ITIT-12: Turbulence measurements with Poker Flat Incoherent Scatter Radar (PFISR) -A hypothesis test approach

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Poker Flat Incoherent Scatter Radar (PFISR)

PFISR has been operated at Poker Flat Research Range (PFRR, 65.13° N, 147.47° W) since 2007 (Fig. 1). The ability to steer on a pulse-to-pulse basis provides both high spatial and temporal resolution (Nicolls&Heinselman,2007). PFISR operates at 450 MHz, and has a narrow beam width of 1°×1.5° and a vertical resolution of 750m (for this experiment). Maximum time resolution is 2.7.s (Nicolls et al., 2010)

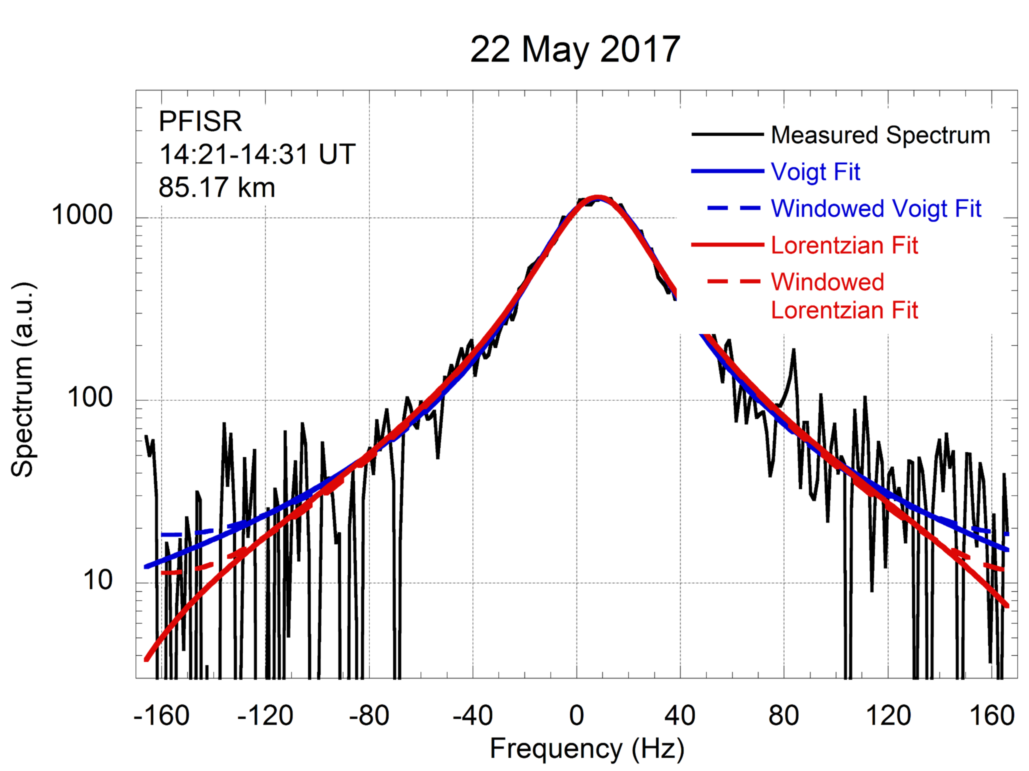
ISR Spectra and Turbulence

The incoherent scatter radar (ISR) signal is due to Thompson scatter of radio waves by free electrons. However, the spectrum of incoherent scatter radar depends not only on the motion of electrons but also of the dynamics of the electrons and ions (Kudeki and Milla, 2011). The spectrum of the scattered radio waves consists of a narrow ion-line superimposed on a broader electron-line (Bhattacharyya, 1992). Multiple studies have shown that in the D-region, where the plasma is the collision-dominated, the ISR signal spectrum has a Lorentzian shape.

