The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2025-38

Satellite Navigation Science and Technology for Africa

23 March - 9 April, 2009

Scintillation Modelling

BENIGUEL Yannick
I.E.E.A.
13 Promenade Paul Doumer
92400 Courbevoie
FRANCE

Scintillation Modelling

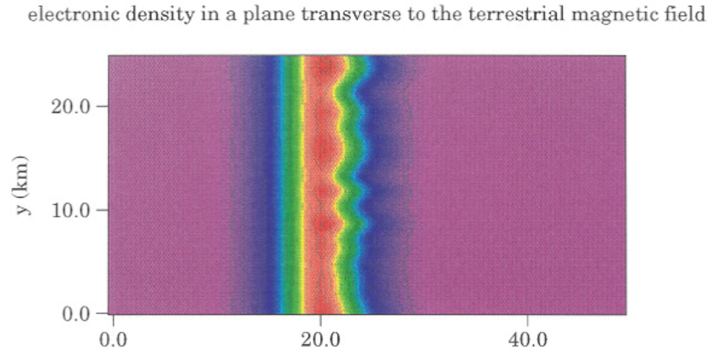
Y. Béniguel, IEEA

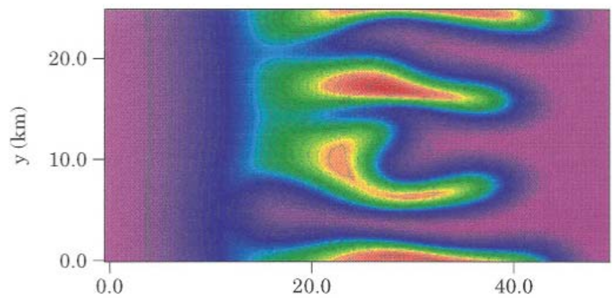
Contents

- Model description
- Comparisons with measurements
- Mapping developments

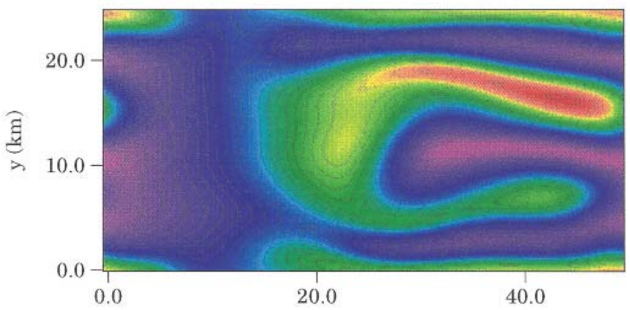
Instability development vs time transverse to the magnetic field plane

Solving Boltzman equations

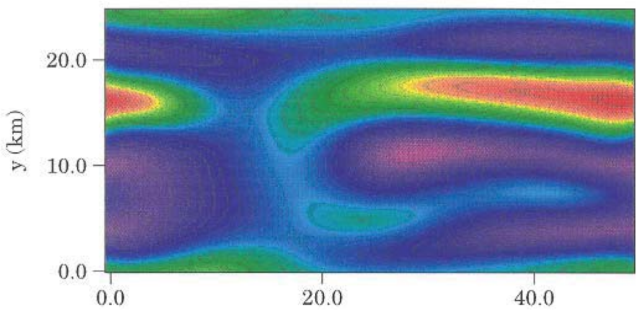




t = 50 s.



t = 100 s.



t = 150 s.

Propagation through a Gaussian lens

We assume a unitary field with a Gaussian phase distribution at z = z_1

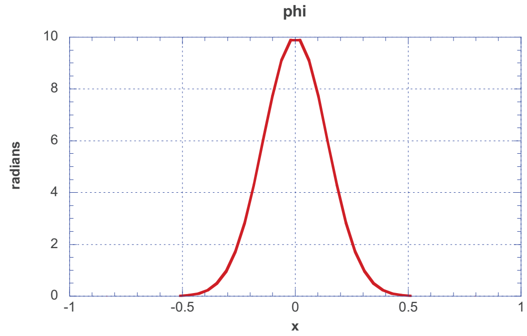
$$E(x,0) = \exp(-j\Phi_0 \ \exp(-x^2/r_0^2))$$

The field at z_2 may be obtained using the Fresnel Kirchhoff integral

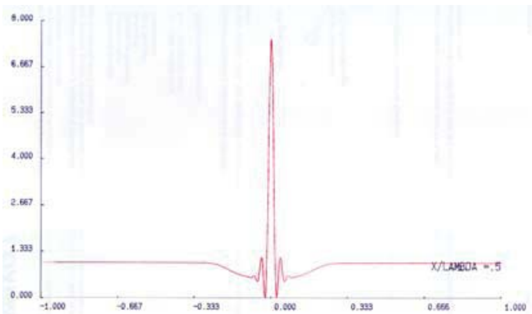
$$E(x,z_2) = \sqrt{\frac{-j2\pi(z_2 - z_1)}{k}} \int_{-\infty}^{\infty} \exp(jk(z_2 - z_1)) \exp\left\{\frac{-jk(x-\xi)^2}{2(z_2 - z_1)}\right\} E(\xi, z_1)\, d\xi$$

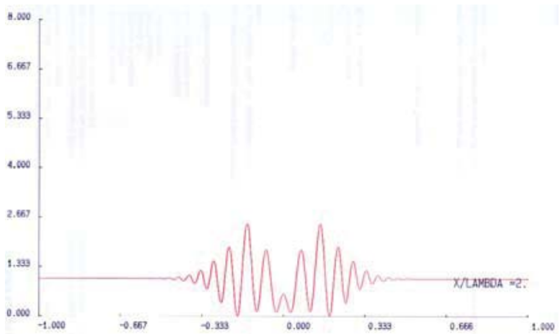
where the space Fourier transform of the field has been made

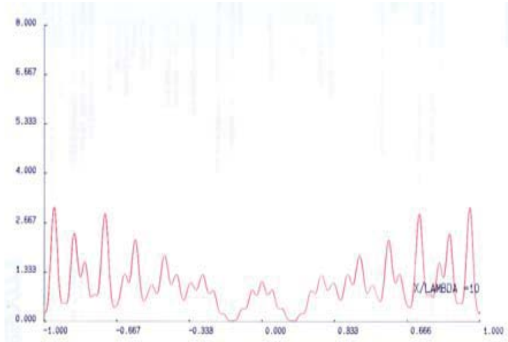
Propagation through a Gaussian lens



Initial impulse



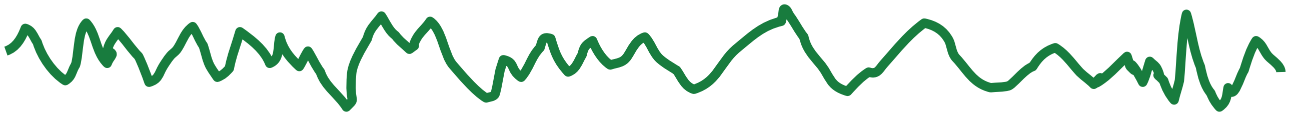




z / λ = 0.5 **z / λ = 2.** **z / λ = 10.**

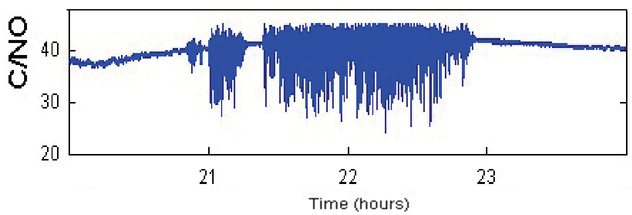
Medium with a random dielectric constant

F layer



Fluctuations of the electronic density

$$E(x,z) = e^{jkz} \int \hat{E}(K,0) \exp\left(\frac{jK^2 z}{2k} + jKx \right) dK$$



receiver

GISM scintillation model

- NeQuick to provide the background ionosphere
- Medium defined by statistical parameters
- Multiple phase screen theory
- Resolution using an FFT algorithm
- includes an orbit generator (GPS, GLONASS, Galileo)

Phase Synthesis

- Pb : to synthesize a random signal Y(x) with a pre - defined spectral density G(ν)

Linear filter : Y(x) = R(x) * X(x)

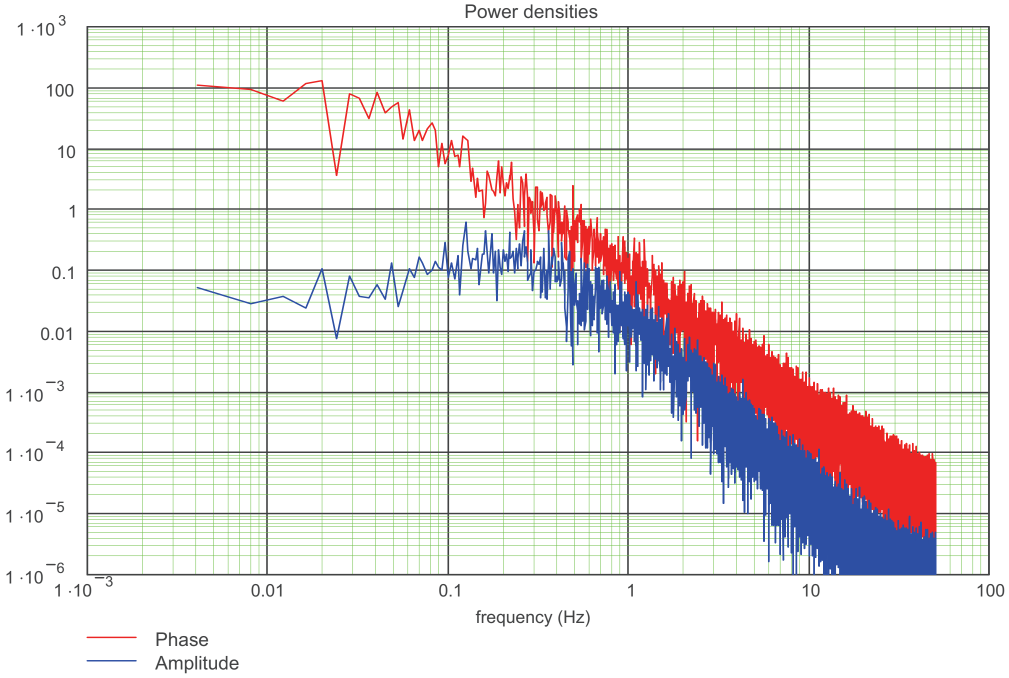
Spectral density of the input signal : $\gamma_X(\nu) = 1$

Filter gain G(ν) such that $G(\nu) = [S(\nu)]^{1/2}$

$S(\nu)$ is the spectral density of the signal to be synthesized

Result obtained by inverse Fourier transform

Signal spectrum (GISM)



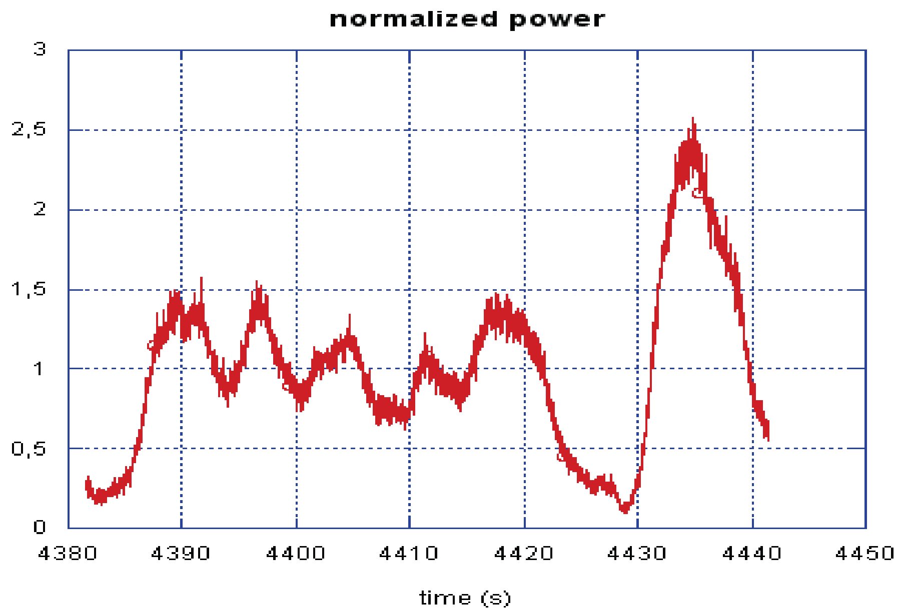
3 parameters for the spectrum

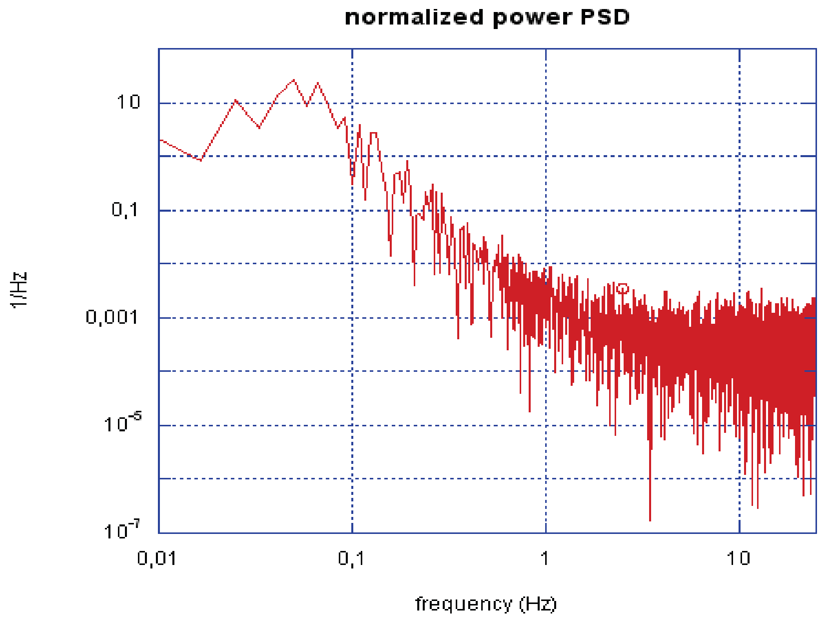
- the slope,
- the cut off frequency,
- the low frequency value

