Scintillation Nowcasting with GNSS Radio Occultation Data

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Outline

- Issues for GNSS RO scintillation* observations
- Groud- and space-based RO scintillation comparison
- Geometric considerations
- Tools to Radio-Occulation Scintillation Simulation (ROSS)
- Back-propagation techniques
- Configuration space model
- Summary

* Note that this presentation focuses on equatorial scintillation associated with plasma bubbles

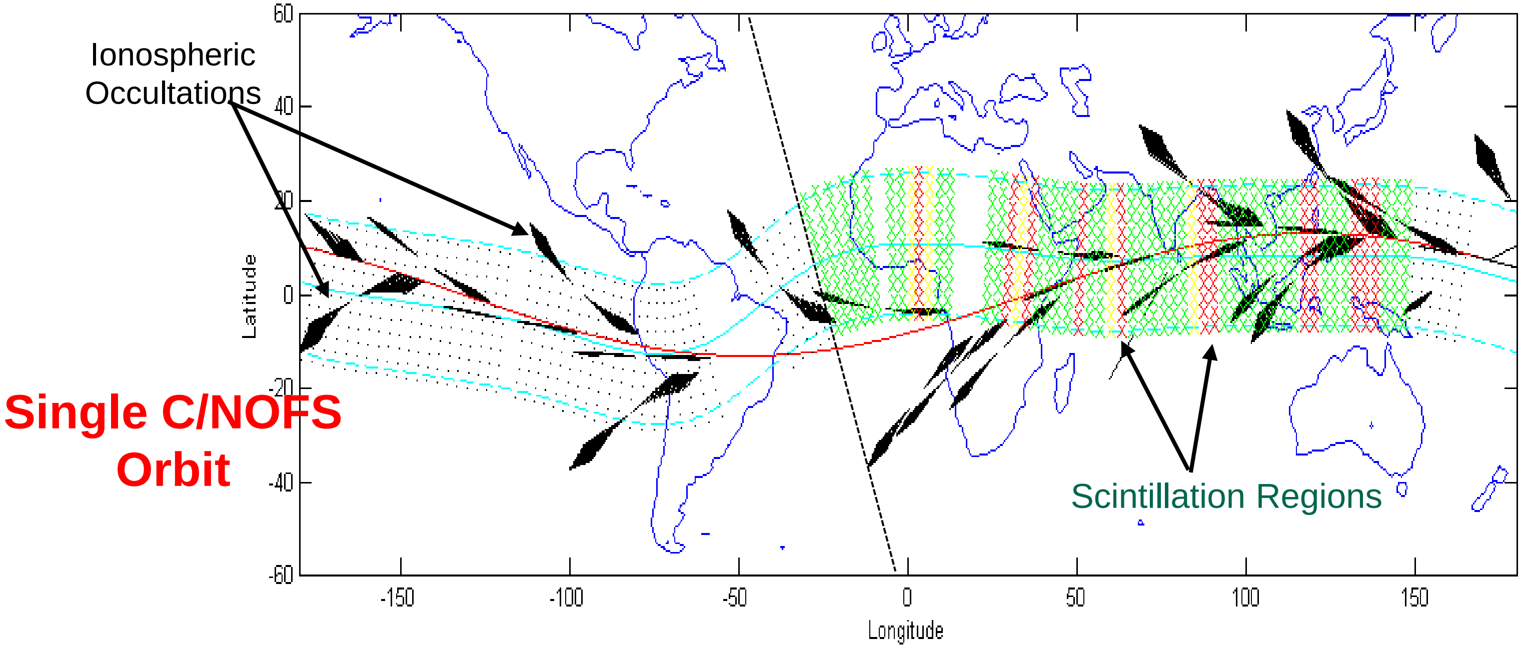
GNSS RO Scintillation Mapping: What makes it so "special"?

Benefits

- Global access
- No ground stations required
- 24/7 wide area coverage

Concerns

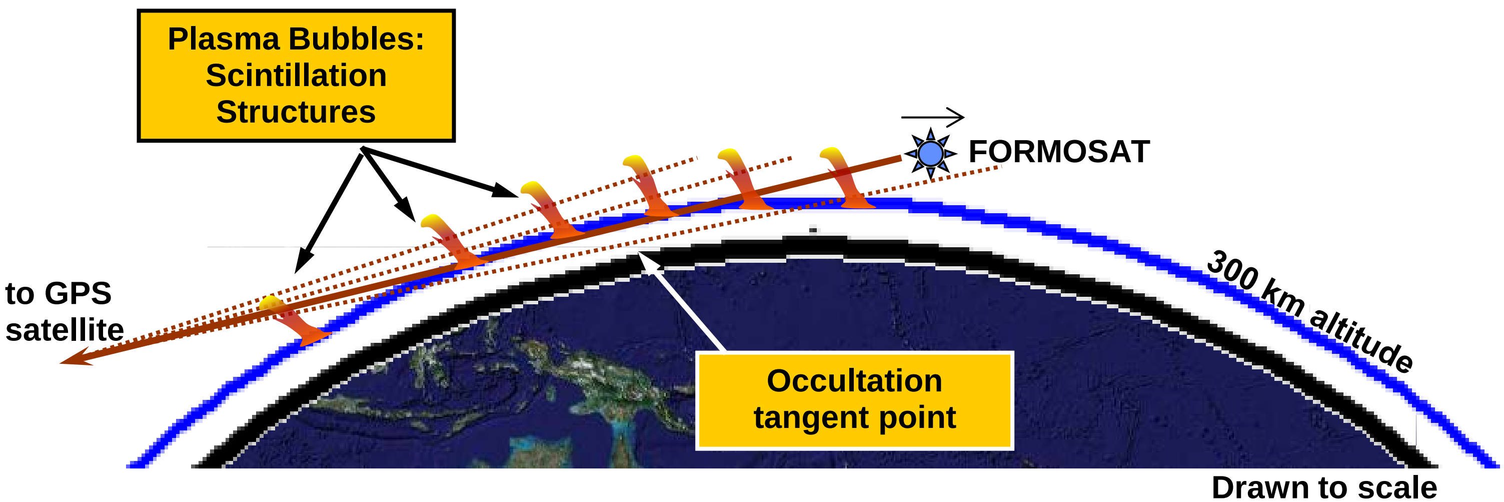
- Accuracy
- Spatial and temporal resolution
- Latency



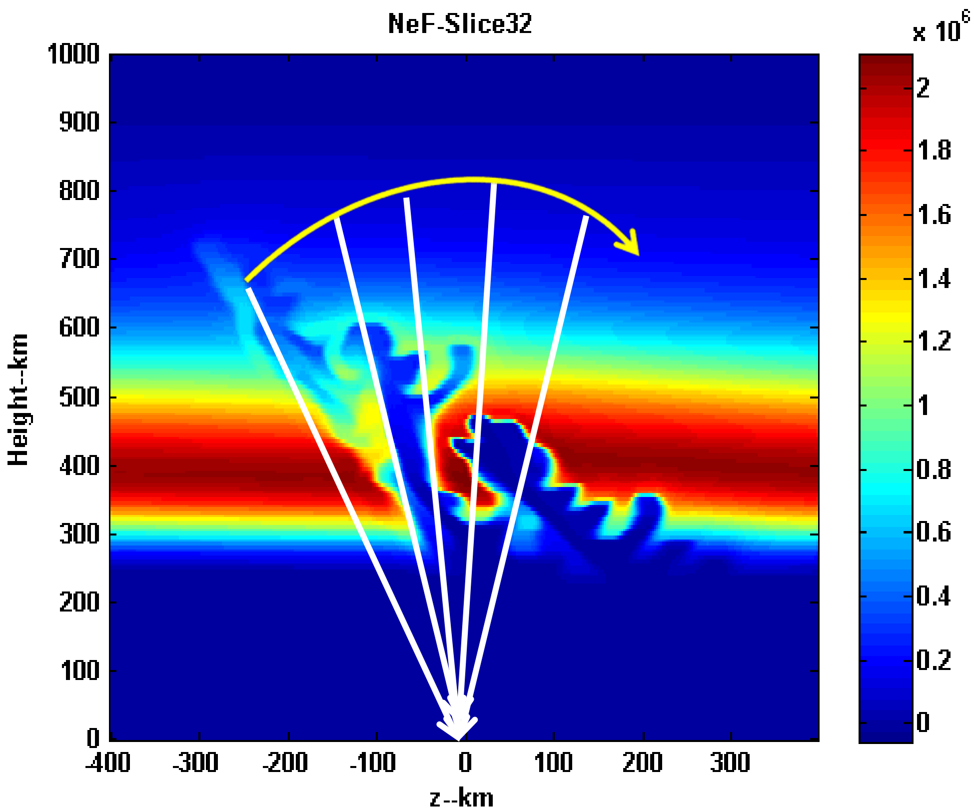
Six satellites in low inclination orbit provide good coverage

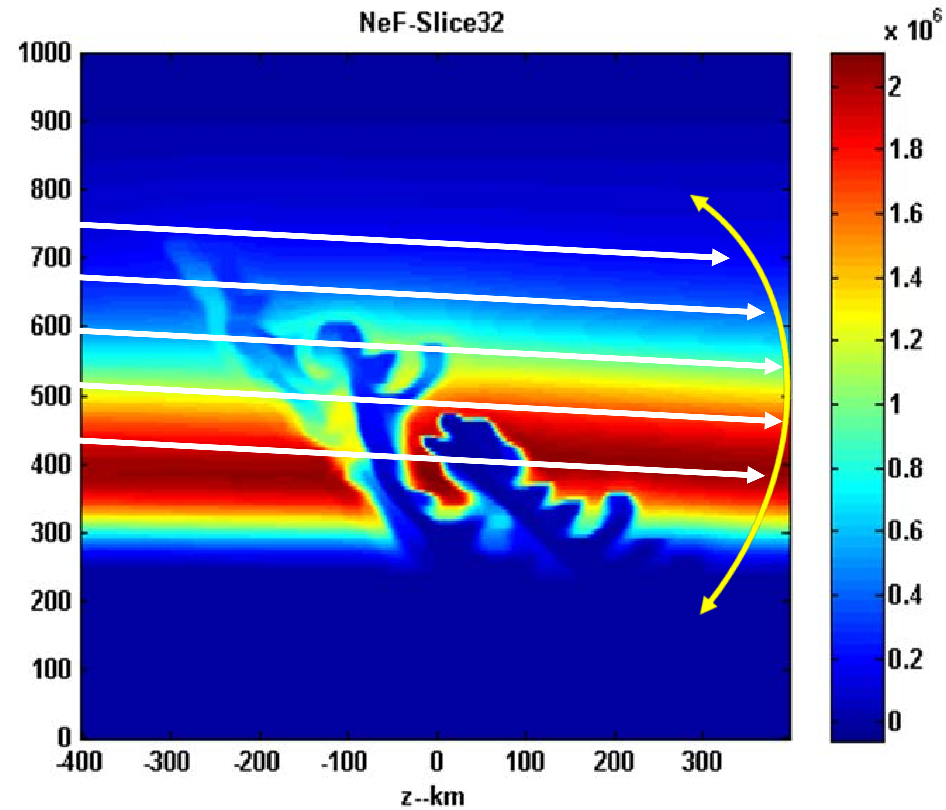
Multiple Structures Creates Complex Propagation Issues

- Observed signal is integrated over long slant path
- Potential for interaction with multiple turbulent plasma structures makes it difficult to adequately constrain inversion problem
- Other sources of information needed (and available)



