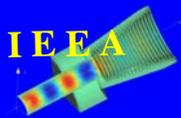


Effects of Ionospheric Scintillations in GNSS Operation

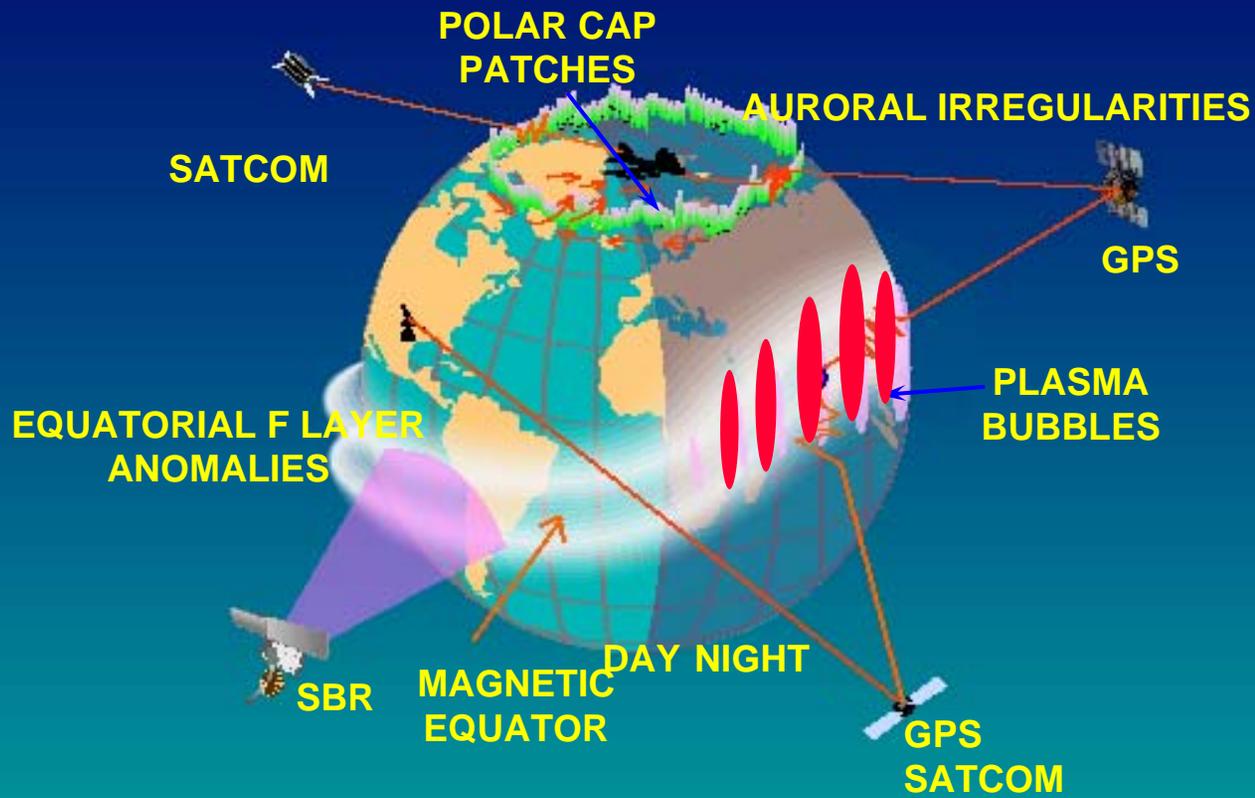
Y. Béniguel, IEEA, France



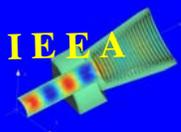
Contents

- Review of scintillations characteristics
- s4, probabilities of occurrence & loss of lock
- Scintillations effects at receiver level
- Positioning errors
- Measurement campaign

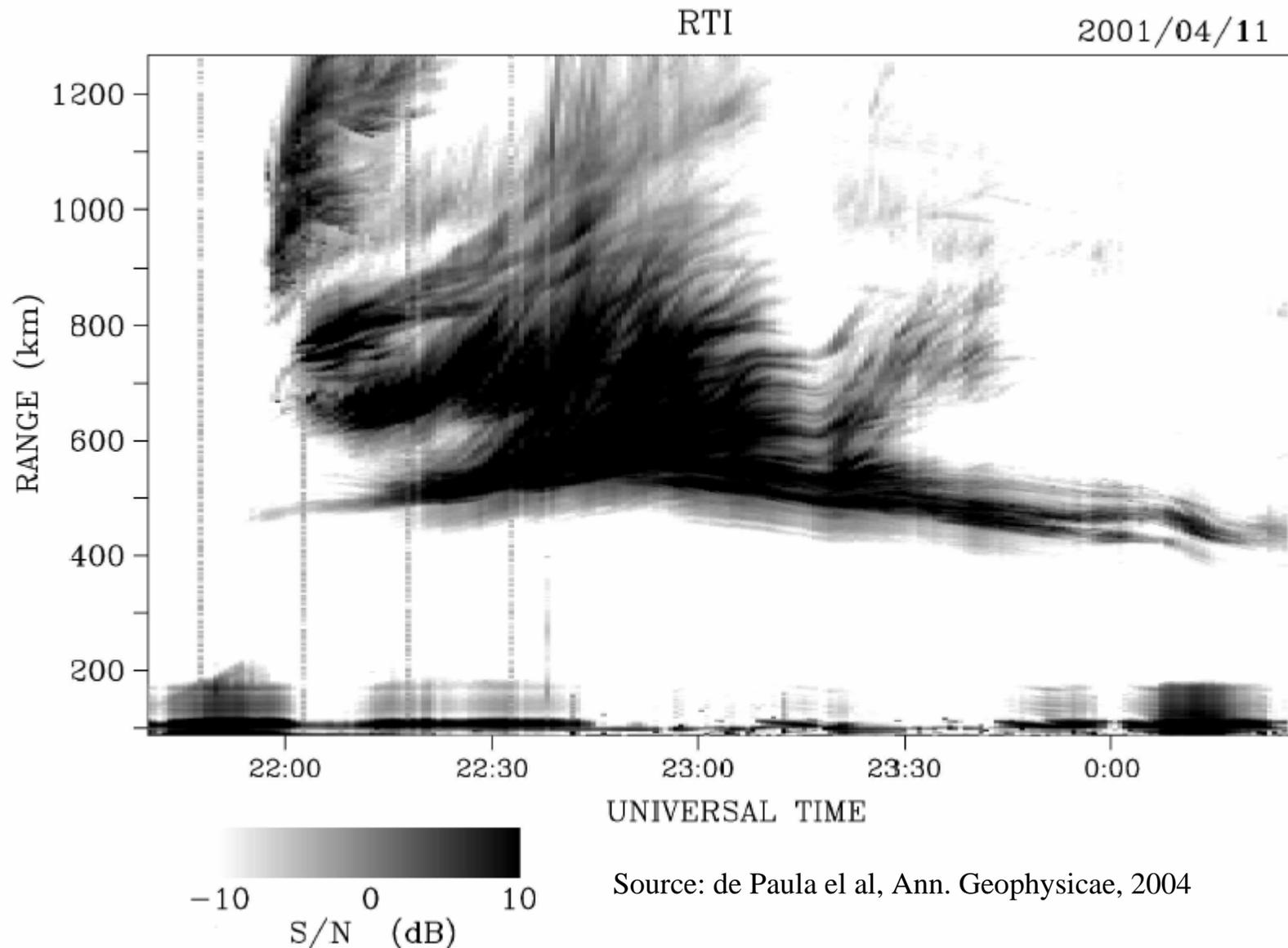
Disturbed Ionospheric Regions and Systems Affected by Scintillation



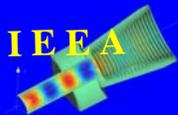
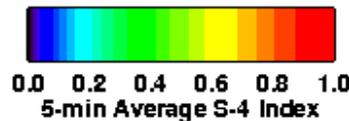
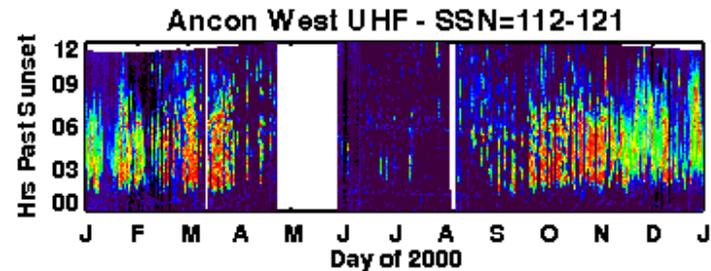
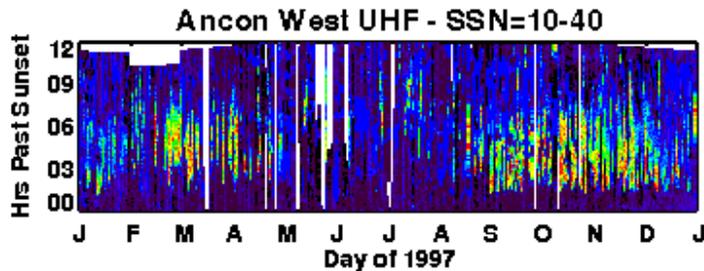
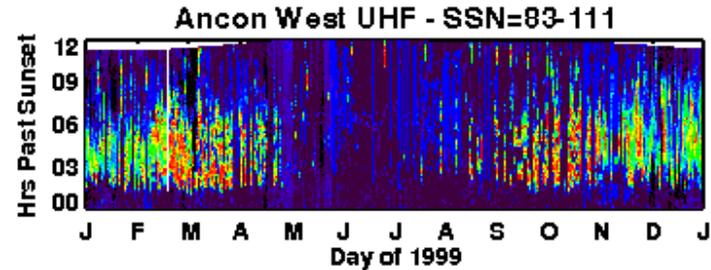
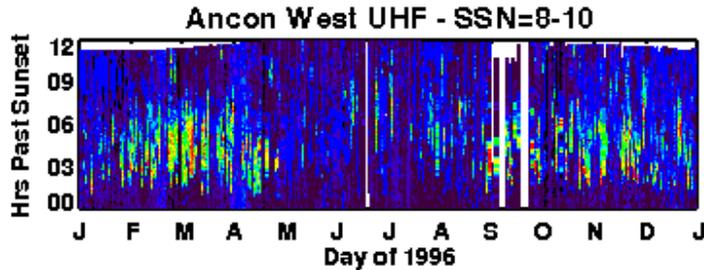
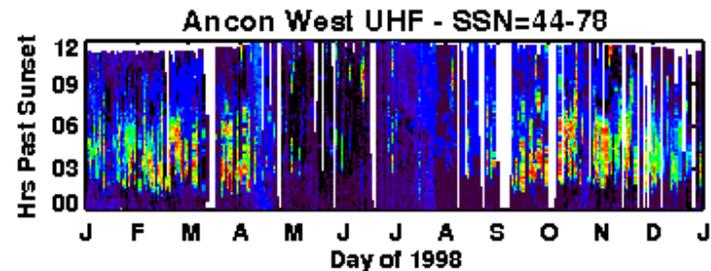
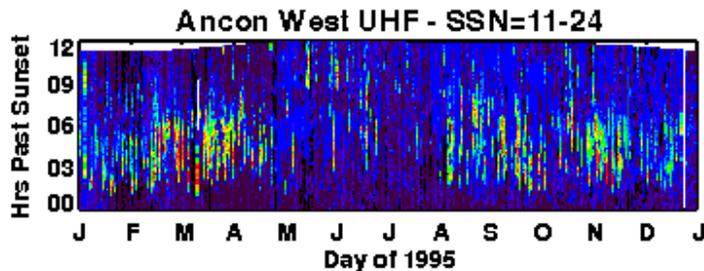
Scintillations Characteristics