Spectrum Analysis

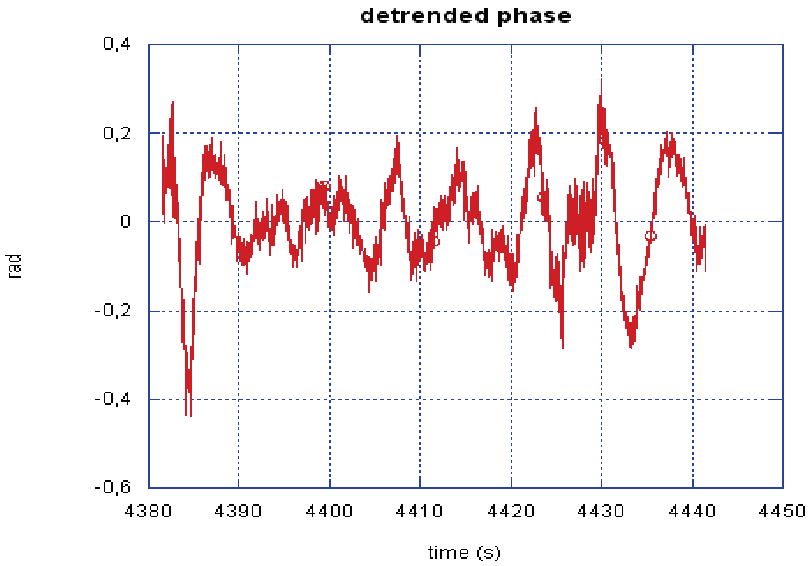
from measurements in South America

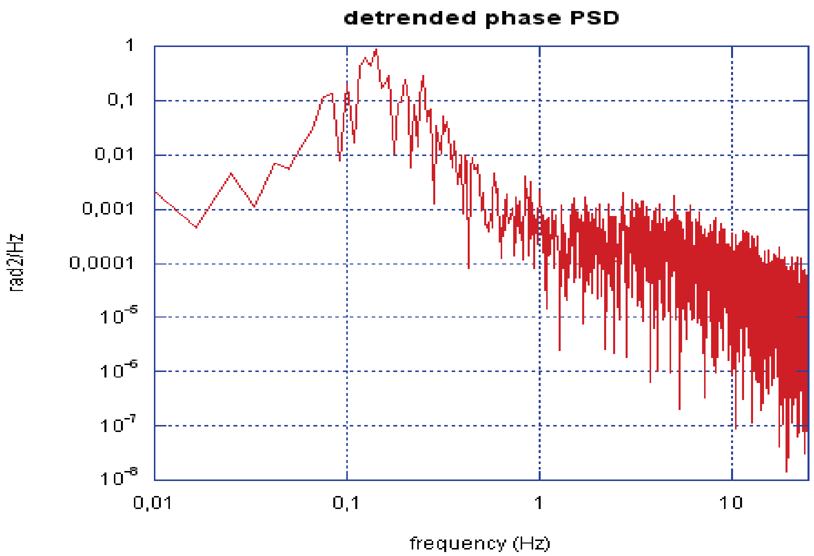
Sample characteristics : S4 = 0.51, sigma phi = 0.11





Sample characteristics : S4 = 0.51, sigma phi = 0.11



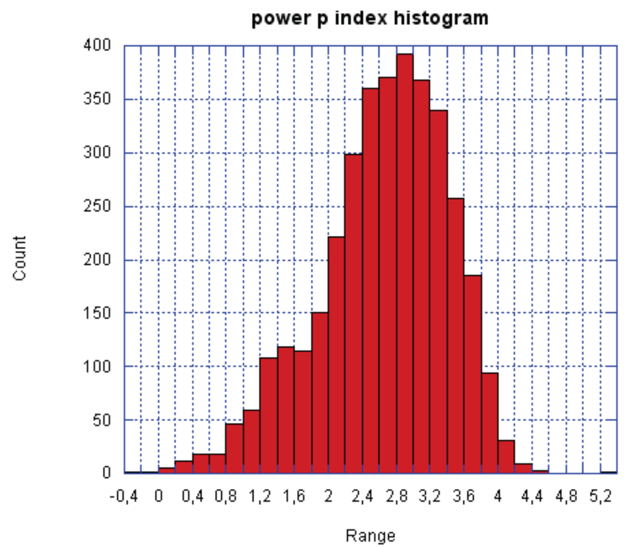


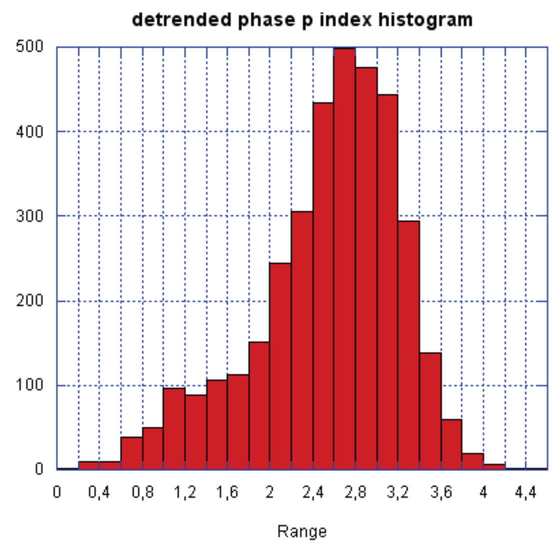
Spectrum parameters

5 days RINEX files considered in the analysis

S4 > 0.2 & sigma phi < 2 (filter convergence)

2 parameters to define the spectrum : T (1 Hz value) & p



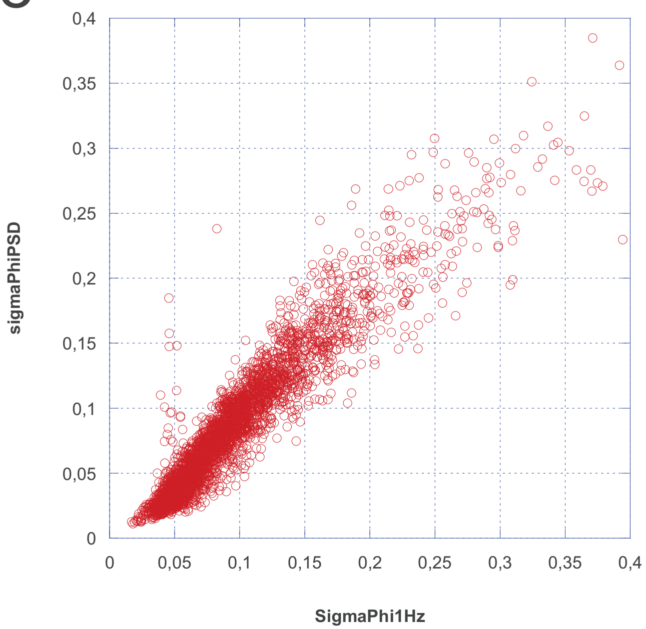


IEEA

Phase variance : time domain vs frequency domain

$$\sigma phi^2 = 2\int_{fc}^{\infty} PSD(f)df = 2\int_{fc}^{\infty} Tf^{-p}df = 2T\left[\frac{f^{-p+1}}{-p+1}\right]_{fc}^{\infty} = \frac{2T}{(p-1)fc^{p-1}} \qquad \text{(if p > 1)}$$

Slope set to 2.8



linear relationship

Scintillations strength

Scintillations Parameters
S4 and σ_Φ

S4 standard deviation of the intensity

σ_Φ standard deviation of the phase

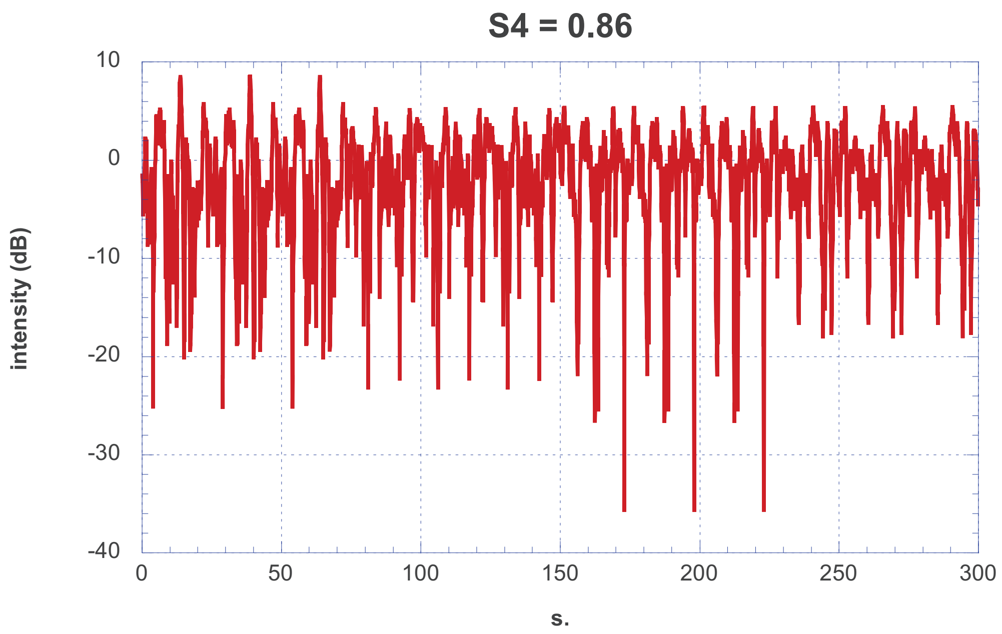
Weak fluctuations hypothesis

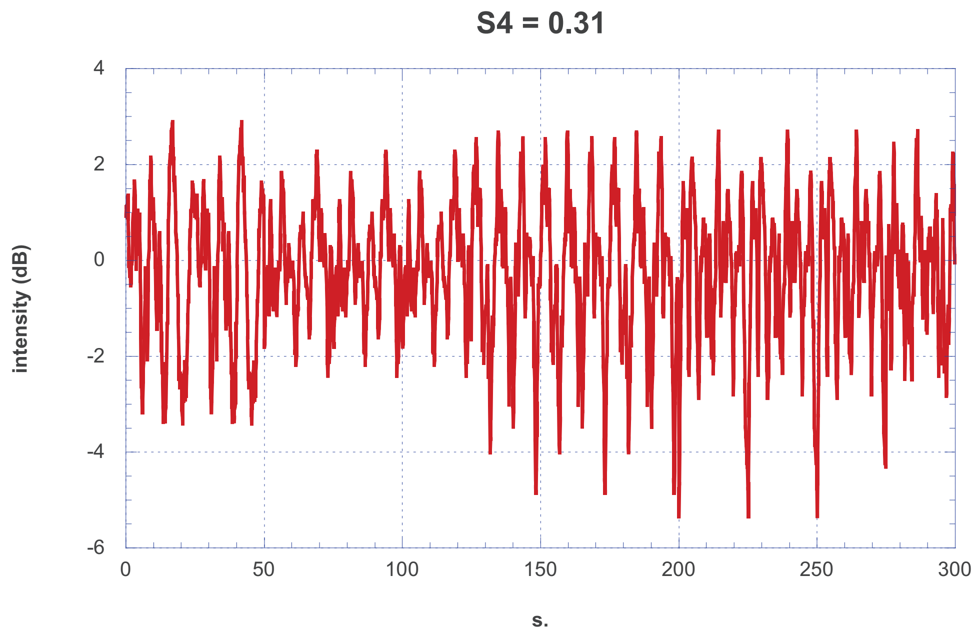
$$\sigma_\Phi^2 = 2(\lambda r_e)^2 \, L \, L_0 \, \sigma_{Ne}^2$$

$$S_4^2 = 4 \, (\lambda r_e)^2 \, L \, C_s \int \sin^2(q^2 Z) \, \cos(q\rho) \frac{dq}{(1 + (q/q_0)^2)^{p/2}}$$

L is the propagation distance inside the fluctuating medium

L_0 is the average size of the inhomogeneities
500 < L_0 < 1 km will contribute to scintillations → 1st Fresnel zone

