REX Radio Path Measurement

Characterization and Classification

Outer Heliosphere Workshop
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Topics presented from:

Radiopath Characterization and Structure of the Solar Plasma

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Abstract

The journey of the New Horizons spacecraft through the solar system afforded the opportunity to measure the structure of the solar plasma using microwaves of 4.2 cm wavelength transmitted from earth and received by the REX instrument on the spacecraft. At a cadence of approximately once per month, when the spacecraft was not in hibernation, powerful unmodulated uplinks were transmitted with a frequency stability to a few parts in 10^{14th} and their waveforms were recorded on the spacecraft by REX as in-phase and quadrature narrowband samples using a frequency reference with stability of a few parts in 10^{13th}. The recorded waveforms exhibit effects of multipath interference from which the structure of the solar plasma is inferred.

Keywords: Solar Plasma; Microwave Observations

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Outline

1. Radio Path Characterization objectives
2. Radio Path Metrics and Attributes
3. Radio Path Structure
4. Modelling the Solar wind
5. Connection between Model and Structure

Motivations and Incentives

1. REX's 'Line Integral' method is unique
   → Not your typical total electron content measurement

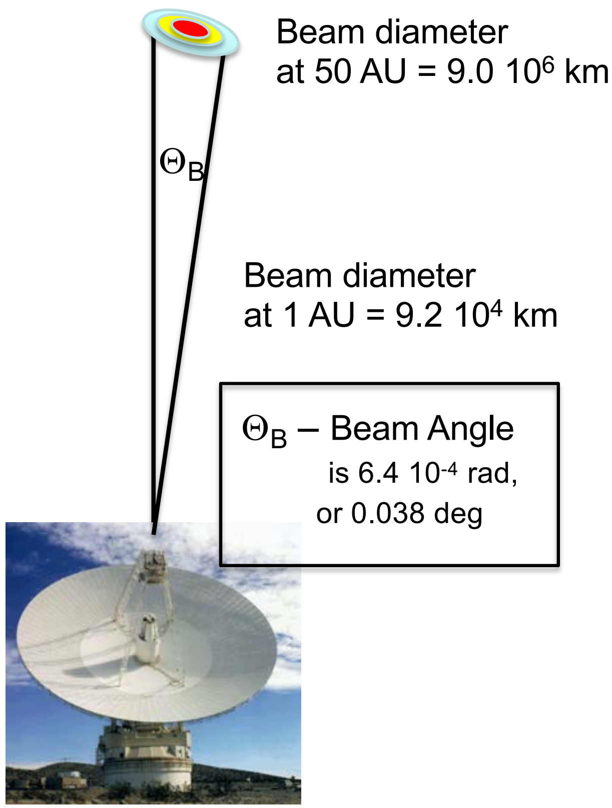
2. Complements in-situ densities

3. Invertible method is novel
   → Analogous to a constrained tomography
   → Similarly reveals structure along the path

4. Get quasi-global knowledge of the Heliosphere

5. Validate Solar wind models

REX Radio Path Characterization Objectives

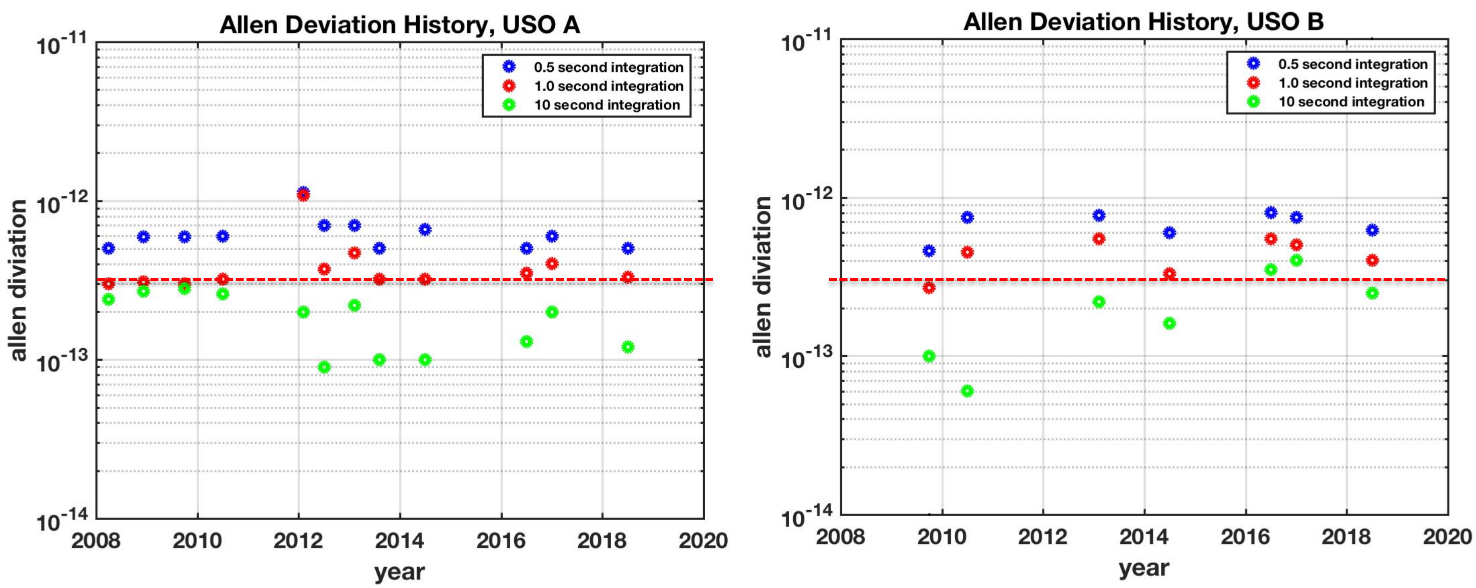


DSS14, 70m Tx

- Radio signal, 4.c cm λ, transmitted from earth
  - Powerful transmission from the DSN, [175 GW EIRP]
    - Two polarizations, one uplink per polarization
  - Coherent, single frequency, stable to 1 part in 10^{14}
  - Received at New Horizons, high SNR, typically 10^6.
- Measure Uplink Waveforms
  - Stability vs SC distance from Sun
    - Uplink frequency variation
    - Uplink amplitude (and Power) variation
- Radio Path Irregularity
  - Evaluate radio signal propagation through the solar system
  - Quantify Magnitude and Nature of Multipath Propagation
    - For both polarizations (RCP & LCP)

Uplink History to New Horizons

USO Frequency Stability History



Radio Path Measurement Synopsis

Radio signal received by REX are sinusoidal voltages,

> In two polarizations, $v_P(t)$, P = RCP or LCP:

>> Right-hand circular (RCP), and left-hand circular (LCP).

Each polarization is sampled *in-phase* and *quadrature*.