VHF RADAR RANGE - TIME - INTENSITY BACKSCATTERED ECHOES FROM IONOSPHERIC IRREGULARITY FOR APRIL 11 2001

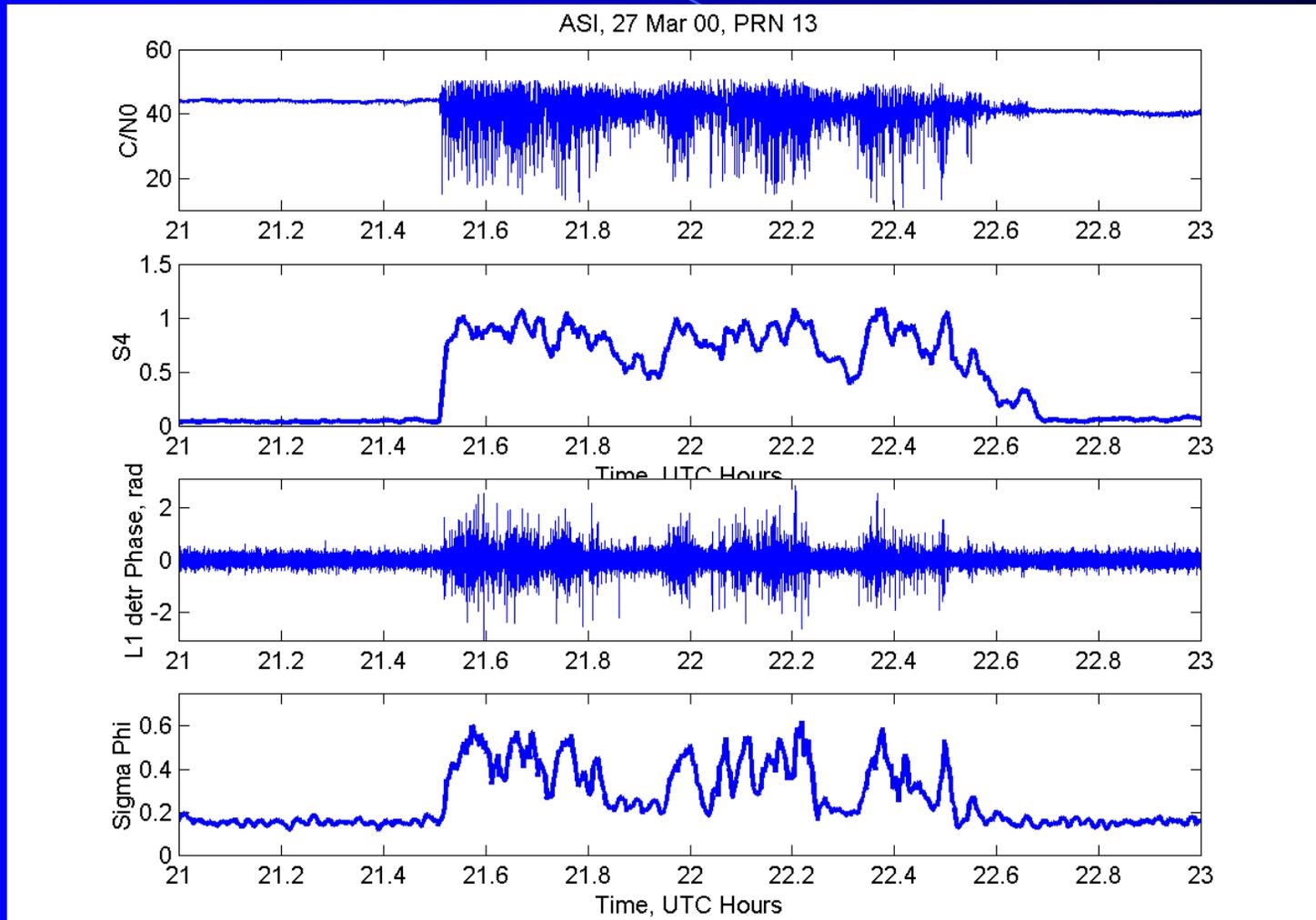


Solar Cycle Variations at Ancon, Peru (0° Mlat)



Source : K. Groves, AFRL

L1 Intensity & Phase Data: S4 and σ_ϕ



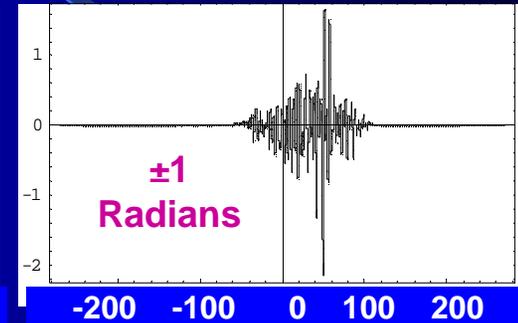
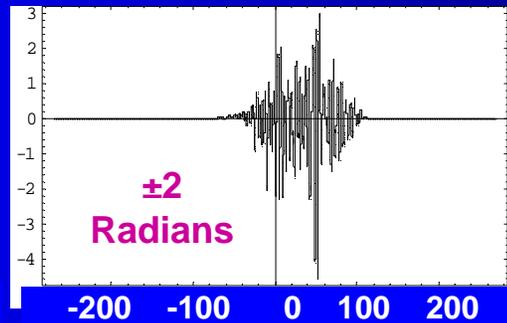
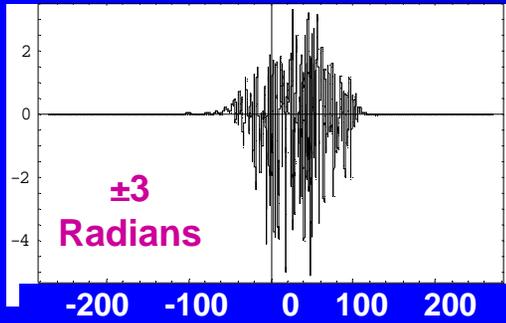
Scintillation Receiver Data

VHF

UHF

L-Band

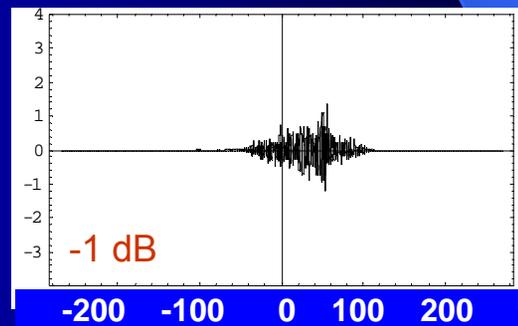
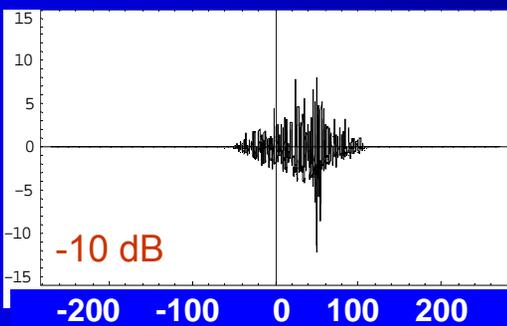
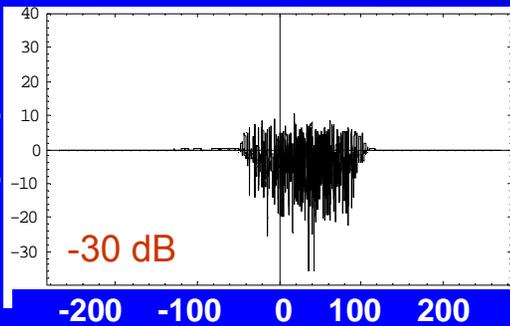
Rapid Phase
(Radians)



σ_ϕ

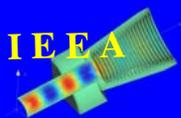
Distance (km)

Amplitude
(dB)

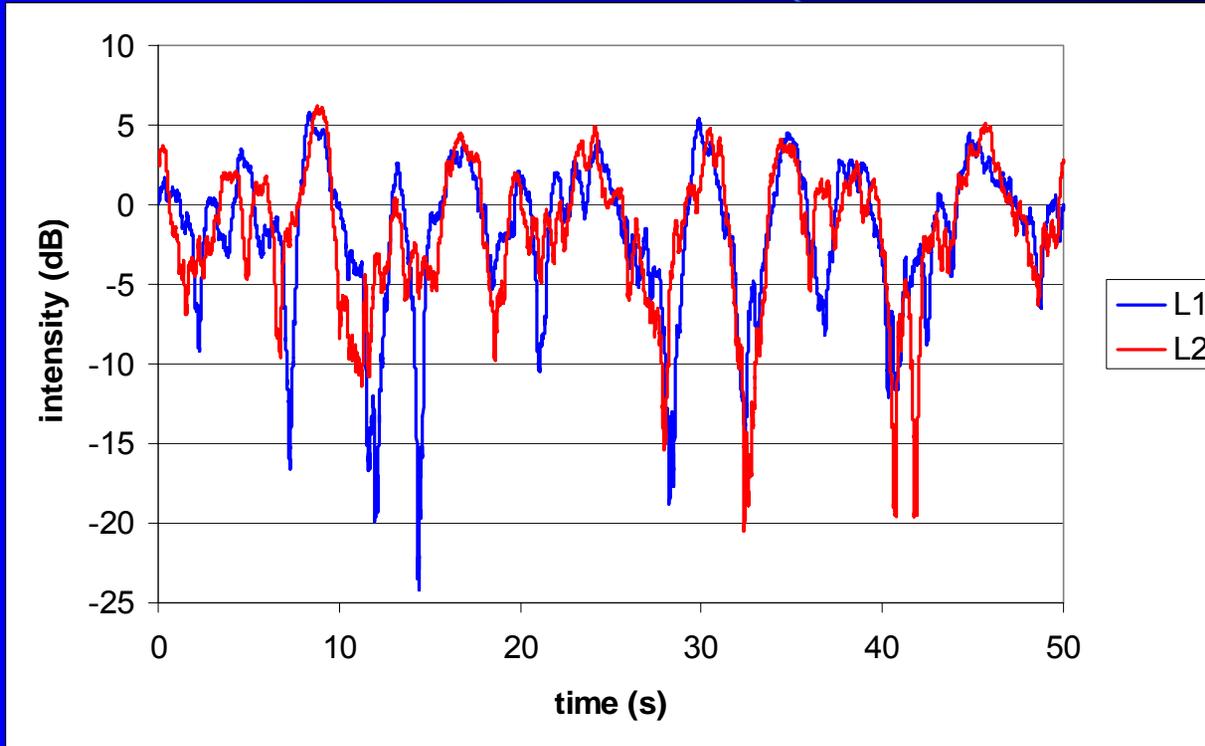


S_4

Distance (km)



Frequency Correlation



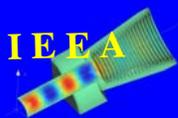
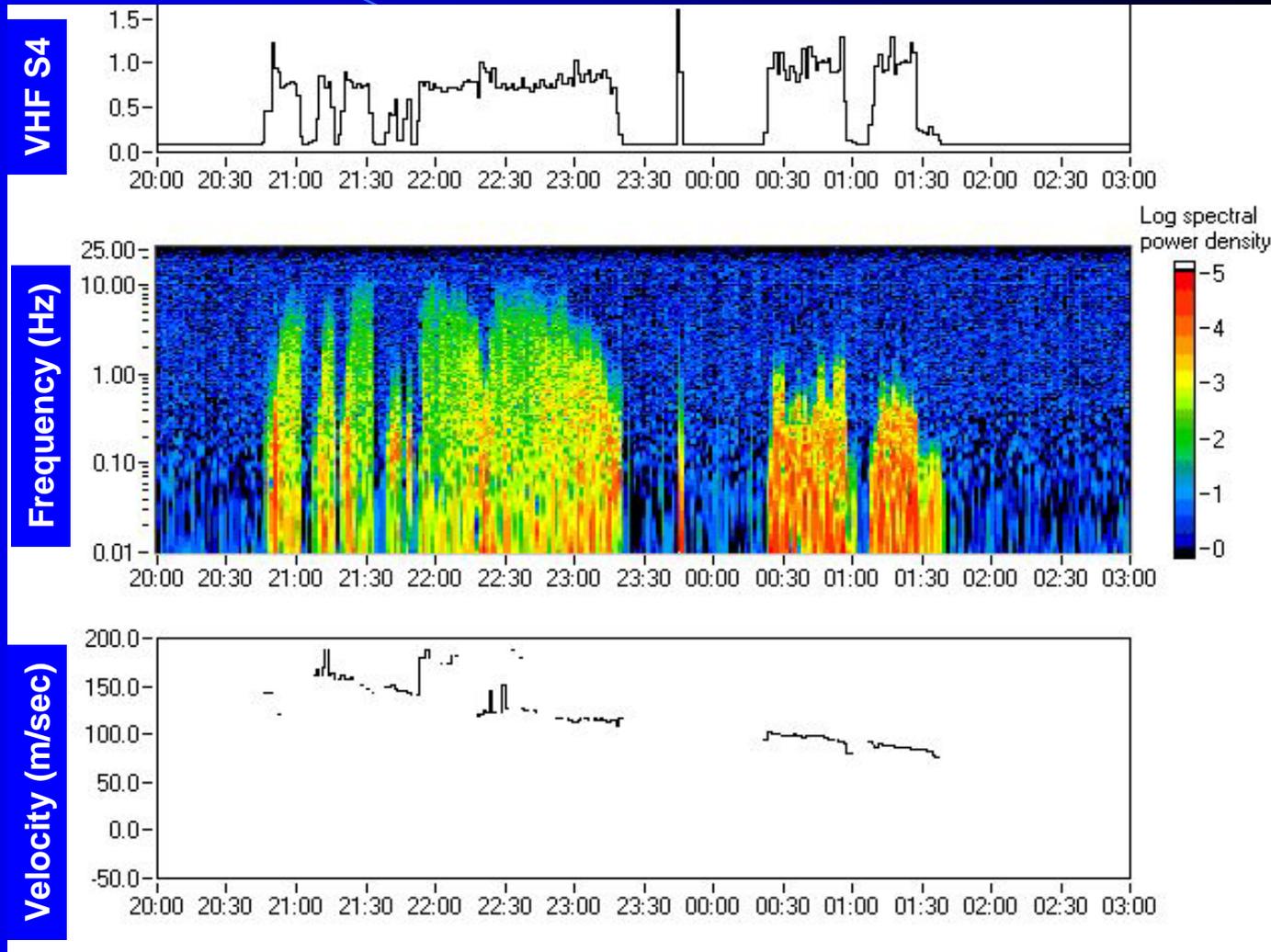
GISM result

Diurnal Variation of Scintillation

- S4 near unity; actually increases after midnight

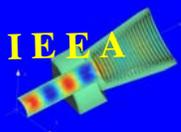
- High frequency component decreases beginning about 22:30; markedly after midnight

