GISM
Global Ionospheric Scintillation Model

http://www.ieea.fr/en/gism-web-interface.html

Y. Béniguel, IEEA

- Béniguel Y., P. Hamel, “A Global Ionosphere Scintillation Propagation Model for Equatorial Regions”, Journal of Space Weather Space Climate, 1, (2011), doi: 10.1051/swsc/2011004

Contents

Measurement Campaigns

PRIS

Béniguel Y., J-P Adam, N. Jakowski, T. Noack, V. Wilken, J-J Valette, M. Cueto, A. Bourdillon, P. Lassudrie-Duchesne, B. Arbesser-Rastburg, Analysis of scintillation recorded during the PRIS measurement campaign, Radio Sci., Vol 44, (2009), doi:10.1029/2008RS004090

http://telecom.esa.int/telecom/www/object/index.cfm?fobjectid=29210

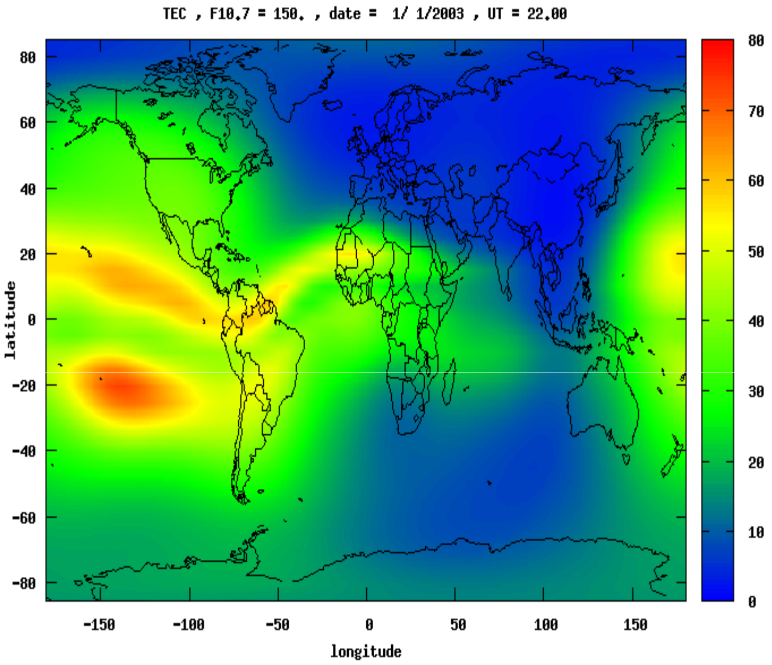
MONITOR

Prieto Cerdeira R., Y. Béniguel, "The MONITOR project: architecture, data and products", Ionospheric Effects Symposium, Alexandria VA, May 2011

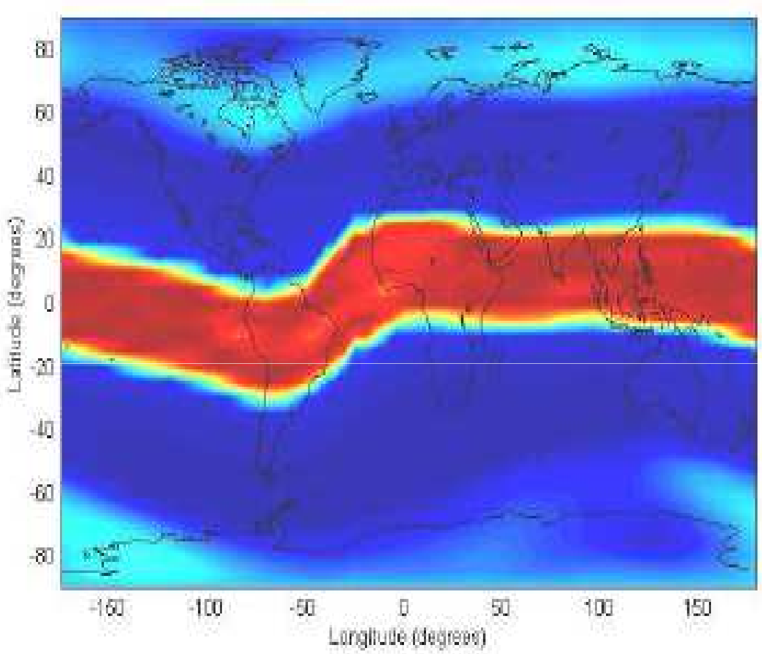
MONITOR Extension

On going; start : 30 june 2014

Ionosphere Variability



TEC Map



S4 map cumulated over 24 hours

Mean Errors
(ray technique calculation)

$$n^2 = 1 - \frac{X}{1 - \frac{Y^2 \sin \vartheta}{2(1-X)} \pm \left[\left(\frac{Y^2 \sin^2 \vartheta}{2(1-X)} \right)^2 + Y^2 \cos^2 \vartheta \right]^{1/2}}$$

$$X = \frac{\omega_P^2}{\omega^2} \qquad Y = \frac{\omega_b}{\omega}$$

Haselgrove equations (Simplified)

$$\frac{d\,x_i}{d\,t} = \frac{c^2\,k_i}{\omega} \qquad \frac{d\,k_i}{d\,t} = -\frac{\omega_P}{\omega}\frac{\partial\,\omega_P}{\partial\,x_i}$$

Bias

Range error

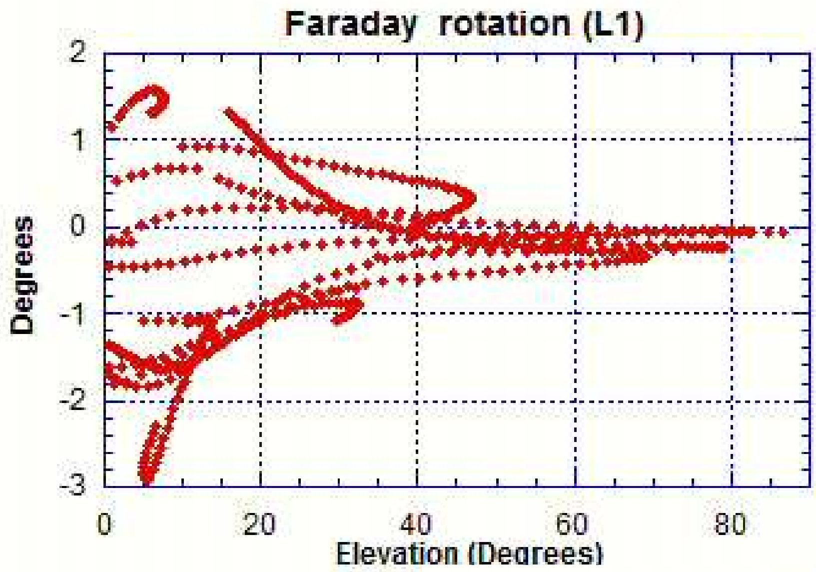
$$\Delta L = \frac{\lambda^2 r_e}{2\pi} N_T \qquad N_T = \int_0^z N_e \, ds \qquad \Delta L = \frac{40.3 N_T}{f^2}$$

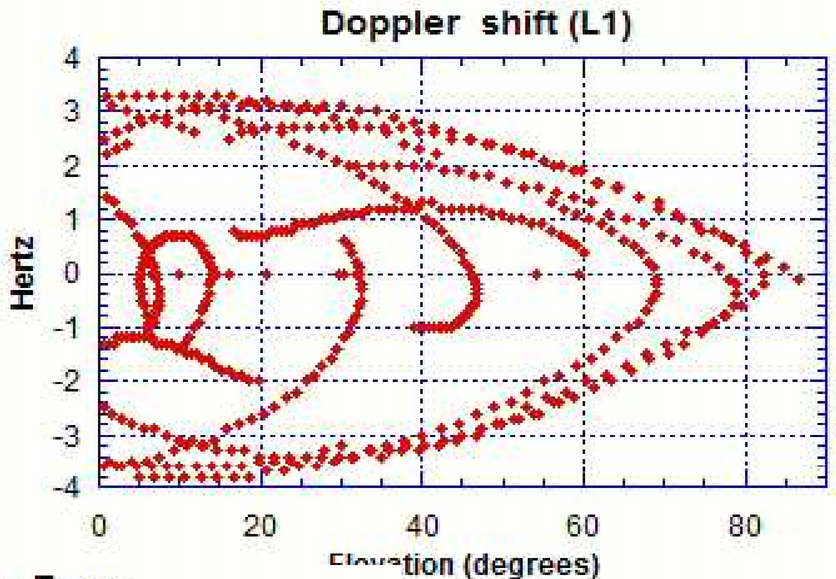
Faraday rotation

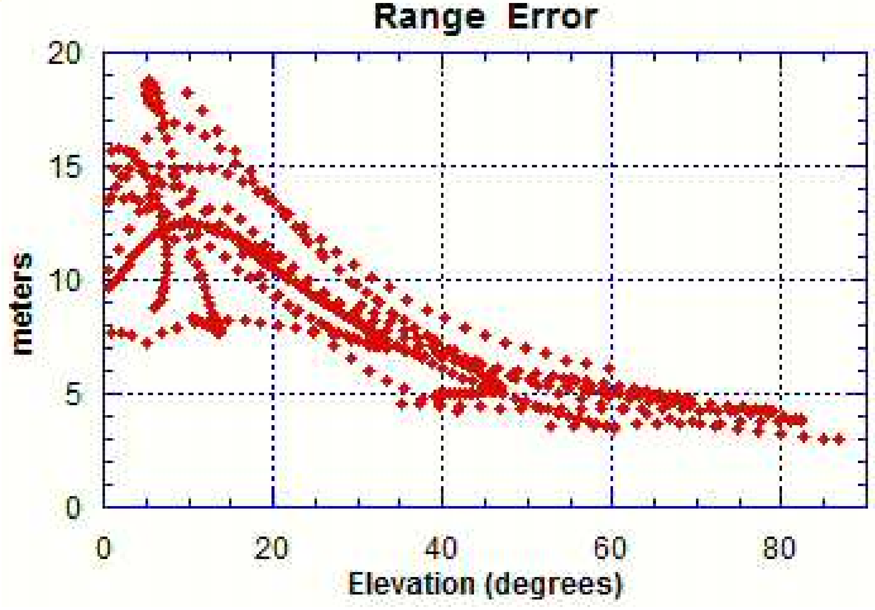
$$\Psi = \frac{e^3}{2\varepsilon_0 c \, m^2 \omega^2} \int_0^z N_e \, B \cos\vartheta \, ds$$

Inputs : Ne ; B at any point inside ionosphere

Example of results / Solar Flux 150

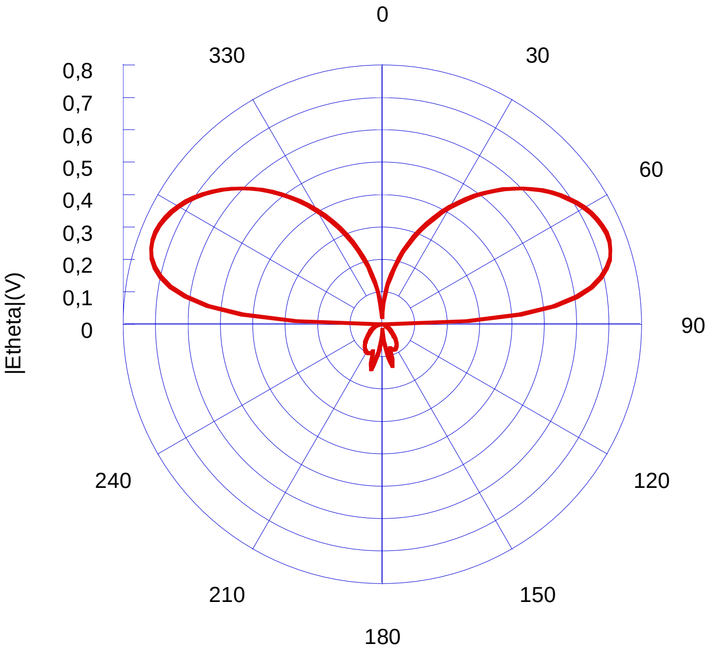


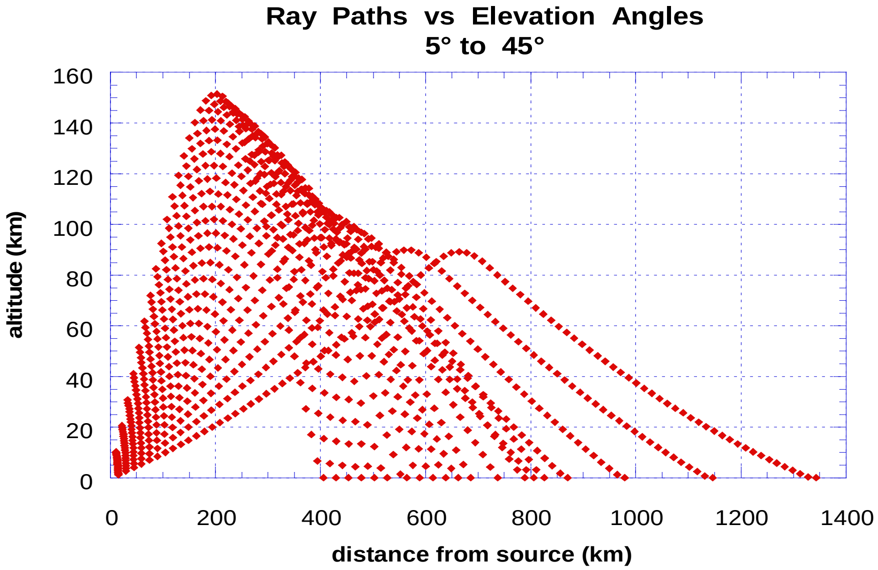




HF Ground to Ground Propagation (Sky Wave)

$$\frac{d\,x_i}{d\,t} = \frac{c^2\,k_i}{\omega} \qquad \frac{d\,k_i}{d\,t} = -\frac{\omega_p}{\omega}\,\frac{\partial\,\omega_p}{\partial\,x_i}$$

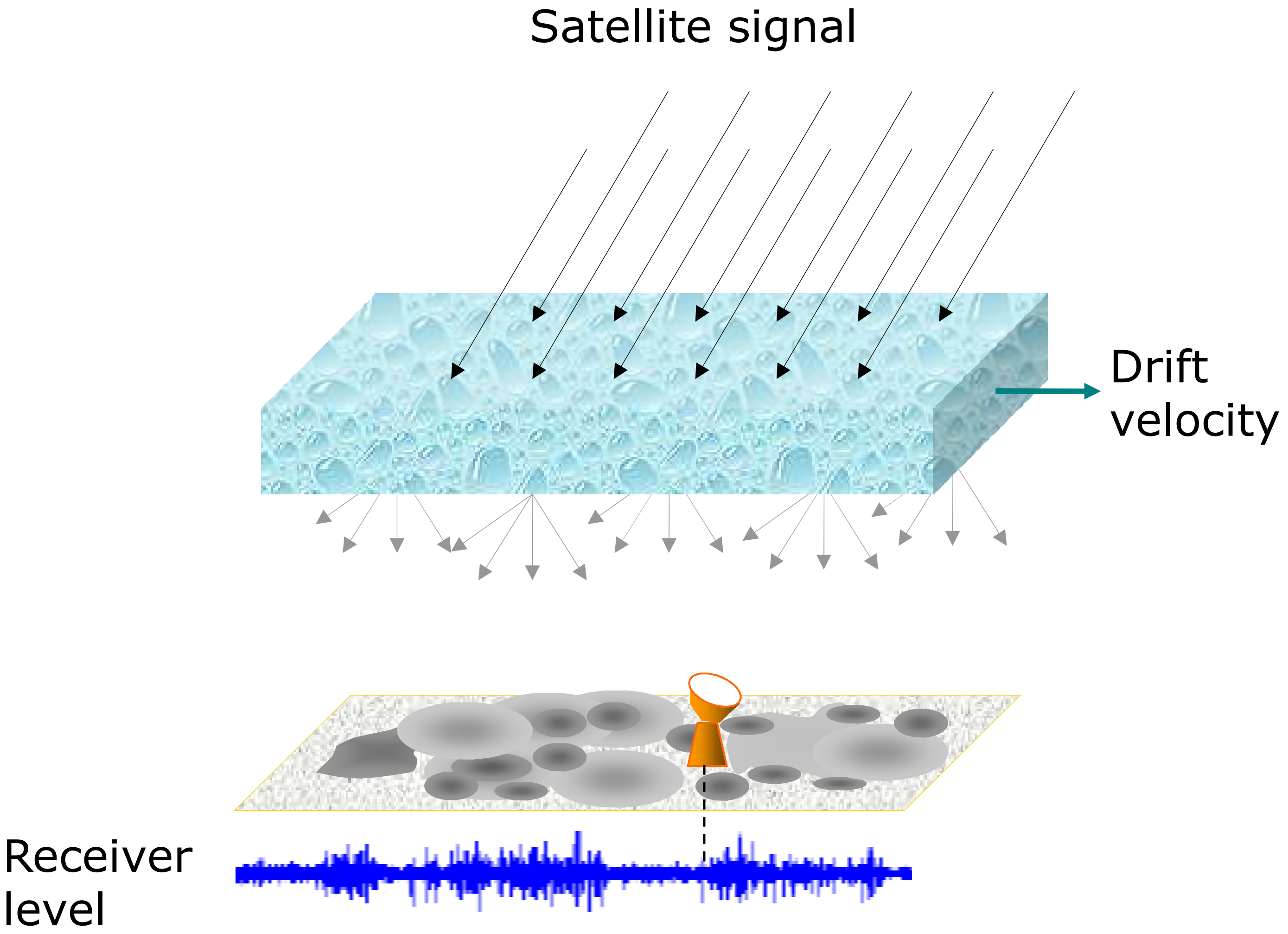




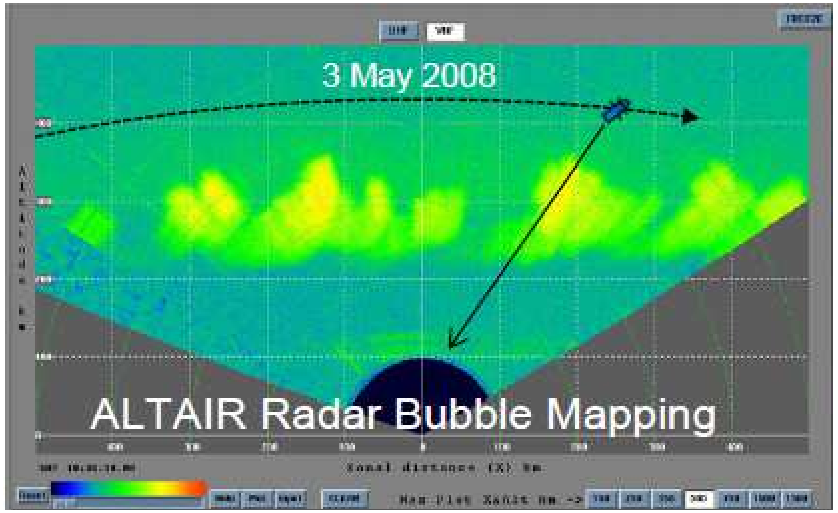
HF Antenna Pattern as an input

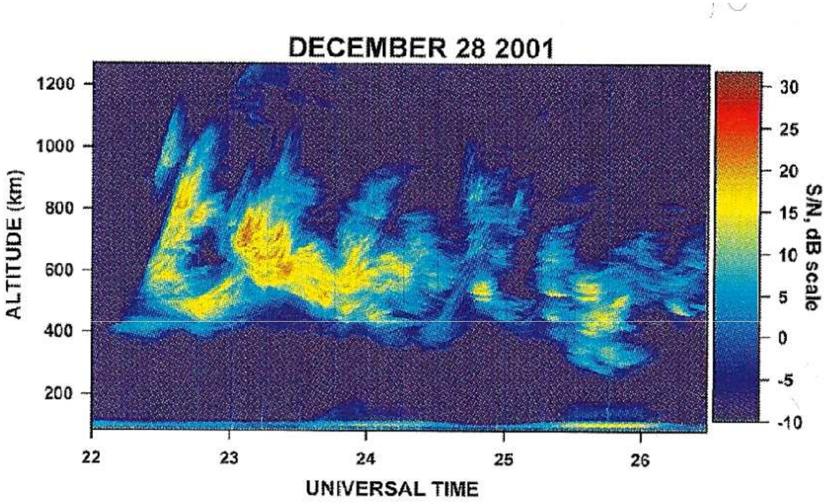
Turbulent Ionosphere (scintillation)