> v_{RCPI}, *in-phase* with the reference oscillator

>> associated with the *real* part X, of a complex representation,

$$Z = X + jY.$$

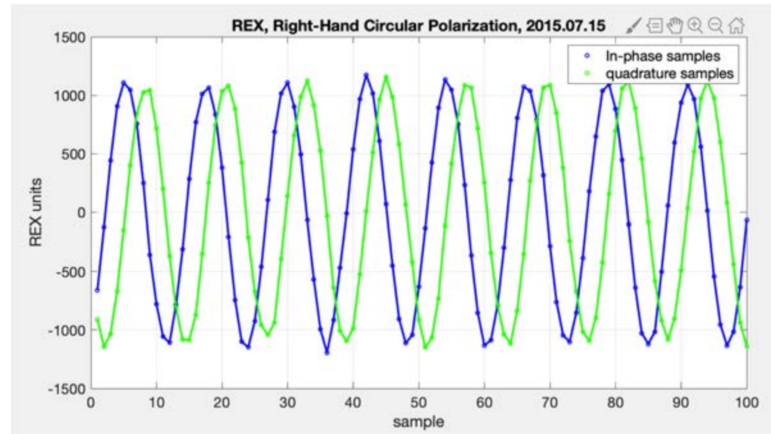
> *quadrature*, v_{RCPQ} or 90-degrees out of phase with the reference,

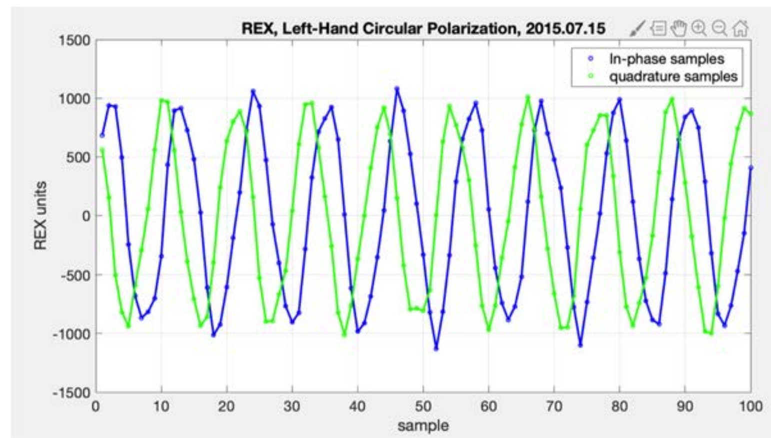
>> associated with the imaginary part Y, of a complex representation.

> resulting *n* samples of the voltages, as

$$>> \quad v_{RCP}[n] = v_{RCPI}[n] + j\, v_{RCPQ}[n]$$

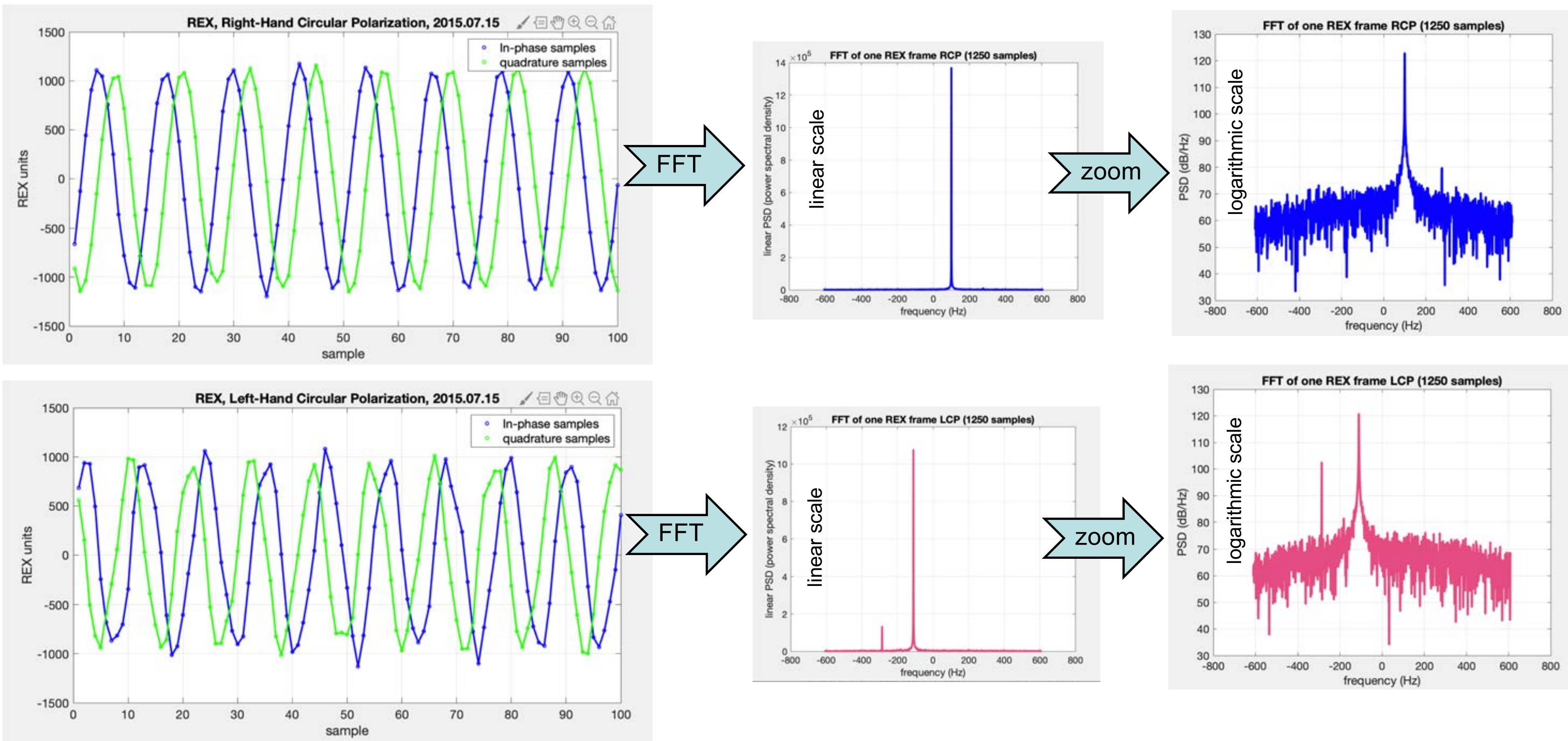
$$v_{LCP}[n] = v_{LCPI}[n] + j\, v_{LCPQ}[n]$$



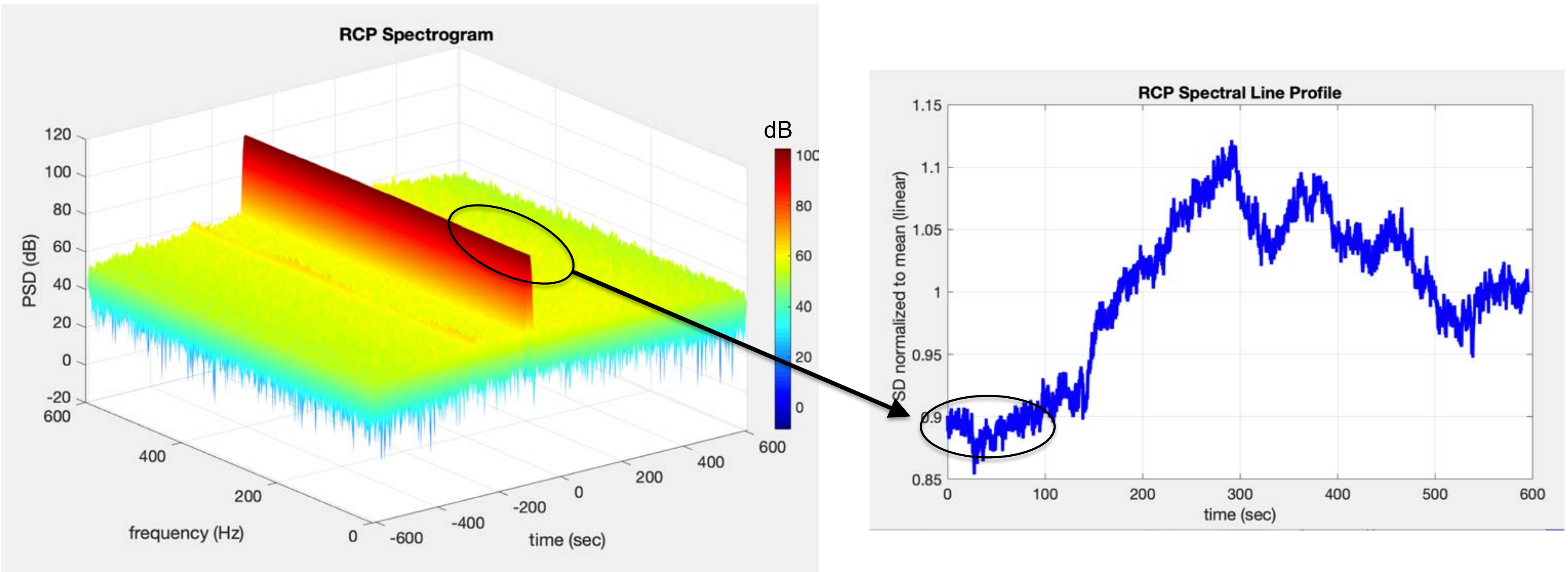


The voltage samples are Fourier transformed to facilitate spectroscopic analysis.

