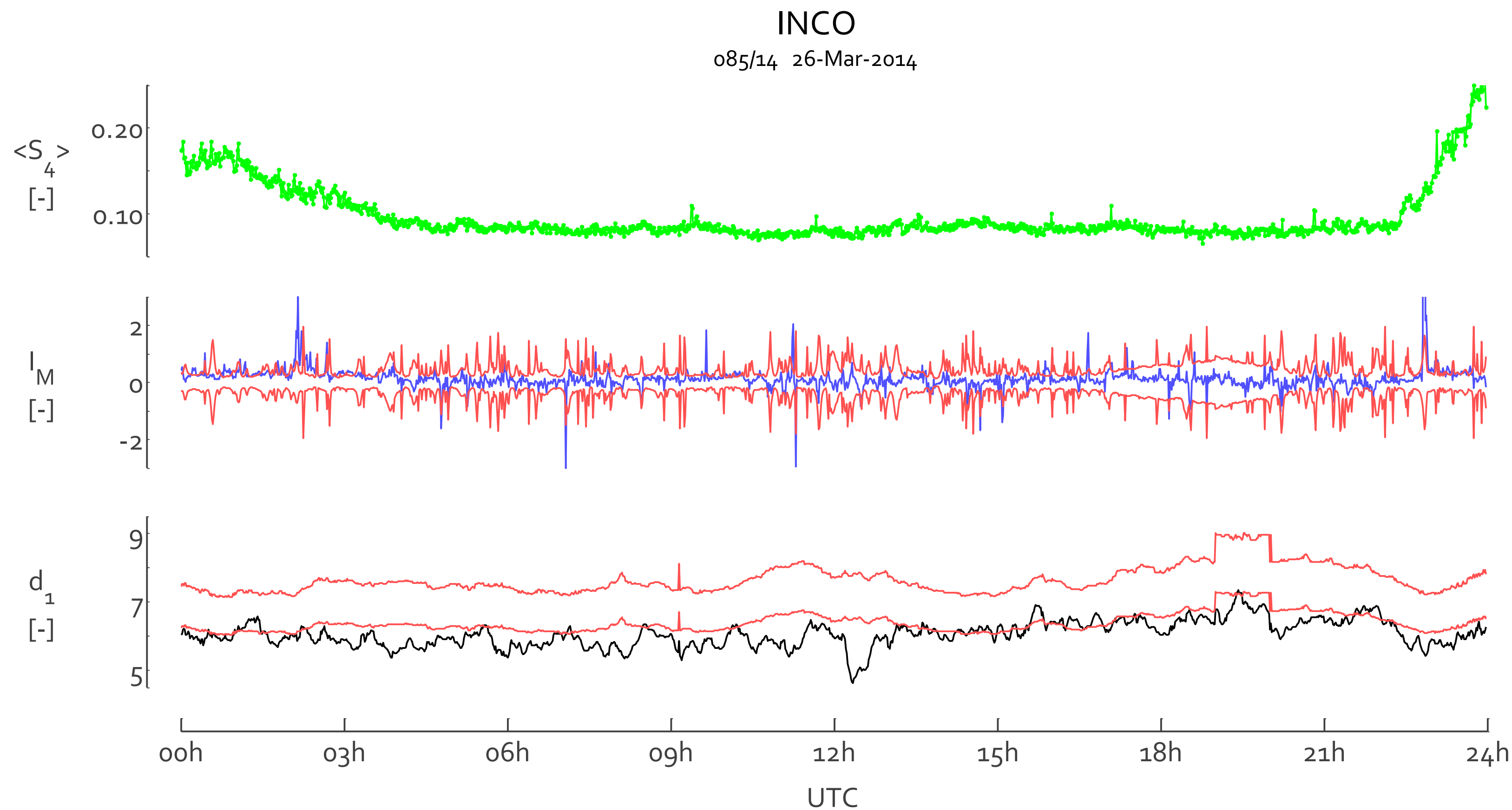

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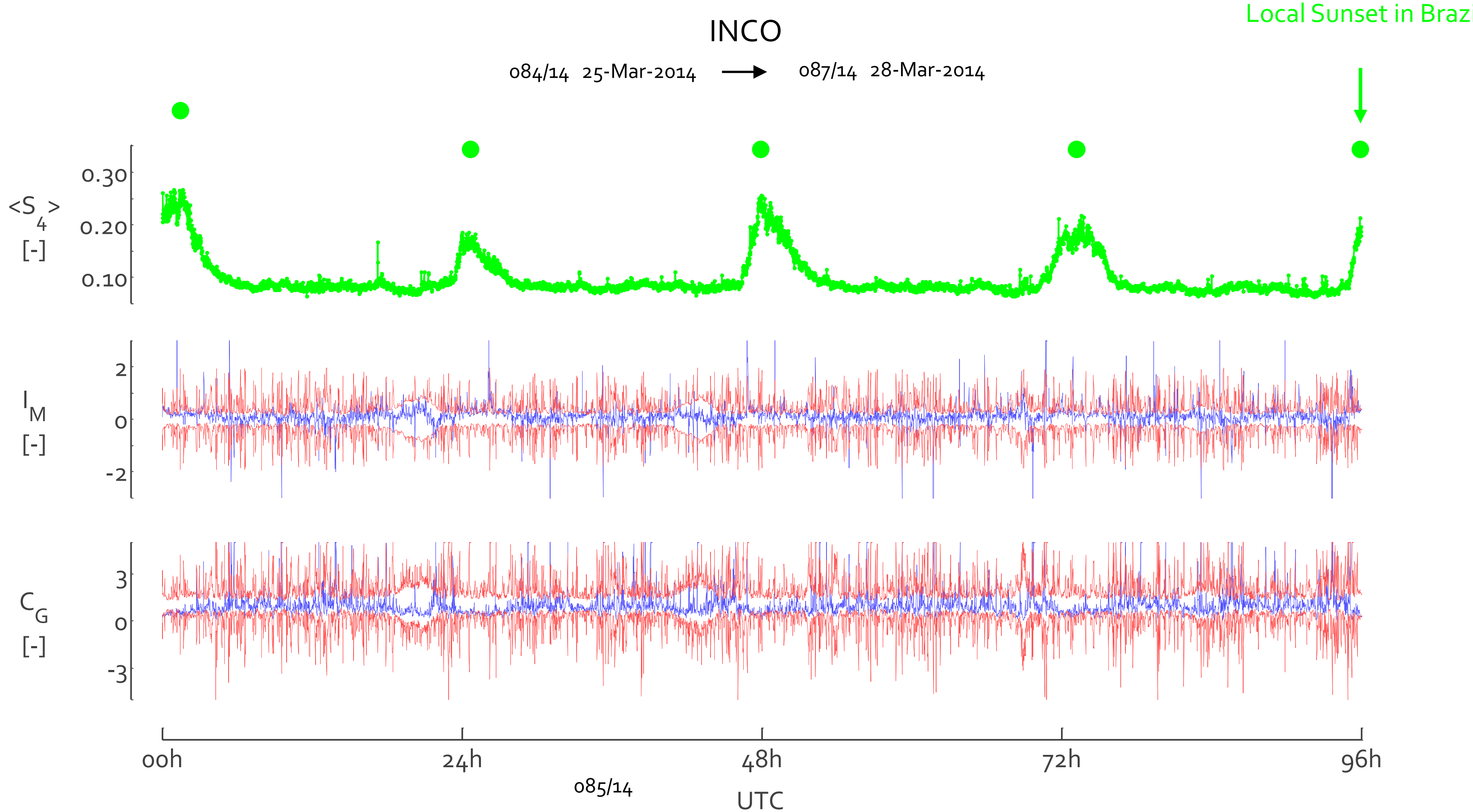

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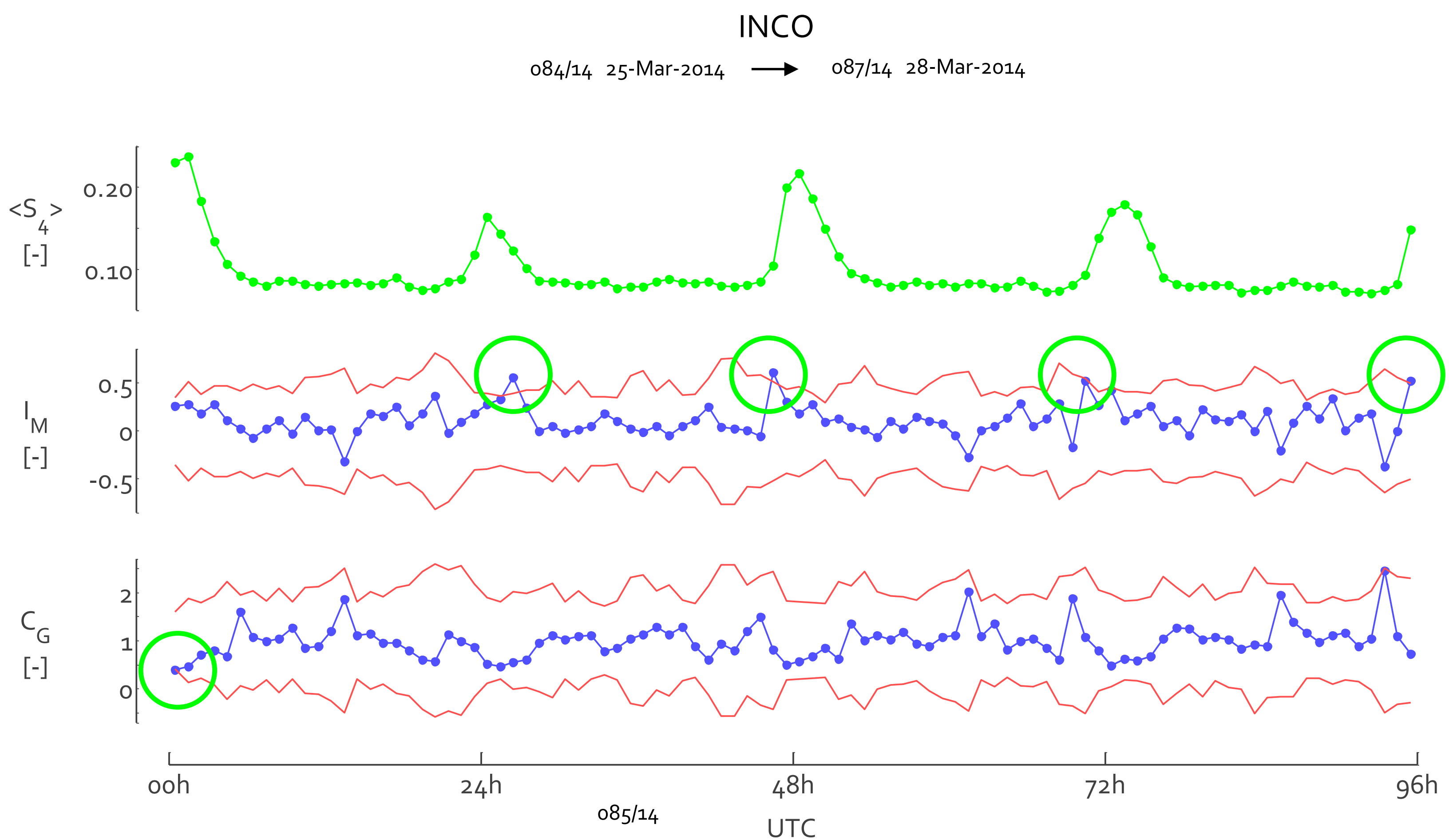

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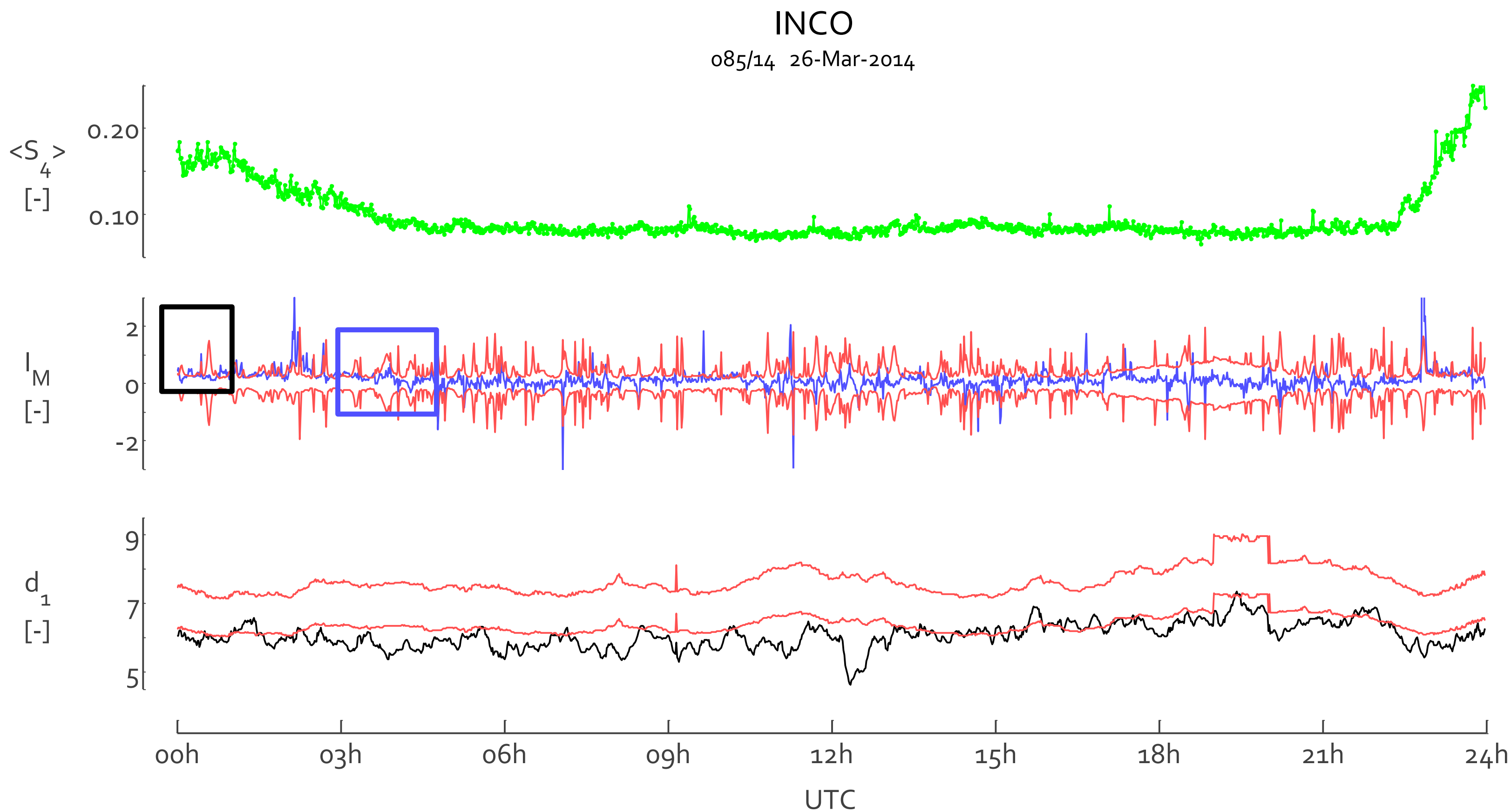
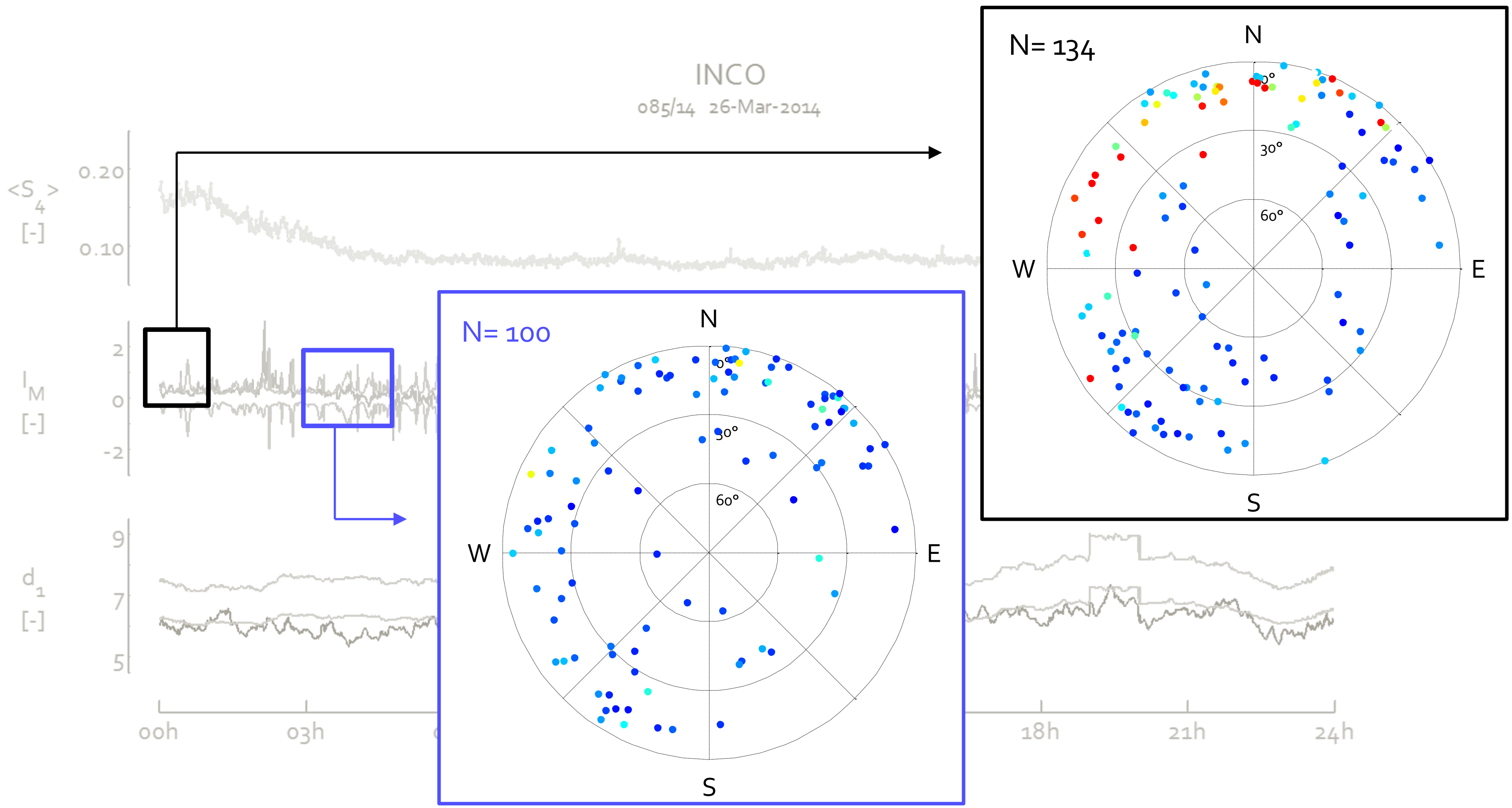


Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency



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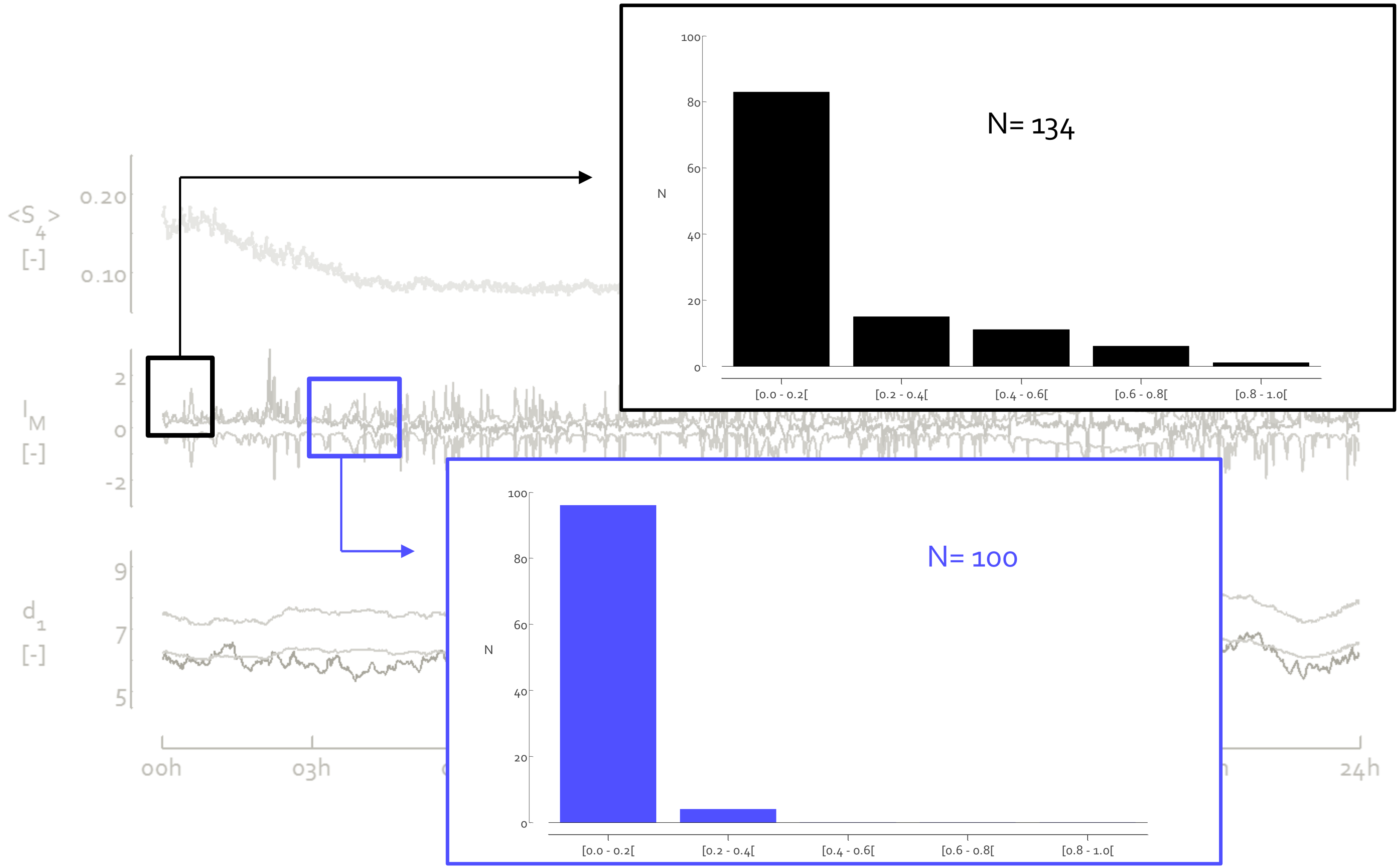
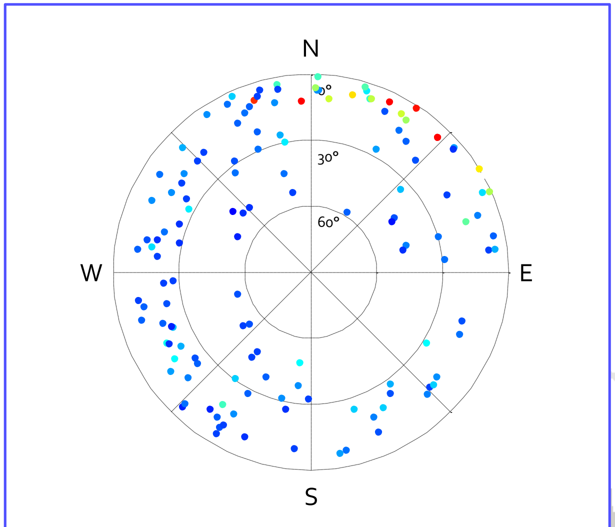


Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency



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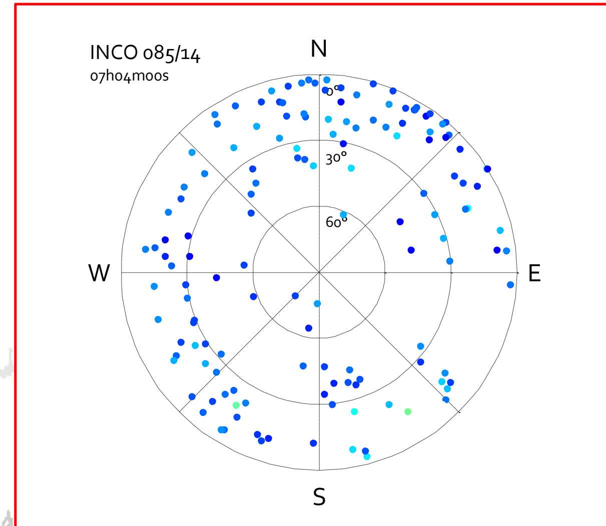
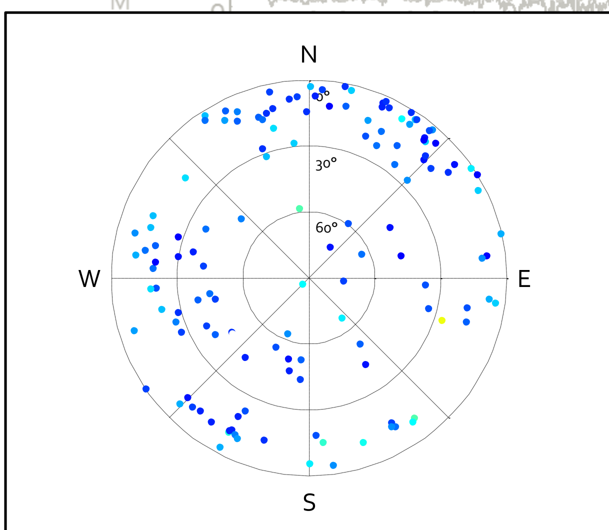
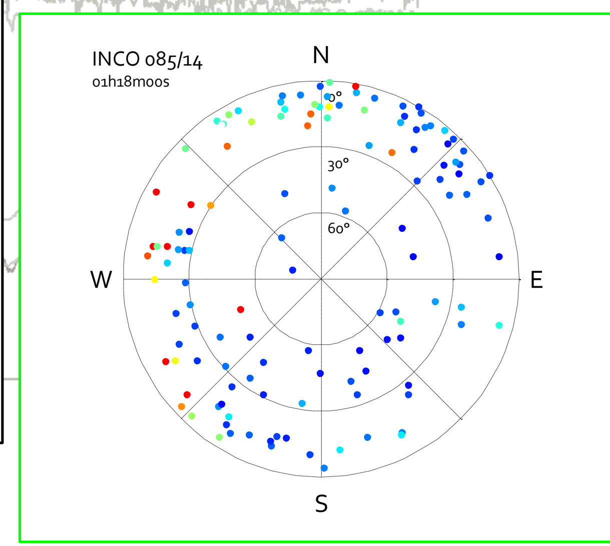


- SAC ++ (I)
- SAC -- (I)
- SAC ~ 0 (I)
- SAC ++ (C)

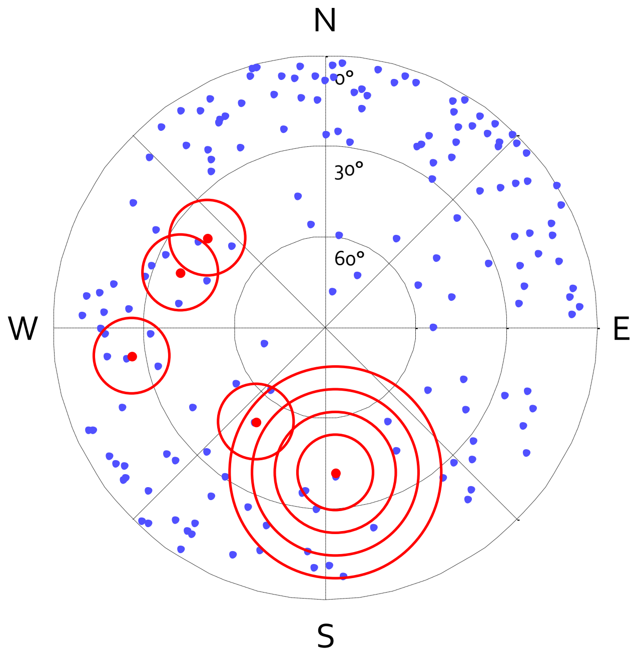




	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●
Interpolation				

Analyse of the Scale of the Spatial Dependency with SAC Correlograms

SAC Correlagram: SAC vs. the Analysis Scale



Moran's I

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

Geary's C

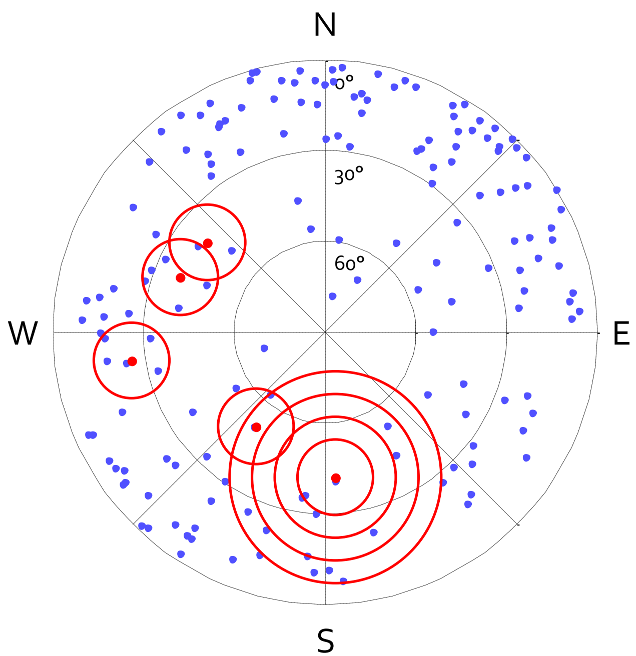
$$C(\omega) = \frac{(N-1)}{2\Sigma_i \Sigma_j w_{ij}} \frac{\Sigma_i \Sigma_j w_{ij} (v_i - v_j)^2}{\Sigma_i (v_i - \bar{v})^2}$$

$$d_{ij} \le \omega_p \Rightarrow w_{ij} = \frac{1}{d_{ij}^2}$$

$$d_{ij} > \omega_p \Rightarrow w_{ij} = 0$$

Analyse of the Scale of the Spatial Dependency with SAC Correlograms

SAC Correlagram: SAC vs. the Analysis Scale



Moran's I

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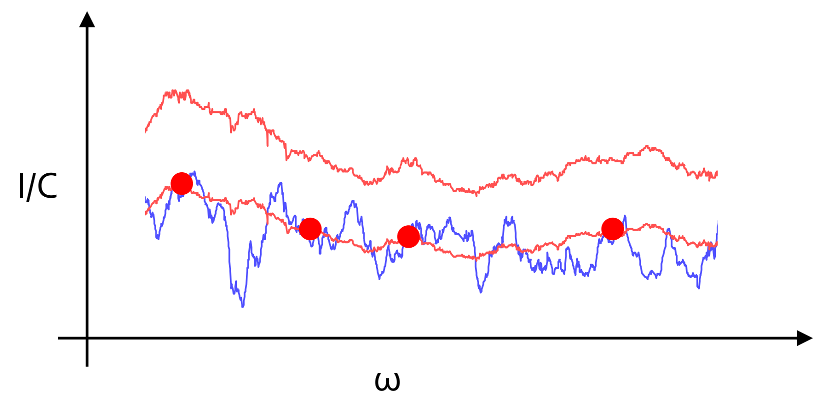
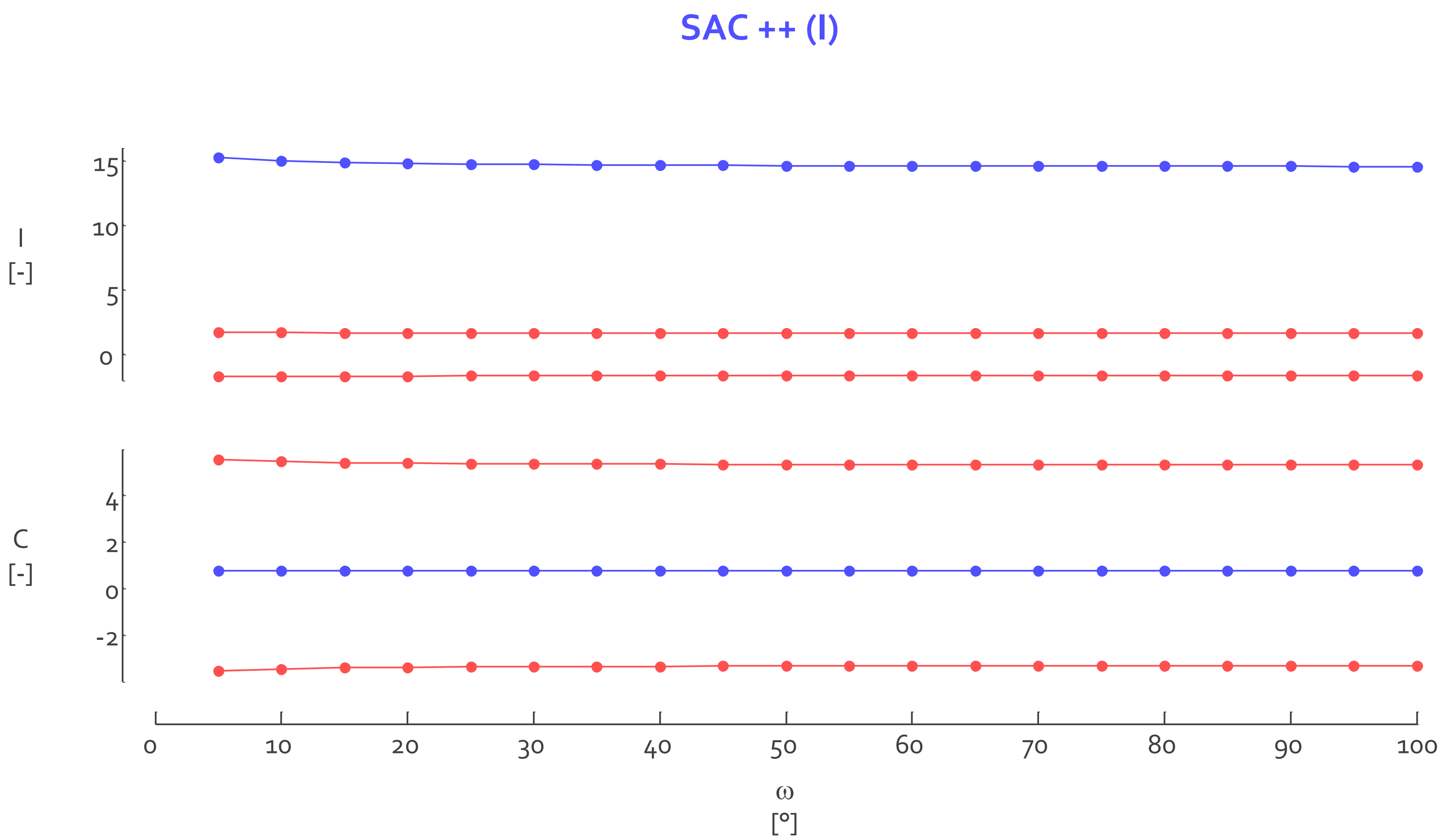
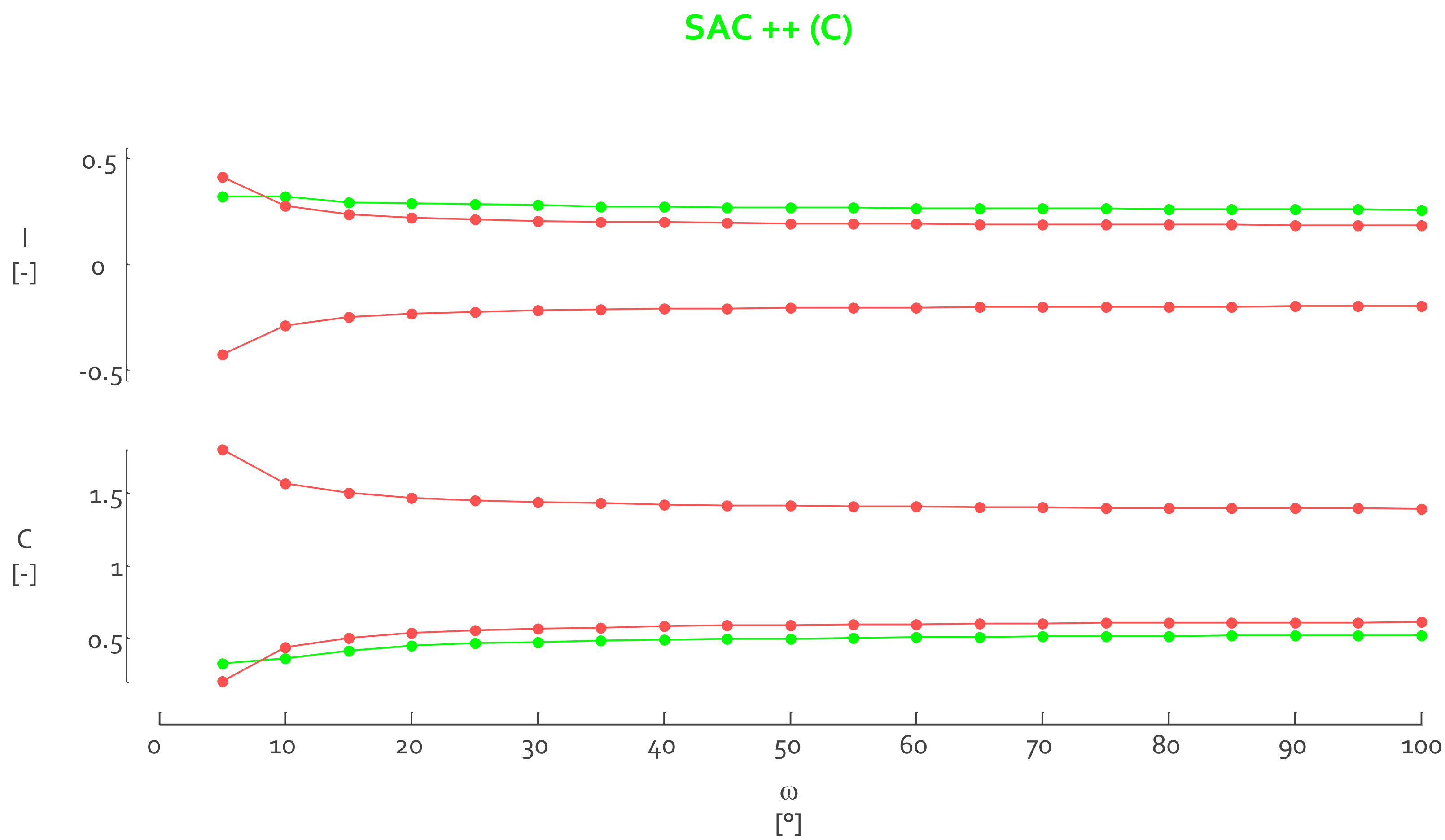


Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency



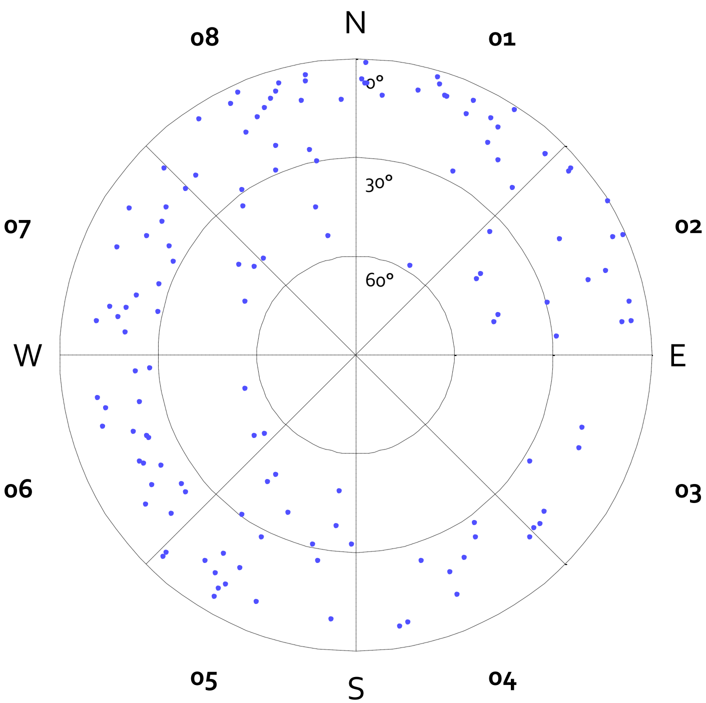
Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency

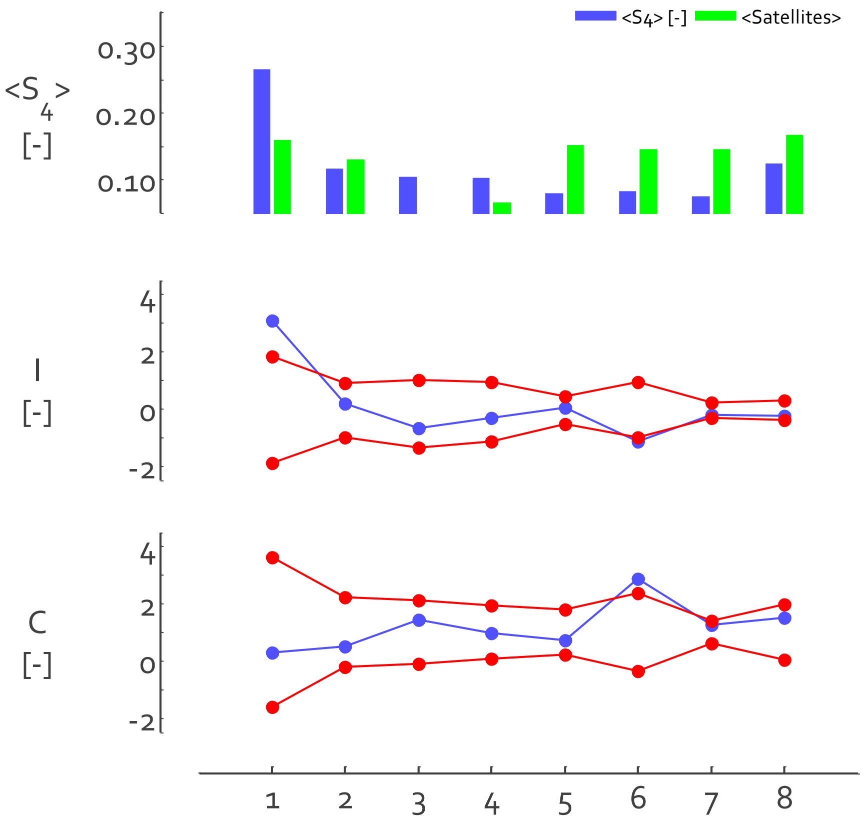


	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●
Interpolation				

Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency

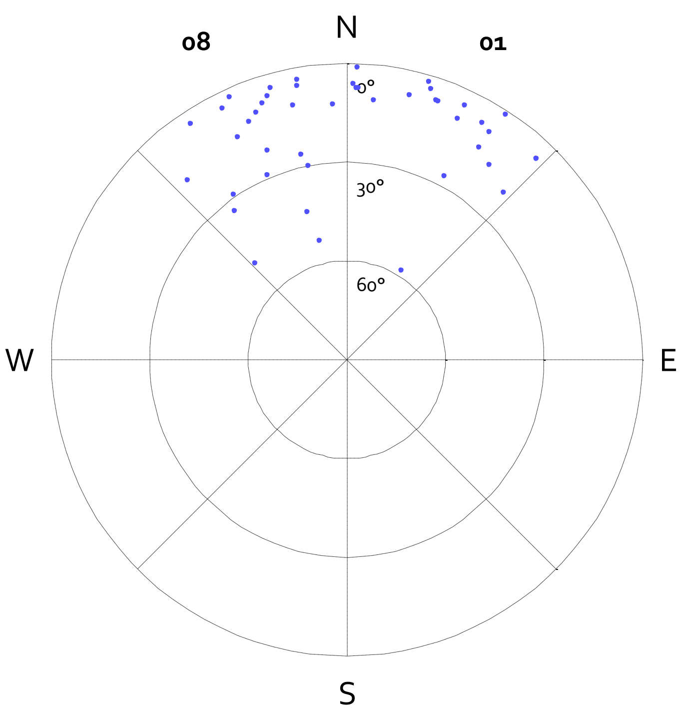
SAC ++ (I)

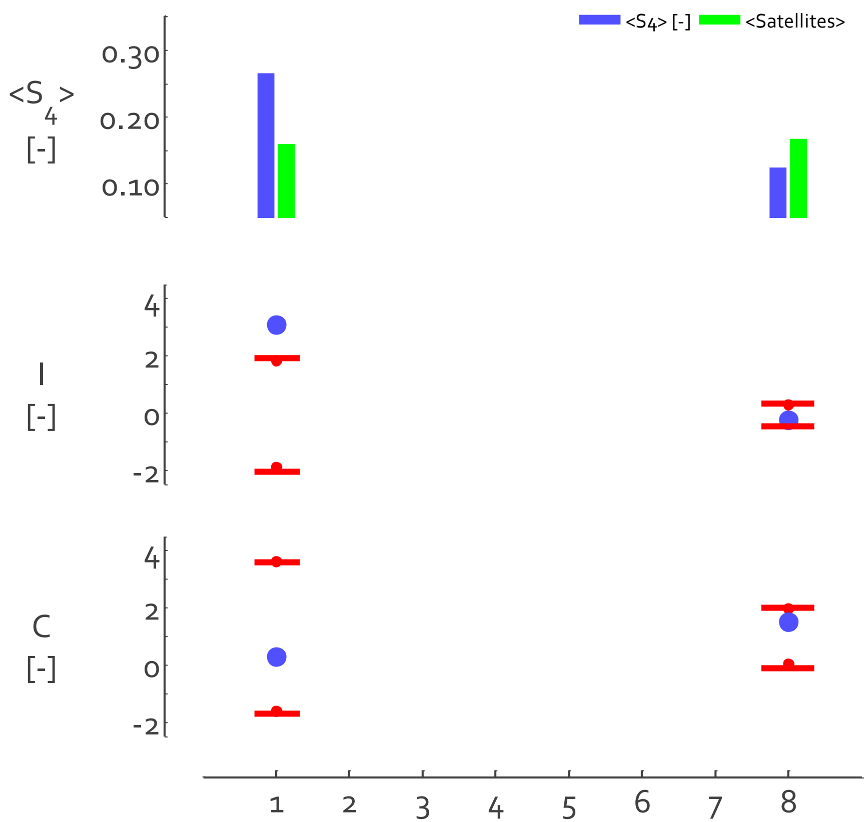




Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency

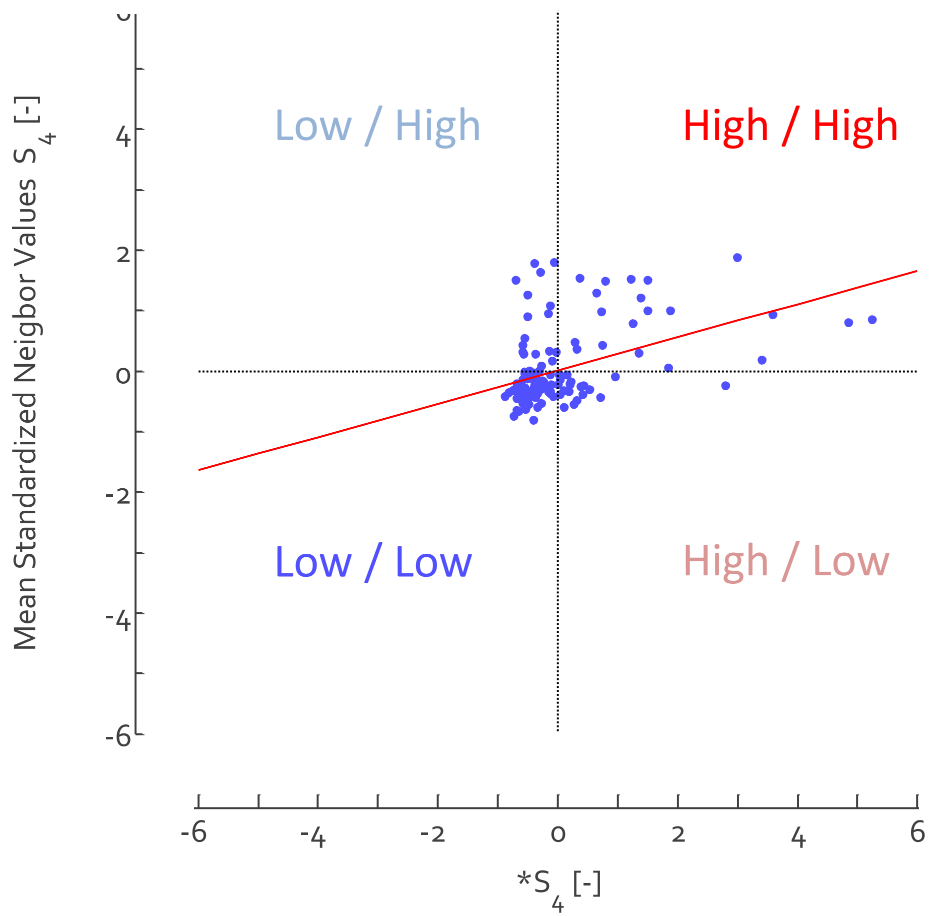
SAC ++ (I)





Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency

Moran’s I Index

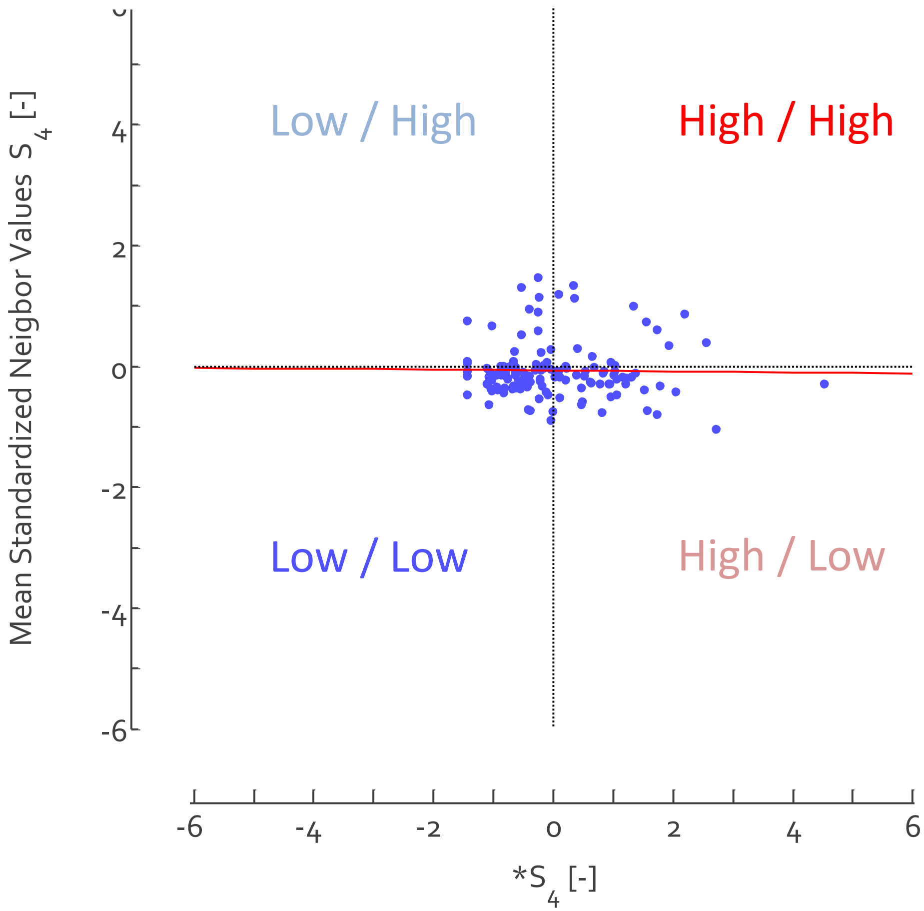


SAC ++ (I)

I = 0.277

Spatial AutoCorrelation Indicators detect and quantify the Spatial Dependency

Moran's I Index

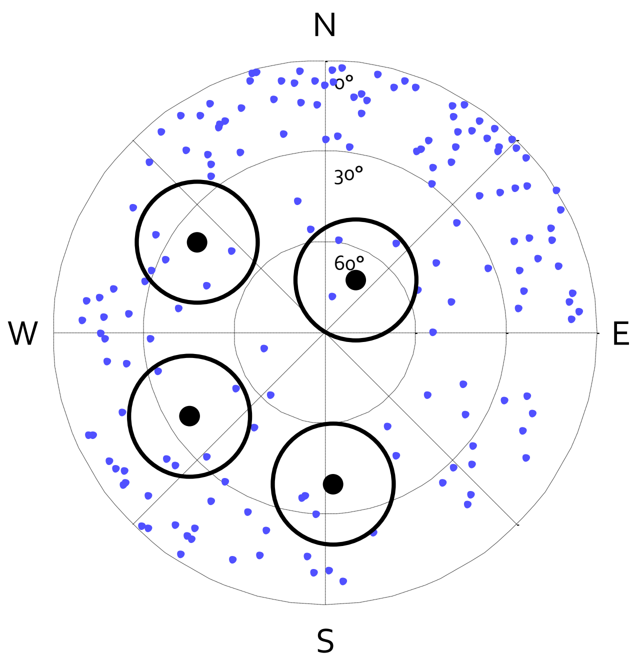


SAC -- (I)

I = -0.008

Analyse of the Local Components of the Global Spatial Autocorrelation

Local Spatial Autocorrelation Indices



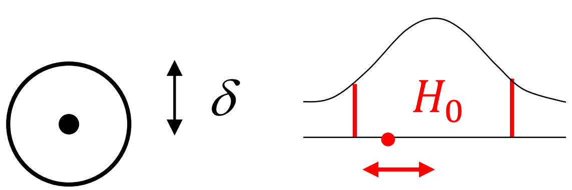
Local Moran's I

$$I_i(\delta) = \frac{v_i - \bar{v}}{S^2} \Sigma_j w_{ij} (v_j - \bar{v})$$

Local Geary's C

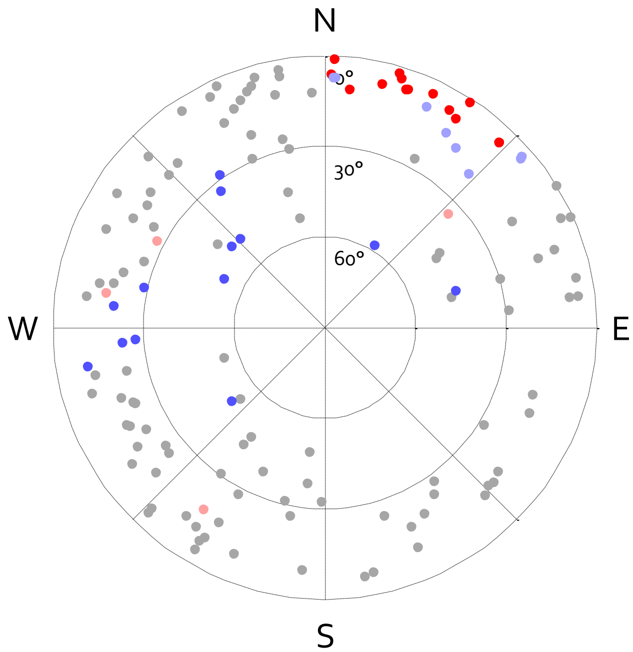
$$C_i(\delta) = \Sigma_j w_{ij} (v_i - v_j)^2$$

$$S = \frac{\Sigma_j v_j^2}{N-1} - \bar{v}^2 \quad \forall i \neq j$$



Analyse of the Local Components of the Global Spatial Autocorrelation

Local Spatial Autocorrelation Indices



Local Moran's I

$$I_i(\delta) = \frac{v_i - \bar{v}}{S^2} \Sigma_j w_{ij} (v_j - \bar{v})$$

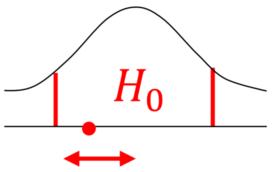
$$S = \frac{\Sigma_j v_j^2}{N-1} - \bar{v}^2 \quad \forall i \neq j$$

