COMBINATION OF A RADIO WAVE SCATTERING ALGORITHM WITH COHERENT RADAR DATA FOR EQUATORIAL SCINTILLATION PREDICTIONS

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Outline

- Introduction, Motivation and Objectives
- Instrumentation (Coherent Radar and Scintillation Monitor) and Data Description
- Algorithm for Slant Propagation Through an Irregularity Layer
- Screen Model Based on Radar RTI (Range-Time-Intensity) Data
- Results and Discussion
- Conclusion

Introduction

- Ionospheric scintillation may significantly affect the operations of space-based communication and navigation systems.
- For their support, short-term specification and forecast systems based on real-time measurements are needed.
- C/NOFS is based on an equatorial non-GSO satellite. Data from sensors on board drive an equatorial ionospheric model to forecast the onset of plasma instability and its evolution. Radio wave scattering theory determines the scintillation of satellite signals propagating through the medium and received on the ground. Results will be validated by measurements performed using beacon transmissions.

Introduction

- However, sensors on board any orbiting satellite only detect electron density fluctuations within an extremely limited altitude range.
- On the other hand, radars give us a picture of small-scale turbulence that shows large variations of backscattered power with range. It is reasonable to expect variations in the amplitude of km-scale irregularities with altitude as well.
- Height-dependent distributions of the turbulence may improve scintillation forecasting from space-based in situ observations.

Introduction

- Our forecasting capability could increase if we were able to directly relate the intensity of radar backscatter to the amplitude of km-scale fluctuations causing scintillation.
- This is a difficult problem, with too many uncertainties.

Objectives

- To perform a rough estimation of the scintillation index S_4 at 1575 MHz by the application of a 3D propagation algorithm to a combination of coherent radar RTI data with a simplified wideband spectral model of electron density fluctuations.
- To compare the results from the above model with GPS scintillation measurements from INPE’s equatorial observatory at São Luís, MA Brasil.

Instrumentation and Data Description

- The São Luís coherent scatter radar (2.3º S, 44º W, dip latitude 1.3º S, declination 19º W) is conceptually similar to the JULIA radar at Jicamarca and operates at 30 MHz to detect 5-m ionospheric irregularities.
- The radar consists of indoor equipment and two arrays of 16 Yagi antennas arranged side-by-side in the magnetic E-W direction.

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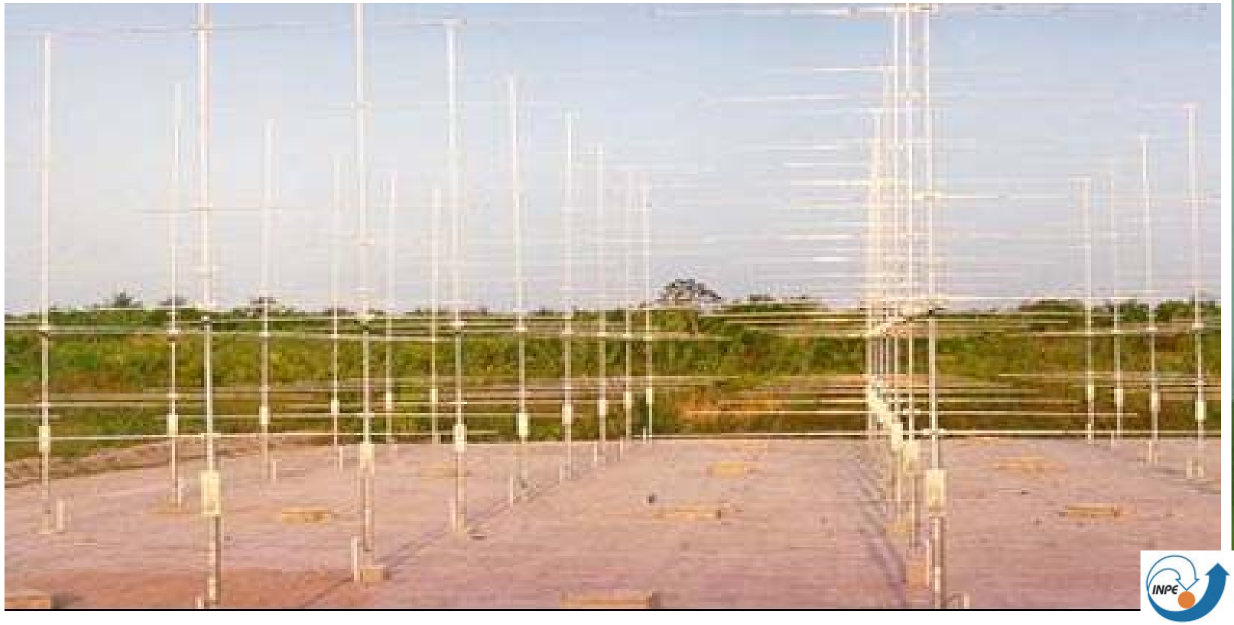
Instrumentation and Data Description

- The half-power beam width in the magnetic E-W plane is about 10º. The radar samples the medium up to 1400 km with 2.5 km resolution.



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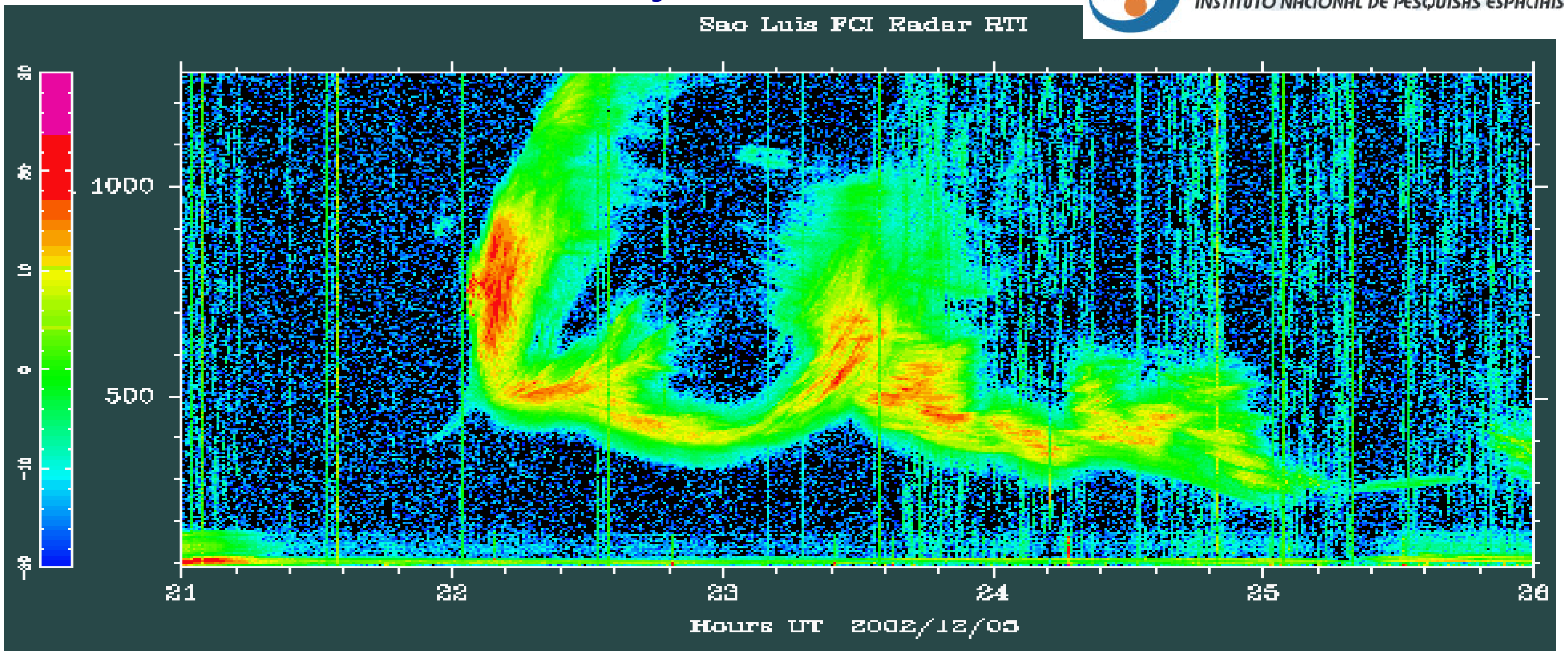
Instrumentation and Data Description

- The São Luís radar generates real-time RTI (range-time-intensity) maps of 5-m scale irregularities, which will be explored later.
- Post-processing also provides vertical and zonal drift information, which will not be used today.