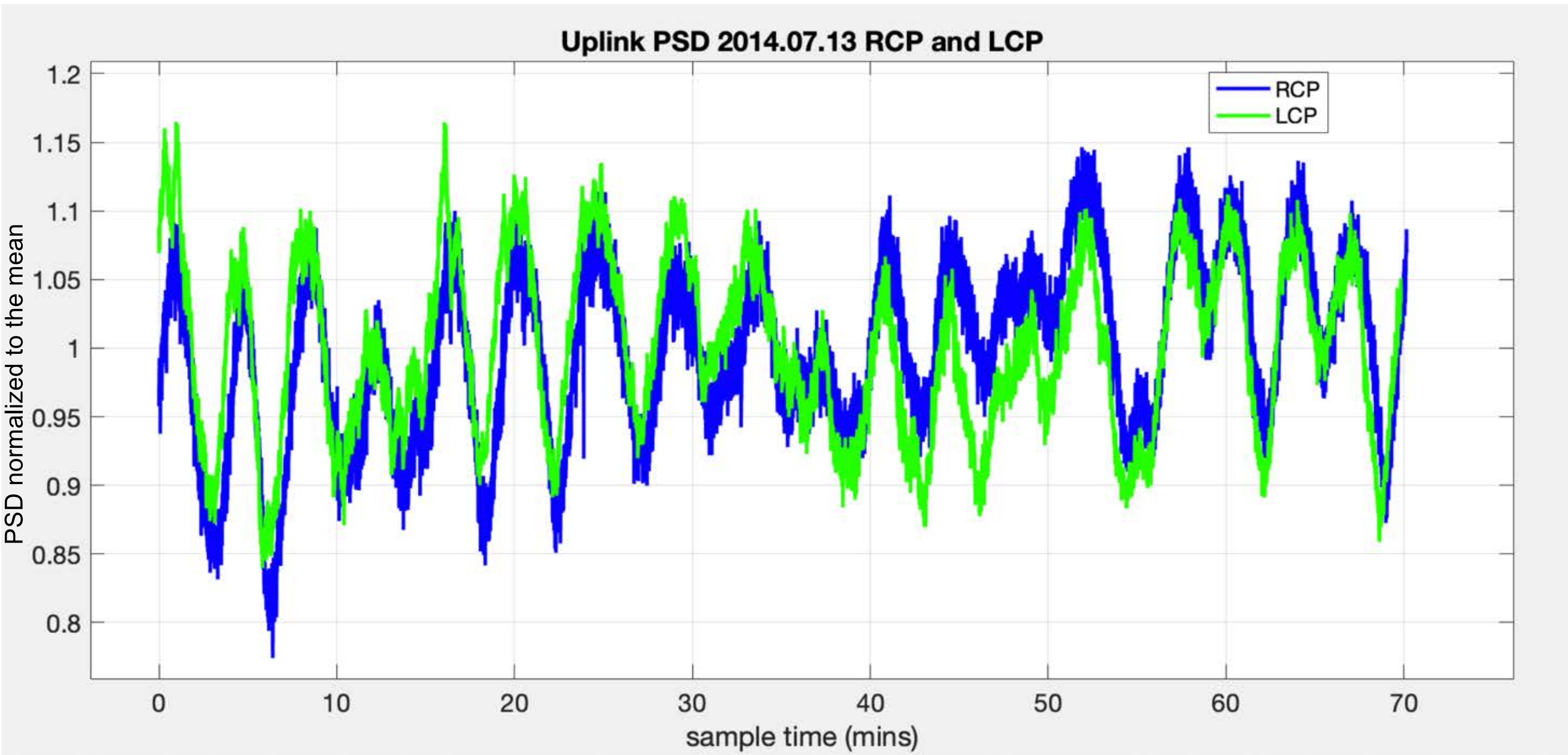
Fourier Spectroscopy



Spectral Line Properties



Multipath Evidence 2014.07.13 ACO8



Outline

1. Radio Path Characterization objectives
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4. Modelling the Solar wind
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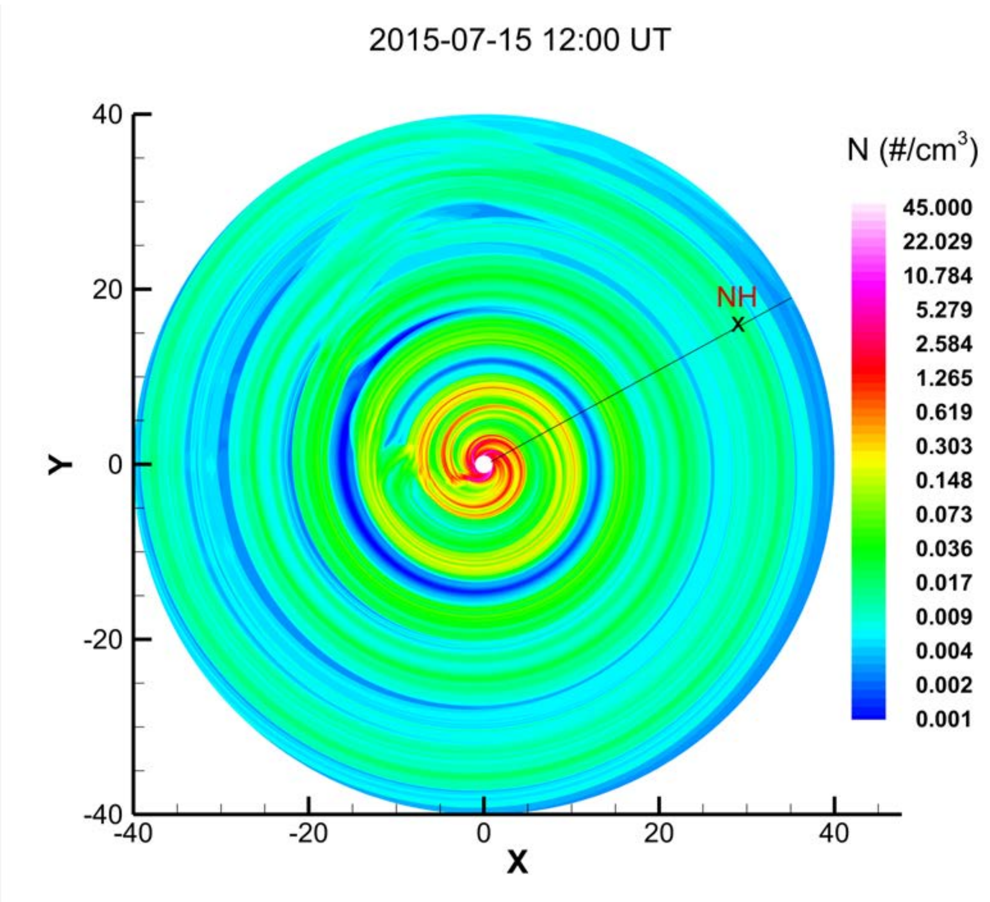
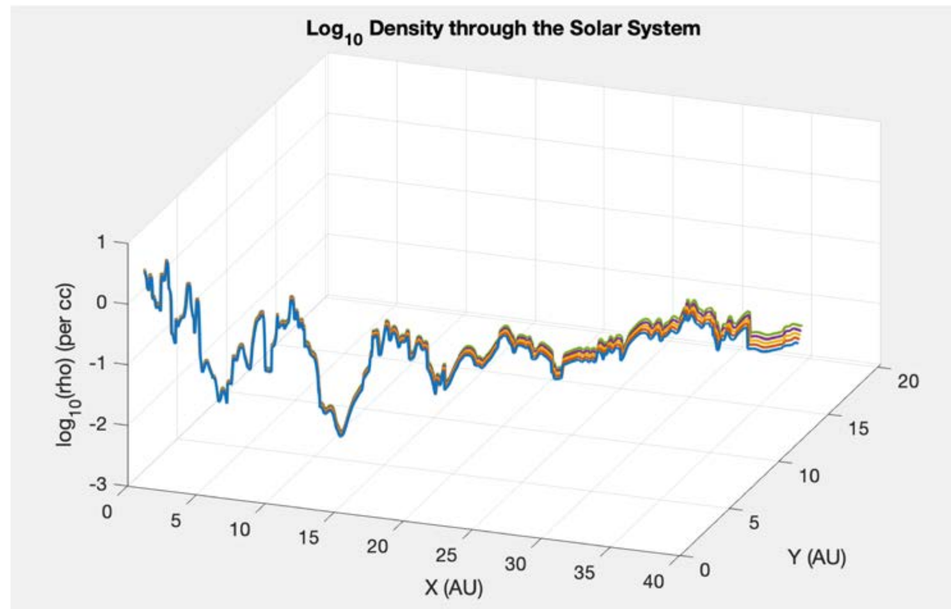
Wave Propagation with Model of the Solar Plasma*