- Drift velocity decreases throughout the evening

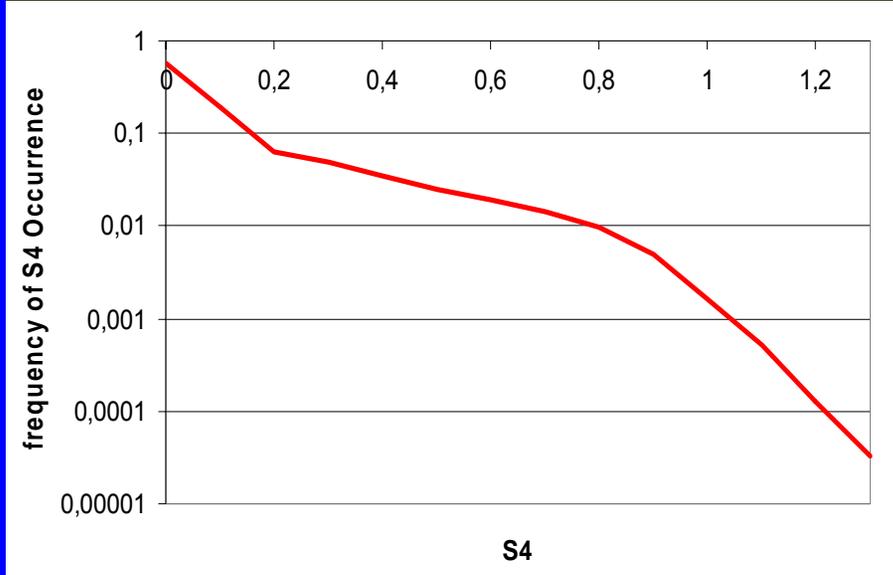


Courtesy: K. Groves AFRL

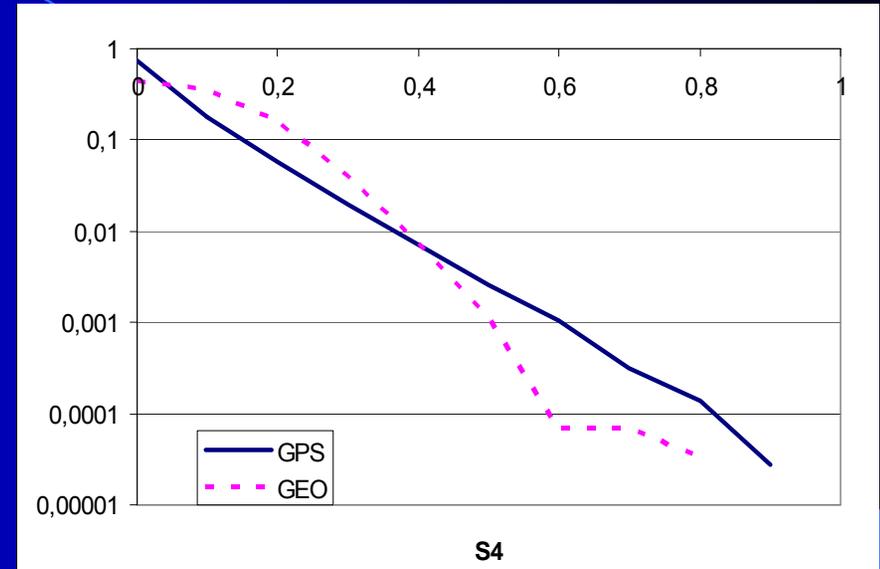
s4 probability



Probability of S4

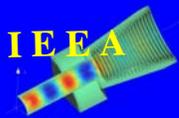


São Jose dos Campos, Brazil
2 weeks of data, 2002
flux number 190



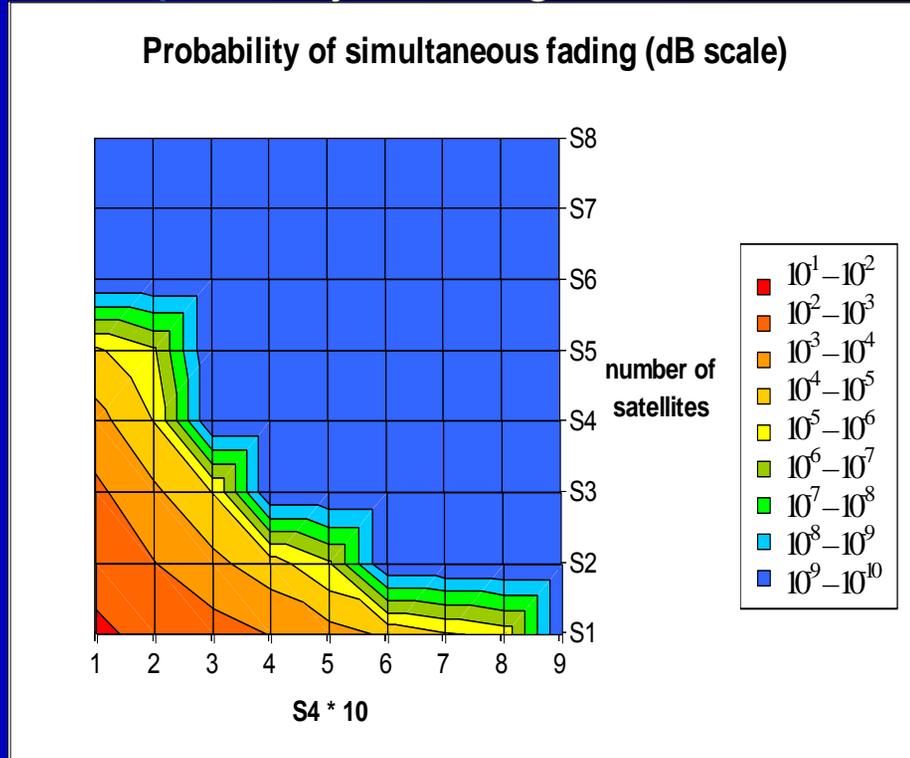
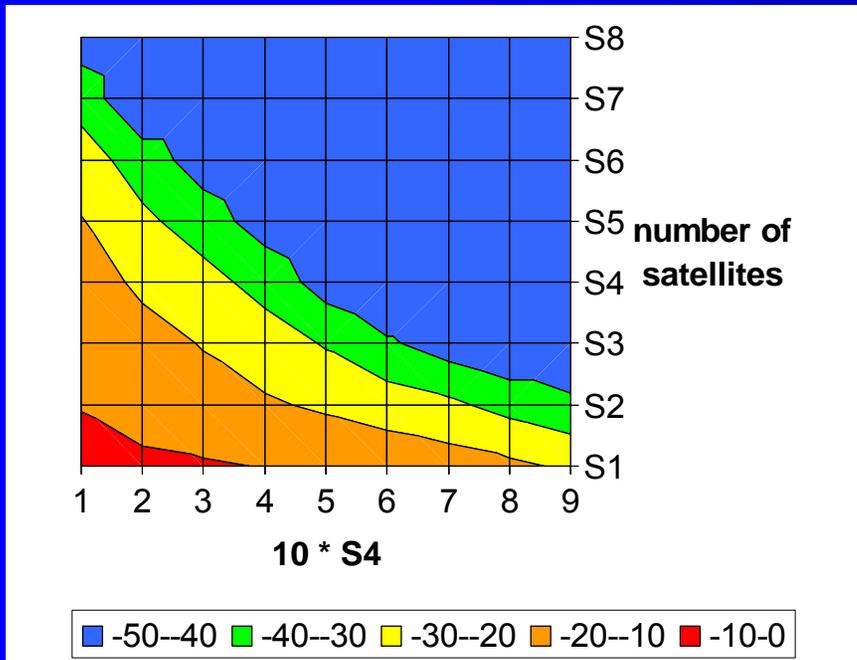
Douala, Cameroon
5 months of data, 2004
flux number 110

Log normal probability



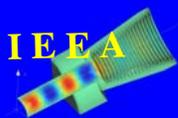
Satellites Affected Simultaneously by Scintillations

Probability to have several satellites simultaneously with a given value of S4 (Log scale)

