Constrained And Unconstrained Power Law Irregularity Models for Interpreting Strong Scintillation Data

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Introduction

- In a recently published work, we extended the phase screen power law theory of ionospheric scintillation to account for the case where the refractive index irregularities follow a two-component power-law spectrum*.
- A specific normalization was invoked to exploit self-similarity and achieve a universal scaling, such that different combinations of perturbation strength, propagation distance, and frequency produce the same results.
- In a companion paper, Rino employed the two-component structure model to interpret in-situ observations of the disturbed low-latitude ionosphere made by C/NOFS†.

*Carrano, C., C. Rino, A theory of scintillation for two-component power law irregularity spectra: overview and numerical results (2016), Radio Sci., 51, doi:10.1002/2015RS005903.

†Rino, C., C. Carrano, K. Groves, P. Roddy, A characterization of intermediate-scale spread-F structure from four years of high-resolution C/NOFS satellite data (2016), Radio Sci., 51, doi:10.1002/2015RS005841.

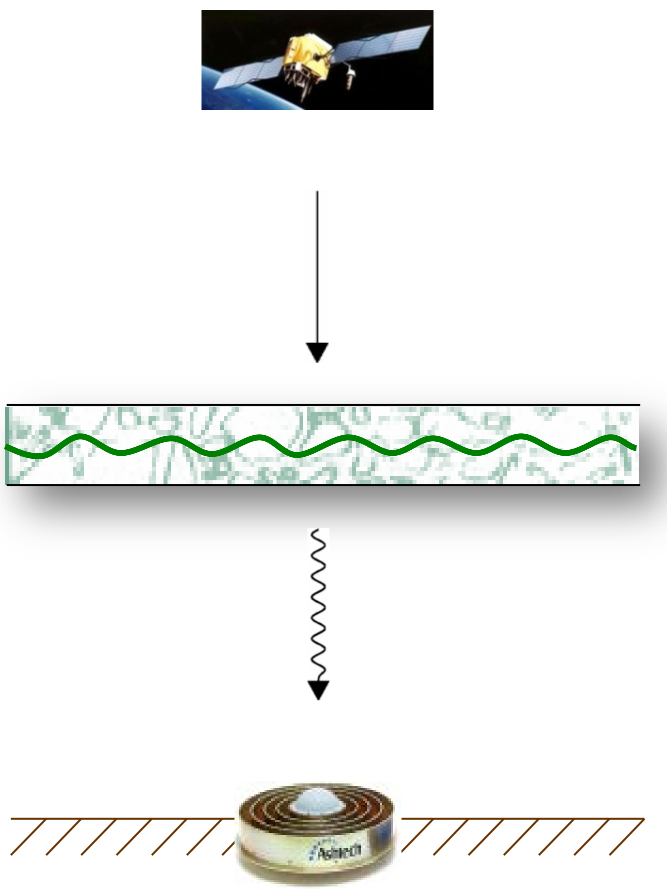
Introduction (2)

- This theory may also be applied to the inverse problem, whereby phase screen parameters are retrieved from measured scintillation time series.
- The screen parameters are determined via least-squares fitting the measured intensity spectral density function (SDF) with the model. We used this to interpret strong GPS scintillations collected during the COPEX experiment in Brazil*
- In this talk, we compare constrained and unconstrained power law irregularity models. By comparing predictions of these models we can deduce the influence of outer and inner scales during strong scatter and also how they affect the inverse problem.
- We apply an inverse method called Irregularity Parameter Estimation to interpret strong scintillations caused by field-aligned irregularities at Ascension Island.

*Carrano, C., C. Valladares, and K. Groves (2012), Latitudinal and local time variation of ionospheric turbulence parameters during the Conjugate Point Equatorial Experiment in Brazil, International Journal of Geophysics, vol. 2012, Article ID 103963, 16 pages, doi:10.1155/2012/103963.

Phase Screen Theory

Beacon Transmitter



Receiver

Signal scintillation

- Intensity spectral density function (SDF):

$$\Phi_I(q) = \int_{-\infty}^{\infty} \exp\left\{-g\left(r, q\rho_F^2\right)\right\} \exp(-iqr)\,dr$$

Fresnel scale

- Structure interaction function:

$$g(r_1, r_2) = 8\int_{-\infty}^{\infty} \Phi_{\delta\phi}(q) \sin^2(r_1 q/2) \sin^2(r_2 q/2) \frac{dq}{2\pi}$$

Phase SDF

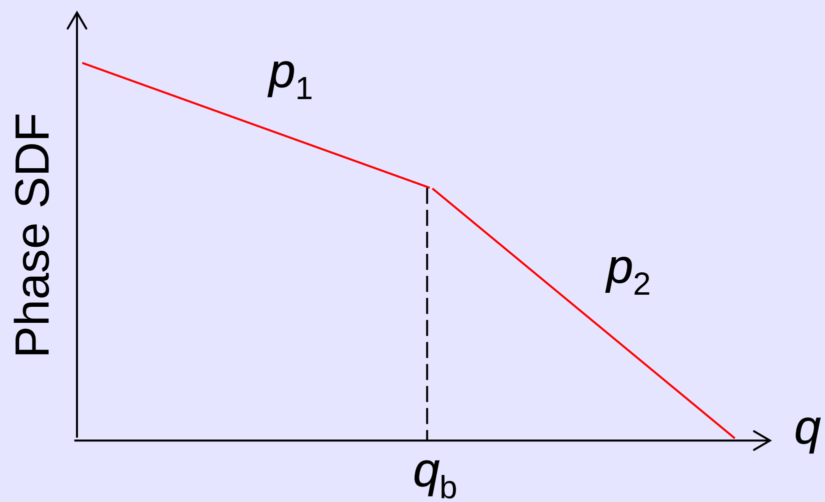
- Scintillation index and correlation function:

$$S_4^2 = \frac{1}{2\pi}\int_{-\infty}^{\infty} \Phi_I(q)\,dq - 1$$

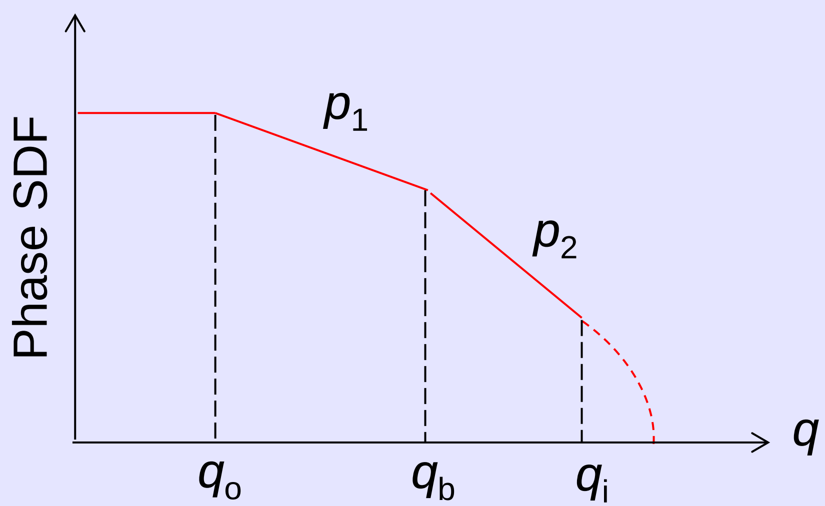
$$R_I(r) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \Phi_I(q)\cos(qr)\,dq$$

Power-law Irregularity Models

Unconstrained Model: a piecewise power-law with two components



Constrained Model: same as above, but embedded between outer and inner scale cutoffs



These two models "bracket" case of a naturally occurring outer scale

Universal Scaling

- For any piecewise power-law irregularity model, normalizing by the Fresnel scale (ρ_F) casts the problem in dimensionless (universal) form.

- Normalized quantities:

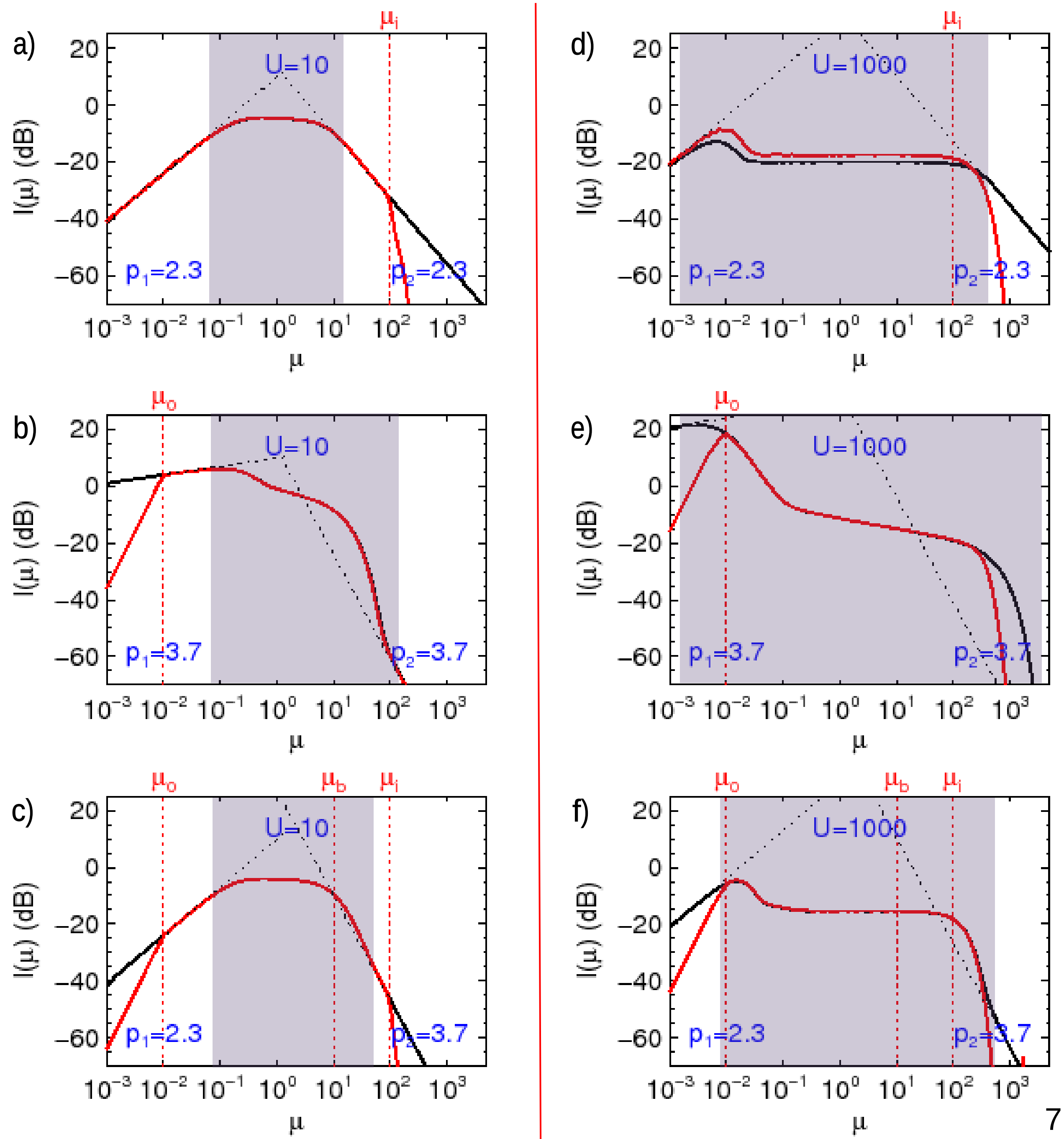
  μ – spatial wavenumber (1=Fresnel)
  μ_o, μ_b, μ_i, – outer scale, intermediate break scale, inner scale wavenumbers
  $P(\mu)$ – phase SDF
  $I(\mu)$ – intensity SDF

- The universal scattering strength, *U*, is defined to be $P(\mu=1)$.
  For weak scatter, $U \ll 1$ and for strong scatter $U \gg 1$.