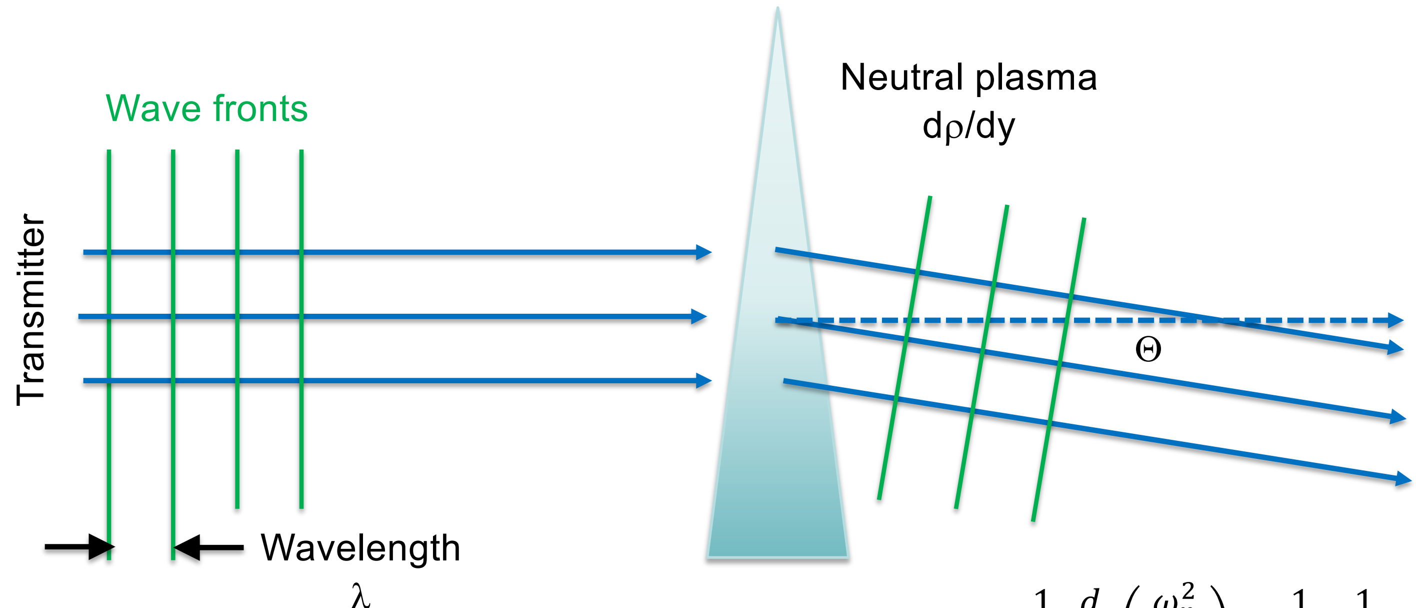
→ Propagate microwaves with density *(r,ϕ)* profile



* Contributions from Tae Kim

Refraction of Microwaves in the Solar Plasma

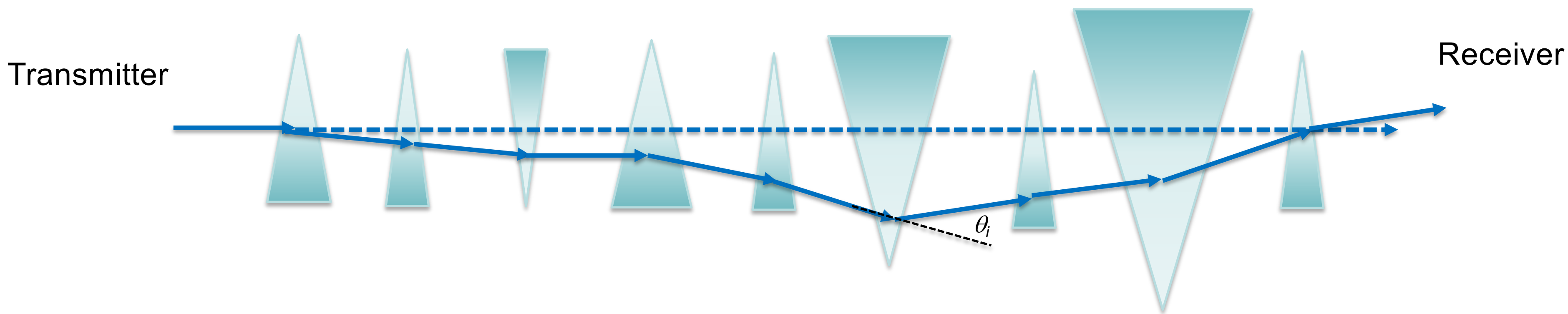
Basic example, plane waves



$$tan\theta = \frac{1}{2}\frac{d}{dy}\left(\frac{\omega_p^2}{\omega_{XB}^2}\right) = \frac{1}{2}\frac{1}{\omega_{XB}^2}\frac{e^2}{\epsilon_0\, m_e}\frac{d\rho}{dy}$$