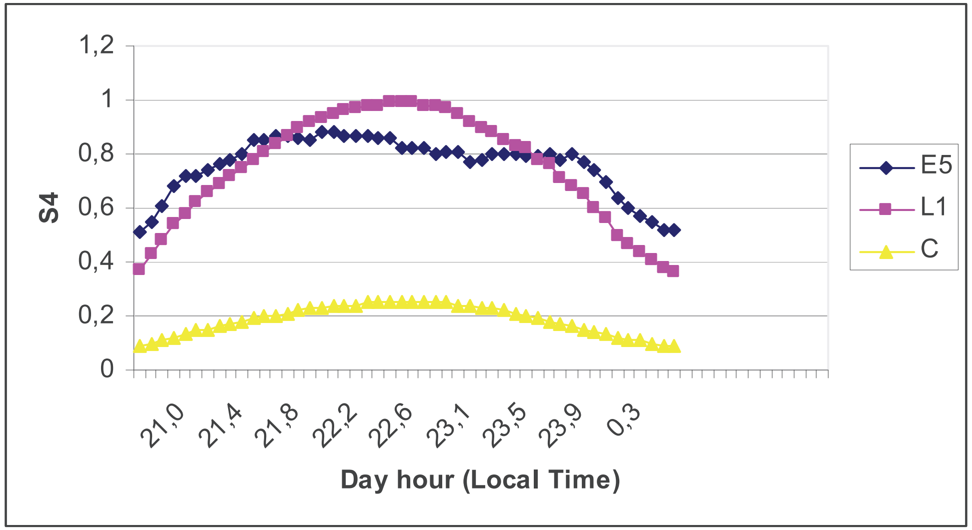


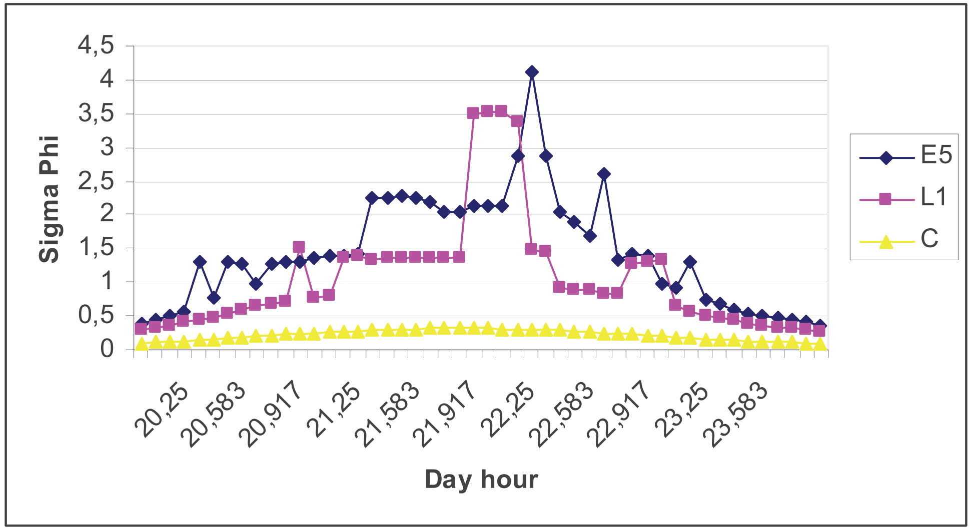


Low : S4 < 0.3

Medium : 0.6 < S4 < 0.3

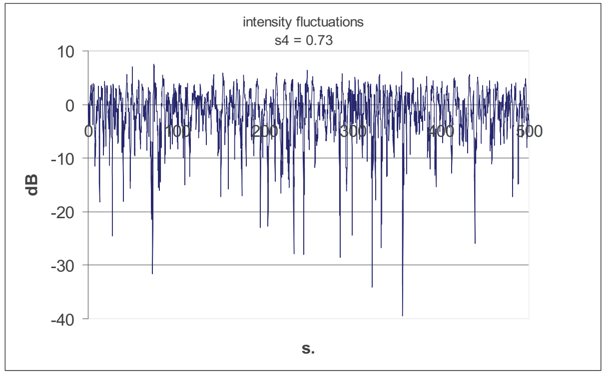
Strong : S4 > 0.6



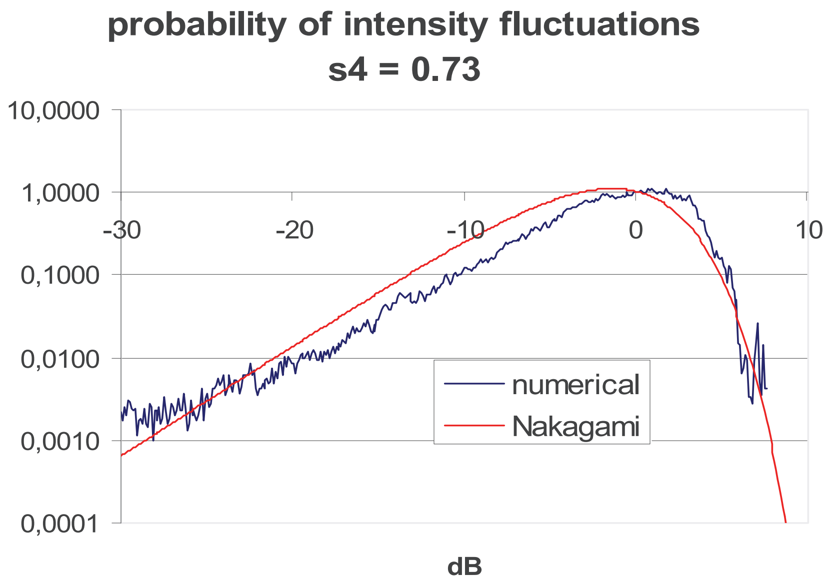


Scintillation levels depending on the local time

Probability of intensity Modelling

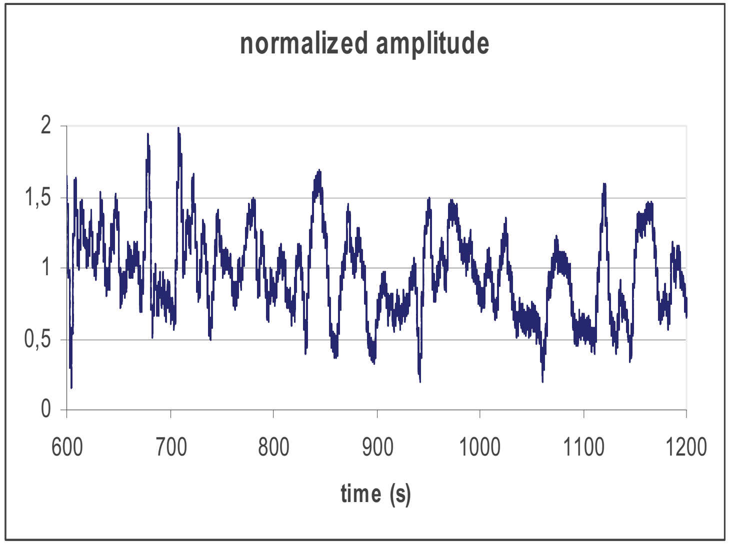


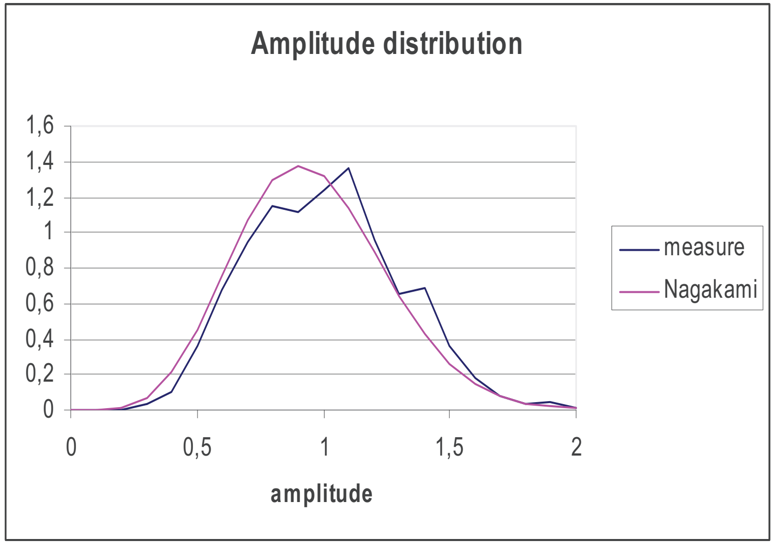
GISM output

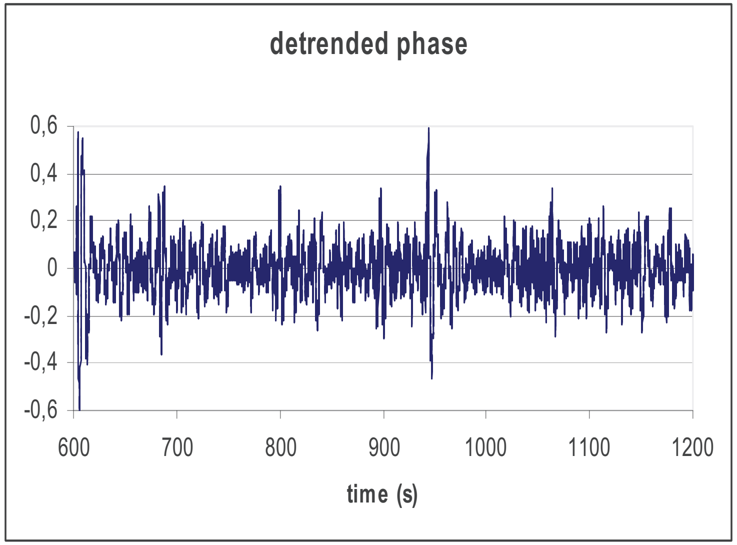


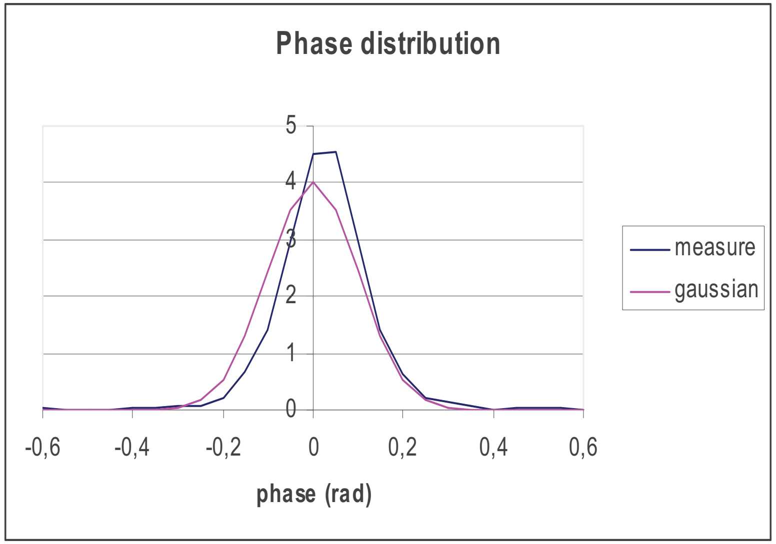
Nakagami law $p(A) = \frac{2\, m^m\, A^{2m-1}}{\Gamma(m)} \exp(-m A^2)$ with $m = 1 / S_4^2$

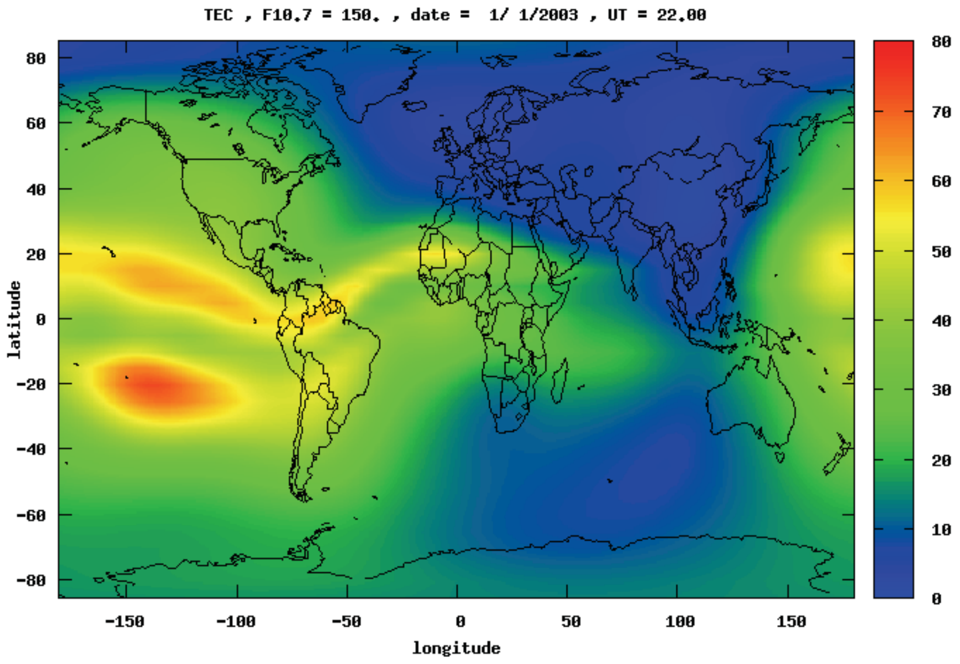
10 minutes sample with S4 = 0.6 & sigma phi = 0.1