- p_1, p_2, μ_o, μ_b, μ_i and *U* specify all solutions for 2-component spectra
  (i.e. different combinations of perturbation strength, propagation distance, and frequency produce identical results).

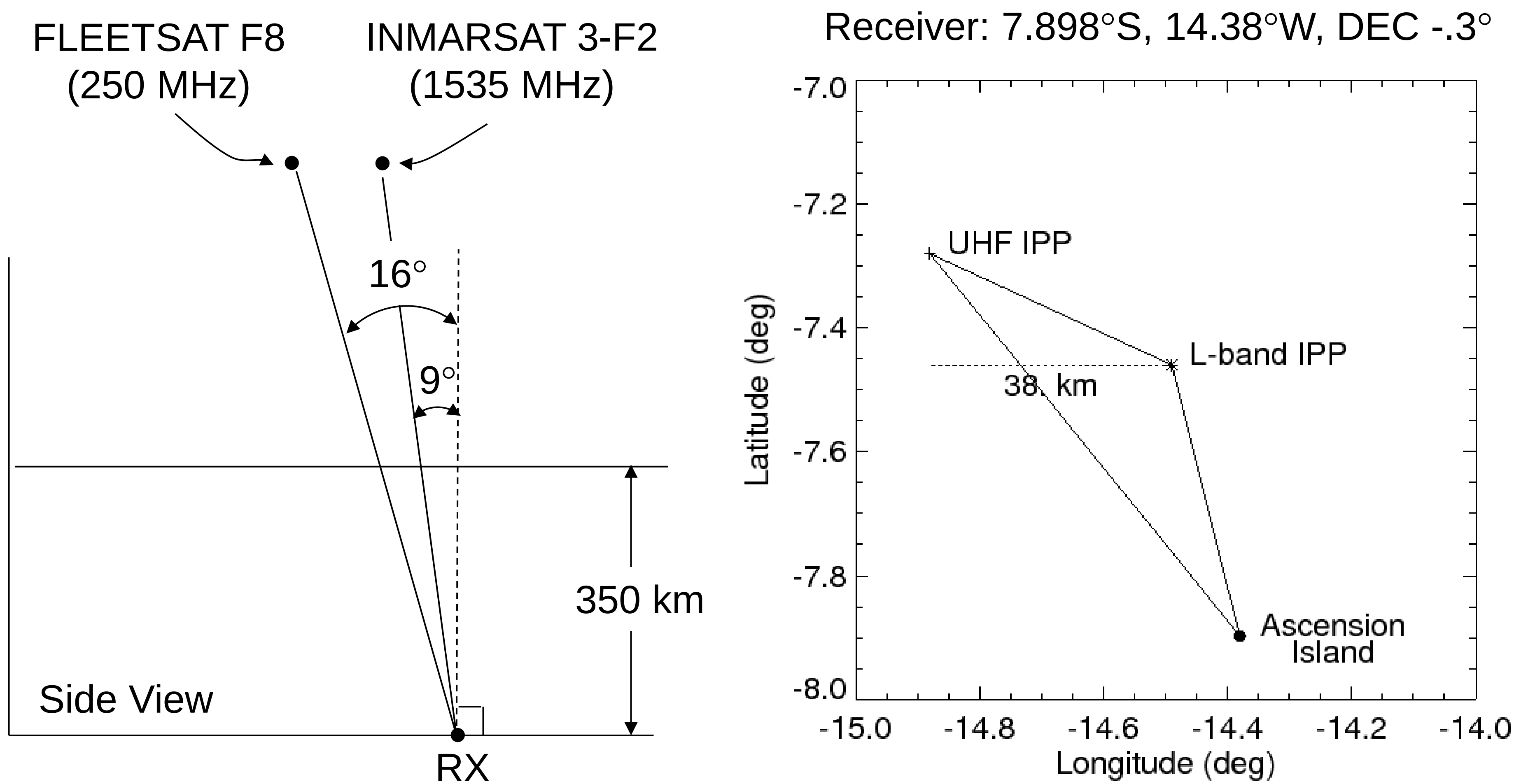
Local and Non-local Effects

- Plots compare intensity SDFs using unconstrained (black) and constrained (red) models.
- Shading indicates departure from power law behavior caused by nonlinear effects.
- In left plots, outer / inner scales occur within the linear regions (no shading). Effects of spectral break are felt locally; *black and red curves are coincident except near the break*.
- In right plots, outer / inner scales occur in nonlinear region (because *U* is larger). Effects of spectral break can be non-local; *differences between black and red curves occur far from break*.

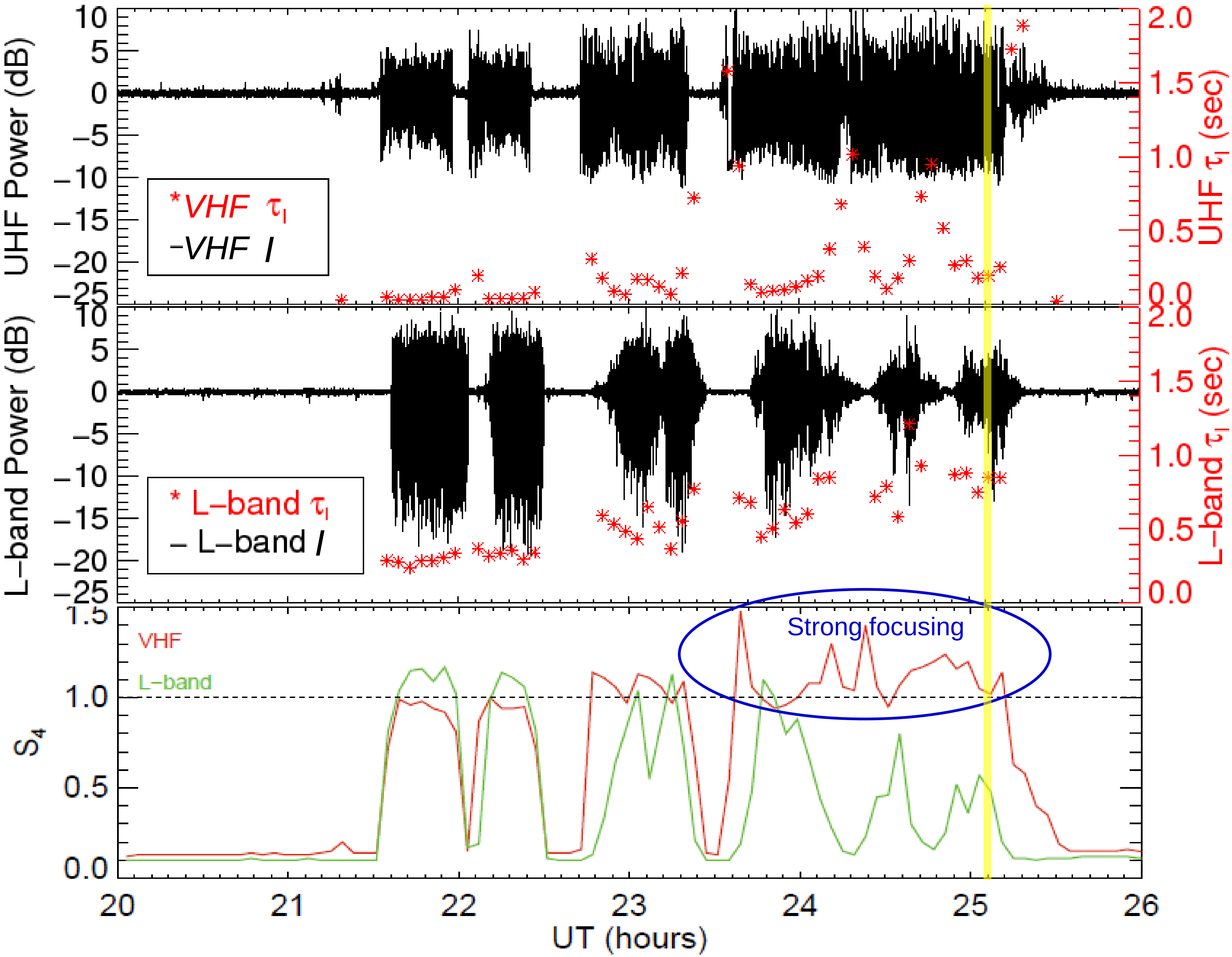


AFRL Campaign at Ascension Island, March 2000
(Carrano et al., AGU 2013)

- Geostationary satellites broadcasting radio signals at VHF (250 MHz) and L-band (1535 MHz) were monitored along nearly co-linear links.
- The VHF data were acquired using spaced antennas to measure zonal irregularity drift. Zonal drift was used to convert time-series to spatial series.