PFISR has a the narrow beam with high range resolution. Thus, we can neglect spectral broadening processes such as beam broadening and wind-shear broadening (Nicolls et al, 2010). We assume that the only broadening of the vertical beam is due to turbulence. In a turbulent environment the ISR spectrum is Doppler-broadened by the turbulent motion of the plasma. The resultant ISR signal spectrum has a Voigt shape, which is the convolution of a Gaussian shape and a Lorentzian shape. From the root-mean-square (RMS) width of the Gaussian component of the Voigt spectrum, we can determine the RMS wind fluctuations and thus derive the energy dissipation rate of turbulence.

The spectrum measured by the radar includes aliasing and windowing effects and yields modified Lorentzian and Voigt shapes. An example of a measured spectrum with the best fit to the Lorentzian and Voigt spectra (unmodified and modified is shown below). We define a spectral quality factor (SQF) to quantify the quality of a spectrum. It's the ratio of the power in the spectrum divided by the power in the noise.

We designed a specific observation configuration to study turbulence measured by the vertical beam. The radar beam is pointed vertical during the whole observation cycle to maximize the power in the vertical. The experiment is carried on May 22, 2017 UT.



Hypothesis Test

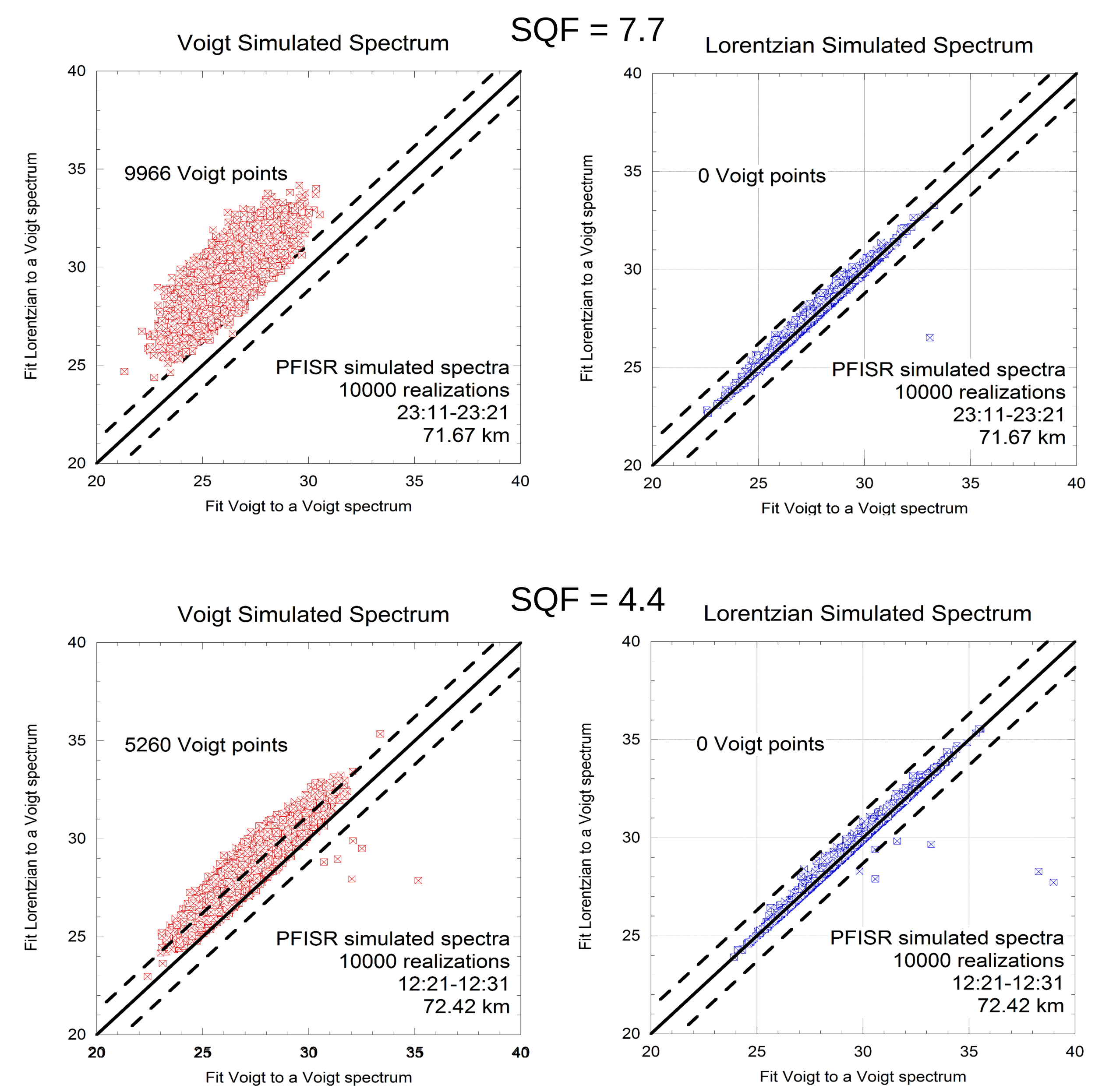
The fact that the turbulent and non-turbulent spectra have different shape allows us to detect the existence of turbulence with a hypothesis test. The hypothesis test is conducted as follows:

1) We estimate the RMS difference between the radar spectrum and the fitted (Lorentzian or Voigt) spectrum, E_{RMSV} and E_{RMSL}
2) We identify the best fit as that with the smallest value of E_{RMS}
3) If the difference in E_{RMS} is less than the standard error in the E_{RMS}, then the fits are ambiguous
4) If the E_{RMS} of one fit is smaller than the other by a margin of the standard error, then that fit is significant. And we conclude that turbulence is present (Voigt) or not present (Lorentzian)

Monte Carlo Method

We conducted a Monte Carlo experiment to characterize the uncertainty of the fitting parameters and the significance of the hypothesis test. In the Monte Carlo experiment, simulated spectra are constructed by adding white noise to ideal Lorentzian and Voigt spectrum. The properties of the noise and ideal spectrum are based on each radar spectrum. These simulated spectra are fitted to a Lorentzian shape and a Voigt shape. This is repeated for N times. The standard deviation of the simulated parameters characterize the uncertainty in the spectral estimates. The hypothesis test is applied to the simulated spectra. The number of Voigt spectra when fitting to N Voigt simulated spectra and N Lorentzian spectra are retrieved.

We show two cases on the right. In the first case, SQF=7.7. Out of the 10000 realizations, 9966 of the turbulent spectra are identified as Voigt. None of the non-turbulent spectrum is identified as Voigt. In the second case, SQF = 4.4. 5260 turbulent spectra are identified as Voigt. None of the non-turbulent spectra are identified as Voigt



