2458-3

Workshop on GNSS Data Application to Low Latitude Ionospheric Research

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Ionospheric Structure and Scintillation

Charles Rino

Boston College
USA

Strada Costiera, 11 - 34151 - Trieste - Italy • Tel. +39 0402240111 • Fax. +39 040224163 • sci_info@ictp.it • www.ictp.it

Ionospheric Structure and Scintillation

Charles Rino[1]
Charles Carrano[2]

[1]Visiting Scholar, Boston College, Institute for Scientific Research

[2]Boston College, Institute for Scientific Research

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Workshop on GNSS Data Applications to Low Altitude Ionospheric Research

International Center for Theoretical Physics

Trieste, Italy

May 2013

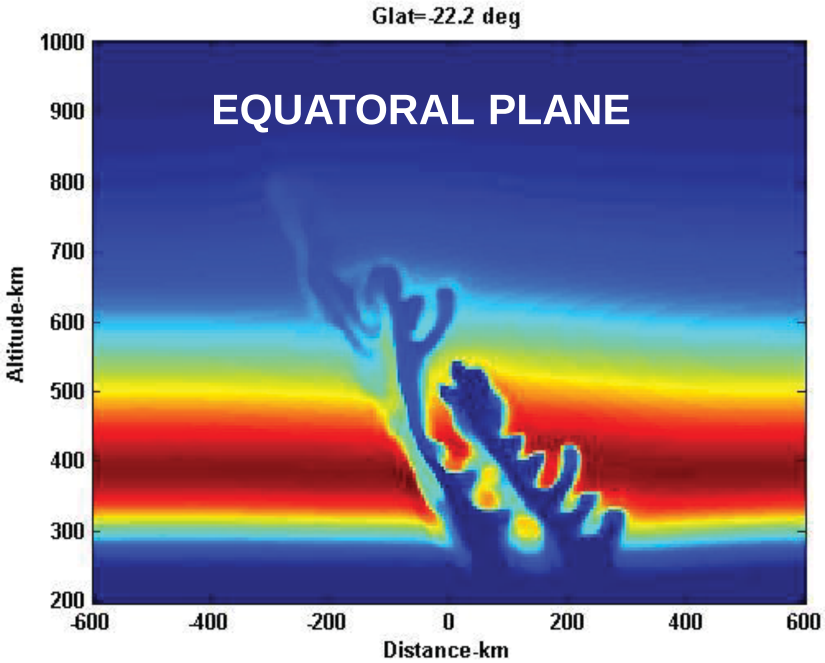
OUTLINE

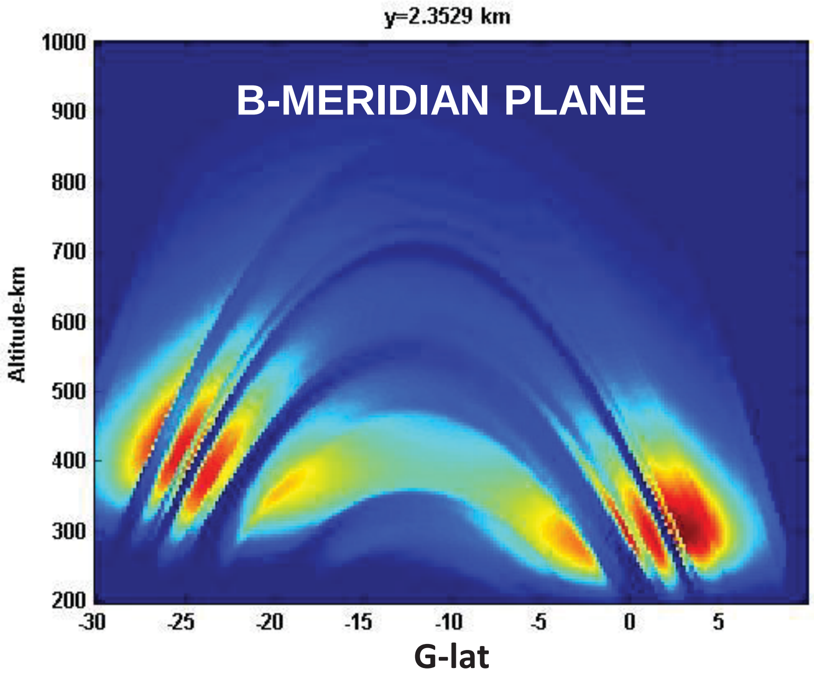
1. Ionospheric Structure
   - Structure Characterization
2. Scintillation
   - Overview
   - Recent Applications

A systematic characterization of

Ionospheric Structure

Physics-Based Models





STRUCTURE CHARACTERISTICS

- **Inhomogeneous**
- **Anisotropic**
- **Current resolution limit of ~5 km excludes intermediate scale structure that causes scintillation**

Simulations provided by John Retterer, Boston College

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Formal Structure Definition

$$N(\mathbf{r},t) = \bar{N}(\bar{\mathbf{r}},\bar{t})(1+\delta N(\Delta\mathbf{r}-\mathbf{v}\Delta t)/N_0)$$

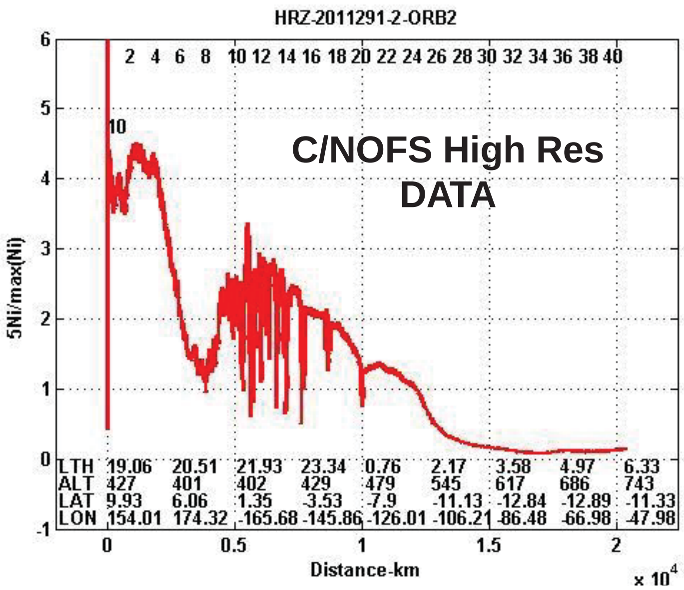
Slowly varying average centered at $\bar{\mathbf{r}}$ & $\bar{t}$

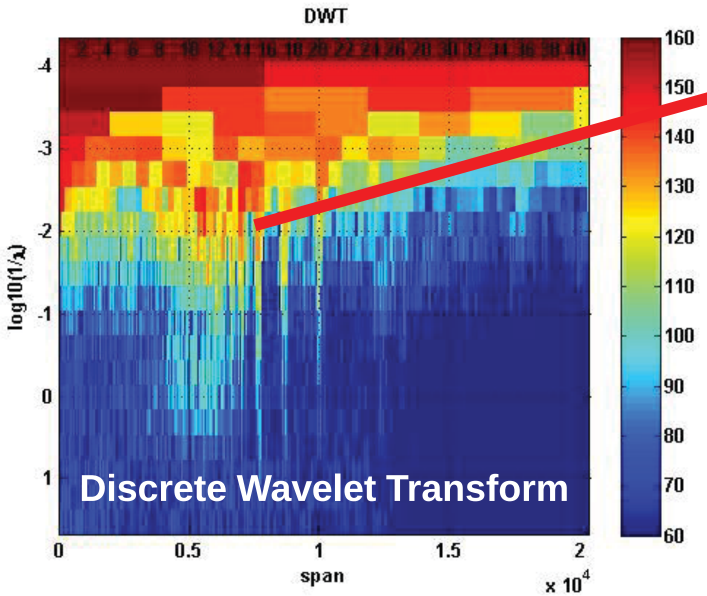
Random component with mean zero over volume defining $\bar{N}(\bar{\mathbf{r}},\bar{t})$

Structure frozen within volume defining $\bar{N}(\bar{\mathbf{r}},\bar{t})$

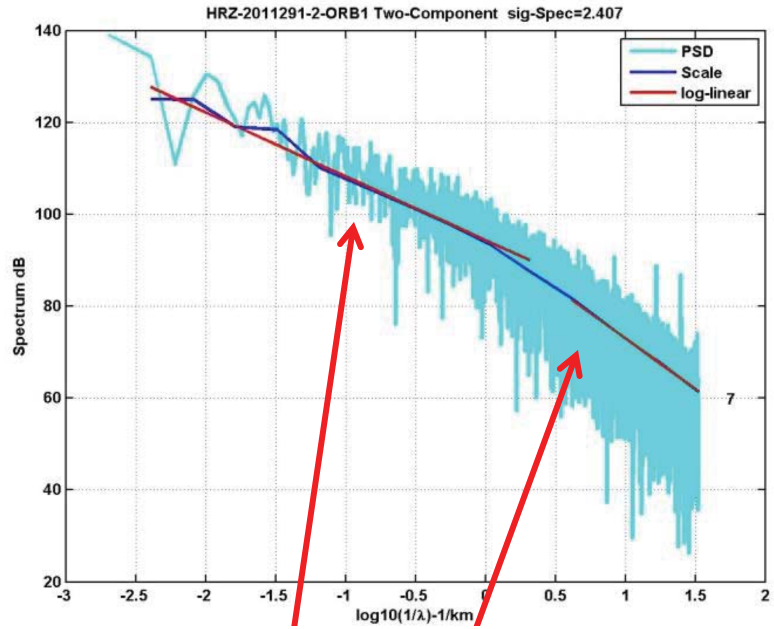
$\delta N(\mathbf{r})/N_0$ is typically imposed as a stochastic overlay with a well-defined spectral density function