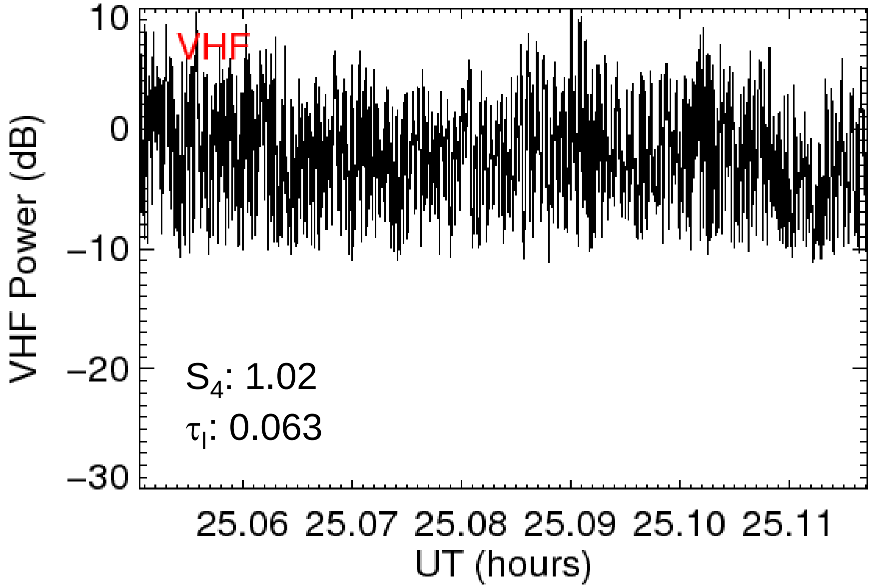


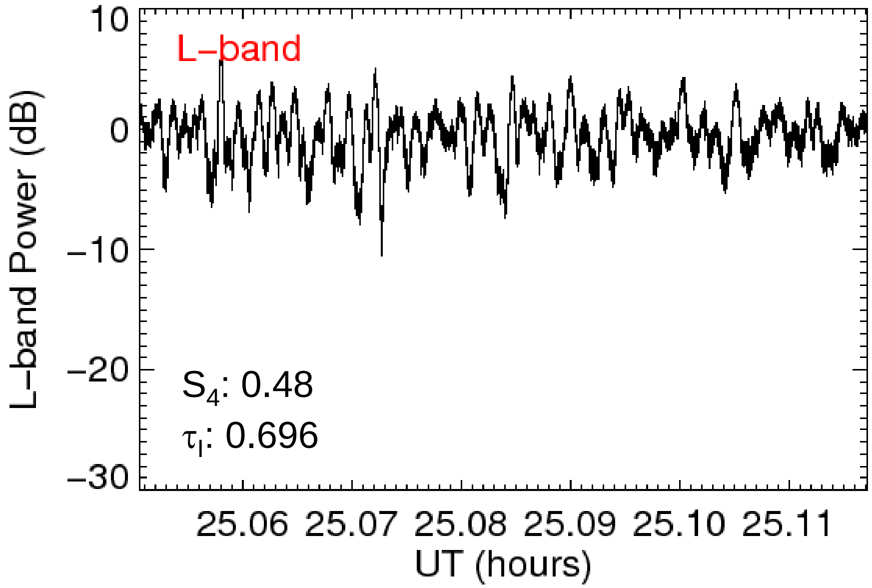
Ascension Island, 22-23 March 2000



Signal Intensity (50 Hz)

Late Evening (25.117 UT)

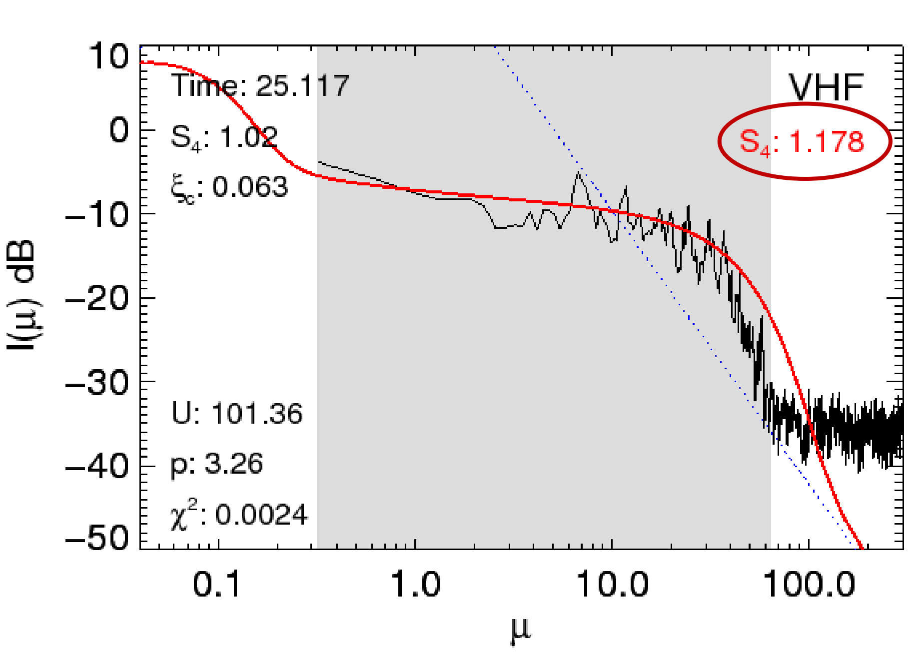


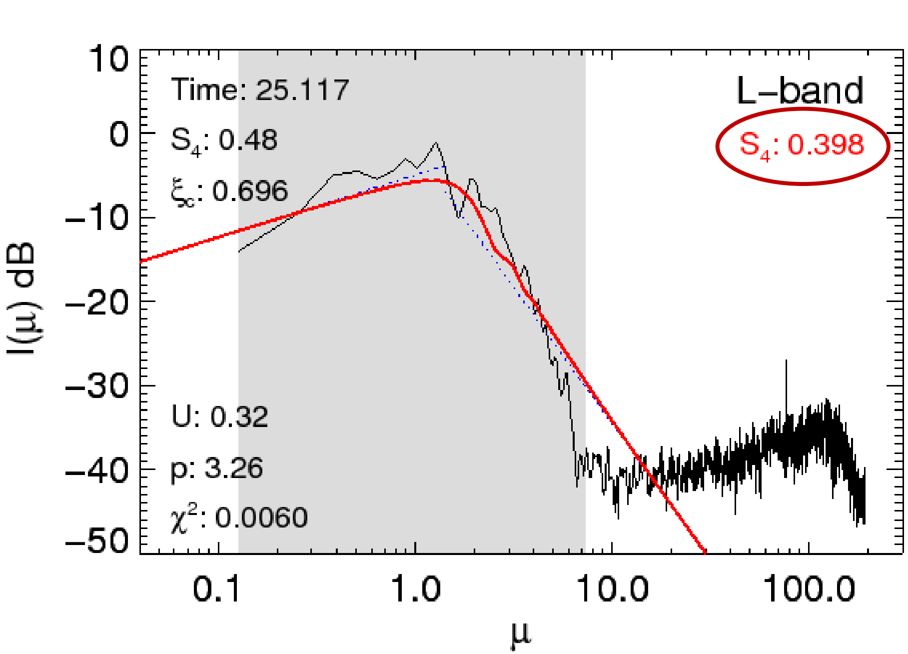


Irregularity Parameter Estimation (One-Component)