Mapping RO Observations to Ground-based (User) Geometry

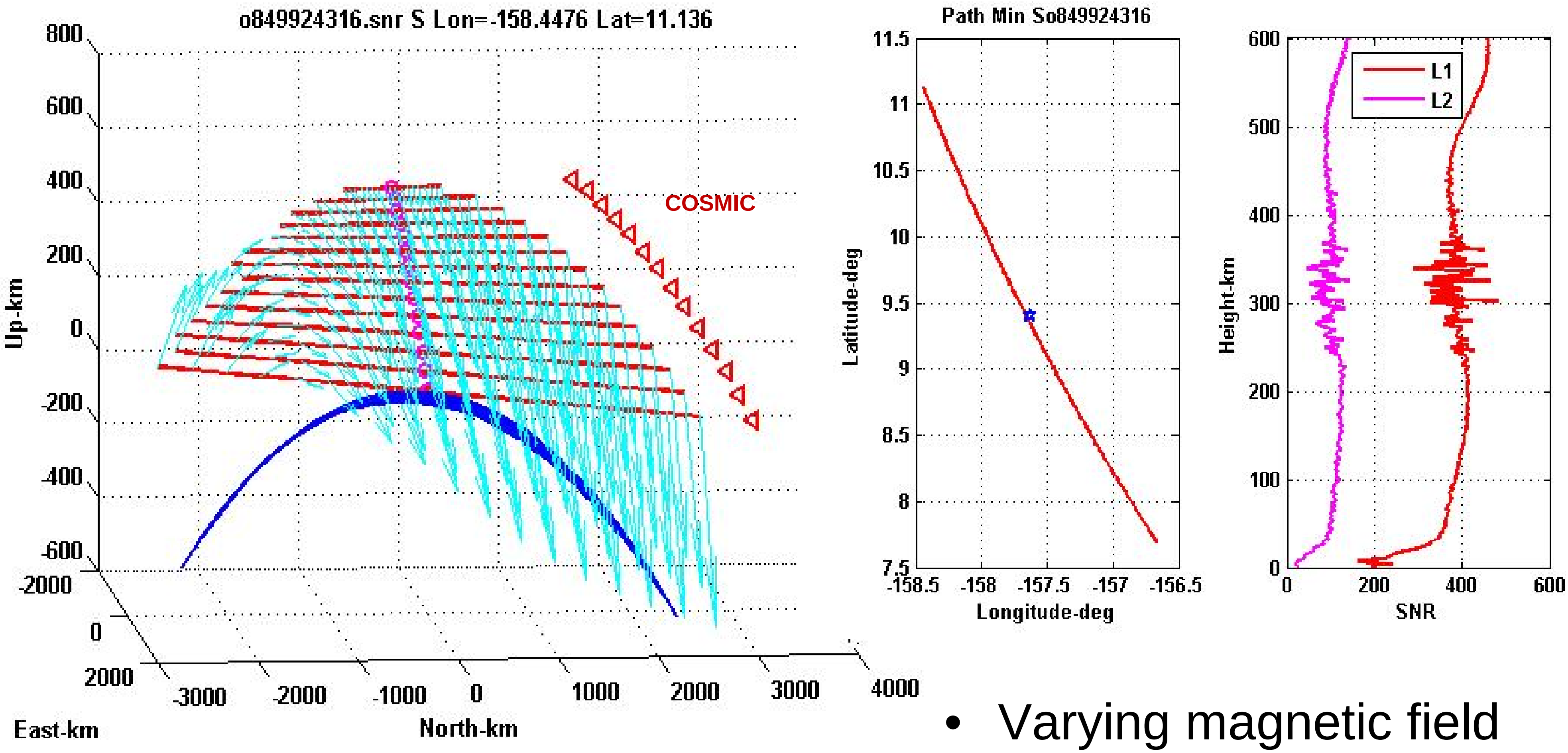




- Structure intercepted across layers
- Path integrated structure maps onto two-dimensional plane at observation point

- Structure intercepted along layers
- Path integrated structure cannot be mapped in conventional ways

COSMIC OCCULTATION GEOMETRY
Parameter Variations Along Raypaths



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

- Varying magnetic field geometry
- Varying effective scan velocity

RO Geometries: Issues for Scintillation Mapping

Characteristic	Impact
• Long slant paths	Geolocation
– Potential for multiple regions	Distribution of irregularities
– Large density variance	Difficulty tracking phase
– Large range of relevant Fresnel scales	Difficulty separating spatial/temporal scales
• Varying magnetic field geometry • Varying effective scan velocity	Requires multiple complex serial calculations
• Quasi-parallel propagation paths relative to the magnetic field	Not described by existing models

Quick-Look Study: Comparisons Near Kwajalein

- Used COSMIC occultation data from:
  - 12 July 2006 to 24 March 2007
  - 1 January to 8 August 2008
  - 0700 – 1700 UTC (~1930 – 0530 LT)
- Geographic window of comparison:
  - The occultation must transect the mid-level of the F-layer (300km) within
    - the latitudes of the equatorial magnetic belt
    - ± 5º longitude of the Kwajalein Atoll (AFRL VHF receiver)

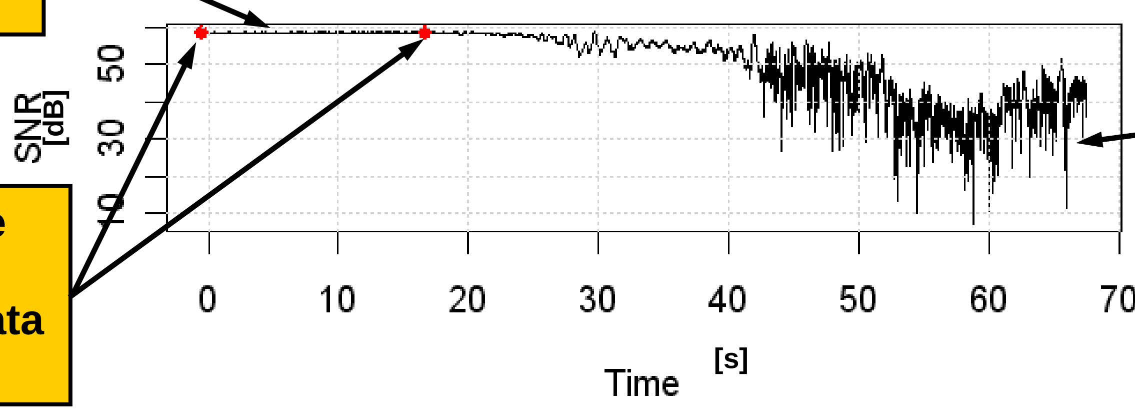
1249 occultations used in the study

COSMIC L1 SNR Data

Typical COSMIC GPS radio occultation data for a setting occultation, using 50Hz data.

Ionospheric scintillation can be seen here, before lower atmosphere effects obscure it

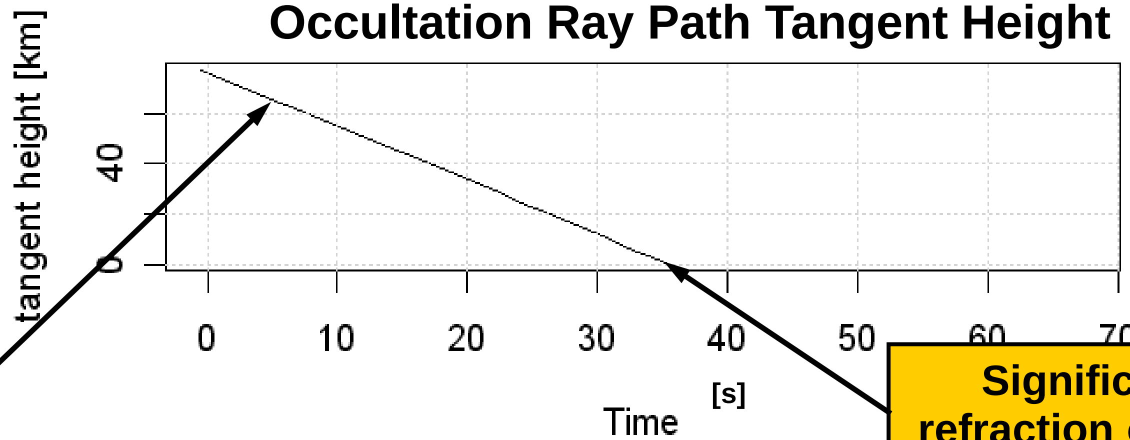
COSMIC L1 SNR Data near Kwajalein



Tropospheric effects become overwhelming as the ray path bends

Analysis software automatically extracts relevant data segment

Occultation Ray Path Tangent Height



Straight-line ray tangent height computations are valid at ionospheric heights

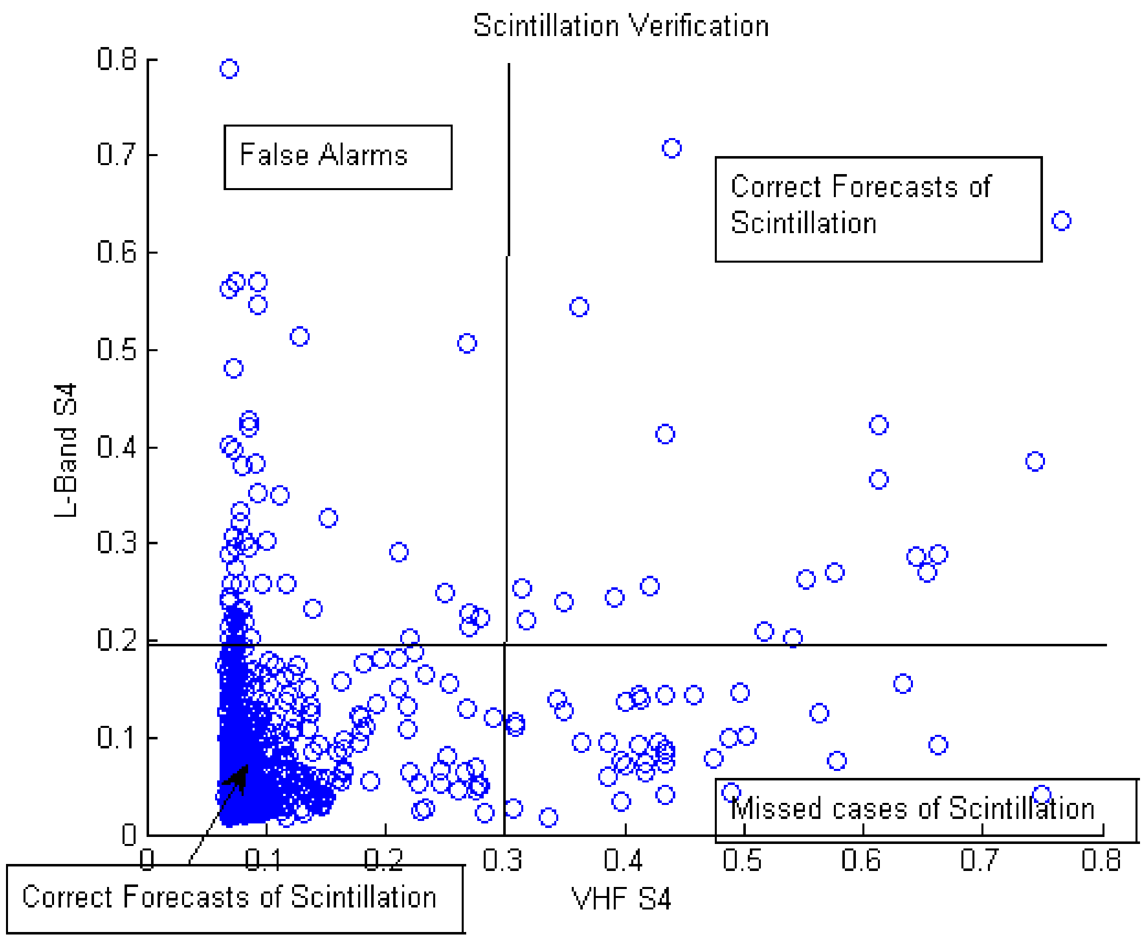
Significant ray path refraction occurs at lower altitudes. Straight line path is not valid.