Structure Characteristics <= Data





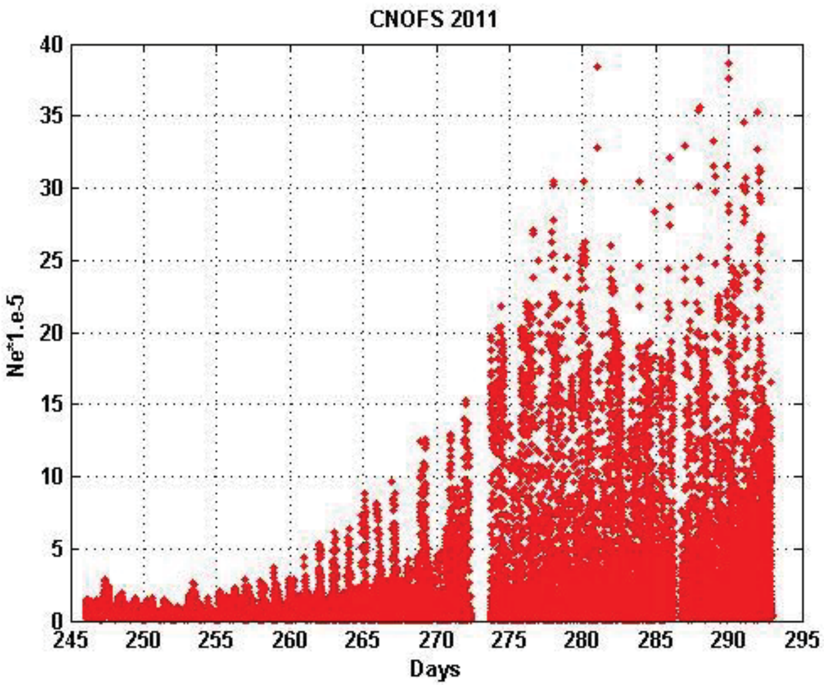
Spectral Density Function for well-developed segments

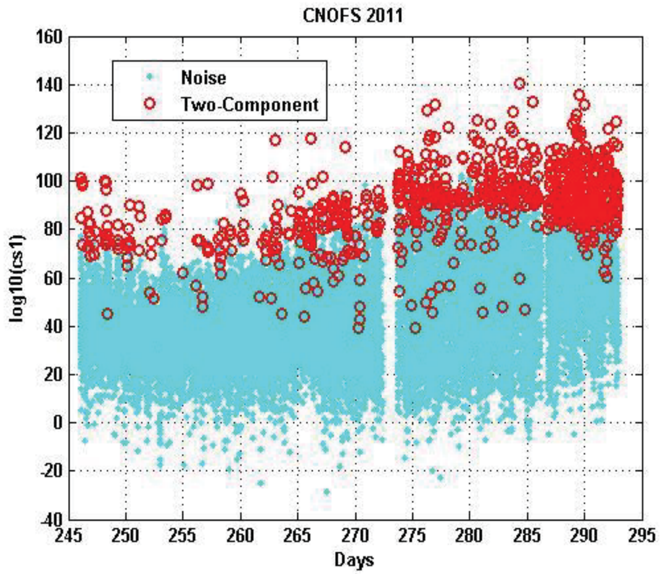


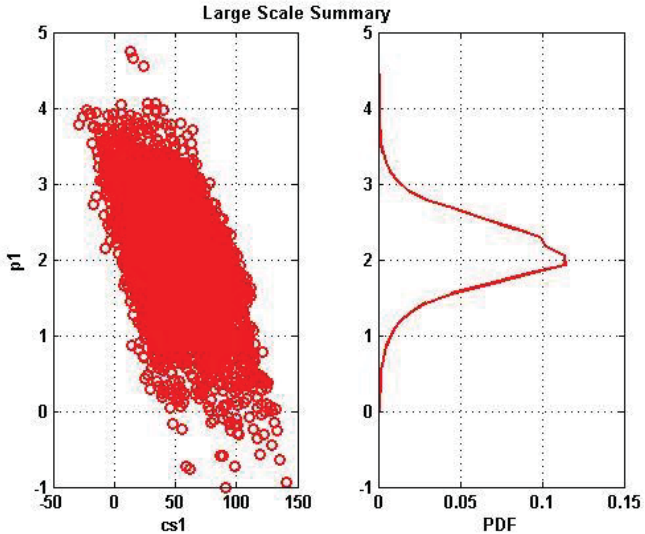
$$\varphi(q) = \begin{cases} c_s q^{-p_1} & \Delta q \le q < q_0 \\ \underbrace{\left(c_s q_0^{(p_2-p_1)}\right)}_{C_s^{(2)}} q^{-p_2} & q_0 \le q < q_{\max} \end{cases}$$

Equatorial Spread F

285 consecutive C/NOFS data sets recorded 2011 day 246 through day 292







79,449 segments analyzed, 62,512 (79%) achieved overall least-square errors less than 10, 59,849 segments noise-limited (p2<p1). Only 2663 noise free (p1<p2).

Structure Summary

- Data interpretation and extrapolation require a 3D structure model
- The model must accommodate inhomogeneous distributions with field-aligned structure that subtend scale sizes from hundreds of kilometers to hundreds of meters.
- Transition from quasi-deterministic variation to stochastic structure in the scale range from 100 to 10 is ill-defined
  - Fractional Brownian motion provides a theoretical framework that captures the transition
  - Configuration space models have been introduced as a 2.5D alternative
- An inverse power law subtending the entire intermediate scale range (>100 km to <100 m) with 3D index 4 (Kolmorogov index =11/3) will be used as a canonical reference

PRE PUBLICATION REFERENCES:
http://chuckrino.com/wordpress/wp-content/uploads/2013/02/PLPHighResDataPaperRev15.pdf

http://chuckrino.com/wordpress/wp-content/uploads/2013/02/PLPHighResDataPaperRev21.pdf

Scintillation

with modern computational resources

Scintillation Basics

Integral form of Helmholz Equation

$$\psi(\mathbf{r})=\psi_i(\mathbf{r}) + 2k^2 \iiint \frac{\exp\{ik|\mathbf{r}-\mathbf{r}'|\}}{2\pi|\mathbf{r}-\mathbf{r}'|}\delta n(\mathbf{r}')\psi(\mathbf{r}')dV$$

Propagation

Media Interaction

$$\frac{\partial\psi(x,\varsigma)}{\partial x} = ik\Theta\psi(x,\varsigma) + ik\delta n(x,\varsigma)\psi(x,\varsigma)$$

Forward Propagation Equation (FPE)

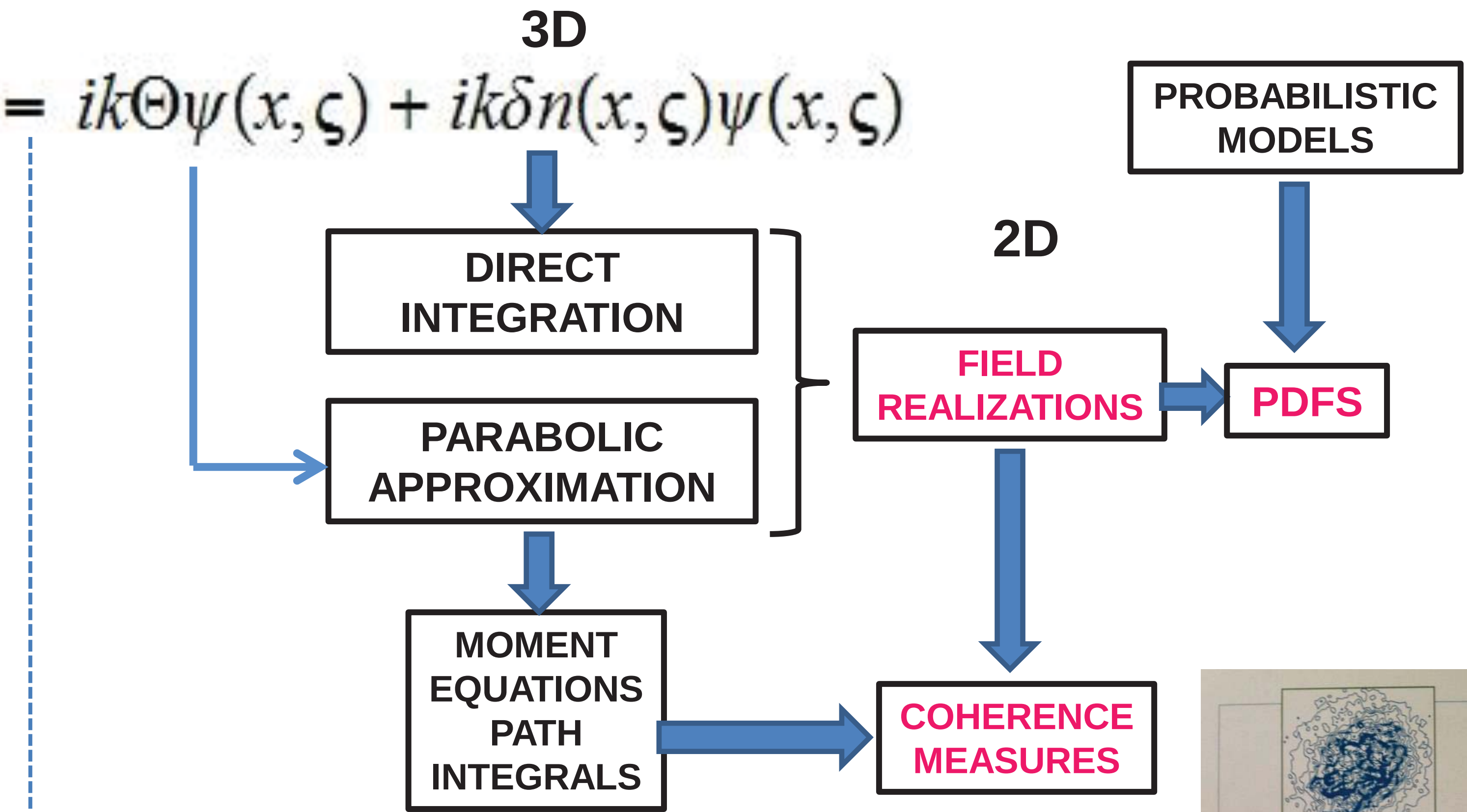
$$\hat{\psi}(\boldsymbol{\kappa};x_0) = \iint \psi(x_0,\varsigma)\exp\{-i\boldsymbol{\kappa}\cdot\varsigma\}d\varsigma$$