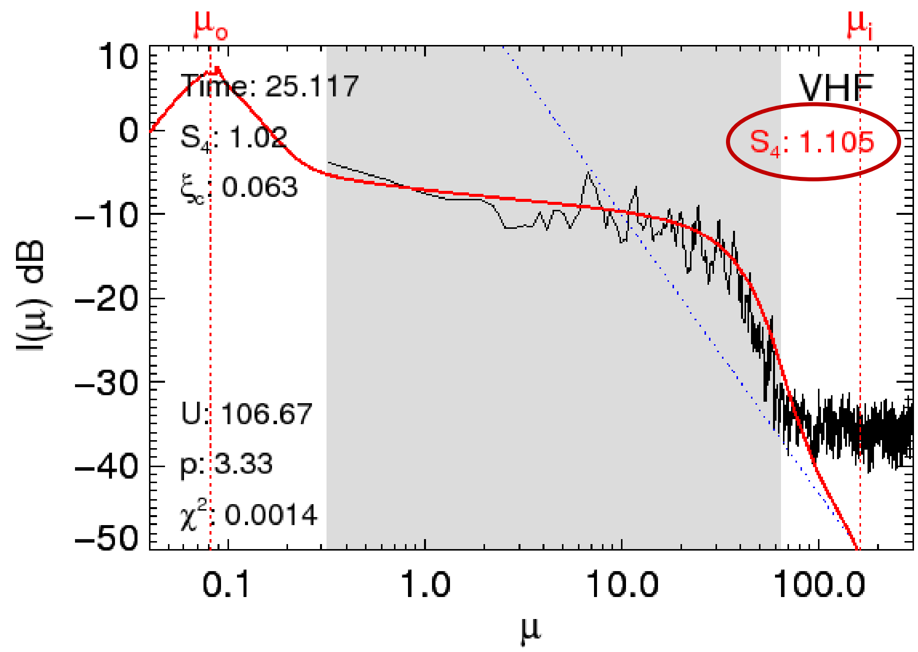
Late Evening

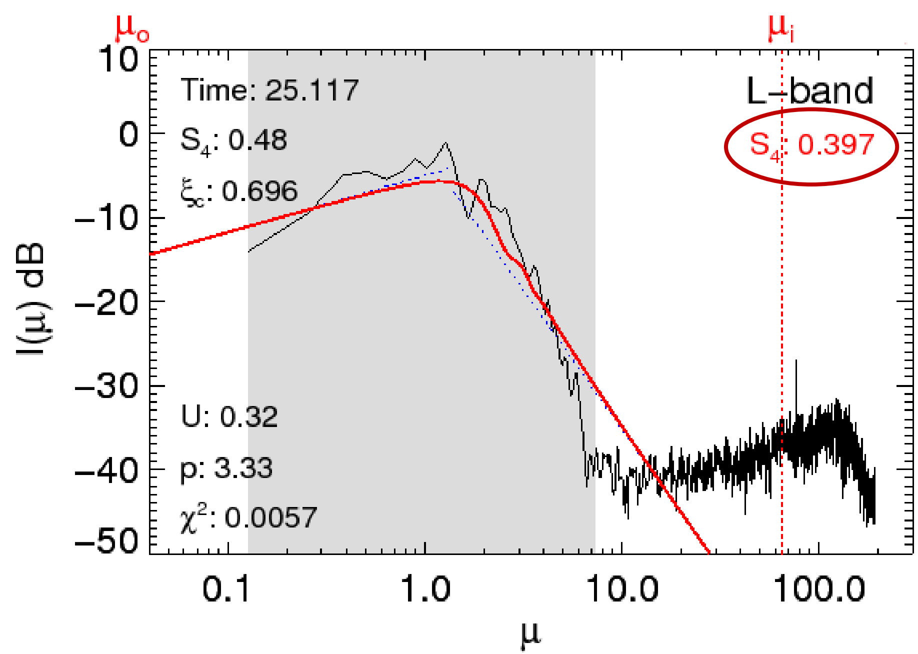
Unconstrained





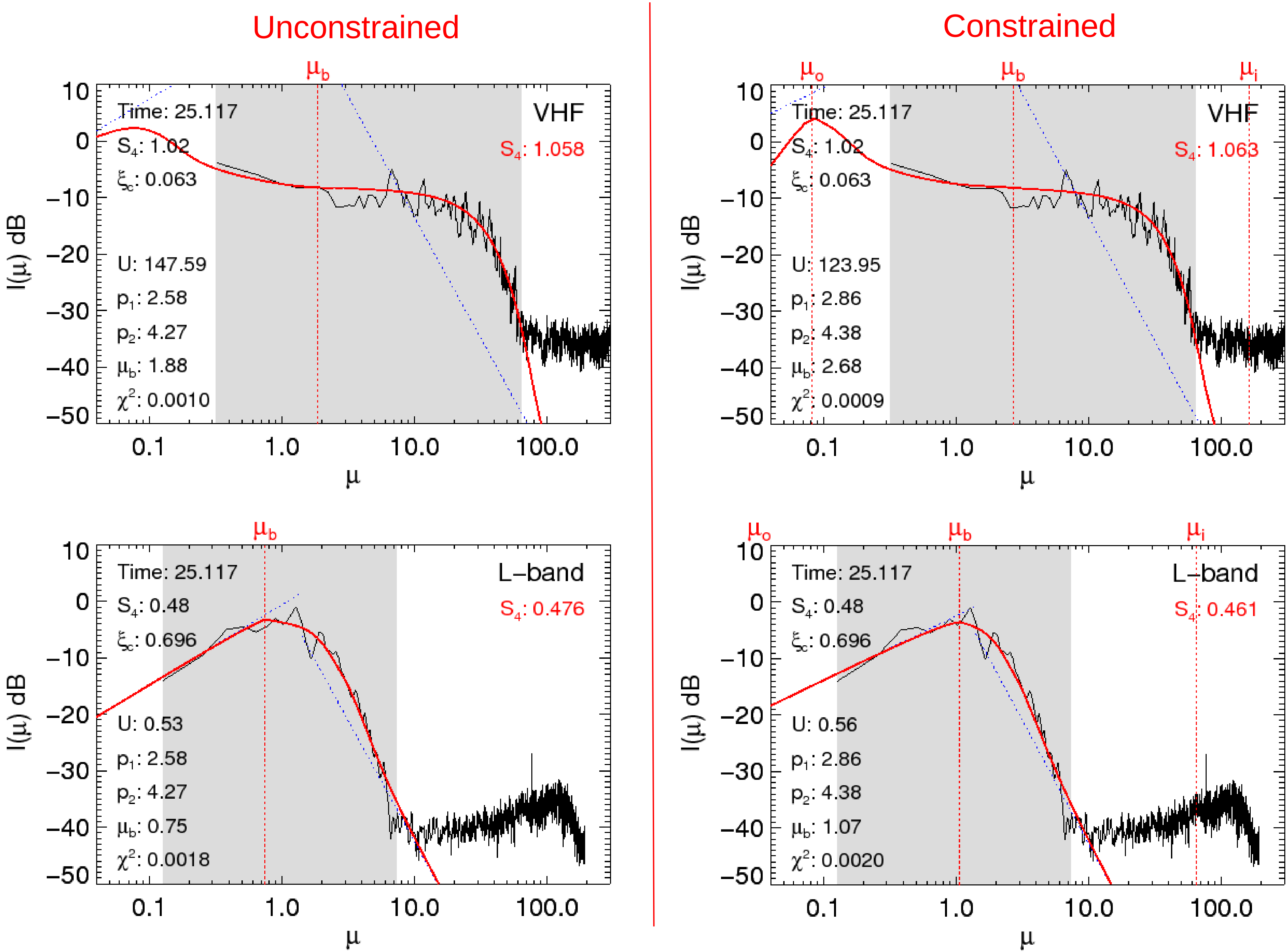
Constrained



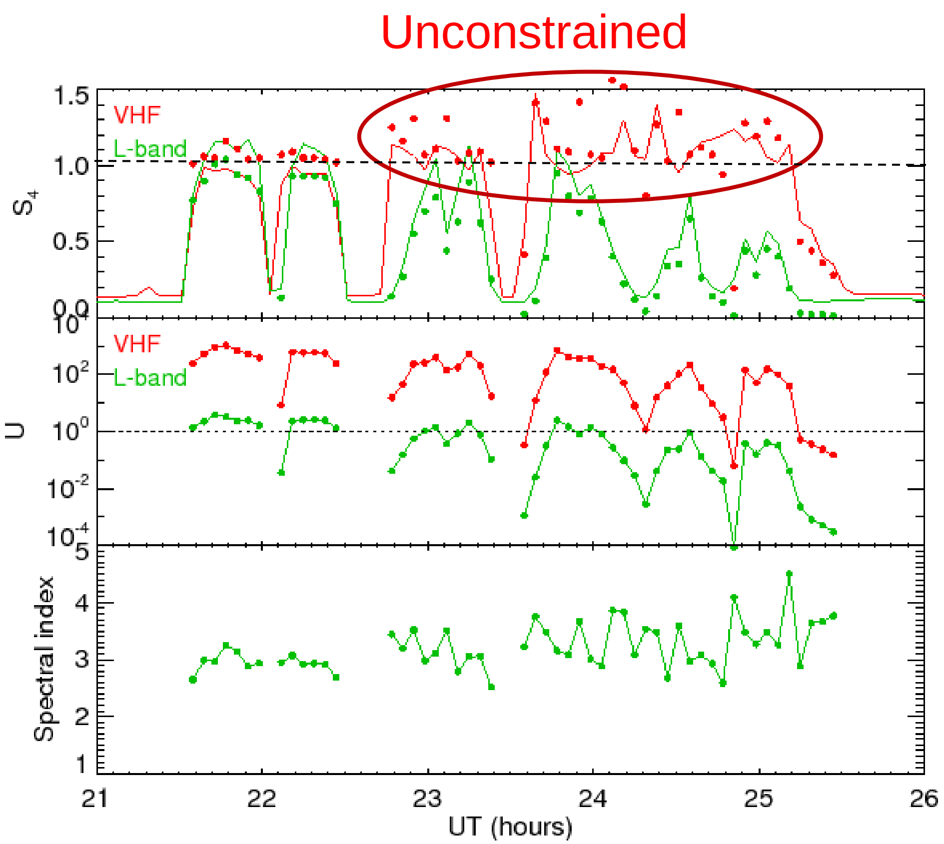


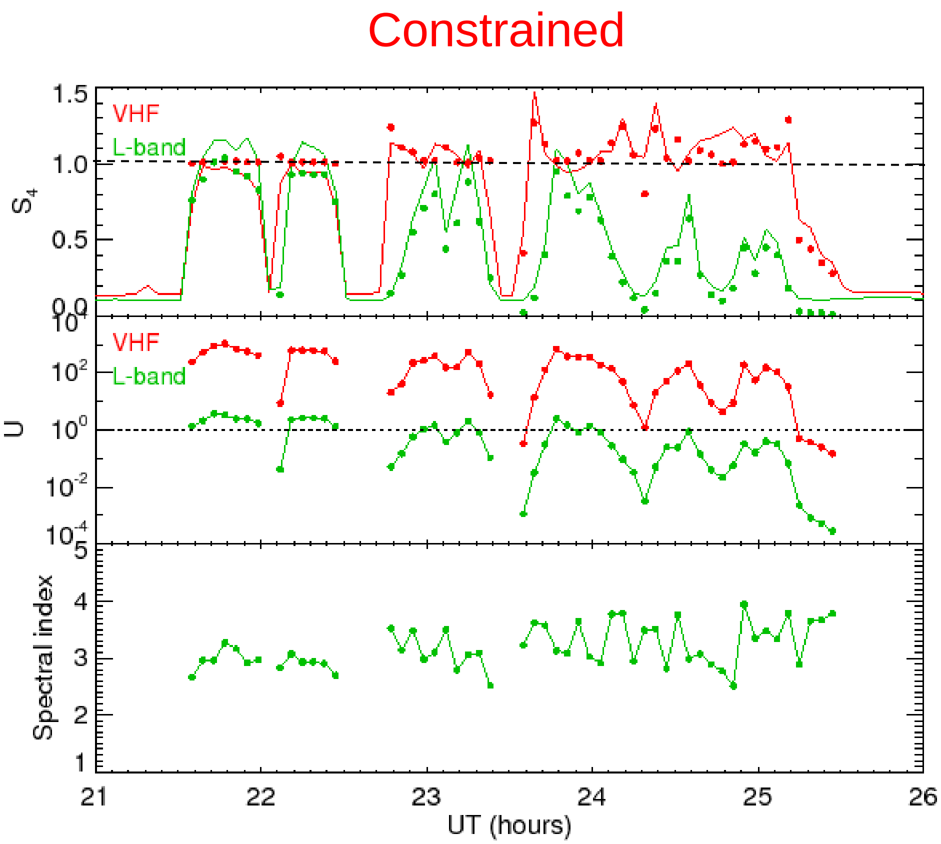
Irregularity Parameter Estimation (Two-Component)

Late Evening



Retrieved Phase Screen Parameters (One-Component)