Instrumentation and Data Description

- Results will be compared with S_4 data from a co-located GPS-based scintillation monitor which is part of INPE’s network of 17 stations.
- The monitors, developed by Cornell University, are capable of sampling the L1 intensity signals (1575.42 MHz) from up to 11 GPS satellites at 50 Hz.
- L1 GPS signals are sensitive to approximately 400-m scale size irregularities.

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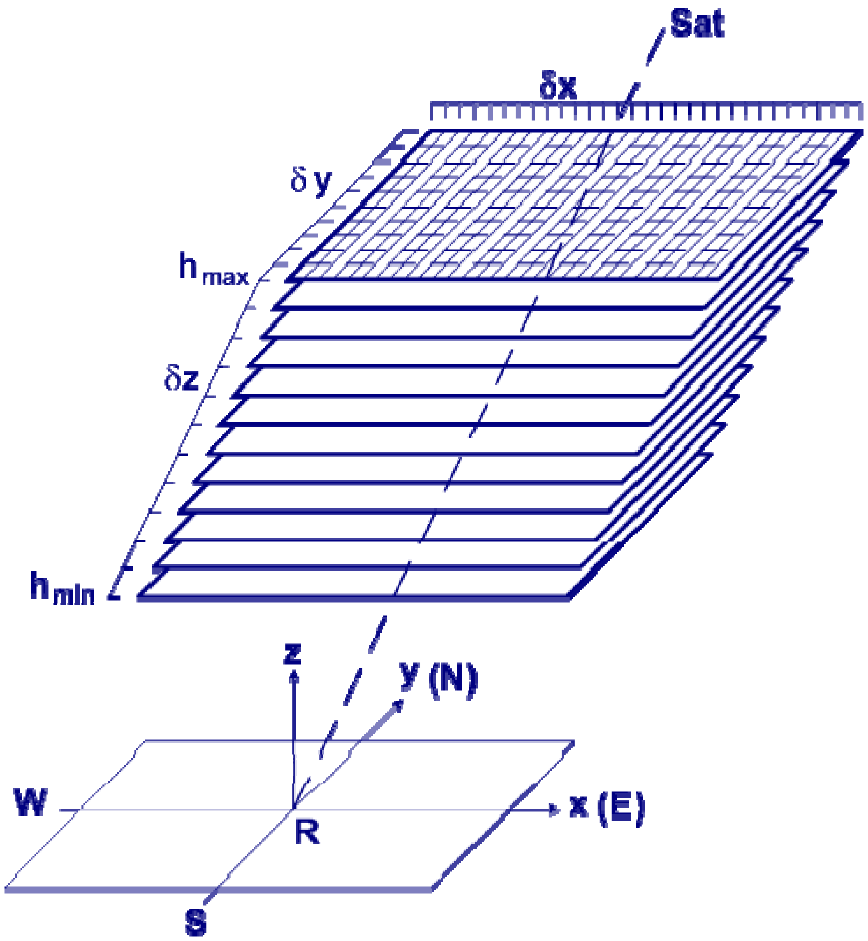
Algorithm for Slant Propagation Through an Irregularity Layer

- The irregularity layer is represented by uniformly-spaced (δz) multiple screens.
- For each screen:
  - assume frozen-in, field-aligned (NS) irregularities drifting eastward;
  - generate zero-mean random density fluctuation with standard deviation ΔN defined over a regular grid (m δx, n δy) according to a 1D spectral density model for the EW direction.
- For each UT: propagation from h_{max} to h_{min} (multiple δz steps), followed by propagation from h_{min} to ground (one step in clear space).



Algorithm for Slant Propagation Through an Irregularity Layer

Assuming the parabolic approximation to the wave equation (neglecting backscattering in the propagation of satellite signals) and after discretization, we relate:

$$u\left(m\delta x-\frac{k_x}{k_z}\delta z, n\delta y-\frac{k_y}{k_z}\delta z, z-\delta z\right)=e^{i\frac{k(\delta\varepsilon_r)}{2k_z}\delta z}\cdot$$

medium

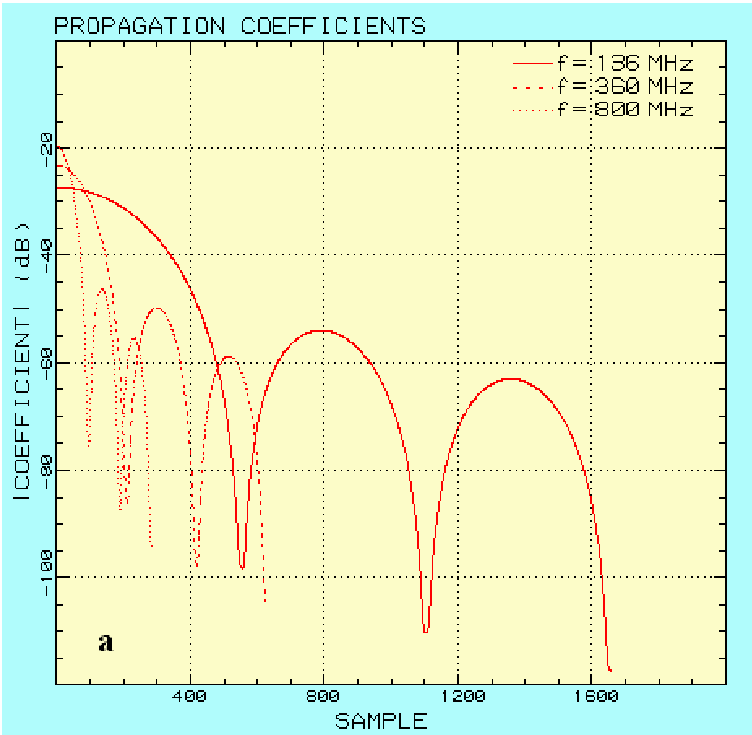
$$\cdot\sum_{p=-P}^{P}\sum_{q=-Q}^{Q}C_p^x C_q^y\, u\left[(m-p)\delta x,(n-q)\delta y, z\right]$$

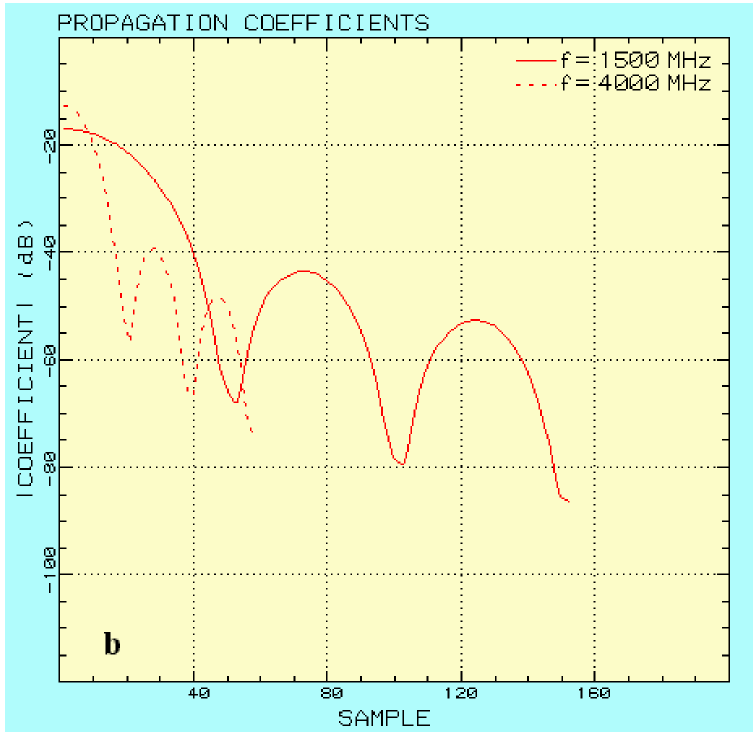
2D convolution

Algorithm for Slant Propagation Through an Irregularity Layer

$$u(m\delta x, n\delta y, 0) = \sum_{p=-P}^{P} \sum_{q=-Q}^{Q} C_p^x C_q^y u[(m-p)\delta x, (n-q)\delta x, h]$$

h = 400 km
δx = 40 m
θ = 0°





Screen Model from Radar RTI Data

- From $\delta\varepsilon_r = -\frac{r_e \lambda_r^2}{\pi}\delta N$ and using a spectral density model, we get

$$S_{\varepsilon_r}^{2D}(0,2k_r) = \frac{r_e^2 \lambda_r^4}{\pi^2} S_N^{2D}(0,2k_r) = \frac{r_e^2 \lambda_r^4}{\pi^2} \frac{(p-2)}{2\pi k_o^2} \frac{\Delta N^2}{[1+(2k_r/k_o)^2]^{p/2}}$$