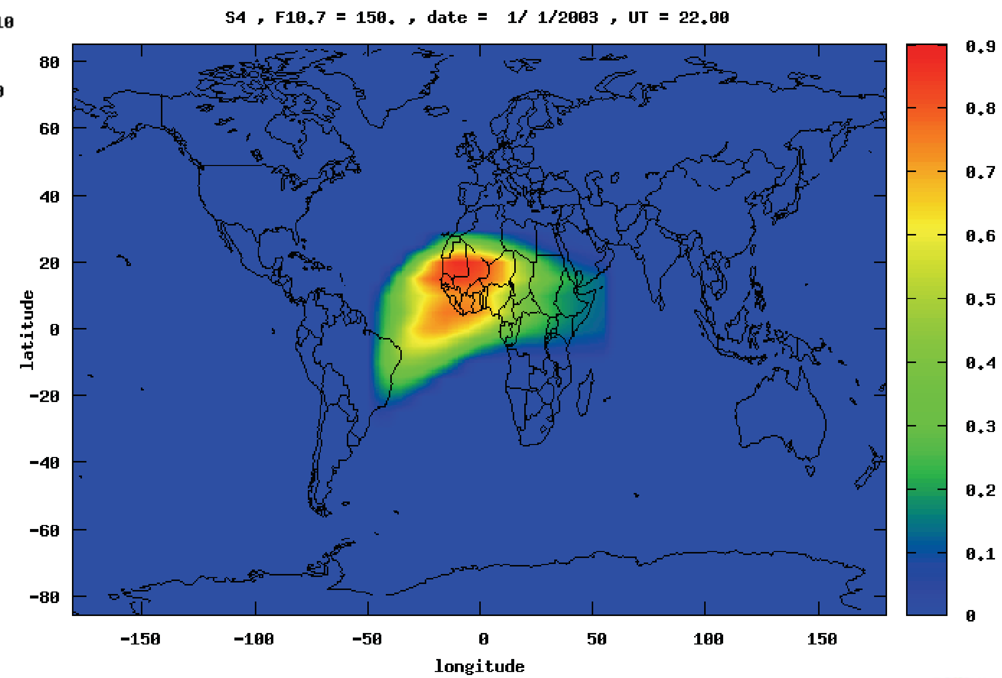






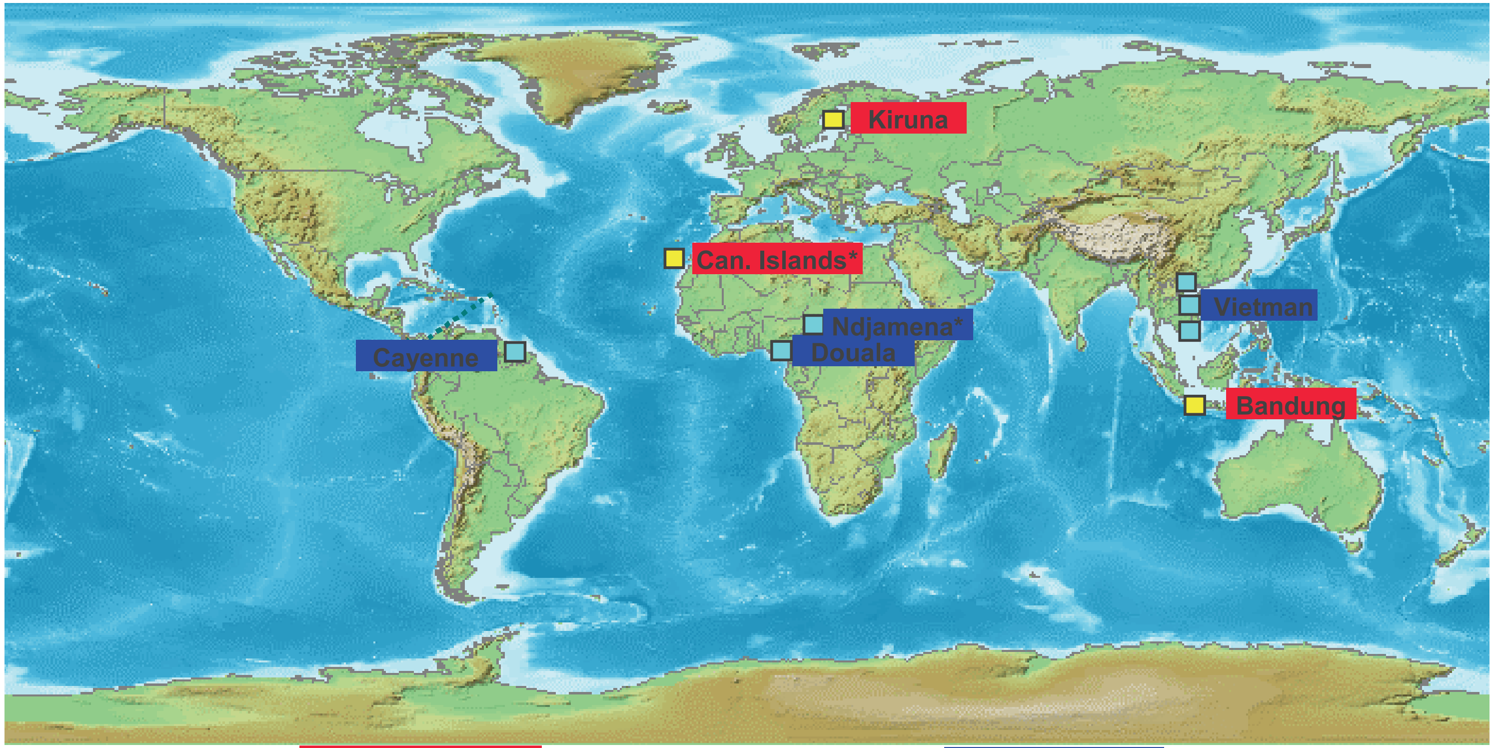


Scintillation map



TEC map

PRIS Measurement campaign



Javad receiver   GSV receiver

offline   on line

Institutions : IEEA (Fr), DLR (Ge), GMV (Sp), ESA / ESTEC, CLS (Fr), U. of Rennes & Brest (Fr)

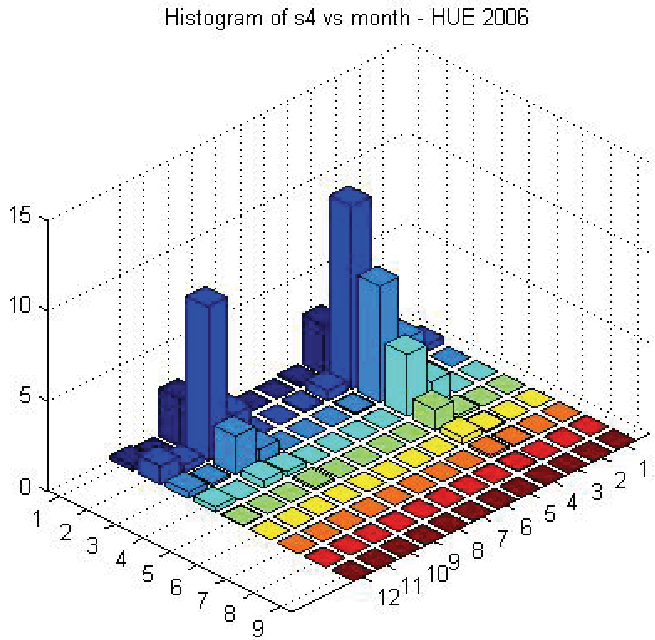
Measurement problems

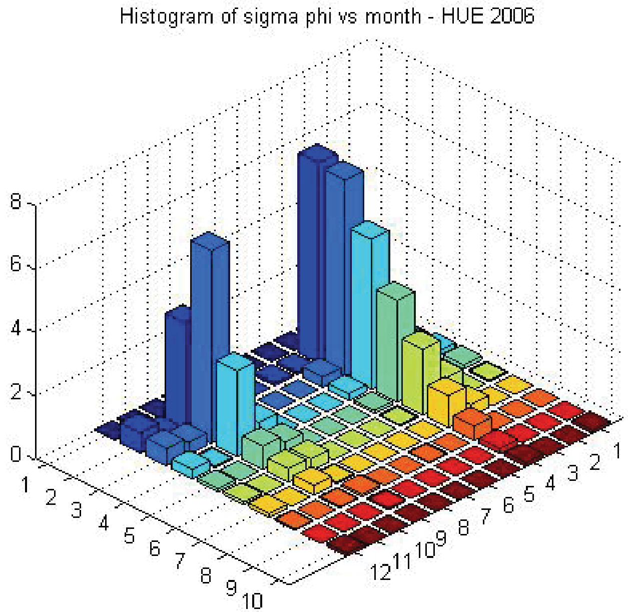
Most of the measurements are affected by multipaths