Physical Mechanism



Medium Radar Observations



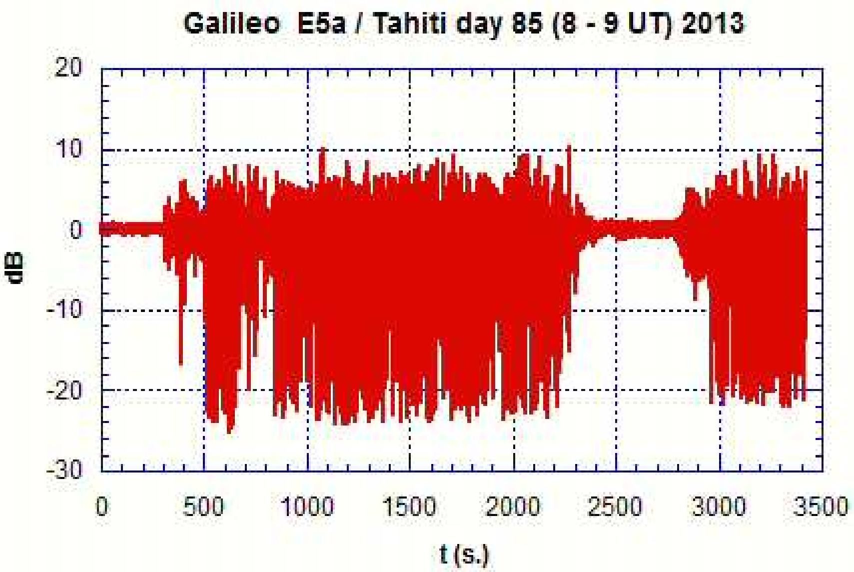


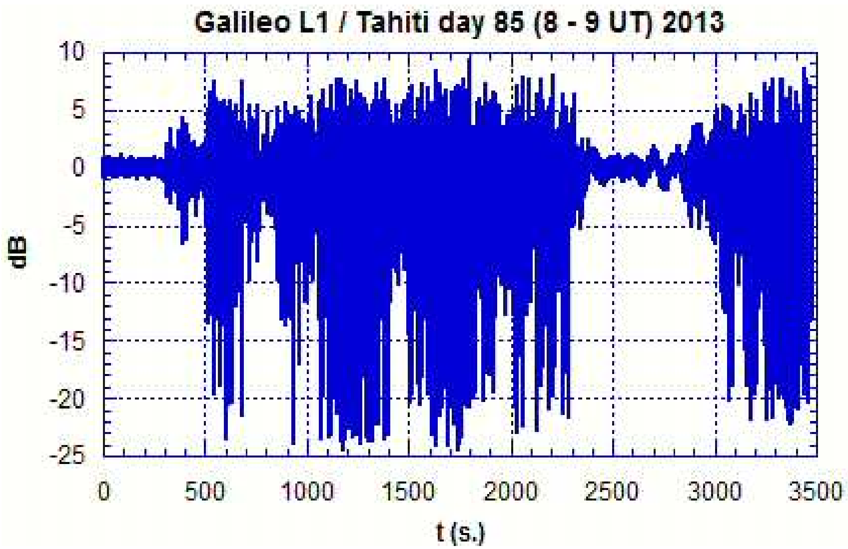
Observations at Kwajalen Islands
Courtesy K. Groves, AFRL

Observations in Brazil
Courtesy E. de Paula, INPE

The vertical extent may reach hundreds of kilometers

Scintillation on Galileo Satellites L1 vs E5a





Field Propagation Equation

$$E(\rho, z, \omega, t) = U(\rho, z, \omega) \exp\left\{ j\left(\omega t - \int \left\langle k(z') \right\rangle dz' \right) \right\}$$

The field amplitude value U is a solution of the the parabolic equation

$$2jk \frac{\partial U(\rho)}{\partial z} + \nabla_t^2 U(\rho) + k^2 \varepsilon_1(\rho)\ U(\rho) = 0$$

Method of solution : phase screen technique

Field Propagation Equation

Solution of the parabolic equation

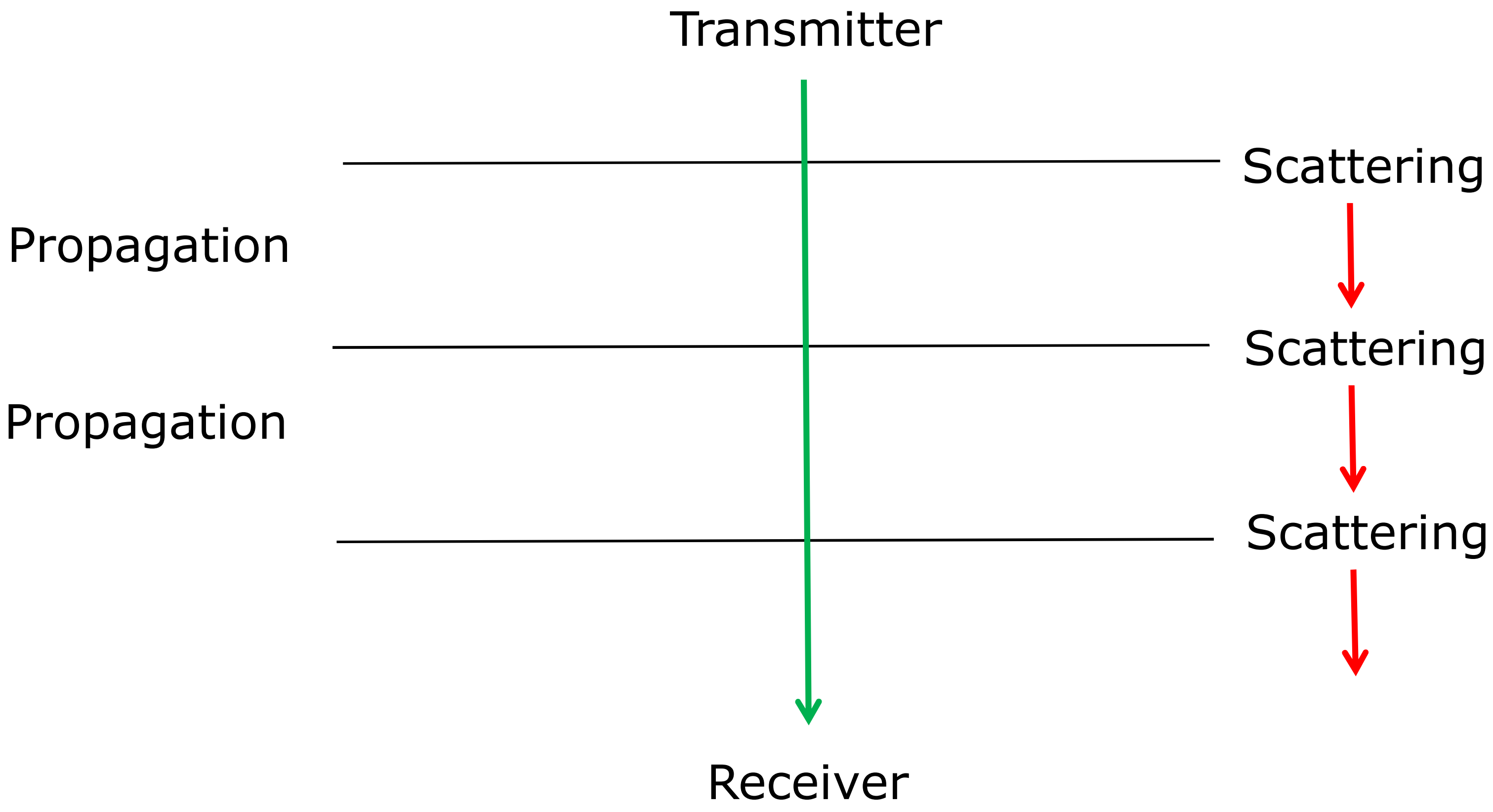
$$2jk\frac{\partial}{\partial z}\langle U(r)\rangle + \nabla_t^2\langle U(r)\rangle + k^2\langle \varepsilon(r)\; U(r)\rangle = 0$$

$$2jk\frac{\partial}{\partial z}\langle U(r)\rangle + \nabla_t^2\langle U(r)\rangle + j\frac{k^3}{4}A(0)\langle U(r)\rangle = 0$$

Using the phase index autocorrelation function

$$B(z,\rho) = \langle \varepsilon(\rho_1)\;\varepsilon(\rho_2)\rangle \qquad A(\rho) = \int B(z,\rho)\, dz$$

Phase Screen Technique



Transmitter

Scattering

Propagation

Scattering

Propagation

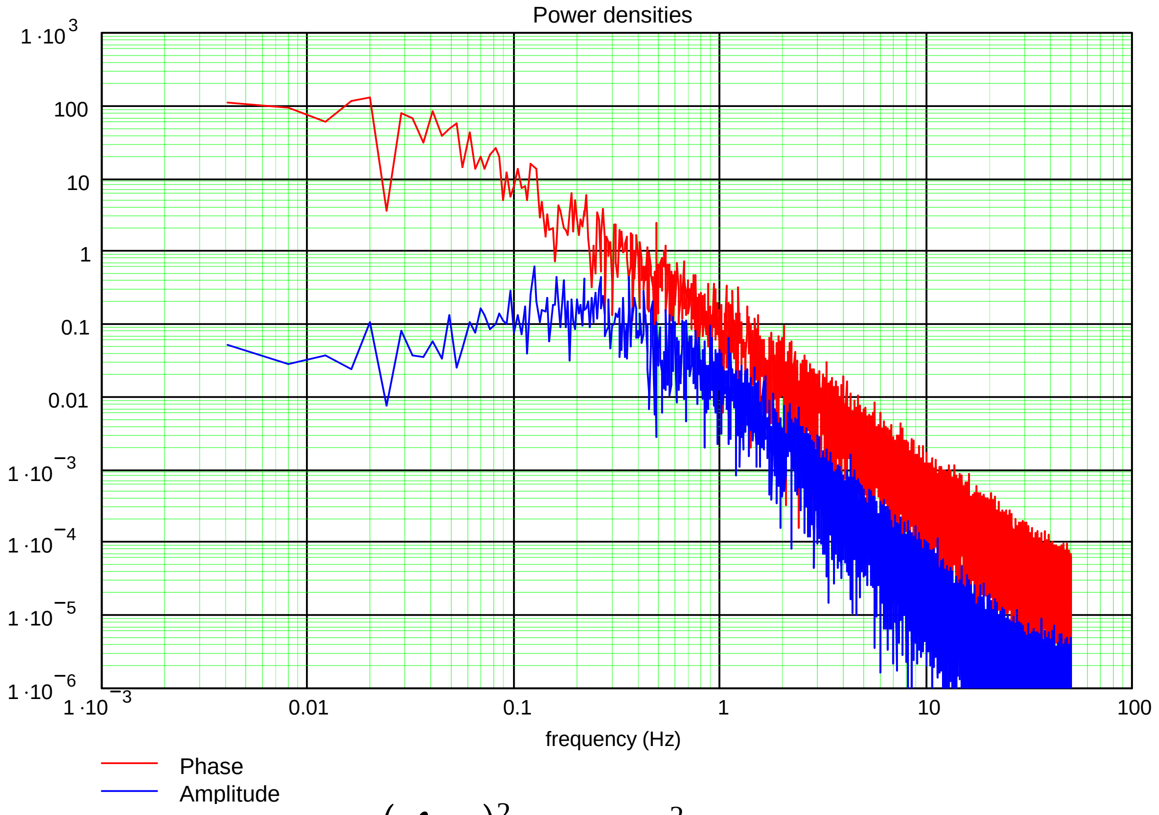
Scattering

Receiver

Propagation : 1st & 3rd terms ; scattering : 2^{nd} & 3rd terms

Medium Characterization Index Spectral Density

Medium’s Phase Spectrum

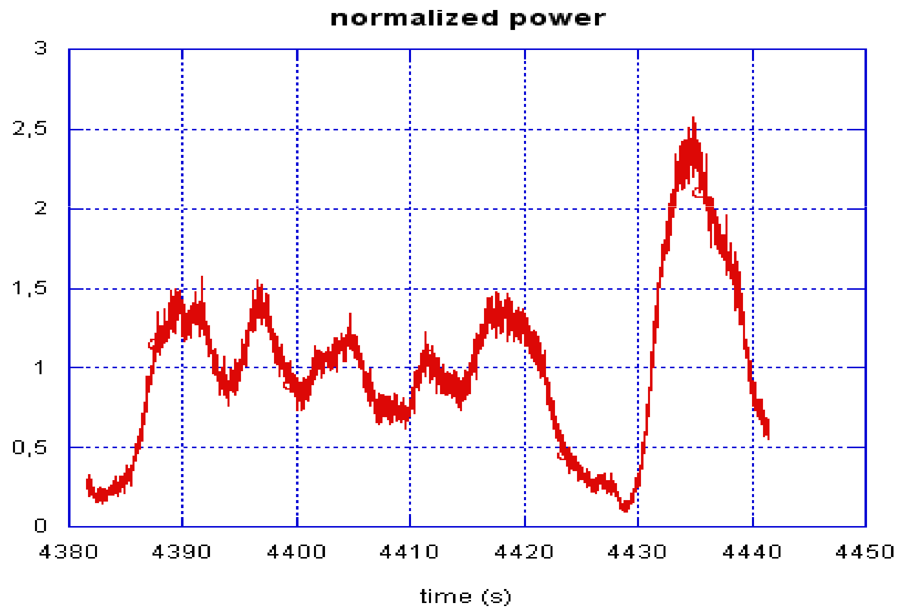


$$\gamma_{\Phi}(K) = \frac{(\lambda r_e)^2 L\, C_S\, \sigma_{Ne}^2}{\left(K^2 + q_0^2\right)^{p/2}} = \frac{C_P}{\left(K^2 + q_0^2\right)^{p/2}}$$