- Therefore the differential cross section of the screen per unit volume becomes

$$\sigma(-\hat{z},\hat{z}) = \frac{L_{ry}}{4} k_r^4 S_{\varepsilon_r}^{2D}(0,2k_r) = \frac{2\pi L_{ry} r_e^2 (p-2)}{k_o^2} \frac{\Delta N^2}{[1+(2k_r/k_o)^2]^{p/2}}$$

Screen Model from Radar RTI Data

- Combining

$$\sigma(-\hat{z},\hat{z}) = \frac{2\pi L_{ry} r_e^2 (p-2)}{k_o^2} \frac{\Delta N^2}{[1+(2k_r/k_o)^2]^{p/2}}$$

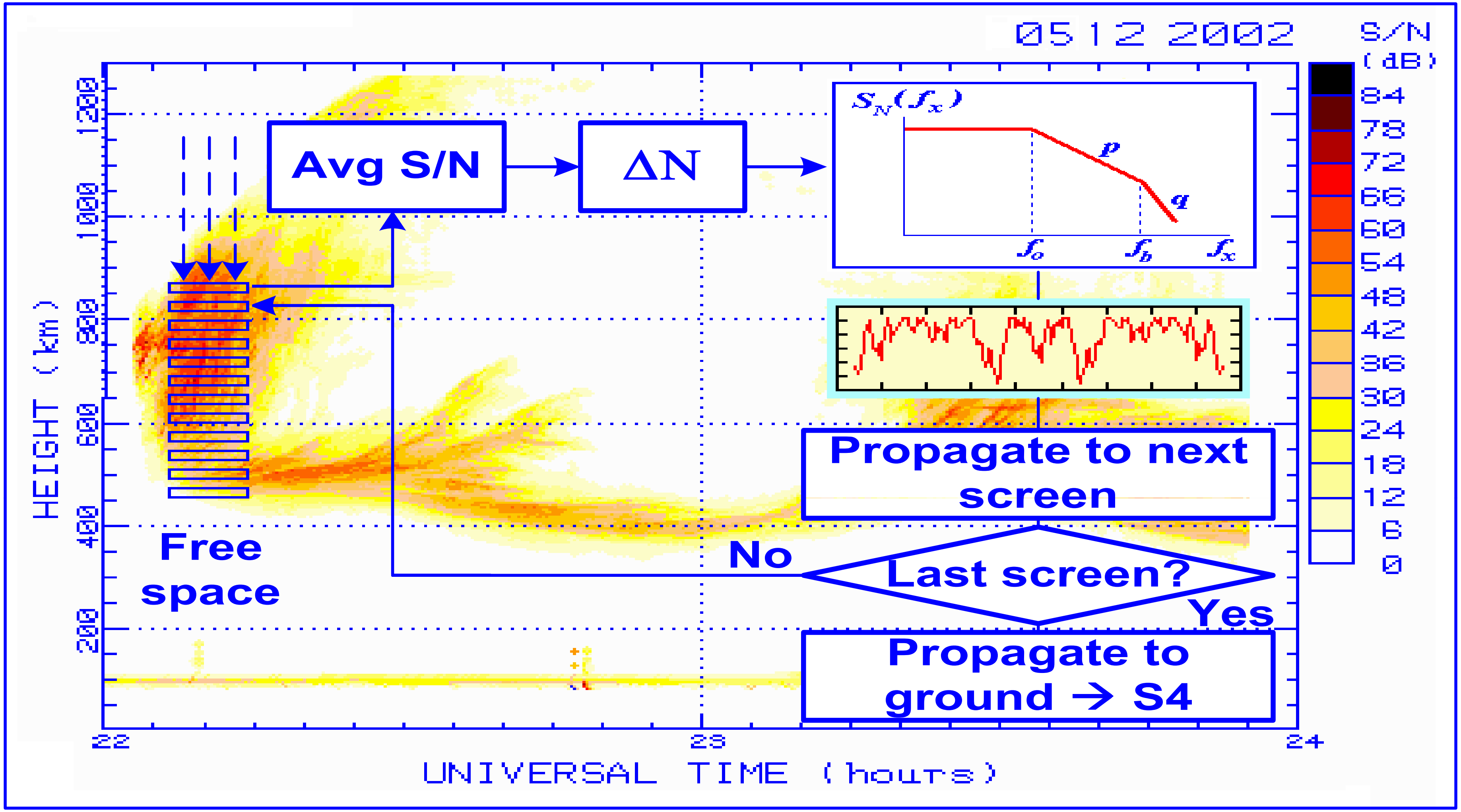
with the radar equation

$$\left(\frac{S}{N}\right) = \frac{1}{2Ln2} \frac{P_t G^2 \lambda_r^2 [\sigma(-\hat{z},\hat{z})V]}{(4\pi)^3 R^4 (k_B TBF)\, L_s L_p}$$

we finally get

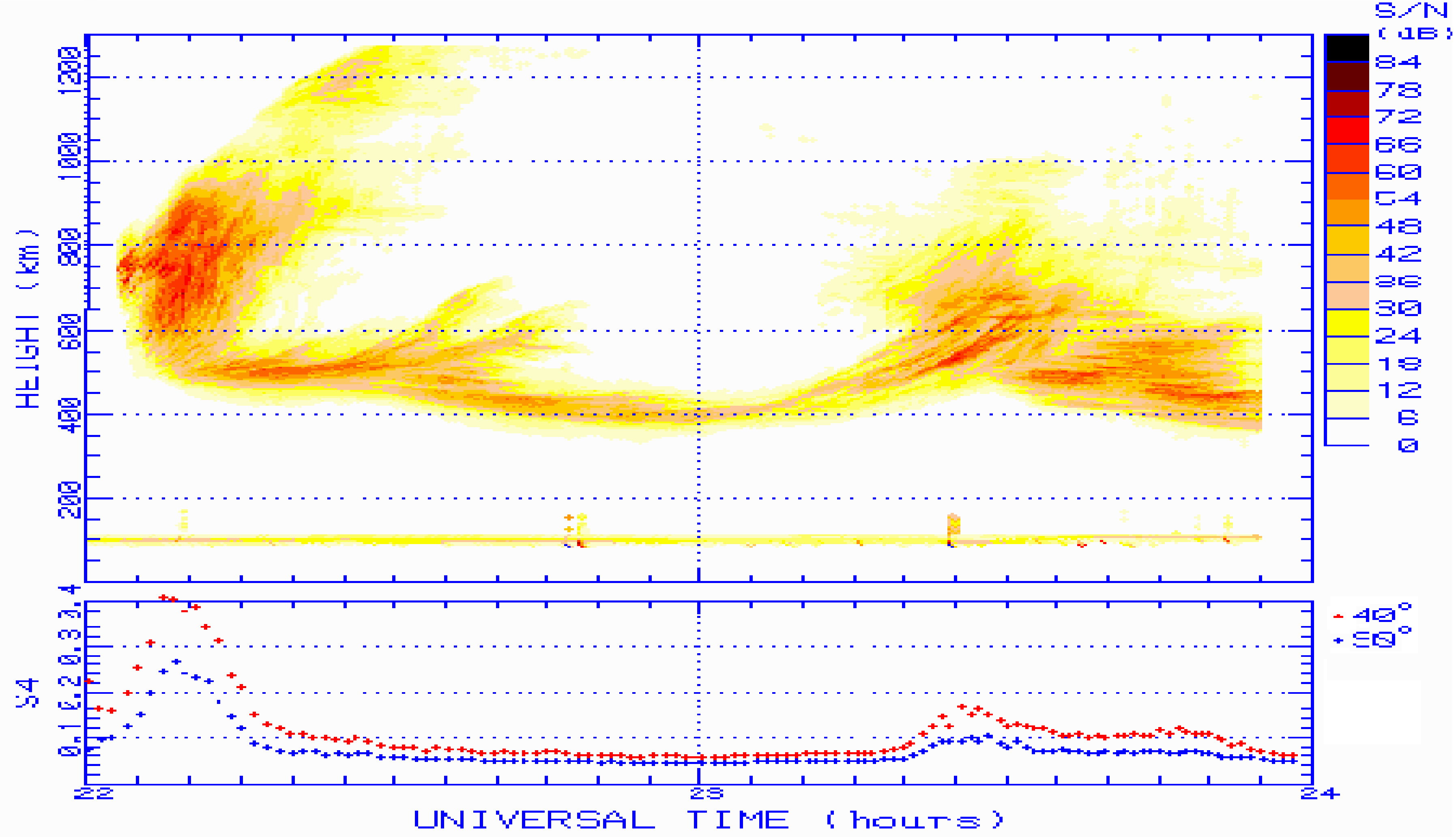
$$\left(\frac{\Delta N}{N_o}\right) = \frac{C_r}{N_o} \frac{\sqrt{R}}{\left(\frac{p}{2}-1\right)} \frac{\lambda_r^2}{L_o^2} \left(1+4\frac{L_o^2}{\lambda_r^2}\right)^{p/2} \sqrt{\frac{S}{N}}$$