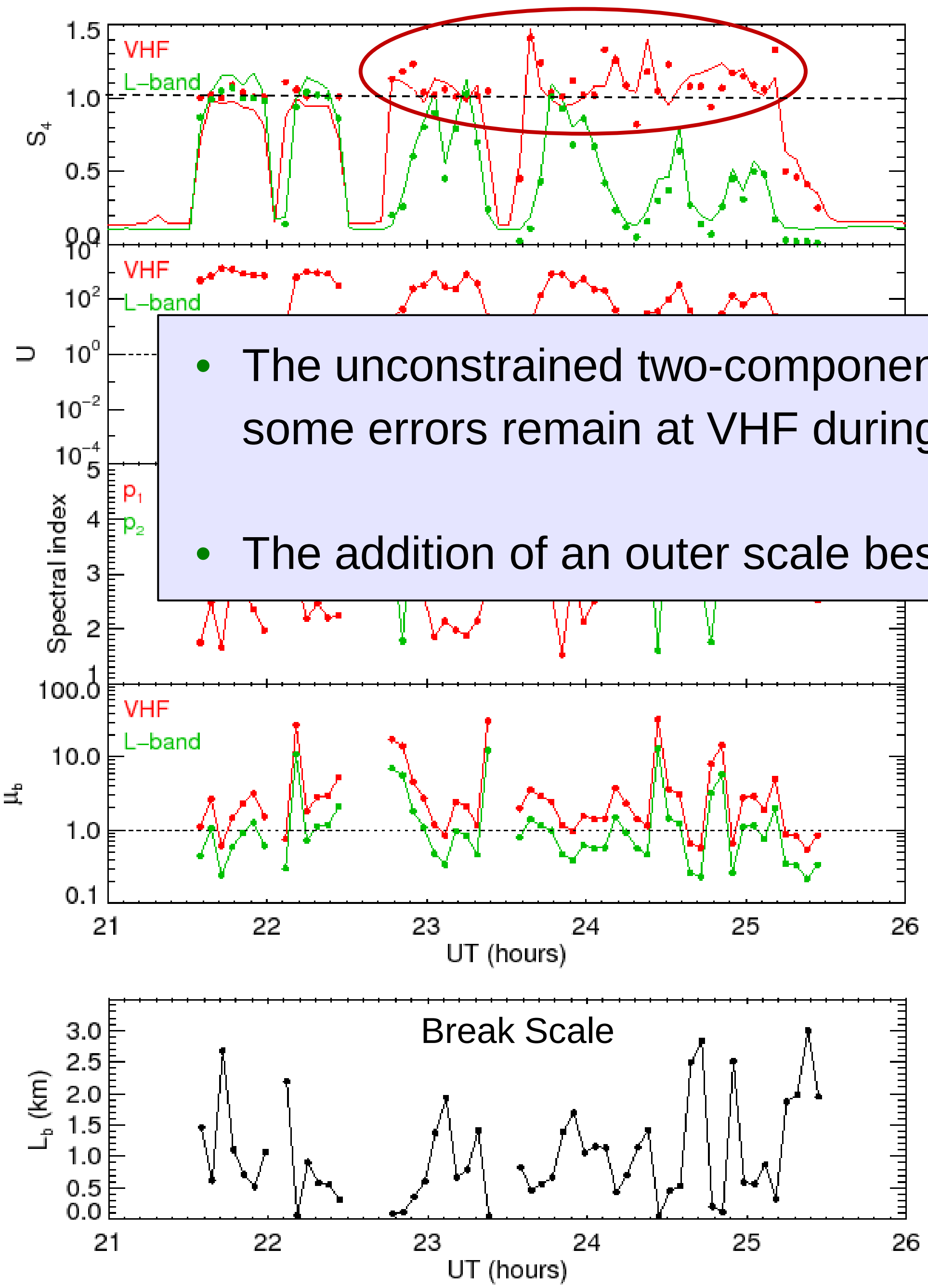




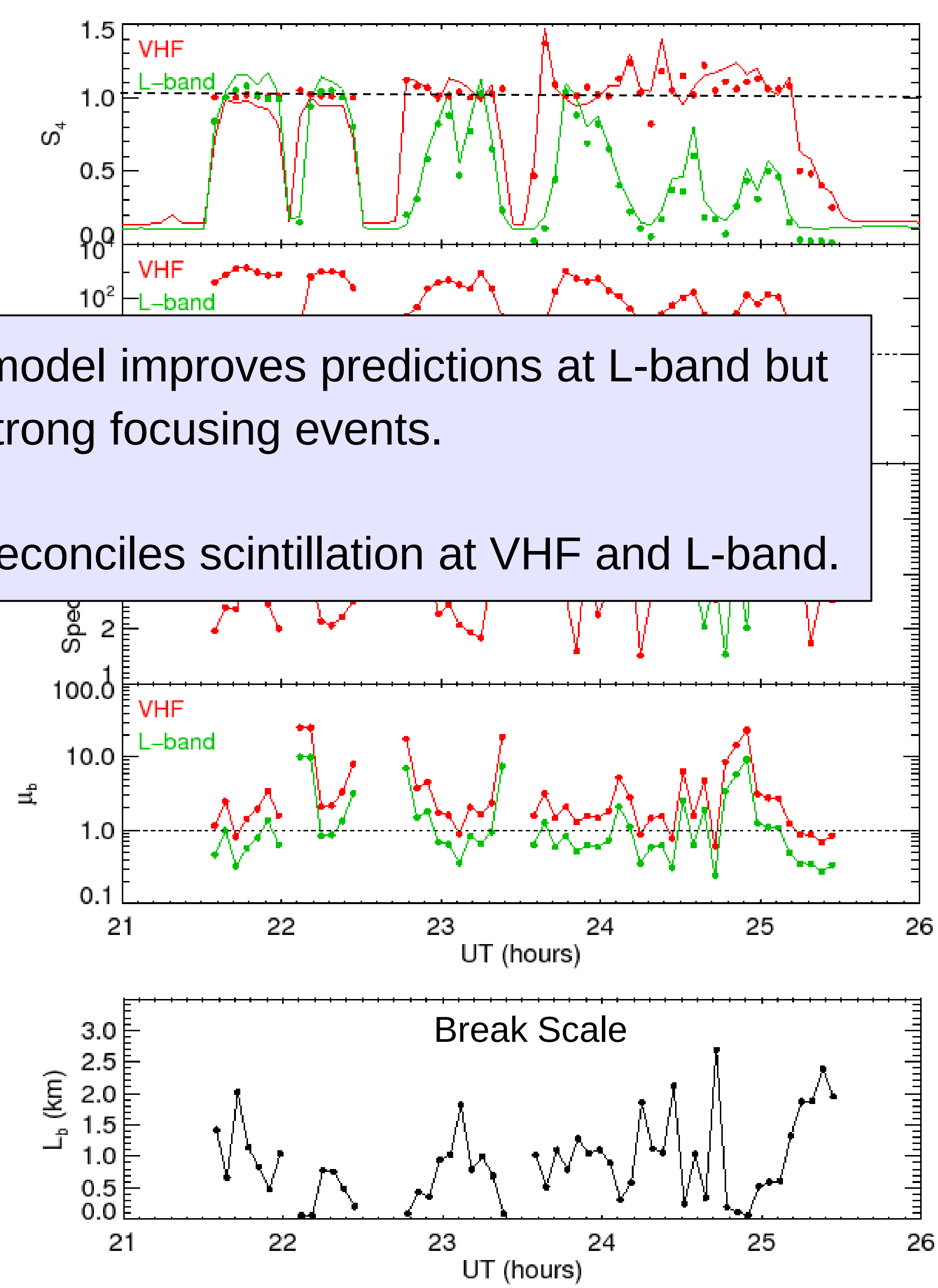
- The unconstrained one-component model is not able to reconcile observations at VHF and L-band (S_4 is overestimated at VHF and underestimated at L-band).
- The outer scale mitigates excess strong focusing at VHF but L-band S_4 remains underestimated.

Retrieved Phase Screen Parameters (Two-Component)

Unconstrained



Constrained



- The unconstrained two-component model improves predictions at L-band but some errors remain at VHF during strong focusing events.
- The addition of an outer scale best reconciles scintillation at VHF and L-band.

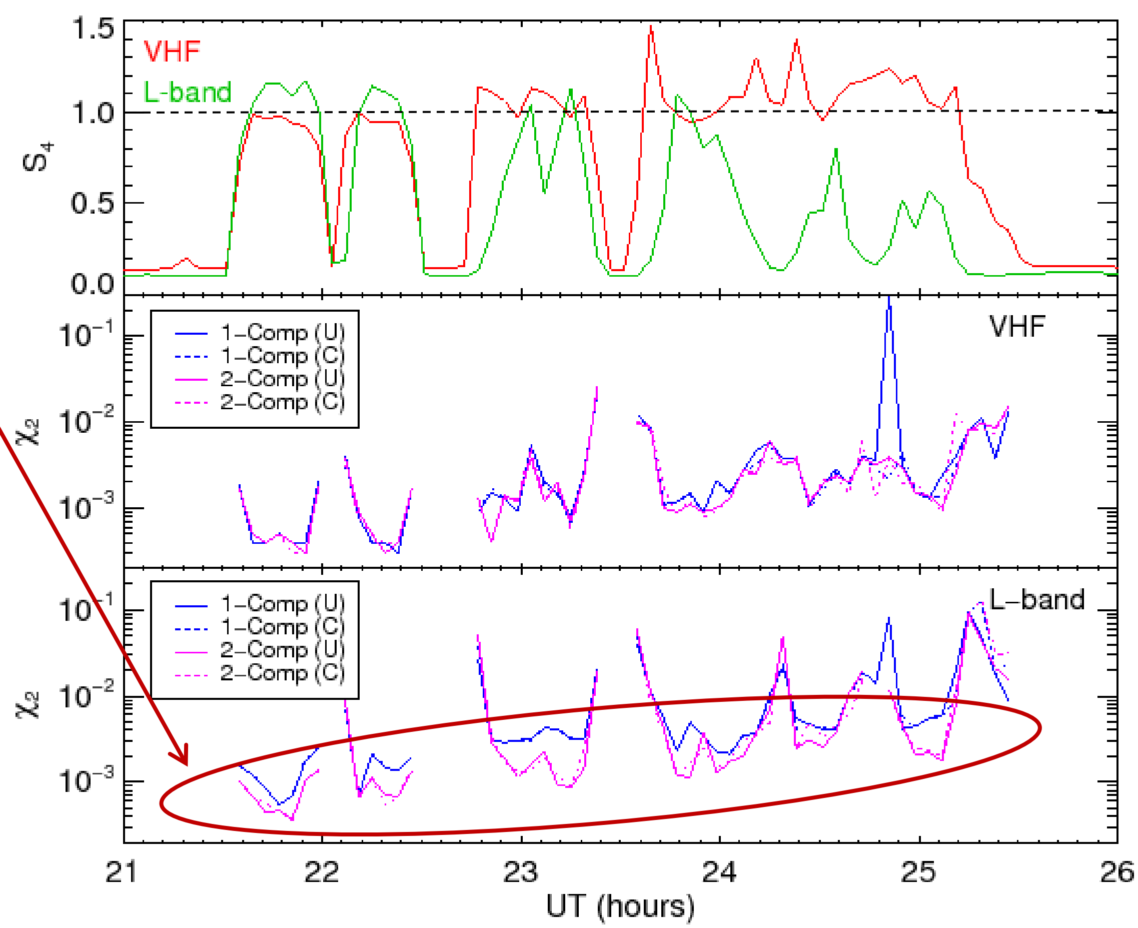
Residuals of Least-Squares Fit (All 4 Models)

- Both an outer scale (1-comp) and intermediate break scale suppress large-scale focusing of VHF signal.

- The two-component models consistently provide a better fit to this data, especially at L-band

- This implies the 2-component model is not simply *emulating the effects of an outer scale*—instead results suggest occurrence of a true spectral break at intermediate wavenumbers (L_b ~ 1 km).

- For this strength of scatter and assumed values of μ_o, μ_i, the outer scale / spectral break plays a role, but the inner scale does not.