For the statistical analysis

- Elevation angle > 20°
- Code Carrier divergence
- S4 > 0.2

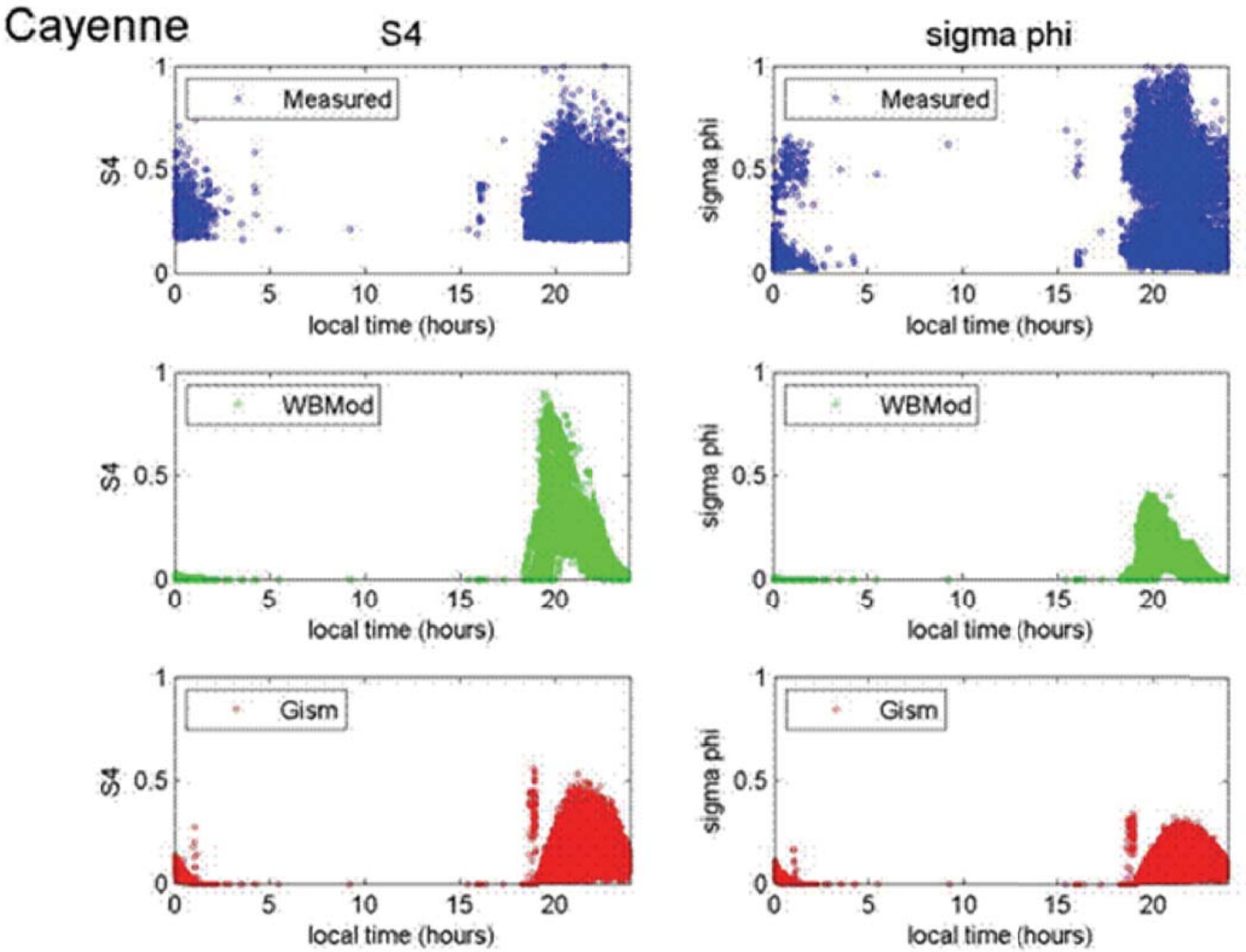
Seasonal Dependency



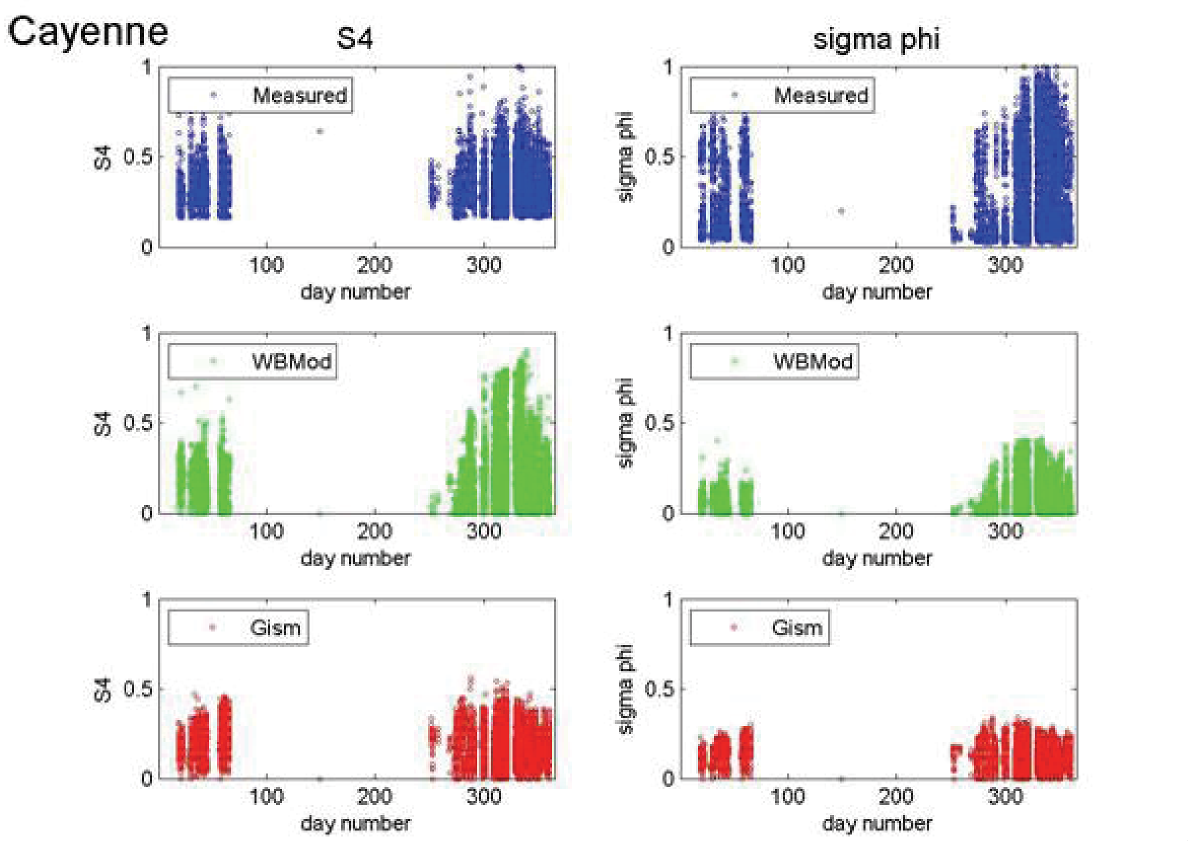


Results obtained using the data base

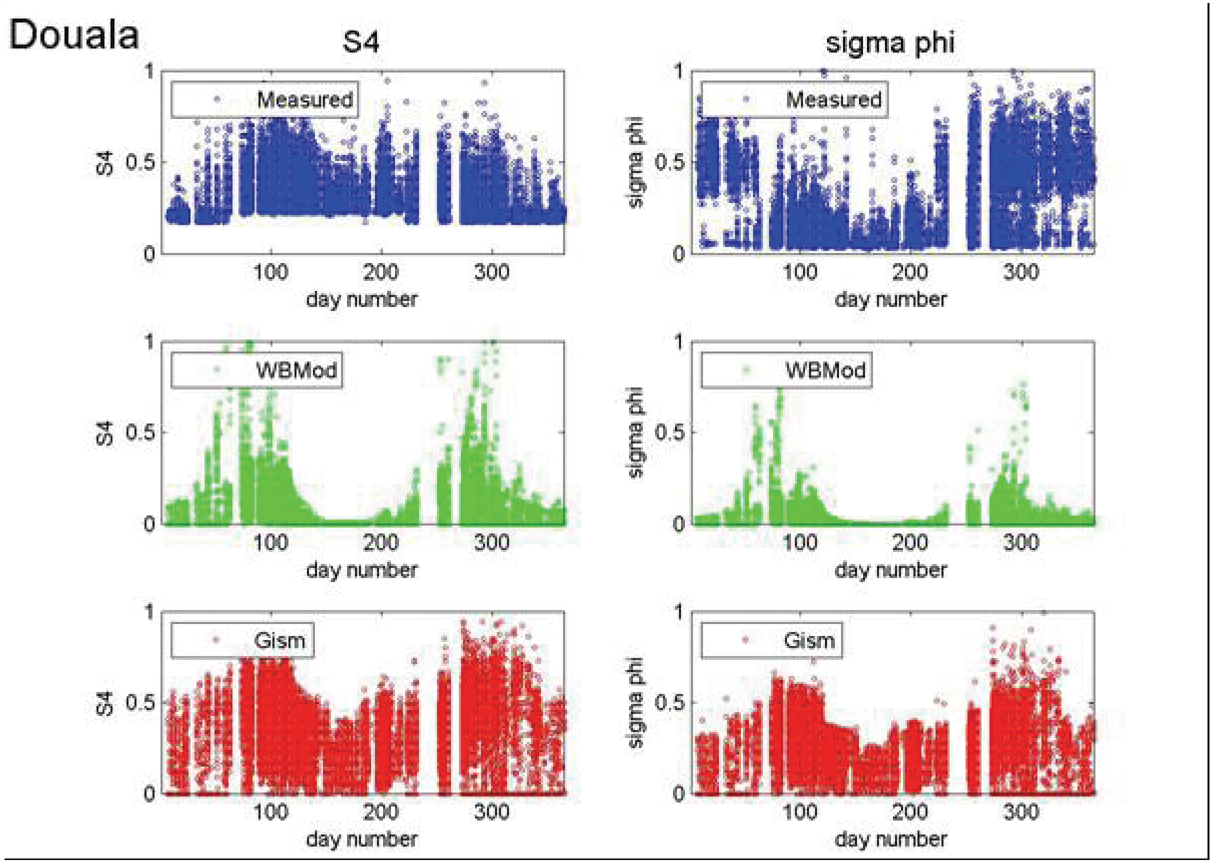
Depending on local time



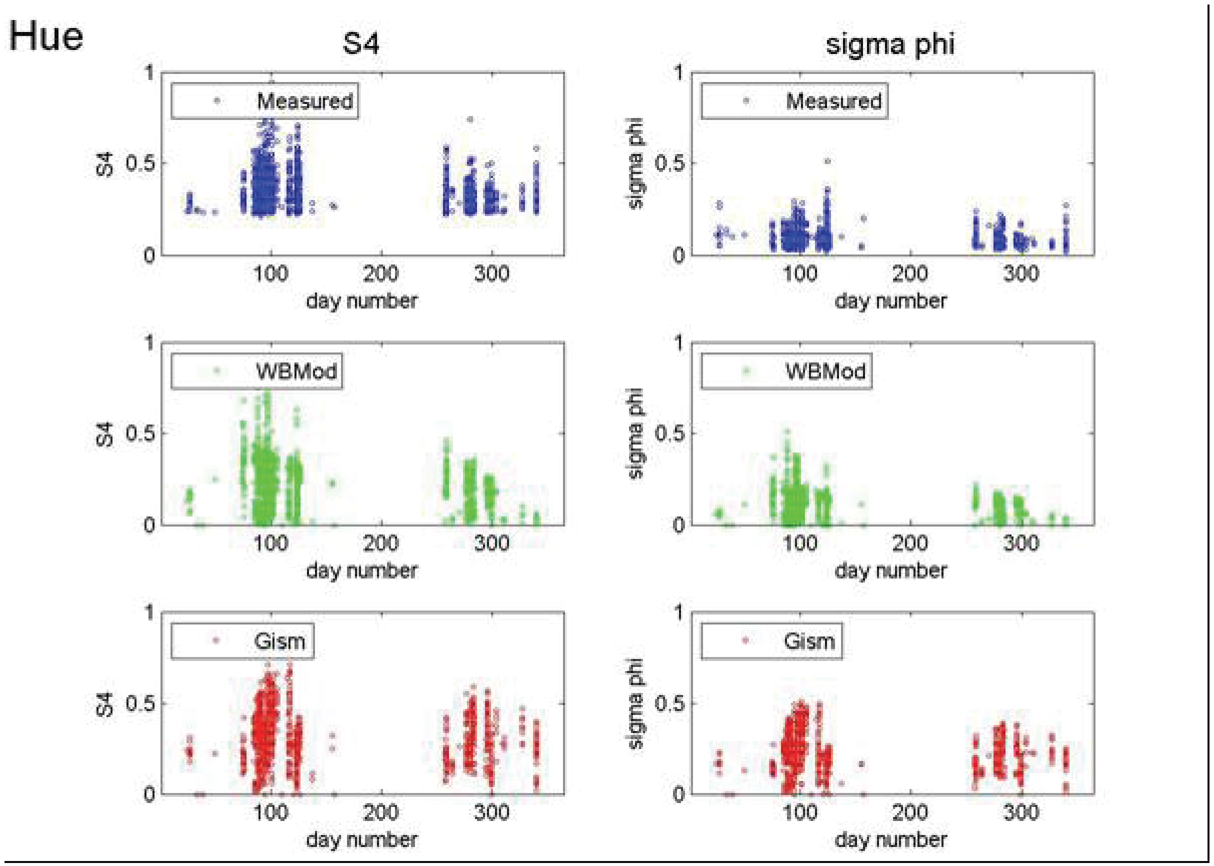
Depending on the day of the year



Depending on the day of the year

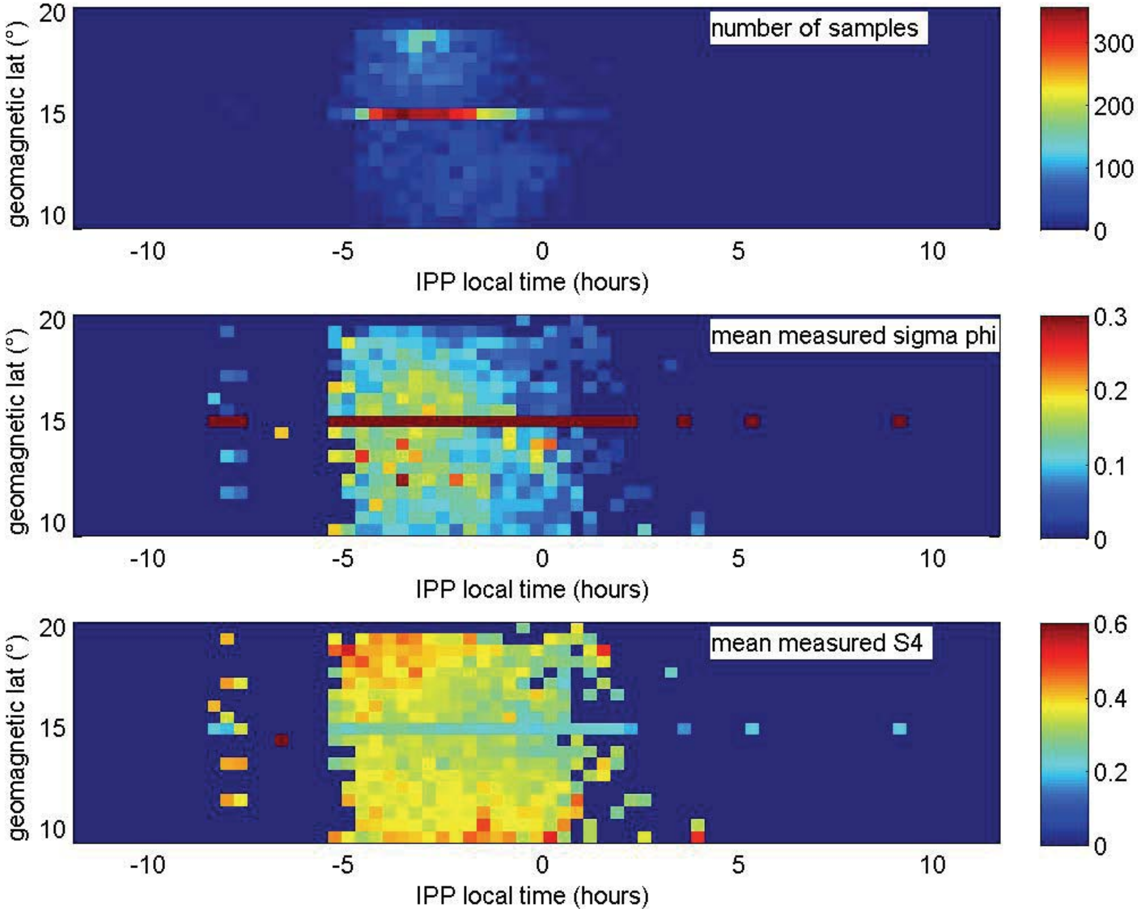


Depending on the day of the year

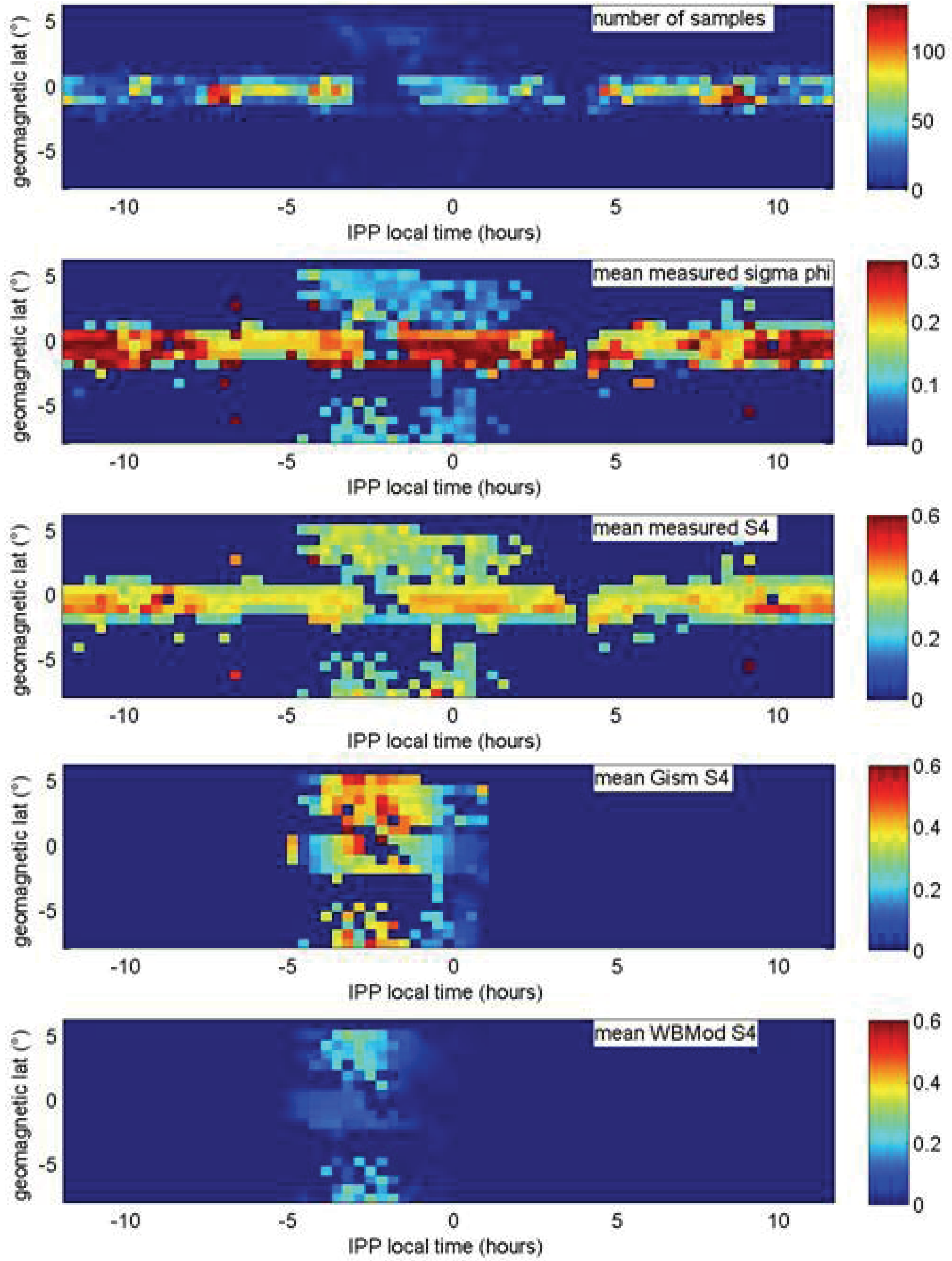


Maps

Cayenne