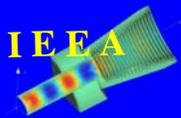


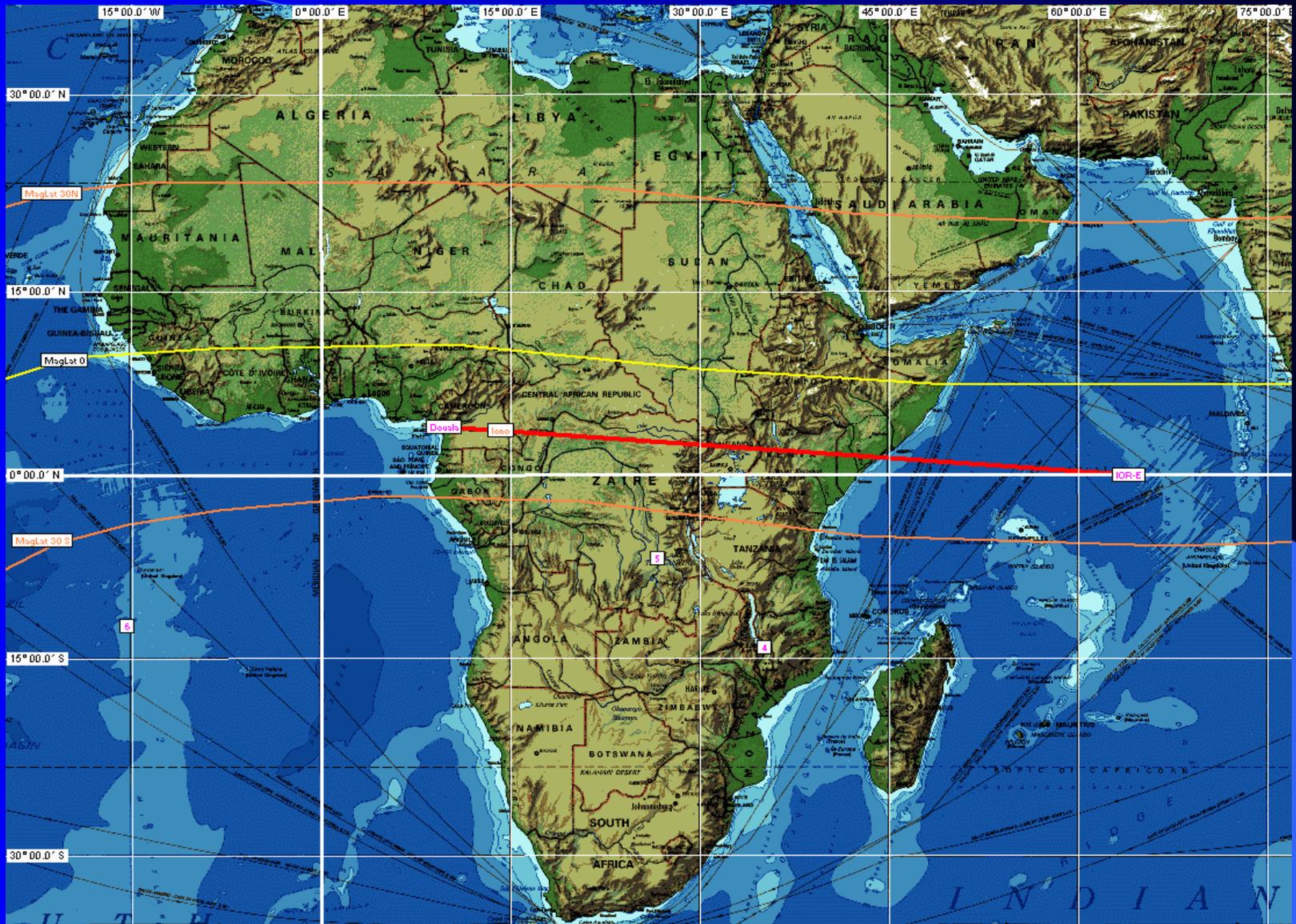
São Paulo / 2002 / flux 190

Douala / 2004 / flux 110

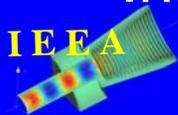


Scintillation Extent Area

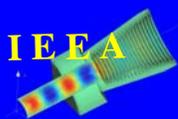
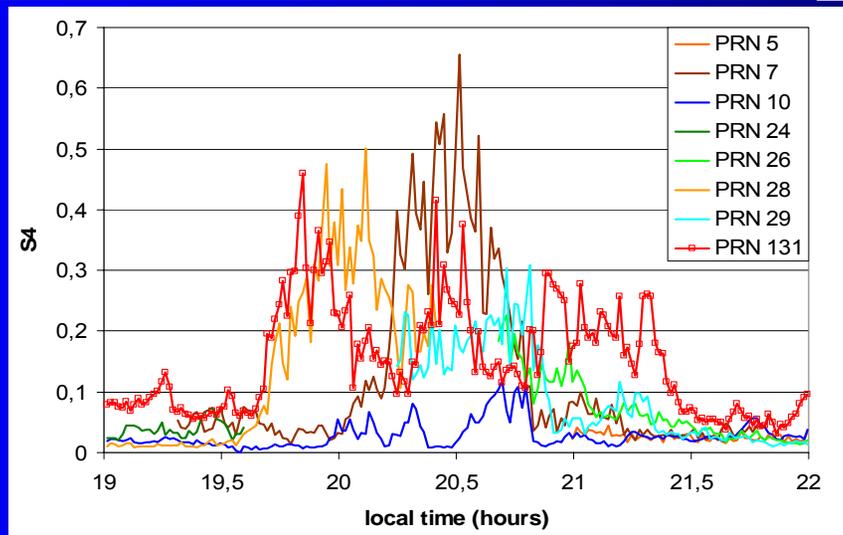
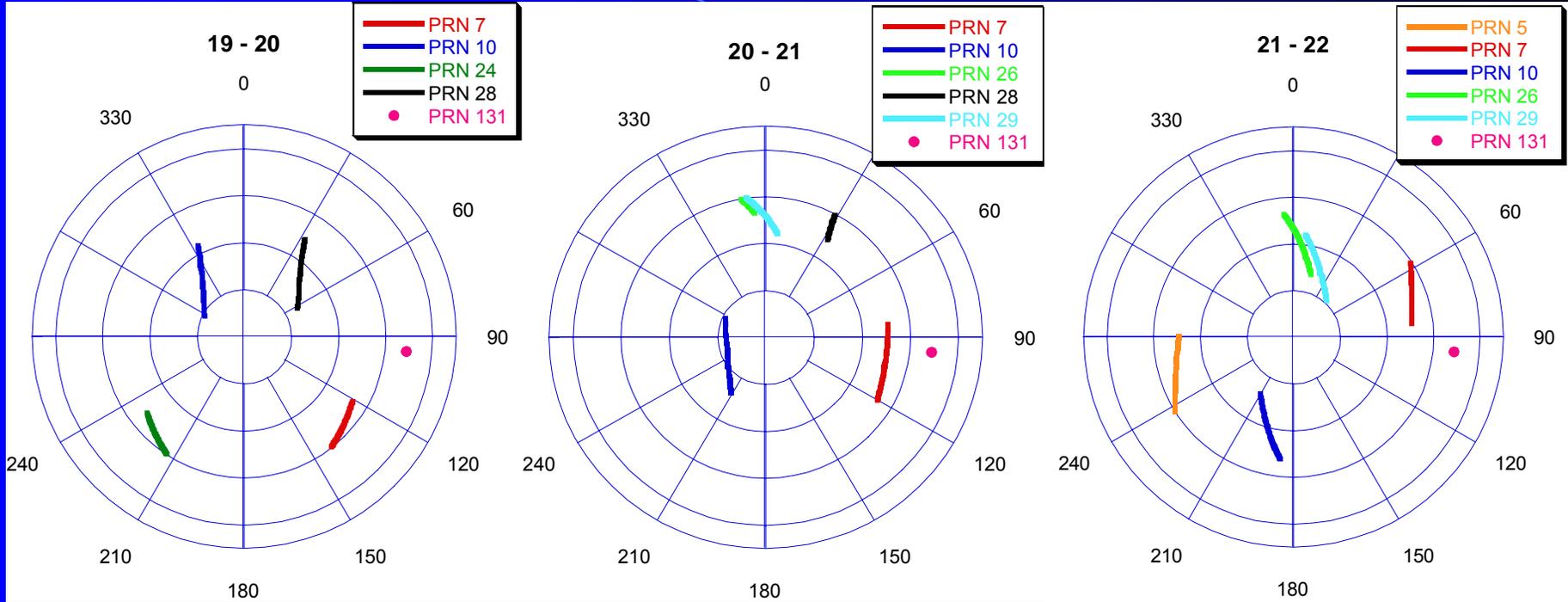




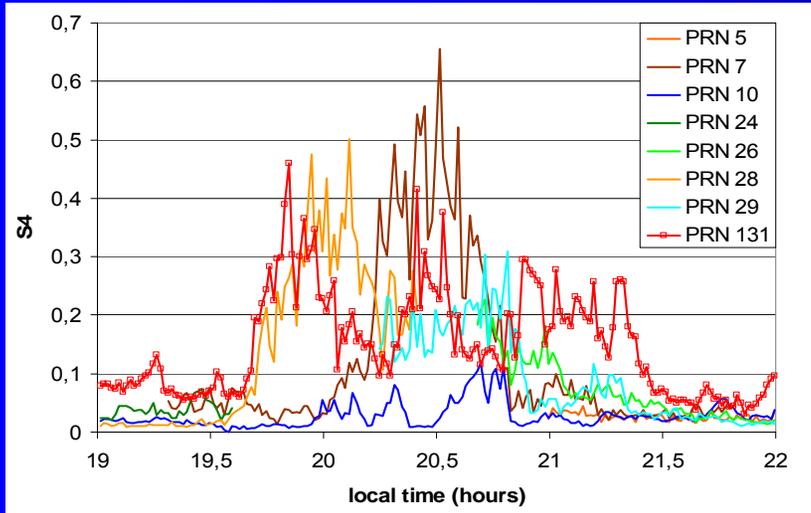
Inmarsat satellite seen with a 28° degrees elevation angle



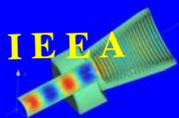
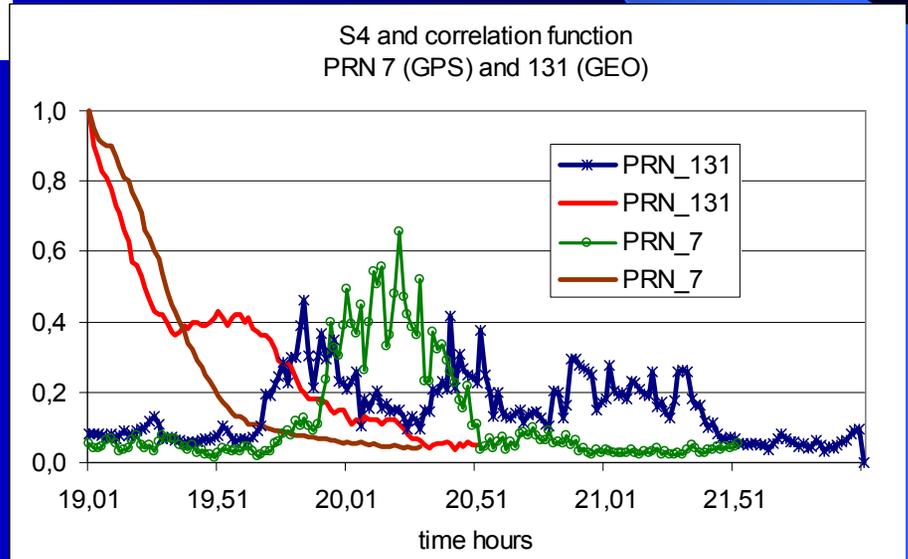
Spatial and temporal correlation



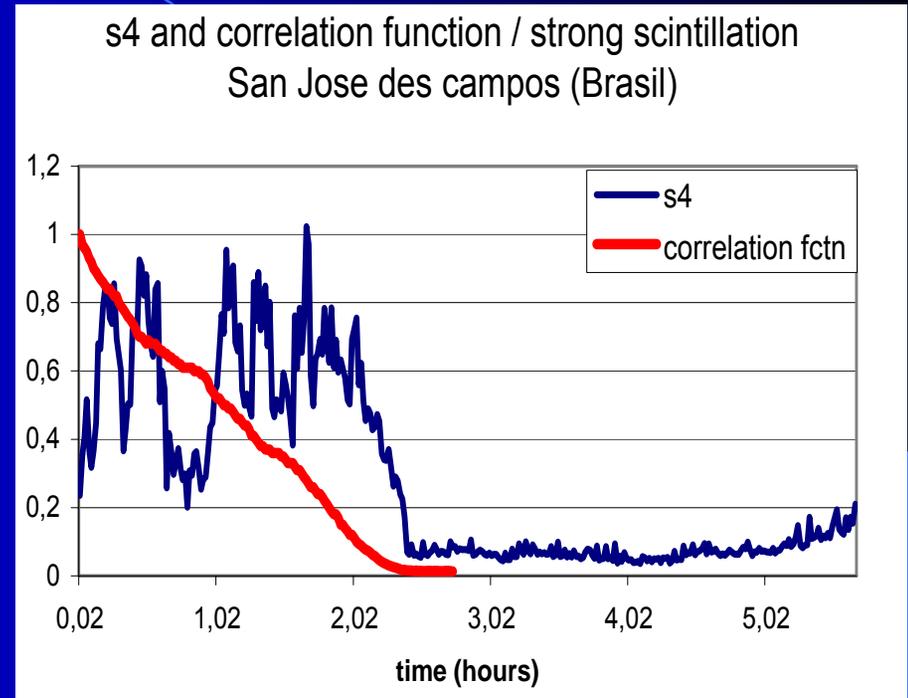
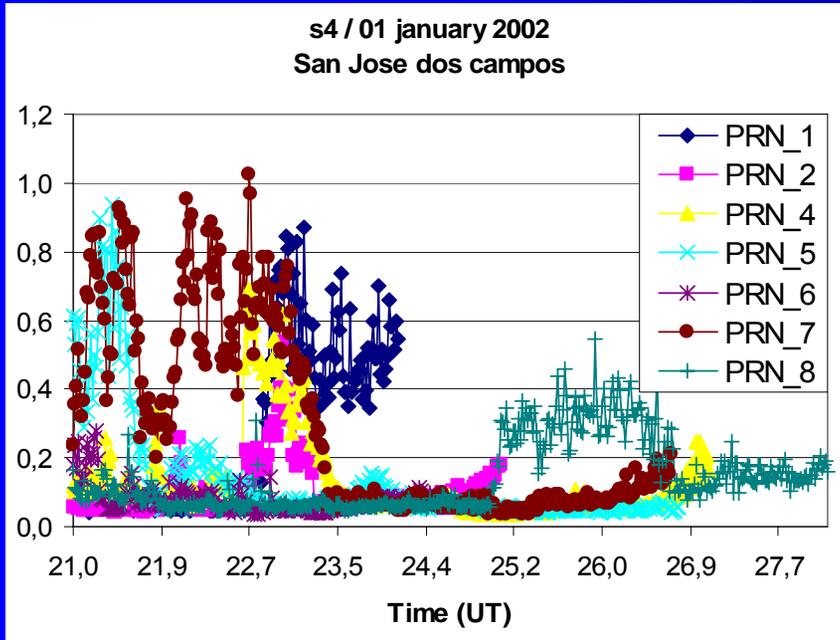
Scintillation extent using the GEO : flux 110



Correlation time
a few tens of minutes

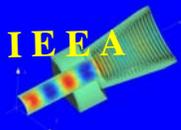


Scintillations extent : Brazil / 2002 / flux 190

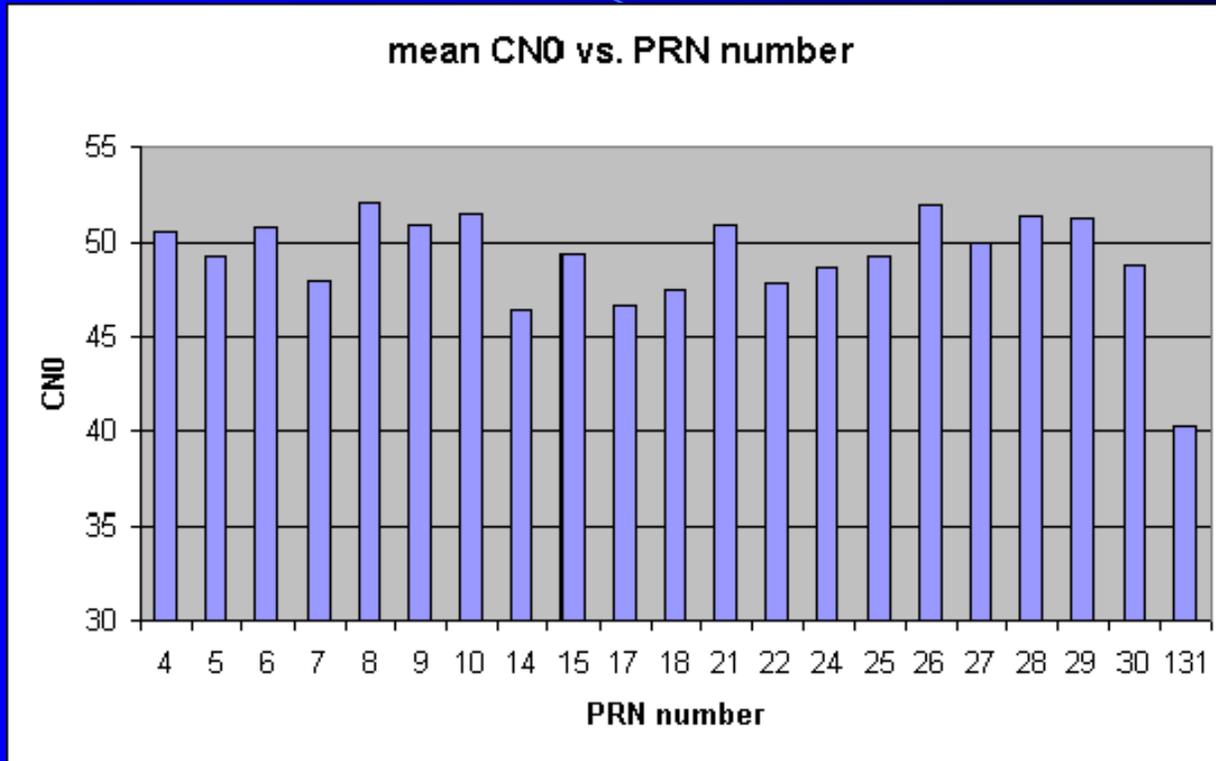


Average extent 40 minutes

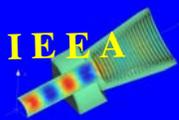
GPS Loss of Lock



Received Power

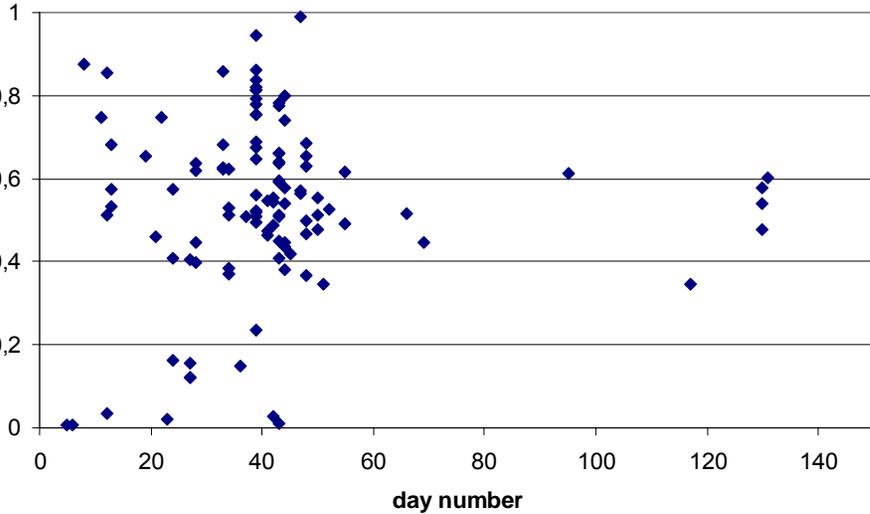


GPS satellites with an elevation angle greater than 30°
 28° of elevation angle for the GEO