Summary

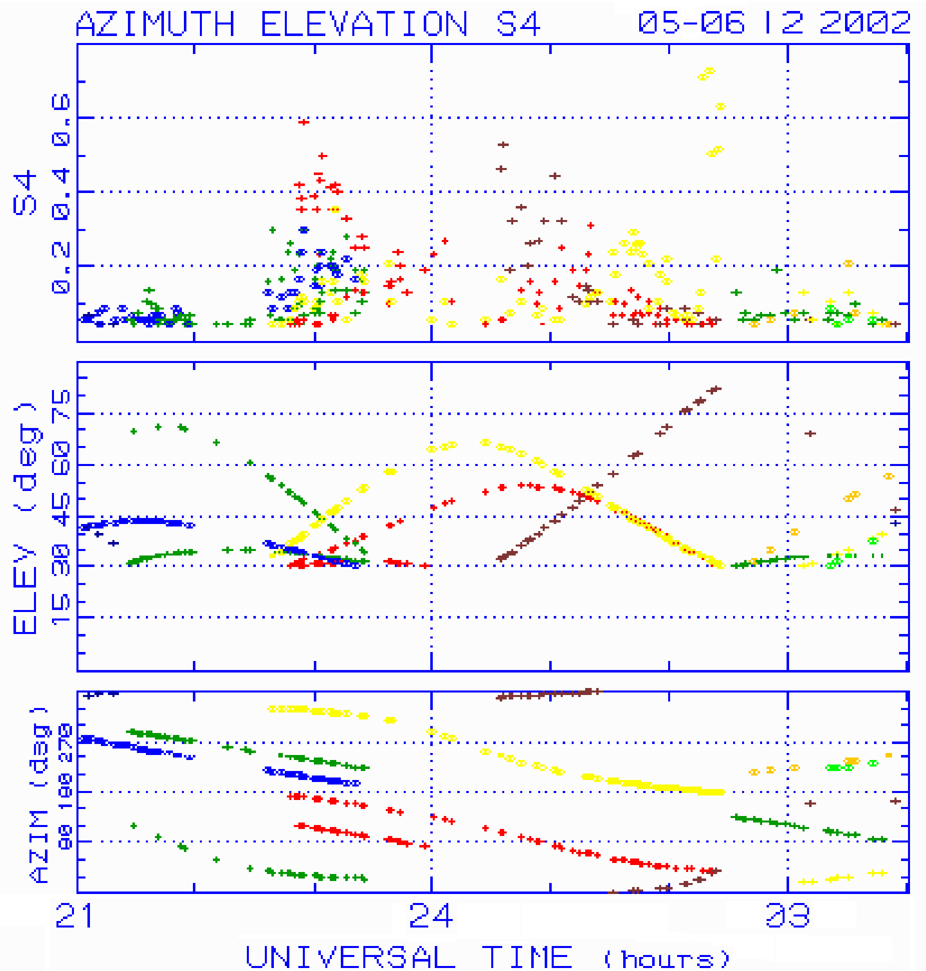


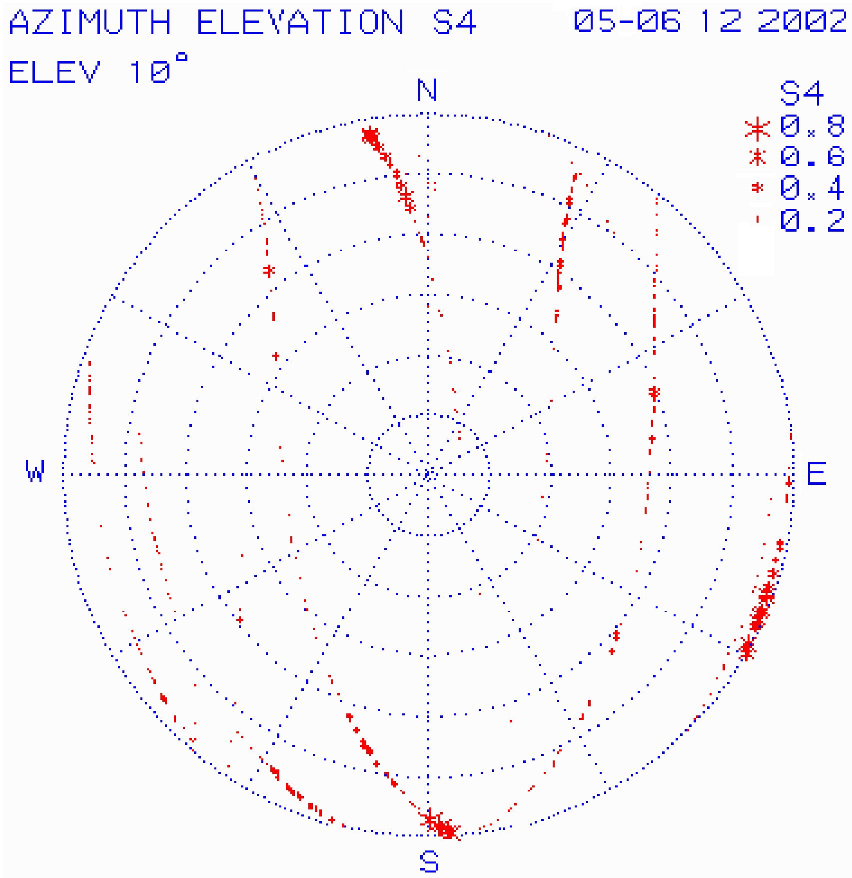
05 12 2002
S/N (dB)
84
78
72
66
60
54
48
42
36
30
24
18
12
6
0
HEIGHT (km)
1200
1000
800
600
400
200
22
23
24
UNIVERSAL TIME (hours)
Avg S/N
ΔN
$S_N(f_x)$
p
q
f_o
f_b
f_x
Propagate to next screen
No
Last screen?
Yes
Propagate to ground → S4
Free space

São Luís RTI Map and Calculated S4 Values at 1575 MHz (Two Elevations – Dec 05 2002)