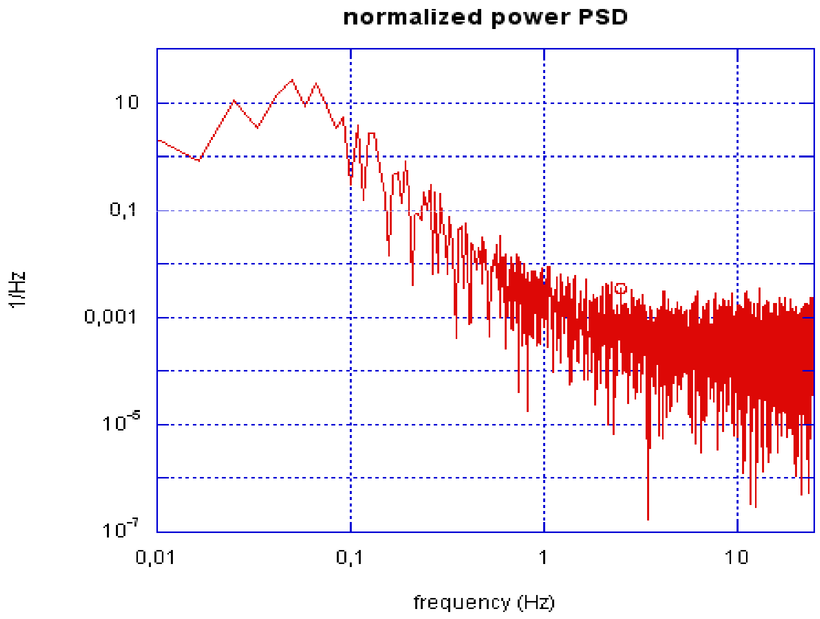
3 parameters : σ_{Ne} ; q_0 ; p

One Sample : Intensity

Sample characteristics : S4 = 0.51, sigma phi = 0.11



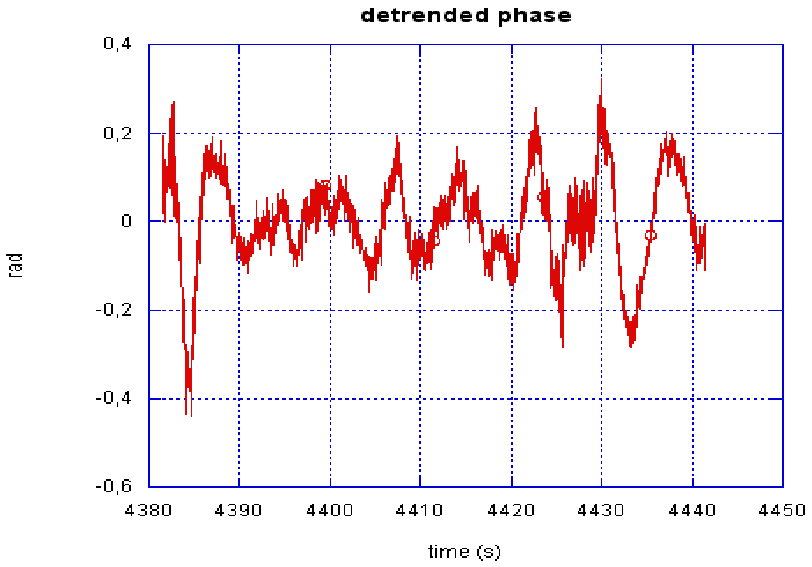
normalized power

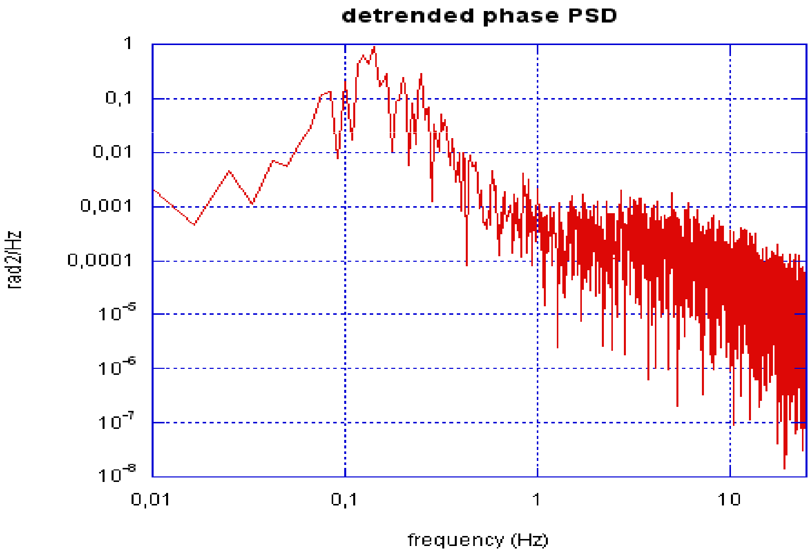


normalized power PSD

One Sample : Phase

Sample characteristics : S4 = 0.51, sigma phi = 0.11



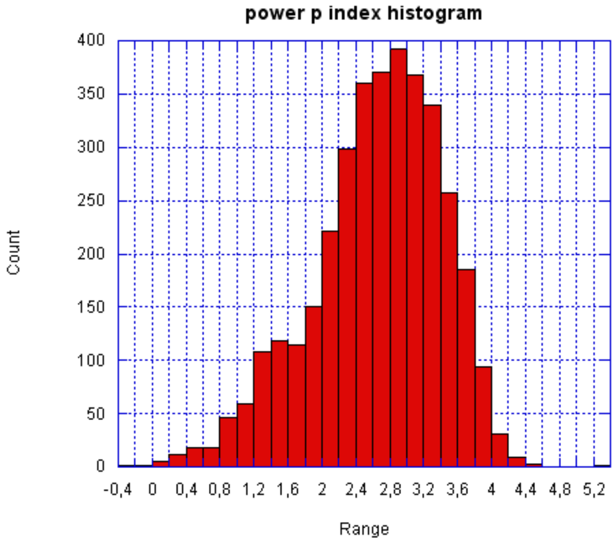


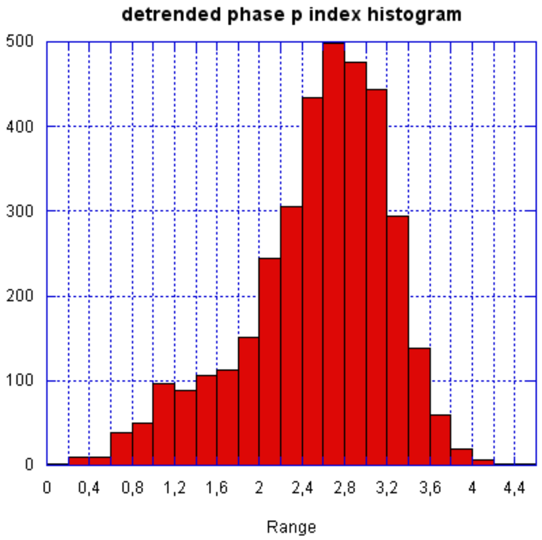
Spectrum Parameters

5 days RINEX files considered in the analysis

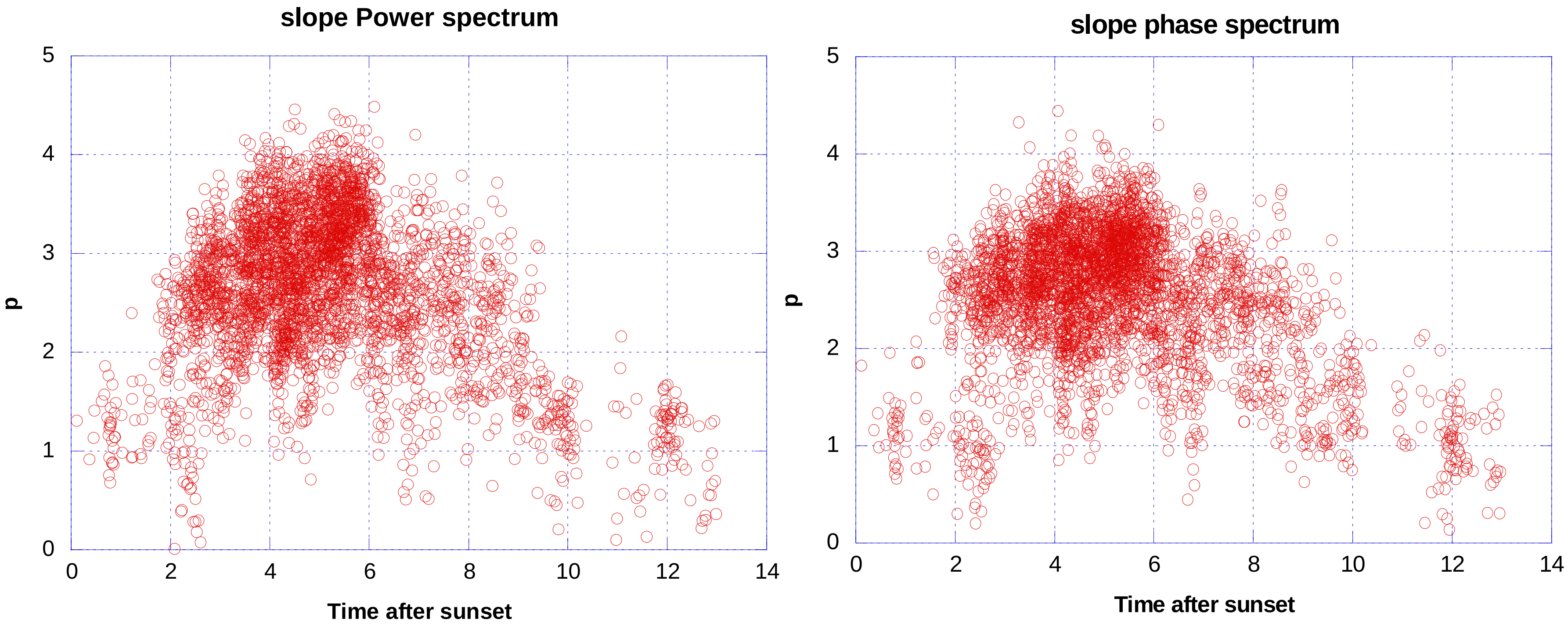
S4 > 0.2 & sigma phi < 2 (filter convergence)

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





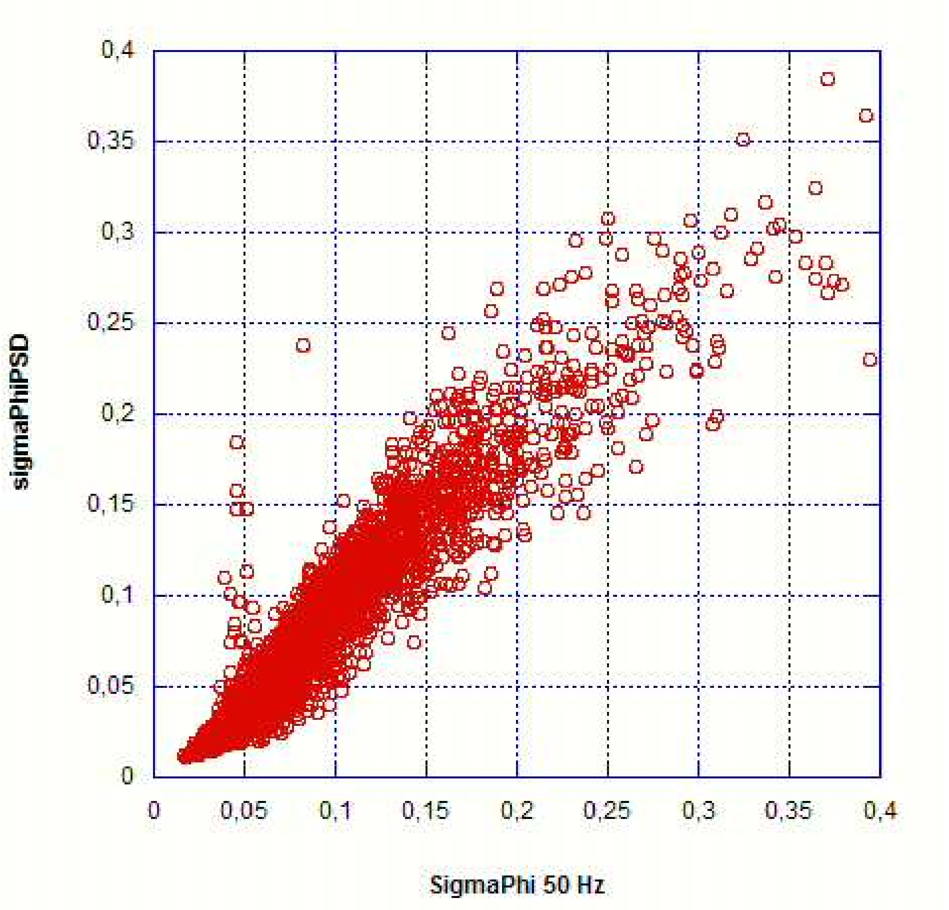
Slope spectrum vs time after sunset



Phase variance
Time domain vs frequency domain

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

Slope set to 2.8



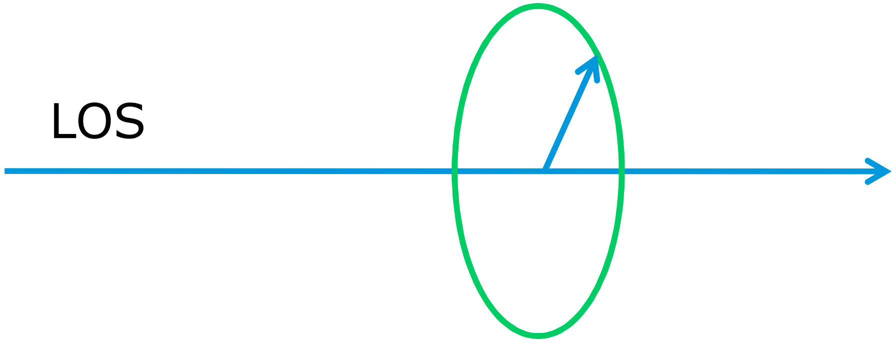
Medium Characterization (Correlation Function)

Isotropic

1D

Anisotropic

2D Analysis : Isotropic Medium



$$B_\Phi(\rho) = \frac{C_P}{(2\pi)^2} \iint \gamma_\Phi(K)\,\exp(-\,j\,\overline{K}.\overline{\rho})\,dK$$

$$\longrightarrow \quad \left[B_\Phi(\rho)\right]_{iso} = \frac{\sigma_\Phi^2}{2^{(p-4)\,/\,2}\;\Gamma\left((p-2)/2\right)} \left(\rho\, q_0\right)^{((p-2)/2)} \; K_{((p-2)/2)}\left(\rho\, q_0\right)$$

$$\sigma_\Phi^2 = B_\Phi(0) = \left(\lambda r_e\right)^2 \; L \; L_0 \; \sigma_{Ne}^2$$

1D Analysis
Isotropic Medium

$$B_{\Phi}(\rho) = \frac{C_P}{2\pi} \int \gamma_{\Phi}(k) \exp(-jk\rho) \, dk$$

$$\left[B_{\Phi}(\rho)\right]_{1D} = \frac{C_P}{2\pi} \frac{\sqrt{\pi}}{2^{(p-3)/2} \, \Gamma\left(p/2\right)} \, q_0^{1-p} \, \left(\rho q_0\right)^{(p-1)/2} \, K_{(p-1)/2}\left(\rho q_0\right)$$

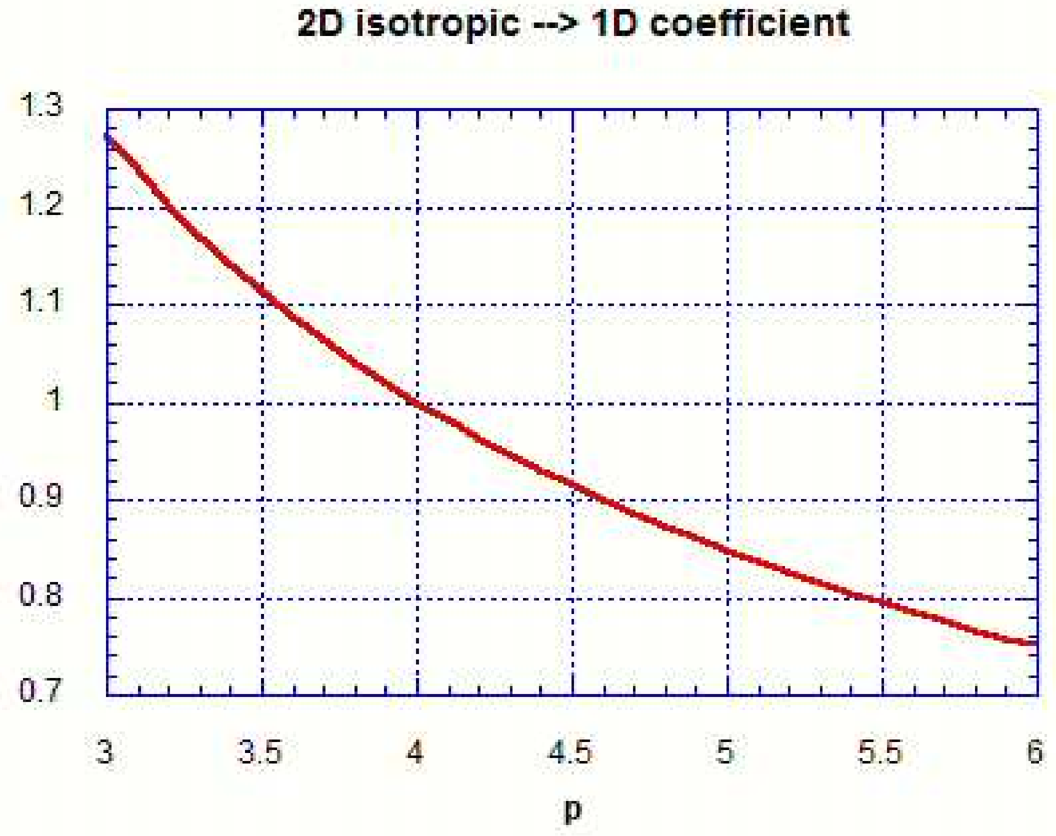
1D vs Isotropic

Slope

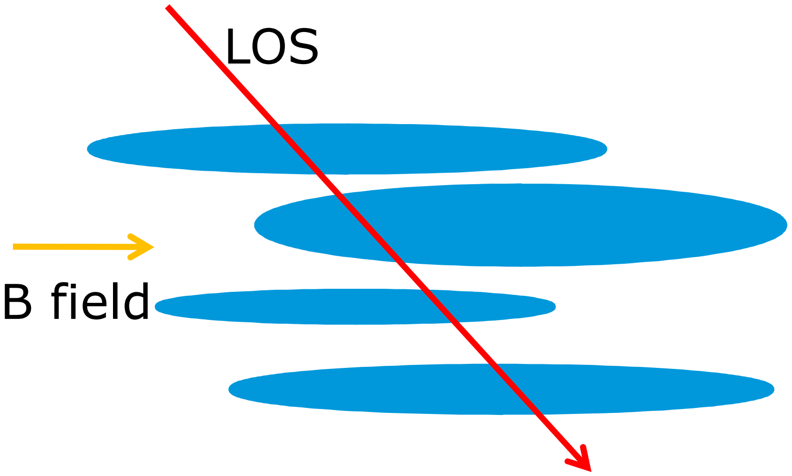
$$p \rightarrow p - 1$$

Multiplicative factor

$$\frac{2\,\Gamma\left(\left(p-1\right)/2\right)}{\sqrt{\pi}\,\Gamma\left(p/2\right)}$$



Anisotropic vs Isotropic



$$\gamma_\Phi(K) = \frac{(\lambda r_e)^2 L\, C_S\, \sigma_{Ne}^2\, a\, b}{\left(q^2 + q_0^2\right)^{p/2}}$$

$$\gamma_\Phi(K) = \frac{a\, b\, C_P}{\left(\left(A K_{x\perp}^2 + B K_{x\perp} q_{y\perp} + C K_{y\perp}^2\right)^2 + q_0^2\right)^{p/2}}$$

Additional geometric factor with respect to the 2D case $G = \frac{ab}{\left(AC - B^2/4\right)^{1/2}}$

a, b ellipses axes

A, B, C trigonometric terms resulting from rotations related to variable changes

Phase Synthesis (1D)

$$\Phi(\rho) = \mathrm{FFT}^{-1}\left(\mathrm{FFT}(u) * \gamma_{\Phi}(k)\right)$$

u random number with a uniform spectral density

Done at each successive layer

Numerical Constraints

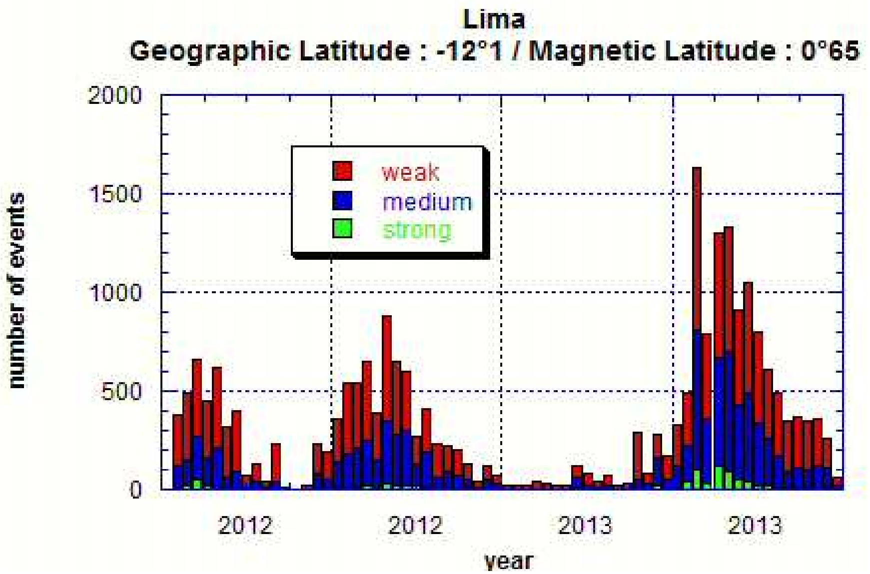
Frequency band	Medium parameters(1)	Phase variance(2) $\sigma_\Phi^2 = (\lambda r_e)^2 \Delta z \, L_0 \, \sigma_{Ne}^2$	Aliasing(3) $L > \frac{z \, \lambda \, \sigma_\Phi}{L_0 \sqrt{2}}$	Propagation $\Delta z < \frac{2 L \Delta x}{\lambda}$
P 450 MHz	$L_0 = 500 m.$ $N_e = 10^{12} el/m^3$ RMS = 20 %	$\sigma_\Phi^2 = 1.41$ $(\sigma_\Phi = 1.19)$	$L > 282$ m. $z = 3.10^5 ; \sigma_\Phi = 1$	$\Delta z < 25 km$ $L = 2500 m.$ $\Delta x = 3.3 m.$
L 1.5 GHz	$L_0 = 500 m.$ $N_e = 10^{12} el/m^3$ RMS = 20 %	$\sigma_\Phi^2 = 0.12$ $(\sigma_\Phi = 0.36)$	$L > 85$ m. $z = 3.10^5 ; \sigma_\Phi = 1$	$\Delta z < 122 km$ $L = 2500 m.$ $\Delta x = 4.88 m.$ (FFT :1024 pts)
S 2.5 GHz	$L_0 = 500 m.$ $N_e = 10^{12} el/m^3$ RMS = 20 %	$\sigma_\Phi^2 = 0.05$ $(\sigma_\Phi = 0.22)$	$L > 51$ m. $z = 3.10^5 ; \sigma_\Phi = 1$	$\Delta z < 203 km$ $L = 2500 m.$ $\Delta x = 4.88 m.$ (FFT :1024 pts)

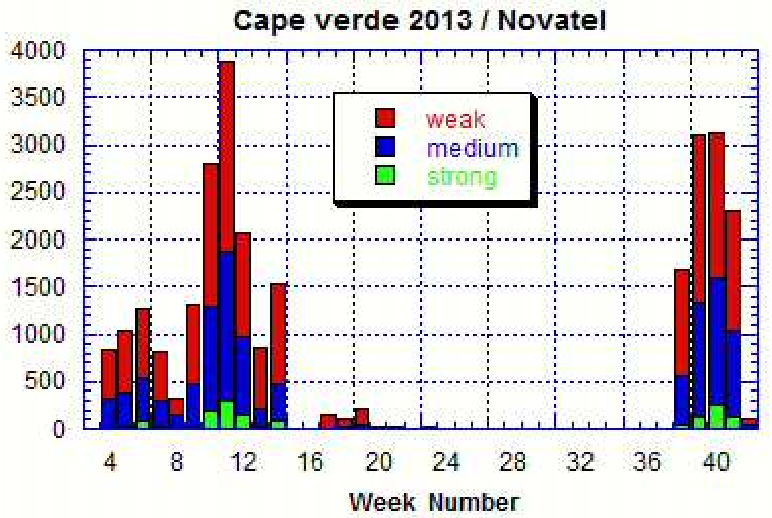
Sub Models
(1 / 2)

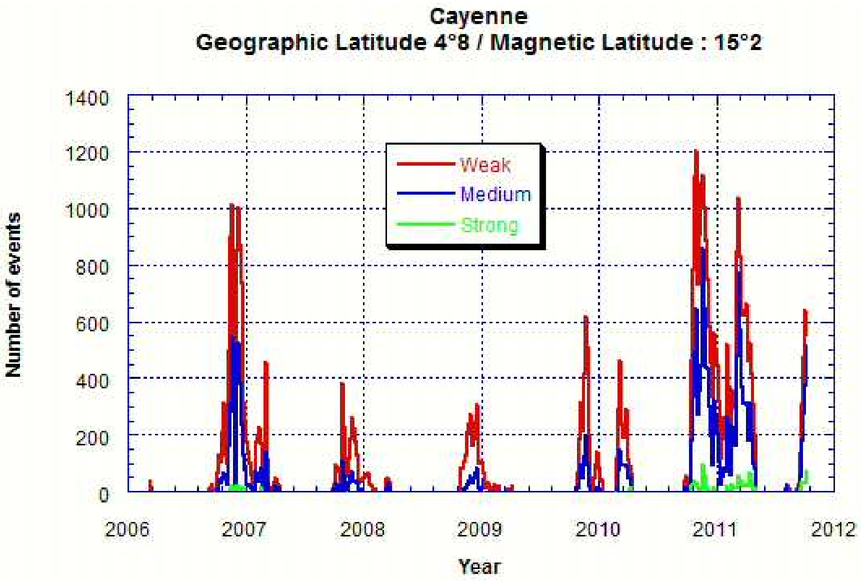
Seasonal Dependency

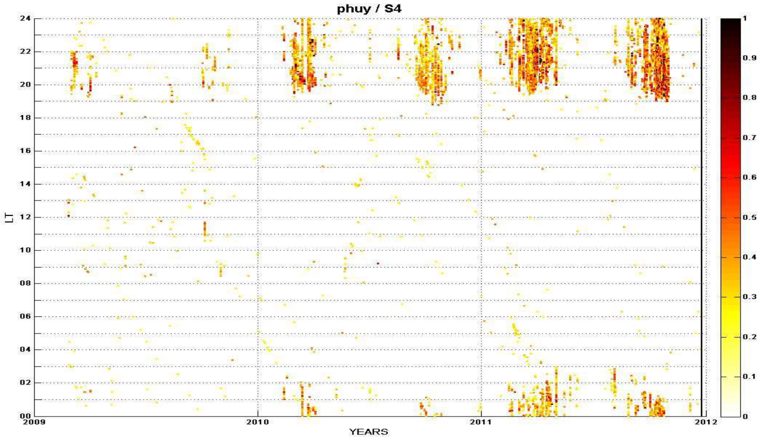
(Low Latitude Scintillations)