COSMIC Comparison Results

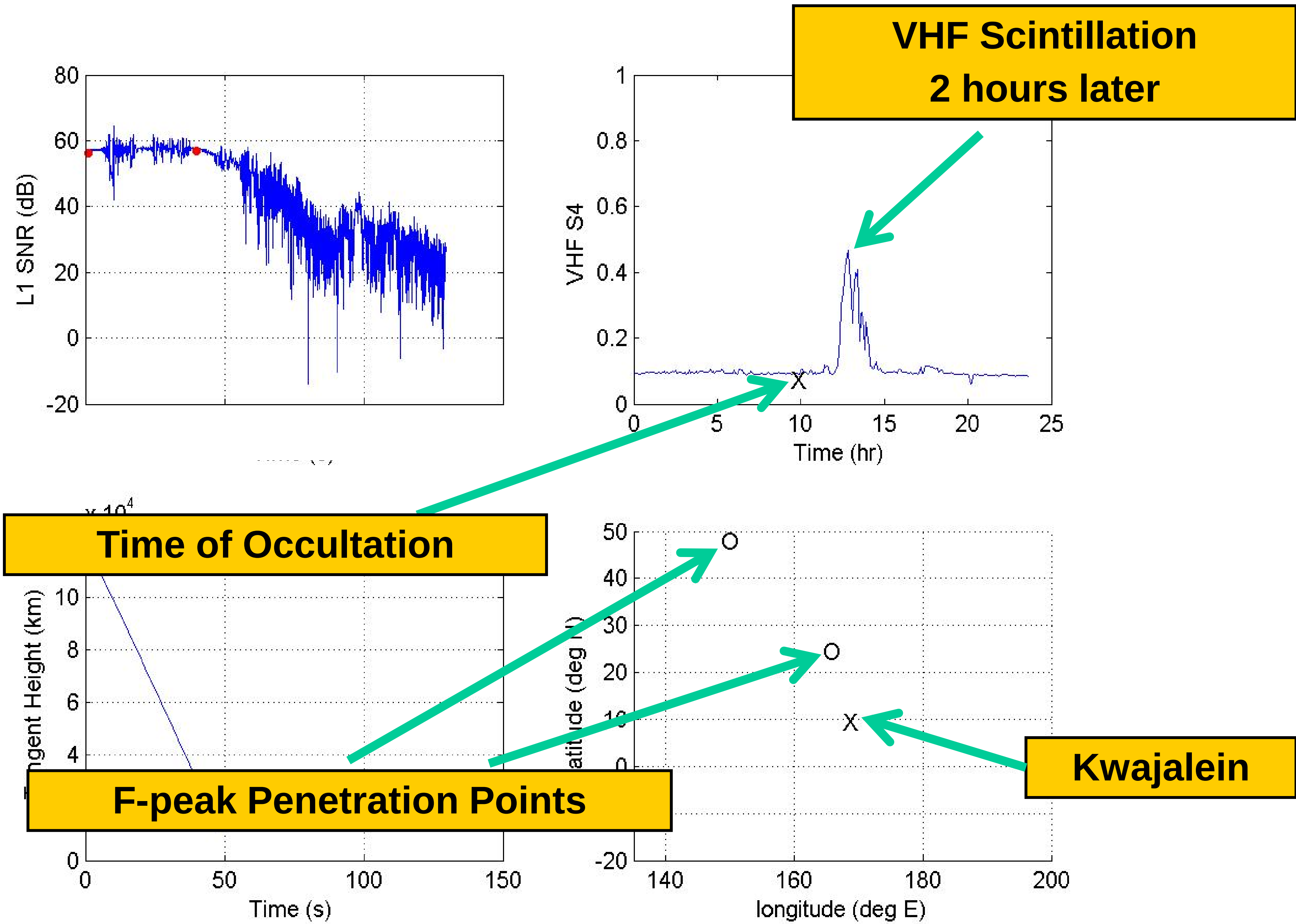
Correlation Coefficient = 0.35

	VHF S4 ≥ 0.3	
L-Band S4 ≥ 0.2	Yes	No
Yes	19	54
No	35	1141

Probability of Detection = 0.35
False Alarm Rate = 0.74



Anatomy of a “False Alarm”



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Inspection of Uncorrelated Cases Greatly Improves Statistics

- 34 geo-location issues
- 9 elevated L-Band S4 but < 0.2
- 7 elevated VHF S4 values but < 0.3
- 12 observed scintillation outside of ± 1.5 hour window
- 1 noise contaminated occultation
- 20 unexplained misses

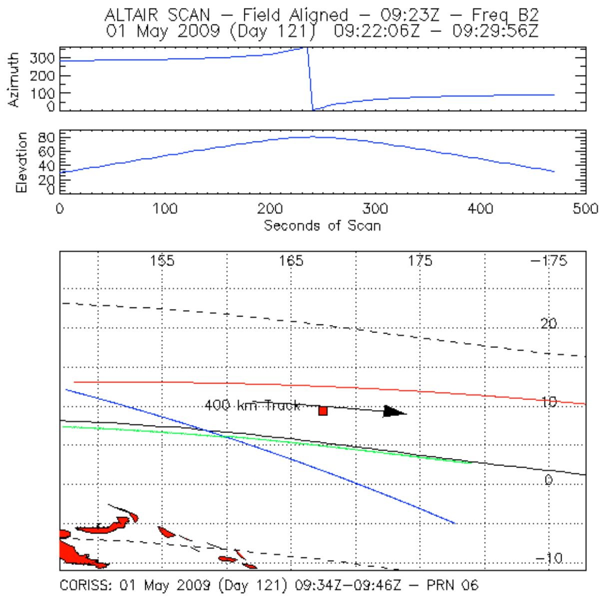
Arguably probability of detection could be as high as 0.74; false alarm rate could be as low as 0.16

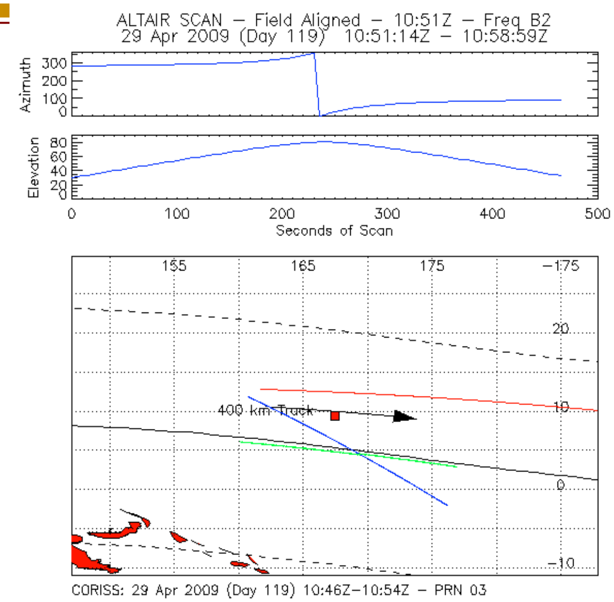
Comparisons with ALTAIR 21 April -- 01 May 2009

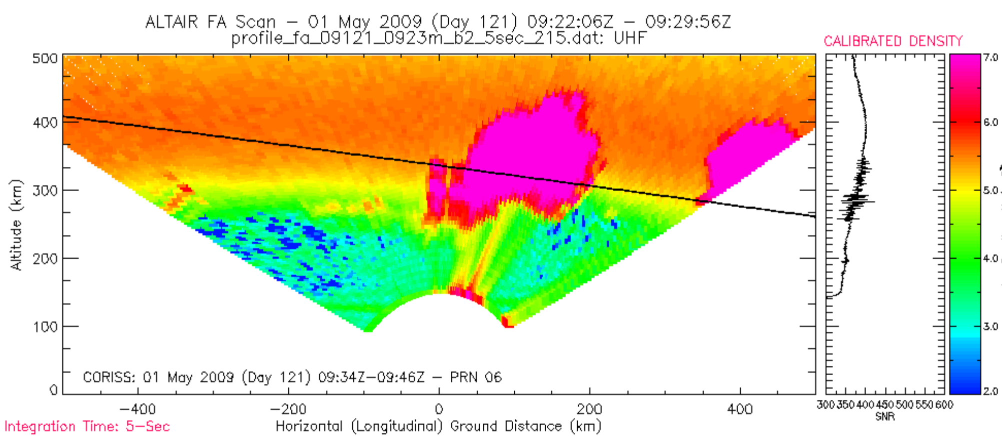
- During a 10-day period a total of 49 GPS post-sunset occultations in the vicinity of Kwajalein were recorded by CORISS (nearly 5 occultations per evening!)
- On most evenings proximate occultations occurred nearly every orbit, a refresh rate of ~100 minutes
- Of 49 total occultations, 26 occurred within the effective field-of-view (FOV) of the ALTAIR radar while it was operating
  - In 15 cases both showed the presence of irregularities; the other cases correctly showed an absence of scintillations: 100% agreement!
- Geometric factors largely determine detection coverage region and mapping resolution in lat/lon

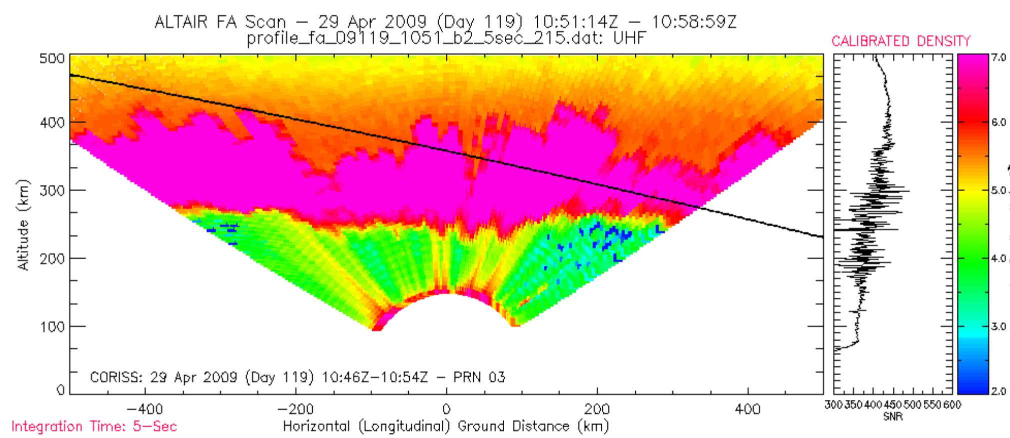
What about other geometries?

Sweeping Tangent Points



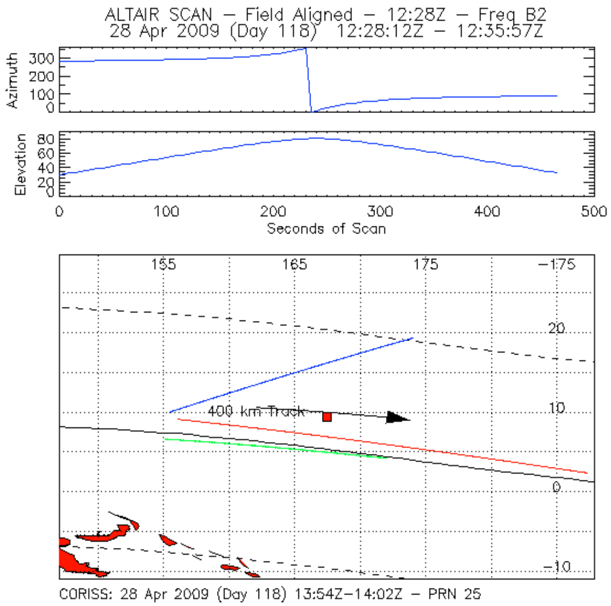


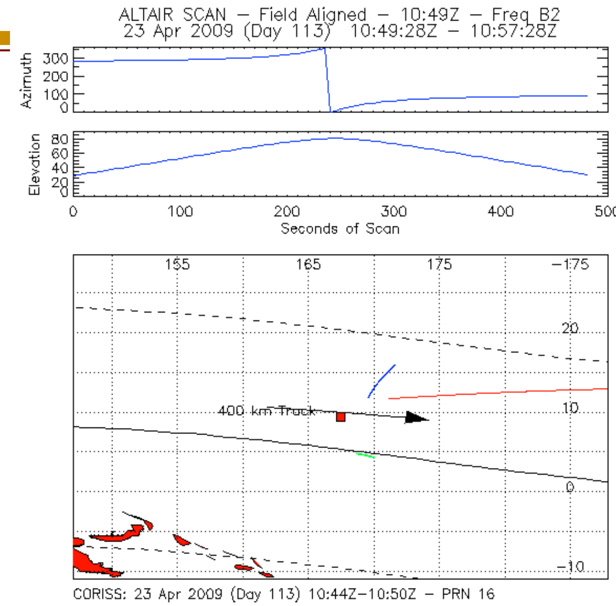


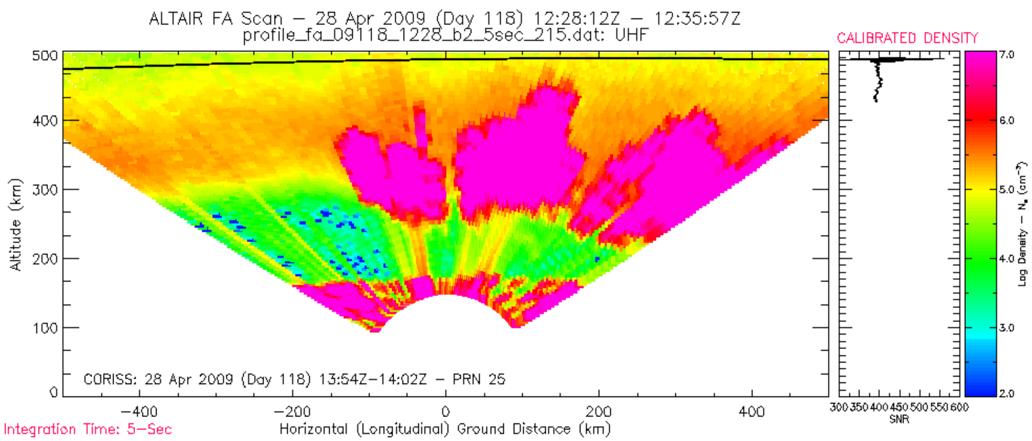


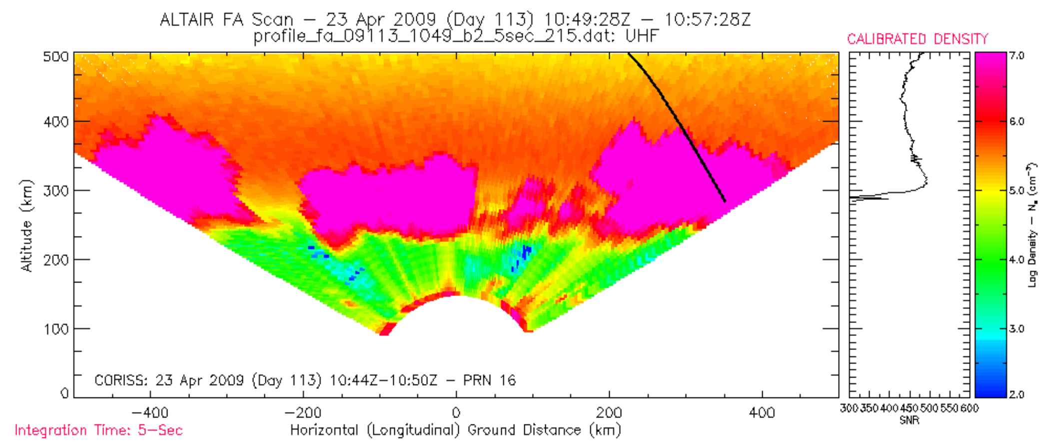
- Side-looking occultation sweeps across longitude as it progresses
- Provides better zonal resolution for geo-location than in-orbit occultations
- Apriori knowledge of bottomside height constrains spatial mapping