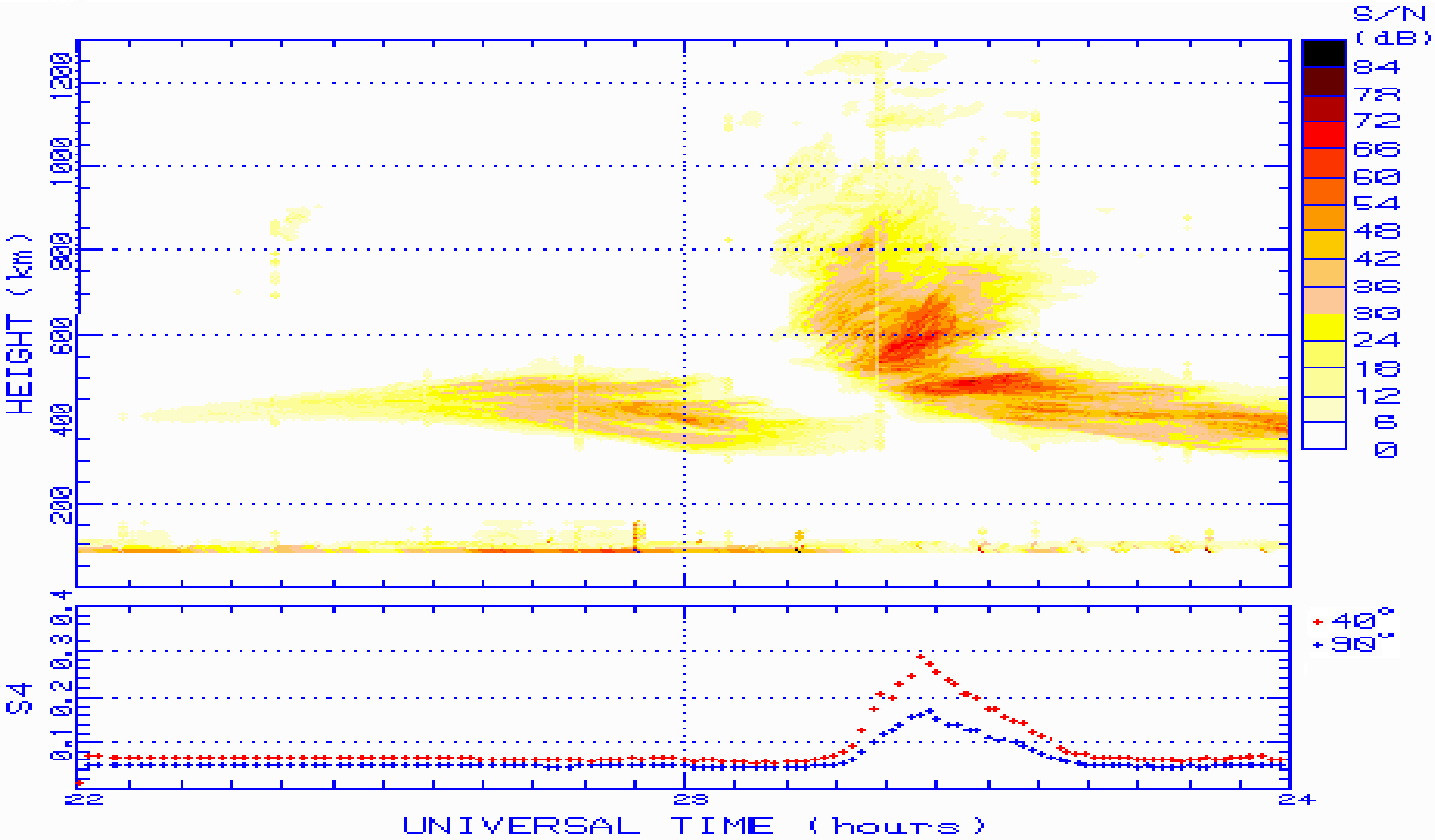


S_4 Measurements around São Luís at 1575 MHz (GPS Monitor)

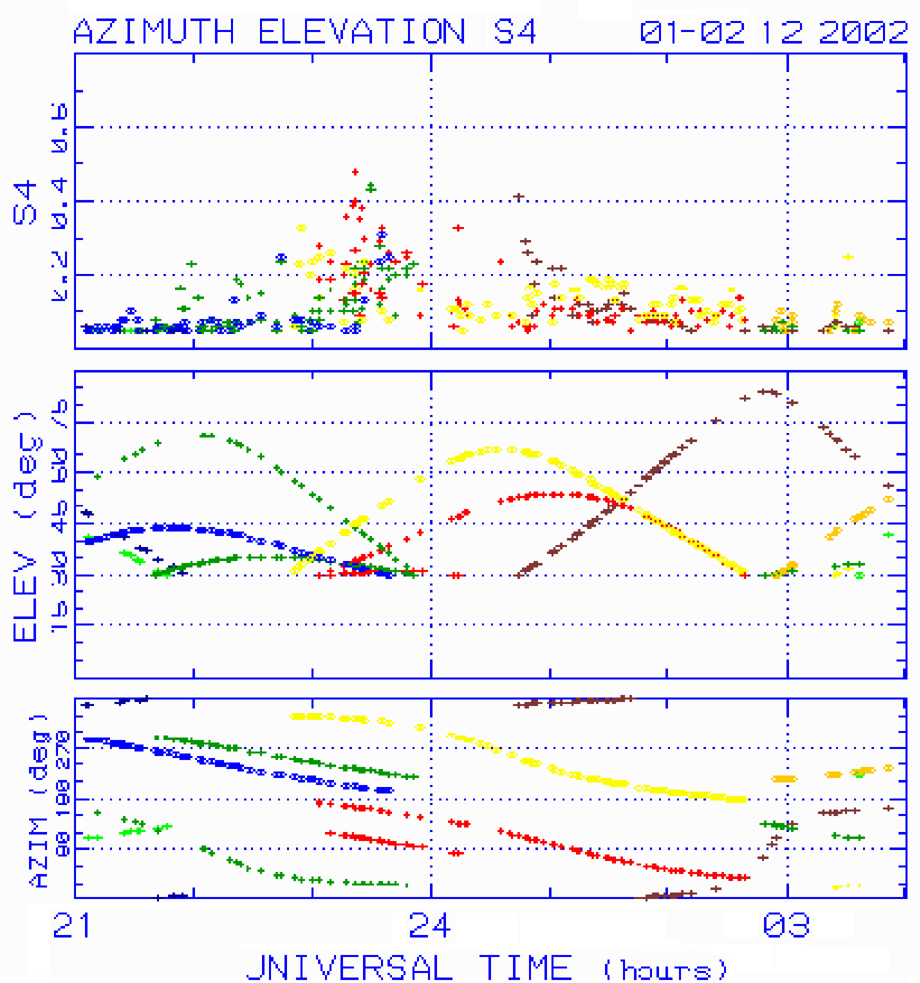


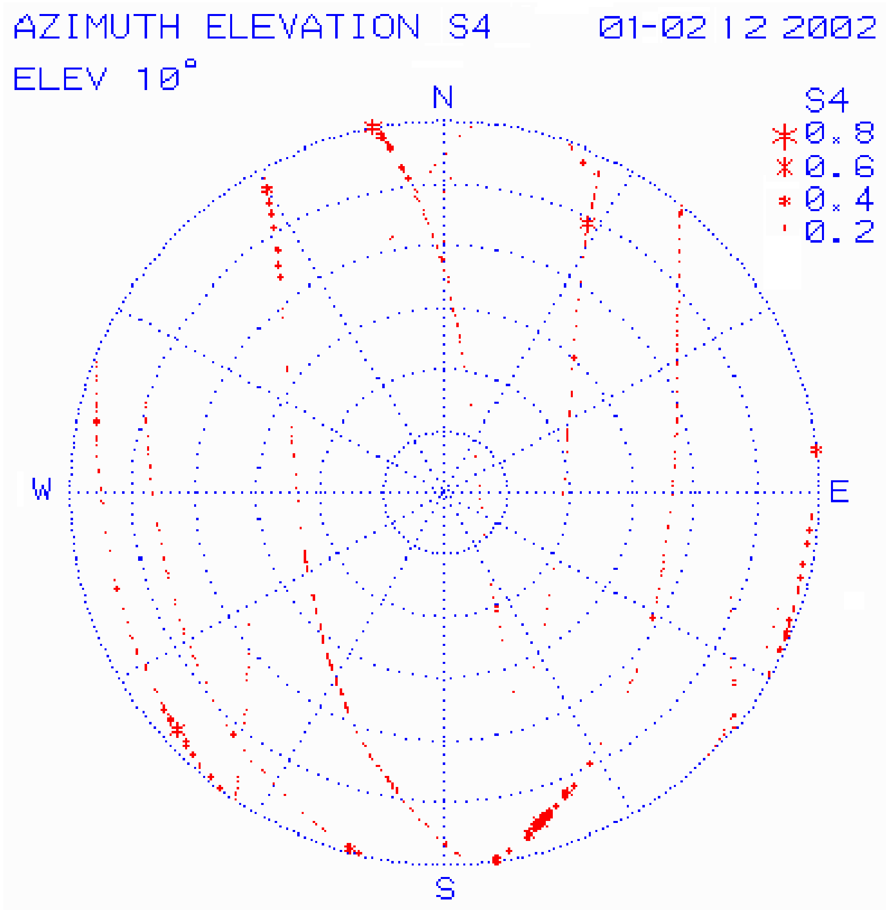


São Luís RTI Map and Calculated S4 Values at 1575 MHz (Two Elevations – Dec 01 2002)