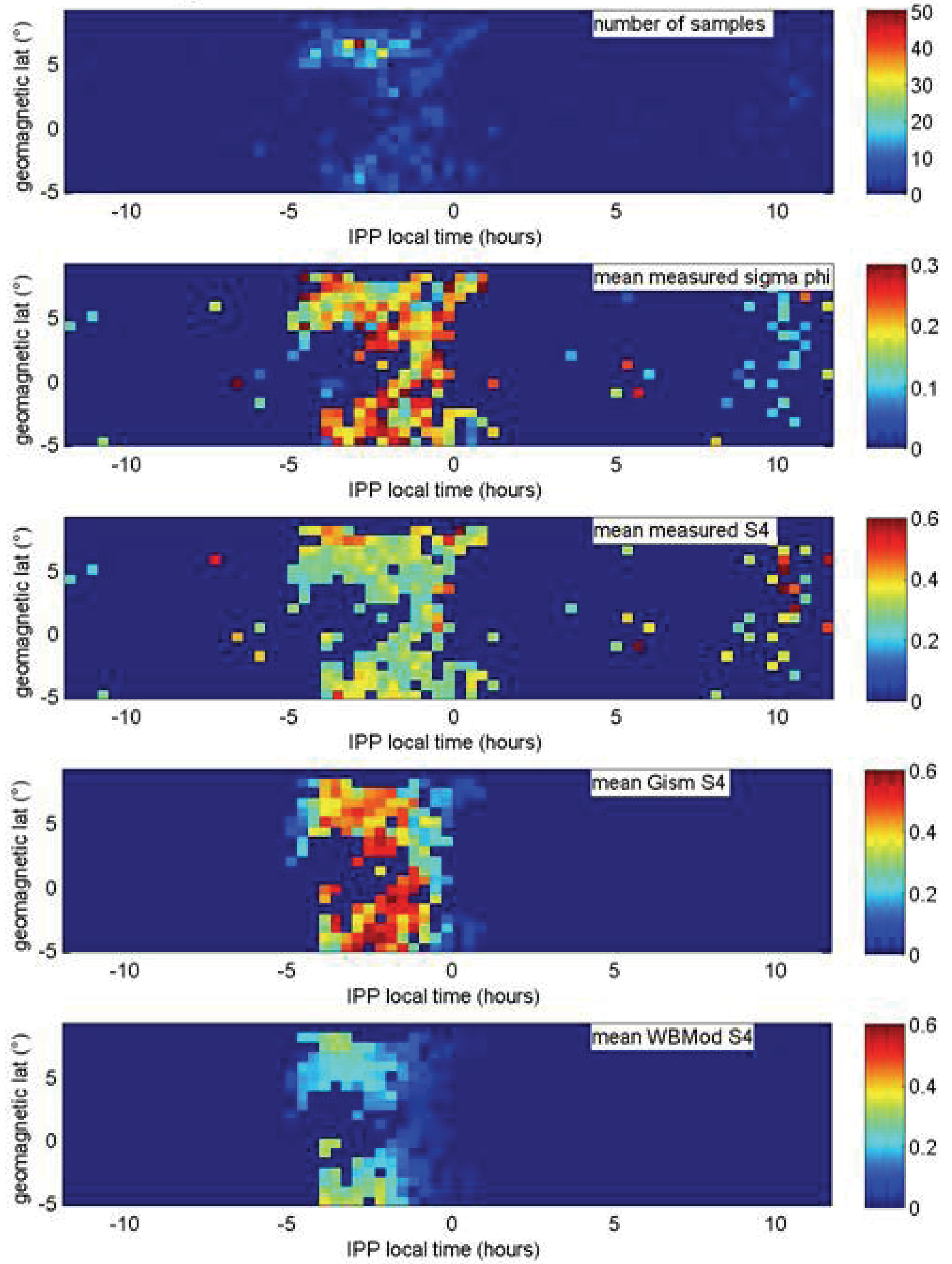

number of samples
mean measured sigma phi
mean measured S4
geomagnetic lat (°)
IPP local time (hours)
20
15
10
-10
-5
0
5
10
300
200
100
0
0.3
0.2
0.1
0.6
0.4
0.2

N'Djamena

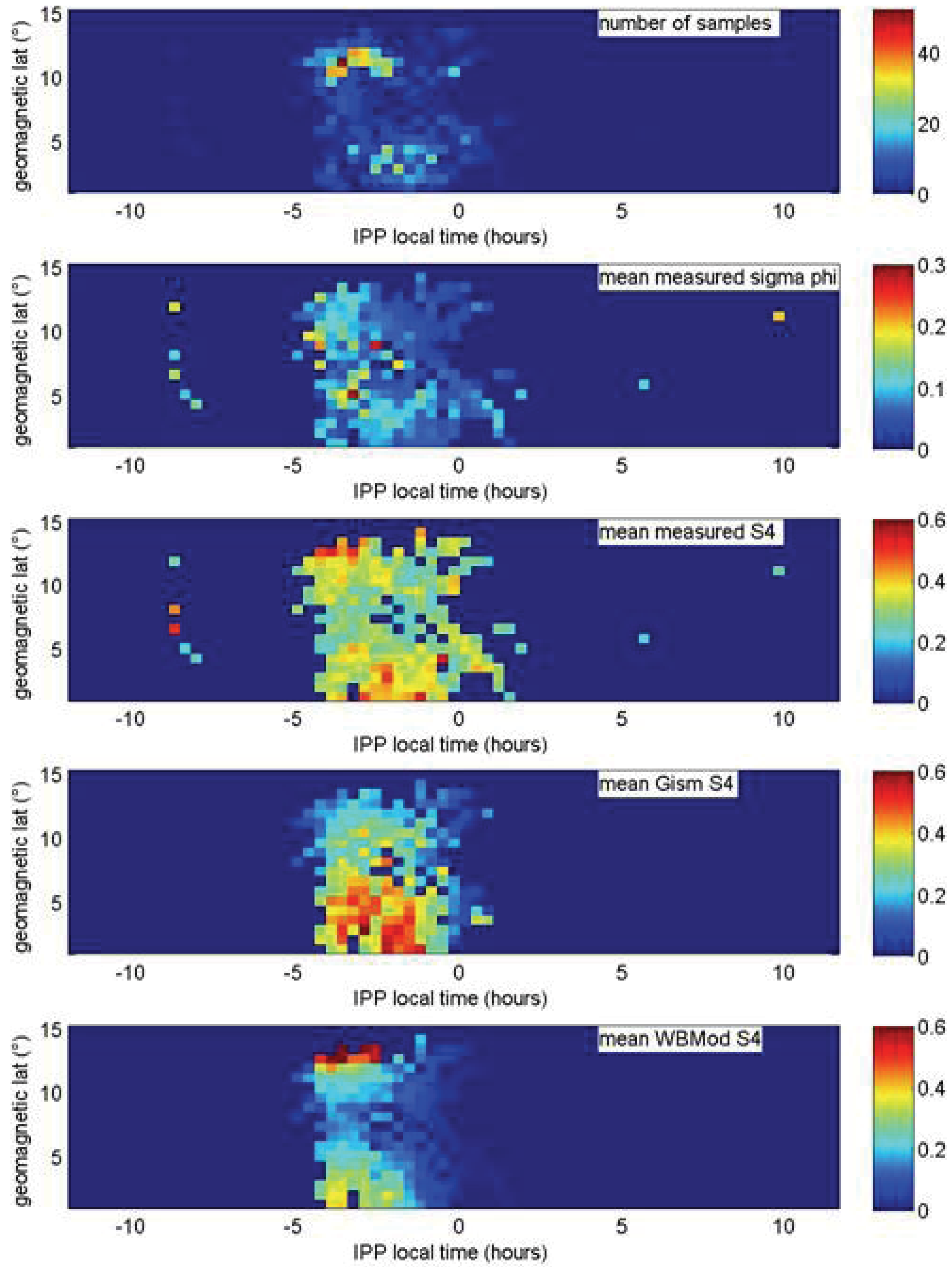


number of samples
geomagnetic lat (°)
IPP local time (hours)
mean measured sigma phi
mean measured S4
mean Gism S4
mean WBMod S4

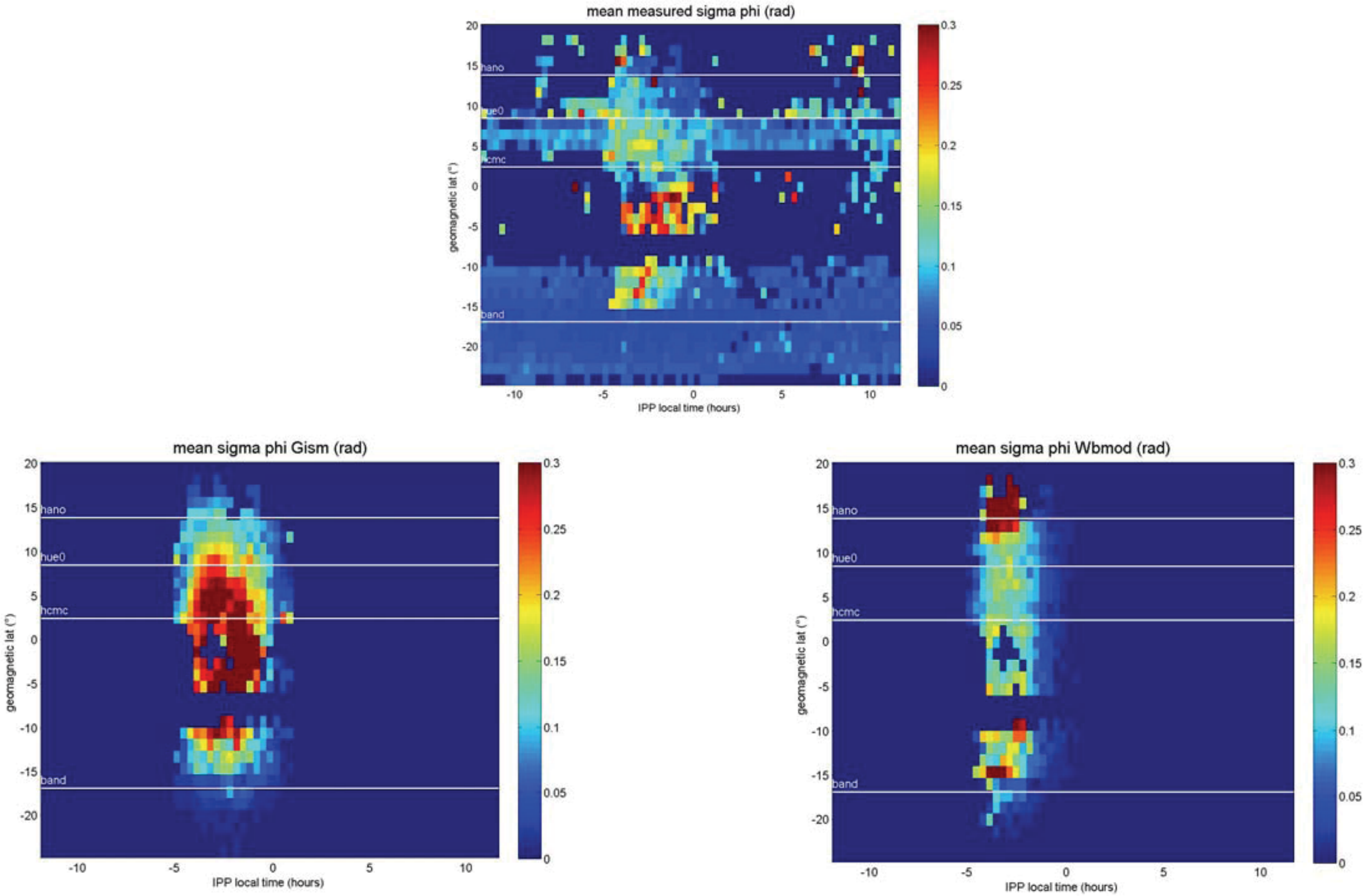
Ho-Chi-Min City



Hue


number of samples
mean measured sigma phi
mean measured S4
mean Gism S4
mean WBMod S4
geomagnetic lat (°)
IPP local time (hours)