High / High

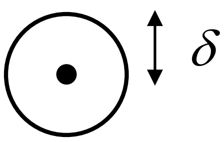
Low / Low

High / Low

Low / High

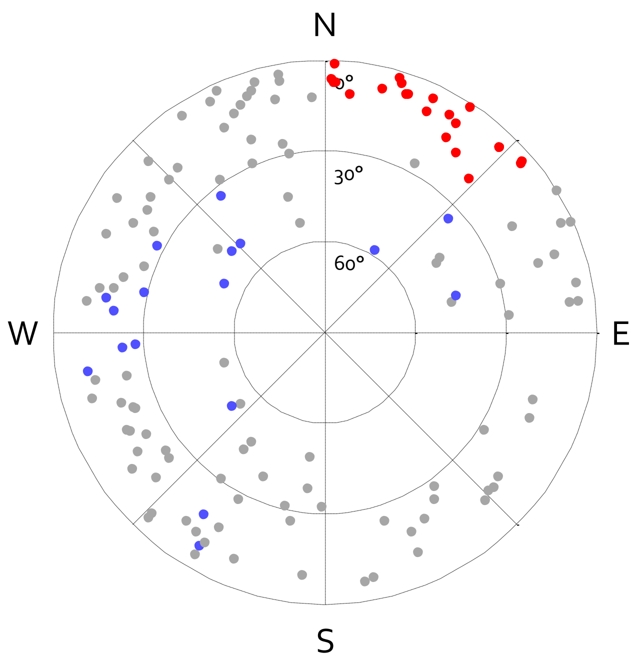


SAC ++ (I)



Analyse of the Local Components of the Global Spatial Autocorrelation

Local Spatial Autocorrelation Indices

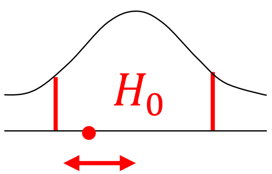


Local Getis-Ord's G

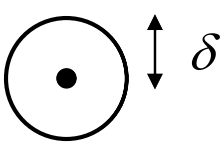
$$G_i(\delta) = \frac{\Sigma_j w_{ij}(\delta) v_j}{\Sigma_j v_j}$$

High

Low



SAC ++ (I)



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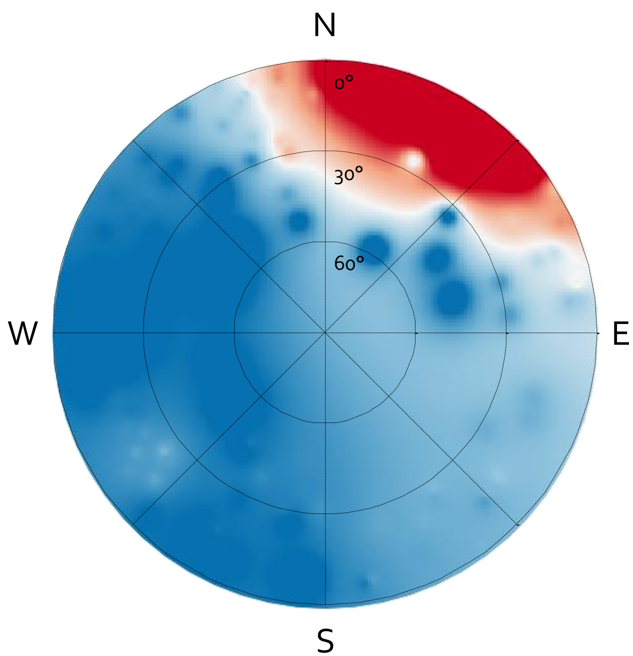

Local Getis-Ord's G

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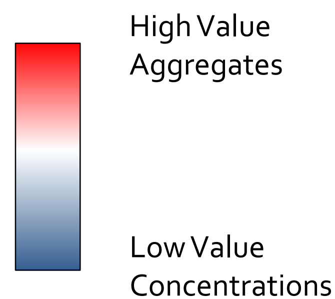
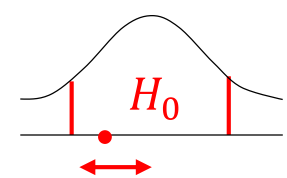
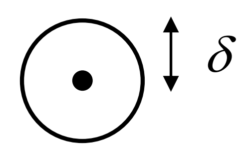


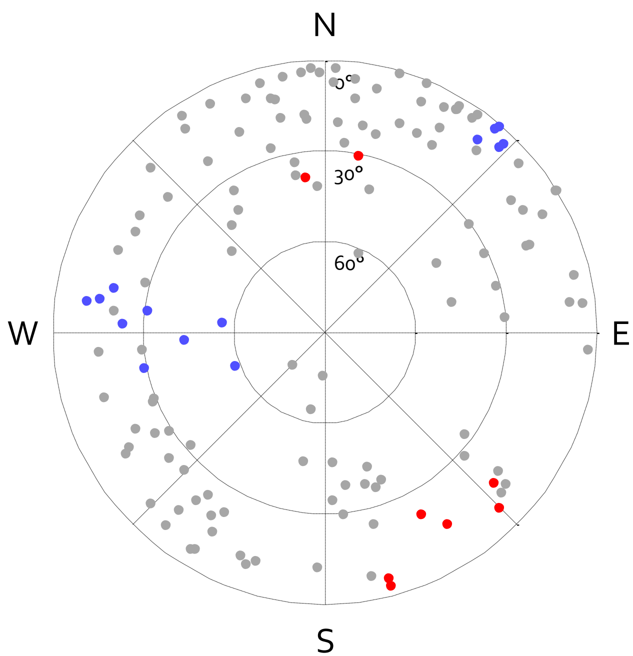


SAC ++ (I)



Analyse of the Local Components of the Global Spatial Autocorrelation

Local Spatial Autocorrelation Indices



Local Getis-Ord's G

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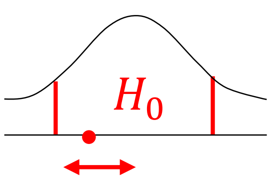
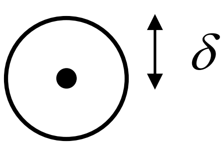
High

Low

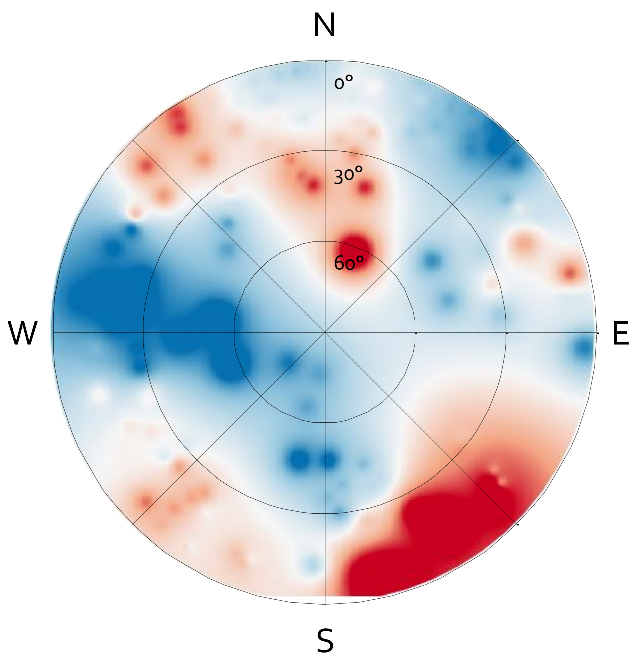


SAC -- (I)



Analyse of the Local Components of the Global Spatial Autocorrelation

Local Spatial Autocorrelation Indices



Local Getis-Ord's G

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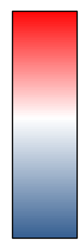
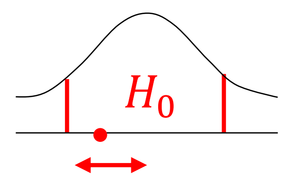
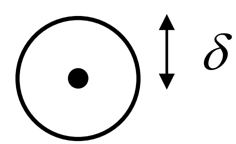


High Value Aggregates

Low Value Concentrations

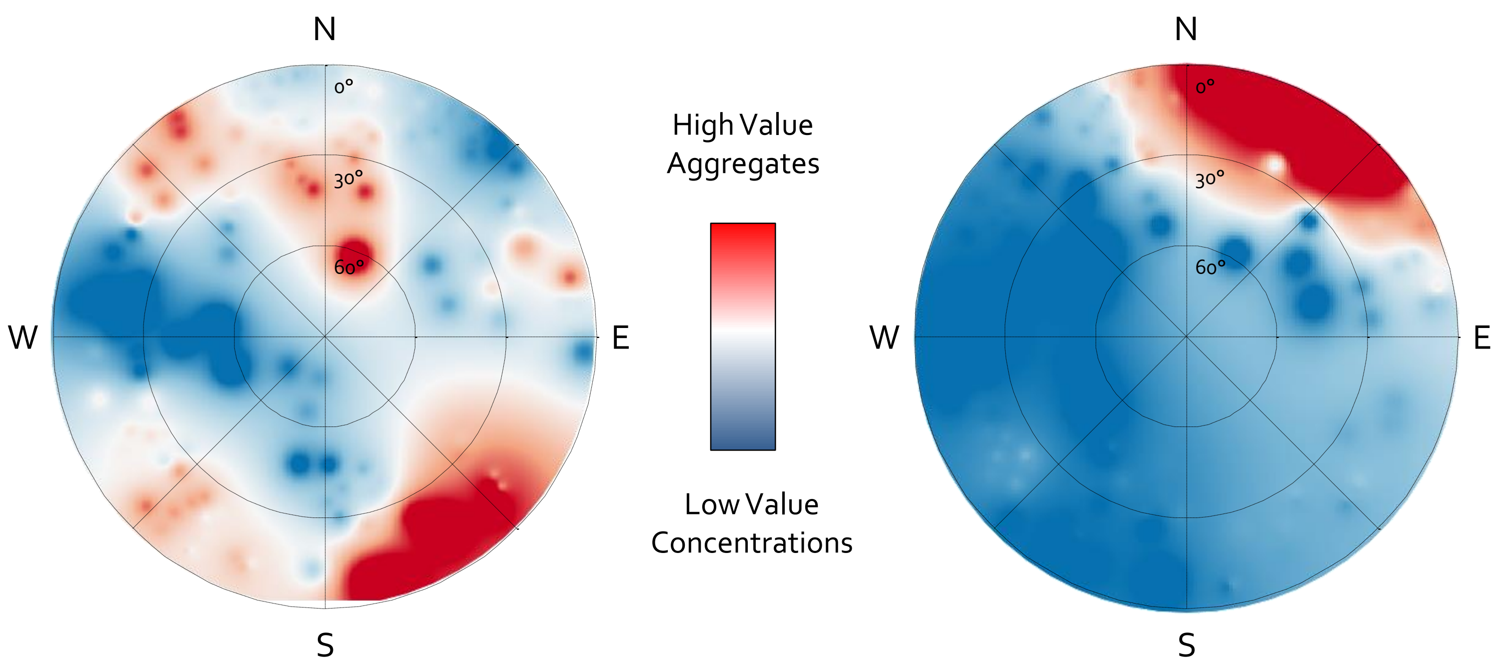


SAC -- (I)



Analyse of the Local Components of the Global Spatial Autocorrelation

Local Spatial Autocorrelation Indices



SAC -- (I)

SAC ++ (I)

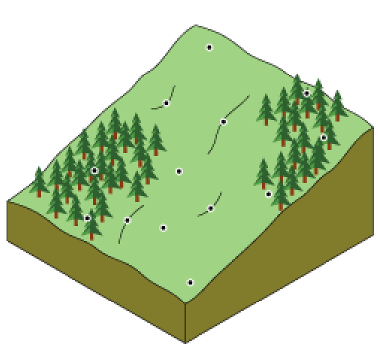
	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●

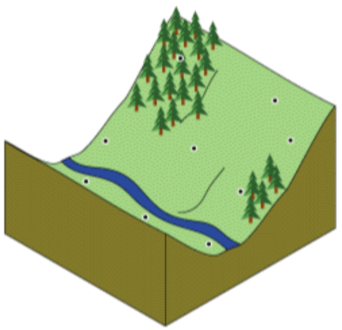
Interpolation

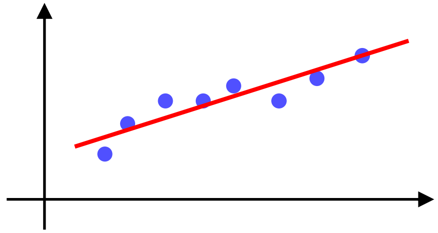
- **Trend Surface Interpolation (TSI)**
- Inverse Distance Weighting (IDW)
- Geostatistic Method (GEO)

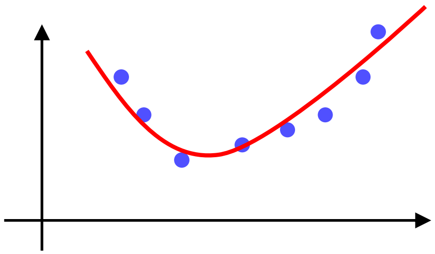
The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 1









Characteristics

- Quantitative Data
- Determinist Method
- Approximative Interpolation
- Global Spatial Extension

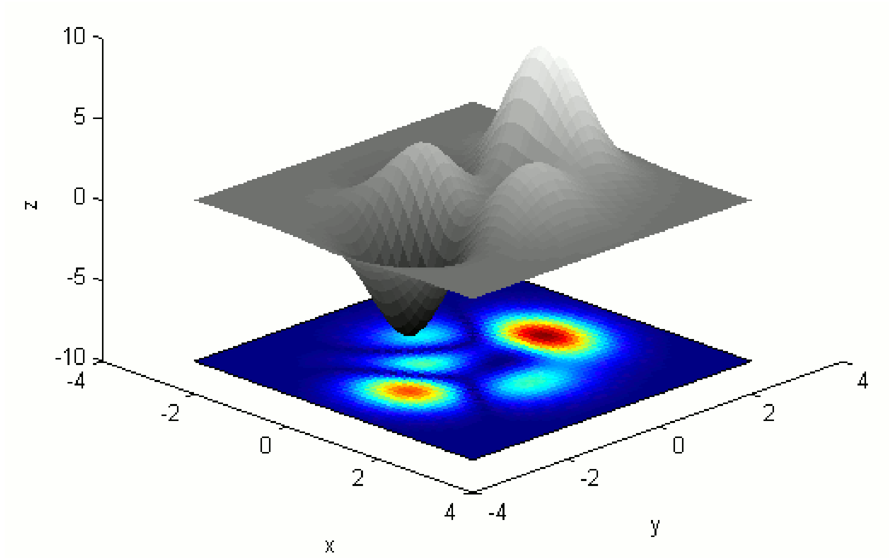
Methodology

- LSA of the Polynomial Surface
- Computation of the Surface
- Assessment of the model

The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 2

$$Y = \beta_0 + \beta_1 X + \beta_2 Y + \beta_3 X^2 + \beta_4 Y^2 + \beta_5 XY + \cdots + \cdots + \beta_{n-1} X^k + \beta_n Y^k$$

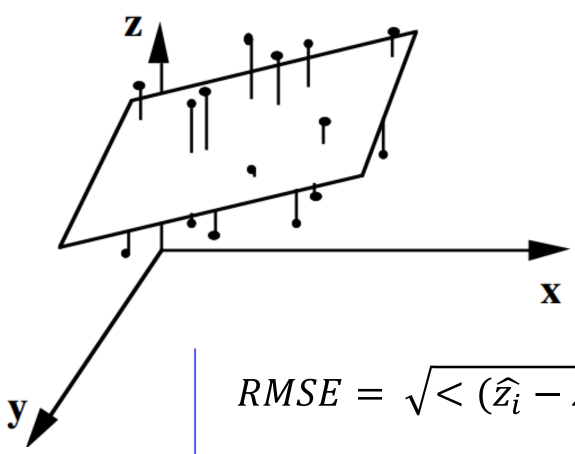


Degree (k)	Parameters (p)
1	3
2	6
3	10
4	15
5	21

The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 3

$$Y = \beta_0 + \beta_1 X + \beta_2 Y + \beta_3 X^2 + \beta_4 Y^2 + \beta_5 XY + \cdots + \cdots + \beta_{n-1} X^k + \beta_n Y^k$$