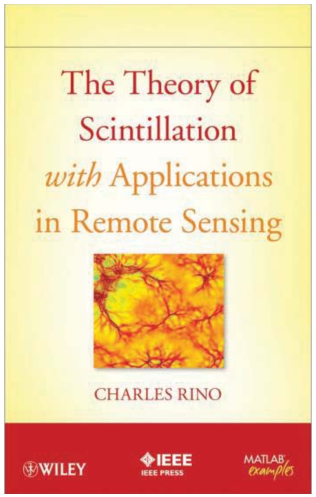
$$\Theta\psi(x,\varsigma) = \iint \hat{\psi}(\boldsymbol{\kappa};x_0)\exp\left\{ik\sqrt{1-(\kappa/k)^2}\,x\right\}\exp\{i\boldsymbol{\kappa}\cdot\varsigma\}\frac{d\boldsymbol{\kappa}}{(2\pi)}$$

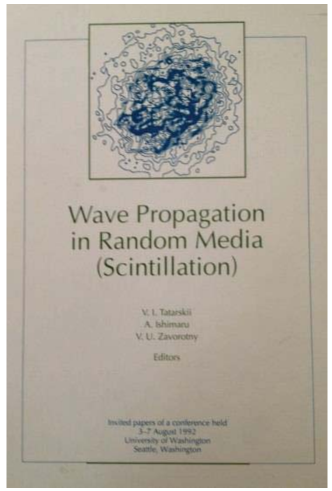
$\sqrt{1-(\kappa/k)^2} \simeq 1-(\kappa/k)^2/2$ Parabolic Approximation

Approaches to Scintillation Modeling

$$\frac{\partial \psi(x,\varsigma)}{\partial x} = ik\Theta\psi(x,\varsigma) + ik\delta n(x,\varsigma)\psi(x,\varsigma)$$







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Numerical Simulations

- The forward propagation equation is valid for any refractive index configuration that has no gradients steep enough to require explicit boundary treatment
- Split-step integration is suggested by the FPE and has proven to be very effective
  - The forward integration step can subtend hundreds of wavelengths, as long the associated amplitude change is small
  - Transverse sampling must capture the smallest significant structure
- Phase-screen realizations are generated by filtering uncorrelated noise
  - Fractional Brownian motion realizations are generated by extending the inverse power law to the largest resolved scale
  - The effects of constrained power-law distributions will be demonstrated

Phase-Screen Model

$$\Phi_I(\boldsymbol{\kappa}; U, \rho_F) = \iint \left(\exp\{-U^{p_1-2}\gamma(\boldsymbol{\eta}, \boldsymbol{\kappa})\} - 1\right) \exp\{-i\boldsymbol{\kappa}\rho_F \cdot \boldsymbol{\eta}\} d\boldsymbol{\eta}$$

$$\rho_F = \sqrt{x/k}$$

$$U = \left(C_p^{\frac{1}{p_1-2}}\right)\rho_F$$

$$C_p = r_e^2 \lambda^2 l_p C_s$$

$$\gamma(\boldsymbol{\eta}, \boldsymbol{\mu}) = 8 \iint \begin{cases} \chi^{-p_1} & \chi < \chi_0 \\ \chi_0^{p_2-p_1}\chi^{-p_2} & \chi > \chi_0 \end{cases} \sin^2(\boldsymbol{\chi} \cdot \boldsymbol{\eta}/2) \sin^2(\boldsymbol{\chi} \cdot \boldsymbol{\mu}/2) d\boldsymbol{\chi}/(2\pi)^2$$

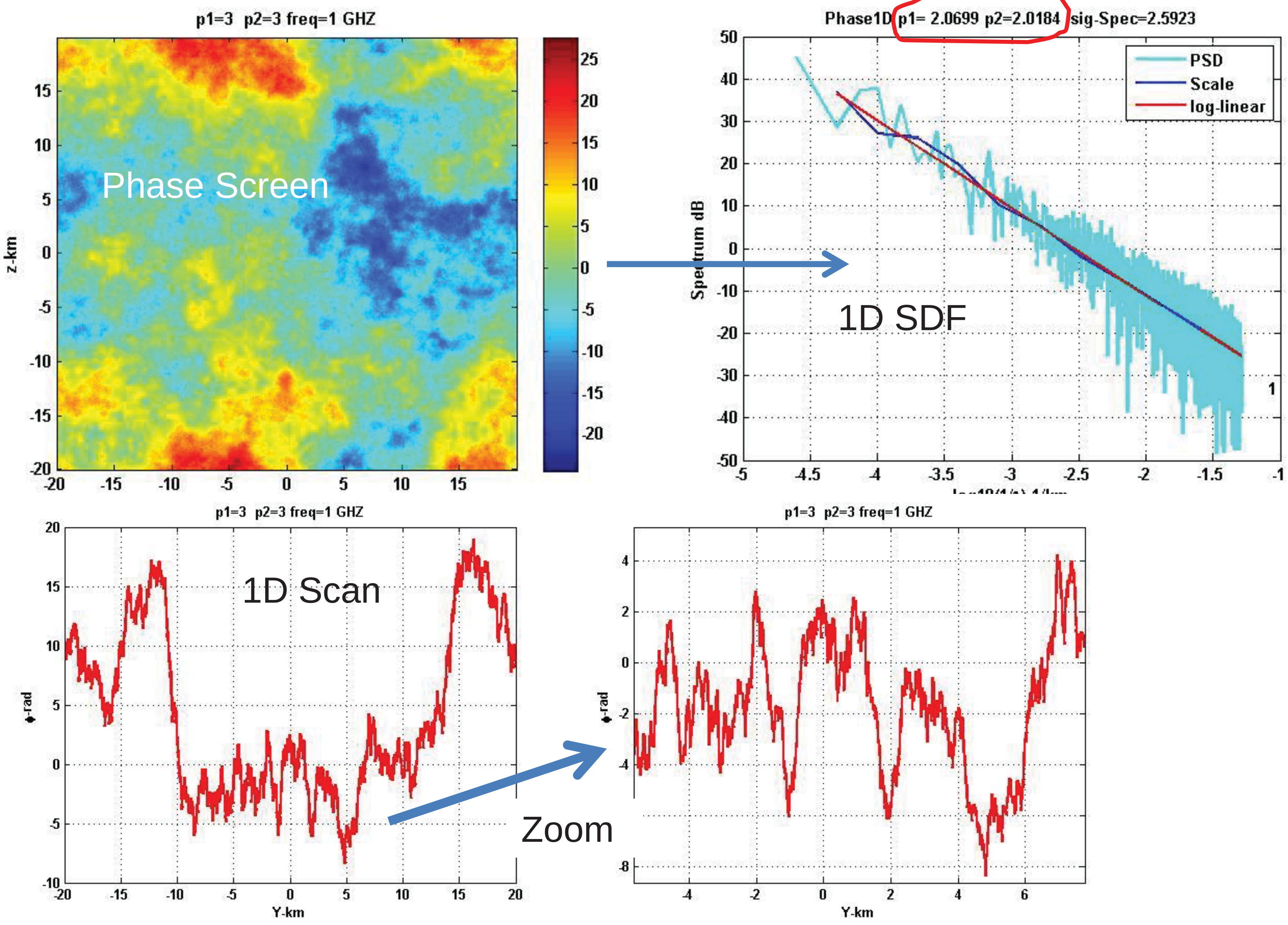
$$\chi_0 = q_0 \rho_F$$

$$\lim_{U \to 0} \Phi_I(\boldsymbol{\kappa}; U, \rho_F) = 4C_p \varphi(\kappa) \sin^2((\kappa\rho_F)^2/2)$$

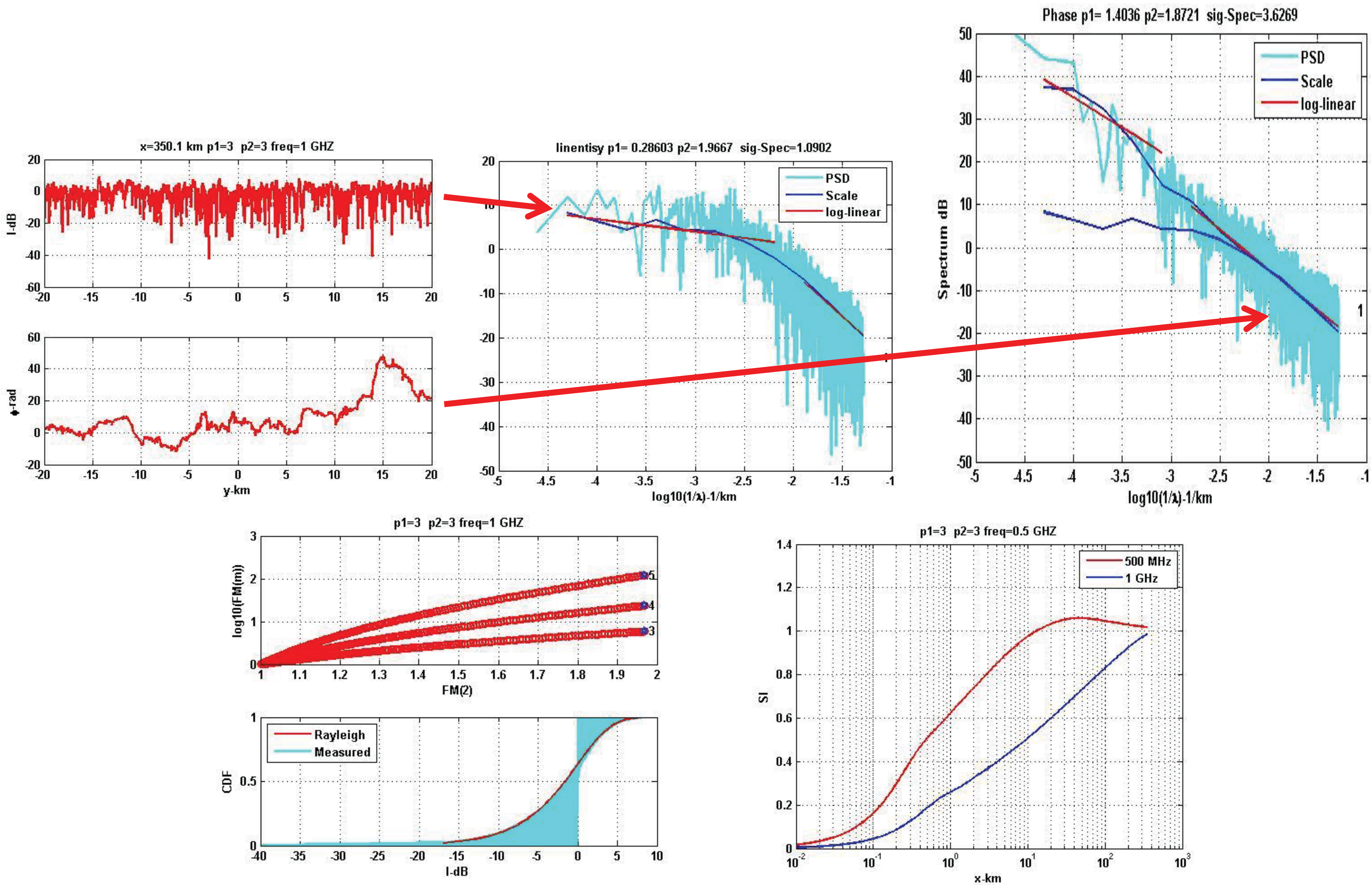
p_1 is the 2D phase power-law index, which is equal to the 3D in-situ power-law index