Bayes Theorem

Bayes Theorem states that

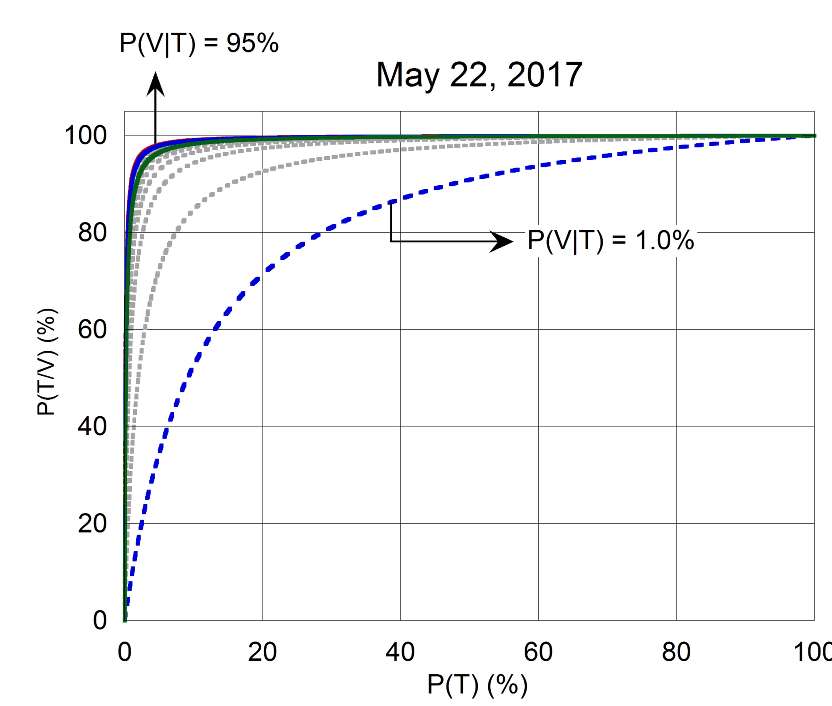
$$P(T|V) = P(V|T)*P(T)/P(V)$$

$$P(V) = P(V|T)*P(T)+P(V|NT)*P(NT)$$

where P(T|V) is the probability that a spectrum identified as Voigt is actually turbulent (namely the significance), P(V|T) is probability that the method identify a turbulent spectrum as Voigt, P(V|NT) is the probability that the method identify a non-turbulent spectrum as Voigt, and P(T) (P(NT)) are the probability that any spectrum is turbulent (non-turbulent).

We show how the significance varies with the value of P(T) in the plot to the right. Assuming P(T)=5%, to guarantee that the significance P(T|V) > 95%, a P(V|T) of 36% or larger is required. While assuming a P(T)=10%, a P(V|T) of 17% is required to get the same significance. P(V|NT) is assumed to be 0.1% in the plot, based on our simulations.

Applying numbers from the two cases above, assuming P(T) = 10%, the significance of the identification are 99% and 98%

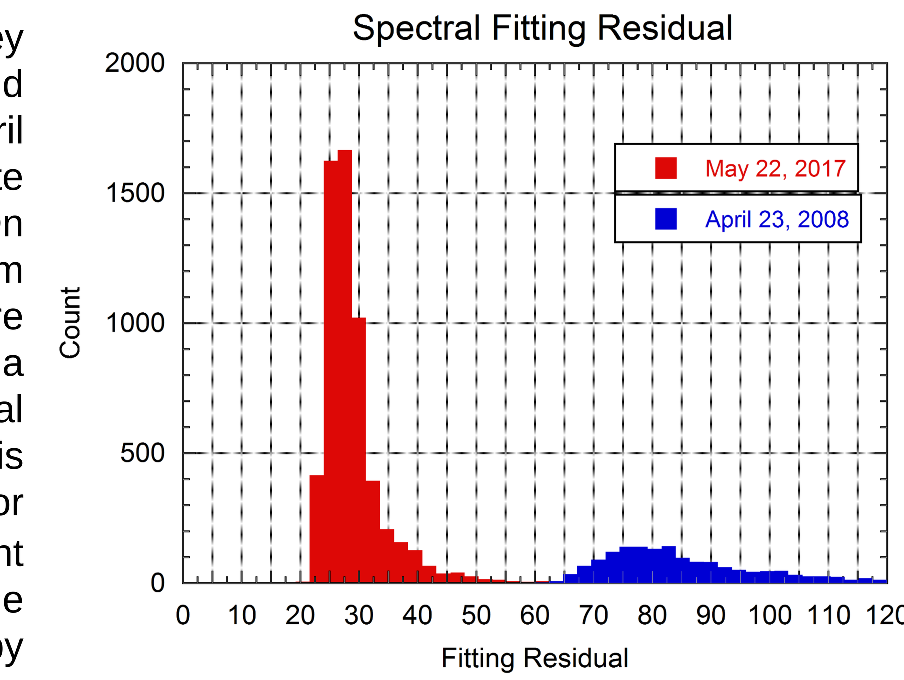


Acknowledgements

This project is supported by the US National Science Foundation (NSF) CEDAR program under the grant "CEDAR: Lidar and Radar Investigations of Turbulence in the Arctic Mesosphere and Lower Thermosphere" (NSF #1243167) The authors thank the staff at PFRR and SRI international for their support of radar observations. We thank Colin Triplett for helpful discussion.