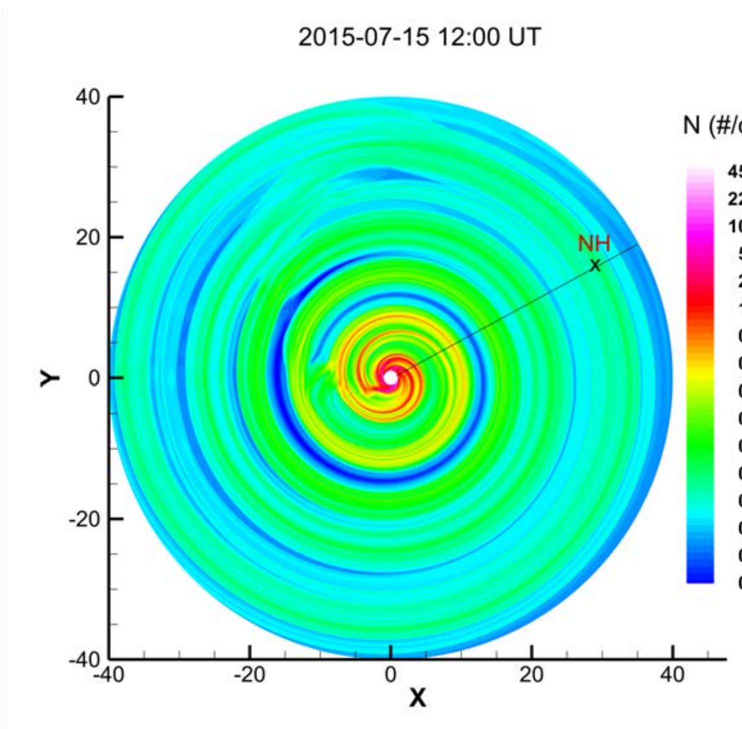
Propagation Method for Microwaves in the Solar Plasma

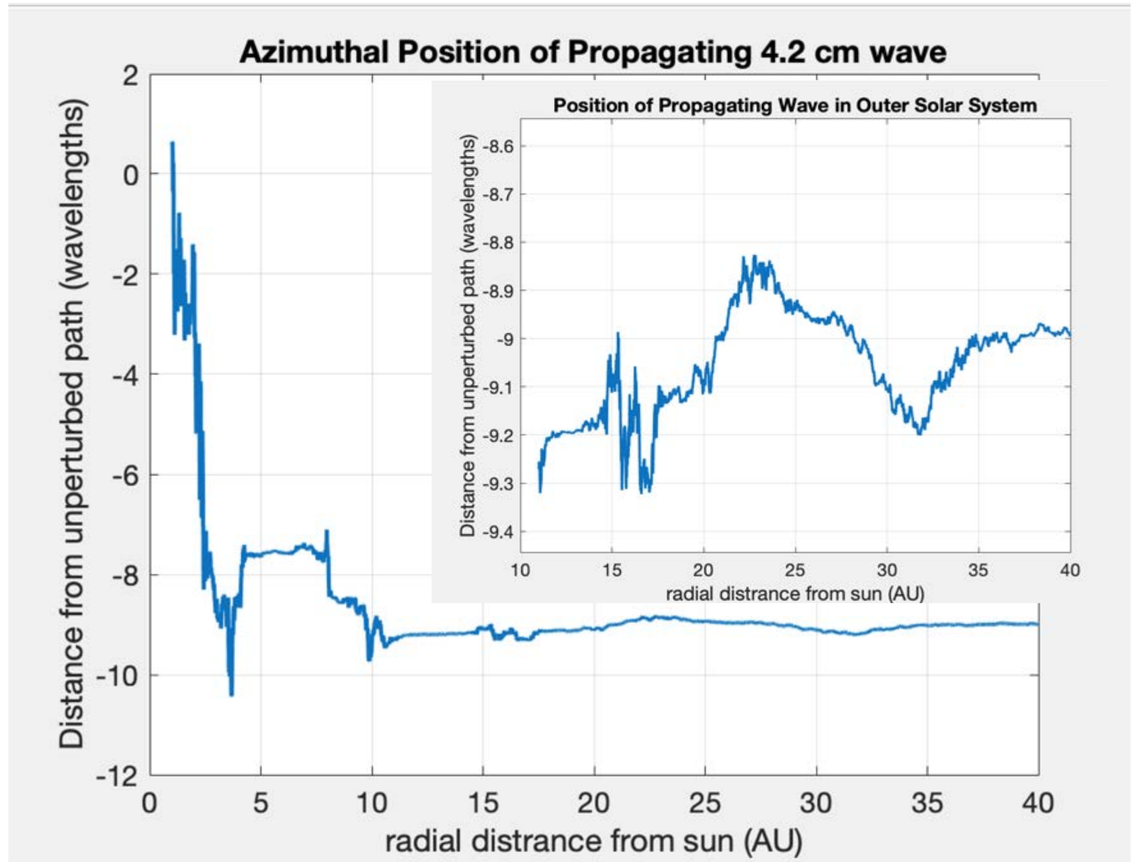
Decimation for propagation of plane waves



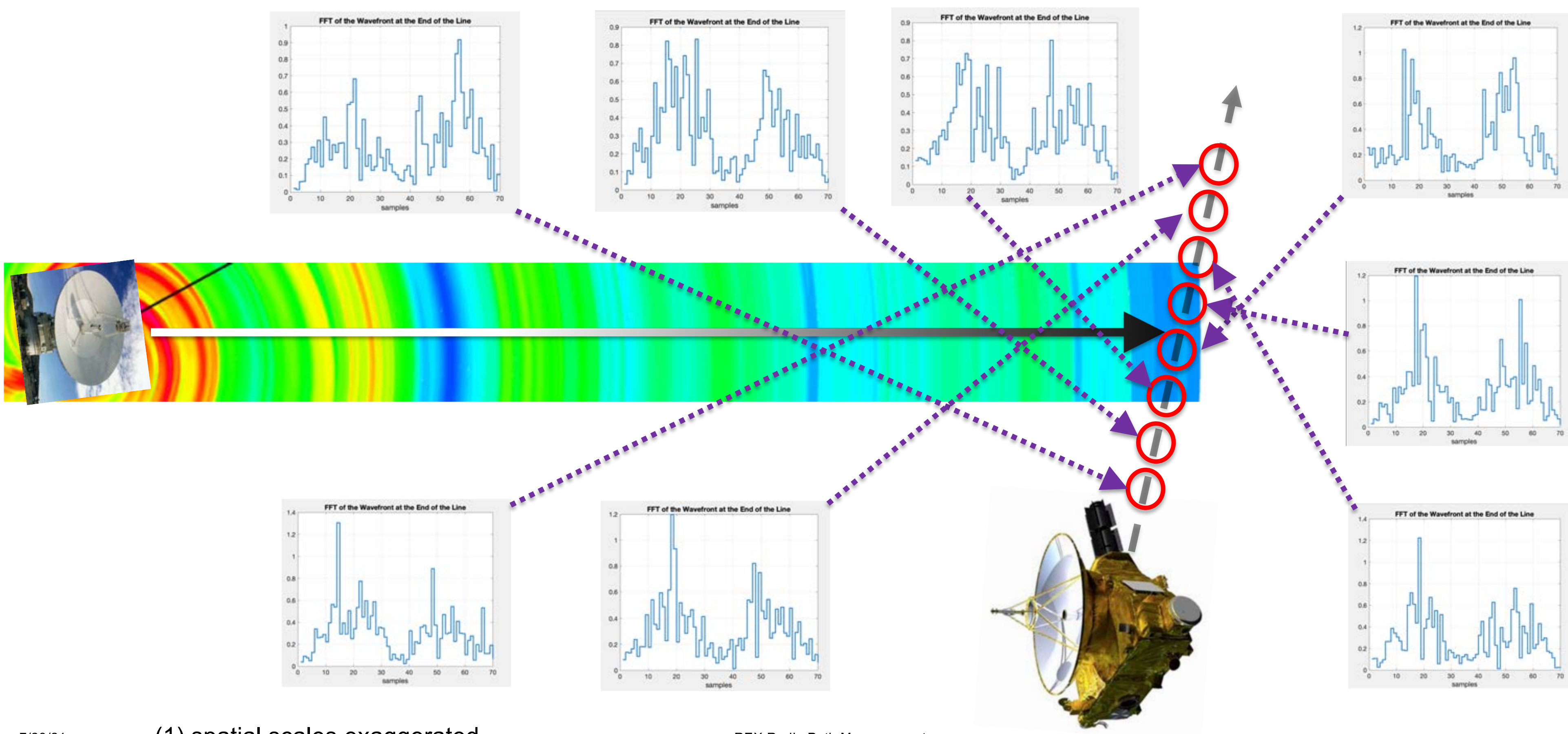
$$tan\theta_i = \frac{1}{2}\frac{d}{dy}\left(\frac{\omega_p^2}{\omega_{XB}^2}\right) = \frac{1}{2}\frac{1}{\omega_{XB}^2}\frac{e^2}{\epsilon_0\, m_e}\frac{d\rho_i}{dy}$$