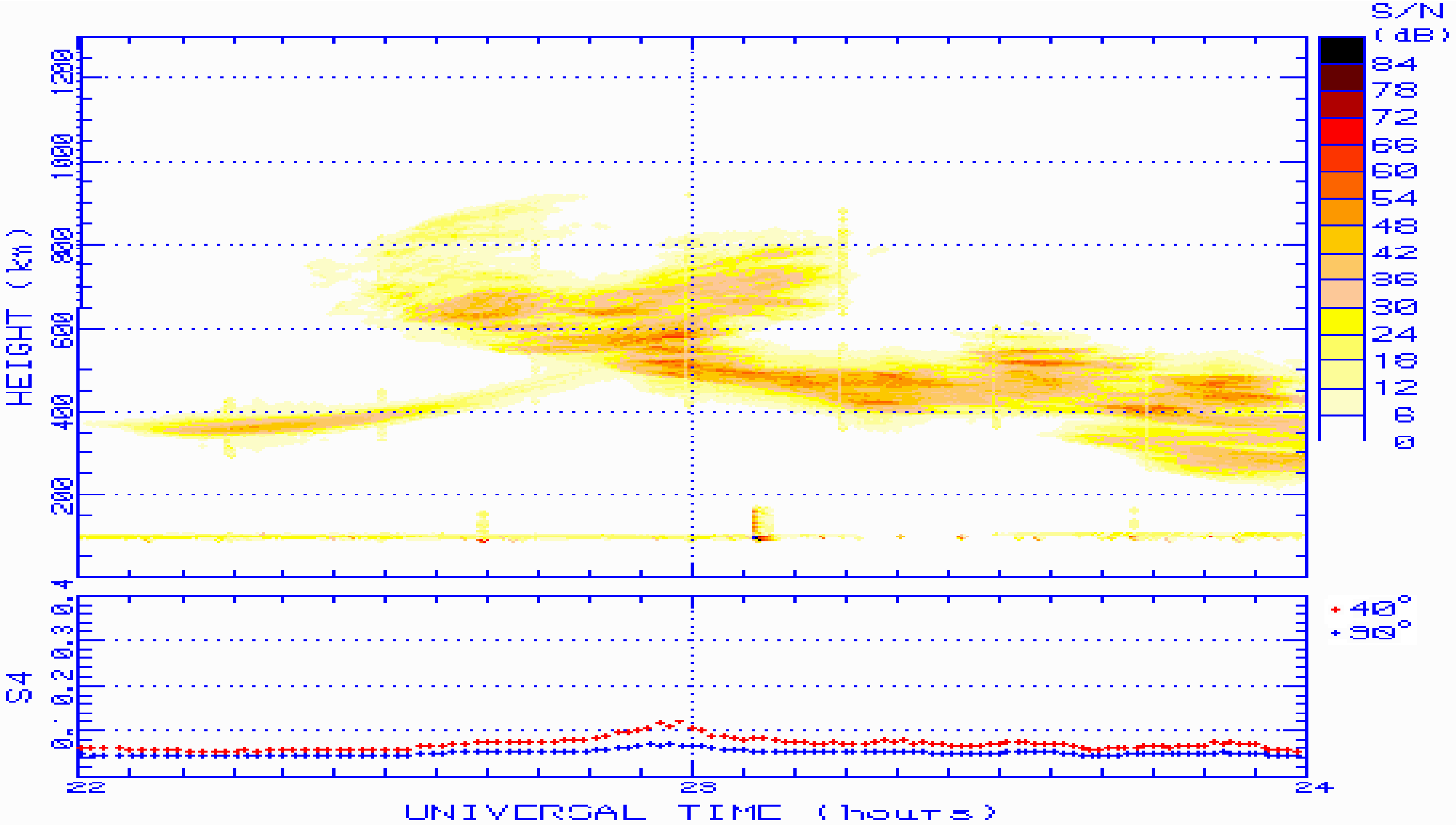


S_4 Measurements around São Luís at 1575 MHz (GPS Monitor)

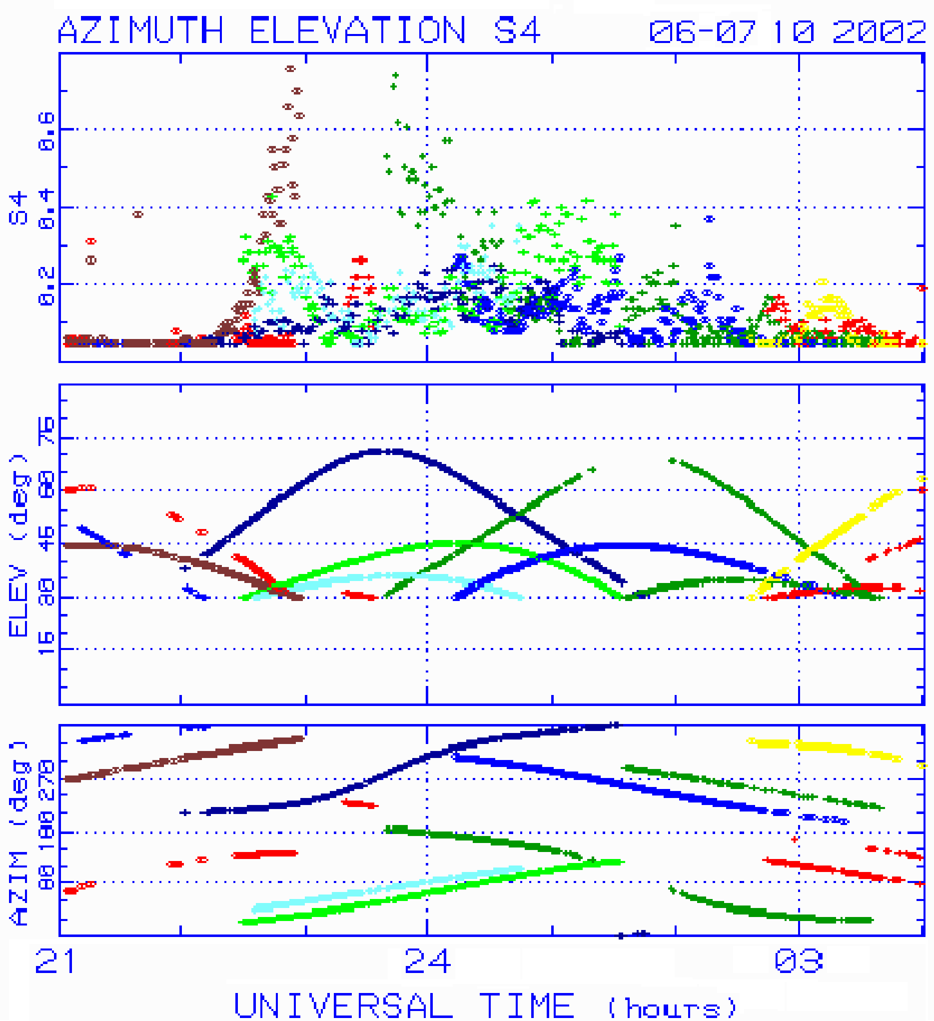


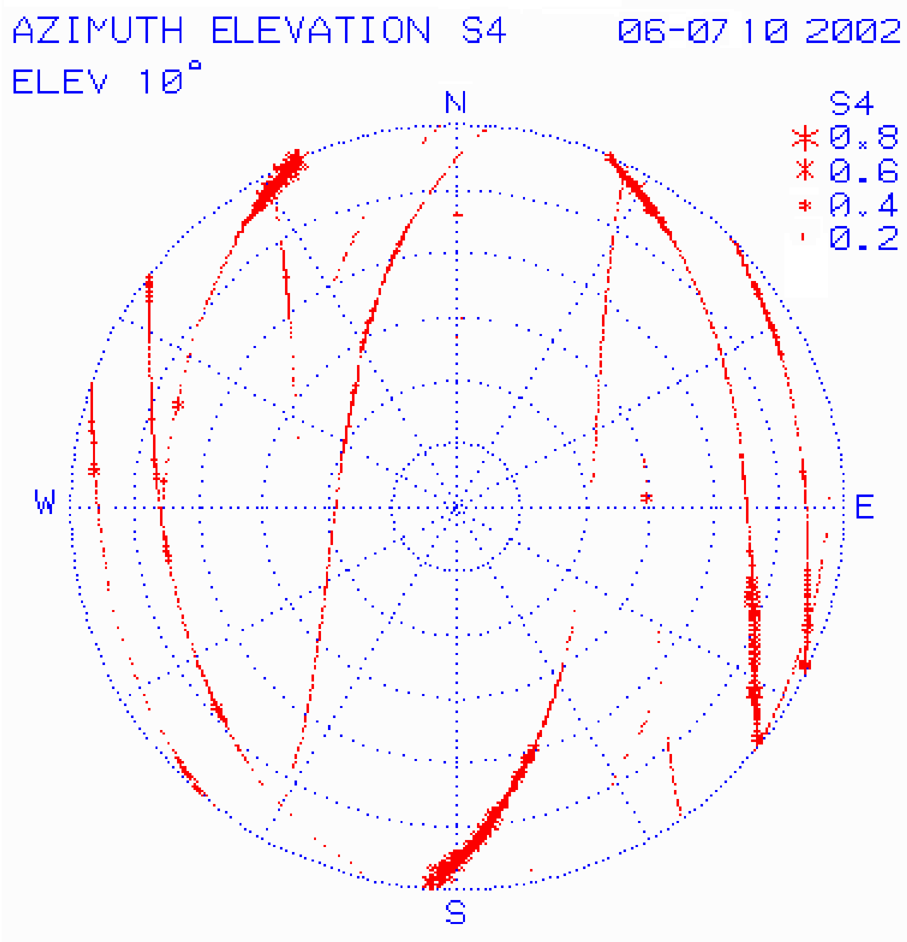


São Luís RTI Map and Calculated S4 Values at 1575 MHz (Two Elevations – 06 Oct 2002)



S_4 Measurements around São Luís at 1575 MHz (GPS Monitor)





Conclusion

- A model for the estimation of the scintillation index S_4 by the application of a 3D propagation algorithm to a combination of coherent radar RTI data with a simplified wideband spectral model of electron density fluctuations has been described.
- The predictions from the model seems to be consistent with GPS scintillation measurements from INPE’s equatorial observatory at São Luís, MA Brasil, but further tests are required.