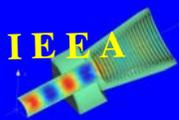
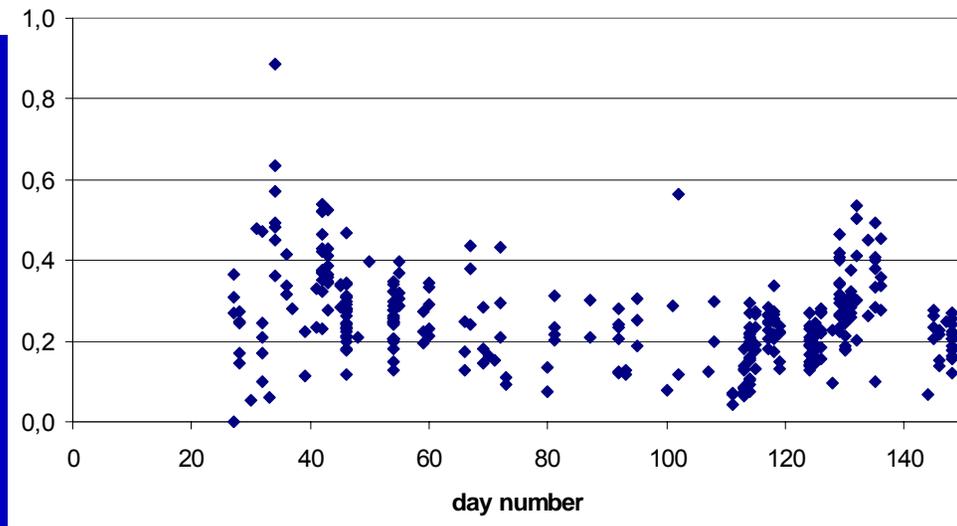


Loss of Lock L1

S4 before loss of lock (GPS satellites)

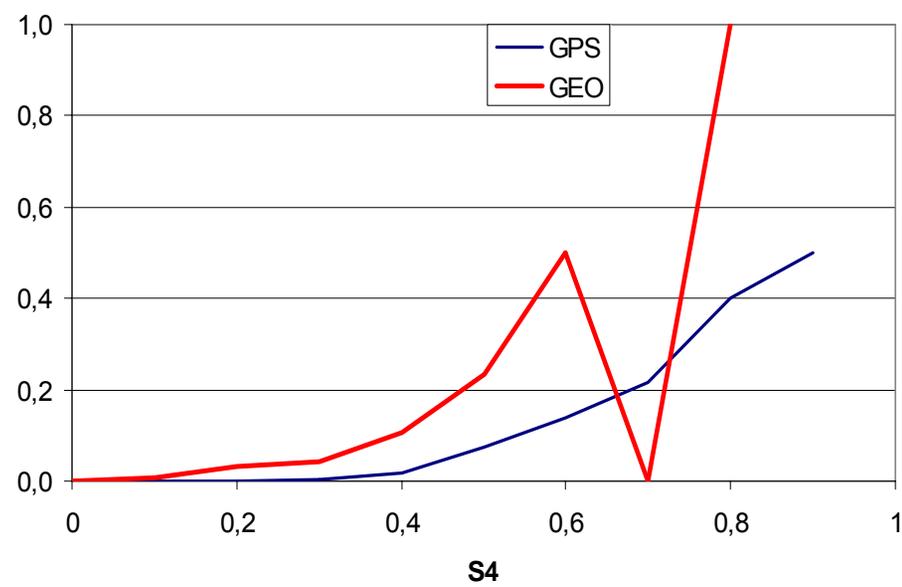
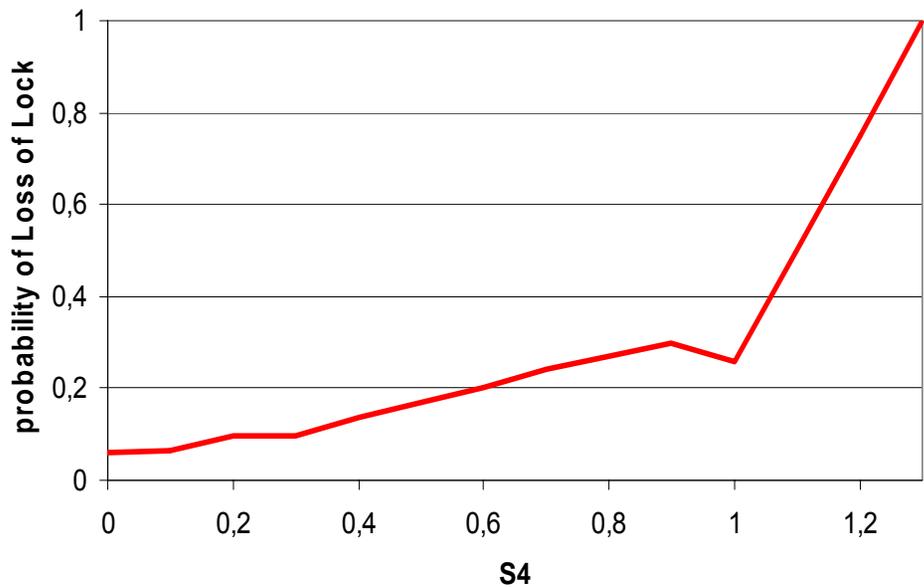


S4 before loss of lock (GEO satellite)



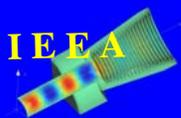
Loss of Lock Probability

Non identical receivers

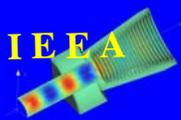


São Paulo / 2002 / flux 190

Douala / 2004 / flux 110



Scintillations at receiver level



Phase noise at receiver level

$$\sigma_{\Phi}^2 = \sigma_{\Phi S}^2 + \sigma_{\Phi T}^2 + \sigma_{\Phi, \text{osc}}^2$$

$\sigma_{\Phi S}^2$

Phase scintillation

$\sigma_{\Phi T}^2$

Thermal noise

$\sigma_{\Phi, \text{osc}}^2$

Oscillator noise

Thermal noise

$$\sigma_{\Phi T}^2 = \frac{B_n \left[1 + \frac{1}{2 \eta (c / n_0) (1 - 2 s_4^2)} \right]}{(c / n_0) (1 - s_4^2)}$$

s_4 scintillation index

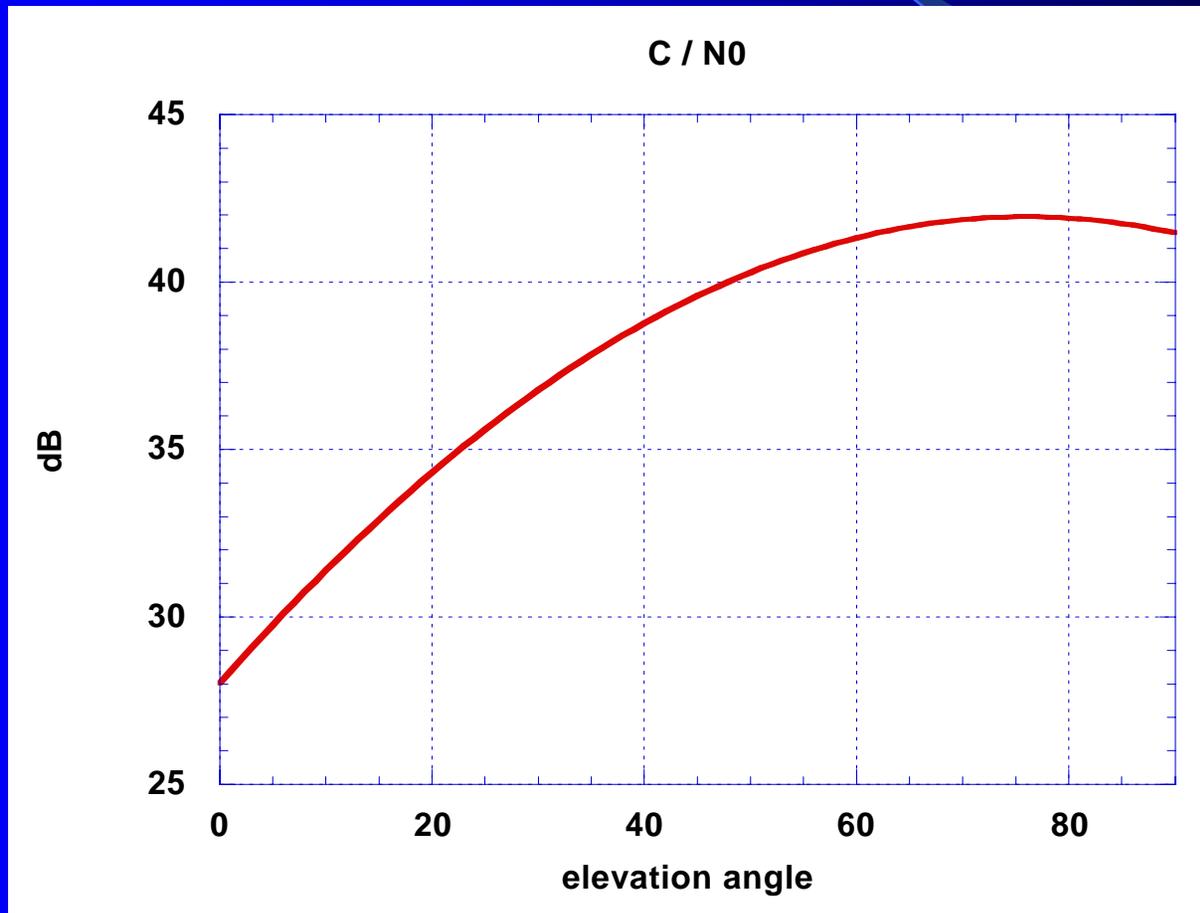
C / N_0 signal to noise ratio

η predetection integration time

B_n receiver bandwidth

C / N₀ calculation

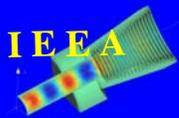
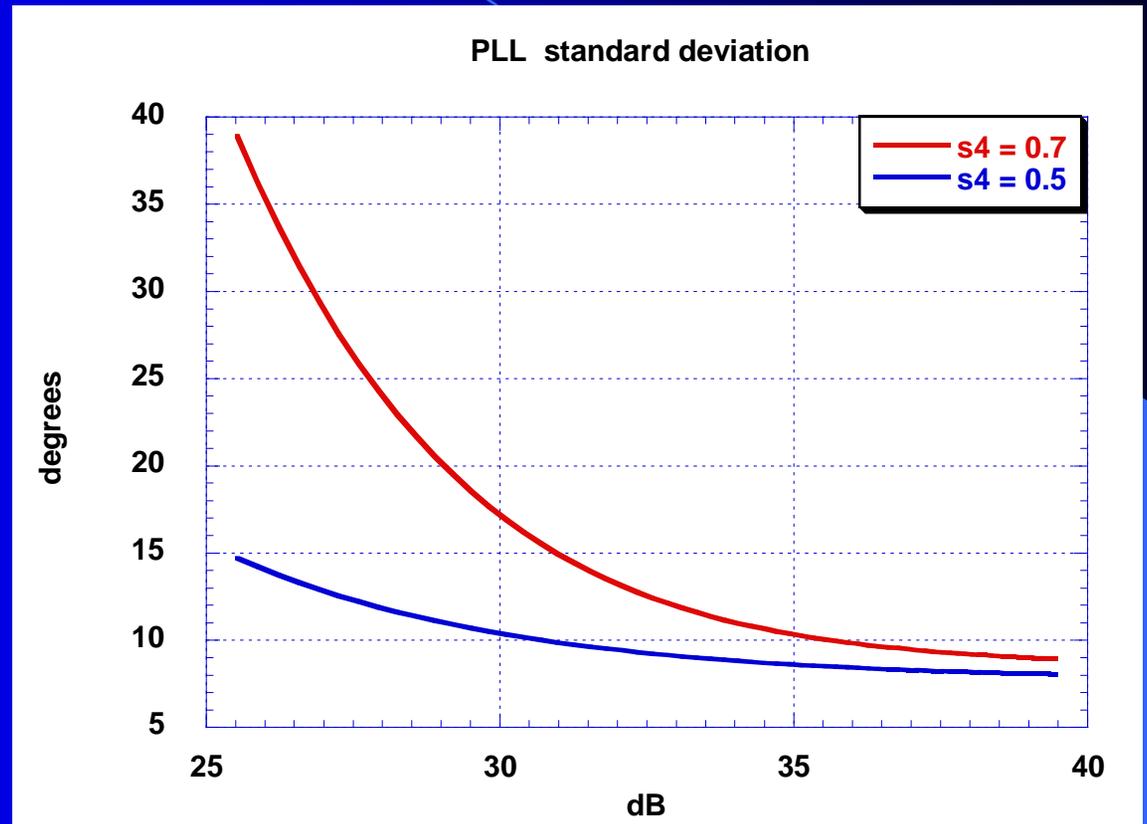
$$C / N_0 = P_0 + G_t + G_r - \text{Propag losses} - \text{Insertion Losses} - N_0$$