Scintillation Events Histograms

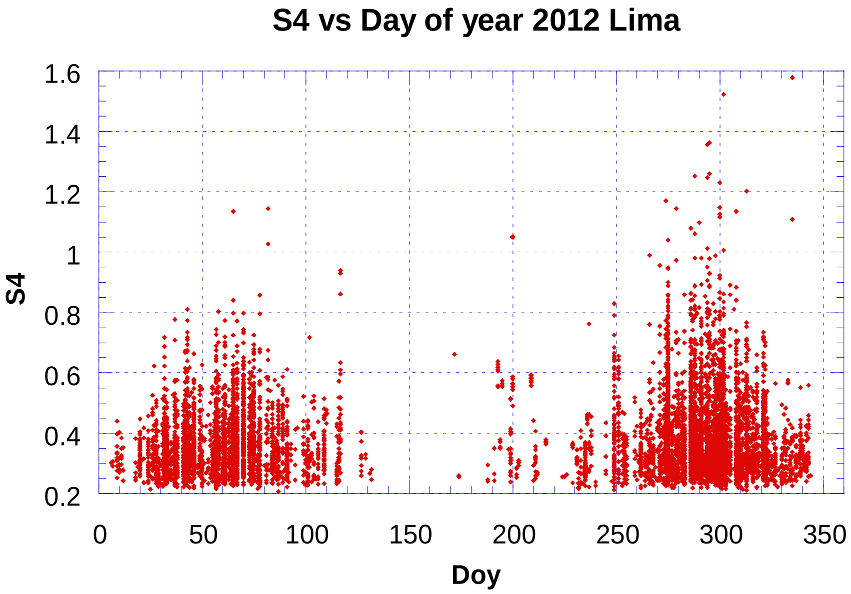

Lima
Geographic Latitude : -12°1 / Magnetic Latitude : 0°65

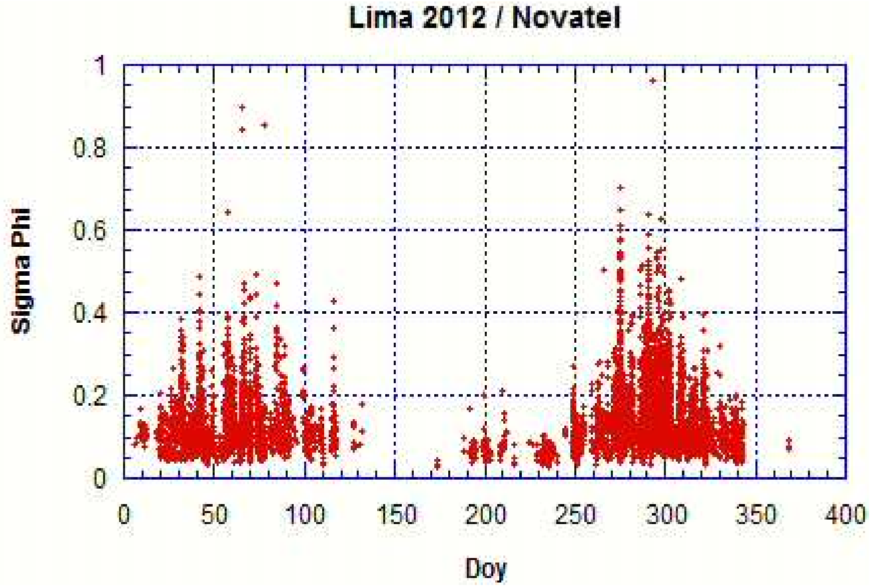

Cape verde 2013 / Novatel


Cayenne
Geographic Latitude 4°8 / Magnetic Latitude : 15°2

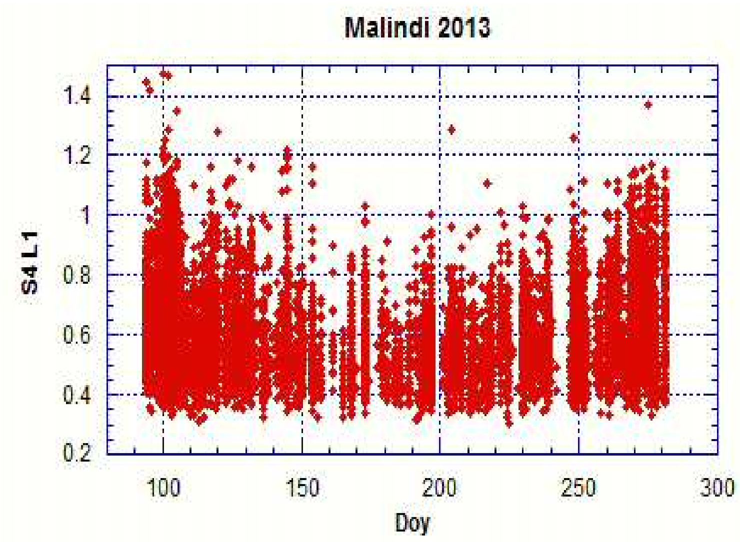

phuy / S4

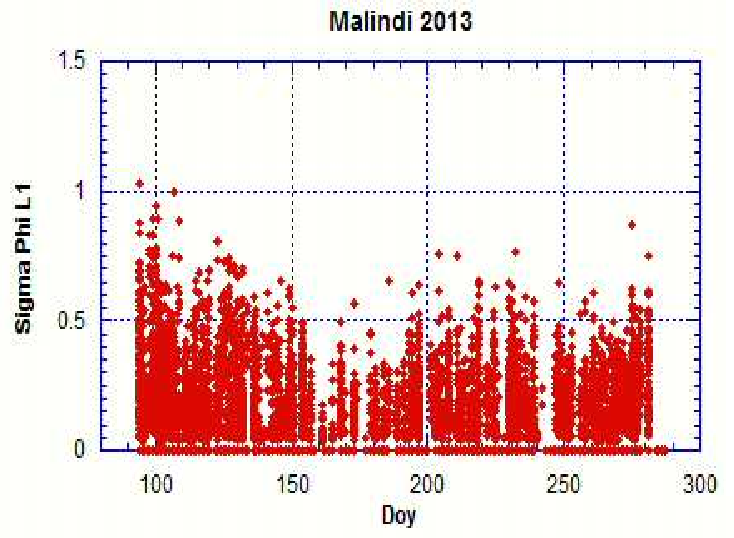
Scintillation Events / Lima 2012

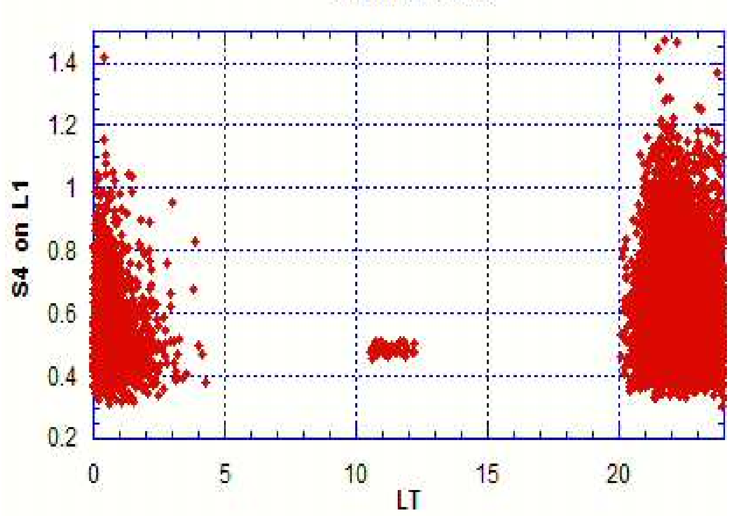

S4 vs Day of year 2012 Lima

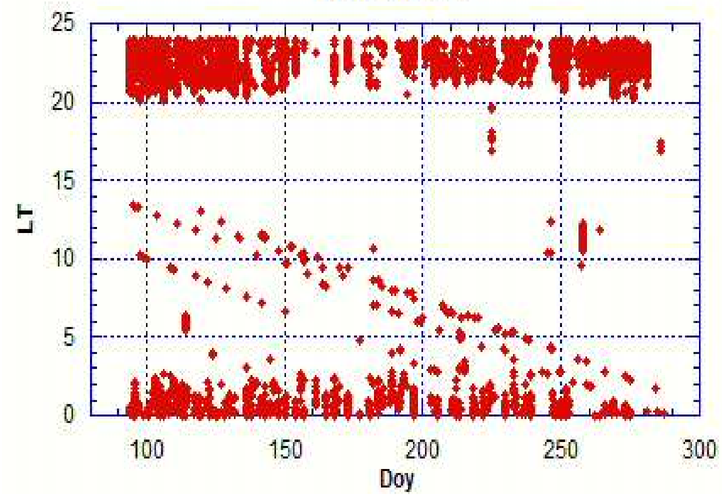

Lima 2012 / Novatel

Measurements in Malindi, Kenya

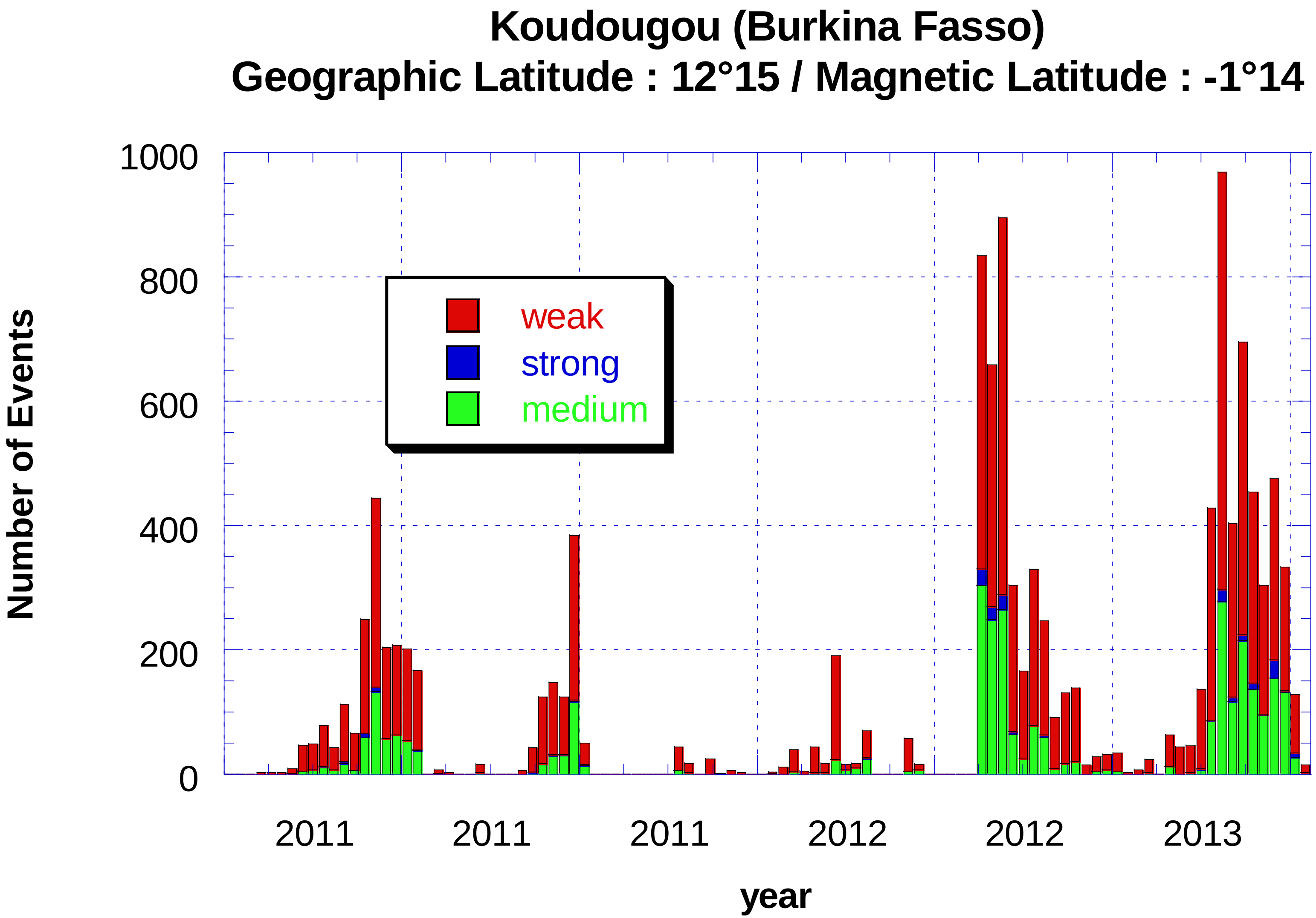








Measurements in Burkina Fasso

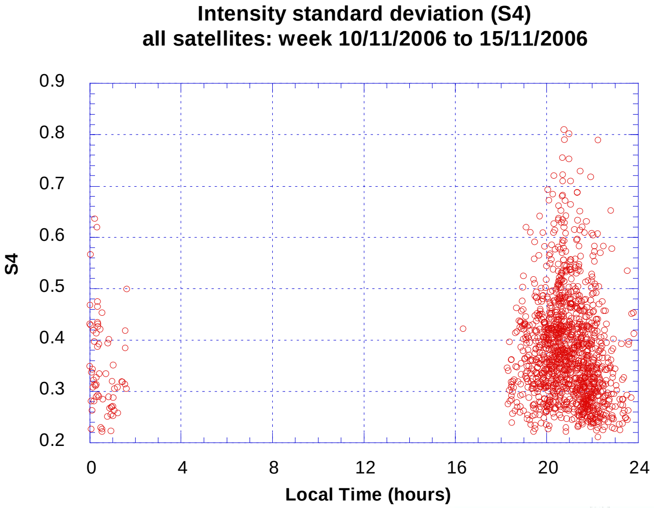


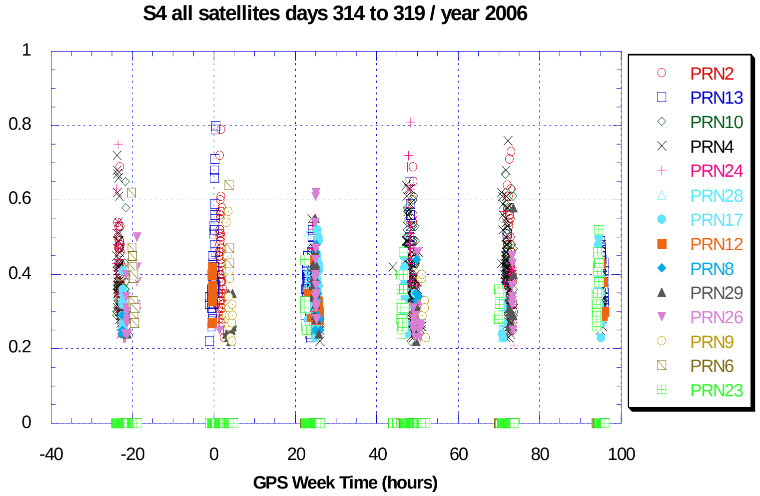
Sub Models
(2 / 2)

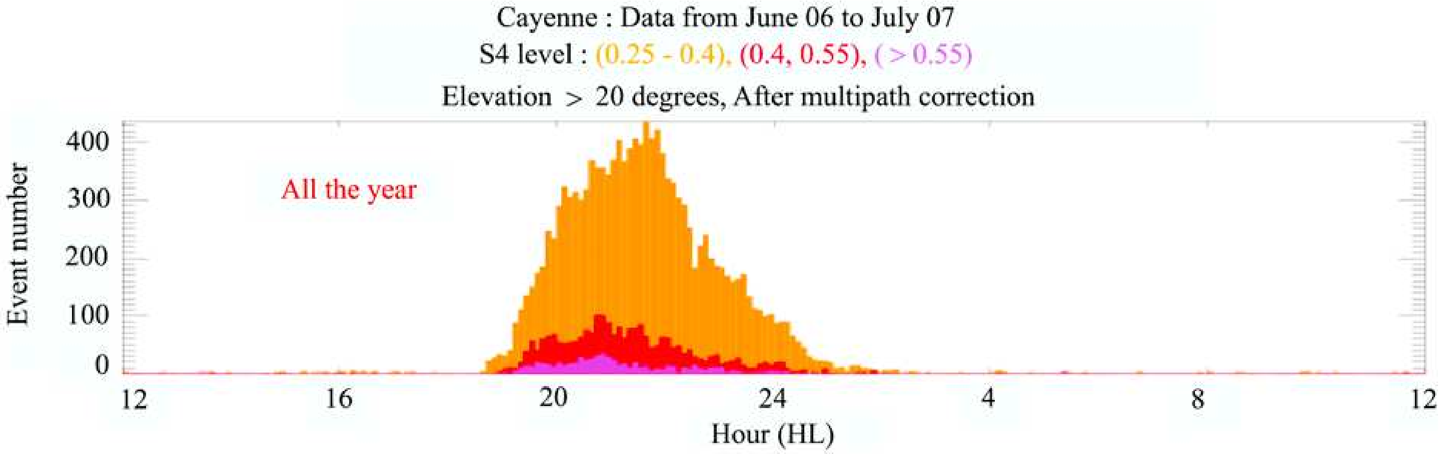
Local Time Dependency

(Low Latitude Scintillations)

One week of measurements in Guiana







Local time : post sunset hours (CLS measurements, PRIS Campaign)

Checking Results

- Indices
- Inter frequency correlation
- Probability of intensity
- Fades distribution
- Loss of Lock

Medium Characterisation

Mean Effects (Sub Models)

NeQuick, Terrestrial Magnetic Field (NOAA)

Geophysical Parameters

SSN, Medium Drift Velocity

LT & Seasonal dependency

Scintillations (Fluctuating medium)

Spectrum slope (p), BubblesRMS, OuterScale (L_0)

Anisotropy ratio

Numerical Implementation

The model includes an orbit generator (GPS, Glonass, Galileo, …)

Inputs

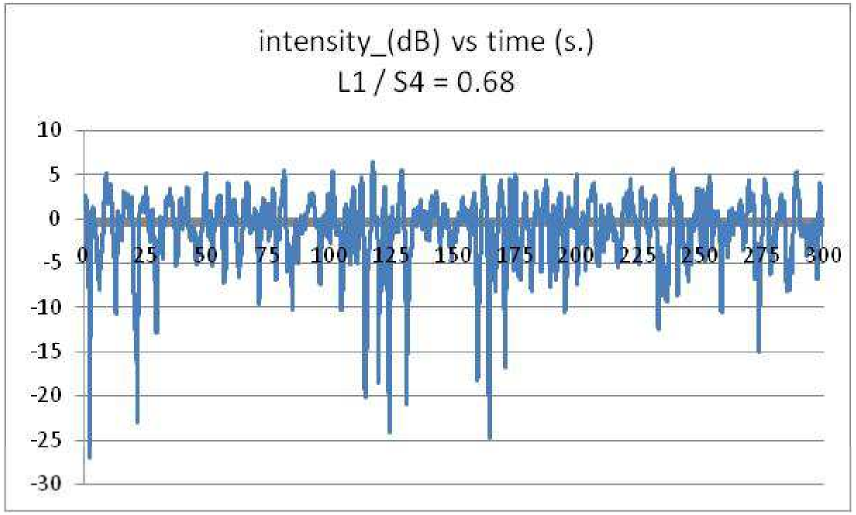
- Medium Characterisation
- Geophysical Parameters
- Scenario

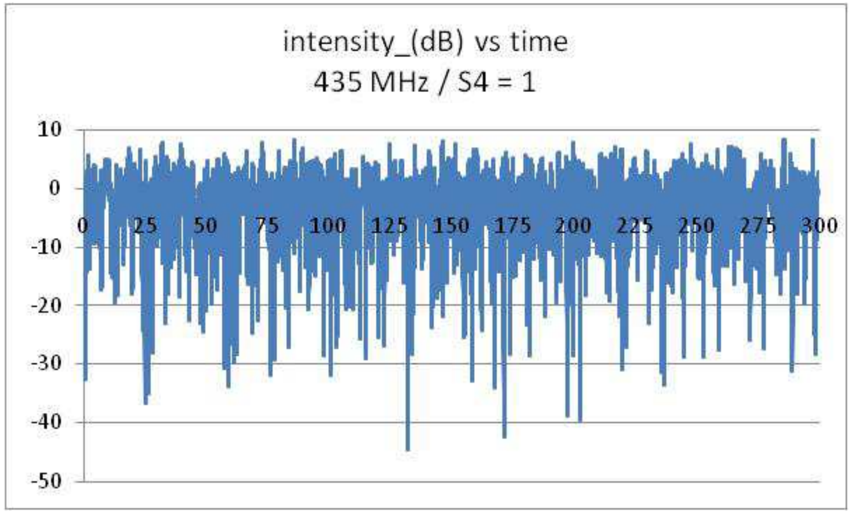
Intermediate calculation : LOS, Ionisation along the LOS