Mapping from higher magnetic latitudes





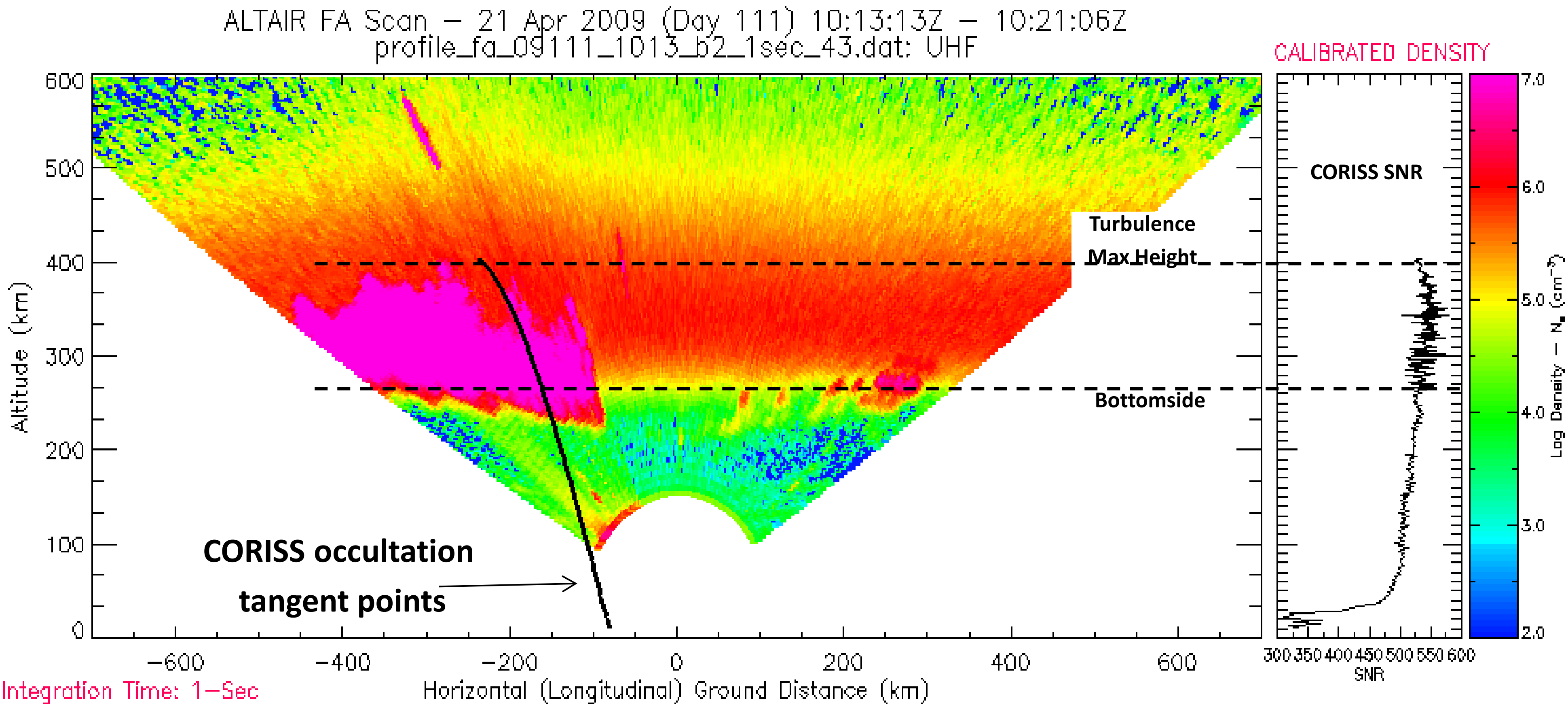




- Poleward occultations quickly map to higher apex altitudes; effective sampling altitude may be above irregularity regions
- Sub-ionospheric tangent point altitudes can map into F-region heights at magnetic equator while actual sampling region is below ionosphere

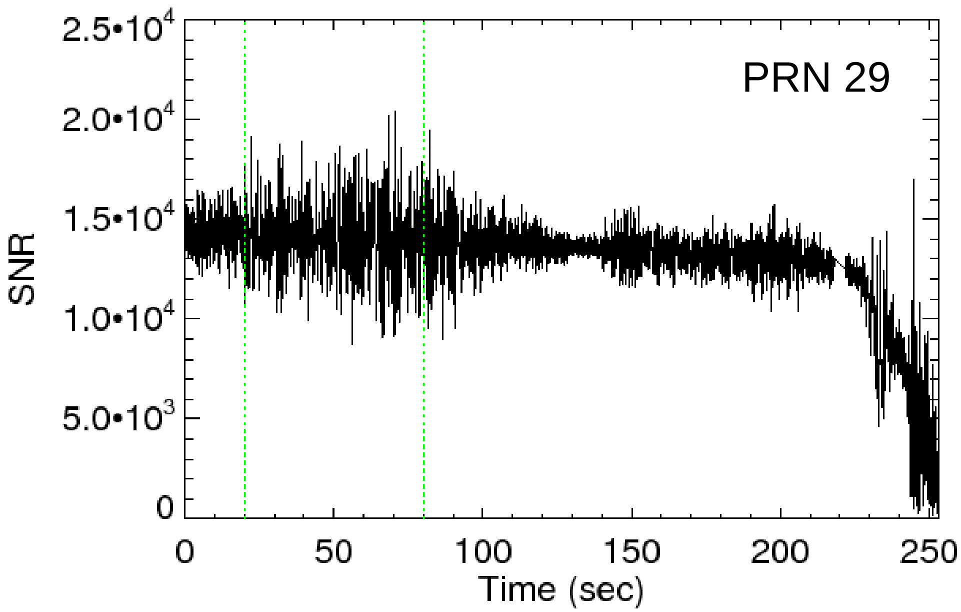
Case Study
21 April 2009

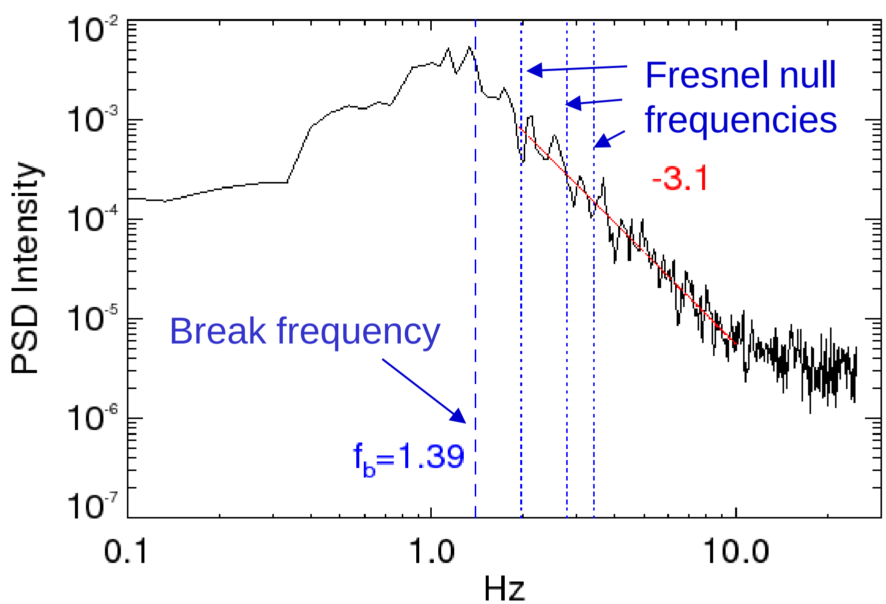
Carrano et al., Rad. Sci.,
doi:10.1029/2010RS004591, 2011



Both width and placement in good agreement with spectral analysis result

Locating the Scattering Region for an East-West Occultation





- Compute intensity PSD of scintillating signal
- If scatter is weak, mean distance to the scattering region along line of sight (LOS) is:

$$d_s = \frac{1}{2\lambda}\left(\frac{V_{scan}}{f_b}\right)^2$$

- If propagation is orthogonal to B, then V_{scan} is component of V_{ipp} perpendicular to the LOS:

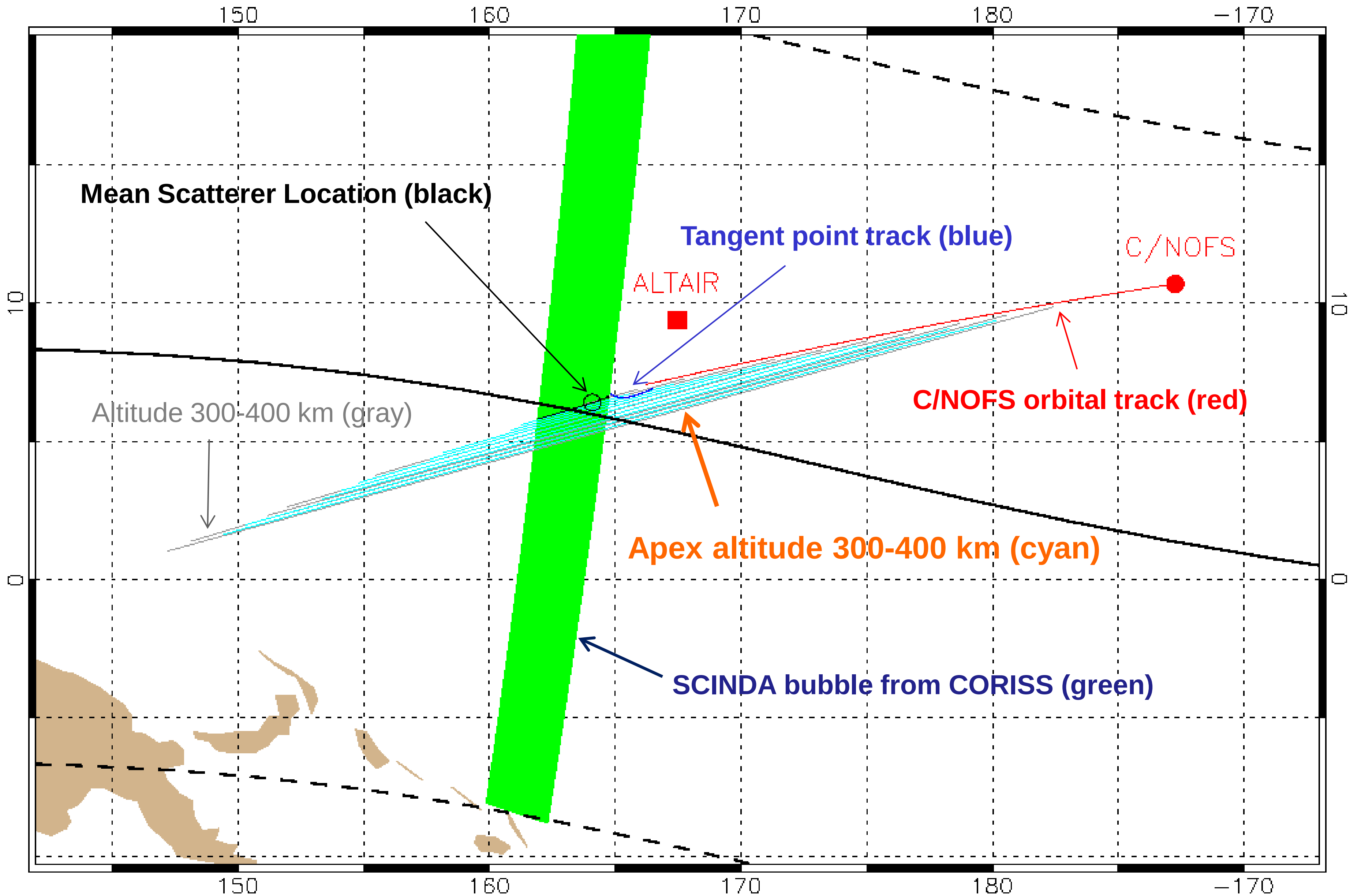
$$V_{scan} = V_{\perp}^{C/NOFS} + \frac{d_s}{d}\left[V_{\perp}^{GPS} - V_{\perp}^{C/NOFS}\right]$$

where d is the distance between the C/NOFS and GPS satellites.