Power-Law Index Dependence

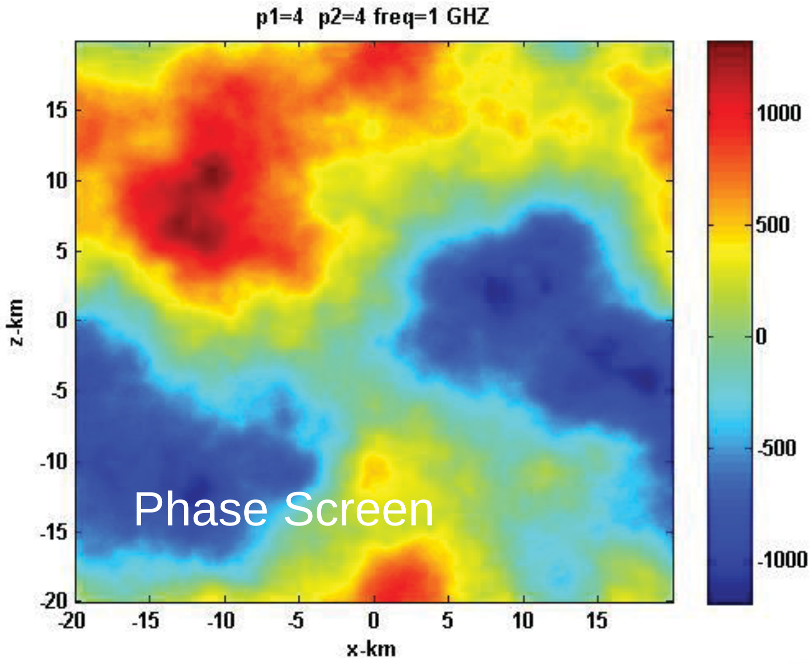
P(3D)=3 Phase Screen Realization
Infinite Outer Scale

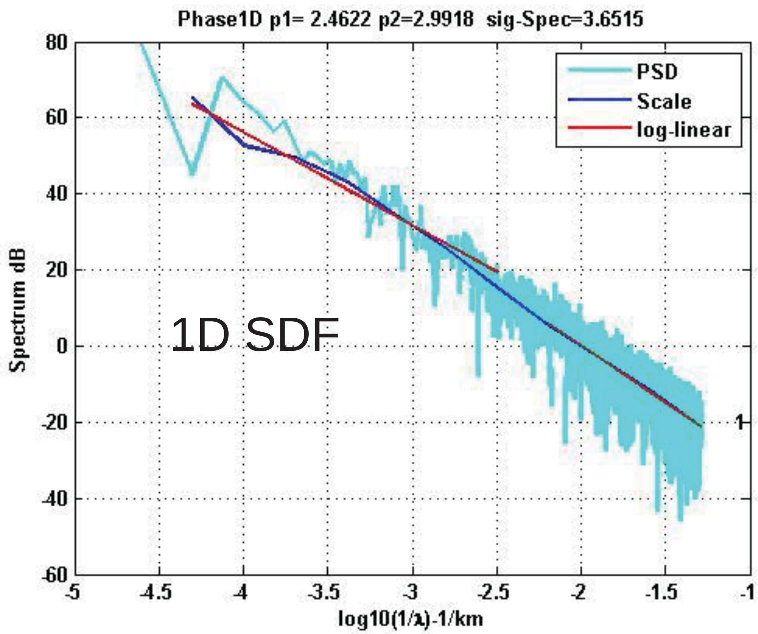


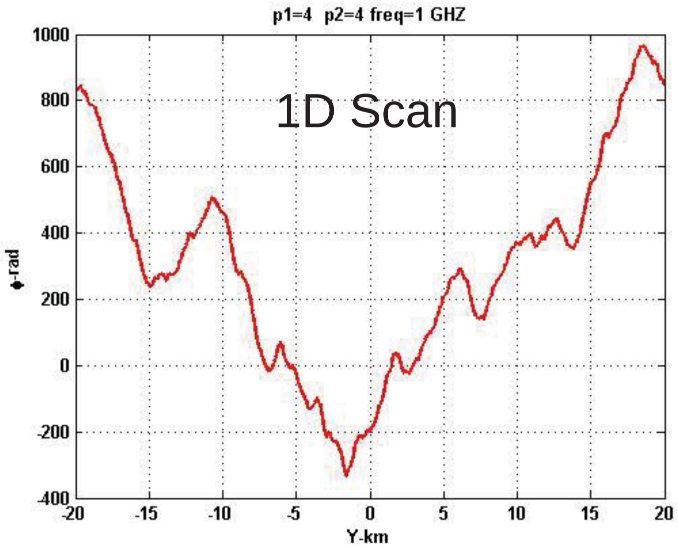
P(3D)=3 Phase Screen Field Evolution



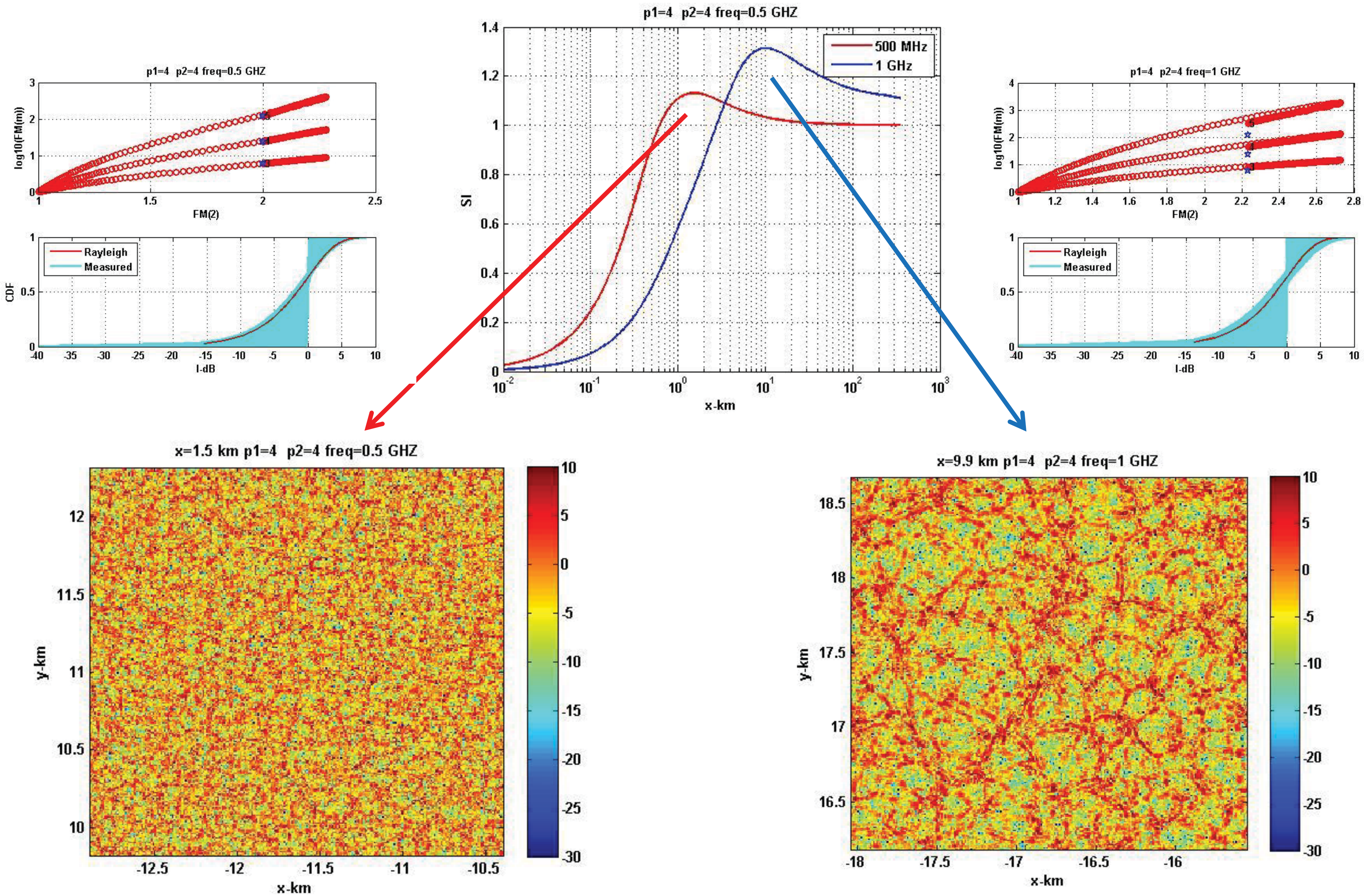
P(3D)=4 Phase Screen Realization
Infinite Outer Scale