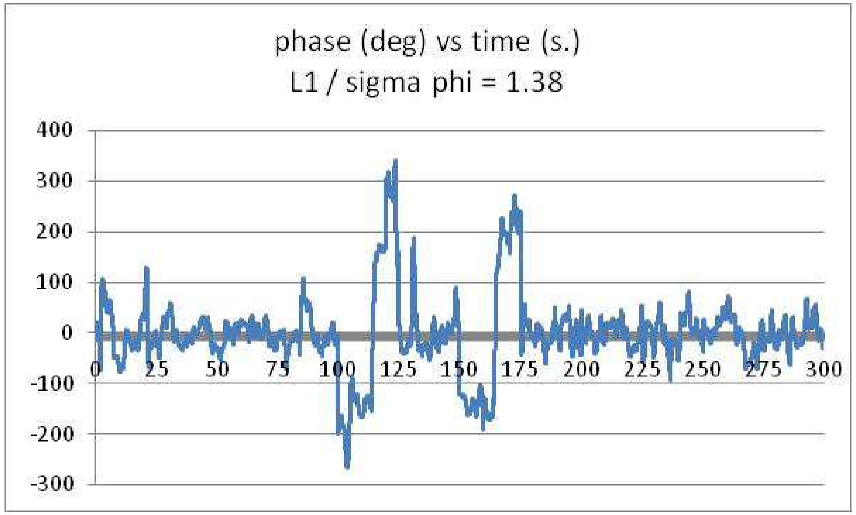
Outputs

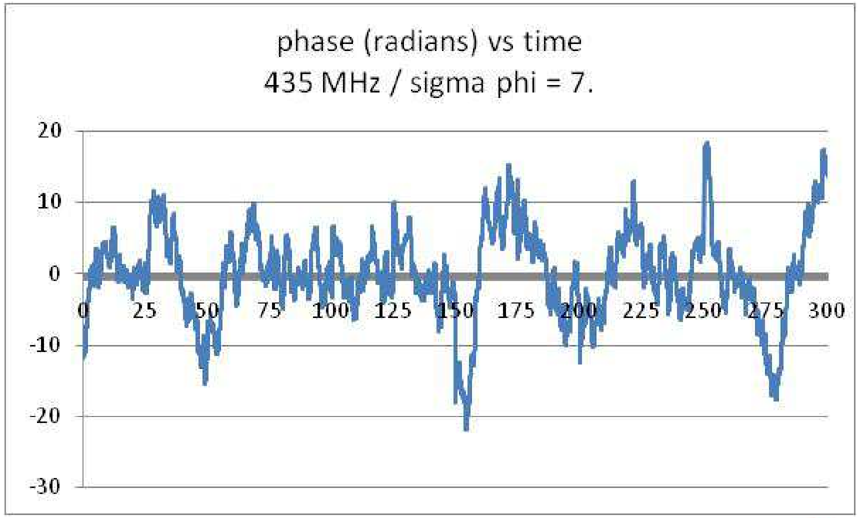
- Scintillation indices
- Correlation Distances (Time & Space)
- Scattering function

Signal at receiver level

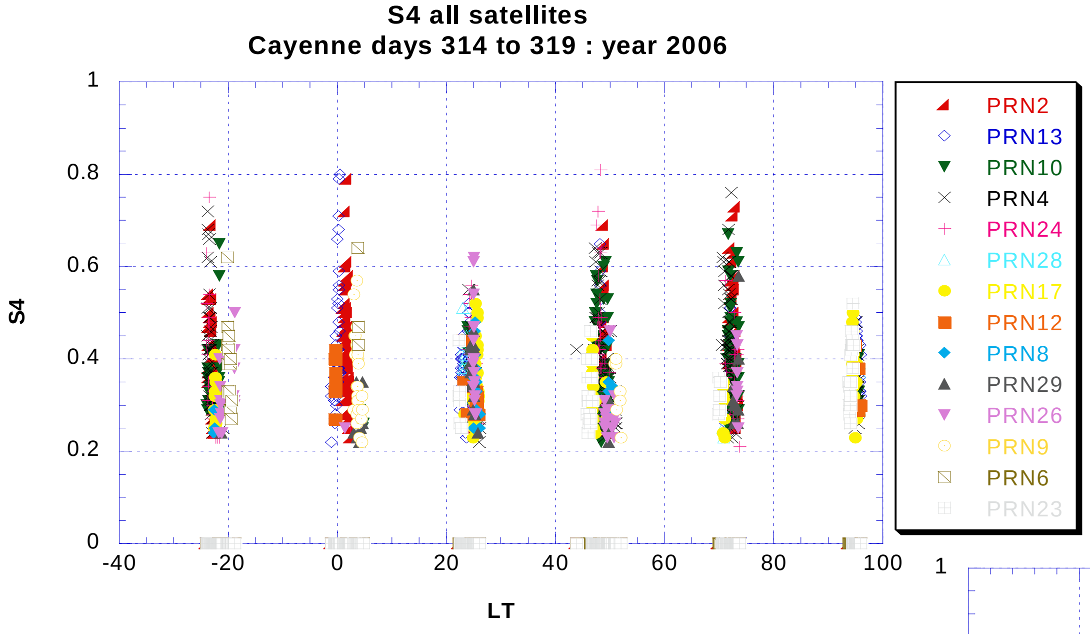

intensity_(dB) vs time (s.)
L1 / S4 = 0.68


intensity_(dB) vs time
435 MHz / S4 = 1


phase (deg) vs time (s.)
L1 / sigma phi = 1.38


phase (radians) vs time
435 MHz / sigma phi = 7.

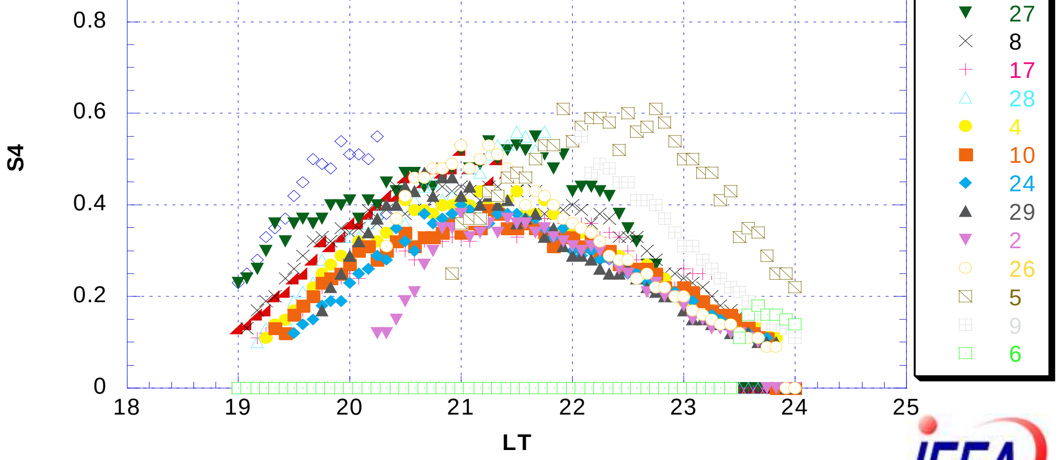
Modelling vs Measurements (Intensity)



S4 all satellites
Cayenne days 314 to 319 : year 2006

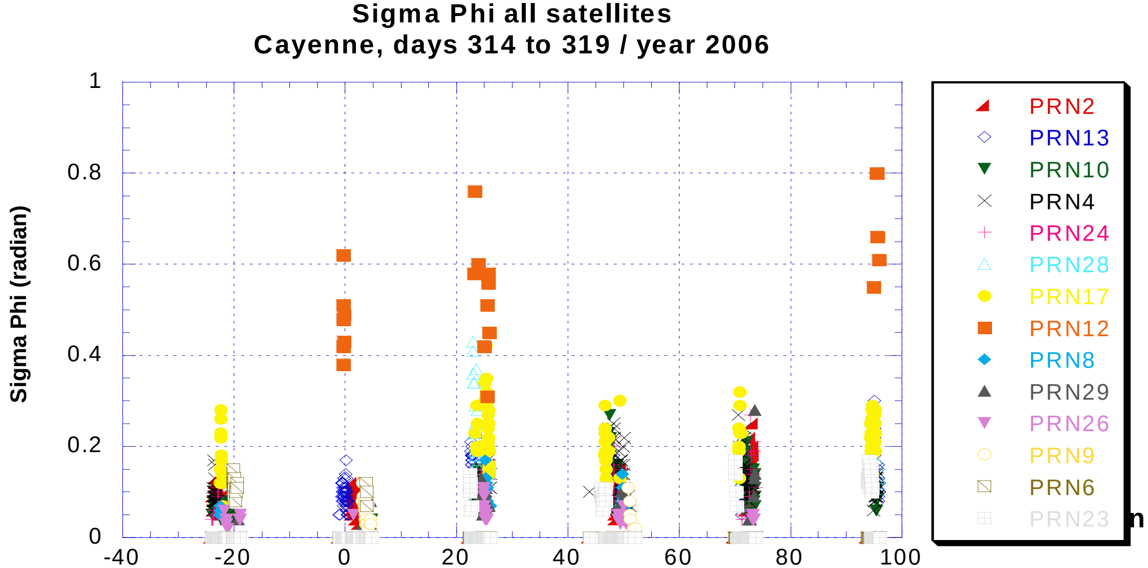
Measurements

Modelling



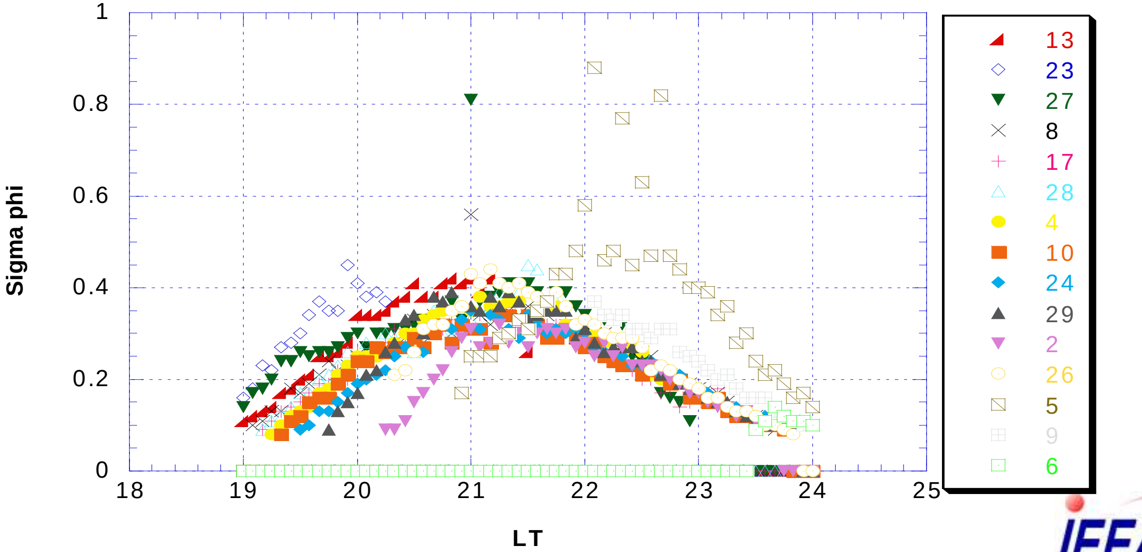
Cayenne day 314 / 2006
GISM

Modelling vs Measurements (Phase)



The phase RMS value is slightly lower than the S4 value

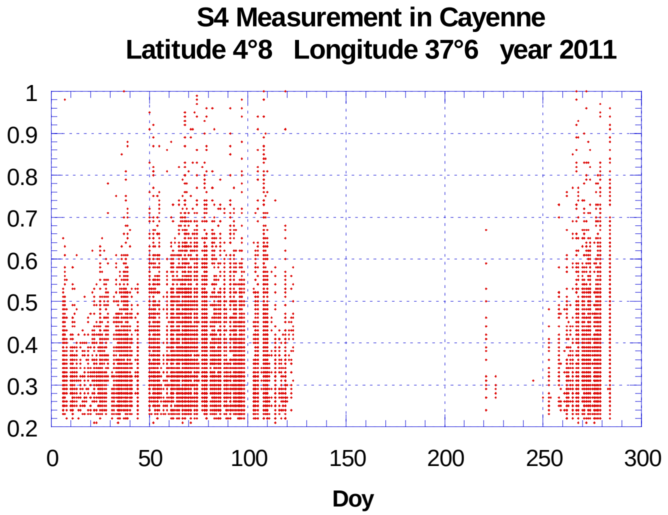
← **Measurements**



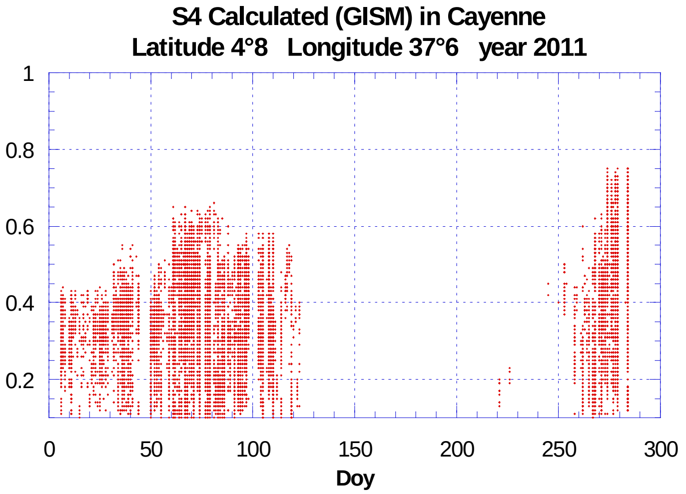
Modelling →

Some samples exhibit high values (both measurements and modelling) due to the phase jumps