Example Propagation of 4.2 cm Waves Through Solar Plasma Model





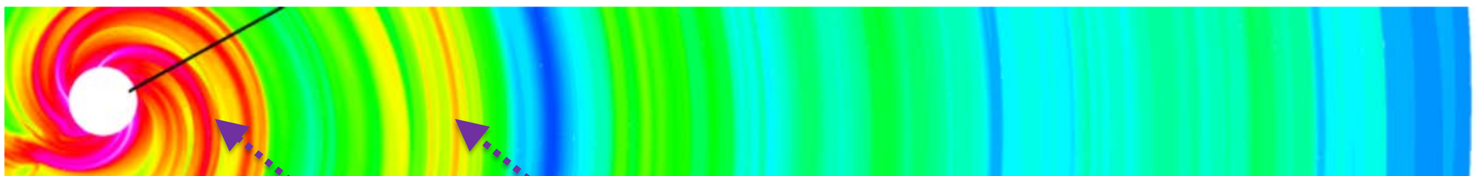
REX ‘flying’ through the wavefronts[(1)]



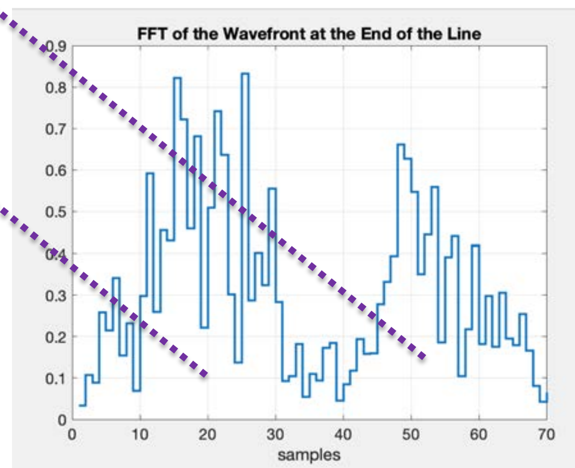
(1) spatial scales exaggerated

Mapping REX Wavefront Spectra to Structure Along the Path - 1

Example using 4.2 cm wave propagation in solar plasma model

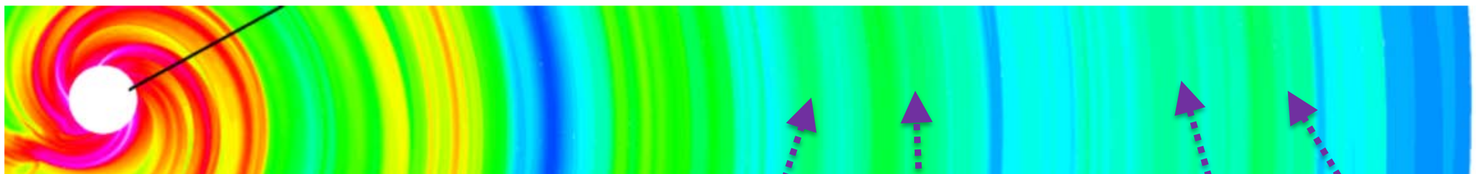


By removing portions of the plasma densities along the path:

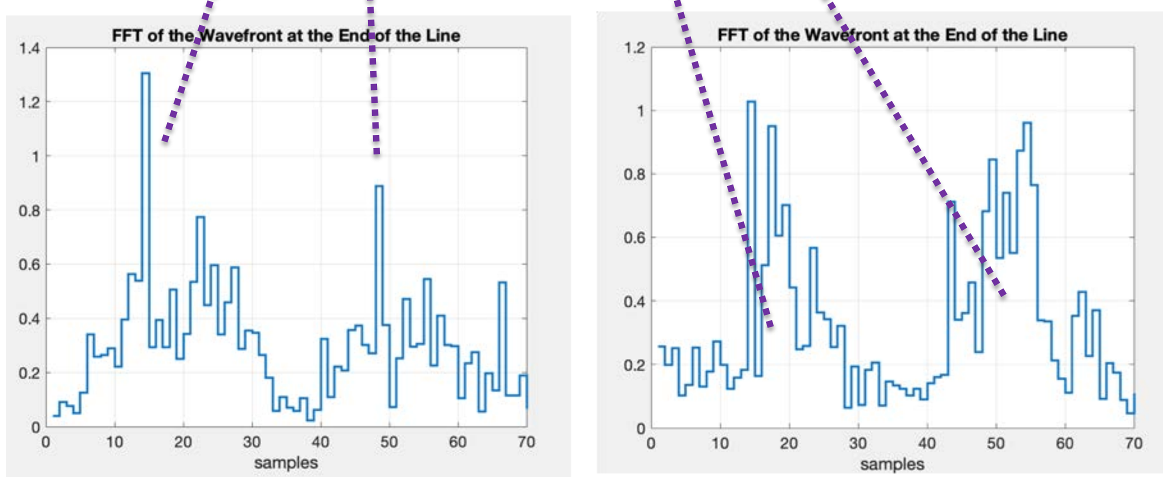


Mapping REX Wavefront Spectra to Structure Along the Path - 2

Example using 4.2 cm wave propagation in solar plasma model



By removing portions of the plasma densities along the path:



Connections to the Radio Path

Conjecture I: Spectroscopy of received signal reveals the structure of the radio path.

> Prior measurements have been of total electron content.
> Novel measurement of structural variations along the radio path.

Importantly, the radio path encodes in each signal the history of its propagation.

> It is a limited-knowledge tomography of the solar plasma.
> Albeit a tomographic 'distortion'.

Conjecture II: The attributes of the tomography can be 'inverted'.

> Turning the distortion into an attribute.

Testing and Validating the Conjecture

Solar wind measurement have motivated simulators and simulations[1].

> Comparison of the radio path characterizations with the simulator's model.

> Valuable collaboration with Heather Elliott, and Tae Kim.

> New Horizons' position used to model solar plasma distribution along the radio path.

> Radio signal propagated along the path.

> Comparison at the end of the path of the propagated signal's behavior with the REX measurements.