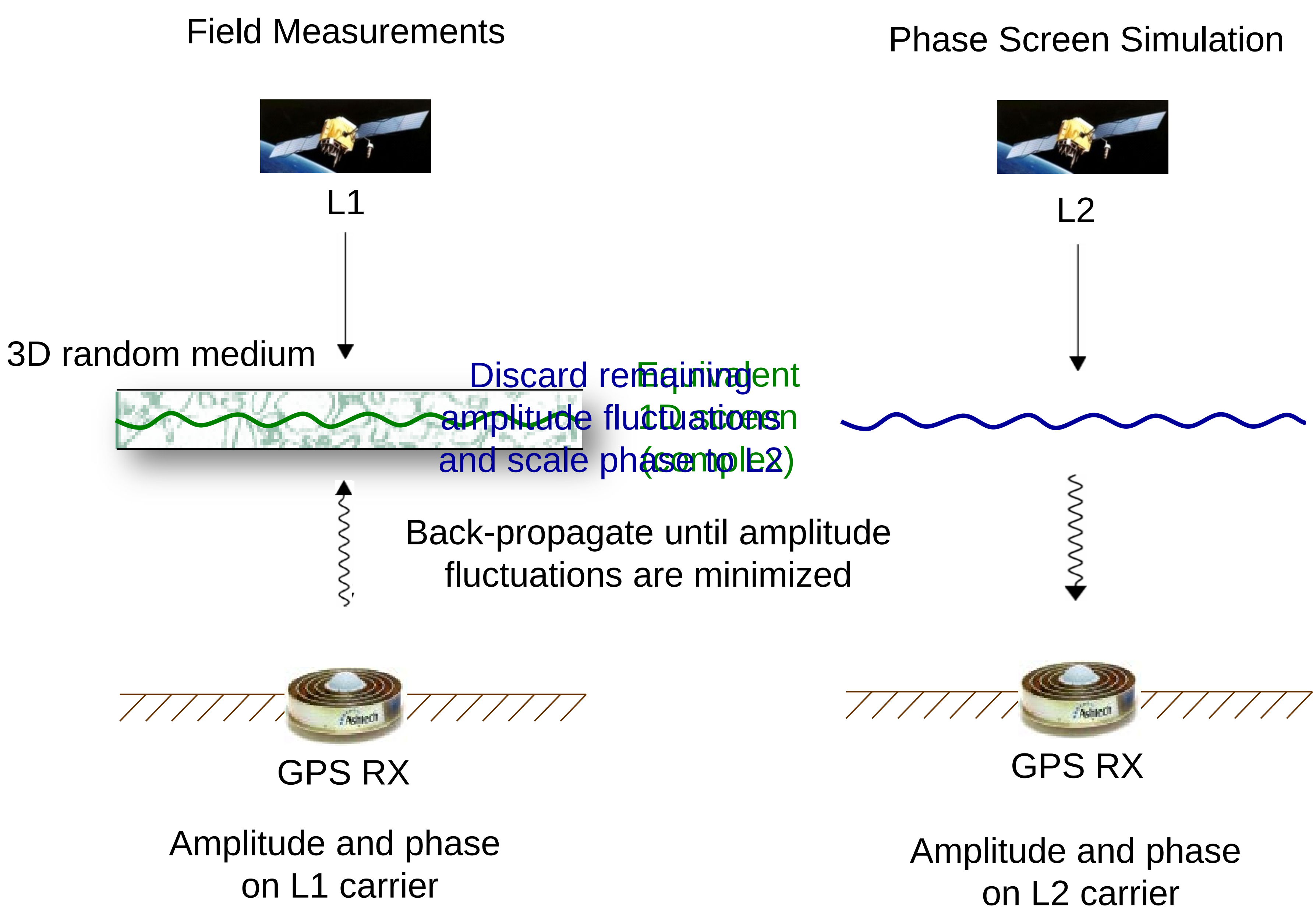
- Solving these simultaneously gives the scan velocity and distance to scattering region.

Mean scattering distance: 627 km, location: (6.40°, 164.1°), intensity spectral index ≈ 3