Degree (k)	Parameters (p)
1	3
2	6
3	10
4	15
5	21

$$RMSE = \sqrt{< (\widehat{z_i} - z_i)^2 >}$$

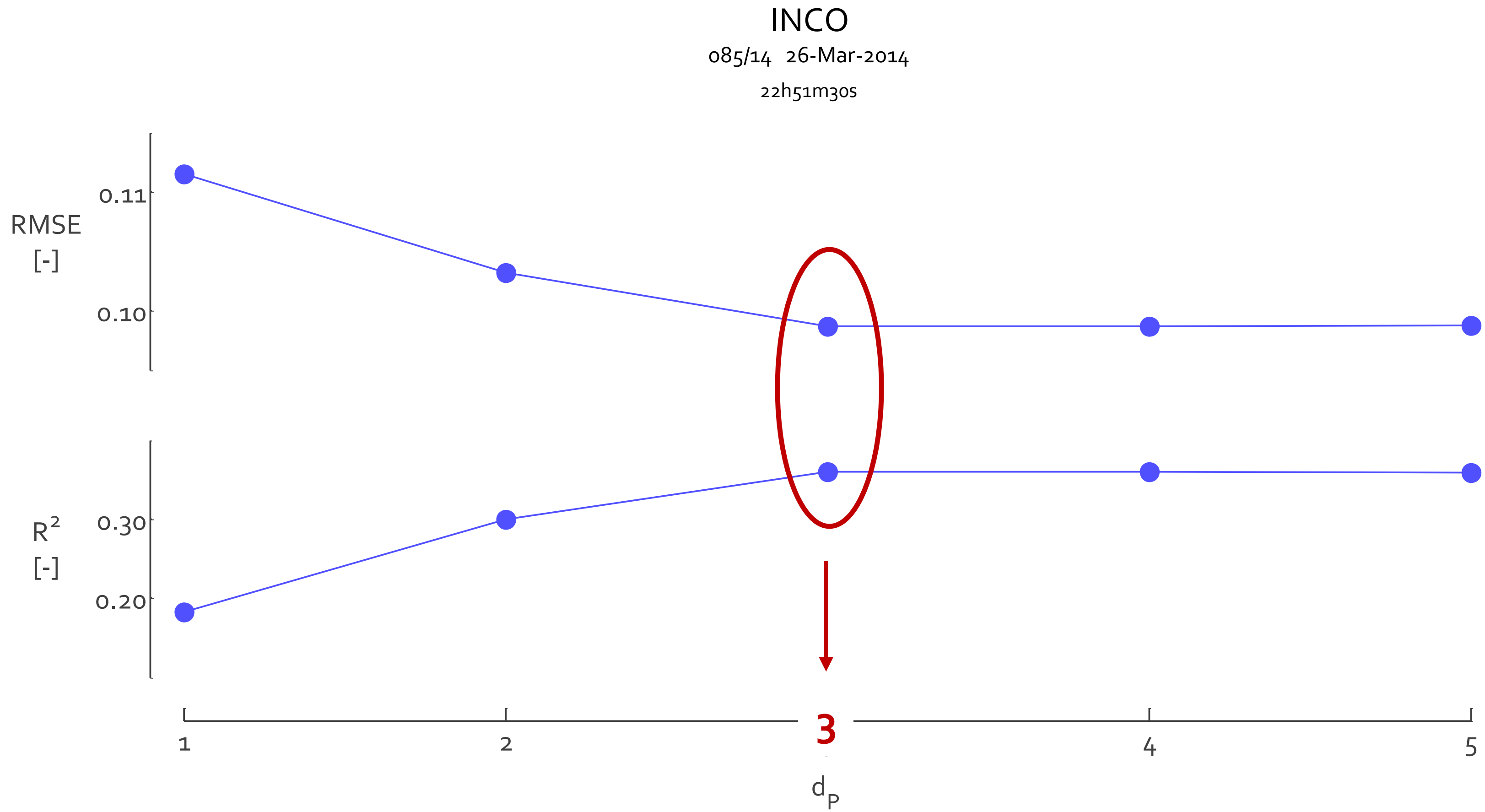
$$R^2 = 1 - \frac{SSE}{SST}$$

$$\widehat{R^2} = R^2\text{-}(1\text{-}R^2)\,\frac{p}{n}$$

The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 4

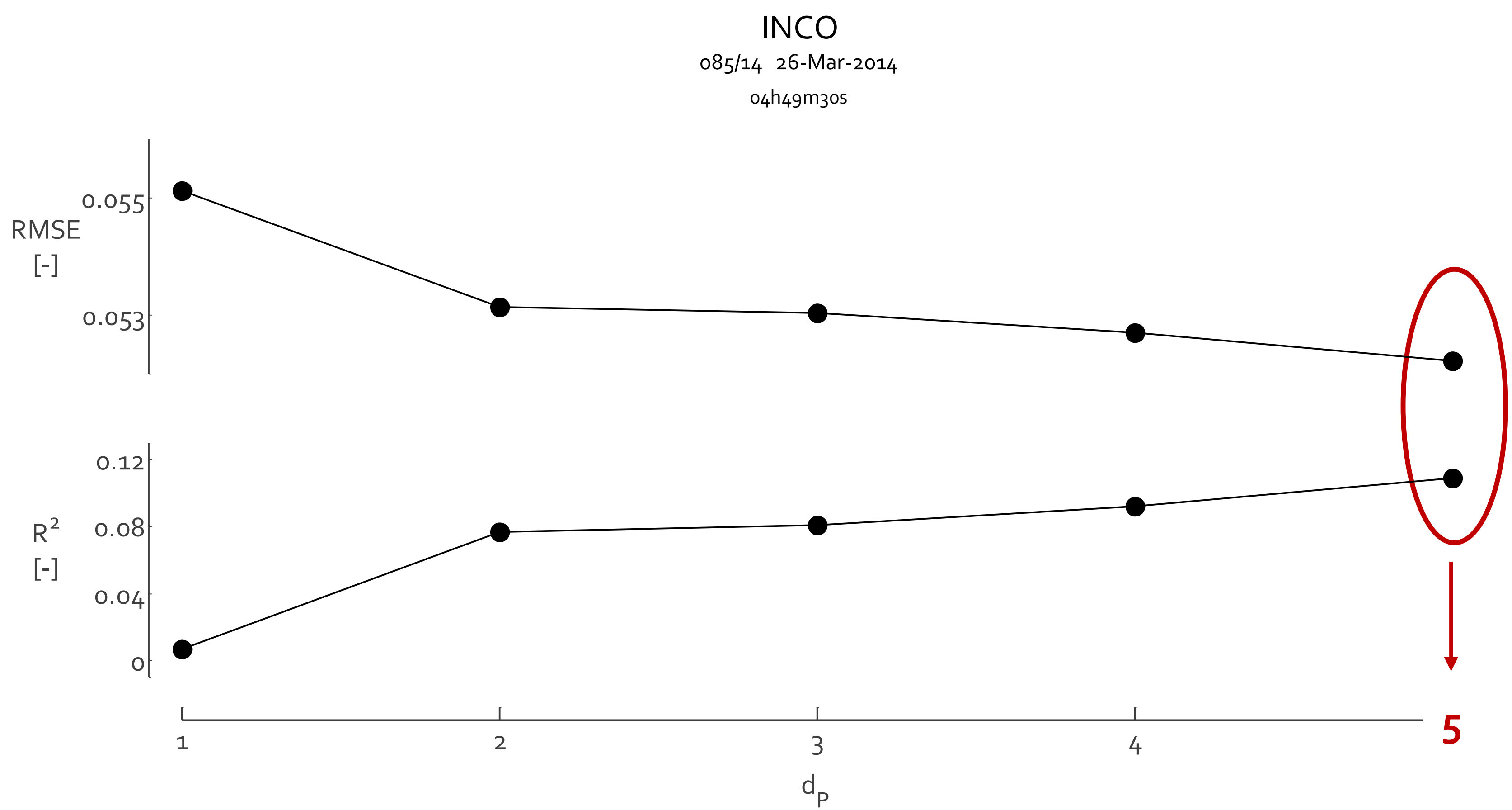
SAC ++ (I)



The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 5

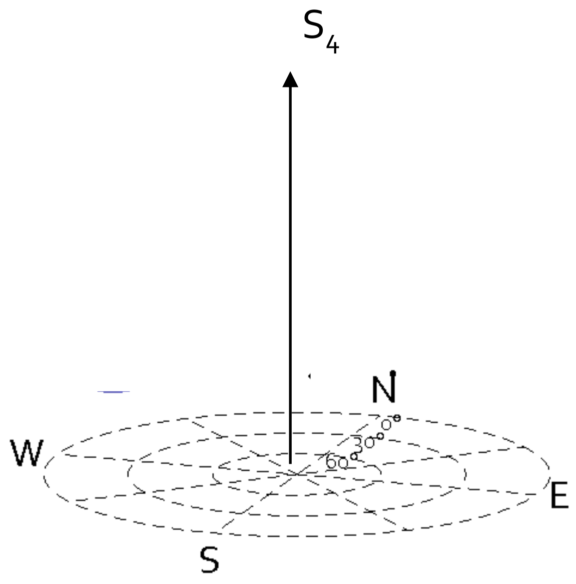
SAC ~ 0 (I)



The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 6

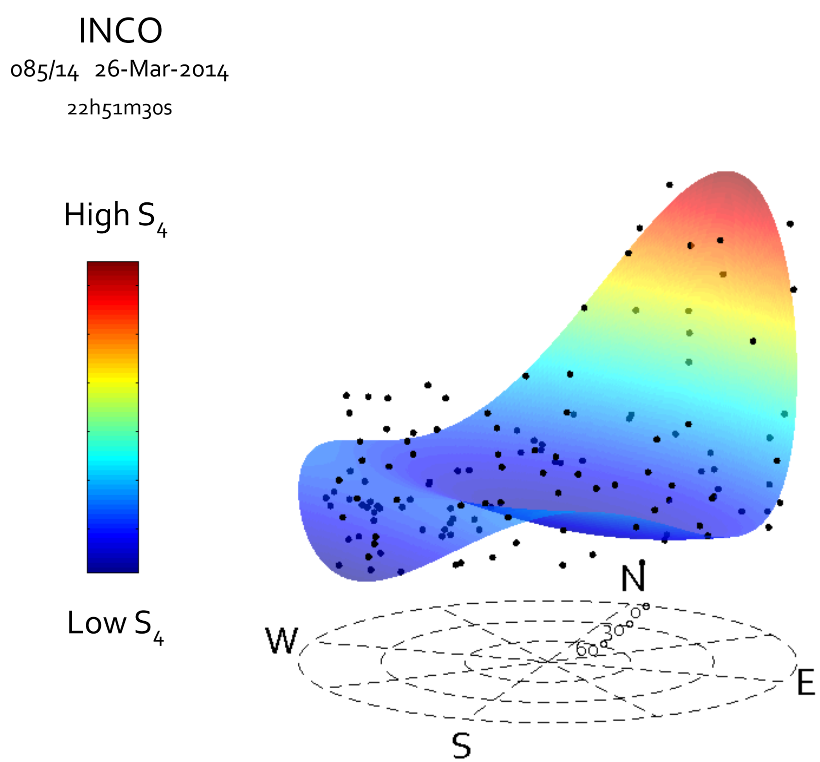
SAC ++ (I)



The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 6

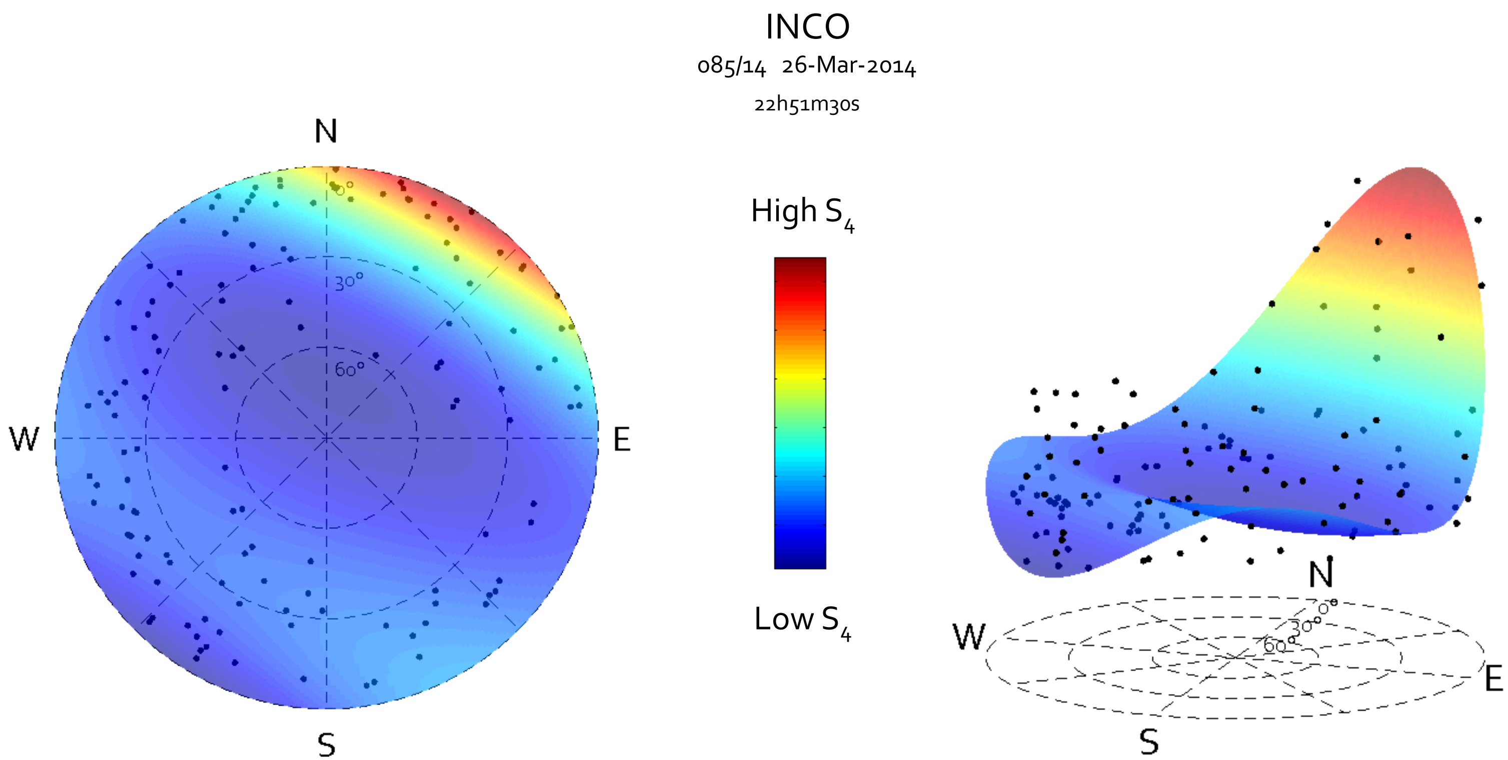
SAC ++ (I)



The Experimental Field can be continously represented by an Interpolation Surface

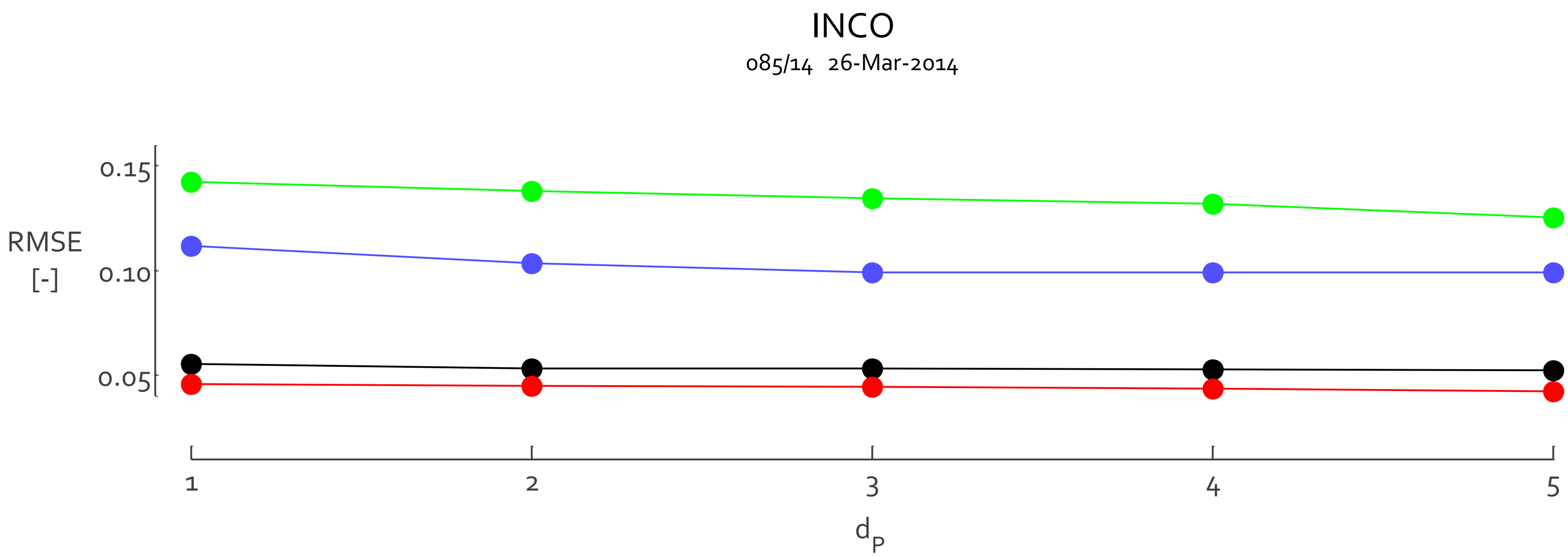
Trend Surface Interpolation (TSI) - 6

SAC ++ (I)