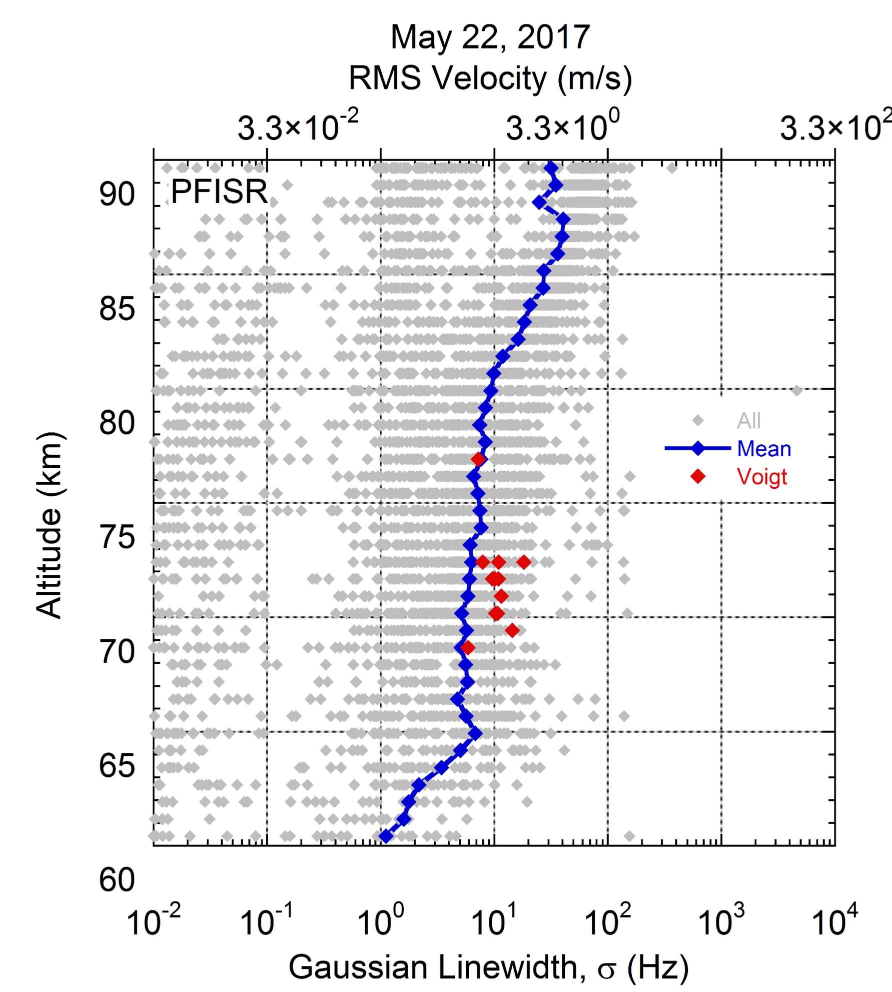
Influence of radar power

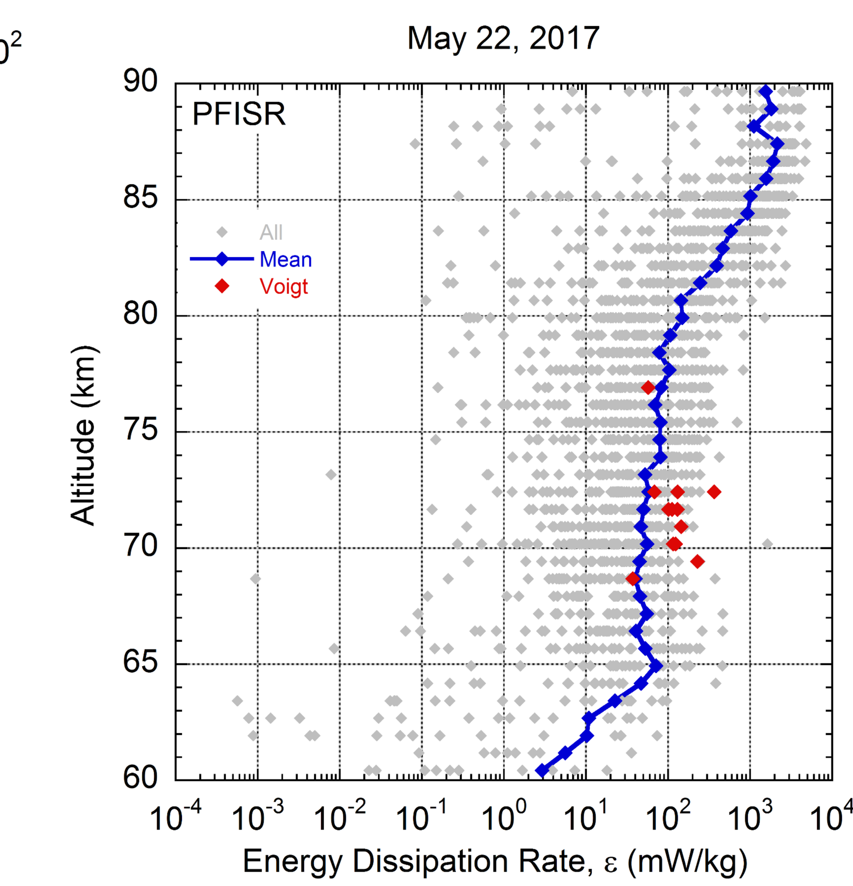
We analyzed two sets of data. They were obtained on April 23, 2008 and May 22, 2017, respectively. On April 23, 2008, the radar beam alternate among 7 different directions. On May 22, 2017, the radar beam remained vertical. Seven times more spectra were averaged to form a single spectrum in the vertical beam. The fitting residual is expected to be improved by a factor of $\sqrt{7}$, as clearly seen in the right figure. This indicate that the increasing the radar power, either by combing the beams, or extending the radar antenna, will improve the spectral quality. Hence increase the significance of turbulence detection



Results

We show the value of the Gaussian linewidth, the RMS turbulent velocity and the turbulent energy dissipation rate retrieved on May 22, 2017. There are 6400 spectra on this night. 5528 spectra are ambiguous, 90 spectra are Lorentzian and only 12 spectra are identified as Voigt. These points cluster and form a turbulent layer between 69 km and 72 km. This layer is intermittent in time as well. It exists between 12 UT and 15 UT, and between 23 UT and 1 UT as well. The value of the turbulent energy dissipation rate varies between 37 mW/kg and 366 mW/kg. The mean value is 142 mW/kg. To compare, the mean value of all data in the same altitude range is 71 mW/kg.