Scintillation Modelling vs Measurements

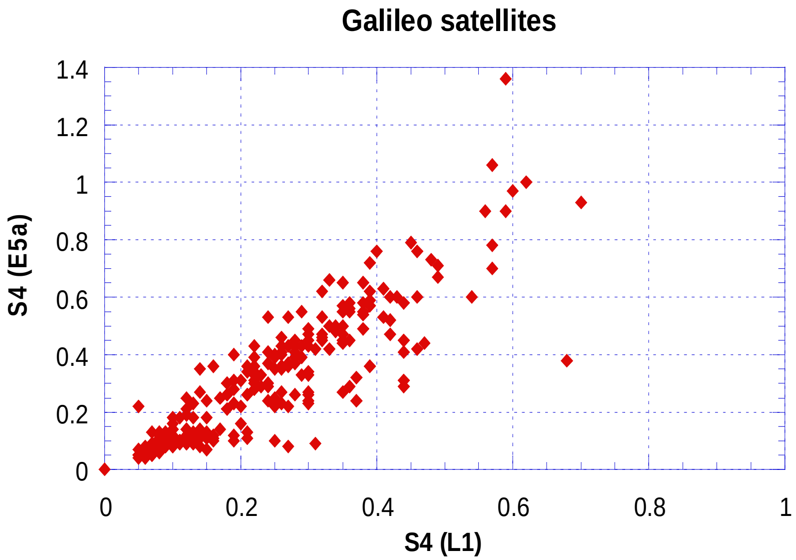


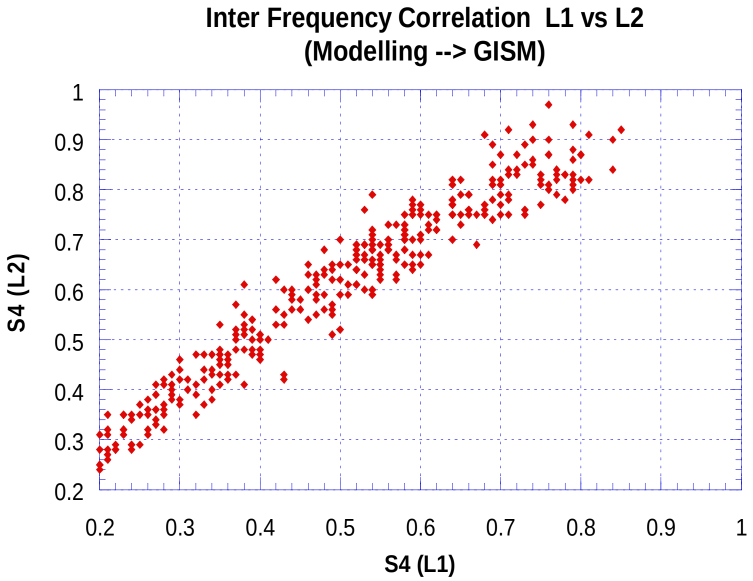
Measurements



Modelling

Scintillation Index Dependency on Frequency

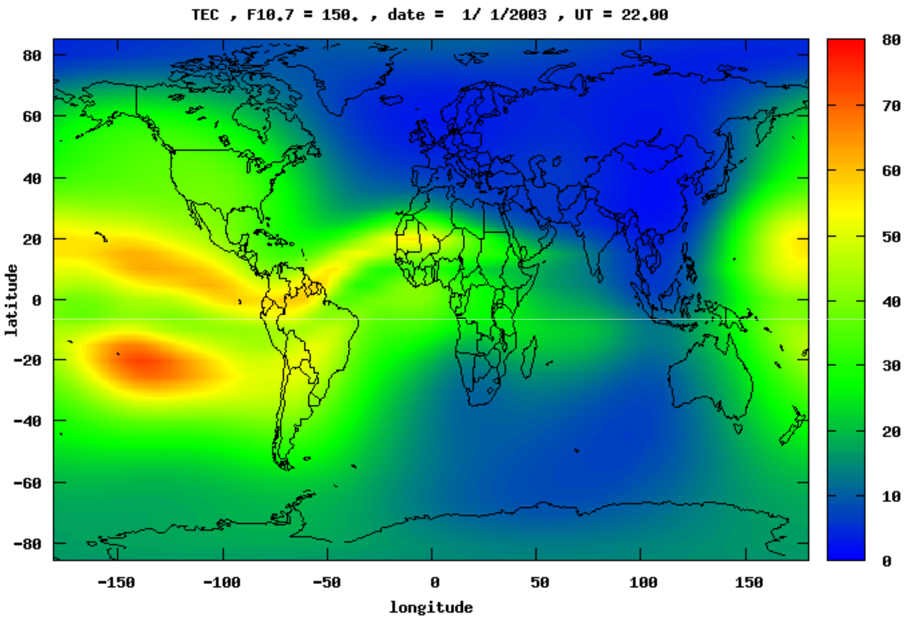




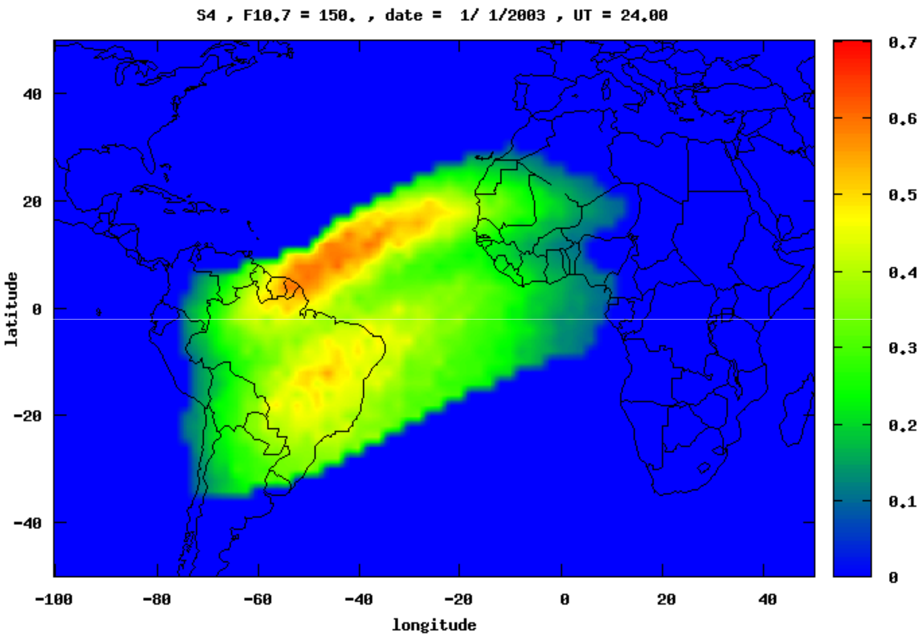
using Yuma files

IEEA

Global Maps



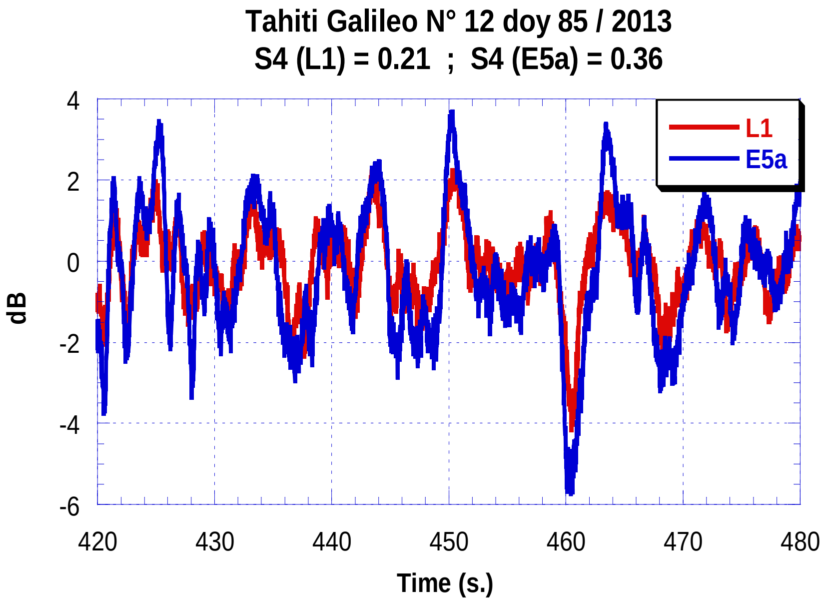
TEC Map Modelling

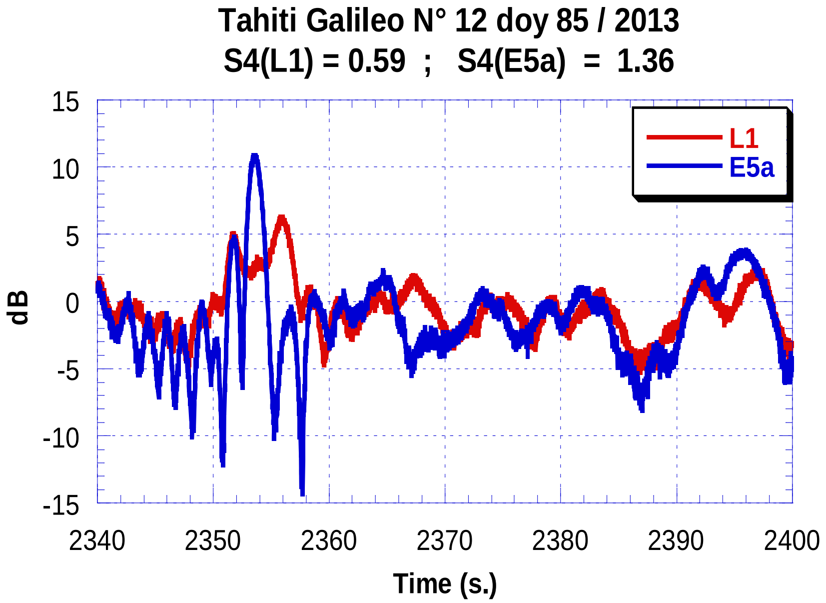


Scintillation Map Modelling

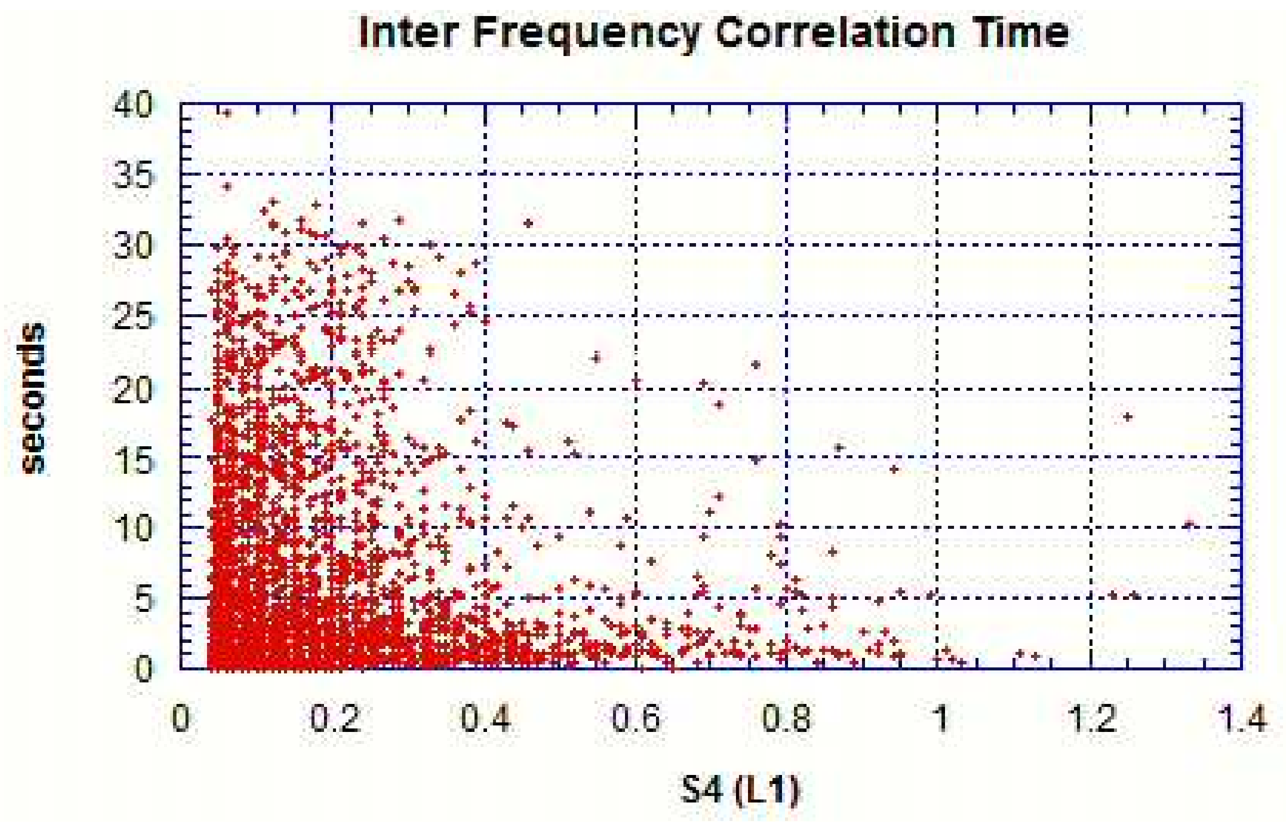
Inter Frequency Correlation

Weak scintillations vs strong scintillations

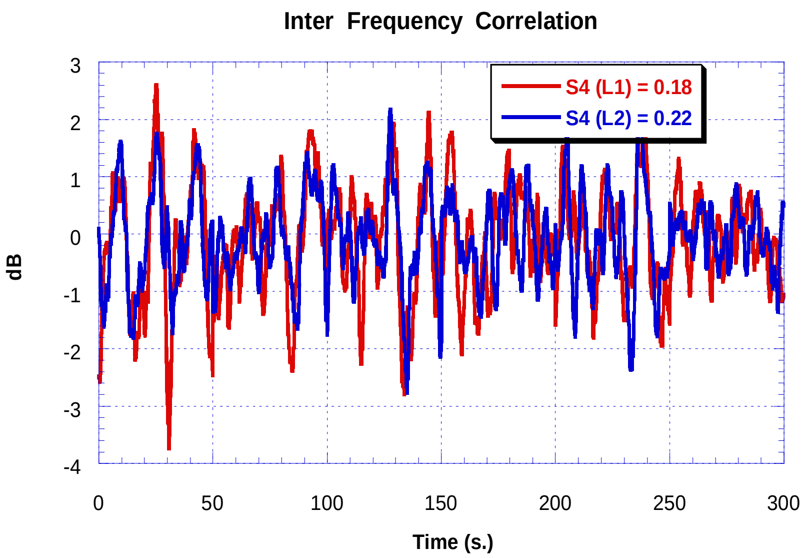


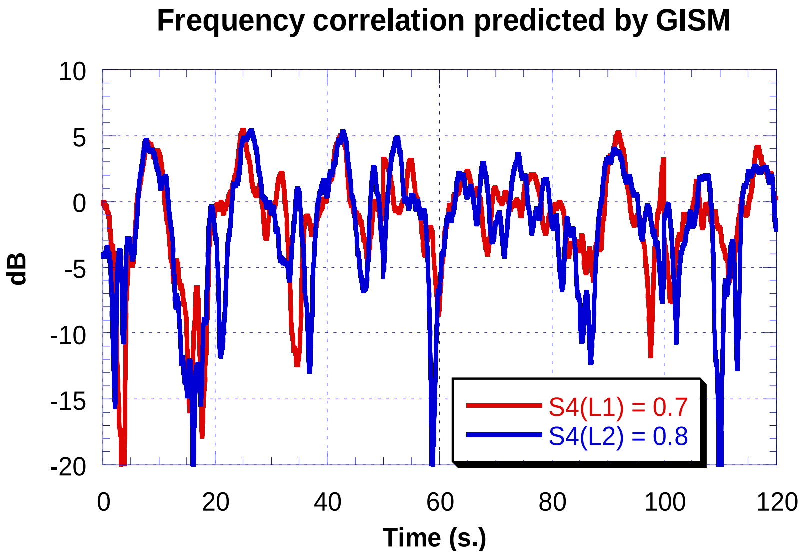


Inter Frequency Correlation Time Using 1 week of measurements in Tahiti



Frequency Correlation (Modelling)





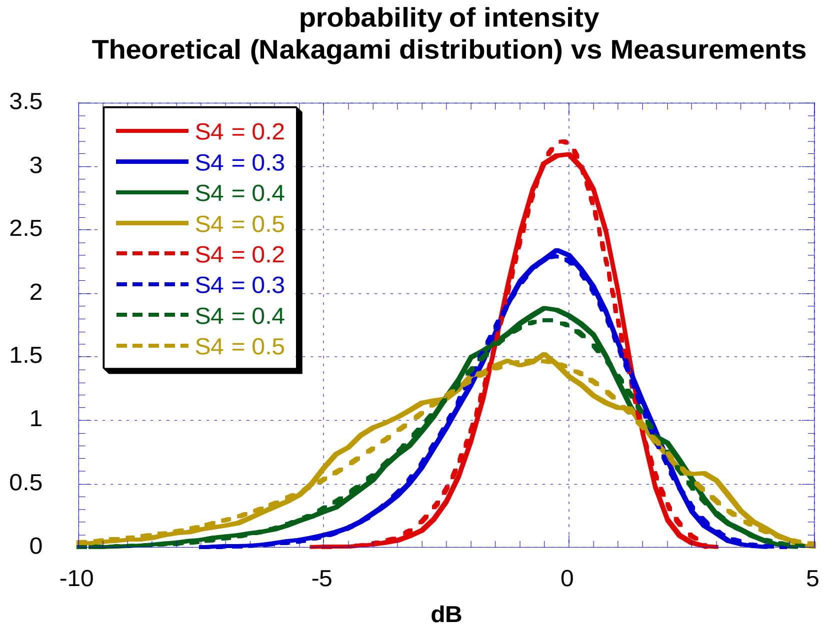
Weak scintillations

Strong scintillations

Loss of Lock

Probability of Loss of Lock

Loss of Lock when σ_ϕ > threshold value



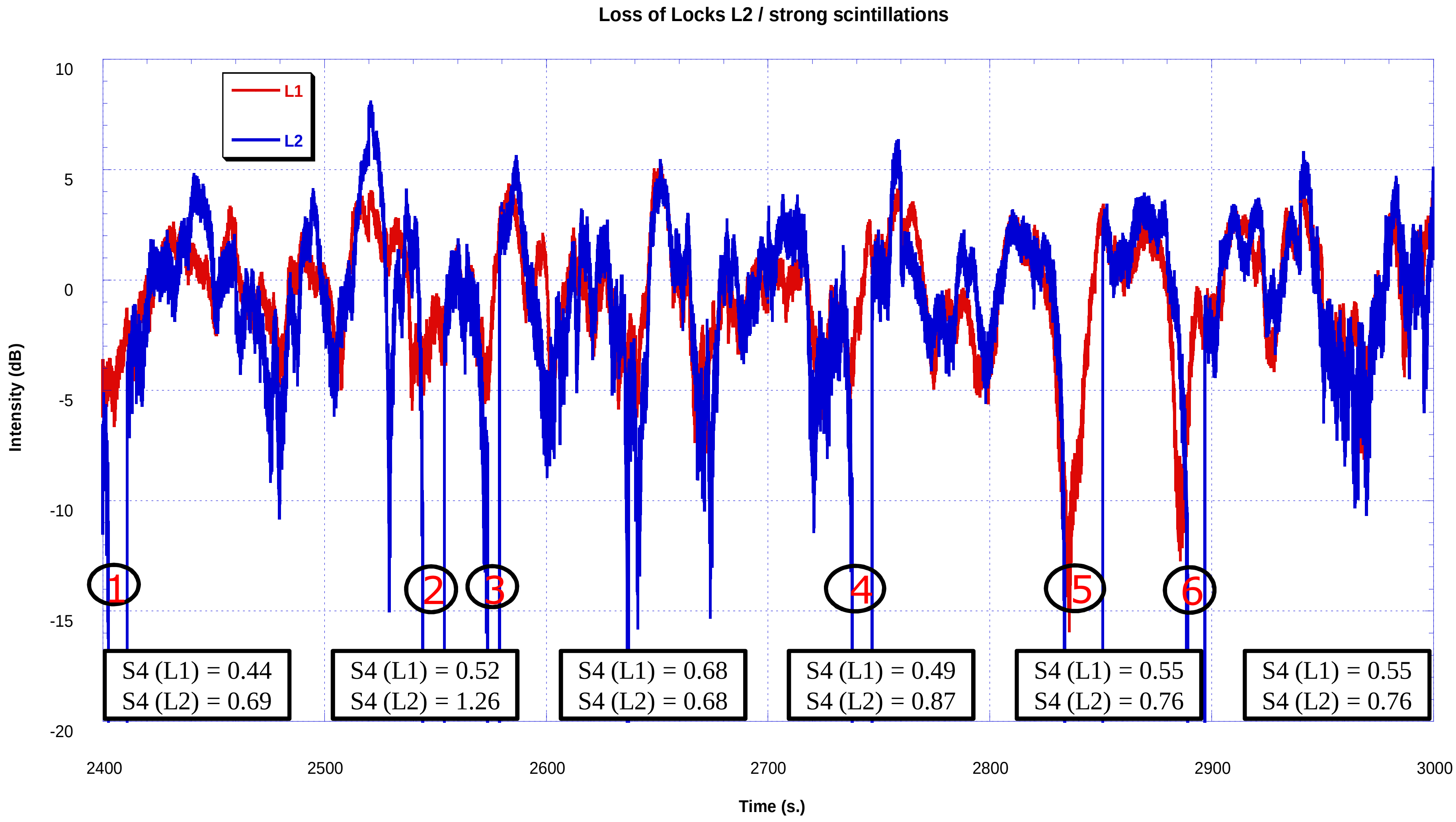
The phase noise is related to the Intensity of the received signal

$$\sigma^2_{\Phi T} = \frac{B_n}{(c/n_0)\ I}\left[1 + \frac{1}{2\eta\,(c/n_0)\ I}\right]$$

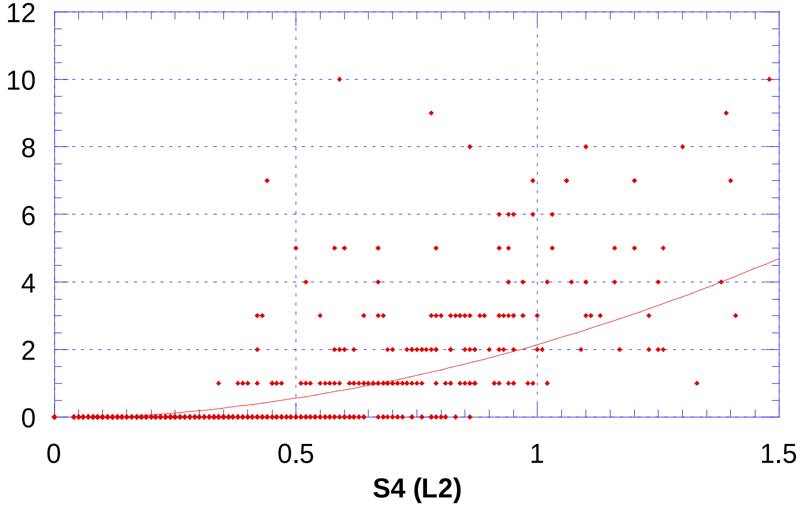
p(I) Nakagami distributed

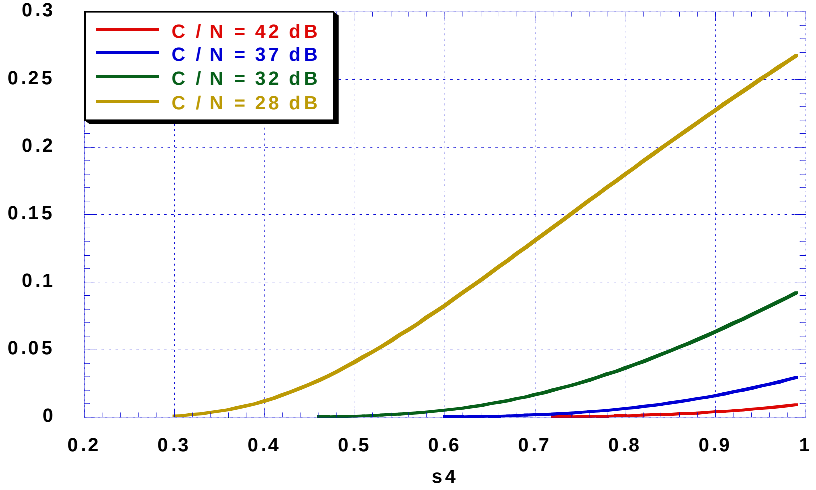
Probability of Loss of Lock is p(σ_ϕ) > threshold value

Loss of Lock (Measurements in Tahiti)



Loss of Lock
Measurements vs Modelling


Number of Loss of Lock on L2
(Measurements)