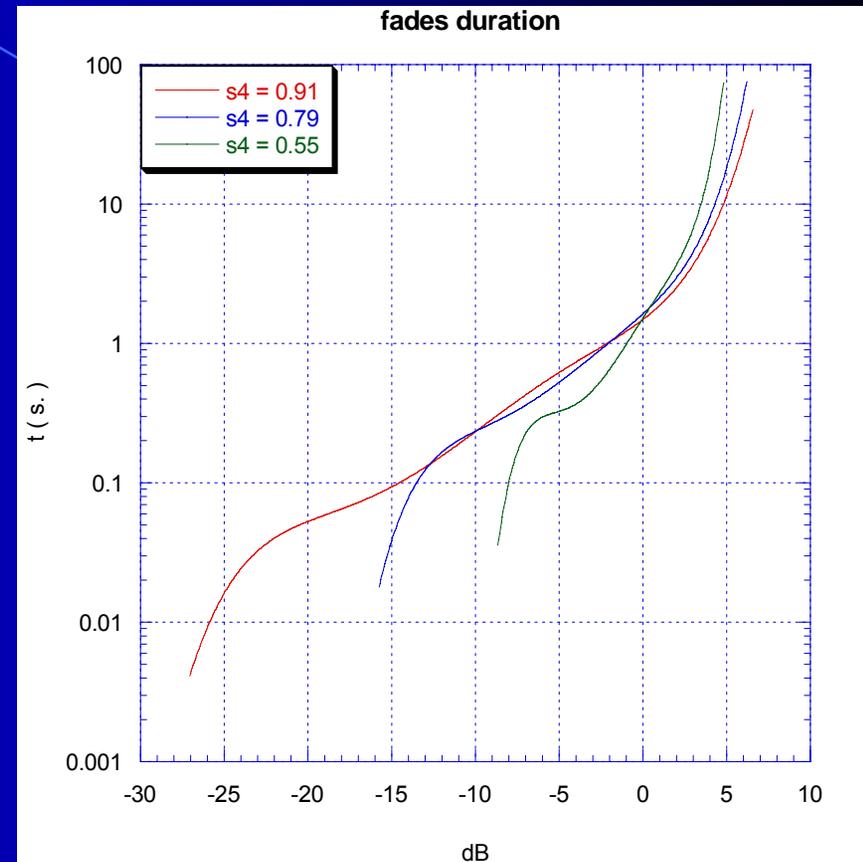
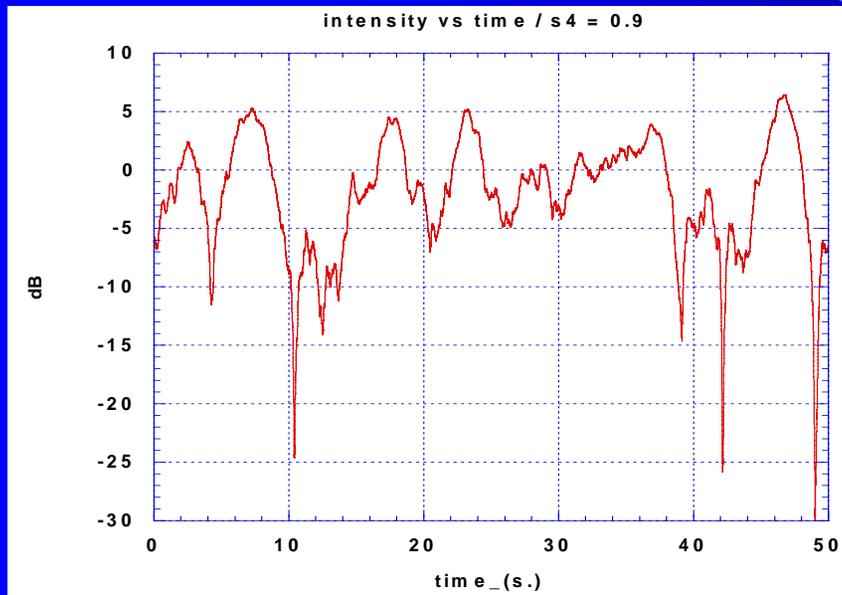
σ_{PLL}

Loss of lock

15°



Fade Duration vs Depth



Fade duration to be compared with the predetection integration time

if $> \eta$ then it decreases C / N_0

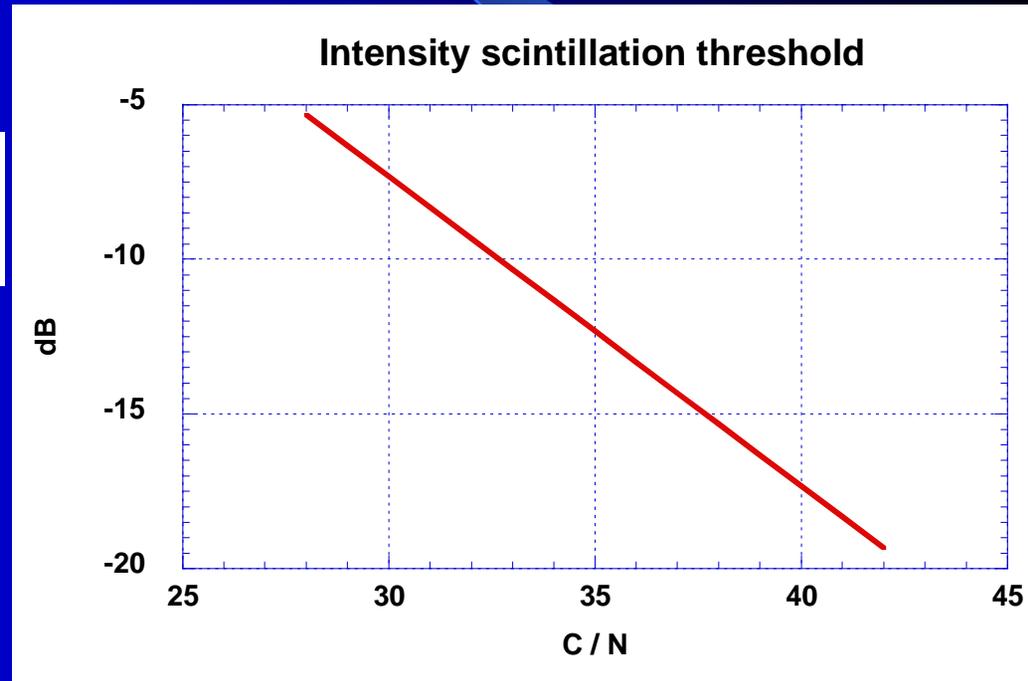
$10 \text{ ms} < \eta < 20 \text{ ms}$

Loss of Lock Thresholds

- The thermal noise is the essential contribution to the DLL
- The level is decreased by the fade depth

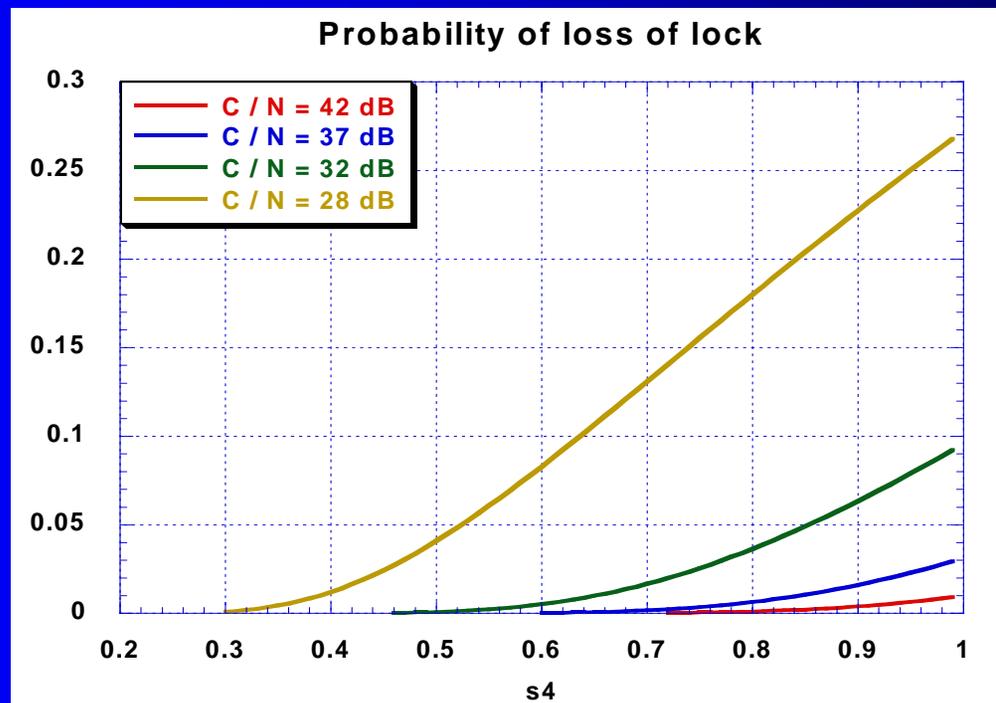
$$\sigma_{\Phi_T}^2 = \frac{B_n}{(c/n_0) I} \left[1 + \frac{1}{2\eta (c/n_0) I} \right]$$

I scintillation intensity

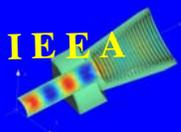


Loss of Lock Probability

- The probability of intensity is Nakagami distributed
- The loss of lock probability is the corresponding cumulative probability, given the threshold



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

Receiver DLL model

$$\sigma_{\tau}^2 = \frac{B_n d \left[1 + \frac{1}{\eta (c/n_0)_{L1-C/A} (1 - 2S_4^2(L1))} \right]}{2 (c/n_0)_{L1-C/A} (1 - S_4^2(L1))}$$