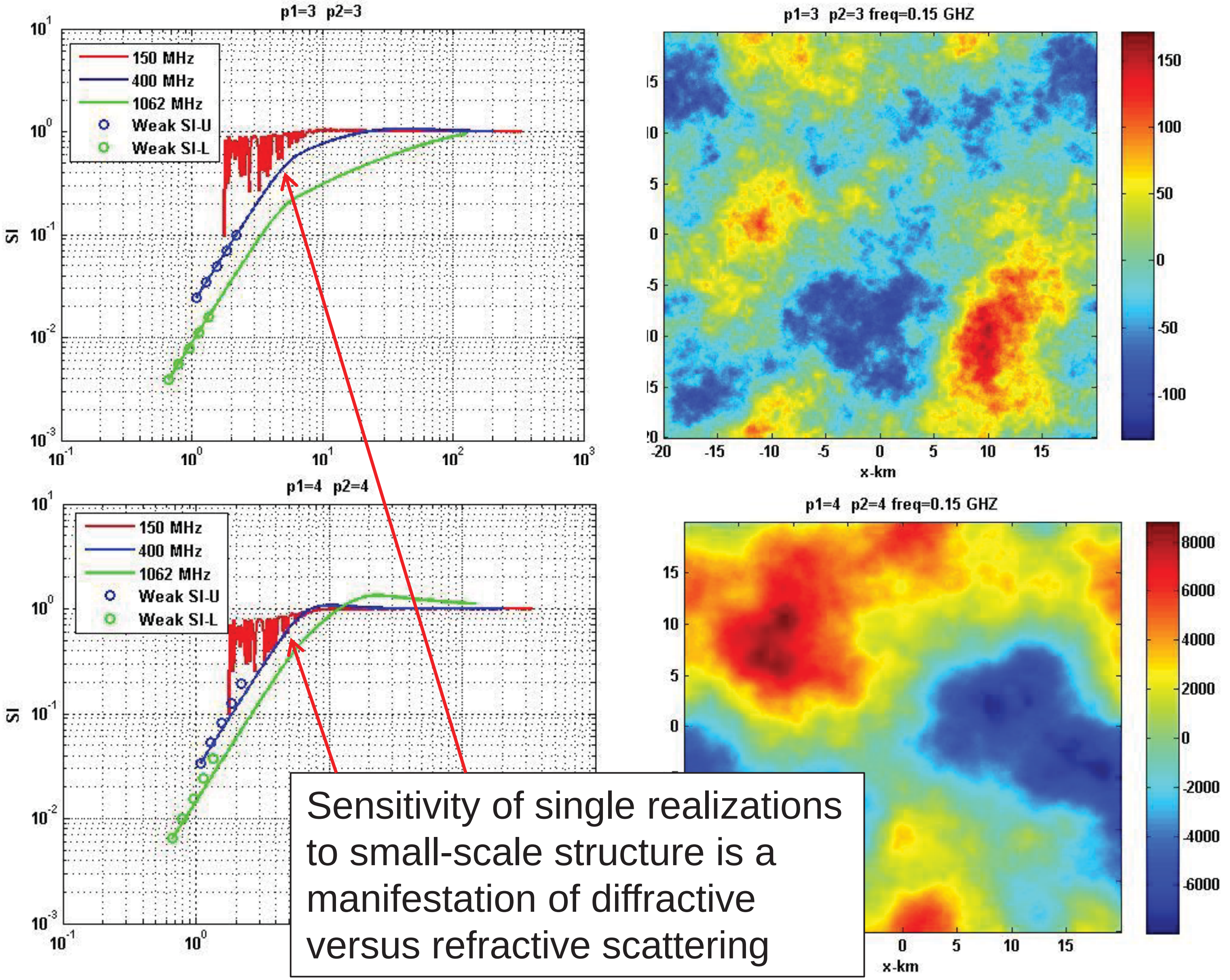
P(3D)=4 Phase Screen Field Evolution



Phase-Screen Scintillation continued

Frequency Dependence

CEROS Frequency Dependence P1=3&4



Sensitivity of single realizations to small-scale structure is a manifestation of diffractive versus refractive scattering

Scintillation Summary

- **3D Propagation simulations using 2D phase-screen realizations illustrate critical dependencies on power-law index, phase turbulent strength, and Fresnel radius**
  - **Ongoing research is pursuing the critical parameter dependencies and extensions to the two-component model**
  - **The phase-screen model can accommodate oblique propagation geometries and anisotropy, but the amount of computation is prohibitive for data interpretation and predictive modeling**
- ***Equivalent* 2D propagation models provide a viable alternative with very encouraging results, which will occupy the remainder of this presentation**

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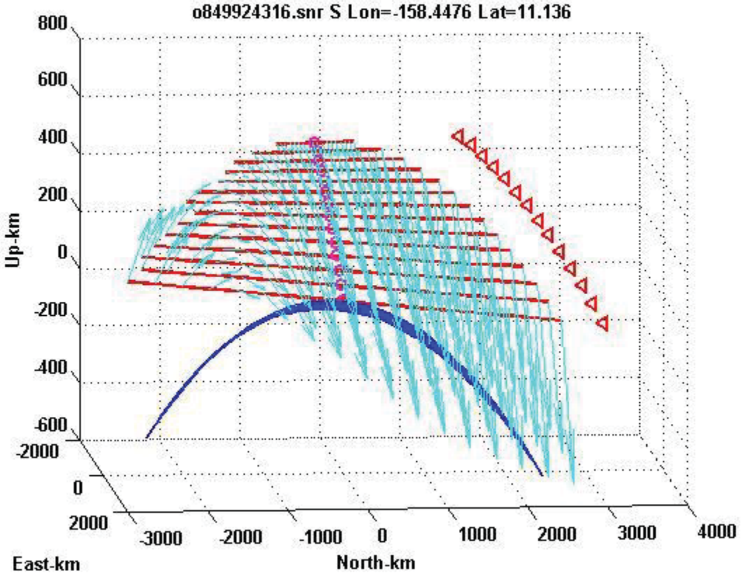
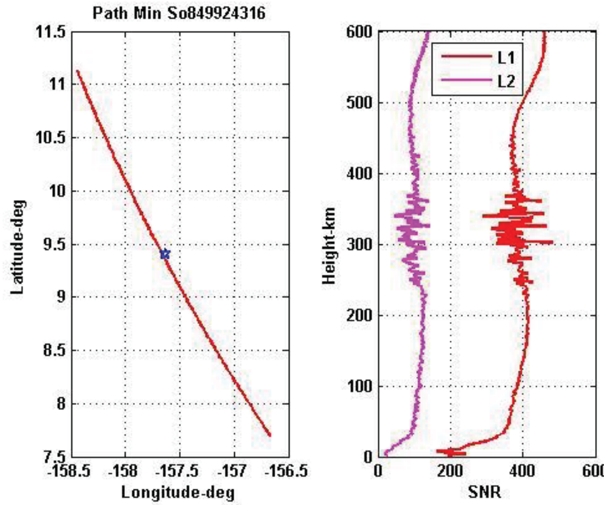
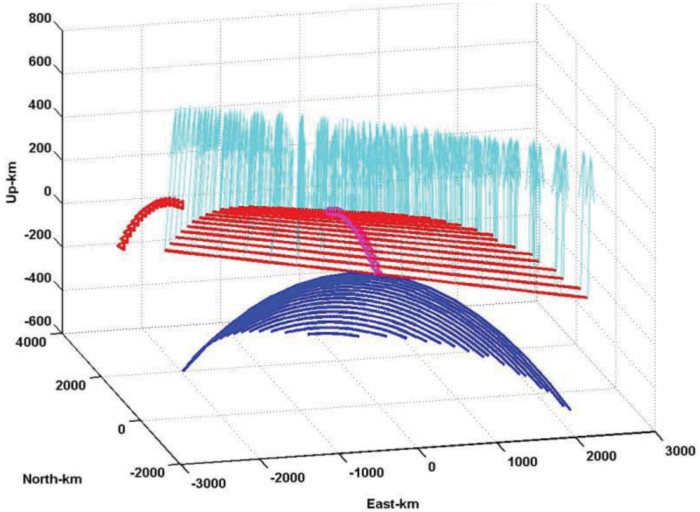
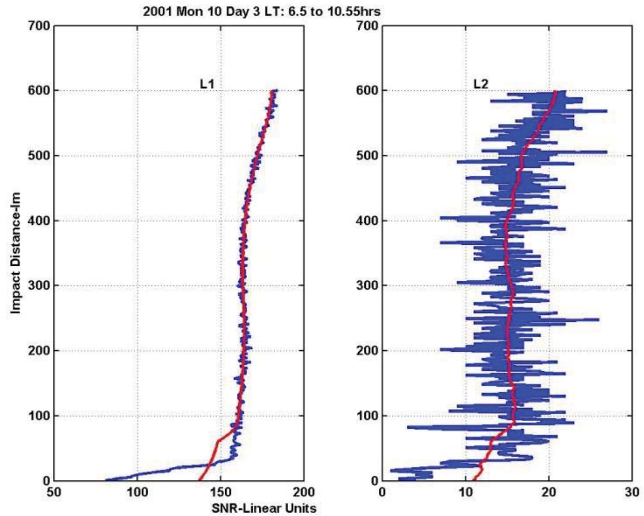
COSMOC GPS Occultation