Spawning a Bubble from CORISS Observations

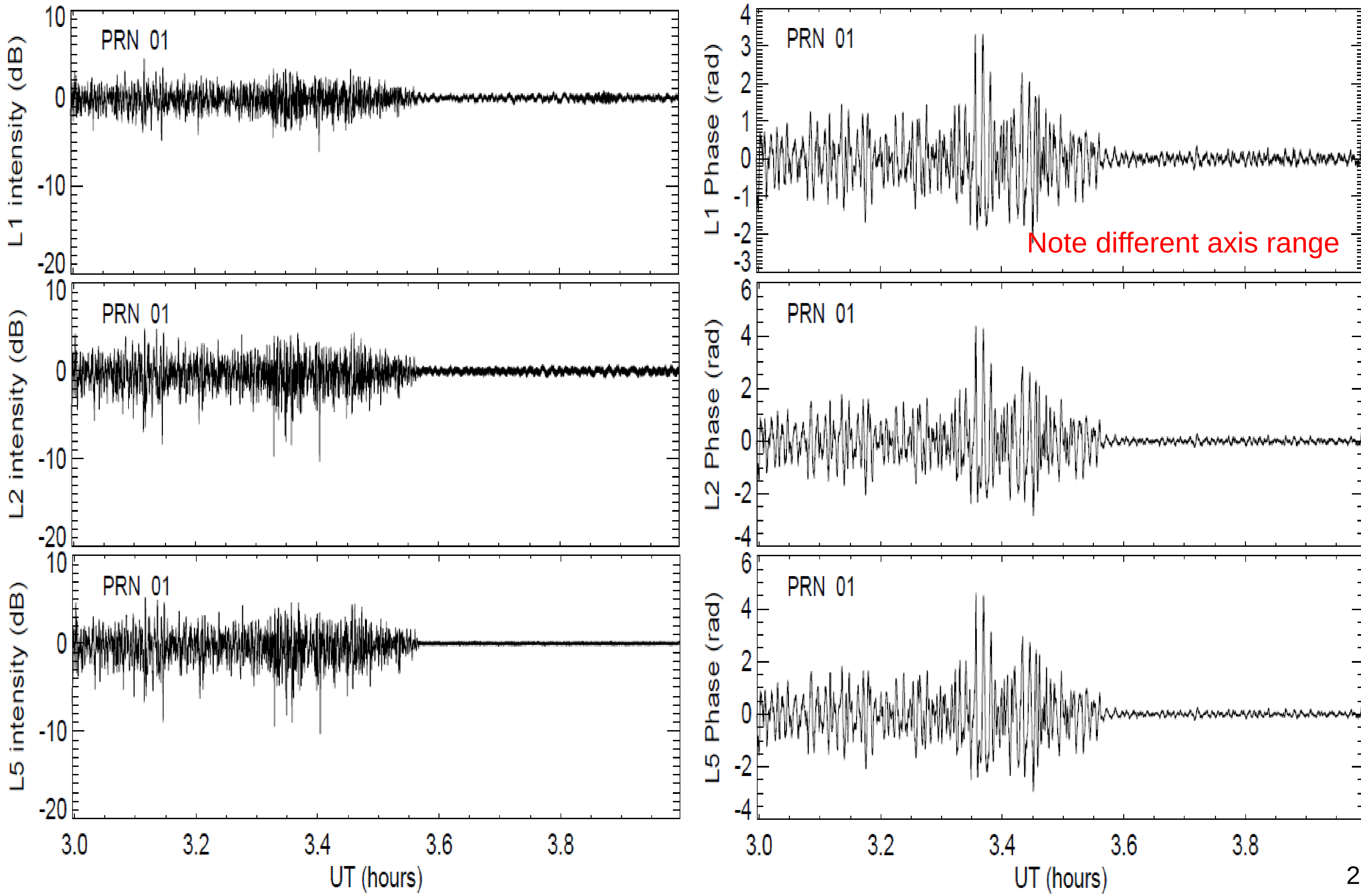


Inverse Diffraction Method: Back Propagation



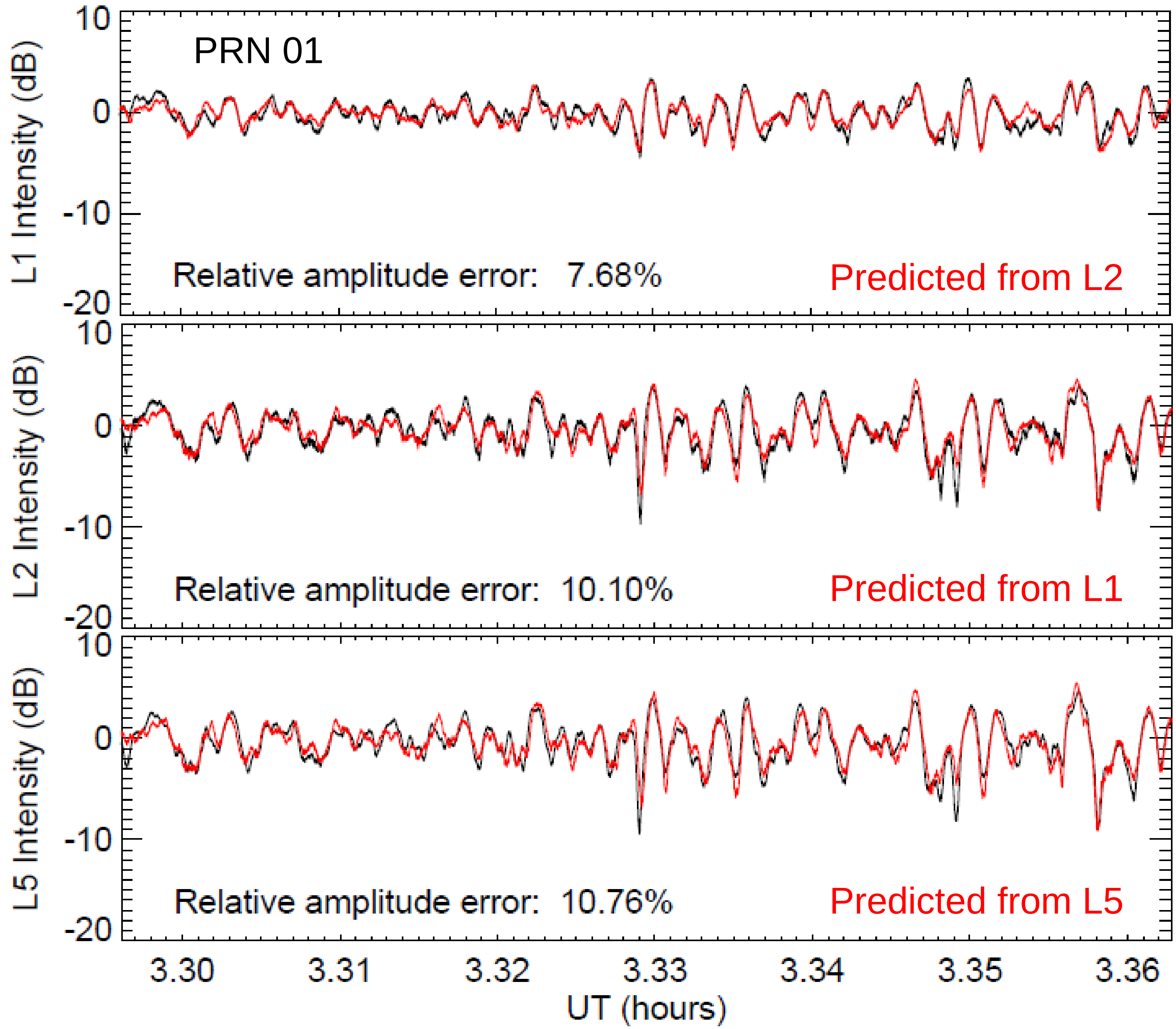
2013 Day 052 – PRN 01

Example using actual GPS data

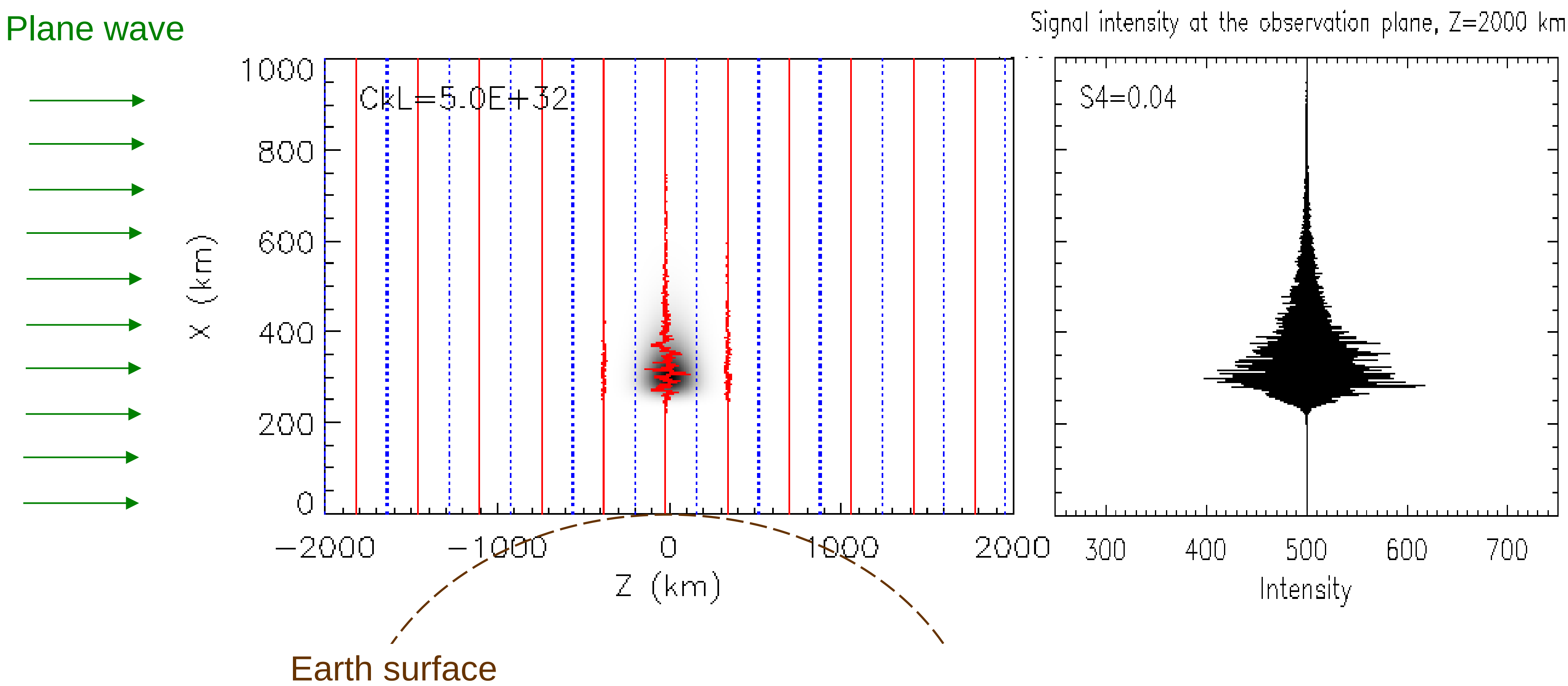


2013 Day 052 – PRN 01

Black – measured, Red - Predicted



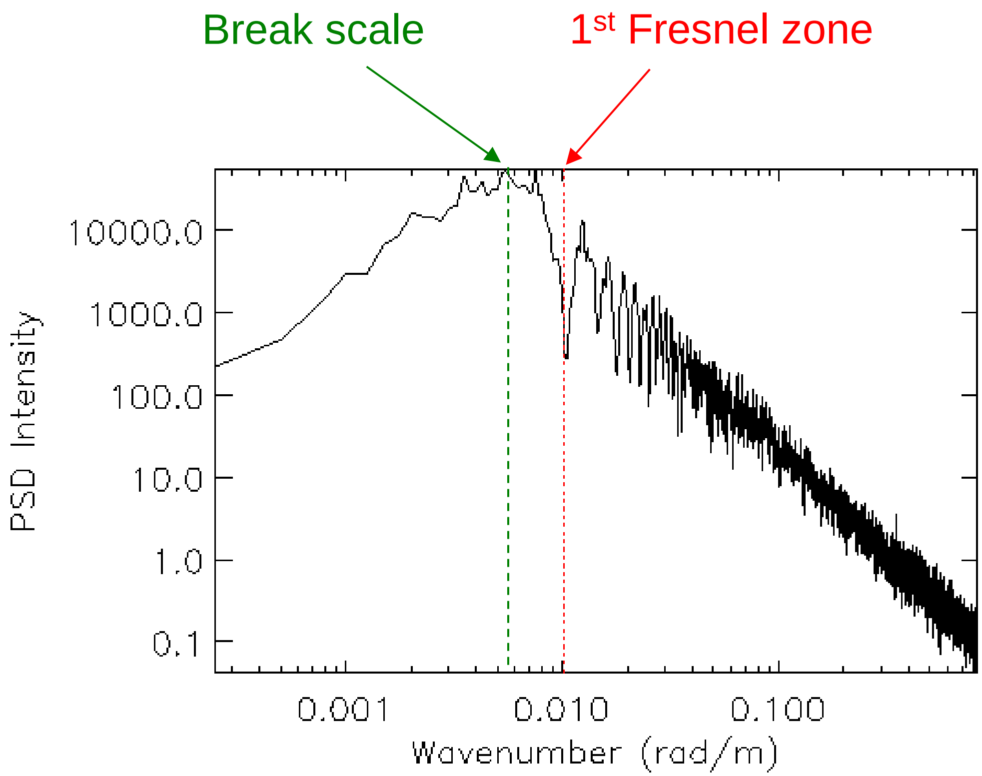
Multiple Phase Screen Simulation
RO Propagation through a Single Bubble



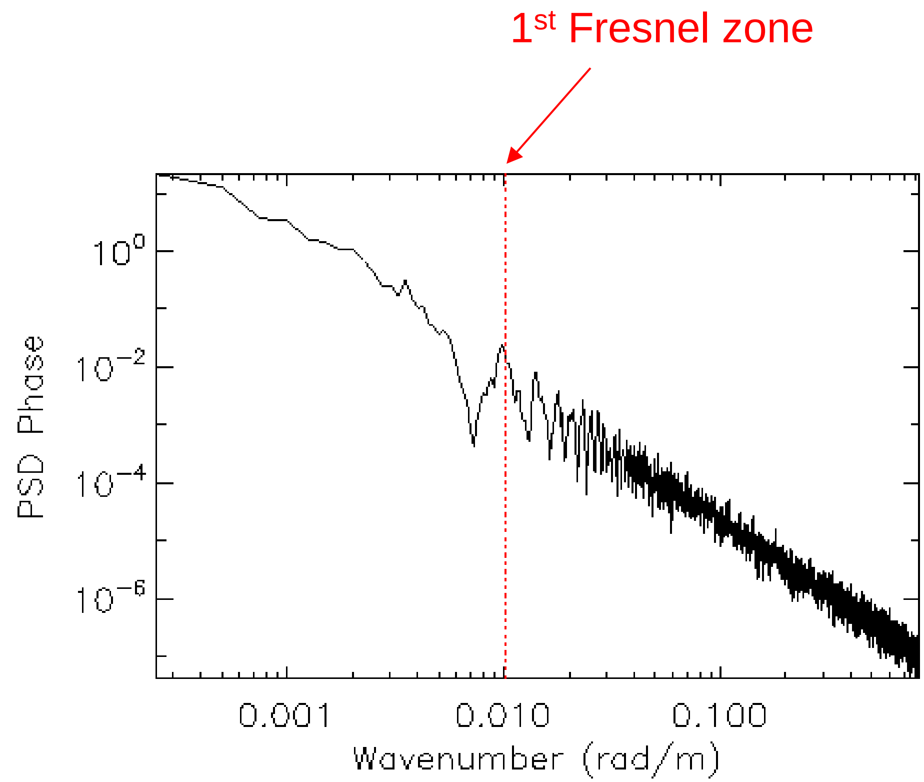
In the case of propagation through a single bubble located at the tangent point, the apparent altitude of the intensity fluctuations is approximately the altitude of the bubble.

RO Propagation through a Single Bubble

Intensity PSD

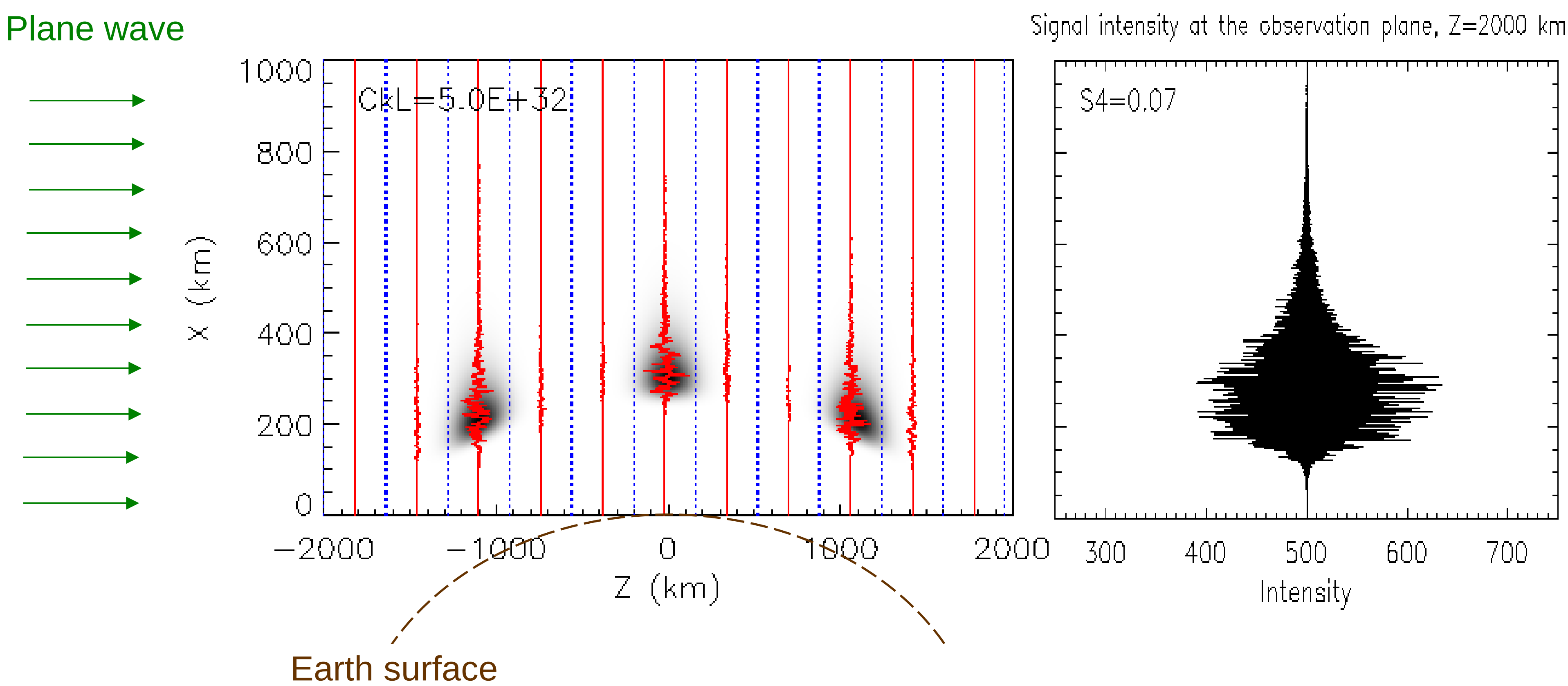


Phase PSD



Since the bubble is thin (it was specified to have width of 100 km), Fresnel nulls in the intensity and phase spectra are clearly evident. *The distance (d) to the bubble along the occultation raypath can be readily determined from the 1st Fresnel zone, $k_F = 2\pi(\lambda d)^{-1/2}$.*