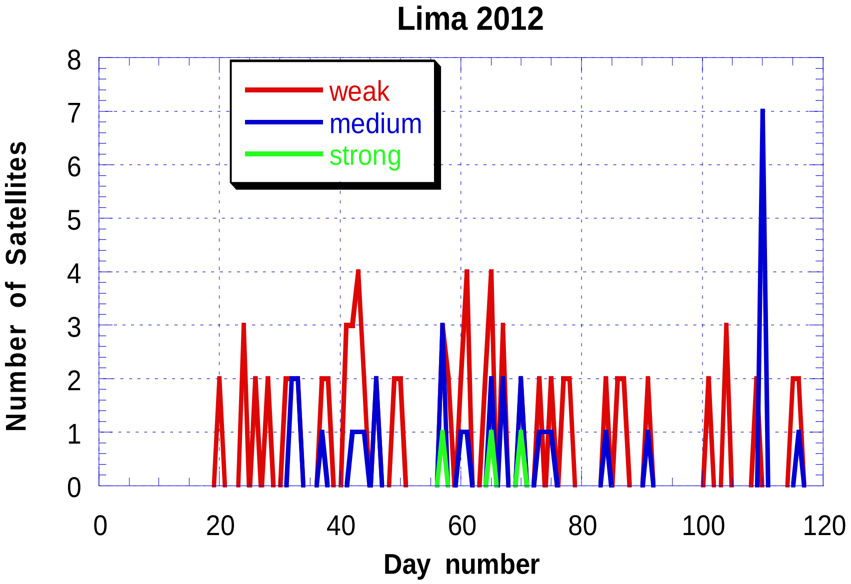

Modeling
Probability of loss of lock

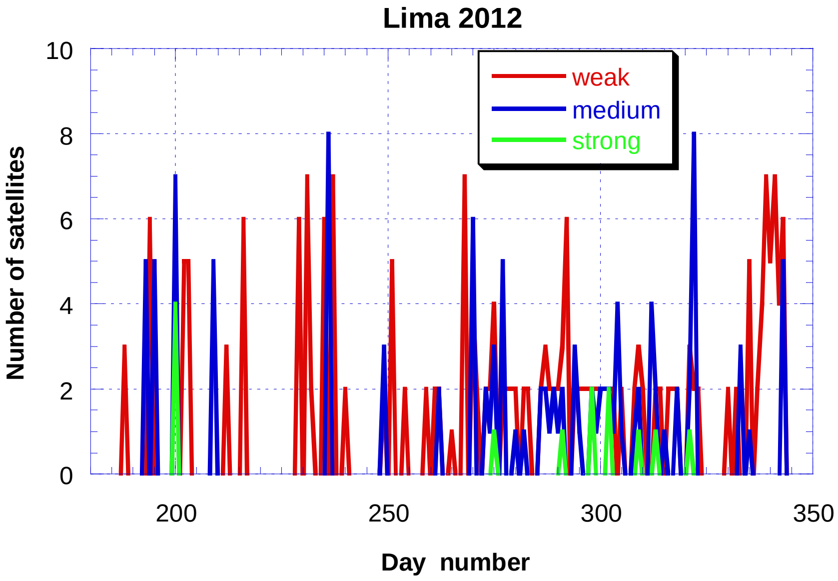
3 days of analysis in Tahiti

Geographical Extent

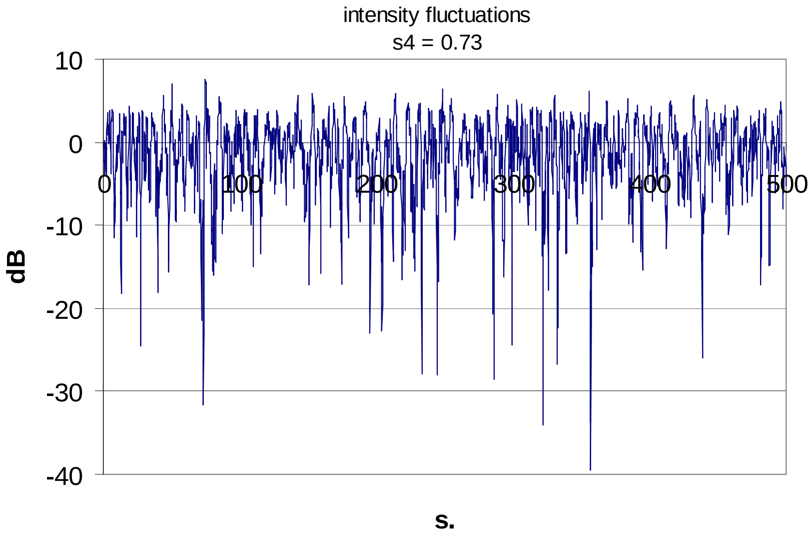
Simultaneous Scintillation

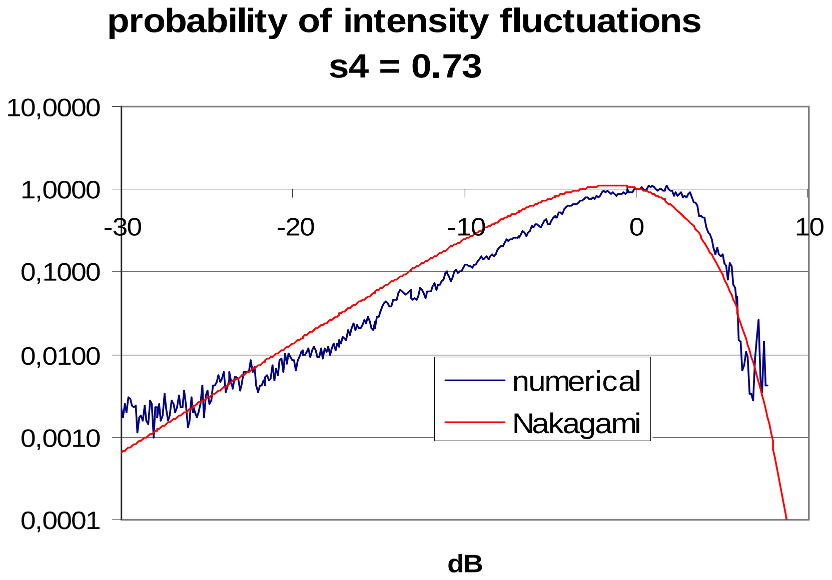
Number of Satellites Simultaneously Corrupted by Scintillation





Probability of intensity / Modelling



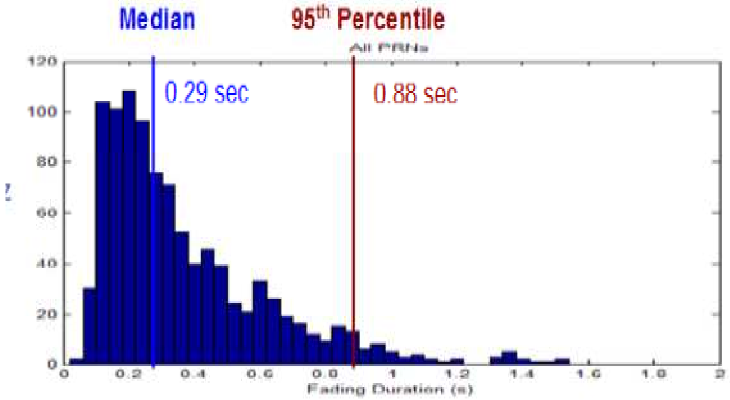


GISM output

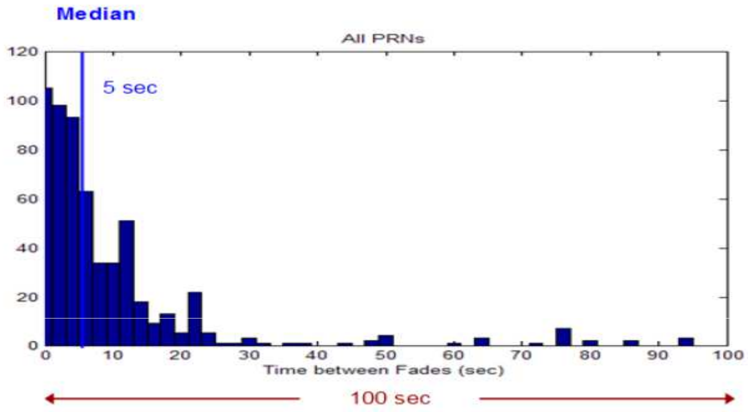
Nakagami law $$p(A) = \frac{2\, m^{m}\, A^{2m-1}}{\Gamma(m)} \exp(-m A^{2})$$ with $$m = 1 / S_4^2$$

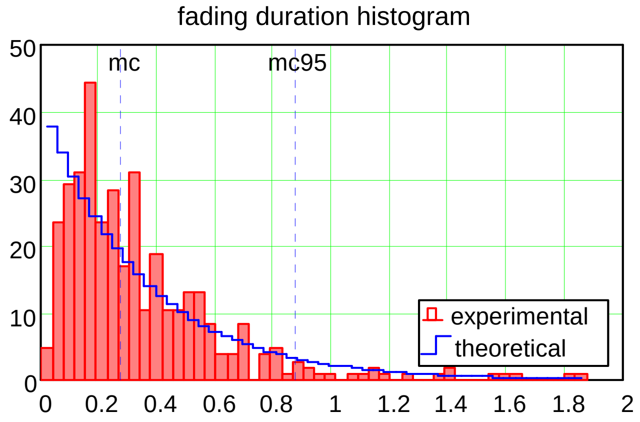
Fades Statistics

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

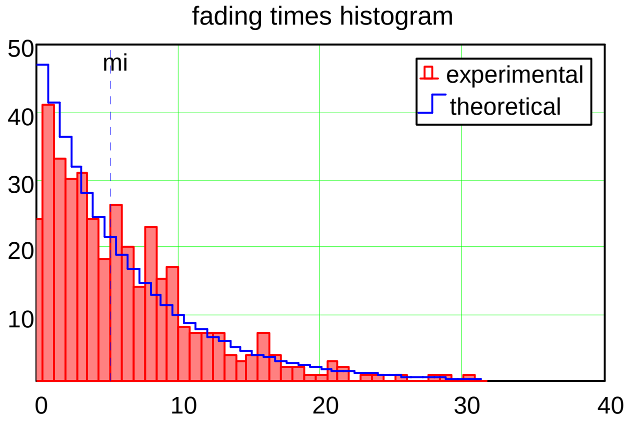


1.Real data





2.GISM simulation



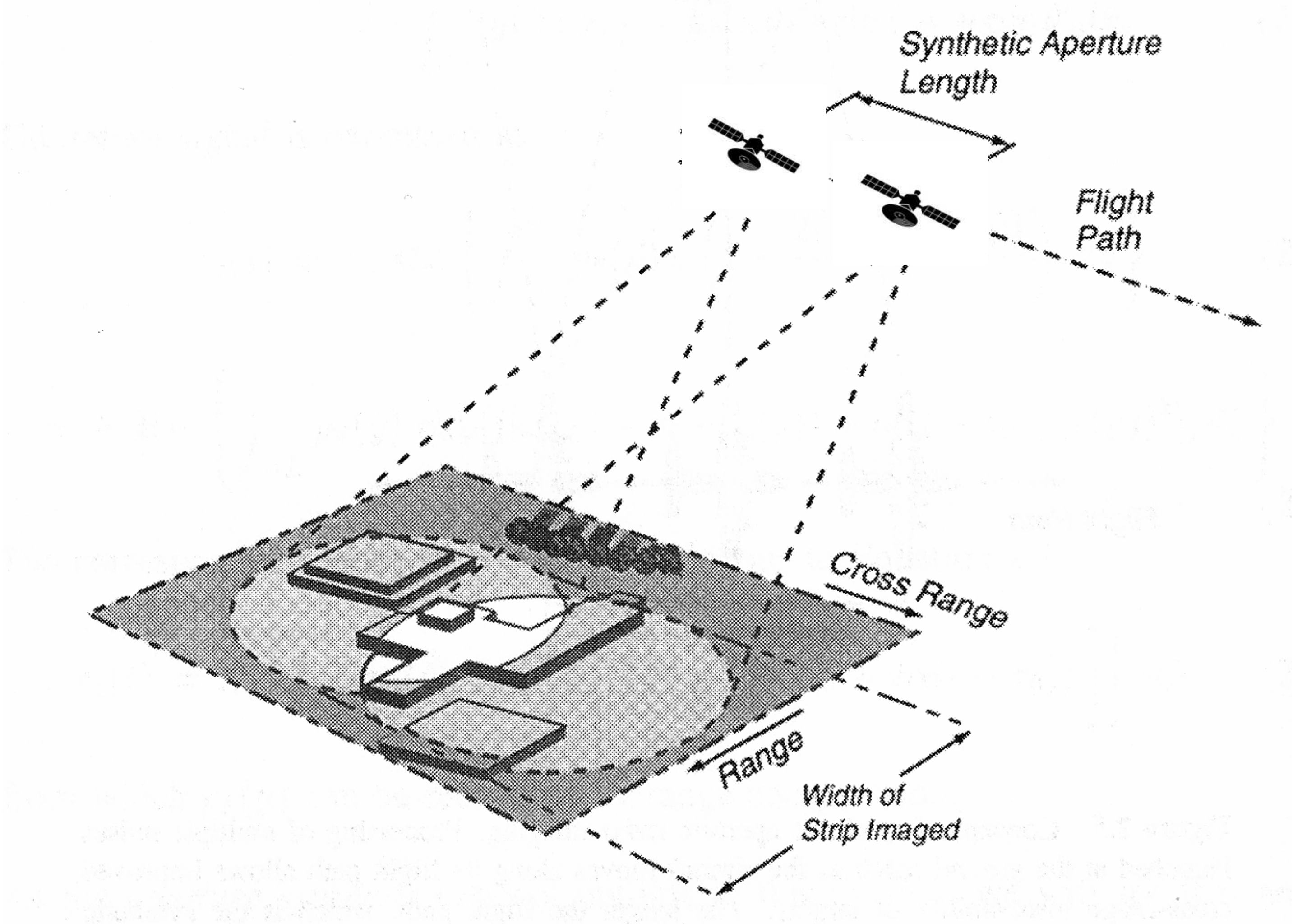
Probability of intensity / Modelling

Nakagami vs measurements

Radar Observations

Mutual Coherence Function

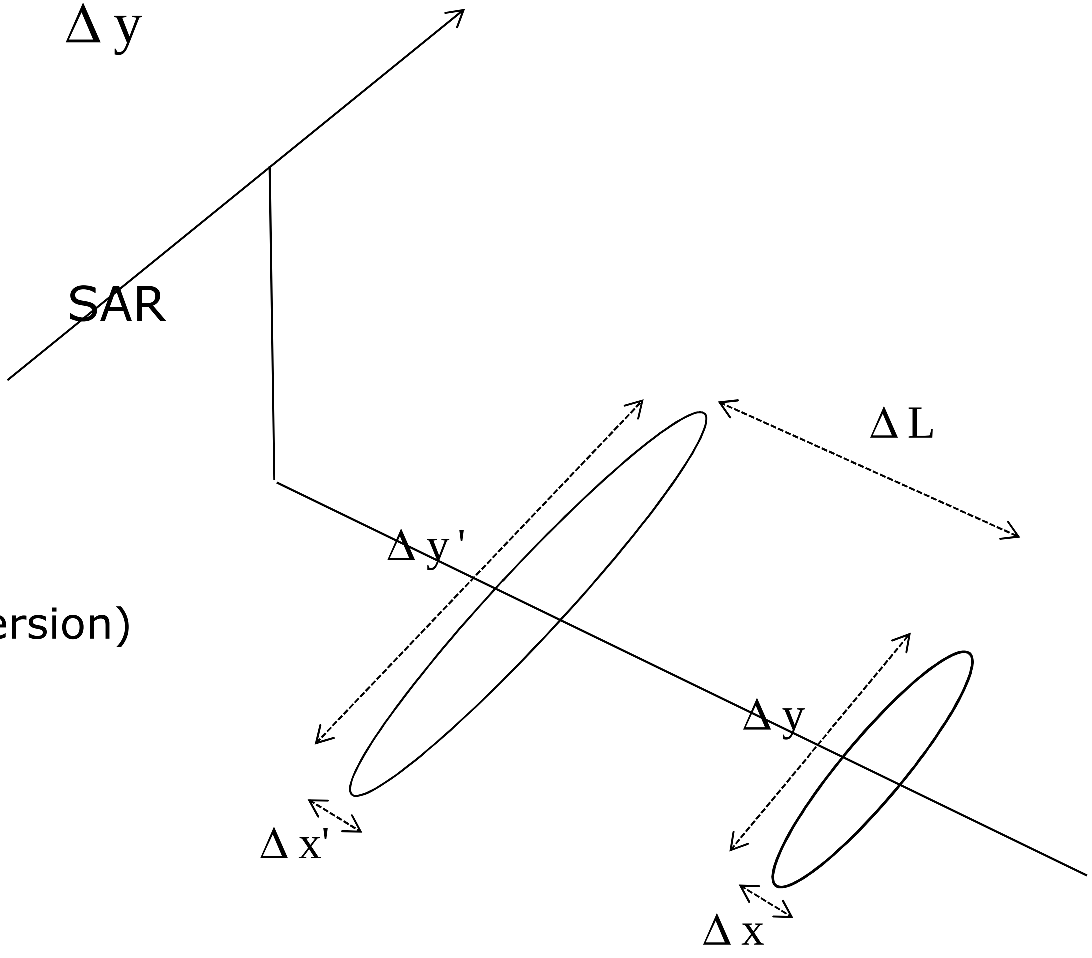
Correlation distance vs LSAR



L_e Synthetic Aperture Length → 10 km

Ionosphere Effects

Free Space Resolution Δx Δy



Ionosphere Effects

- $\Delta x'$ Pulse broadening (dispersion)
- $\Delta y'$ Turbulence Effect
- ΔL Group Delay

Two Points - Two Frequencies Coherence Function

$$\Gamma(z, k_1, k_2, \rho_1, \rho_2) = \left\langle U_1(z, k_1, \rho_1)\ U_2^*(z, k_2, \rho_2) \right\rangle$$

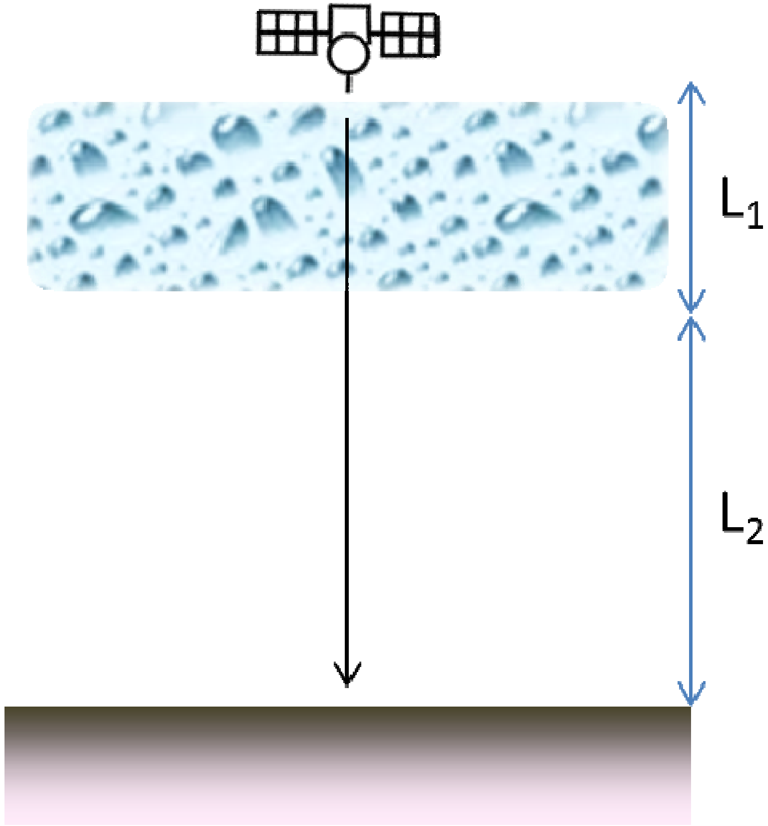
Using the parabolic equation

$$\left[\frac{\partial}{\partial z} - \frac{j}{2}\frac{k_d}{k_0^2}\nabla_d^2 + \frac{k_p^4}{8\ k_0^2}\left[\frac{k_d^2}{k_0^2} A_\xi(0) + D_\xi(\rho) \right] \right] \Gamma(k_d, z, \rho) = 0$$

The structure function $D_\Phi(z,\rho) = 2\left[B_\Phi(0) - B_\Phi(\rho)\right]$ is quadratic with respect to the distance

Same process than previously : propagation 1st & 3rd terms ;
Diffraction : 2nd & 3rd terms

Two Points - Two Frequencies Coherence Function



$$\Gamma(z, k_1, k_2, \rho_1, \rho_2) = \left\langle U_1(z, k_1, \rho_1)\ U_2^*(z, k_2, \rho_2) \right\rangle$$

Solution (one single screen)

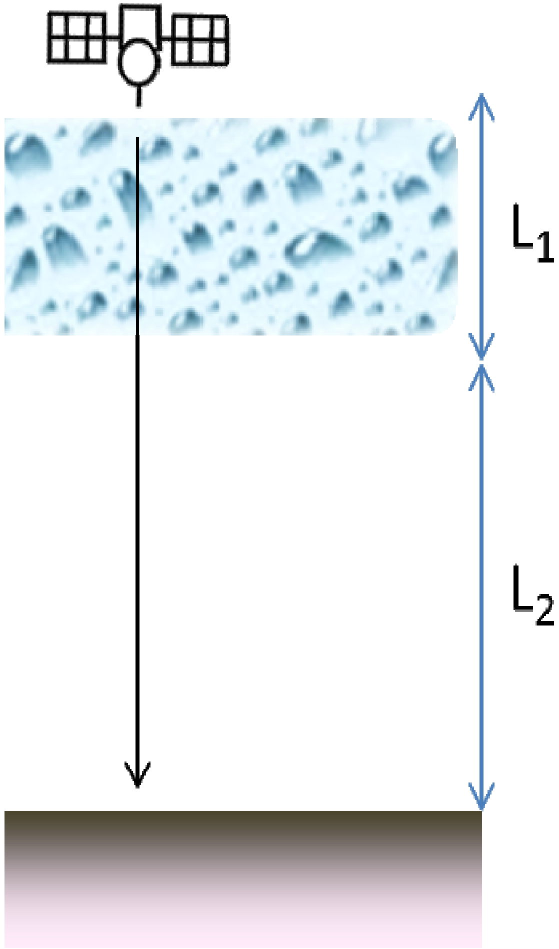
Scattering → 2 constants

$$B = \frac{\sigma_\Phi^2}{2\,\omega^2}$$

$$S = \sigma_\Phi^2 \; (L_1)^2 \; \frac{\mathrm{Log}\,(\mathrm{L}_0 / \ell_i)}{6\,\mathrm{L}_0^2}$$