$B_n = 0.1 \text{ Hz}$

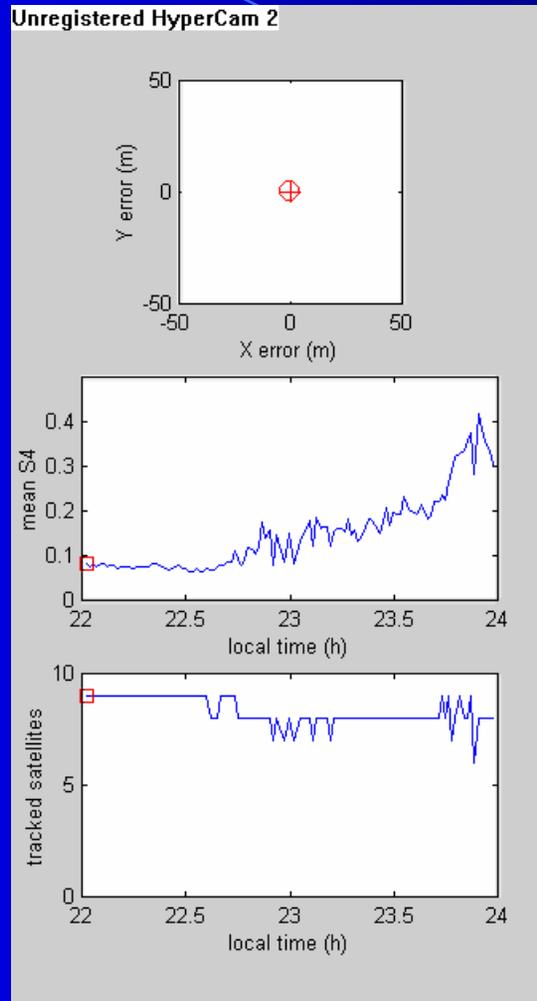
$d = 1.$

$\eta = 0.02 \text{ s}$

$C/N_0 = 35 \text{ dB}$

Chip length = 293.0523 m

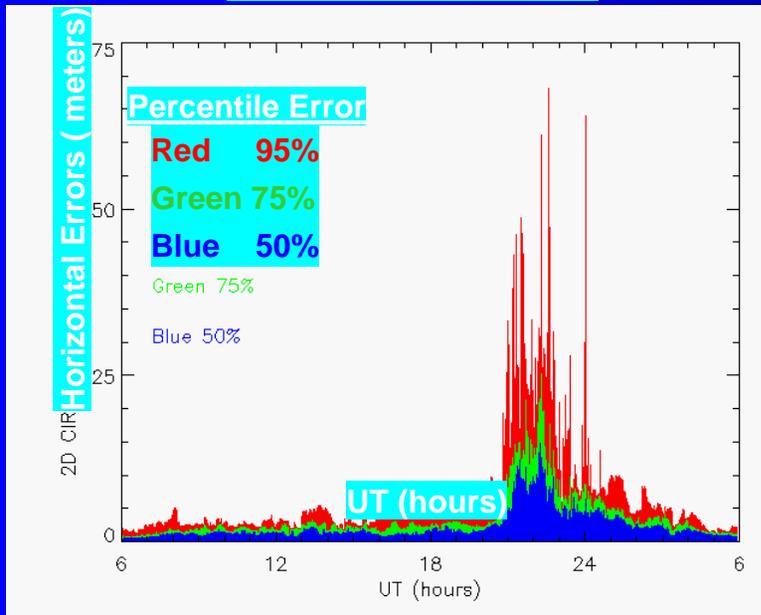
GPS Positioning Errors



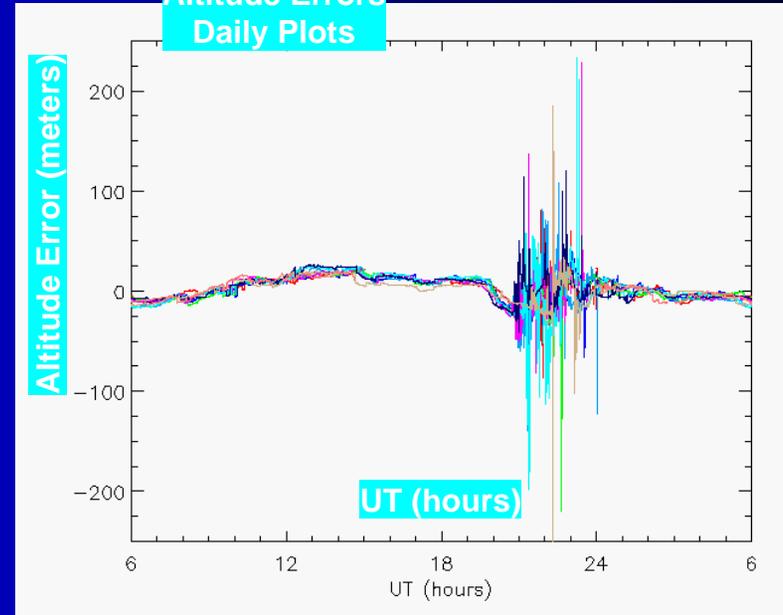
Characteristic Errors and Nightly Occurrence Patterns

Ascension Island, 7- 18 March 2002

Distribution of 2D Errors

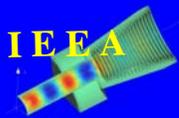


Altitude Errors Daily Plots



- Largest errors occur during period of most severe L-band scintillation, 21:00 to 23:30 UT

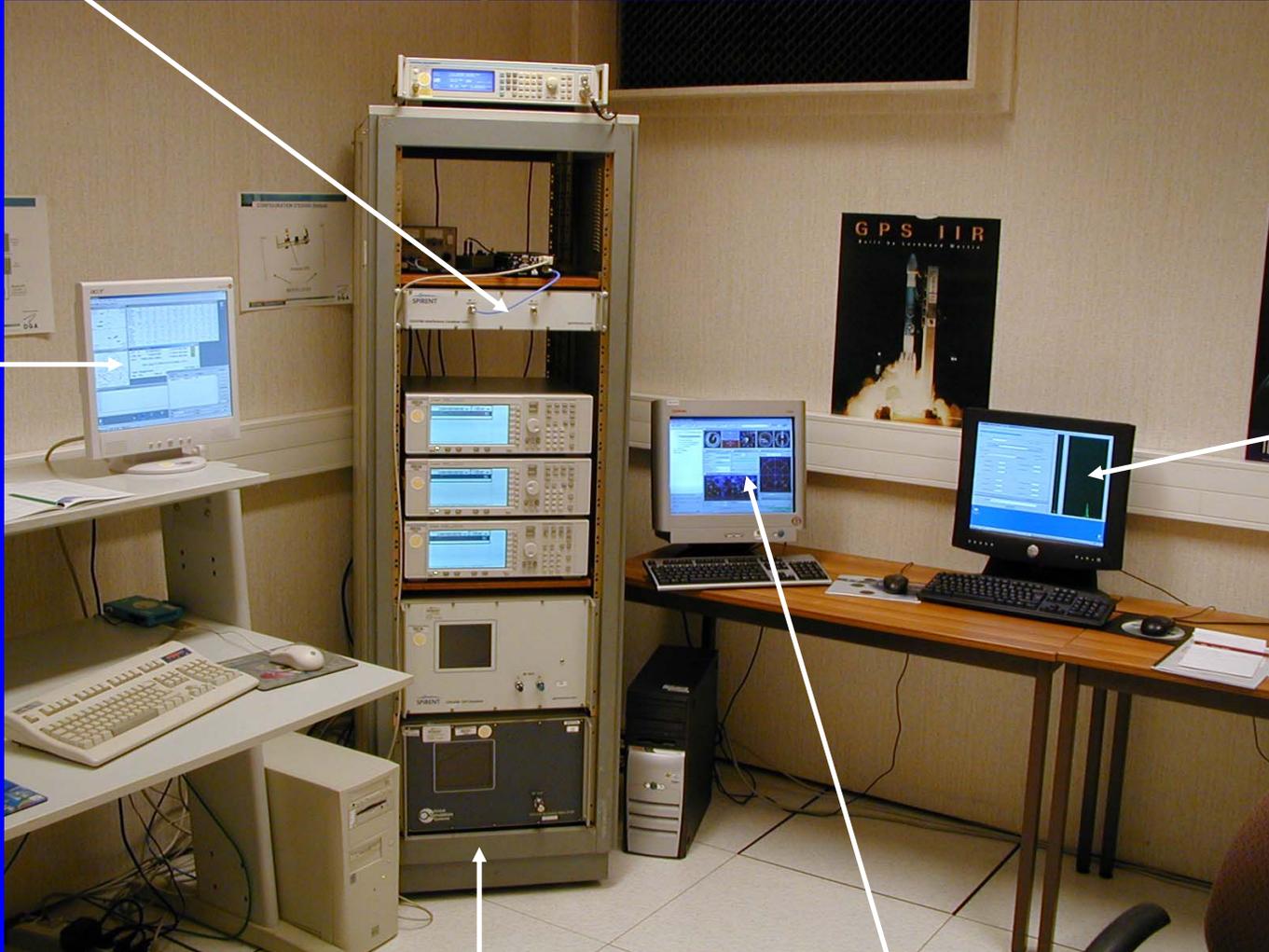
Courtesy : K. Groves, AFRL



Simulations in laboratory

Experimental set up

Receiver under test

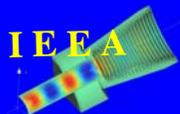


Receiver input unit

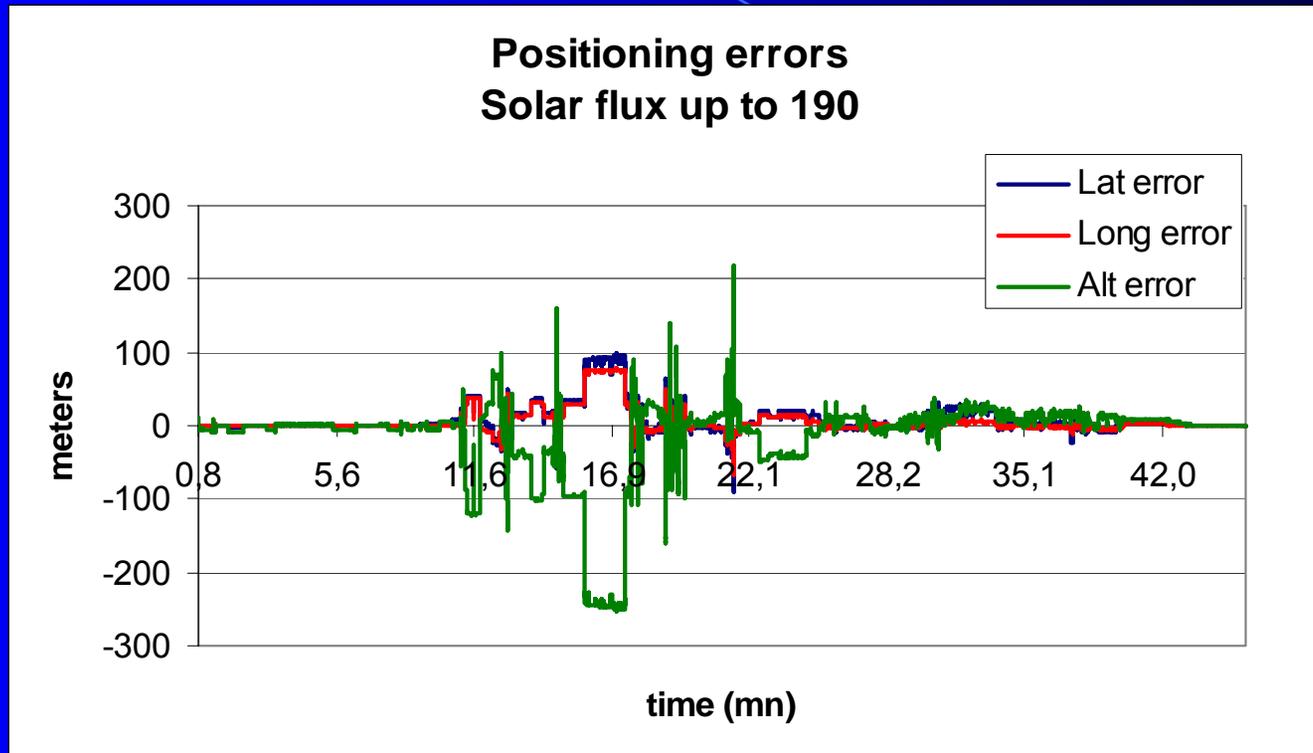
GISM simulator

Spirent GPS constellation generator

Spirent simulator command unit



Positioning errors obtained with the simulator



GISM module activated at $t = 10$ min and deactivated at $t = 40$ min

Each link is modified including a signal modification according to the s_4 value prescribed by the model

Modelling GISM

Mixed climatological / Physical model : background : NeQuick

Multiple phase screen theory / solution of the parabolic equation

Propagation Equations

The Helmholtz equation

$$\nabla^2 E + k^2(z)[1 + \varepsilon(x, z)]E = 0$$

The field expression

$$E(x, z) = U(x, z) \exp\left(i \int_0^z k(z) dz\right)$$

Parabolic equation

$$2ik \frac{\partial U}{\partial z} + \nabla_t^2 U + k^2 \varepsilon U = 0$$

Phase change

$$2ik \frac{\partial U}{\partial z} + k^2 \varepsilon U = 0$$

Propagation

$$2ik \frac{\partial U}{\partial z} + \nabla_t^2 U = 0$$

One phase screen to the next one

$$U(x, z + \Delta z) = \left(\frac{k}{2i\pi\Delta z}\right)^{1/2} \int U(x', z) \exp\left(\frac{ik\Delta z}{2} \varepsilon(x', z)\right) \exp\left(\frac{ik(x-x')^2}{2\Delta z}\right) dx'$$

GISM Outputs

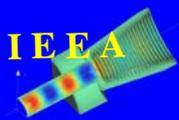
Average errors : range, phase, angular, Faraday rotation

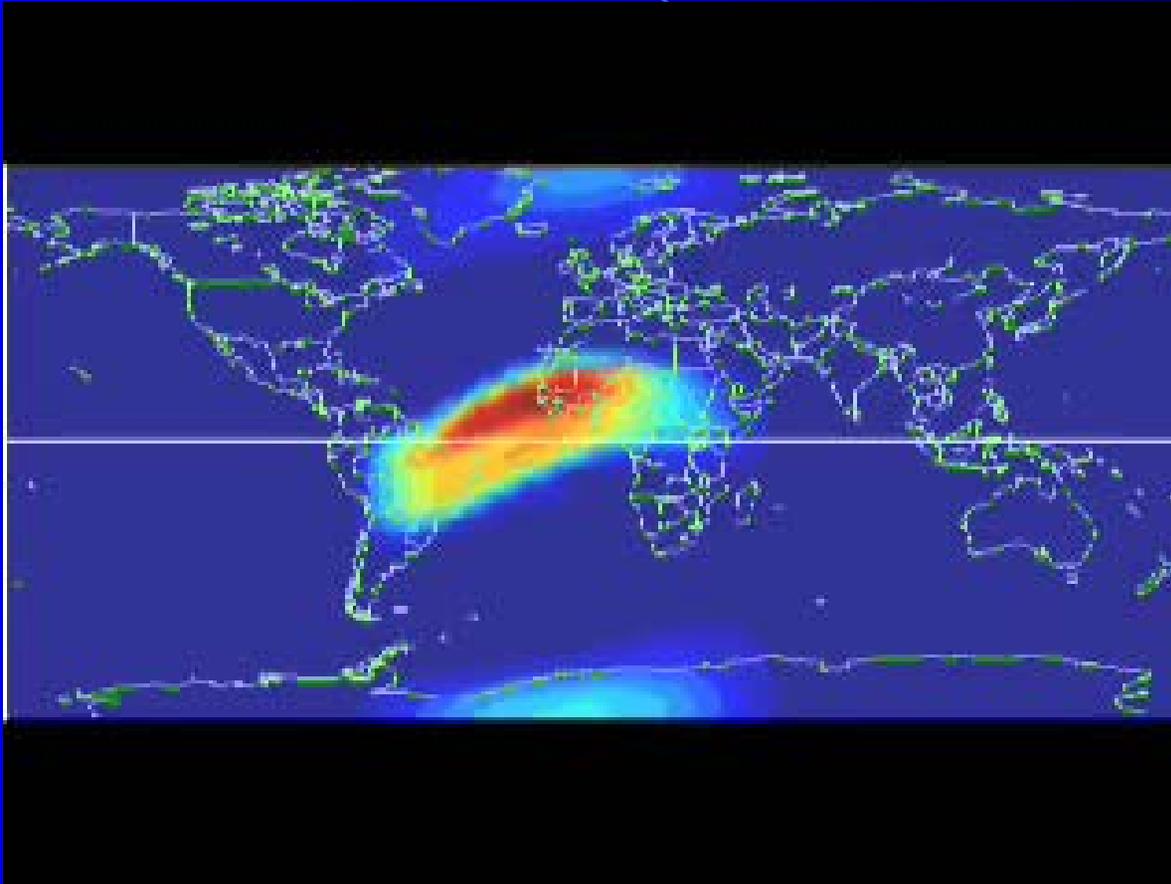
Scintillations

- s_4 & σ_ϕ
- angle of arrival fluctuations
- frequency, space & time coherence lengths
- probabilities
- Spectrum