Conclusion

- The next steps will be to refine the model for electron density fluctuations using in-situ data from sensors onboard C/NOFS, to extend calculations to other frequency band, and to validate the model using the C/NOFS tri-band beacon.
- The products from this and the upcoming work may act as independent validation and calibration tools for the C/NOFS procedures designed to forecast the evolution of ionospheric irregularities and scintillation in near real-time.

Introduction

- Ionospheric scintillation exhibits extreme variability in space and time, significantly affecting the operations of space-based communication and navigation systems.
- For their support, short-term specification and forecast systems based on real-time measurements are needed.
- C/NOFS is based on an equatorial non-GSO satellite. Data from sensors on board drive an equatorial ionospheric model to forecast the onset of plasma instability and its evolution. Radio wave scattering theory determines the scintillation of satellite signals propagating through the medium and received on the ground. Results will be validated by measurements performed using beacon transmissions.

Introduction

- Ionospheric scintillation exhibits extreme variability in space and time, significantly affecting the operations of space-based communication and navigation systems.
- For their support, short-term specification and forecast systems based on real-time measurements are needed.
- At equatorial latitudes, scintillation specification systems are a reality, primarily because the irregularity motion is ordered, the irregularities are field-aligned and the lifetime of scintillation-causing irregularities is long.

Introduction

- SCINDA combines scintillation and zonal drift measurements at two stations by using transmissions from two GSO satellites. The data drives an equatorial scintillation model to provide short-term forecasts of scintillation to users located east of the stations.
- C/NOFS is based on an equatorial non-GSO satellite. Data from sensors on board drive an equatorial ionospheric model to forecast the onset of plasma instability and its evolution. Radio wave scattering theory determines the scintillation of satellite signals propagating through the medium and received on ground. Results will be validated by measurements performed using beacon transmissions.

Introduction

- There have been direct comparisons of radar backscatter with scintillation resulting from propagation through the common volume, based on case studies or statistical analyses. These studies could provide a better understanding of the height-dependence of ionospheric turbulence.
- Our forecasting capability could also increase if we were able to relate the intensity of radar backscatter to the amplitude of km-scale fluctuations causing scintillation.
- This is a difficult problem, with too many uncertainties.

Instrumentation and Data Description

- The São Luís coherent scatter radar (2.3^{o} S, 44^{o} W, dip latitude 1.3^{o} S, declination 19^{o} W) is conceptually similar to the JULIA radar at Jicamarca and operates at 30 MHz to detect 5-m ionospheric irregularities.
- The radar consists of a pulse former, a driver amplifier, two solid-state transmitters, two double-conversion analog receivers, a T/R switch, and two arrays of 16 Yagi antennas with $5\lambda_r/8$ element separation arranged side-by-side in the magnetic E-W direction.

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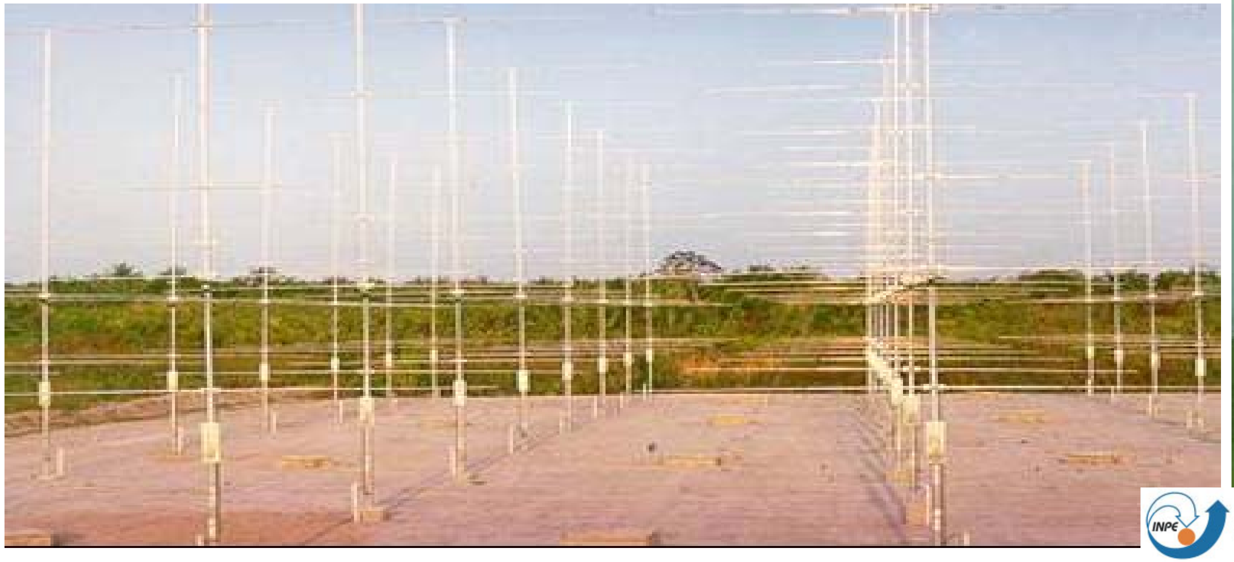
Rede de receptores GPS no território brasileiro

Instrumentation and Data Description

- The transmitters generate 4 kW peak power each with duty cycle of 4.5 % in the spread F mode of operation. The half-power beam width in the magnetic E-W plane is about 10º. The radar samples the medium up to 1400 km with 2.5 km resolution.



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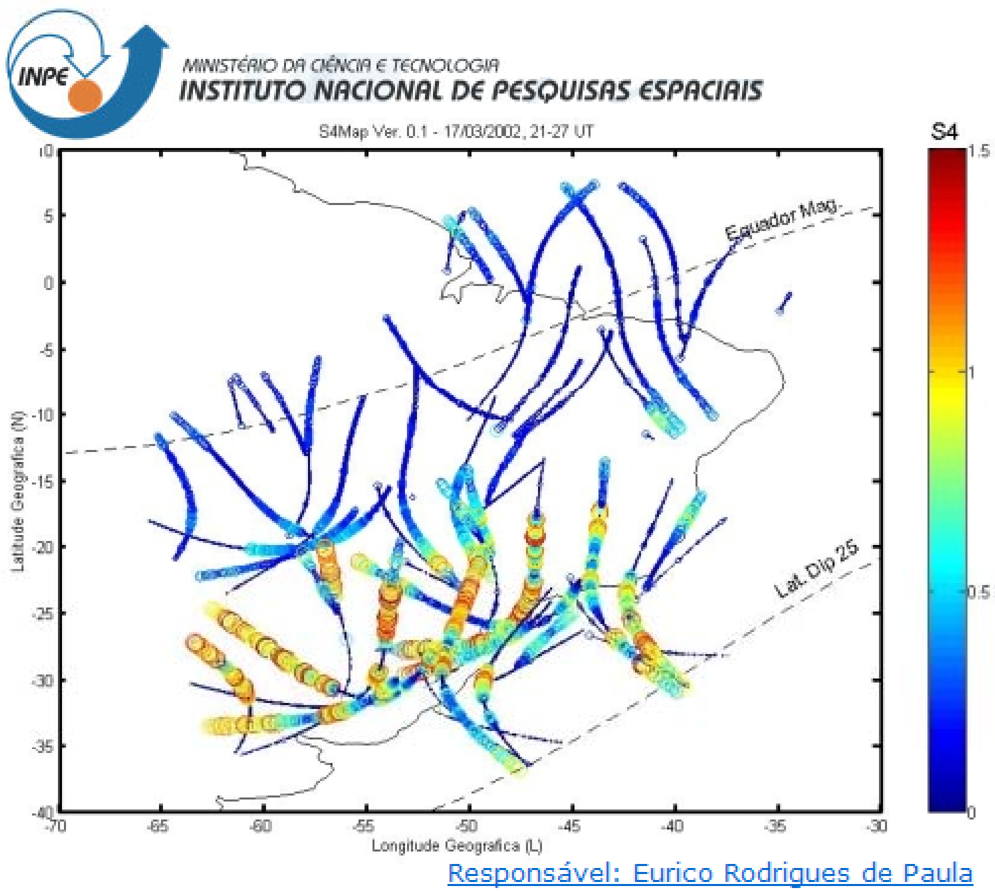
Instrumentation and Data Description

- The scintillation index S_4 (the standard deviation of I/<I>) is routinely calculated every 1 minute using 3000 signal samples for all tracked GPS satellites.
- Typically, S_4 values are low to moderate ($S_4 < 0.5$) in the equatorial region and moderate to high ($S_4 > 0.5$) along the southern crest of the equatorial anomaly.