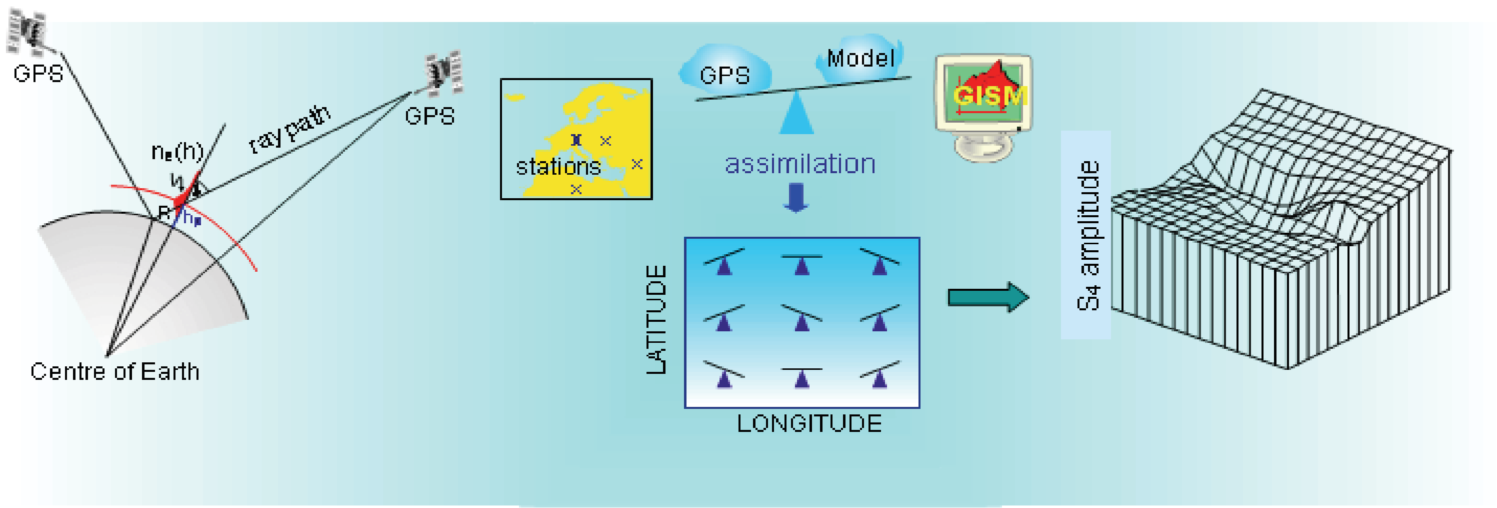
Model / measurement comparison



The model extent area fits with what is obtained by measurements

Assimilation technique principle

Principle of Scintillation Map Generation

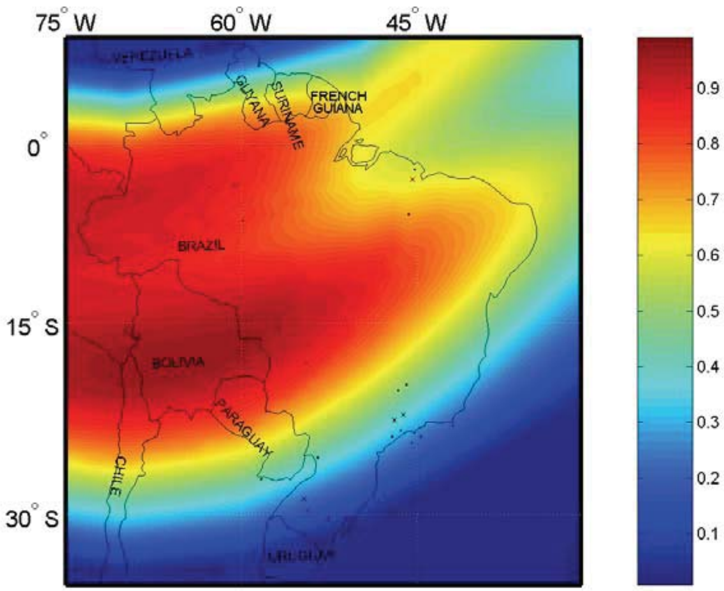


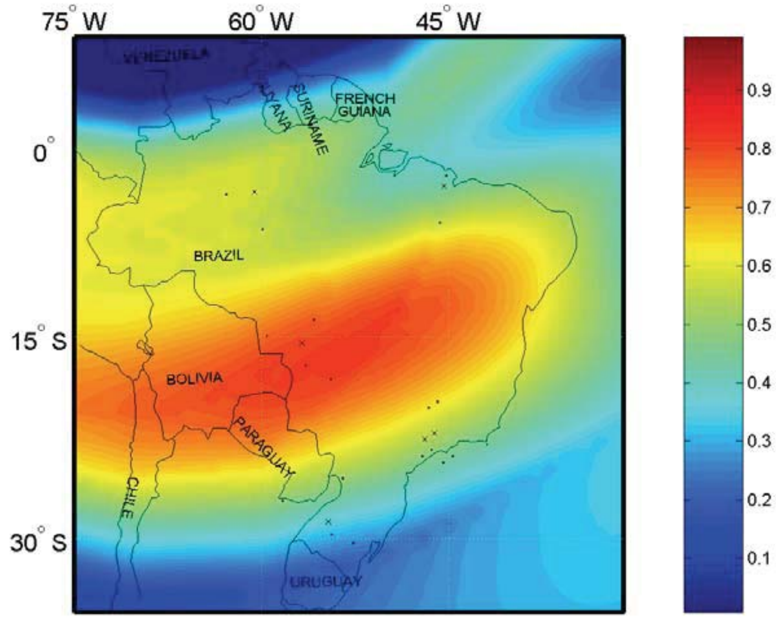
Measurements, S_4 computation

Assimilation of data into the GISM

Scintillation map.

Maps using an assimilation technique



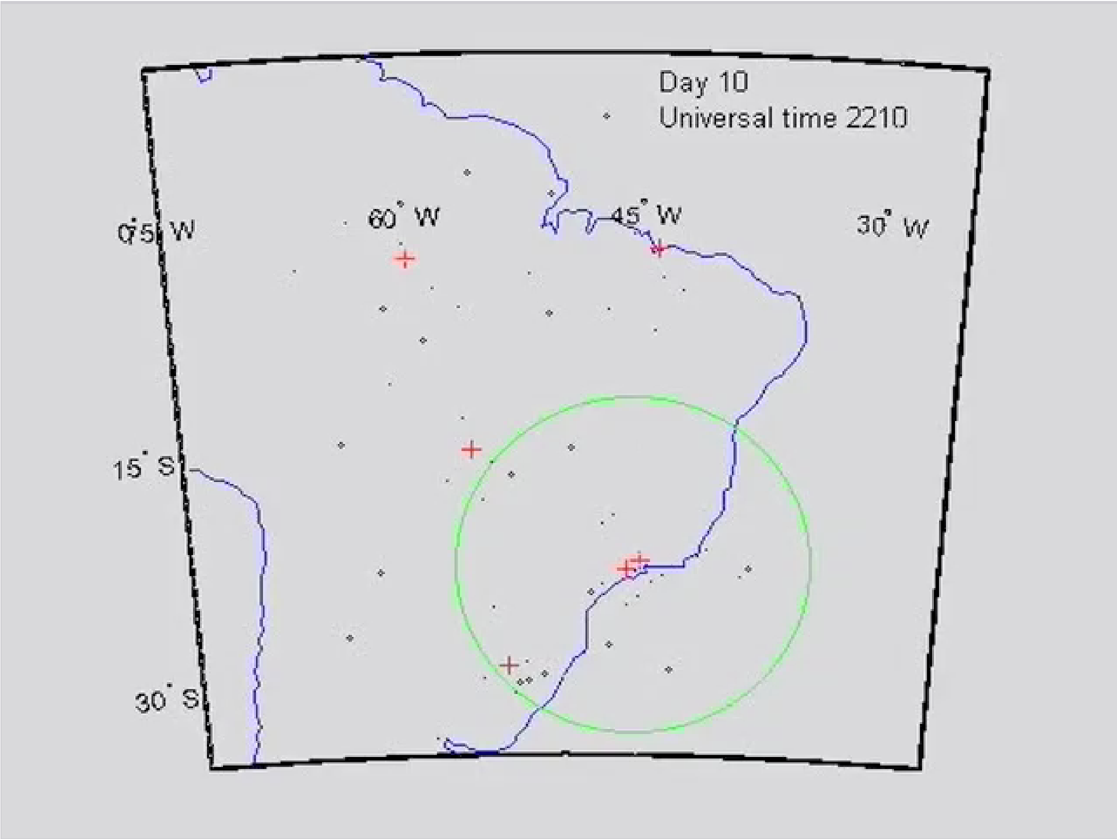


Scintillation measurements over Brazil with 6 stations

movie

- The circle of each IPP is proportional to the measured S4

2 stations are almost collocated : distance = 100 km

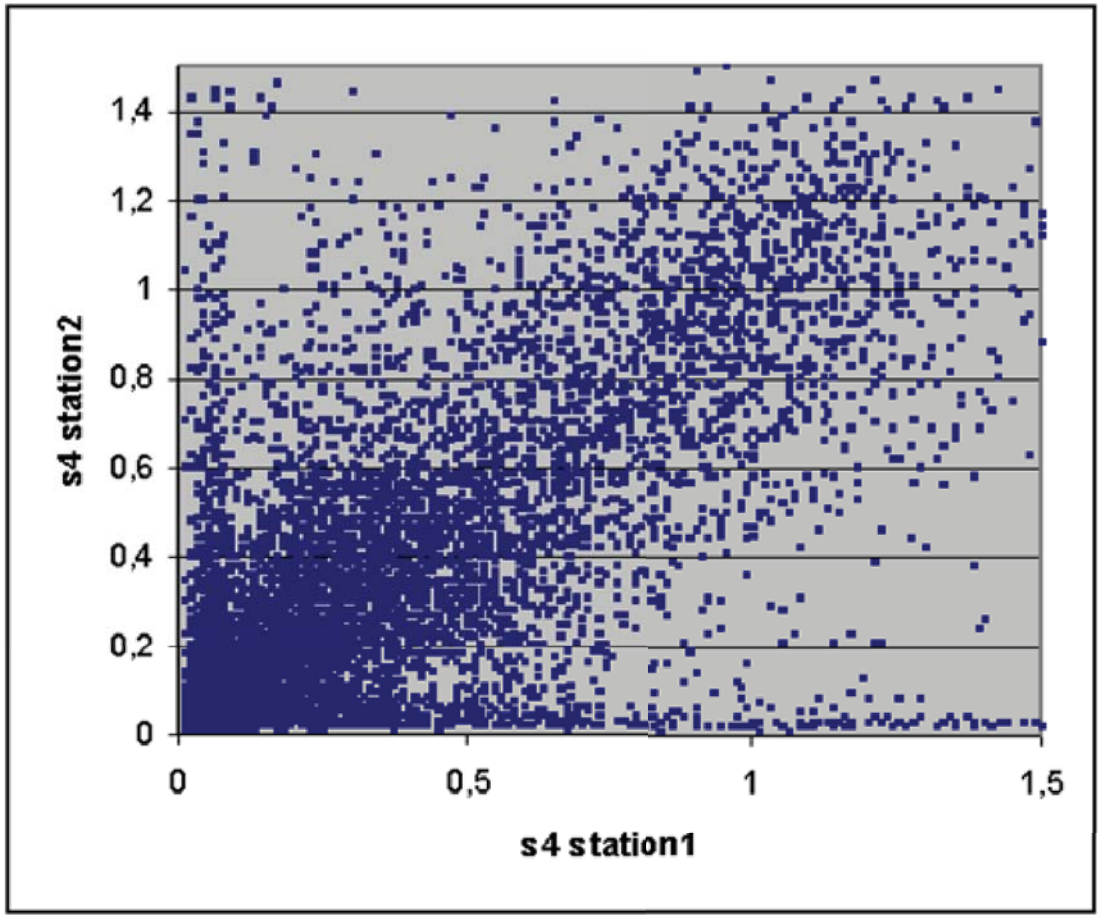


Collocated stations (100 km)

1 week of measurements

All visible GPS satellites are considered

Computed correlation coefficient : 0.8



IEEA

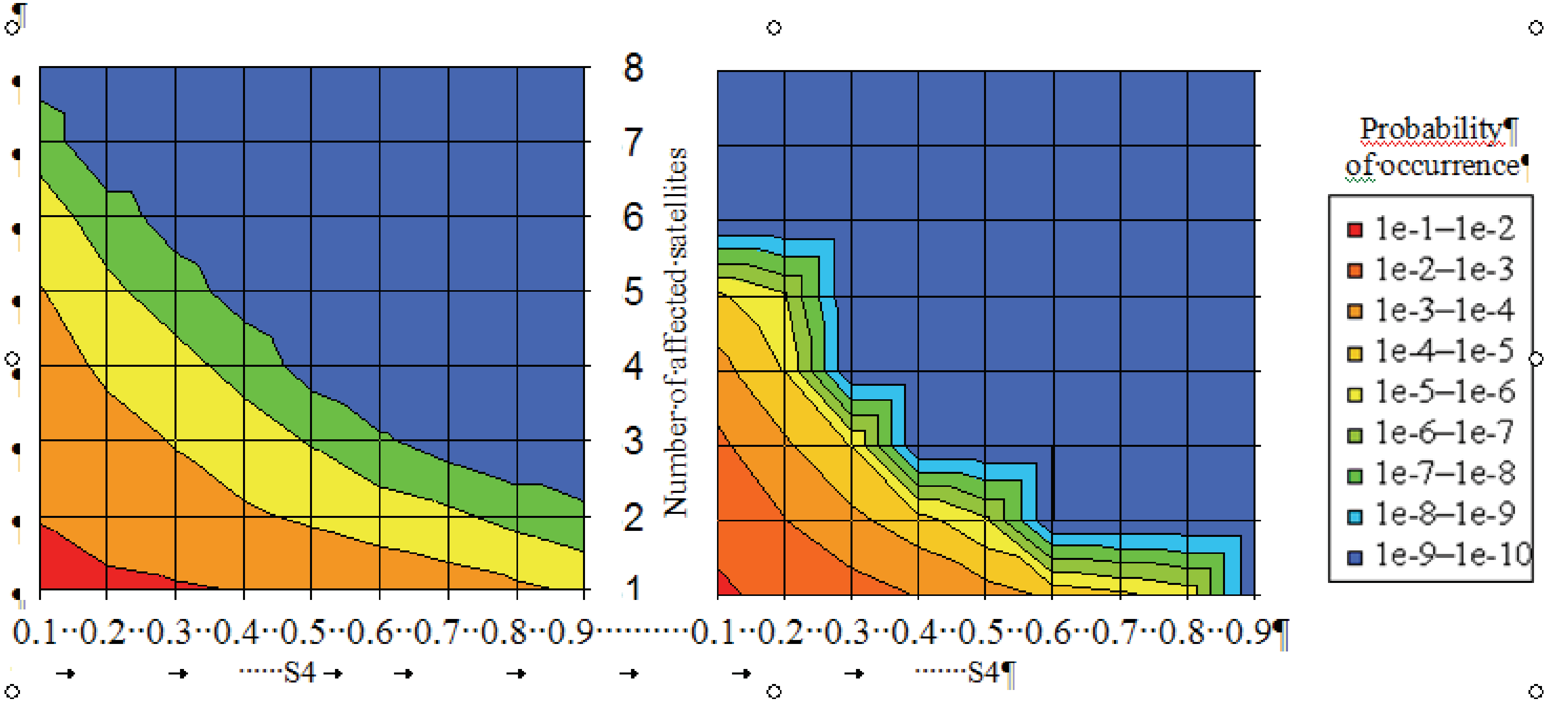
Correlation distance

For a given satellite, the distance between the IPPs is approximately the same than the distance between the stations.