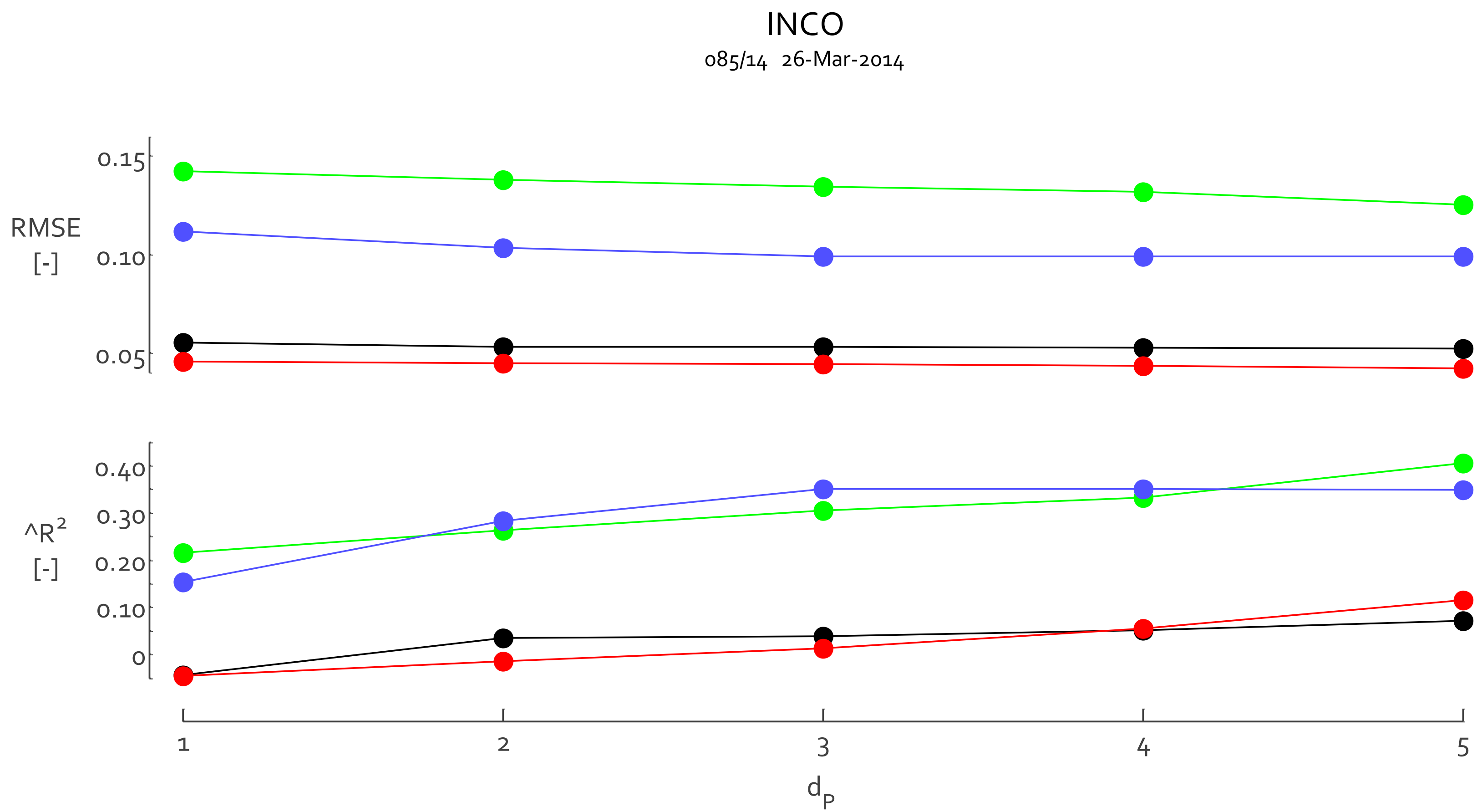
The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 7



The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI) - 7



	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●

Interpolation

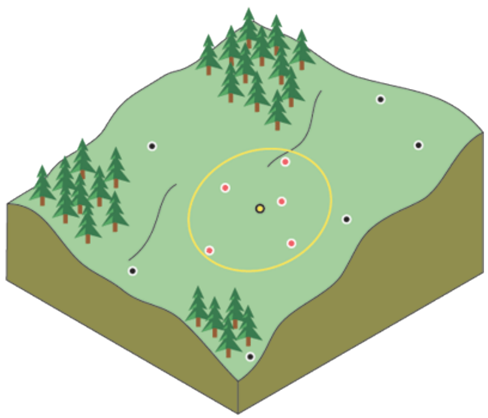
Trend Surface Interpolation (TSI)

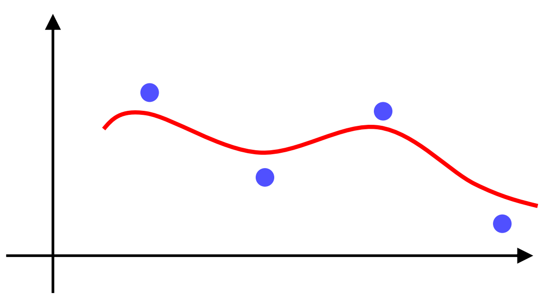
Inverse Distance Weighting (IDW)

Geostatistic Method (GEO)

The Experimental Field can be continously represented by an Interpolation Surface

Inverse Distance Weighting (IDW) - 1





Characteristics

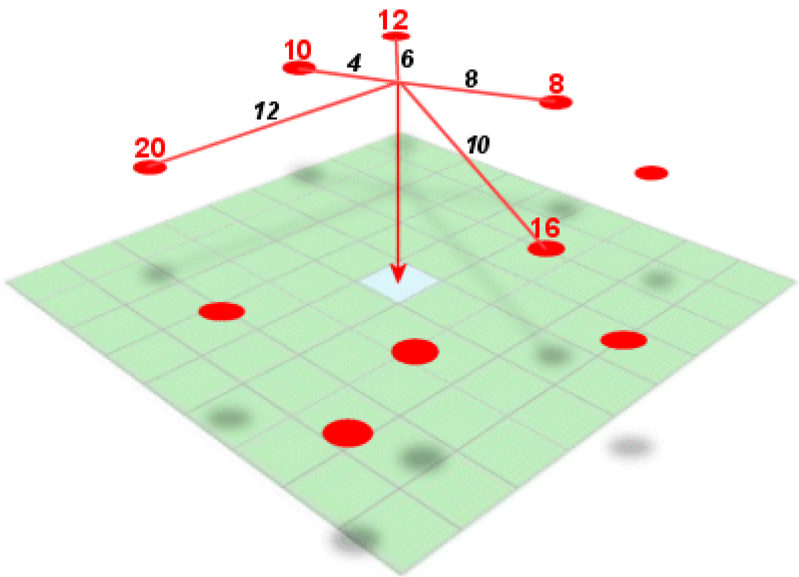
- Quantitative Data
- Determinist Method
- Approximative/Exact Interpolation
- Local Spatial Extension

Methodology

- Parameter Optimization
- Computation of the Surface
- Assessment of the model

The Experimental Field can be continously represented by an Interpolation Surface

Inverse Distance Weighting (IDW) - 2

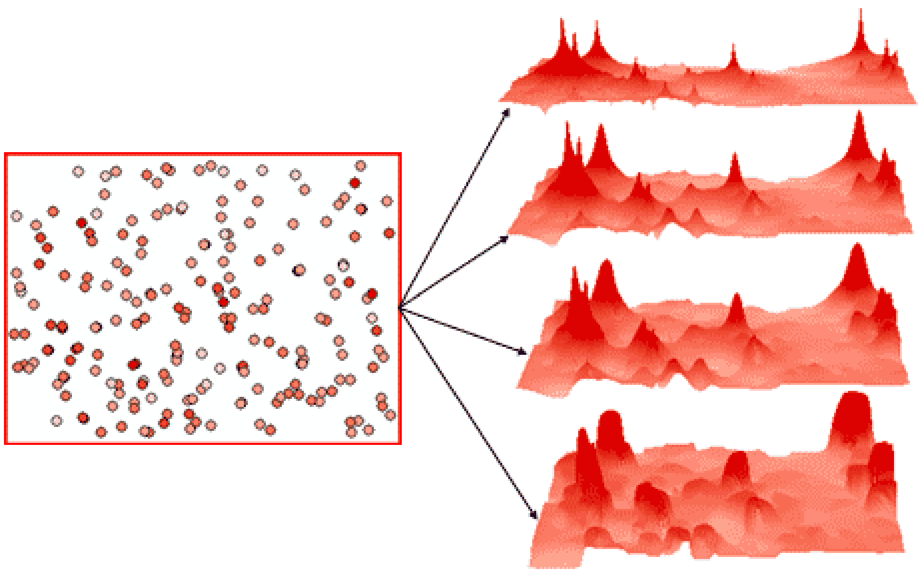


$$\hat{Y}_j = \frac{\sum_i \frac{y_i}{d_{ij}^{\beta}}}{W_j} \quad \rightarrow \quad d_{ij}^{\beta}$$

$$W_j = \sum_i \frac{1}{d_{ij}^{\beta}}$$

The Experimental Field can be continously represented by an Interpolation Surface

Inverse Distance Weighting (IDW) - 2



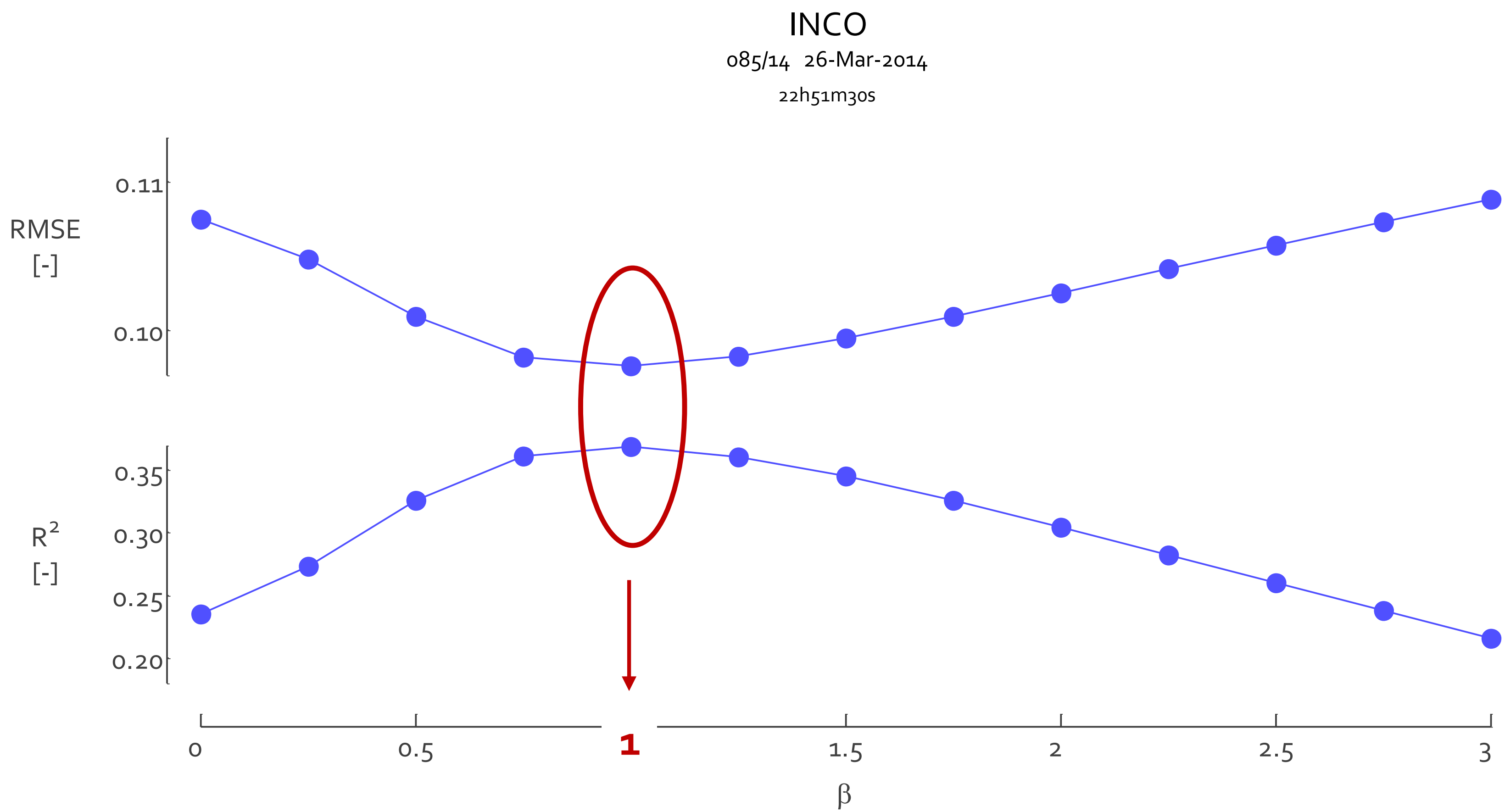
$$\hat{Y}_j = \frac{\sum_i \frac{y_i}{d_{ij}^{\beta}}}{W_j} \rightarrow d_{ij}^{\beta}$$

$$W_j = \sum_i \frac{1}{d_{ij}^{\beta}}$$

The Experimental Field can be continously represented by an Interpolation Surface

Inverse Distance Weighting (IDW) - 3

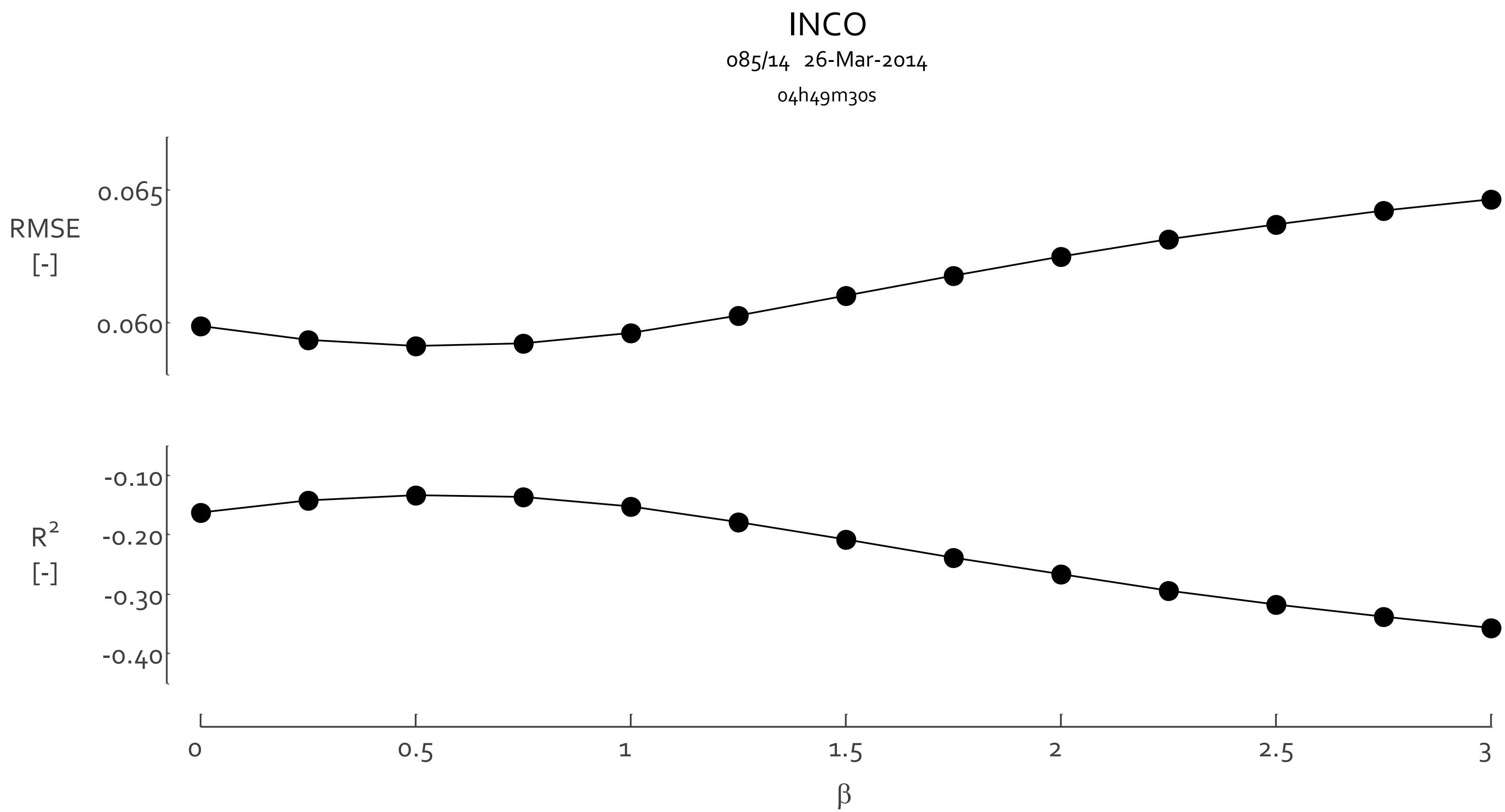
SAC ++ (I)



The Experimental Field can be continously represented by an Interpolation Surface

Inverse Distance Weighting (IDW) - 4

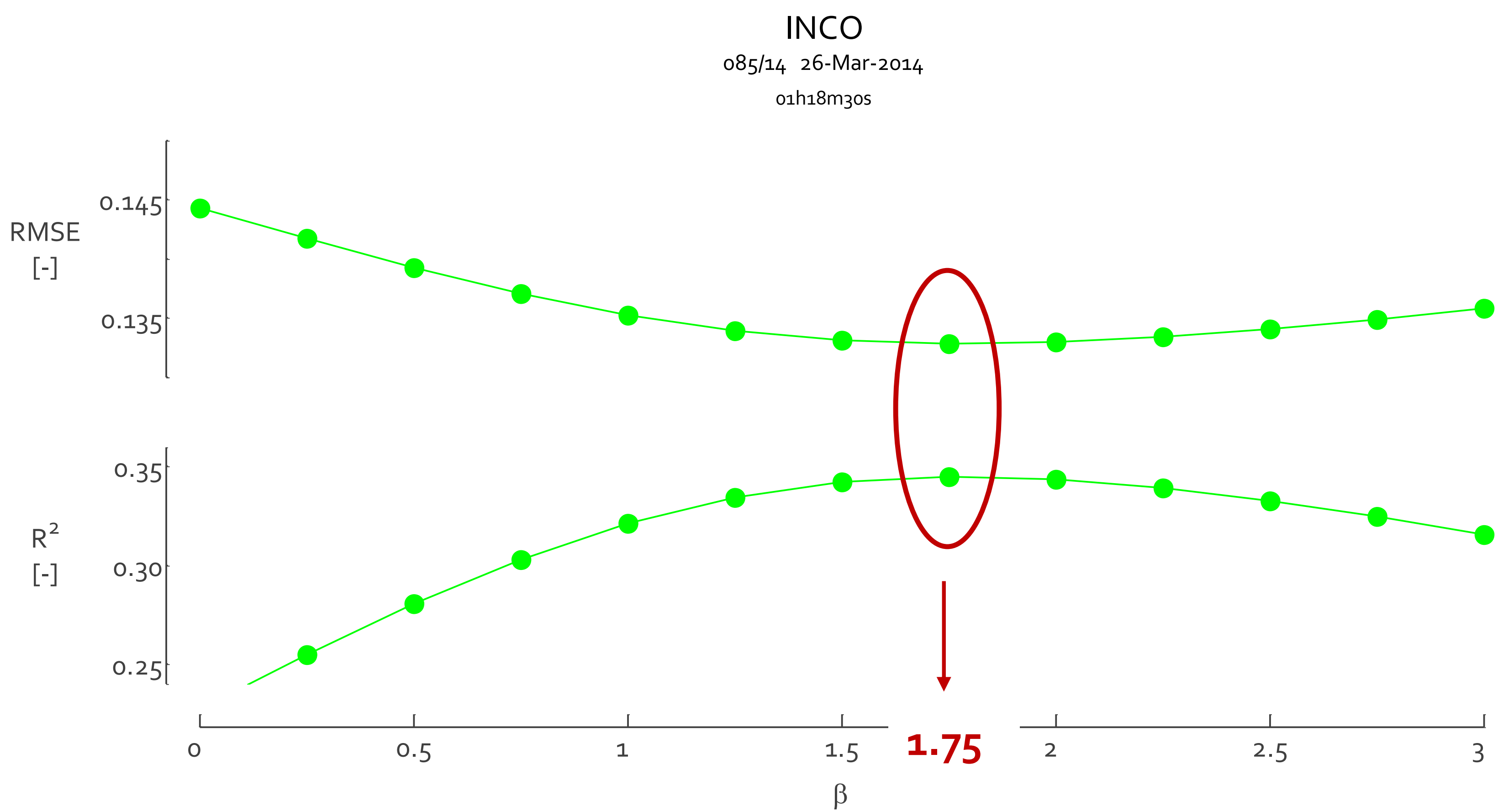
SAC ~ 0 (I)