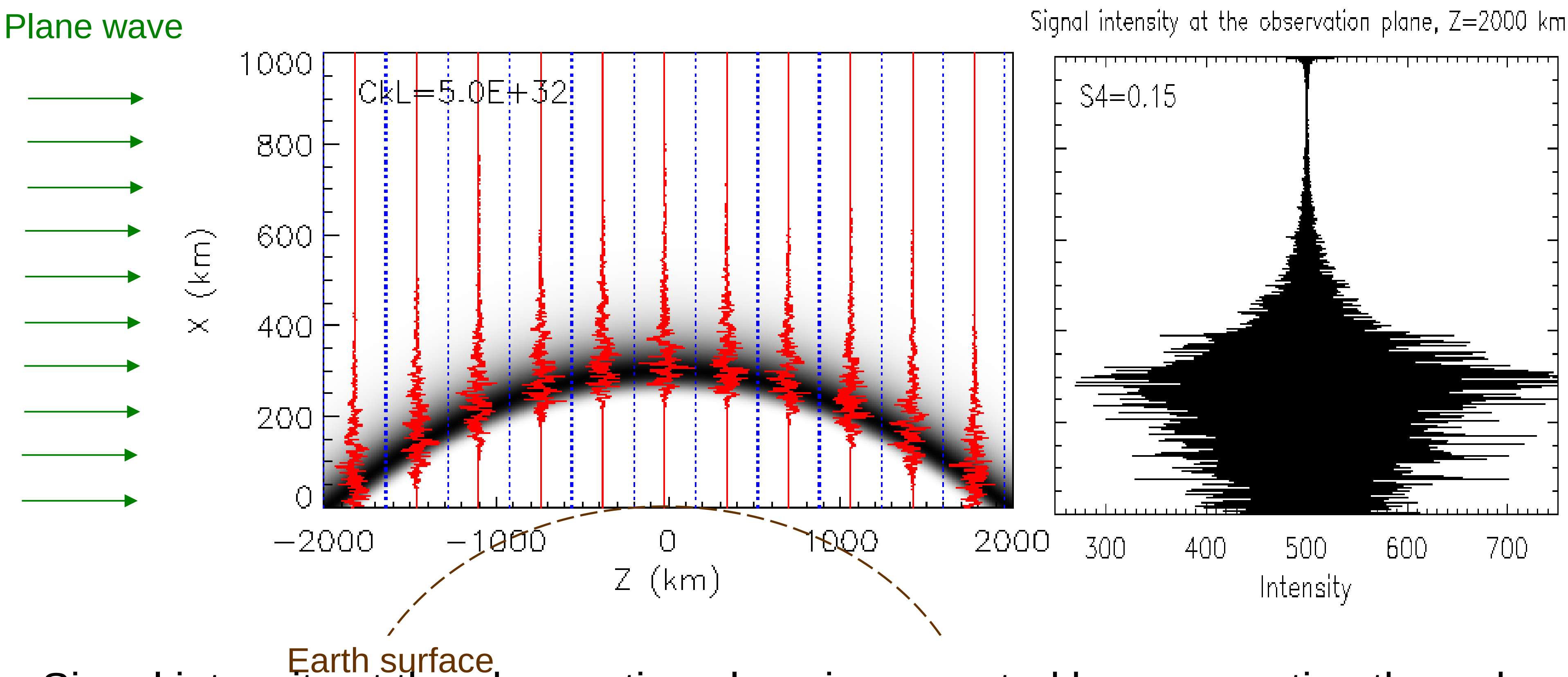
RO Propagation through Multiple Bubbles



In the case of propagation through multiple bubbles, the apparent altitude of the fluctuations in the received intensity is not the actual attitude of the bubbles. Instead, it is determined by the projections of the bubbles onto the observation plane.

RO Propagation through Uniformly Distributed Irregularities

We specify the background electron density as a Chapman layer. Irregularity strength (RMS ΔN/N) throughout the volume is assumed to scale with the background density.



Signal intensity at the observation plane is computed by propagating through multiple phase screens oriented normal to the raypath. The phase in each screen (shown in red) is computed by integrating the density fluctuations between adjacent blue dashed lines.

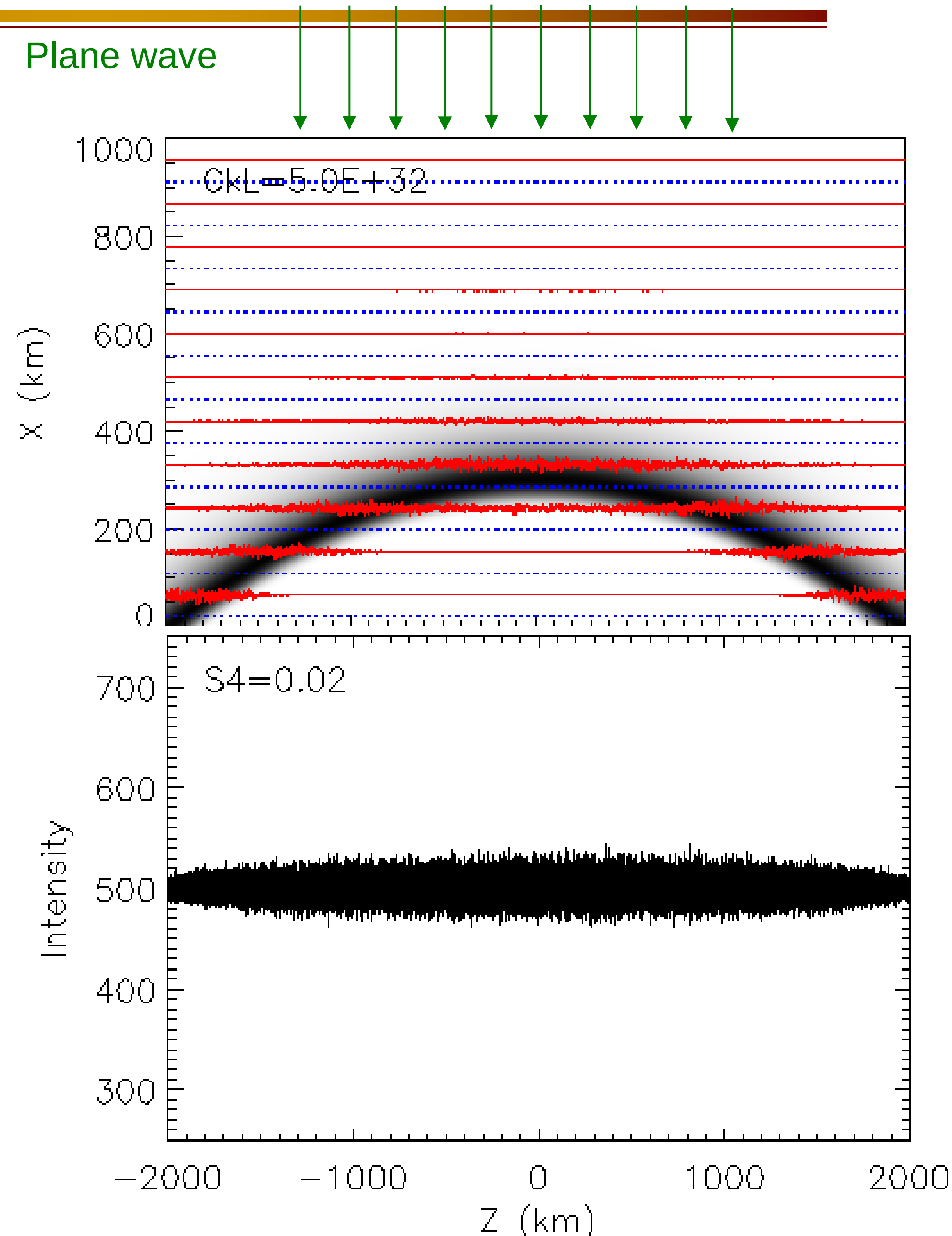
Scattering is strongest at the ionospheric peak height (HmF2), but also occurs at much lower apparent altitudes due to Earth curvature effects.

Space-to-Ground Propagation through Uniformly Distributed Irregularities

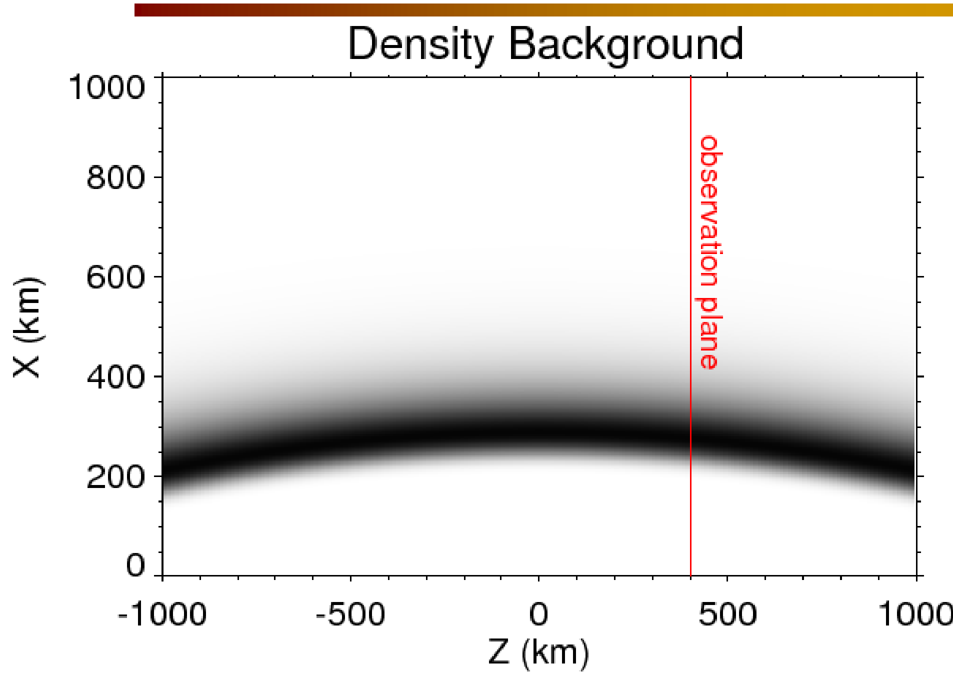
As compared to the radio occultation case, a radio wave propagating from space to ground encounters a thinner layer of irregularities, and propagates a shorter distance after them to the receiver.

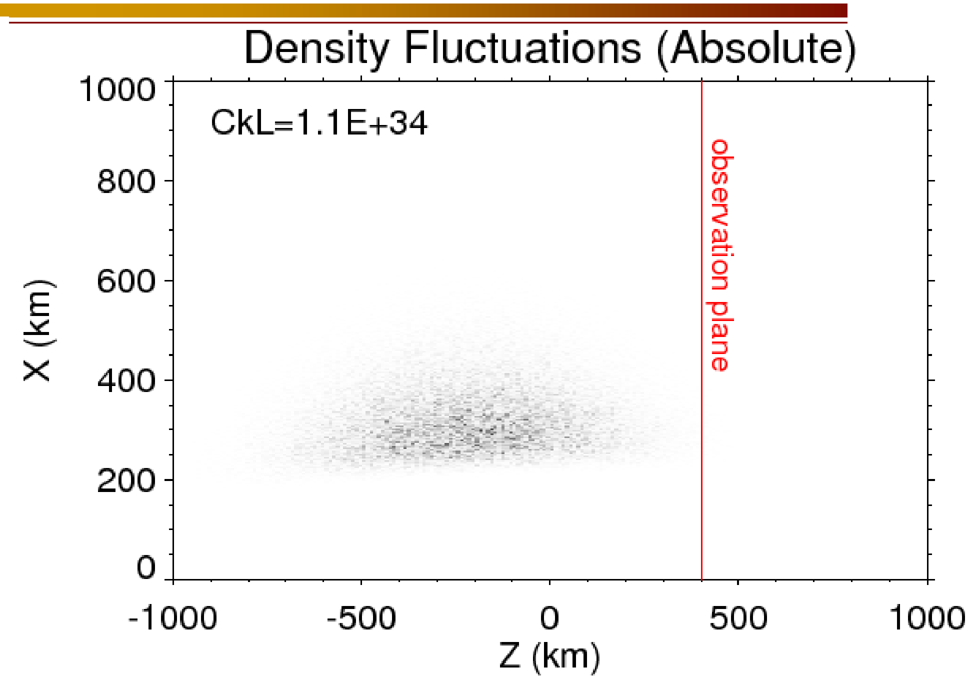
These effects cause the received intensity fluctuations to be weaker for space-to-ground propagation than radio occultation propagation.

In this simulation, the occultation raypath encounters 20 times more TEC than along the space to ground (zenith) raypath, and the scintillation intensity index is 7.5 times greater.