Algorithm for Slant Propagation Through an Irregularity Layer

$$C_o^x = 1 + 2\left[c_1(\beta) - 2c_o(\beta)\right]$$

$$C_p^x = c_{p+1}(\beta) + c_{p-1}(\beta) - 2c_p(\beta)$$

$$c_p(\beta) = \frac{-1}{\sqrt{2i\pi\beta}}\left\{i\ [\pi(\beta p)f(\beta p) - 1]\ e^{i\frac{\pi}{2}(\beta p)^2} + [\pi(\beta p)g(\beta p)]\ e^{-i\frac{\pi}{2}(\beta p)^2}\right\}$$

$$\beta = \sqrt{2\delta x^2 \cos\theta / (\lambda\delta z)} = 2\sqrt{\cos\theta}\left(\delta x / z_f\right) \qquad z_f = \sqrt{2\lambda\delta z}$$

Algorithm for Slant Propagation Through an Irregularity Layer

- Propagation as convolution involving coefficients with decreasing amplitudes.
- Easy to implement truncation criteria (for example, only lobes with maxima above $|C_o|$-*40 dB*).
- Number of coefficients decreases with frequency (local character of propagation at high frequencies)
- Relatively efficient propagation algorithm by *a priori* calculating these coefficients and storing their Fourier Transform, combined with a 2D FFT to evaluate discrete convolutions.
- The set of propagation coefficients has been approximated by the impulse function inside the layer.

Screen Model from Radar RTI Data

- The backscattered radar field from a screen is given by

$$\vec{E}_s = \vec{e}(-\hat{z},\hat{z})\frac{e^{ik_r R}}{R} \quad \text{where} \quad \vec{e}(-\hat{z},\hat{z}) = \hat{e}_i \frac{k_r^2}{4\pi}\int_{\Delta V} \delta n^2(\vec{r}')\, e^{i2k_r\hat{z}\cdot\vec{r}'} dV'$$

- Therefore the differential cross section of the screen per unit volume is given by

$$\sigma(-\hat{z},\hat{z}) = \frac{1}{\Delta V}\left\langle \vec{e}(-\hat{z},\hat{z})\cdot\vec{e}^*(-\hat{z},\hat{z})\right\rangle$$

$$\sigma(-\hat{z},\hat{z}) = \frac{L_{ry}}{4} k_r^4 S_{n^2}^{2D}(0,2k_r)$$

Screen Model from Radar RTI Data

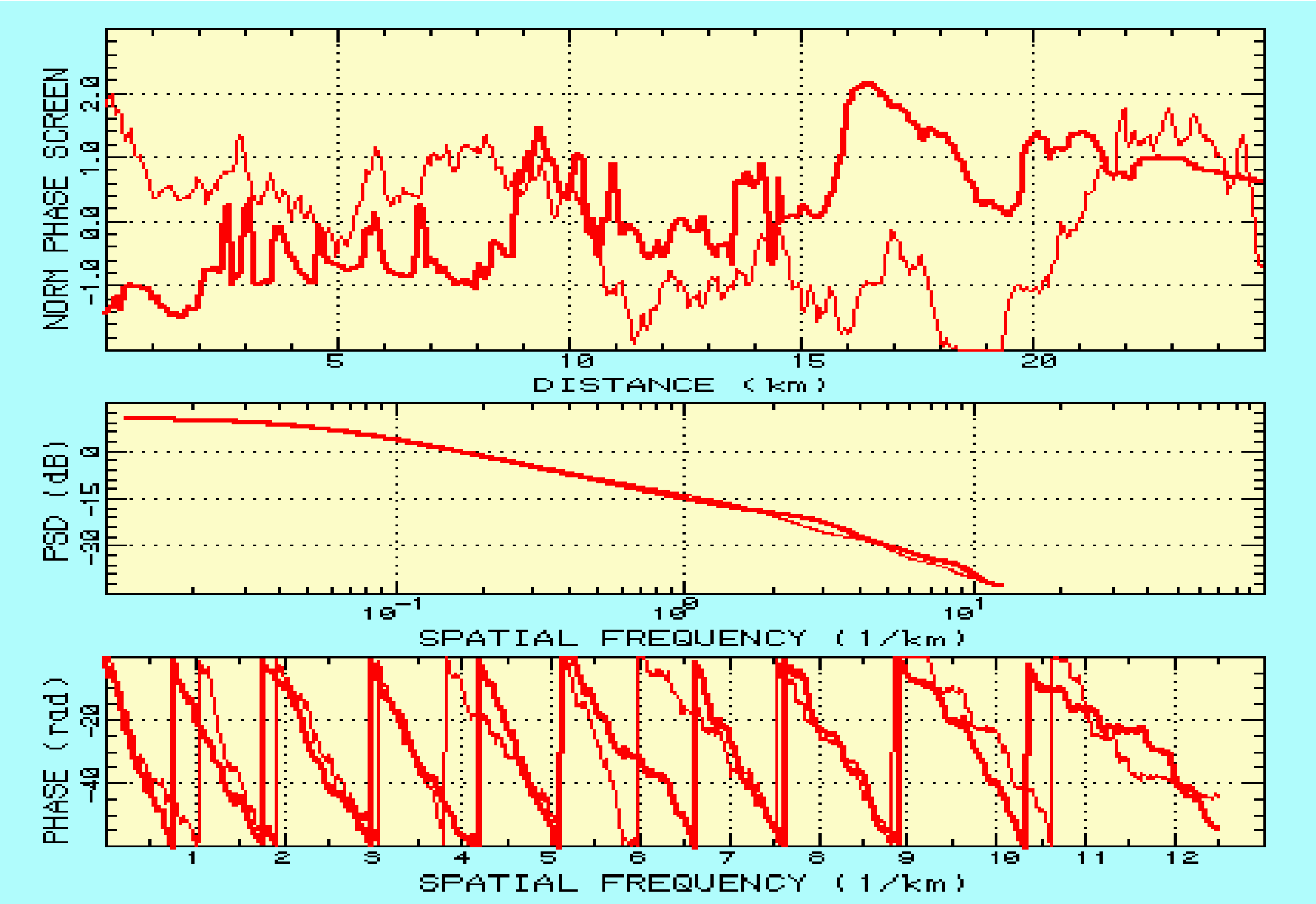
- From $\delta n^2 = -\dfrac{r_e \lambda_r^2}{\pi}\delta N$ and using a spectral density model, one gets

$$S_{n^2}^{2D}(0,2k_r) = \frac{r_e^2\lambda_r^4}{\pi^2} S_N^{2D}(0,2k_r) = \frac{r_e^2\lambda_r^4}{\pi^2}\frac{(p-2)}{2\pi k_o^2}\frac{\Delta N^2}{[1+(2k_r/k_o)^2]^{p/2}}$$

- Therefore the differential cross section of the screen per unit volume becomes

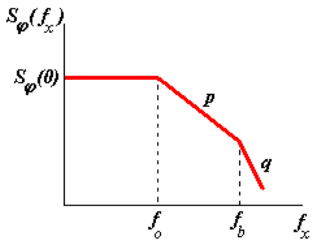
$$\sigma(-\hat{z},\hat{z}) = \frac{2\pi L_{ry} r_e^2 (p-2)}{k_o^2}\frac{\Delta N^2}{[1+(2k_r/k_o)^2]^{p/2}}$$

Screen Model from Radar RTI Data



ΔN from RTI data

$f_o = 0.04\ km^{-1}$
$f_b = 2.50\ km^{-1}$
$p = 1.6$
$q = 3.00$



$$\delta n^2 = -\frac{r_e \lambda_r^2}{\pi} \delta N$$

S_4 Measurements around São Luís at 1575 MHz (GPS Monitor)