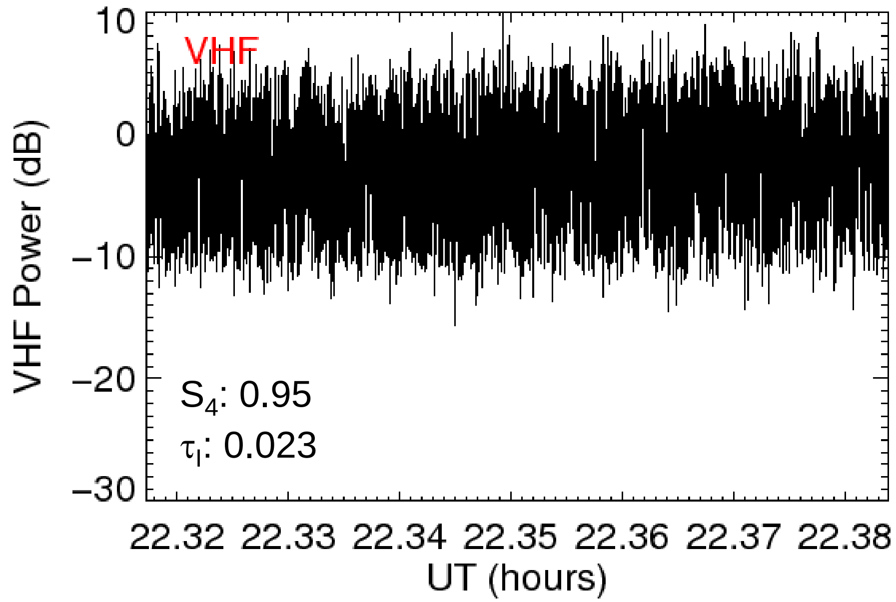
Conclusions

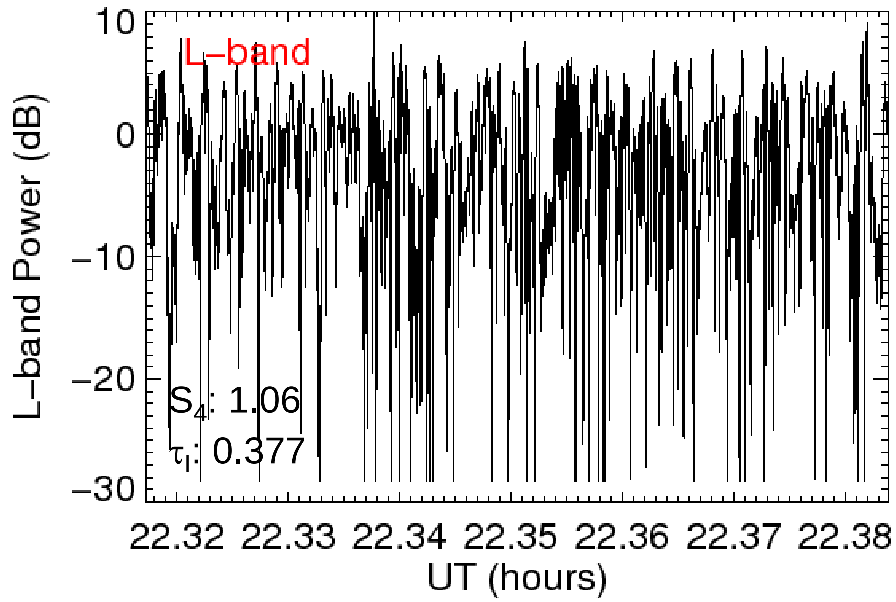
- The influence of a spectral break depends on whether it occurs in the wavenumber range where departures from power law behavior occur due to nonlinear effects.
  - When a spectral break occurs in the “linear” region, the effects are felt locally (in which case the scintillation statistics are relatively insensitive to its presence).
  - When a spectral break occurs in “non-linear” region, its effects can be highly non-local, depending on the low and high frequency slopes of the irregularity spectrum.
- We applied an inverse modeling technique called Irregularity Parameter Estimation (IPE) to infer phase screen parameters from strong scintillations at Ascension Island.
- Application of IPE to the Ascension Island data revealed non-local effects of the outer scale, but no observable effect from the inner scale (the latter is separated too widely from Fresnel scale for the strength of scatter we observed).
- The 1-component model *needs* an outer scale to suppress strong focusing at VHF. The 2-component model benefits marginally (break acts like an outer scale). The 2-component model provides the best fit to intensity spectra and S_4 at VHF and L-band. This suggests presence of an intermediate break scale with $L_b \sim 1$ km.

Extra Slides

Signal Intensity (50 Hz)

Early Evening (22.384 UT)

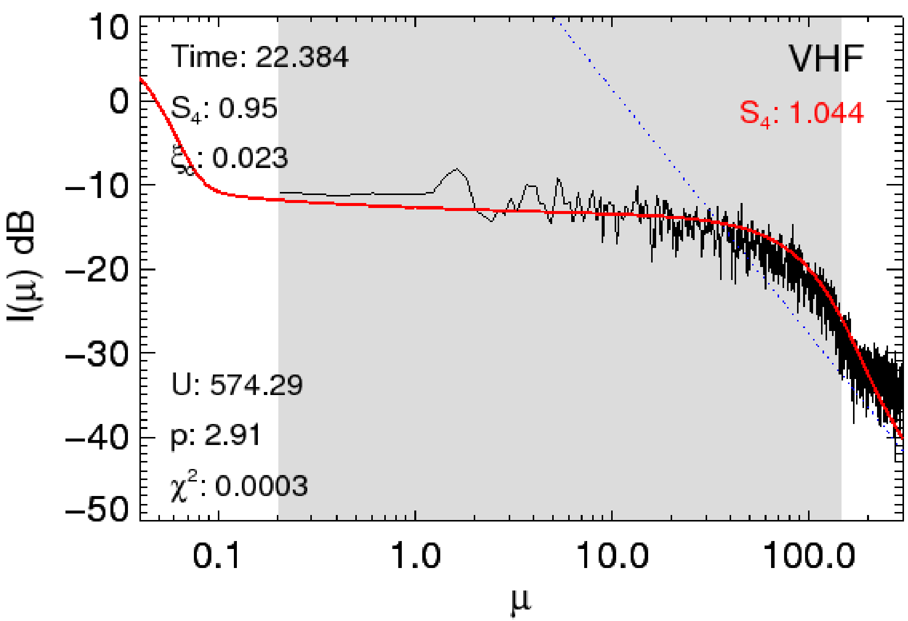


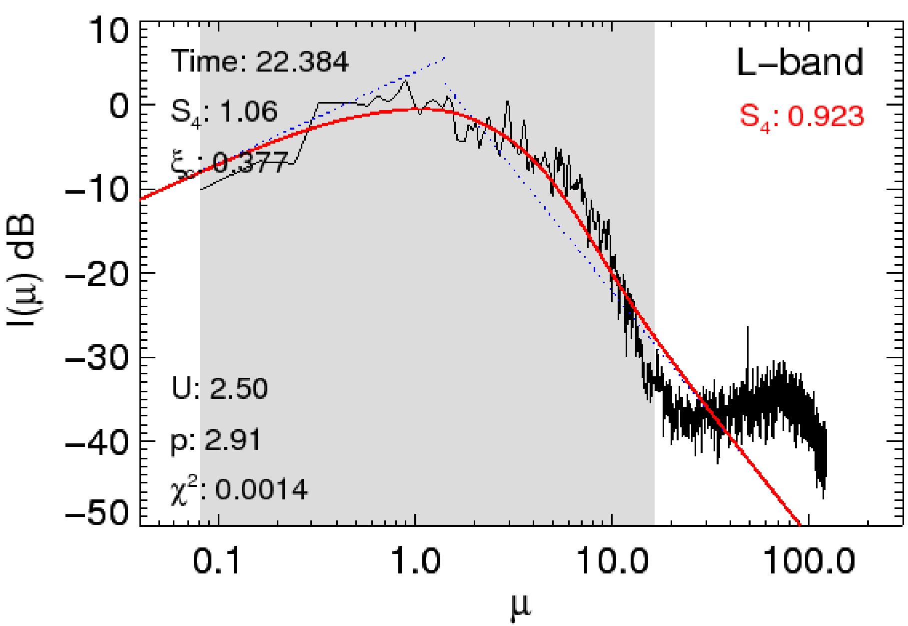


Irregularity Parameter Estimation (One-Component)