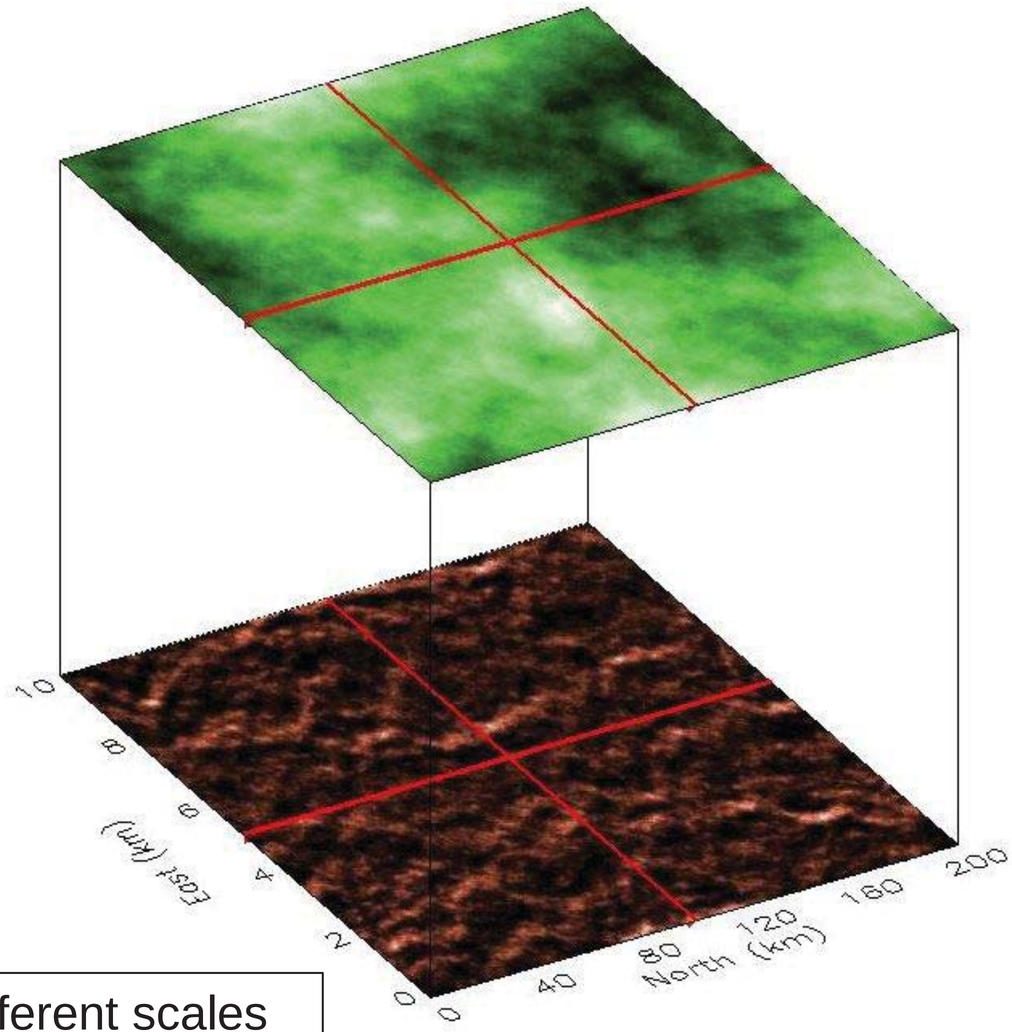
RED => GPS to COSMIC links <800 km
BLUE=> Earth surface projection of links
CYAN=> Magnetic field direction along

Simplifying the theory for real-world

Applications

All the material in this section was generously provide by Charles Carrano
A complete list of his publications and preprints can be found on his BC web page:
https://www2.bc.edu/~carranoc/

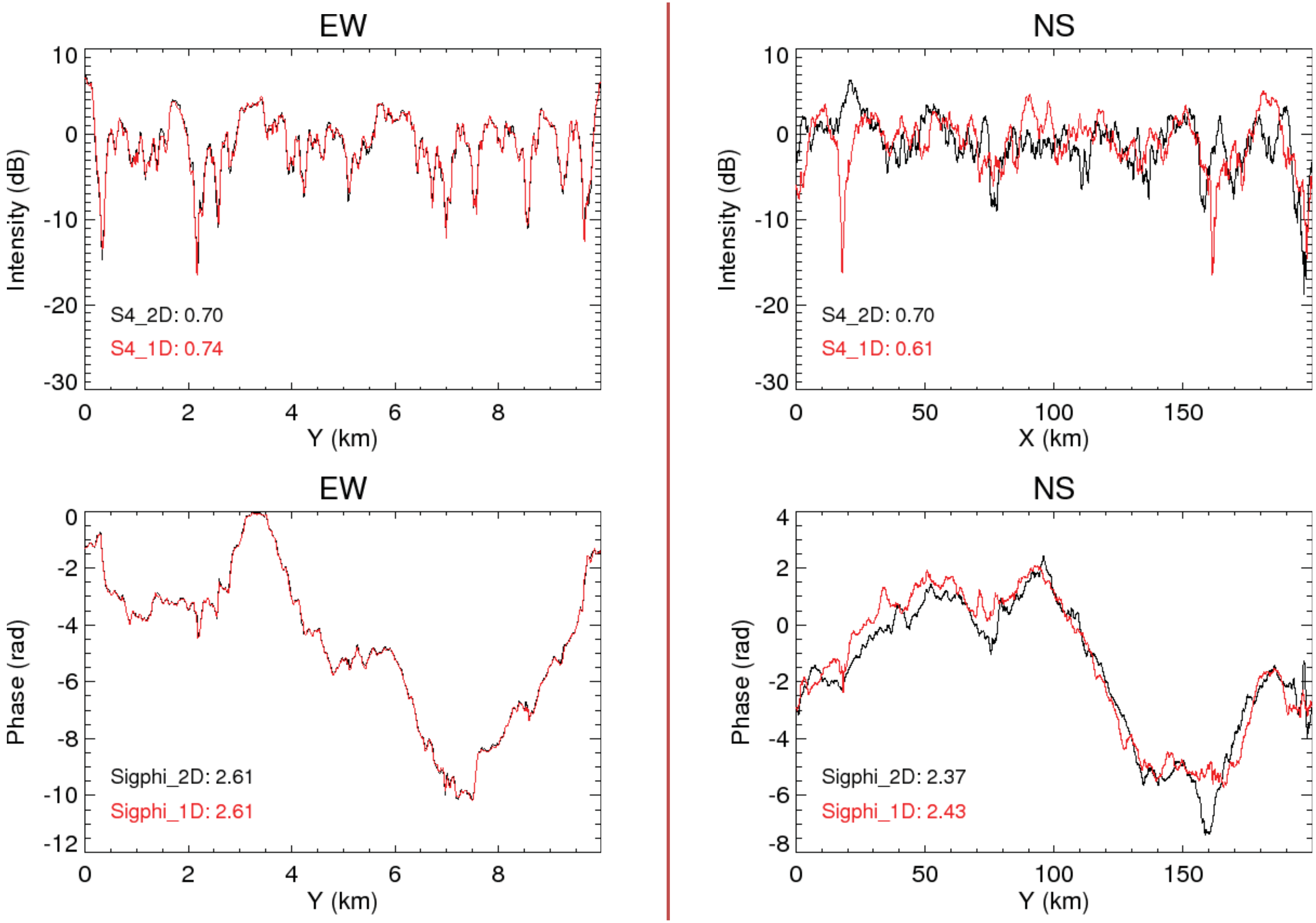
1D Slice verses 1D Simulation



Different scales accommodate 10:1 elongation

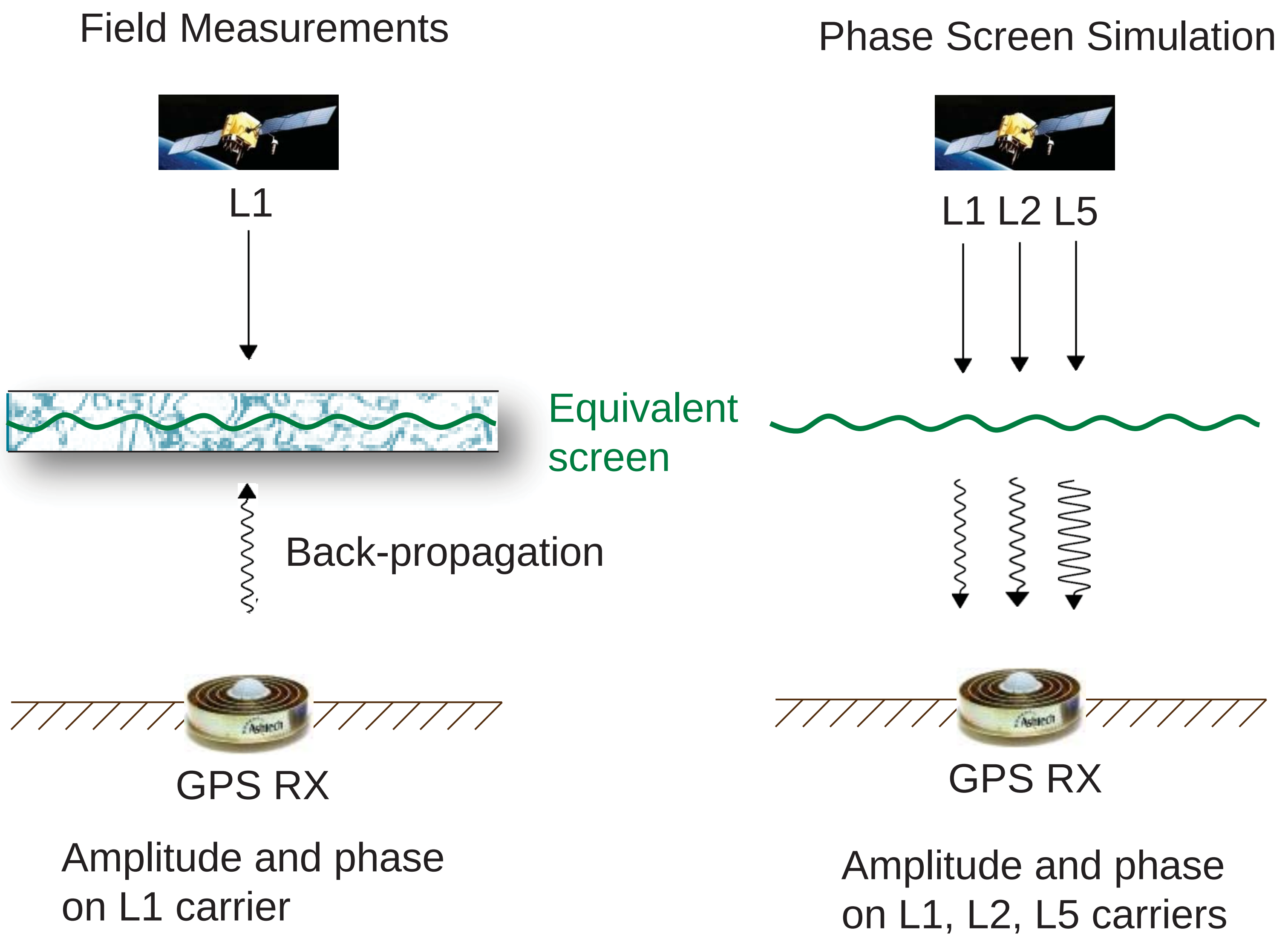
- **Path integration at oblique incidence through elongated structure projects the elongation onto the phase screen**
- **Path motion relative structure presents a 1D scan to an observer**
    - **Space to time conversion imposes an effective velocity**
- **The projection of the scan at the phase screen could be used to initiate an in-plane two-dimensional forward propagation calculation**
- **Charles Carrano has investigated and exploited this concept**