The correlation coefficient between the S4 of 2 IPP is assumed to be a gaussian function of the distance : $c = \exp(-\alpha d^2)$

Since c = 0.8 for d = 100 km, the deduced correlation distance (c = 0.5) is about 175 km.

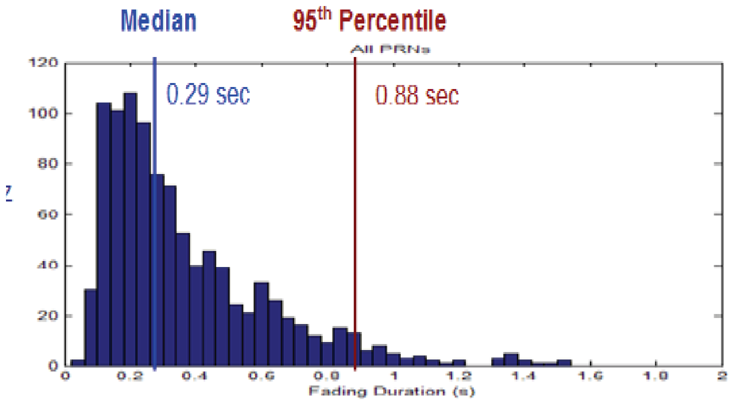
Probability of simultaneous fading

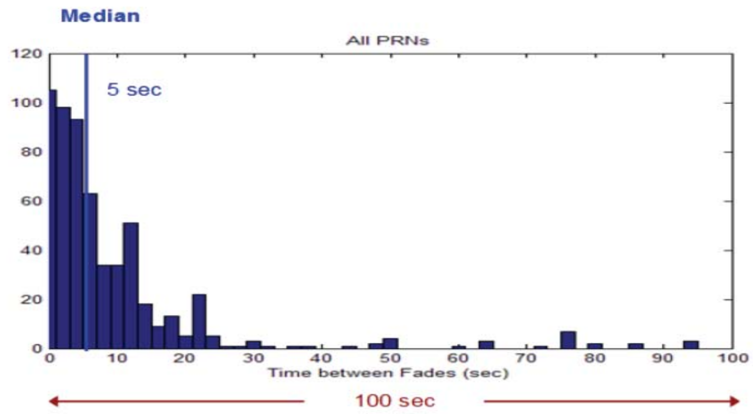


Brazil (190) **Douala (100)**

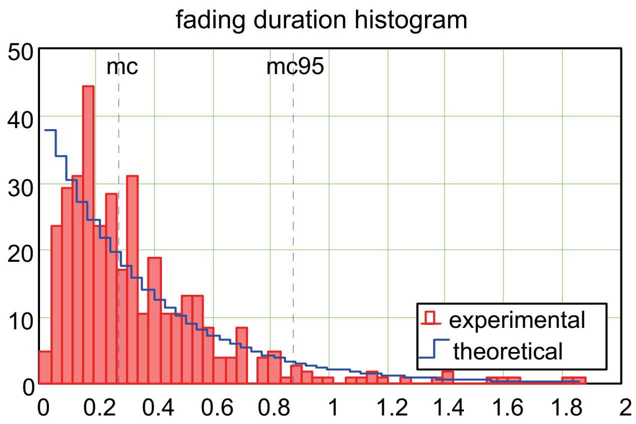
Fades statistics

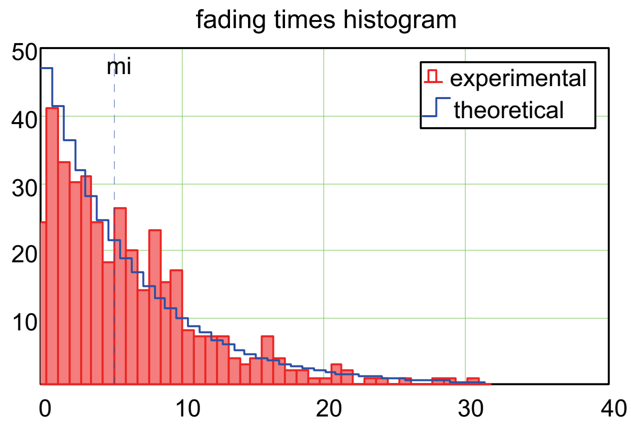
Example of equatorial scintillation in Ascension Island, in solarmax conditions (2001)





Real data

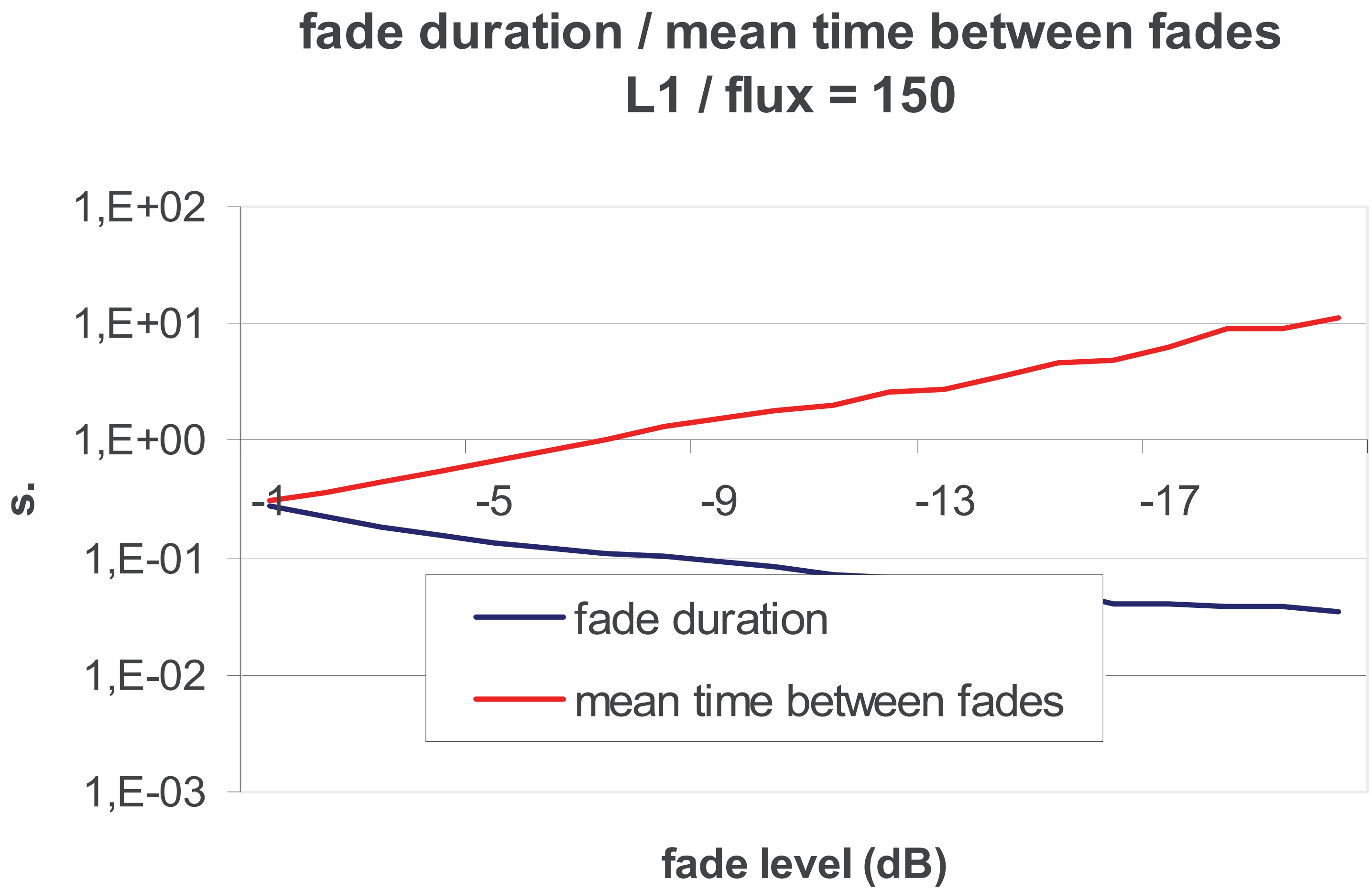




GISM simulation

Source H. Guichon, Thalès

Fade duration / mean time between fades L1 & C band



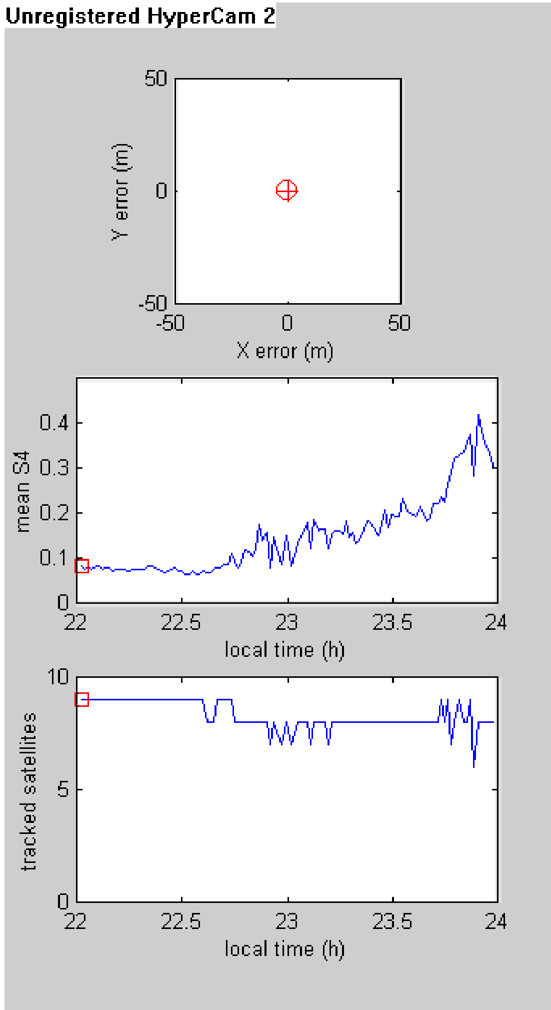
Positioning errors

Simulation

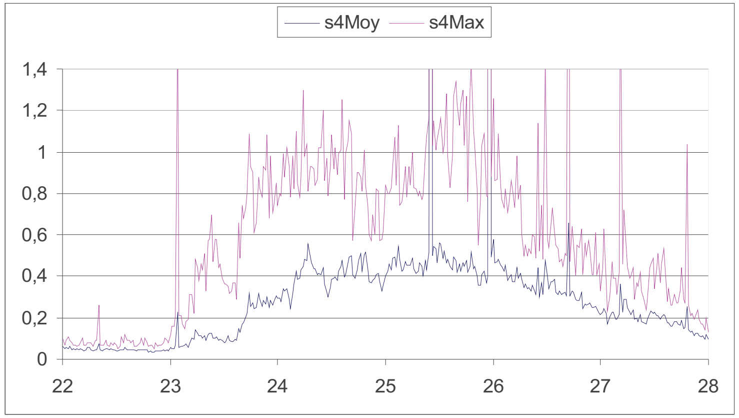
- GPS constellation simulated with a yuma file
- S4 measured for each tracked satellite
- Receiver model described with typical parameters
- Positioning error computed

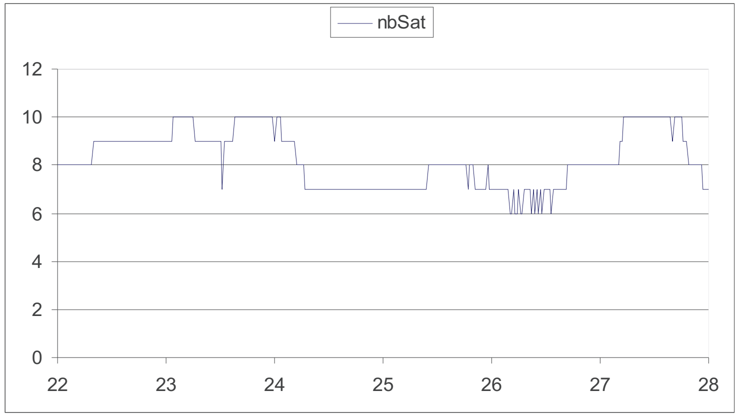
GPS Positioning Errors

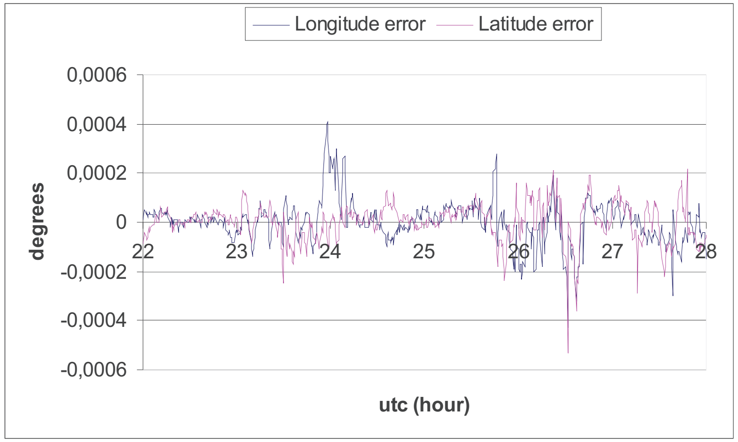
movie



Positioning errors from measurements in Brazil in 2001







Conclusions

- ✓ Results obtained during PRIS campaign at low solar activity exhibit the expected usual trends
- ✓ The GISM model results show a reasonable agreement as compared to measurements
- ✓ Mapping algorithms are being developed
- ✓ Measurement campaign will be continued in the future (Northern Europe, South America, Vietnam & Africa)