The Experimental Field can be continously represented by an Interpolation Surface

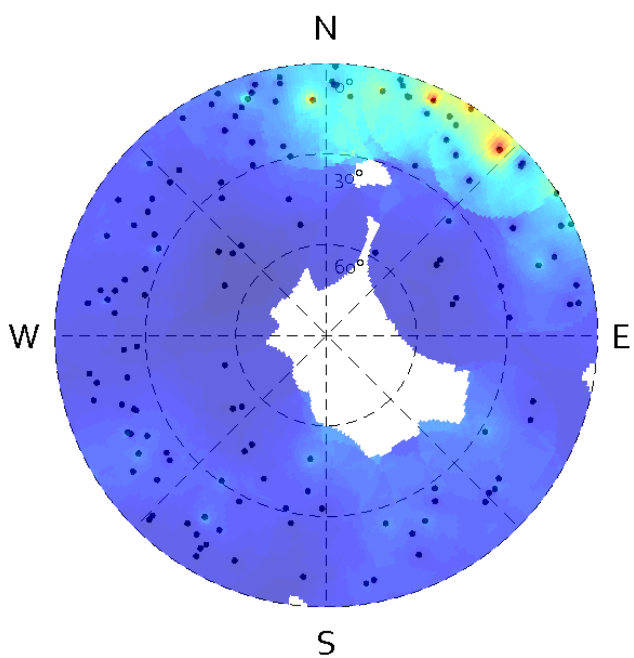
Inverse Distance Weighting (IDW) - 5

SAC ++ (C)



The Experimental Field can be continously represented by an Interpolation Surface

Inverse Distance Weighting (IDW) - 6

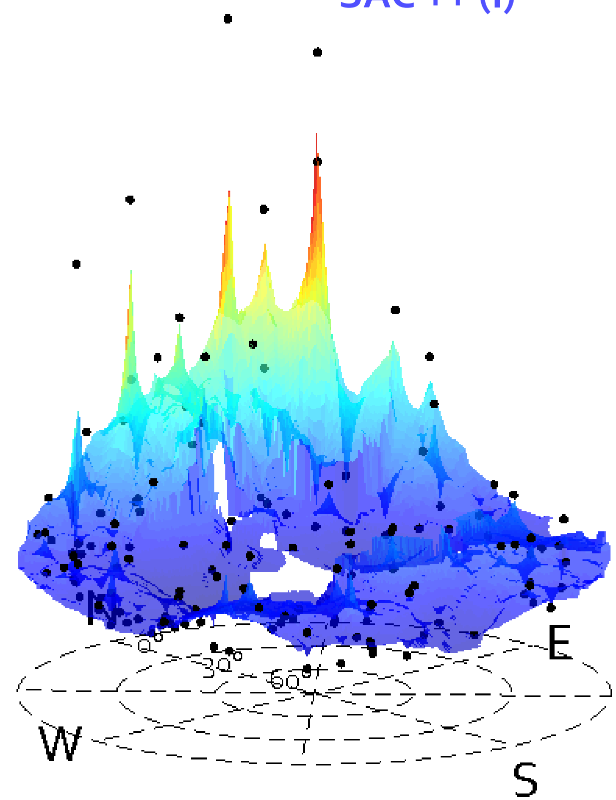


INCO

085/14 26-Mar-2014

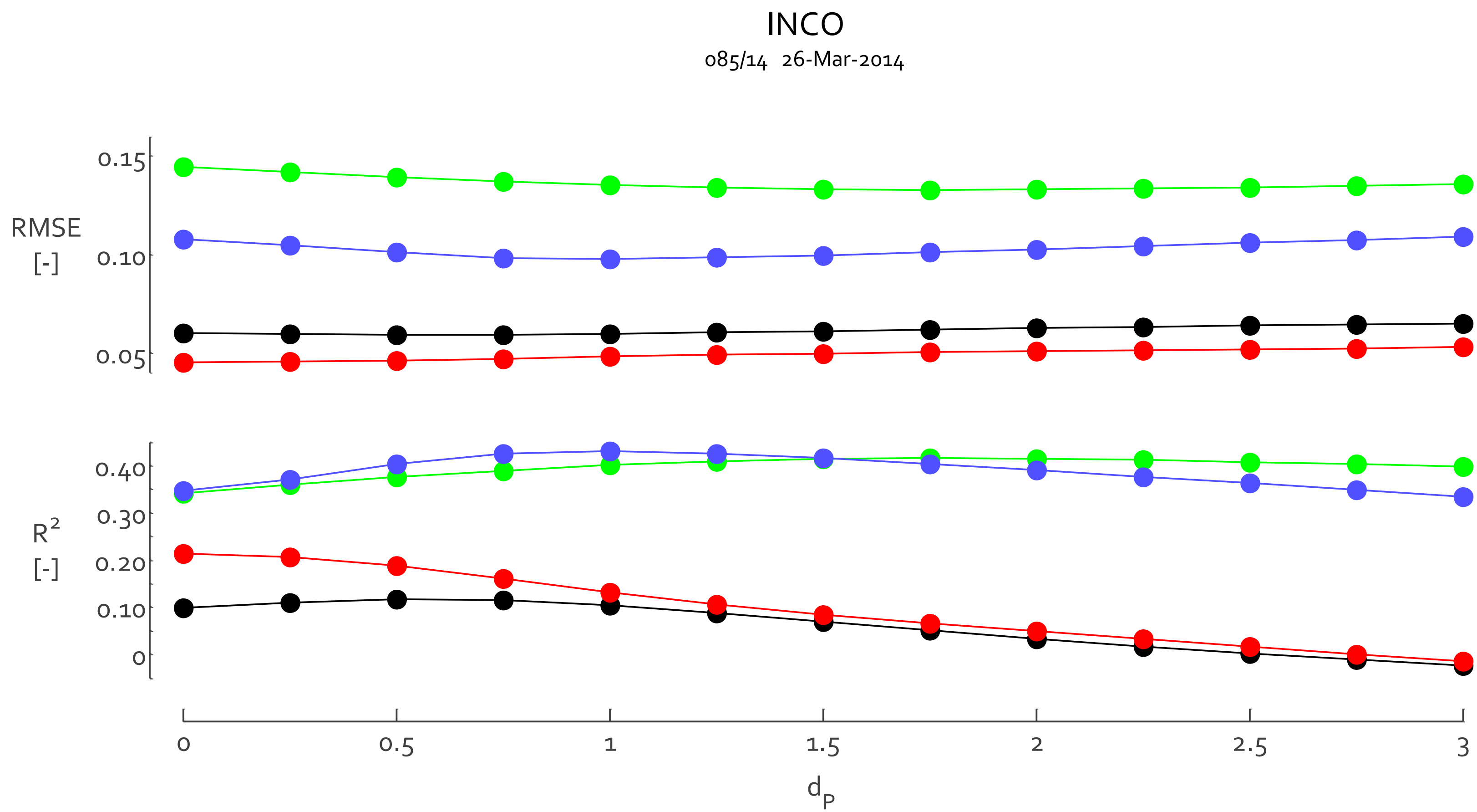
22h51m30s

SAC ++ (I)



The Experimental Field can be continously represented by an Interpolation Surface

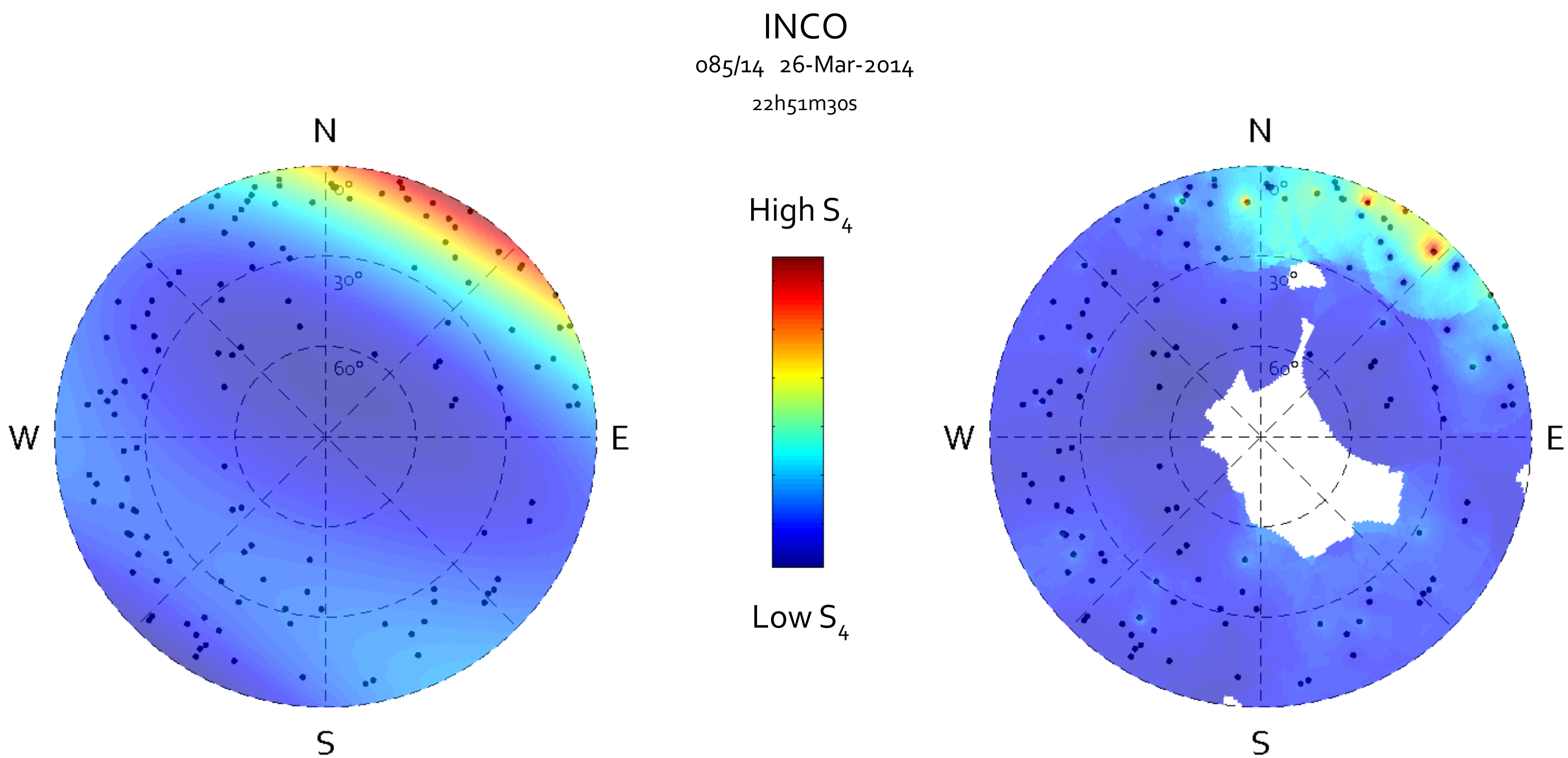
Inverse Distance Weighting (IDW) - 7



The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI)

Inverse Distance Weighting (IDW)

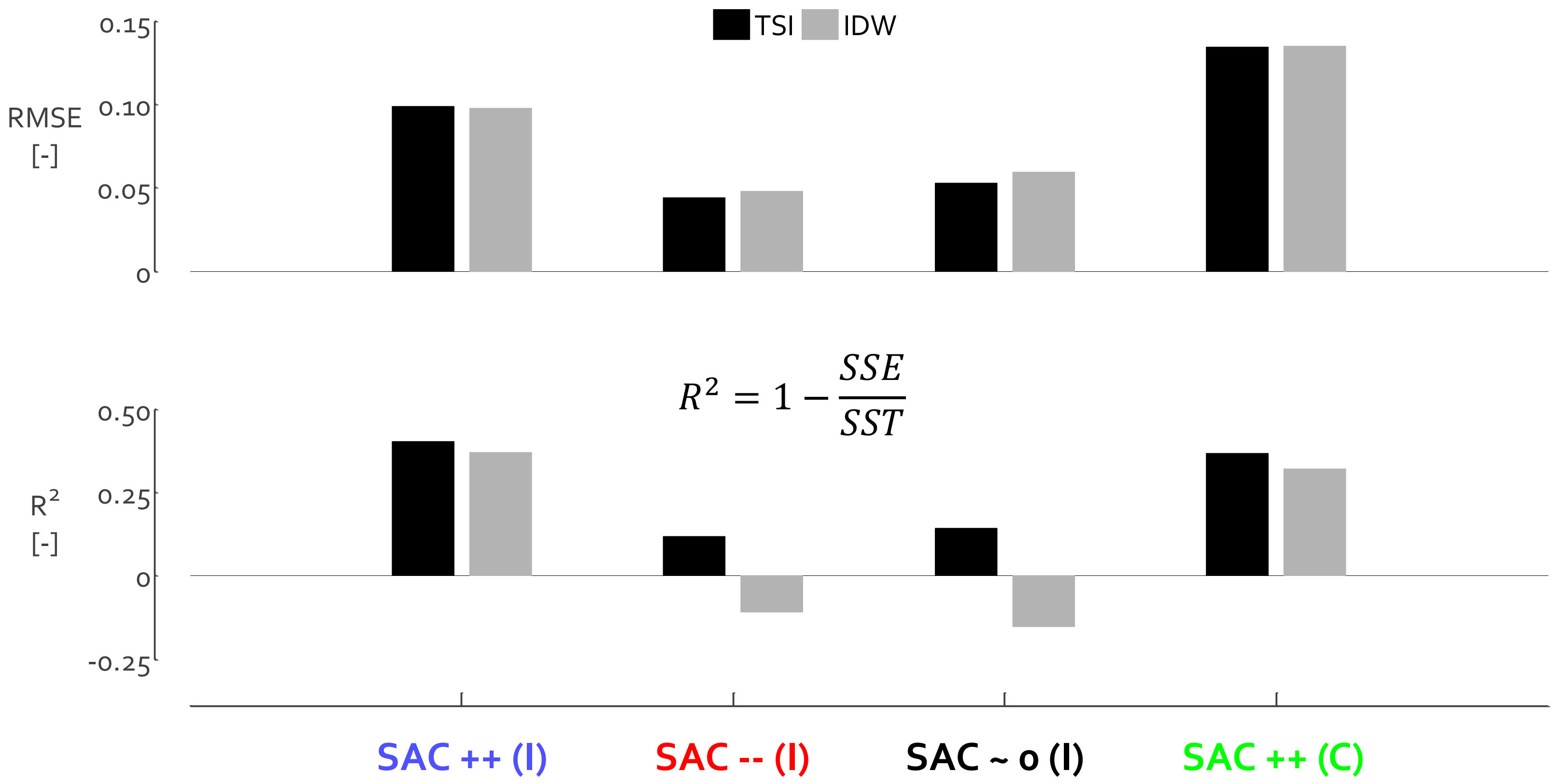


SAC ++ (I)

The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI)

Inverse Distance Weighting (IDW)

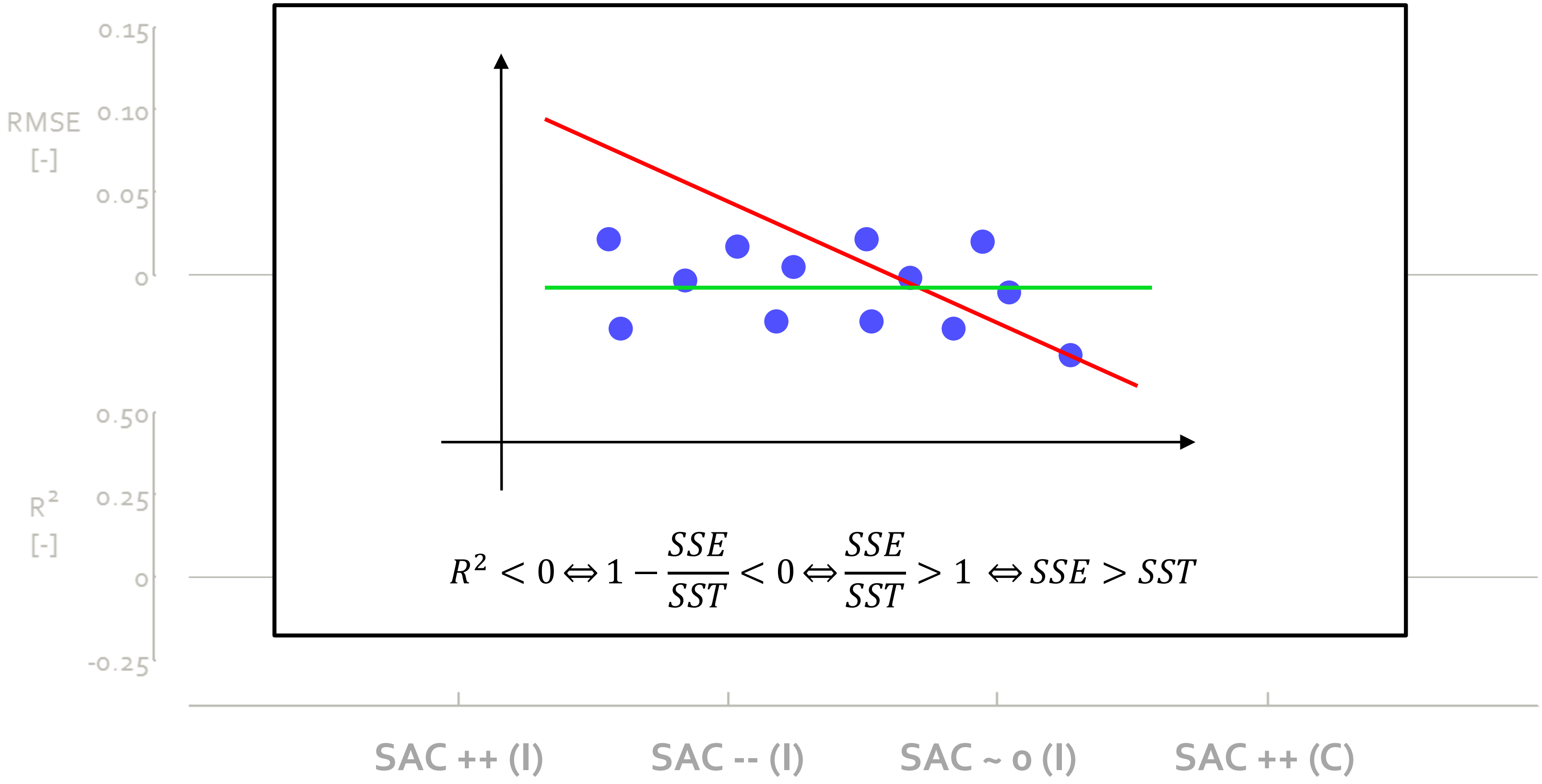


$$R^2 = 1 - \frac{SSE}{SST}$$

The Experimental Field can be continously represented by an Interpolation Surface