References

Bhattacharyya, s, (1992), Incoherent scatter radar as a D-region probe, MS Thesis, University of Alaska Fairbanks, pp142.
Dougherty, J. P. and D. T. Farley (1963), A theory of incoherent scattering of radio waves by a plasma, J. Geo. Res., 68, 5473-5486.
Fejer, J. A. (1963), Scattering of radio waves by an ionized gas in thermal equilibrium, Can. J. Phys., 38, 1114-1133.
Hocking, W. K. (1985), Measurement of turbulent energy dissipation rates in the middle atmosphere by radar techniques: A review, Radio Sci., 20(6), 1403–1422, doi:10.1029/RS020i006p01403.
Hocking, W. K. (1999), The dynamical parameters of turbulence theory as they apply to middle atmosphere studies, Earth Planets Spaces, 51, 525-541
Kudeki E. and M. A. Milla (2011), Incoherent scatter spectral theories—Part I: A general framework and results for small magnetic aspect angles, IEEE Trans. Geosci. Remote Sens., vol. 49, no. 2.
Nicolls, M. J., R. H. Varney, S. L. Vadas, P. A. Stamus, C. J. Heinselman, R. B. Cosgrove, and M. C. Kelley (2010), Influence of an inertia-gravity wave on mesospheric dynamics: A case study with the Poker Flat Incoherent Scatter Radar, J. Geophys. Res., 115, D00N02, doi:10.1029/2010JD014042.

Photographs of PFISR coutresy of Craig Heinselman.