Propagation → 1 constant

$$P = \frac{1}{2\ c\ k^2}\left(\frac{1}{\mathrm{L}_1 + \mathrm{L}_2} - \frac{1}{\mathrm{L}_1}\right)$$



* Nickisch, RS 92, Knepp & Nickisch, RS, 2010

One Single Screen

Analytical solution

$$\Gamma(\tau, K_x, z) = \frac{z}{2\sqrt{BS}}\ \overset{K_x}{\overset{\uparrow}{\boxed{\exp\left(-\frac{z^2 K_x^2}{4S}\right)}}}\ \overset{\tau \text{ and } K_x}{\overset{\uparrow}{\boxed{\exp\left(-\frac{\left(\tau + z^2 K_x^2 P\right)^2}{4B}\right)}}}$$

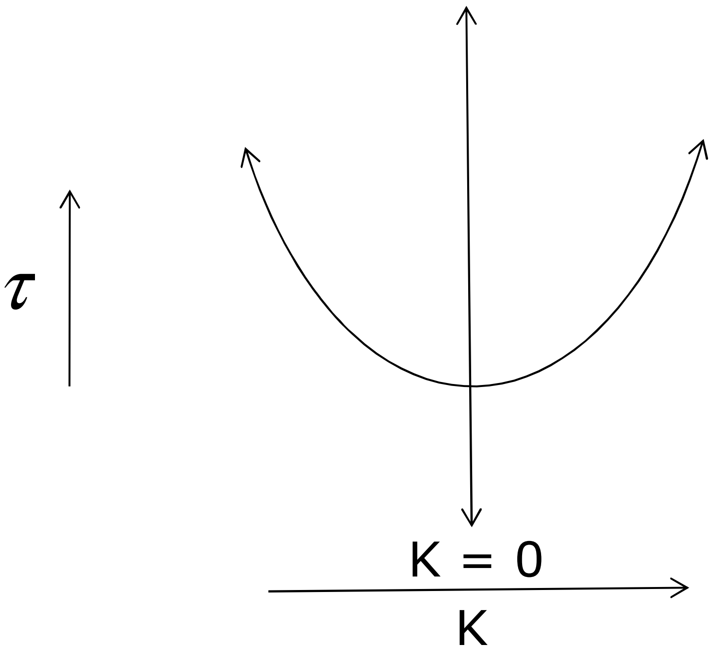
Spreading Extent

$$K = 0 \rightarrow \tau_1 = 2A\sqrt{B}$$

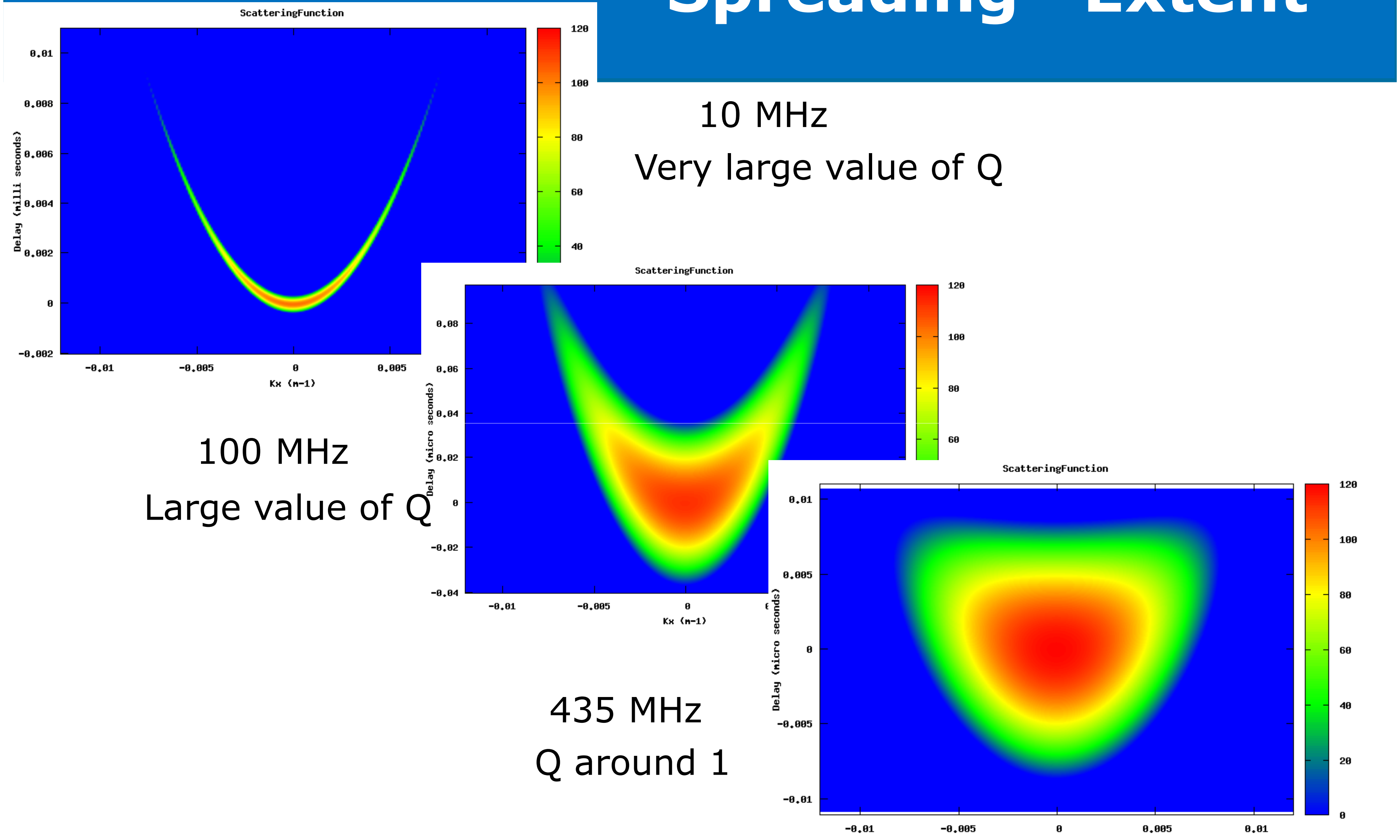
$$K = KMax \rightarrow \tau_2 = 4SPA$$

Spread factor

$$Q = \frac{\tau_2}{\tau_1} = \frac{2\sqrt{A}\,SP}{\sqrt{B}}$$



Spreading Extent



10 MHz

Very large value of Q

100 MHz

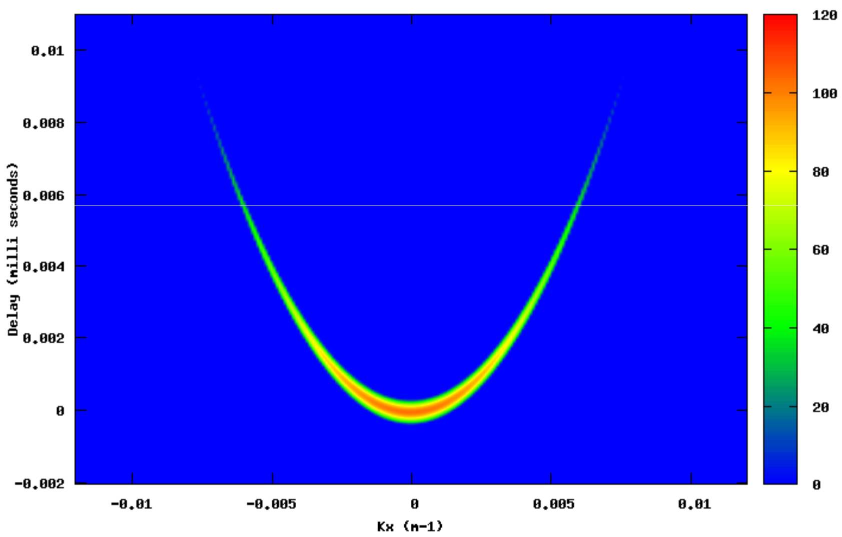
Large value of Q

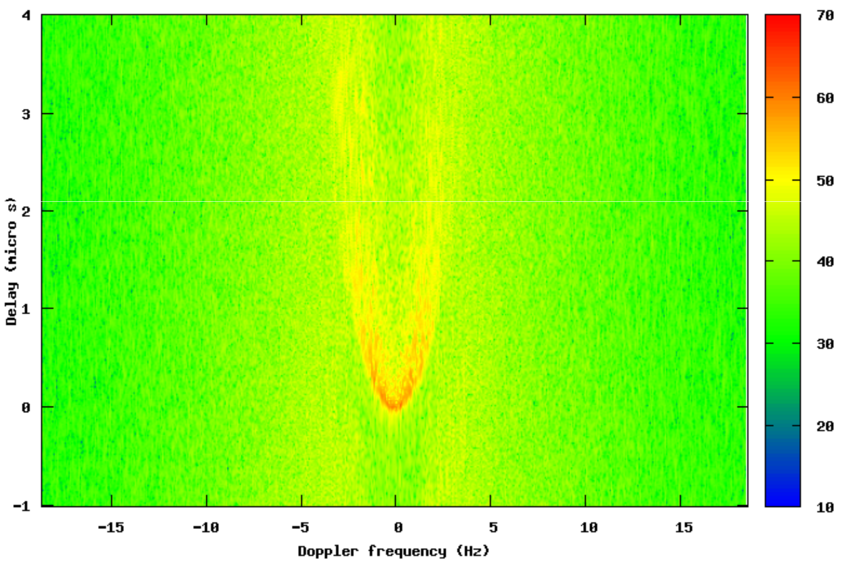
435 MHz

Q around 1

Rogers, N., P. Cannon, and K. Groves, Measurements and simulations of ionospheric scattering on VHF and UHF radar signals: Channel scattering function, Radio Sci., 44, RS0A33, DOI: 10.1029/2008RS004033, 2009.

Analytic vs Numerical


ScatteringFunction


f = 10.MHz SigmaPhi = 10. , ScreensThickness = 100.00 km OuterScale = 1000. m.

Several Screens
Refined Analysis

- The algorithm can easily be generalized

- Different statistical properties may be assigned to the different layers

- Numerical FFT (1D) shall be performed to get the coherence function

Ambiguity Function

$$\chi\,(r, r_0) = \sum_n \int g_n(t, r_n)\; f_n^*(t, r_{0n})\; dt$$

g_n is the received signal and f_n is the matched filter

$$\chi_n\,(r_n\,, r_{0n}) = \frac{1}{(4\pi r_n)^2}\,\exp\,(j\,\Phi_0)\int \exp\left(-\,j\,(\omega-\omega_0)\Phi_1\,-\,(\omega-\omega_0)^2\,\Phi_2\right) d\,\omega$$

Value of Coherent field received

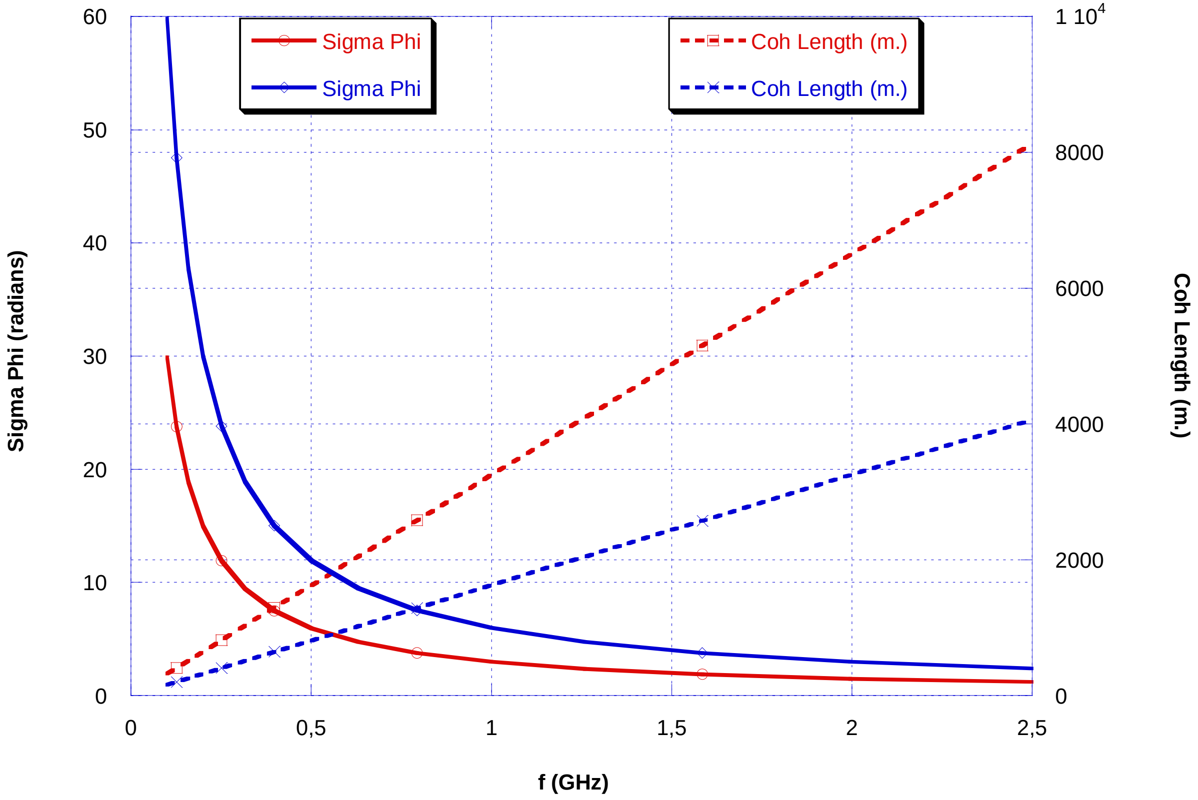
$$\langle\,\chi\,(r, r_0)\,\rangle = \frac{\exp\left(-\,\sigma_\Phi^2\right)}{(4\pi r_0)^2}\int_{-Le/2}^{Le/2}\exp\left(2\,j\,k_0\left(r_0 + \frac{\rho^2}{2\,r_0}\right)\right) d\,\rho = \frac{\exp\left(-\,\sigma_\Phi^2\right)}{(4\pi r_0)^2}\sin c\,\left(k_0\,\rho\,L_e\,/\,r_0\right)$$

An attenuation factor on the coherent component is included

Coherent Length

It is given by function $\Gamma\left(\omega_d\,,\,\rho\,,\,r\right) = \sqrt{\frac{D}{S}}\,\exp\left(-\,B\,\omega_d^2 - D\left(\rho / r_0\right)^2\right)$

Phase Standard Deviation and related Coherent Length
in the case of strong fluctuations (red lines) & very strong fluctuations (blue lines)



Positioning Errors

Modelling

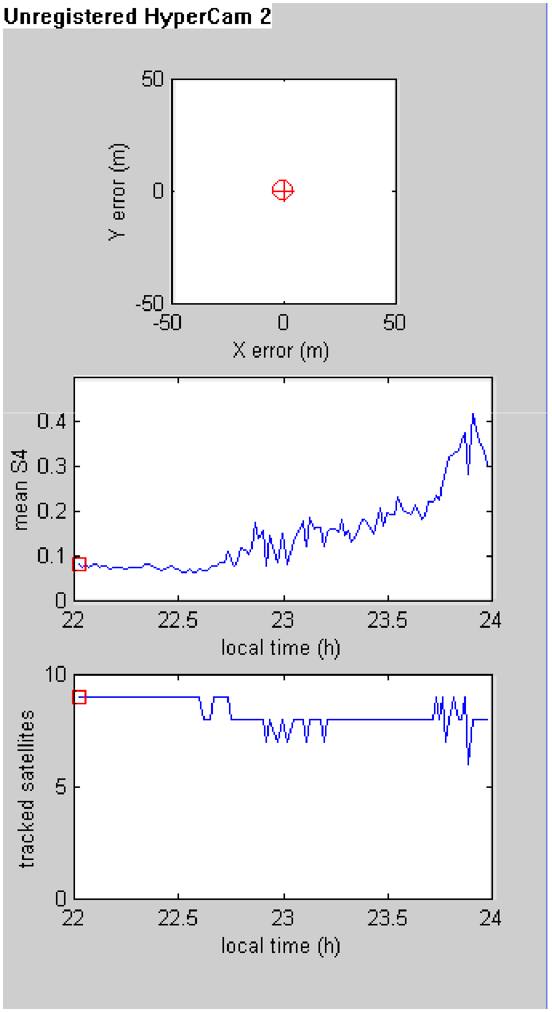
S4 measured for each tracked satellite

σ_τ is calculated taking the thermal noise as the main contribution

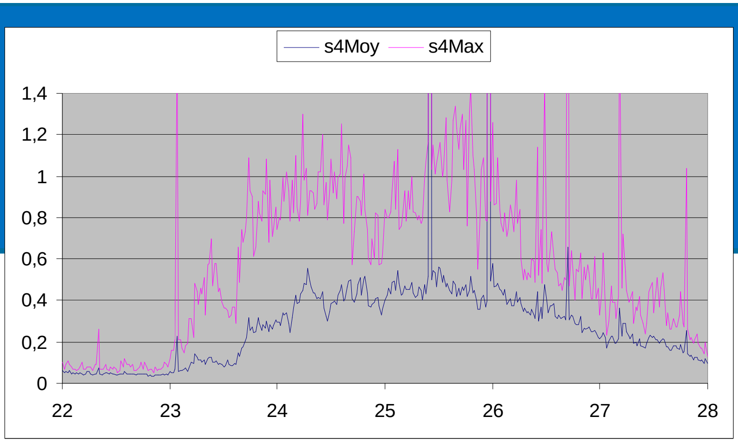
Range error calculated assuming a gaussian distribution

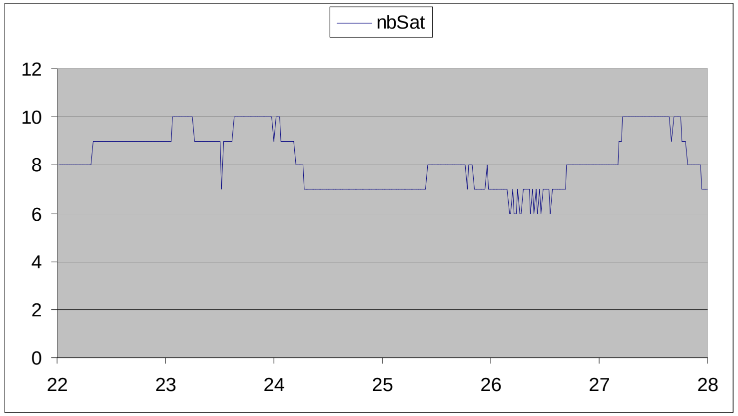
GPS constellation simulated with a yuma file

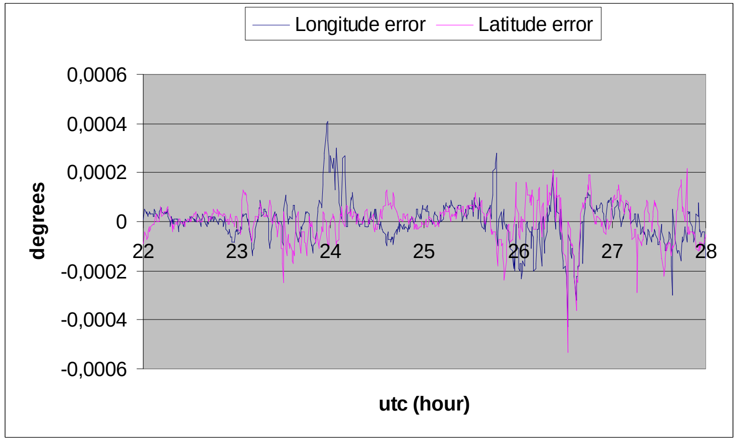
GPS Positioning Errors



Positioning errors from Measurements in Brazil in 2001







Conclusion

- Reasonable agreement between modelling (GISM) and measurements
- Positioning errors due to scintillations may reach values up to 50 meters
- The azimuthal resolution of a SAR may be significantly decreased
- All results will be updated taking measurements campaign data into account