Trend Surface Interpolation (TSI)

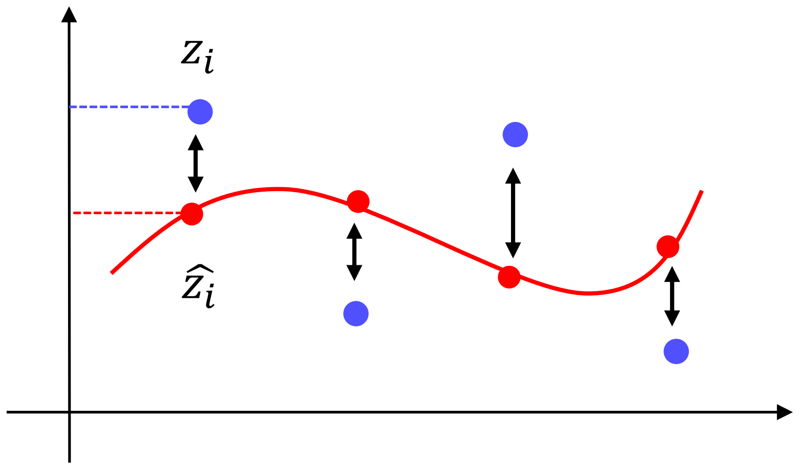
Inverse Distance Weighting (IDW)



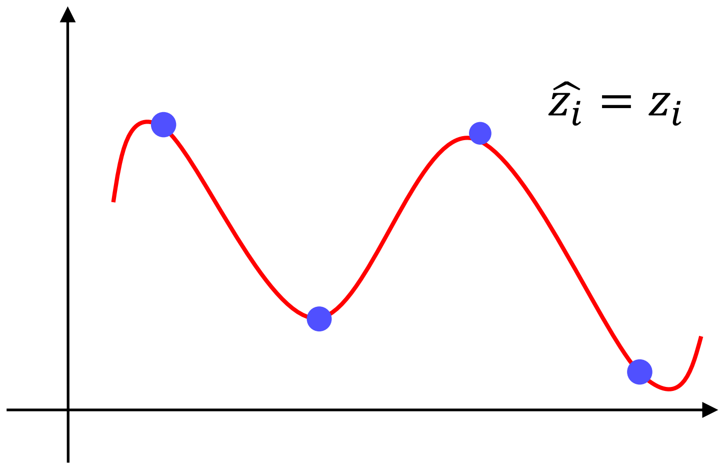
$$R^2 < 0 \Leftrightarrow 1 - \frac{SSE}{SST} < 0 \Leftrightarrow \frac{SSE}{SST} > 1 \Leftrightarrow SSE > SST$$

The Comparison of the Performances of the Interpolation Methods also depends on the Validation Process

Trend Surface Interpolation (TSI)



Inverse Distance Weighting (IDW)

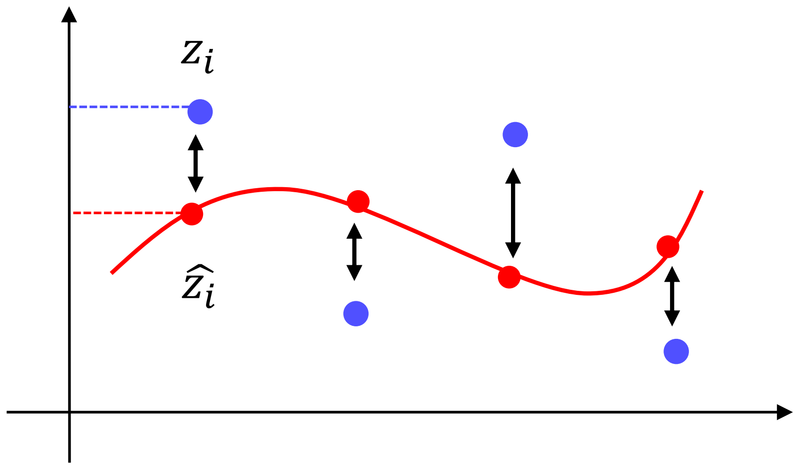


$$RMSE = \sqrt{< (\widehat{z_i} - z_i)^2 >}$$

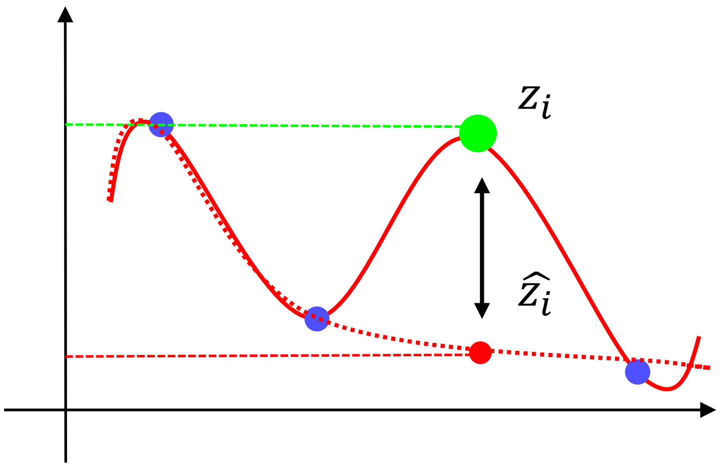
$$R^2 = 1 - \frac{SSE}{SST}$$

The Comparison of the Performances of the Interpolation Methods also depends on the Validation Process

Trend Surface Interpolation (TSI)



Inverse Distance Weighting (IDW)



$$RMSE = \sqrt{< (\hat{z}_i - z_i)^2 >}$$

$$R^2 = 1 - \frac{SSE}{SST}$$

	Description	Detection	Scale	Location
Introduction	●			
Configuration	●	●	●	●
Spatial Dependency	●	●	●	●

Interpolation

Trend Surface Interpolation (TSI)

Inverse Distance Weighting (IDW)

Geostatistic Method (GEO)

Introduction

Objectives

Research

- Background
- Analysis
- Algorithm

Conclusion

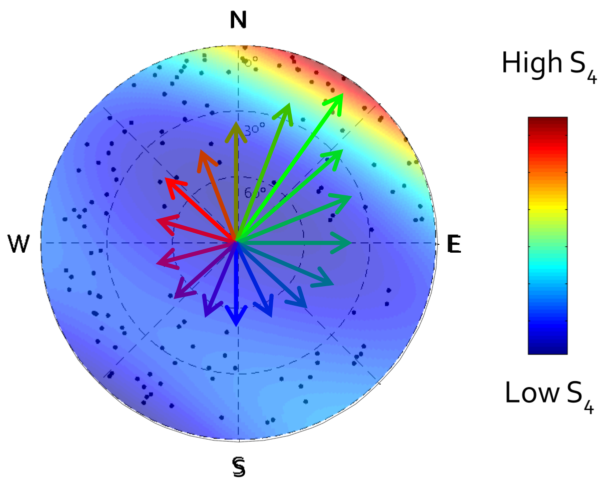
Discussion

We project to develop Spatial Strategies to improve the Performances of Absolute GNSS Positioning Algorithms in case of Ionospheric Scintillations

Spatial Stochastic Modeling

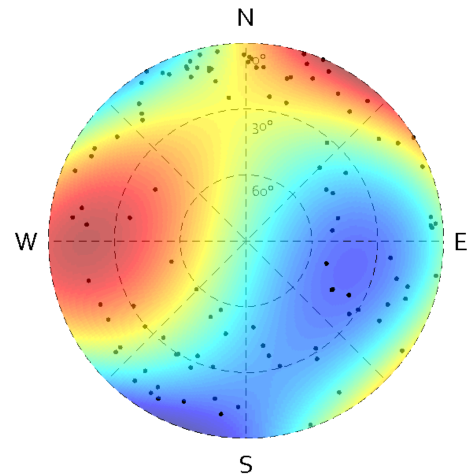
- Variances
- Covariances

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



Spatial Preprocessing Technique

- Cycle Slip Detection
- Noise Assessment
- Spatial Satellite Selection



Introduction

Objectives

Research

Conclusion

Discussion

We lead a complete Spatial Analysis of Ionospheric Scintillation GNSS Measurements for an Equatorial Latitude ISMR Station

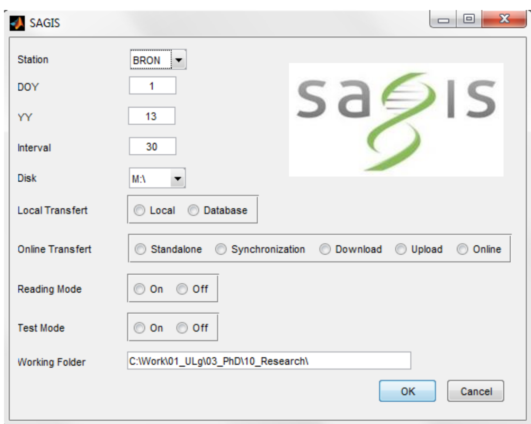
1) Analysis

- Spatial Analysis of Ionospheric Scintillations

→ Tools and Data

- The SAGIS Software is Efficient and has been extensively exploited

▪ Development of SAGIS



Acquisition

Storage

Merging

Computation

Visualization

We lead a complete Spatial Analysis of Ionospheric Scintillation GNSS Measurements for an Equatorial Latitude ISMR Station

1) Analysis

- Spatial Analysis of Ionospheric Scintillations

→ Tools and Data

- The SAGIS Software is Efficient and has been extensively exploited
- The Database expands gradually according to the requests and allows fast subsequent multiple access and treatments

▪ Development of SAGIS

Acquisition

Storage

Merging

Computation

Visualization

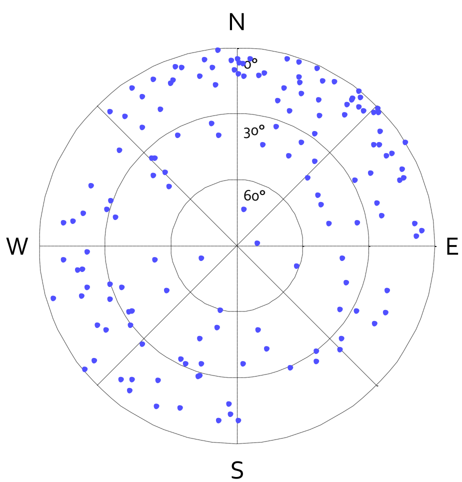
We lead a complete Spatial Analysis of Ionospheric Scintillation GNSS Measurements for an Equatorial Latitude ISMR Station

1) Analysis

- Spatial Analysis of Ionospheric Scintillations

→ Tools and Data

- The SAGIS Software is efficient and has been extensively exploited
- The Database expands gradually according to the requests and allows fast subsequent multiple access and treatments
- Data Merging provides a proper experimental data skyplot supporting statistical and spatial analysis processing



▪ Development of SAGIS

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We lead a complete Spatial Analysis of Ionospheric Scintillation GNSS Measurements for an Equatorial Latitude ISMR Station

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→ Tools and Data

- The SAGIS Software is efficient and has been extensively exploited
- The Database expands gradually according to the requests and allows fast subsequent multiple access and treatments
- Data Merging provides a proper experimental data skyplot supporting statistical and spatial analysis processing
- Visualization Tools help to present the results of spatial interpolation techniques

▪ Development of SAGIS

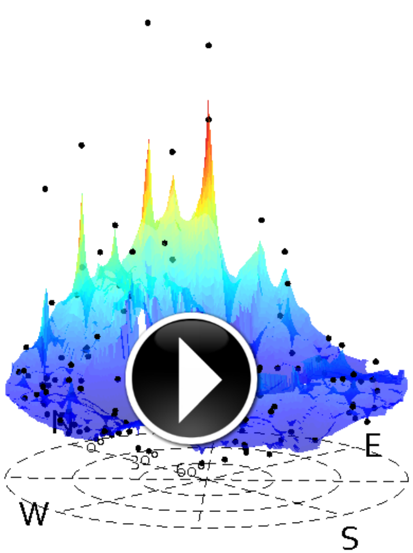
Acquisition

Storage

Merging

Computation

Visualization



We lead a complete Spatial Analysis of Ionospheric Scintillation GNSS Measurements for an Equatorial Latitude ISMR Station

1) Analysis

- Spatial Analysis of Ionospheric Scintillations

→ Tools and Data

→ Configuration

- Cluster Detection
- Cluster Scaling

- GNSS Measurements present frequent signs of clustering

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- Clustering is worth detecting and measuring because it has an impact on the quality of further spatial interpolations
- Clusters can be measured and serve as an input for the interpolation techniques.

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- Global SAC
- Local SAC

- Ionospheric Scintillation Measurements show signs of Spatial Autocorrelation only during intense events

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- Global SAC
- Local SAC

- Ionospheric Scintillation Measurements show signs of Spatial Autocorrelation only during intense events
- The technique of measuring the scale of the Global SAC failed but alternatives exist and need to be tested
- We identified and located the presence of Local SAC in the data even when the Global SAC is not significative which underlines the importance of the local spatial approach

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1) Analysis

- Spatial Analysis of Ionospheric Scintillations

→ Tools and Data

→ Configuration

→ Spatial Dependency

→ Interpolation

- TDI
- IDW

- Application of 2 techniques of Spatial Interpolation on Ionospheric Scintillation Data
- Production of a skymap with both techniques

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GNSS

→ Tools and Data

→ Configuration

→ Spatial Dependency

→ Interpolation

- TDI
- IDW

- Application of 2 techniques of Spatial Interpolation on Ionospheric Scintillation Data
- Production of a skymap with both techniques
- Altough Ionospheric Scintillation Data may present isolated outlayers, the TDI technique show much better results than the IDW (validation!)
- The success of the interpolation technique strongly depends on the presence and the level of (Global) SAC (TDI)
- The TDI technique constitutes a preliminary step for more complex Geostatistics Techniques
- We need to test if Geostatistic Technique exploiting more precisely the SAC can bring better interpolation results (Variogram + Kriging)

Introduction

Objectives

Research

Conclusion

Discussion

Planning

1) Analysis

- M-Signals and M-GNSS
- Repeat the Symptomatic Analysis on Equatorial Data
- Assess the correlation between ISMR and RINEX

Complements

- Descriptive Analysis of Ionospheric Scintillations
- Spatial Analysis of Ionospheric Scintillations

- Implementation and Validation of the Geostatistic Interpolation Technique
- Additional Tests for the SAC Scaling
- Spatial Interpolation Test on Polar Scintillations and High Rate Data
- Understanding the link between the results of the Spatial Analysis with the Physics of the Ionosphere
- Test on other variables
- Validation of the interpolation with external data or a mathematical model

Planning

1) Analysis

November 14

Complements

- Descriptive Analysis of Ionospheric Scintillations
- Spatial Analysis of Ionospheric Scintillations

1 month

2) Algorithm

December 14

- Developement
- Validation

3 months

3) Thesis

March 15

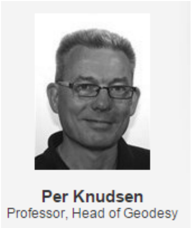
- Writing and Complementary Experiments
- Delivery of the Thesis

3 month

June 15

My Situation

My Goal is to keep Working in the Space Sector (Academic or Industry)



« Guest PhD Student » Position at the Danish Technical University (DTU)

- Access to some courses from Master's and PhD Programmes
- Work on my PhD project at the DTU for an agreed period of time
- Contacts / Ideas / Work Environment / Research Stay / CV

Engineering Master Programme / Selected Courses

- « Earth and Space Physics and Engineering

Earth Physic's and Exploration
Environment and Climate Monitoring
Mapping and Navigation
Space Research

Application for a PostDoc Position at the Danish Technical University (DTU)

Application in a Company (GIS/GNSS)

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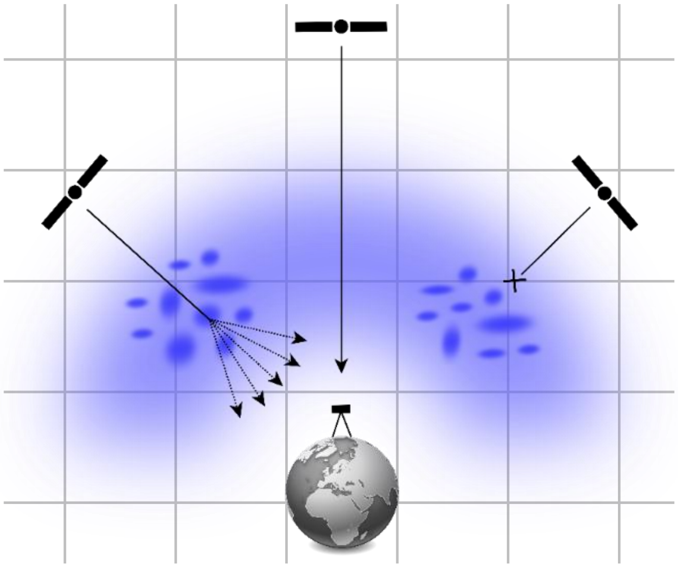
Performances of Absolute GNSS Positioning Algorithms during Equatorial and Polar Ionospheric Scintillations



Matthieu Lonchay

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University of Liège, Belgium

Geomatics Unit

Thesis Committee Meeting

Liège, Belgium

13 November 2014