The model includes an orbit generator allowing performing system analysis

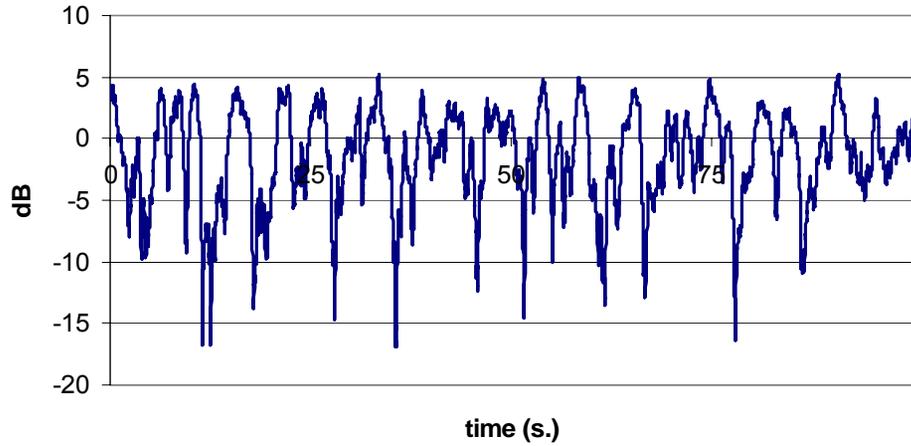
Signal generator for testing receivers in the presence of scintillations



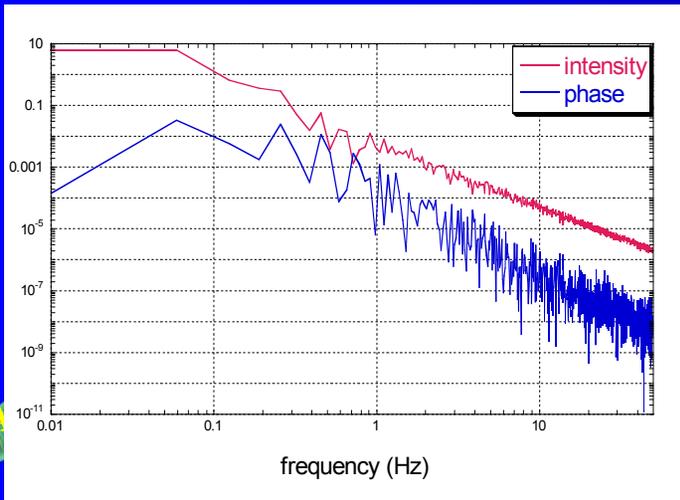
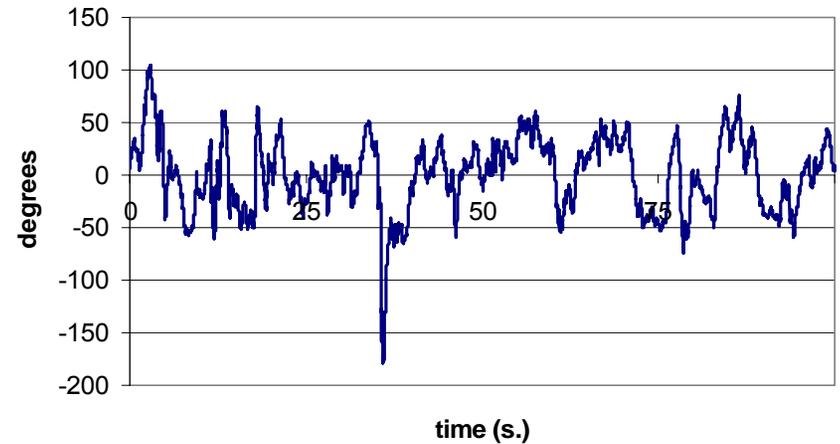


Scintillations results obtained with the model

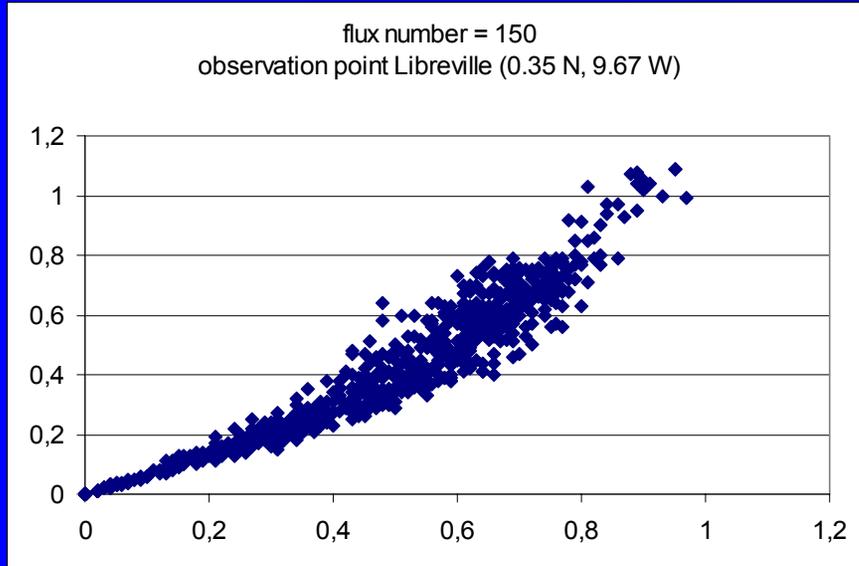
$s_4 = 0.70$



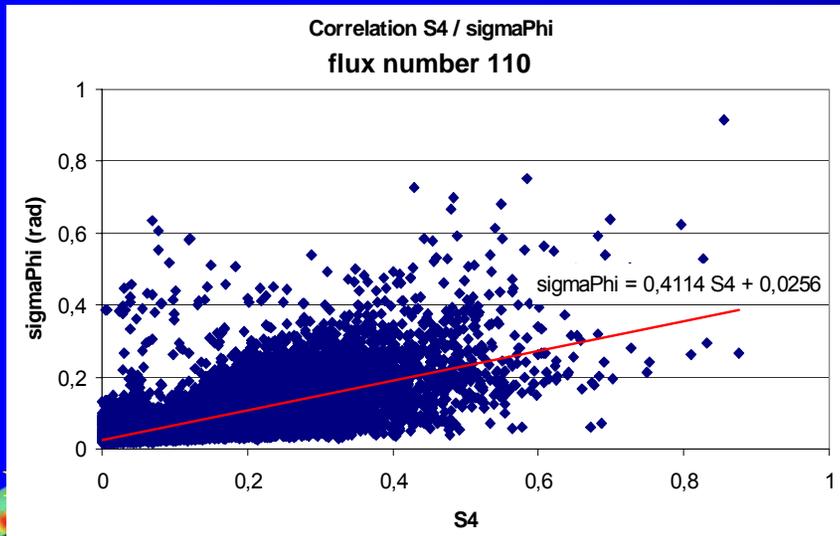
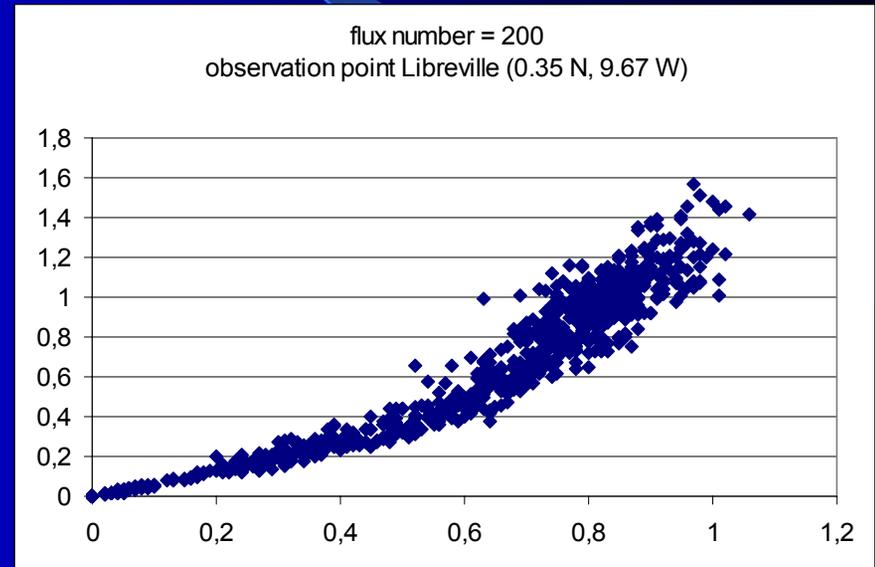
$\sigma_{\phi} = 0.61$



S4 versus sigma phi depending on the flux number

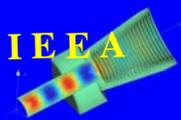


Modelling

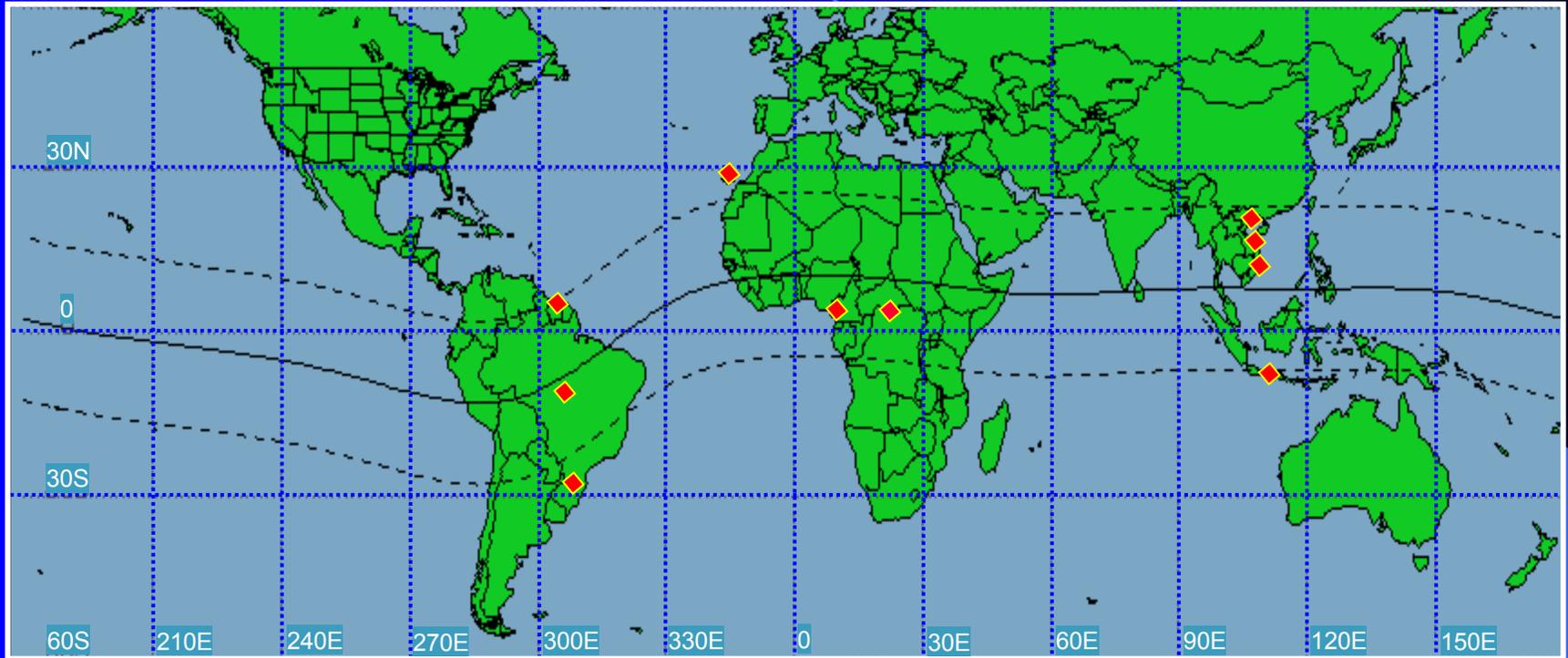


Measurements
Douala (4°N, 9° W)

Measurement Campaign



Project of receivers installation in the equatorial regions



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

Parameters of interest

- S4 and sigma phi
- Time and seasonal dependency
- Extent / Correlation distances
- Probabilities / frequencies of occurrences

Future work

- Measurements campaign data
 - A data base is being built up
 - It will be supplemented by the analysis of the raw data files for some parameters
- Improvement of the GISM model correlatively