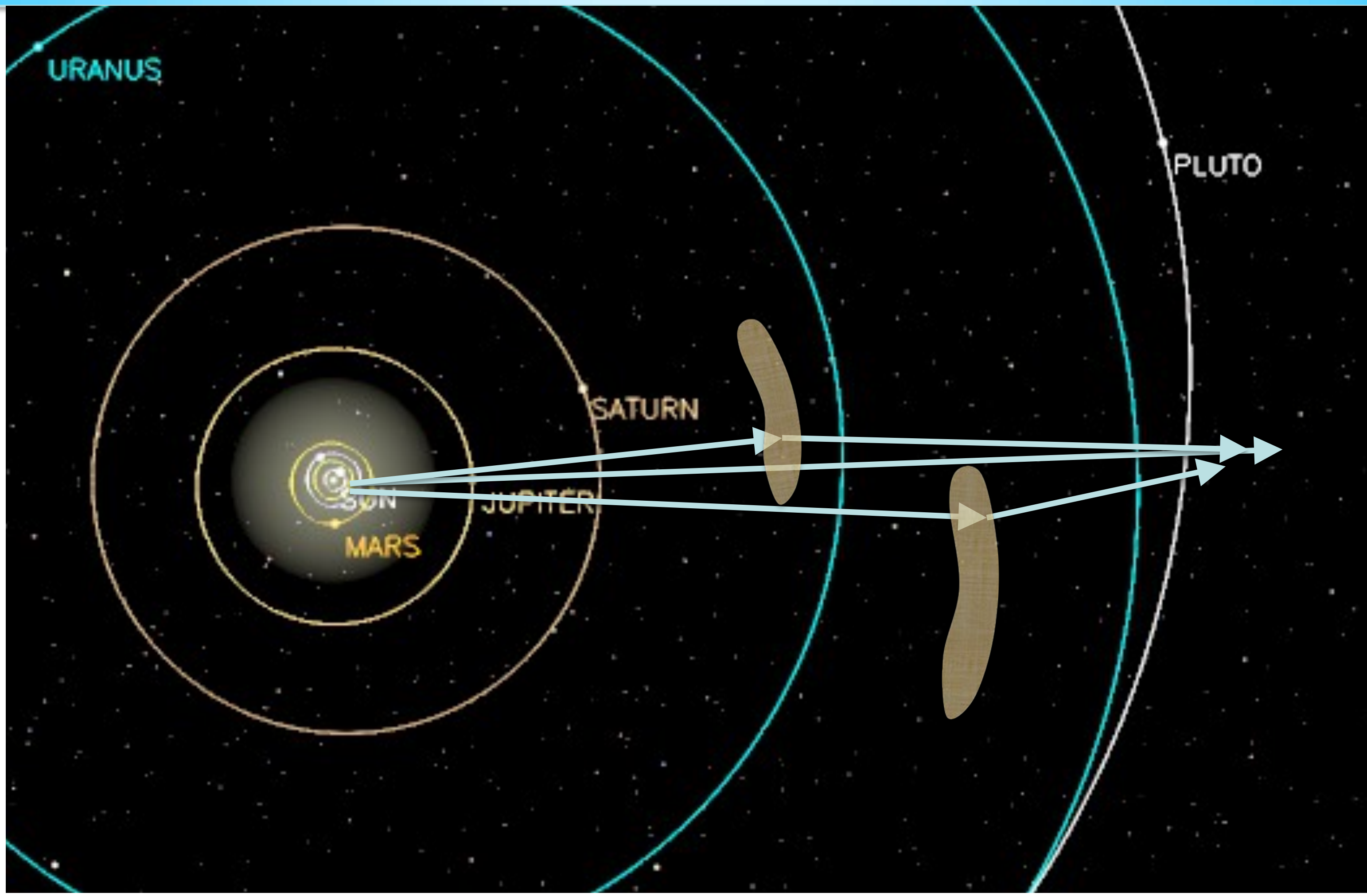
(1) Kim, T. K., Pogorelov, N. V., Zank, G. P., Elliott, H. A., & McComas, D. J. (2016). Modeling the Solar Wind at the Ulysses, Voyager, and New Horizons Spacecraft. The Astrophysical Journal, 832(1), 72. https://doi.org/10.3847/0004-637X/832/1/72

RE-cap

1. REX's 'Line Integral' unique
2. Complements in-situ spacecraft measurments
3. Invertible method is novel
   → Turning distortion into a virtue
4. Heliosphere knowledge non-compact
5. Validate Solar wind models

Supplemental Slides

Multipath along the Radio Path



Multipath in the Solar System

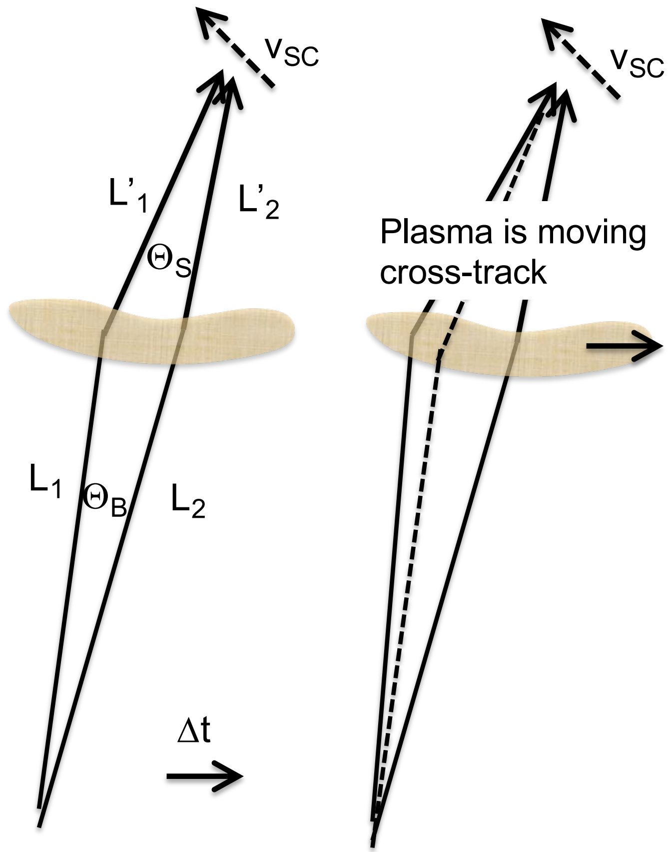
SC is 'flying' though an irregular 'wave-field' from multipath, $W(s)$

Beam diameter at 50 AU = 9.0 10^6 km

Beam diameter at 1 AU = 9.2 10^4 km

Θ_B – Beam Angle
is 6.4 10^{-4} rad,
or 0.038 deg

DSS14, 70m Tx



Plasma is moving cross-track

Wavefield Construction

$$W(s) = \int_a^b ds \int_0^{SC} w(r,s)g(r,s)dr$$

Signal is scattered by plasma
Direction along L1, is changed
by an angle Θ_p, Gaussian
distributed with a sigma of σ_p
into direction L'_1

The path difference *Δpath*, causes
A phase shift $\Delta\phi = 2\pi\, \Delta path/\lambda$.

$$\Delta path = (L_2 - L_1) + (L_2^1 - L_1') = (R - L_1')\left(1 + \frac{\theta_B^2}{2}\right) + L_1'\left(1 + \frac{\theta_S^2}{2}\right)$$

Inverting the Wavefield Integral

$W(\sigma) = \int_a^b ds \int_0^{SC} w(r,s) g(r,\sigma(s)) dr$ Wakefield Integral

$w(r,s) = \frac{1}{r}\exp(-ikr)$ EM wave propagation

$\mathrm{g}(r,s) = g(r)\exp(ik\omega(\sigma(s)))$ Multipath scattering from irregularities

$W(\sigma) = \int_a^b ds\,[w(r,s) * g(r,s)]$ Convolution of propagation with multipath

$W(\sigma) = \int_a^b ds\, H(\sigma(s))\exp(iks\sigma)$ $\quad H(\sigma(s)) = w(r,s) * g(r,s)$

$W(\sigma) = Fouier\ Transform\ (H(s,\sigma)) = W(\sigma(s))\ G(\sigma(s))$ $\quad W(\sigma(s)) = FFT(w(r,s))$, $G(\sigma(s)) = FFT(g(r,s))$

$H(\sigma(s)) = inverse\ Fourier\ Transform\ (W(\sigma))$ → deconvolution of multipath structure