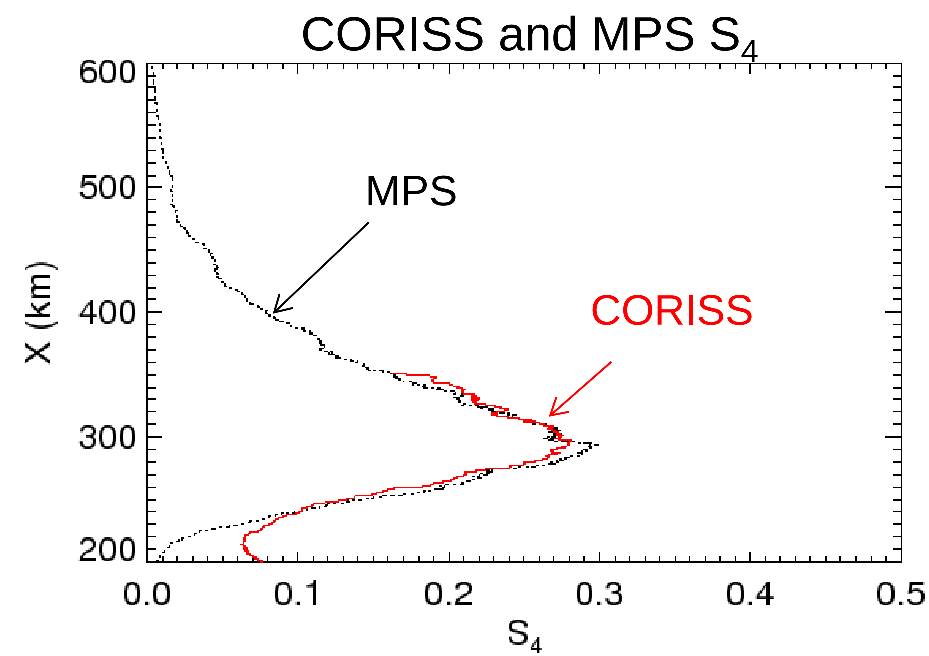
Multiple Phase Screen Simulation of CORISS Scintillation





Simulation Parameters

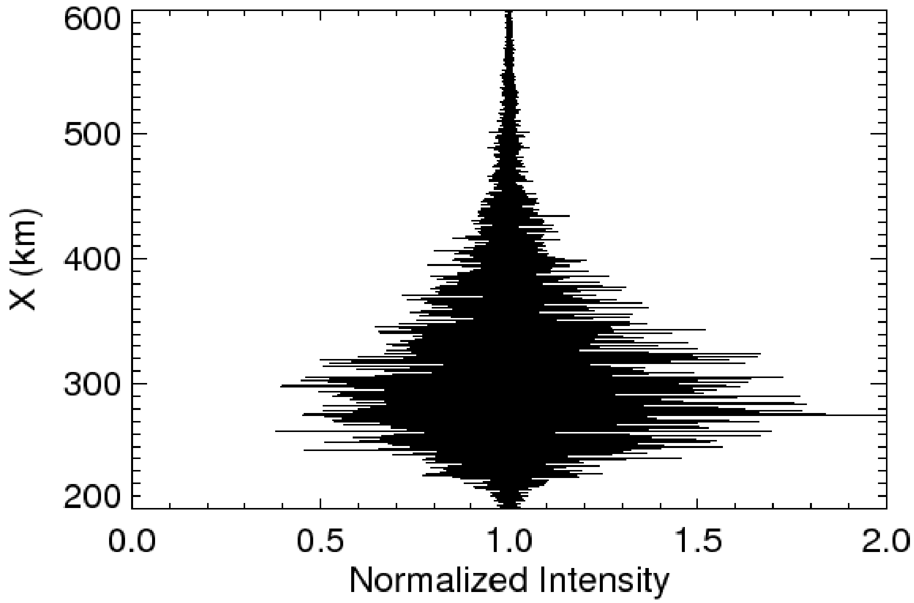
C_kL	1.1×10^{34} (SCINDA)
ν	3/2 (CORISS)
q_0	$2\pi/10$ km
L	61km (ALTAIR)
L_{RO}	232 km (CORISS)
d_s	627 km (CORISS)
NmF2	8.81×10^{11} m^{-3} (ALTAIR)
HmF2	288.5 km (ALTAIR)
Scale Height	31 km (ALTAIR)



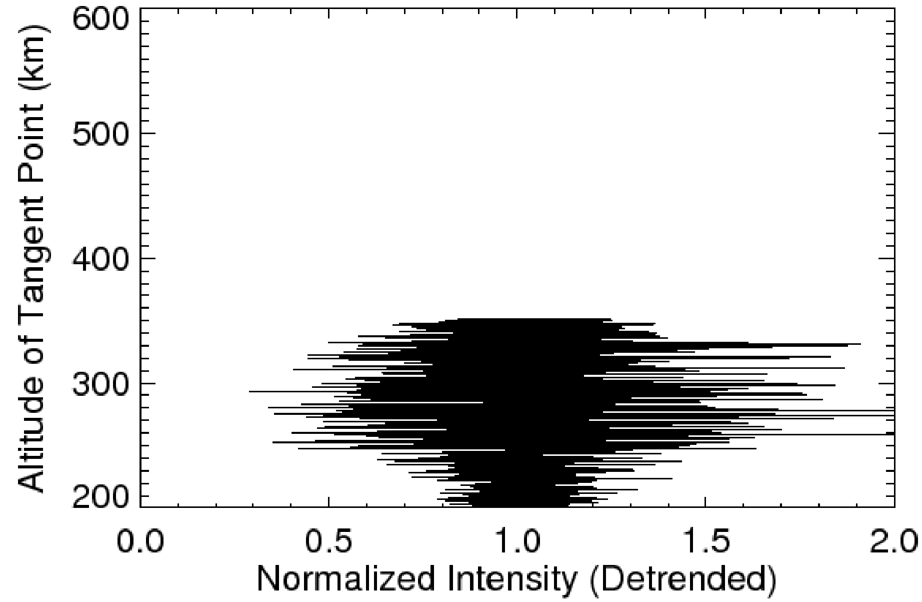
MPS Simulation of CORISS Scintillation

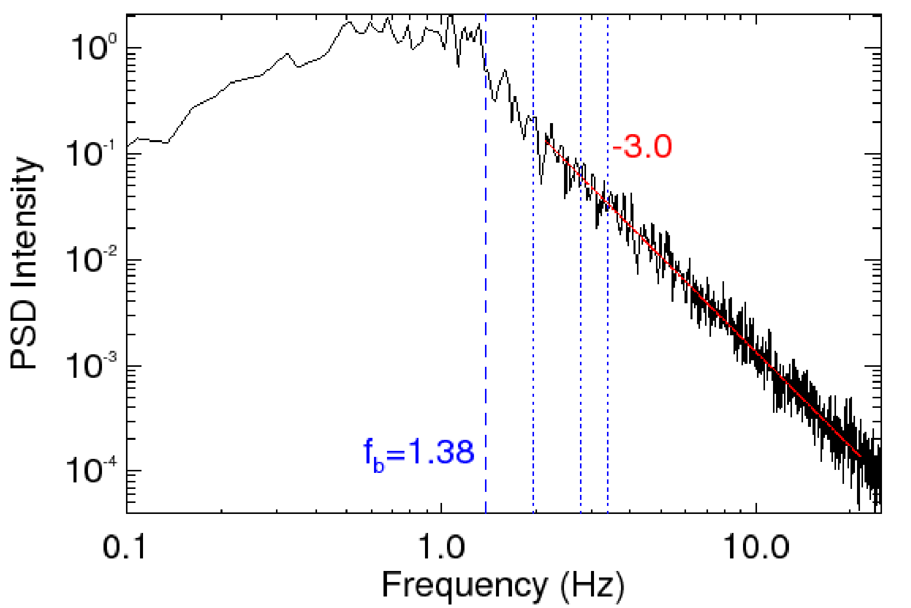
Carrano et al., Rad. Sci.,
doi:10.1029/2010RS004591, 2011

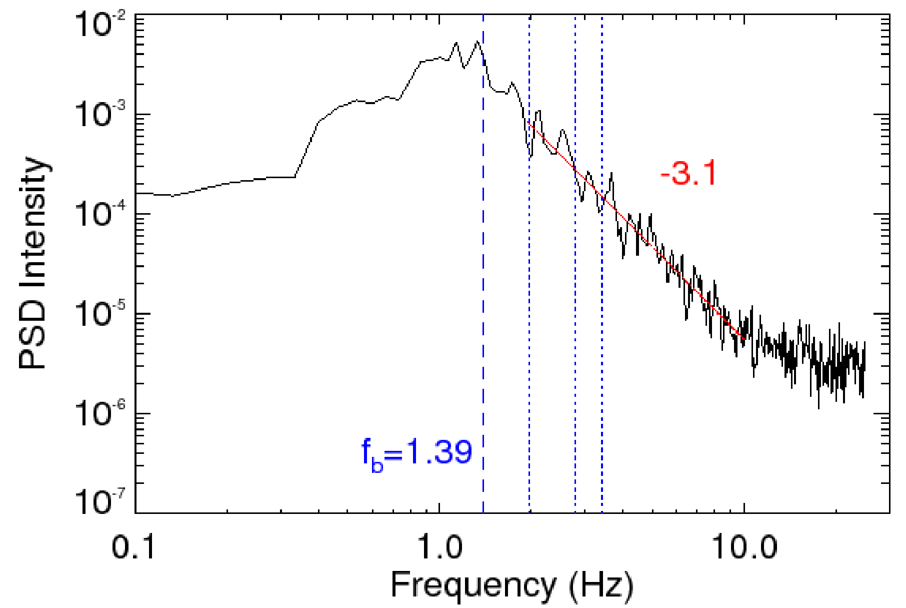
MPS Simulation



CORISS

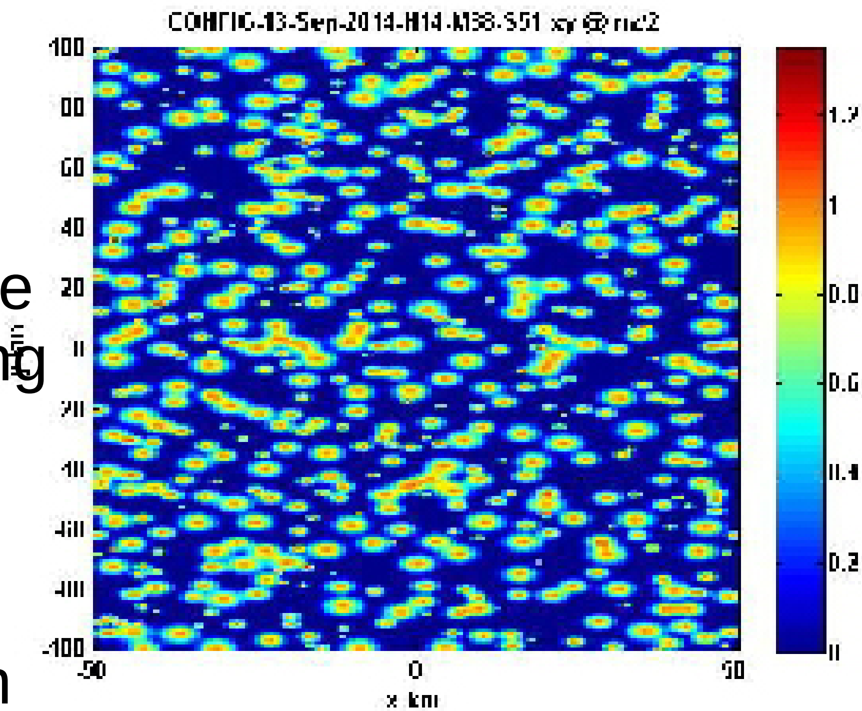






Configuration-Space Model Striation Description

- Results shown thus far assume propagation geometry is perpendicular to the magnetic field
- Under these conditions classic phase screen theory may be applied treating irregularity spectra as power-law
- In the real world the irregularities occur along striations; when looking along B (or nearly so) the correlation lengths are much longer and the spectra do not obey power laws
- A new modeling approach is needed for such quasi-parallel propagation
- Such propagation occurs frequently in RO geometries



Planar cut of electron density variations perpendicular to B from a configuration space model under development by Rino

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Summary

- Mapping equatorial scintillation using RO techniques poses numerous technical challenges
  - Defining spatial distribution of structures over large slant paths potentially transecting multiple contributing structures
  - Varying magnetic aspect angle and scan velocity
  - Regimes where existing phase screen theory is invalid
- Accuracy of results will depend on specifics of geometry, distribution of contributing structures, magnetic field mapping, etc.
- Ancillary information must be applied whenever available
  - In situ density observations to map boundaries (IVM on COSMIC-2)
  - Apriori knowledge of bubble morphology
  - Other ground- and space-based observations

Summary

- Sophisticated tools have been developed to address the complex propagation issues
  - Ionospheric Parameter Estimation (IPE) extracts ionospheric quantities from observed spectra using multi-parameter fitting technique
  - Inverse propagation techniques (Back Propagation)
  - Radio Occultation Scintillation Simulation (ROSS) models occultation geometries with multiple phase screens
  - Configuration-space model under development to address quasi-parallel propagation limits of existing theory

The limits of how well this can be done have not yet been fully determined, but preliminary results suggest that high rate RO data can provide meaningful scintillation detection and characterization