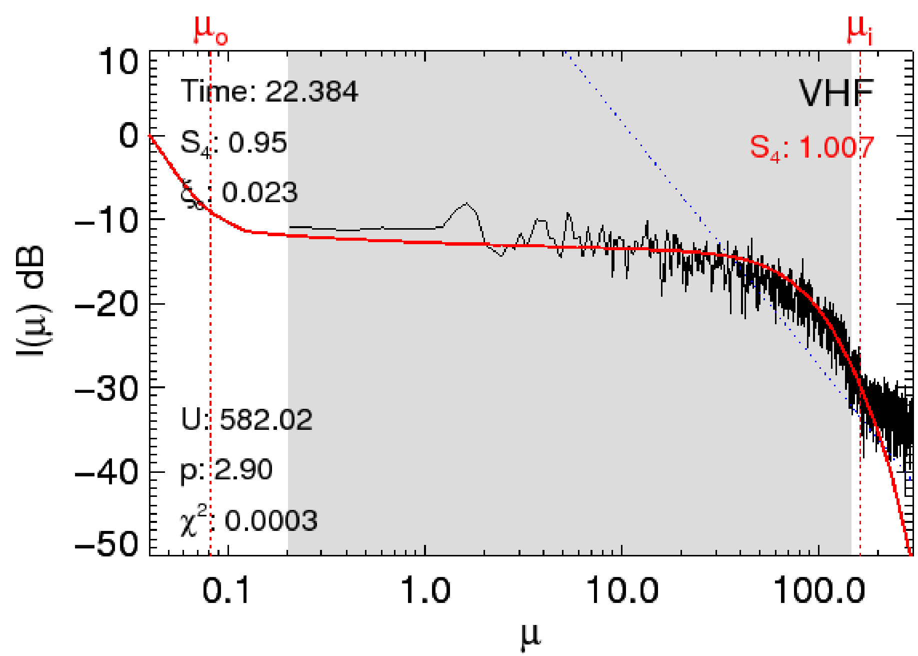
Early Evening

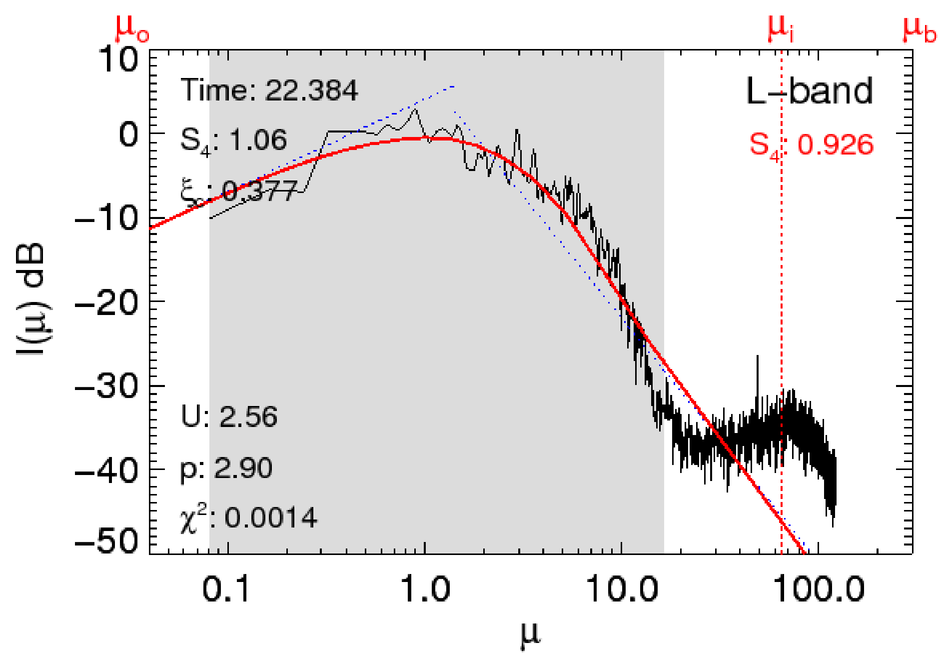
Unconstrained





Constrained (L_o = 20 km, L_i = 10 m)

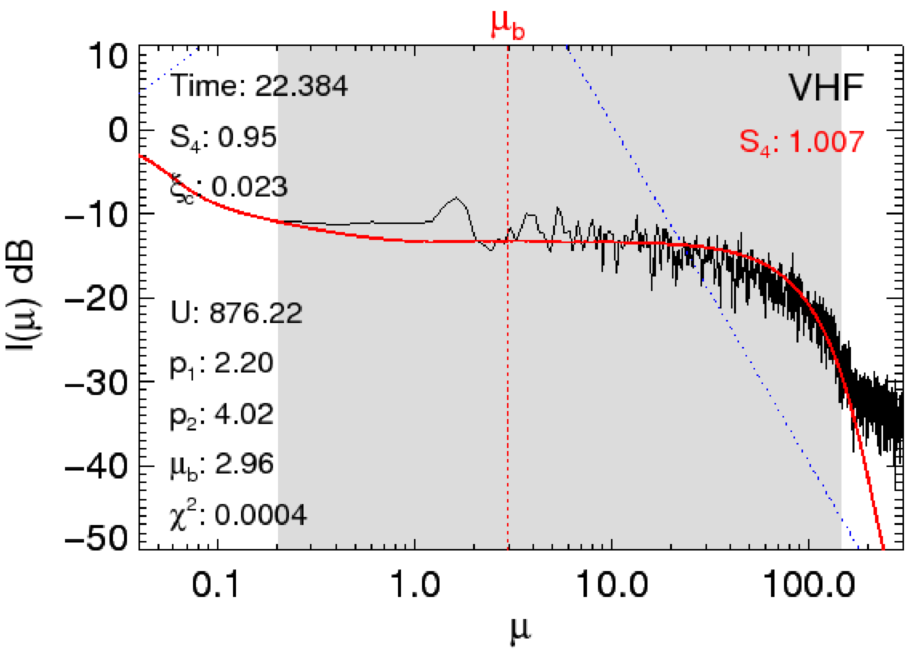


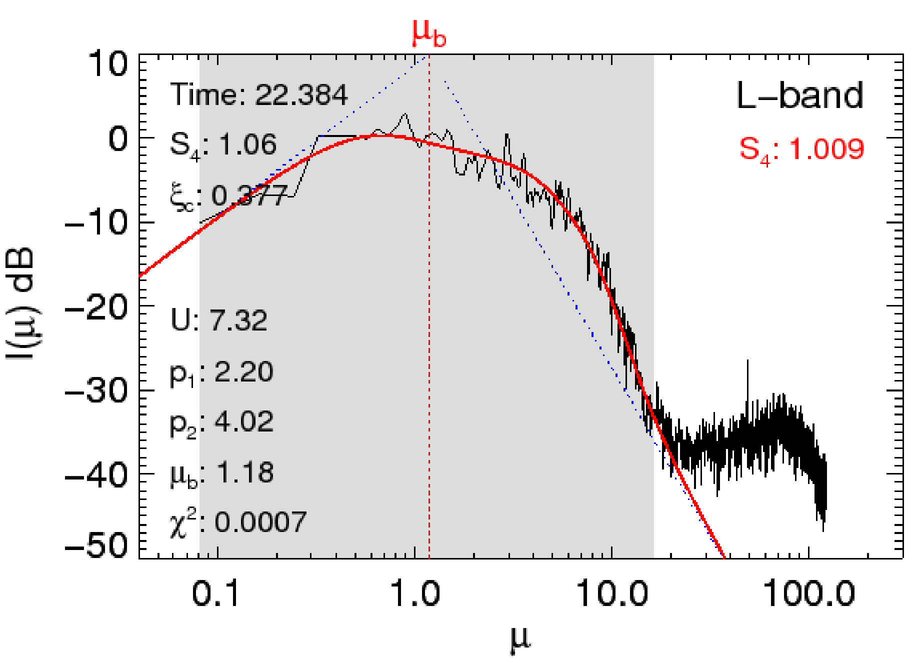


Irregularity Parameter Estimation (Two-Component)