Comparing Forward-Propagation through 2D and 1D Screens

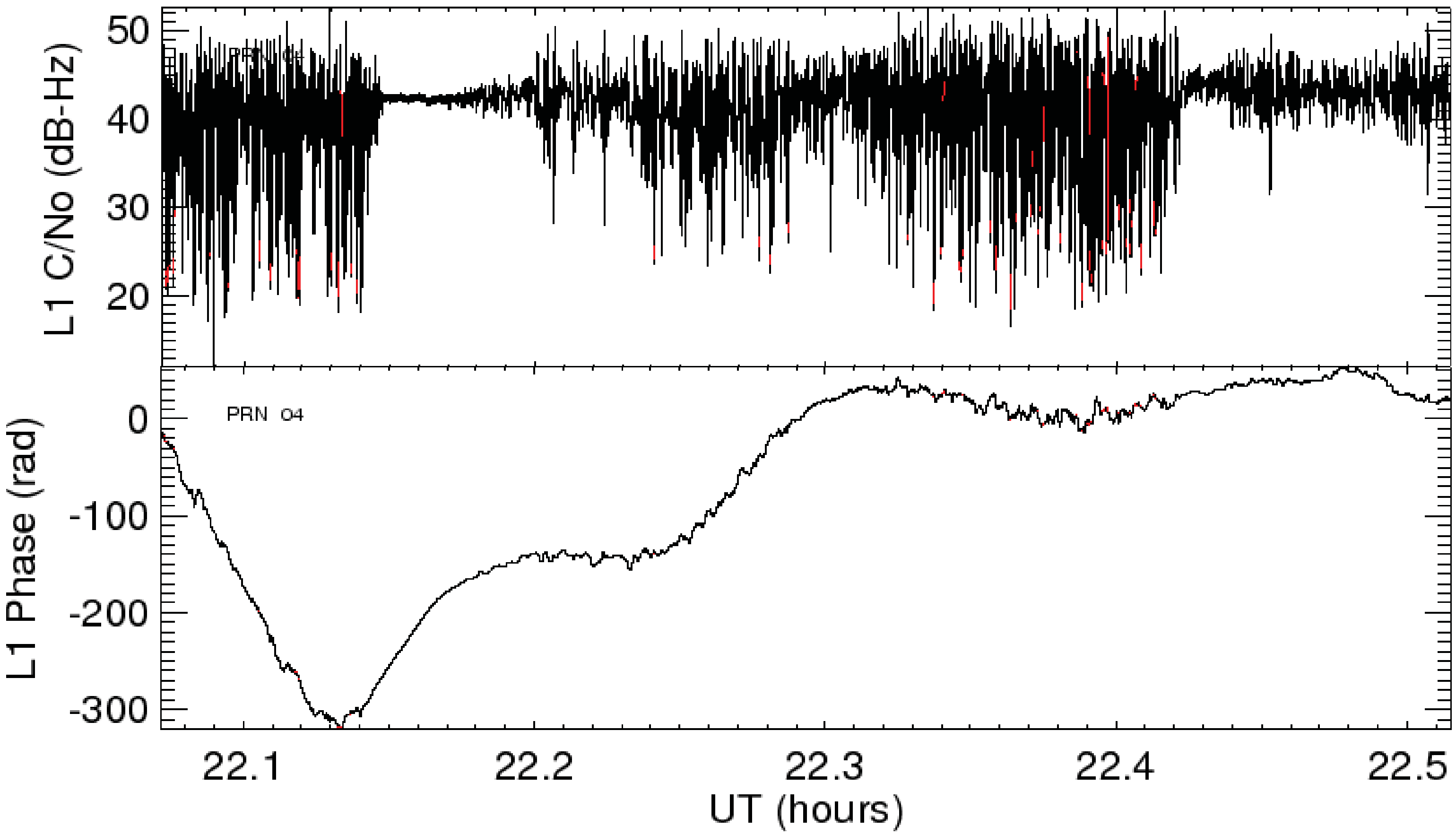


1D propagation results agree with 2D results only when scan is east-west

Deterministic Phase Screen Method

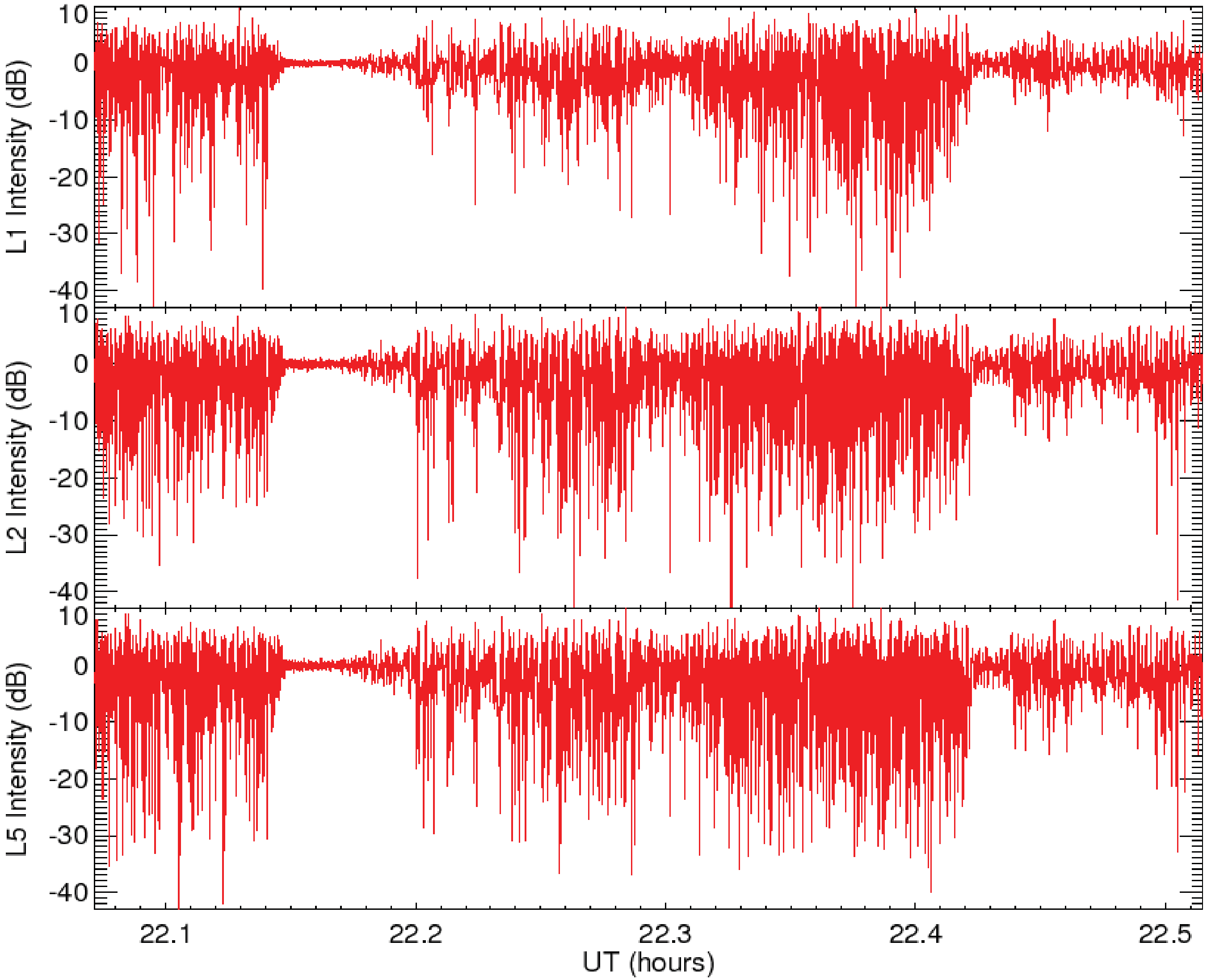


L1 Intensity and Phase Observations



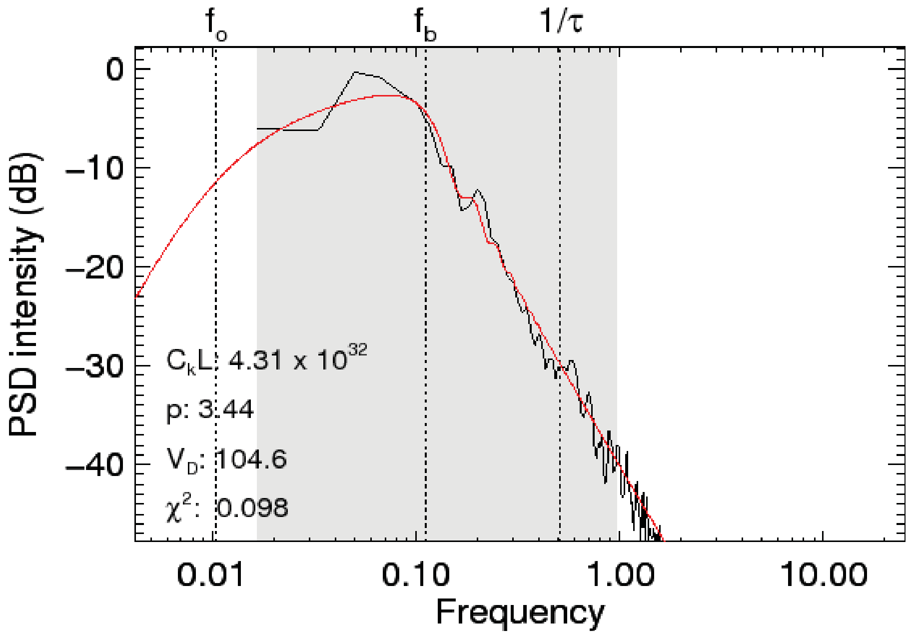
Data collected by AFRL on March 13, 2002 (solar max)
at Ascension Island (7.98°S, 14.4°W, 15°S dip latitude)
using NovAtel GSV4004 receiver