Using Uplink Intensity Fluctuations to Characterize the IPM

The root mean square (RMS) intensity fluctuations expressed relative to the mean intensity is the scintillation index, m

$$m = \frac{\langle \Delta I^2 \rangle^{1/2}}{\langle I \rangle}.$$

m is related to the phase deviation caused by turbulence in the solar wind $m \approx \sqrt{2}\Delta\phi.$

The phase change due to the density structure of the solar wind assumes the density of the plasma is highest towards the sun, which allows the "thin screen approximation," and gives an RMS deviation for the phase.

$$\phi_{RMS} = \lambda r_e (aL)^{1/2} \left[\langle \delta N^2 \rangle\right]^{1/2}$$

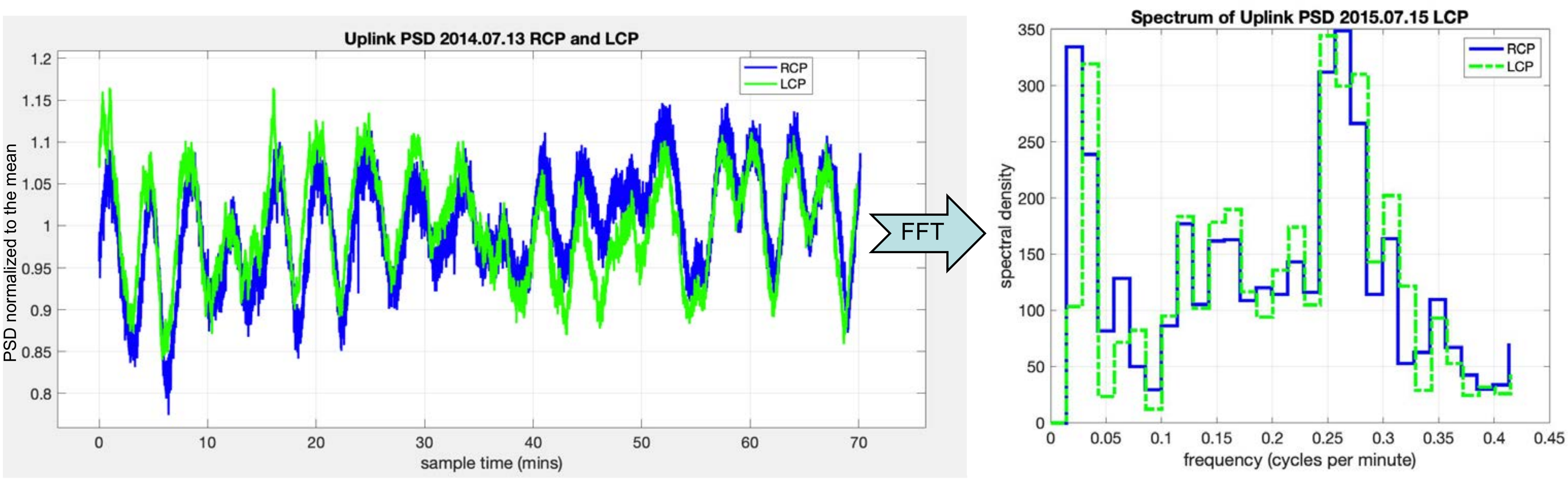
Where λ the wavelength, r_e the classic electron radius, L the thickness of the screen.

Alurkar, S.K. (1997). Solar and Interplanetary Disturbances. Singapore: World Scientific. ISBN 978-981-02-2925-2.

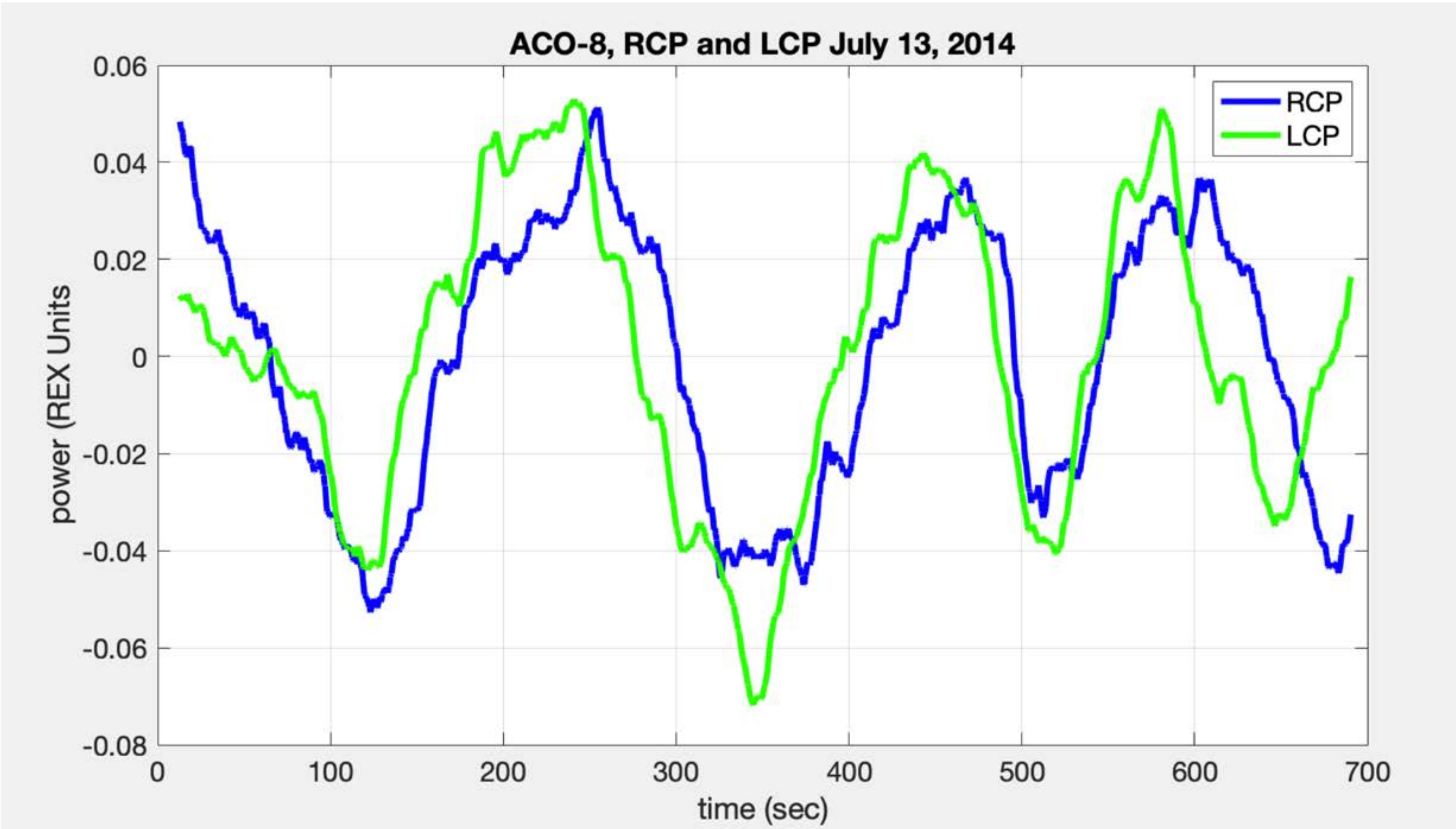
Characterizing the Uplink Signal

- Signal Total Power
- Signal Power Stability
- Signal Power Fluctuation Spectra
- Signal Power Wavelet Transform
- Signal Frequency Allen Deviation
- Signal Phase Stability
- Signal Frequency Wavelet Transform
- Signal Frequency Broadening

Multipath 2014.07.13 ACO8



Multipath Candidate II 2014.07.13 ACO8



Multipath 2016.07.11 Cal Campaign