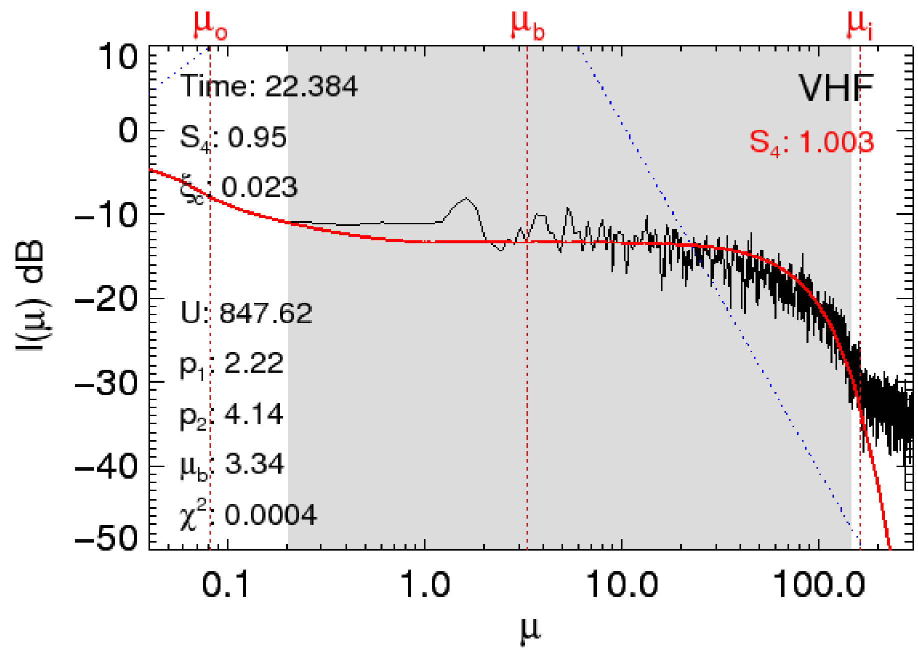
Early Evening

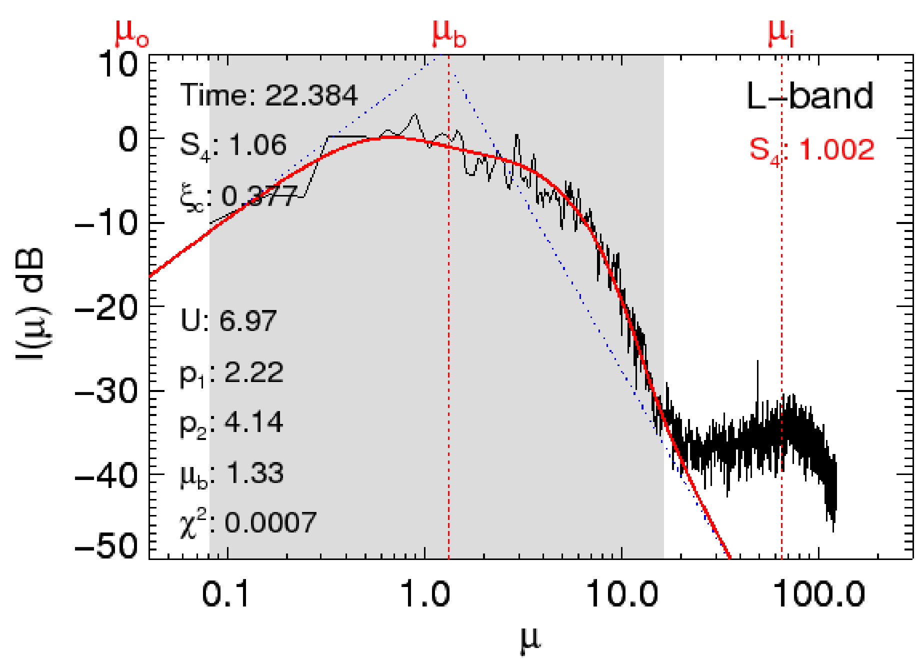
Unconstrained





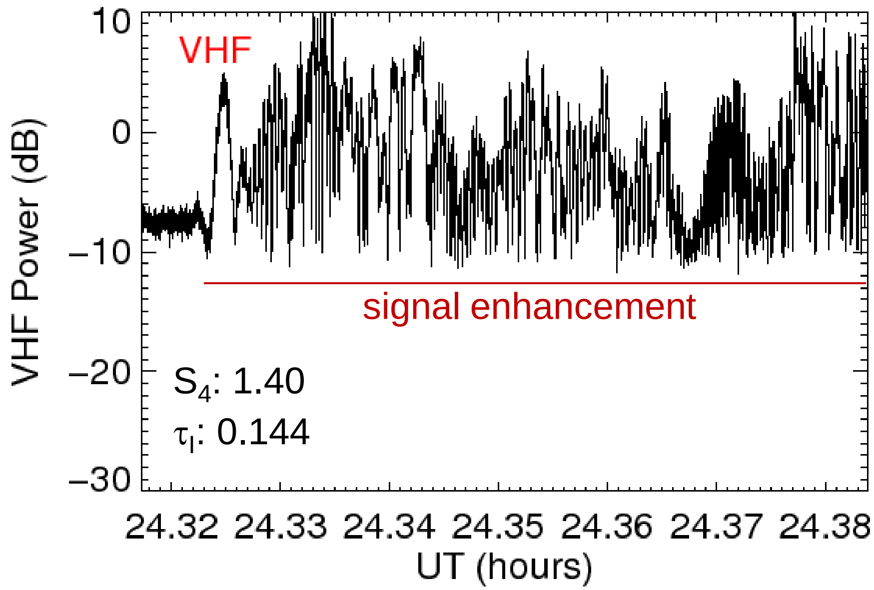
Constrained

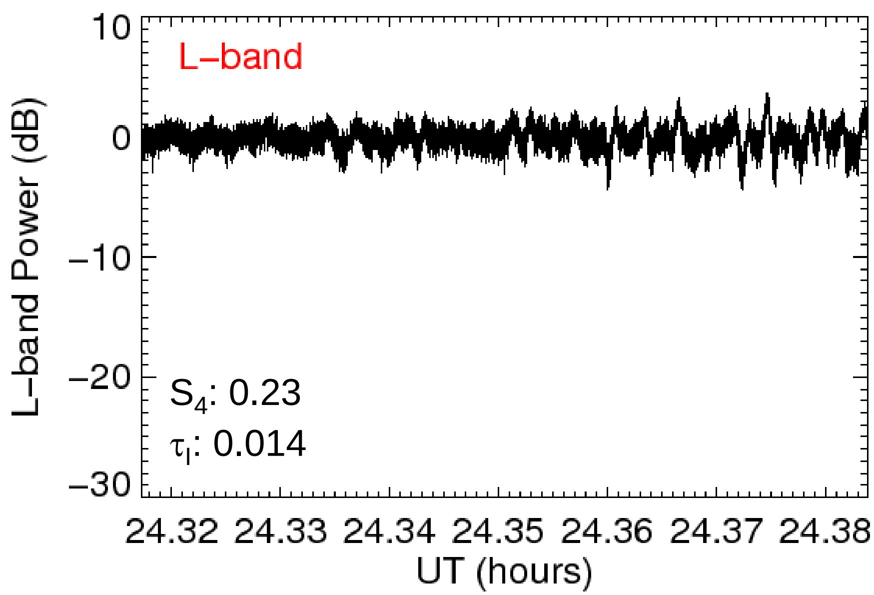




Raw Signal Intensity (50 Hz)

Mid Evening (24.384 UT)

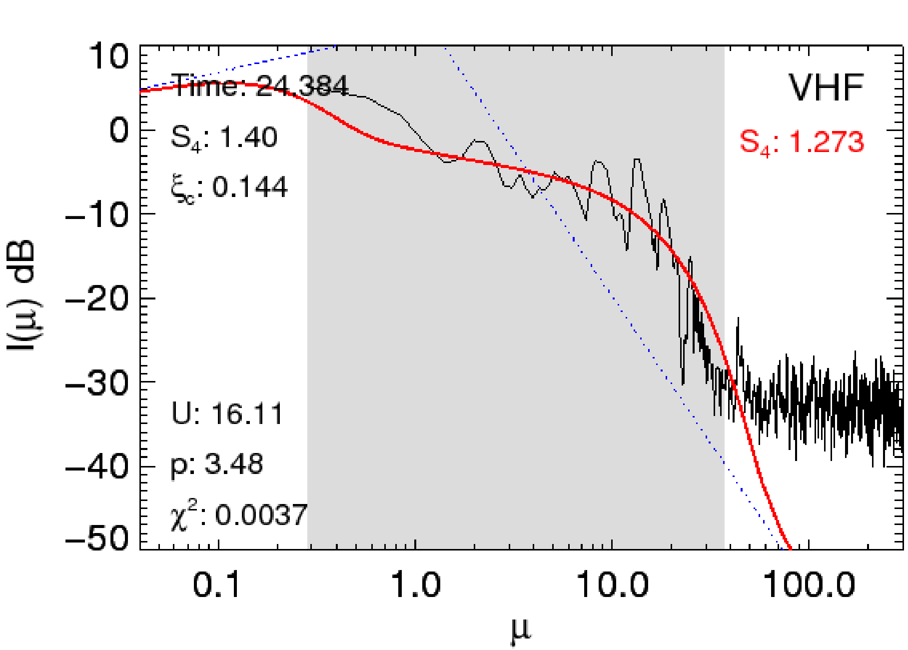


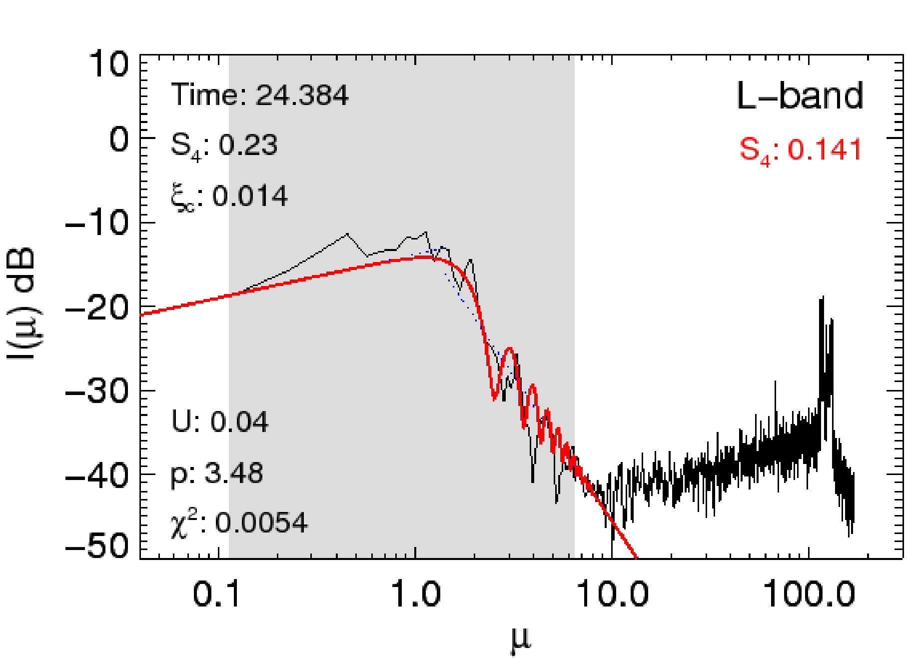


Irregularity Parameter Estimation (One-Component)

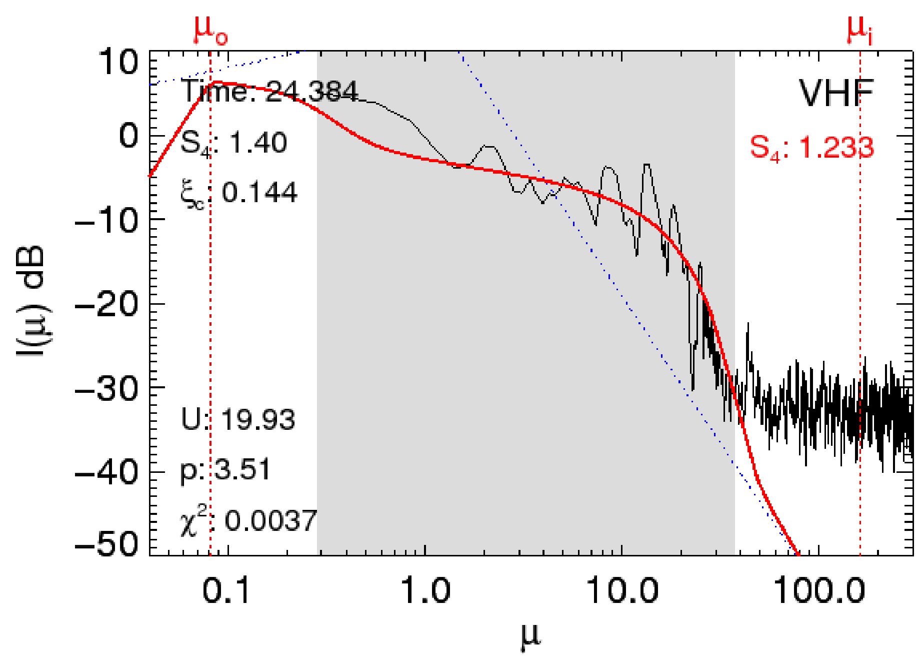
Mid Evening

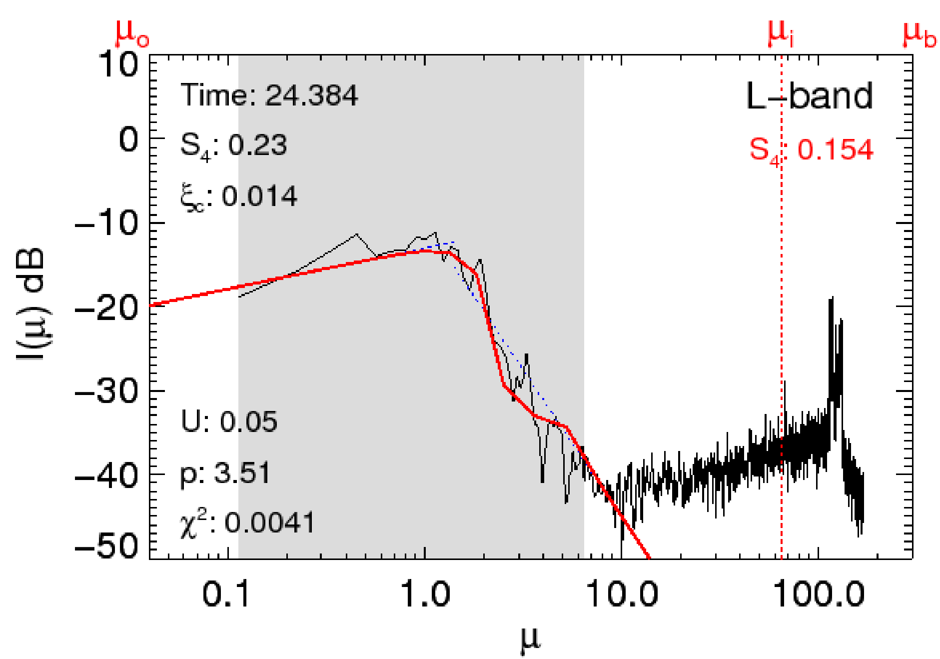
Unconstrained





Constrained





Irregularity Parameter Estimation (Two-Component)

Mid Evening

Unconstrained | Constrained