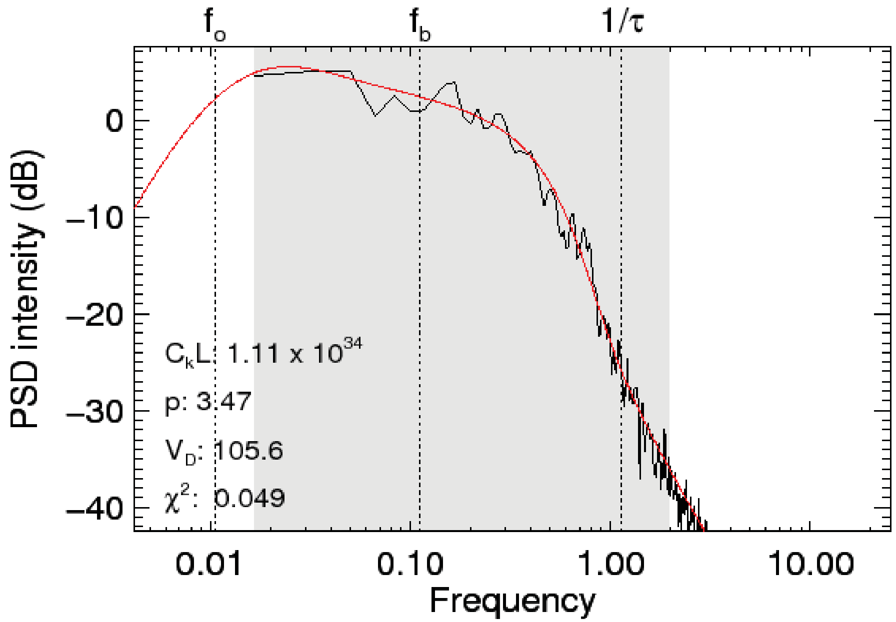
Deterministic Phase Screen Results



Intensity correlations between carrier pairs are calculated from these realizations

Iterative Parameter Estimation





Theoretical predictions derived from two-dimensional phase-screen theory

Accuracy of recovered parameters:

Weak Scatter

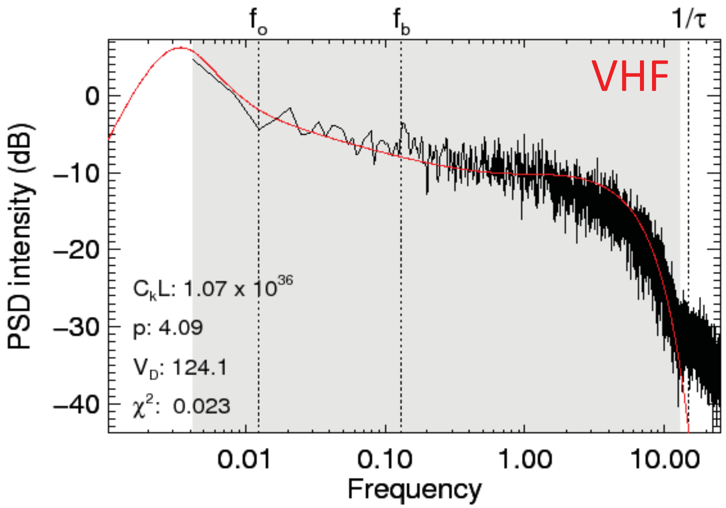
C_kL (14%), p (2%), and V_D (5%) accuracy.

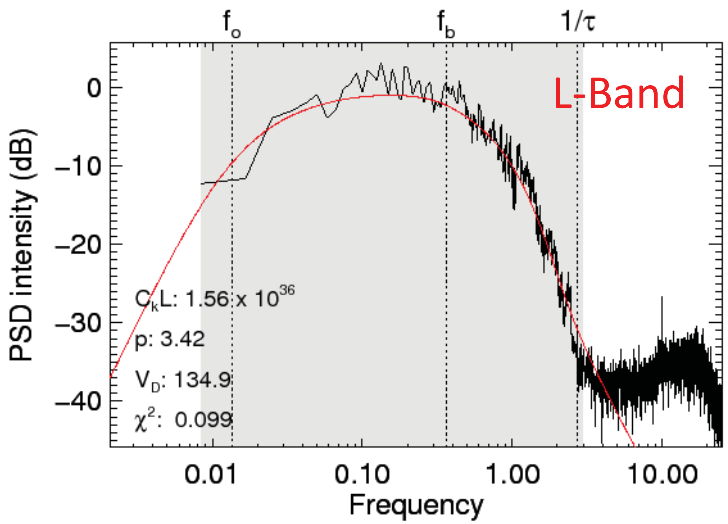
Strong Scatter

C_kL (11%), p (1%), and V_D (6%)

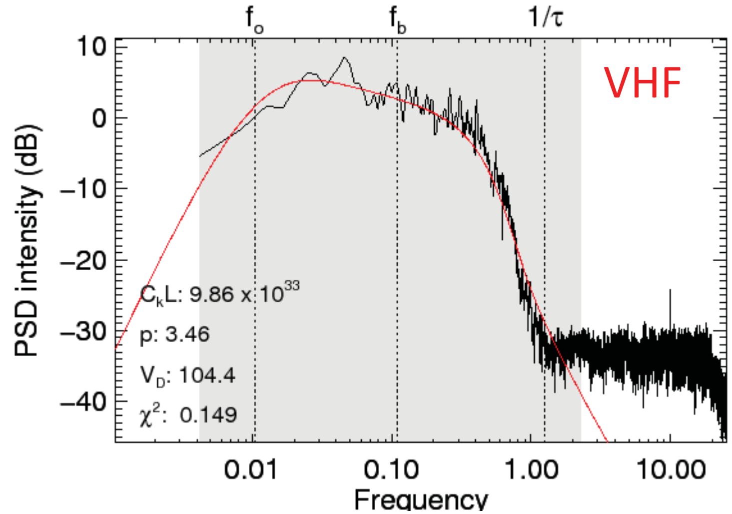
IPE ESF Results for Early and Late Local Times

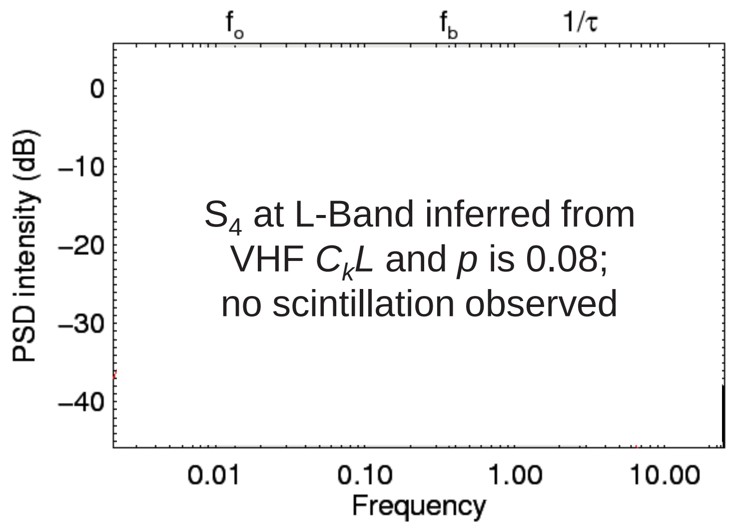
Early Evening (22:02 UT)





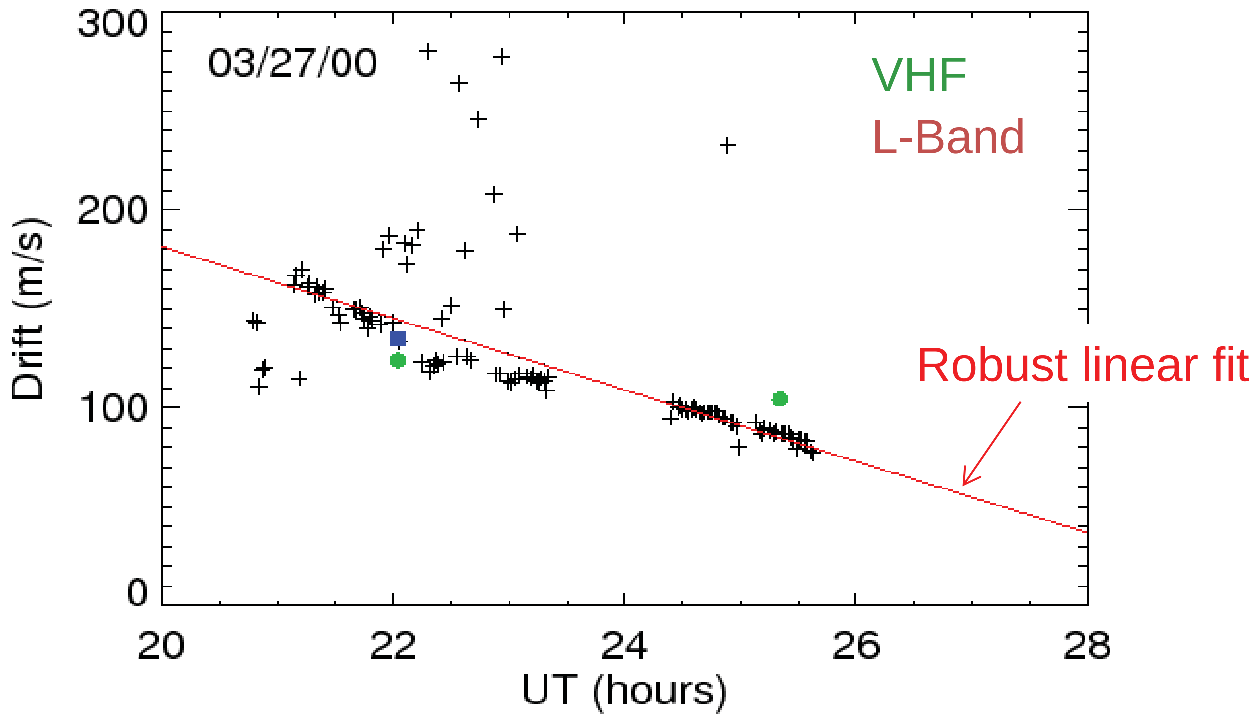
Post Midnight (25:20 UT)





Excellent agreement between screen parameters inferred from VHF and L-Band

Zonal Irregularity Drift Velocity



IPE analysis provides good estimates of the zonal drift using only a single receiver

Concluding Remarks

- Our objective was to present a consistent structure and scintillation model framework with analysis procedures that can be used to validate and refine models
- The strong-scatter theory was emphasized because these conditions are the most stressing for satellite navigation and communication
    - With modern computational resources efficient modeling and data analysis procedures are readily realized
- The challenge for planned experiments is to make sure data quality supports the refined analysis procedures
- Good research topics abound!

It has been my pleasure to present this material
Thank You

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