Recovering ionospheric velocities from SuperDARN returns contaminated by ground/sea scatter

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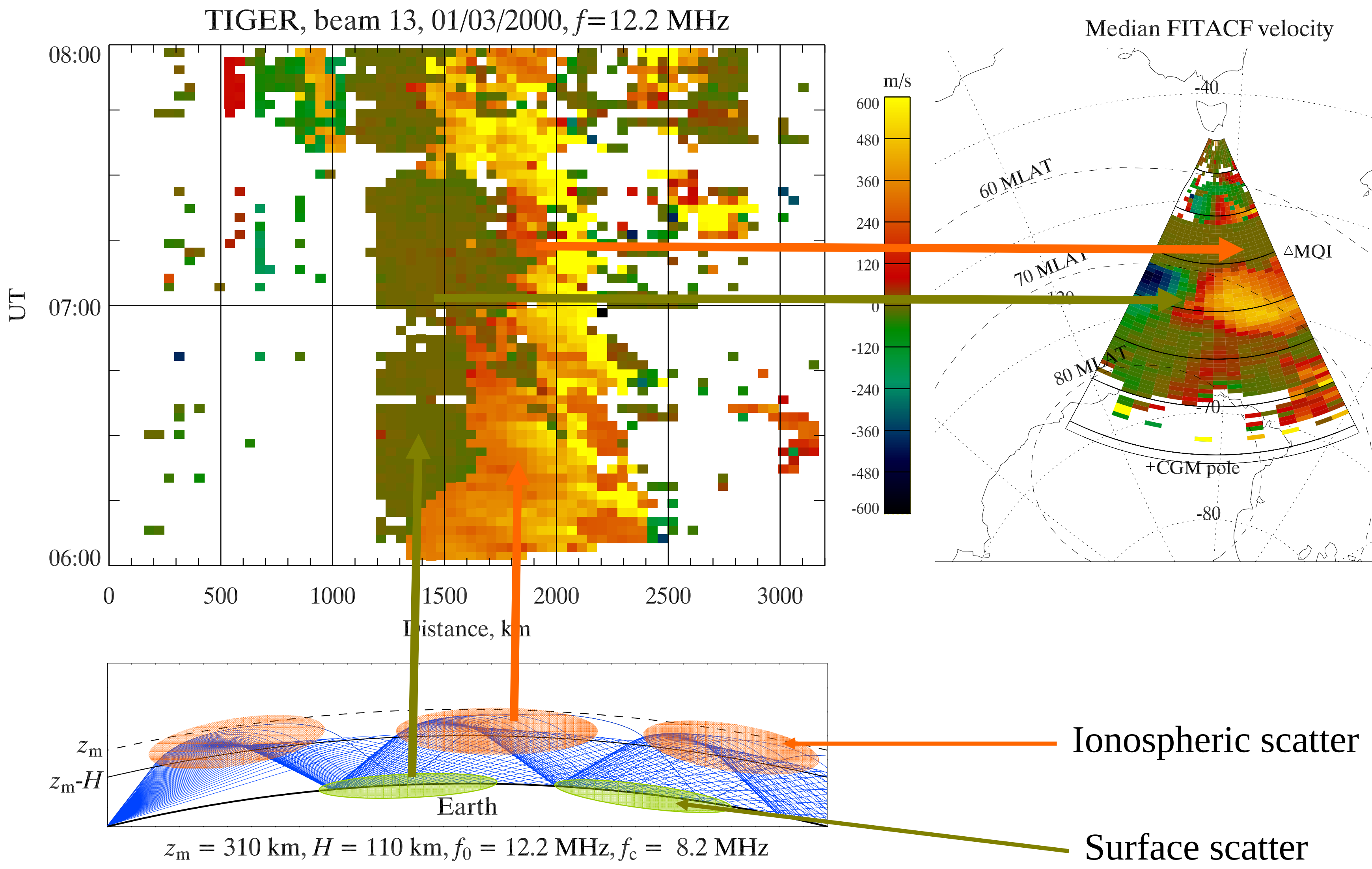
Abstract

SuperDARN velocity data are frequently contaminated by a strong scatter from the sea/ground surface in the vicinity of the skip zone. In this work we studied mixed scatter effects by analysing computer-generated autocorrelation functions with variable signal-to-interference ratios and velocity magnitudes. Obtained information allowed us to develop recognition criteria for contaminated returns and to design an effective algorithm for recovering the ionospheric drift velocities. Application of the new technique to real radar data showed that contamination from the surface scatter leads to overall underestimation of the drift velocity magnitude and can considerably distort medium-scale features of the fitted convection maps.

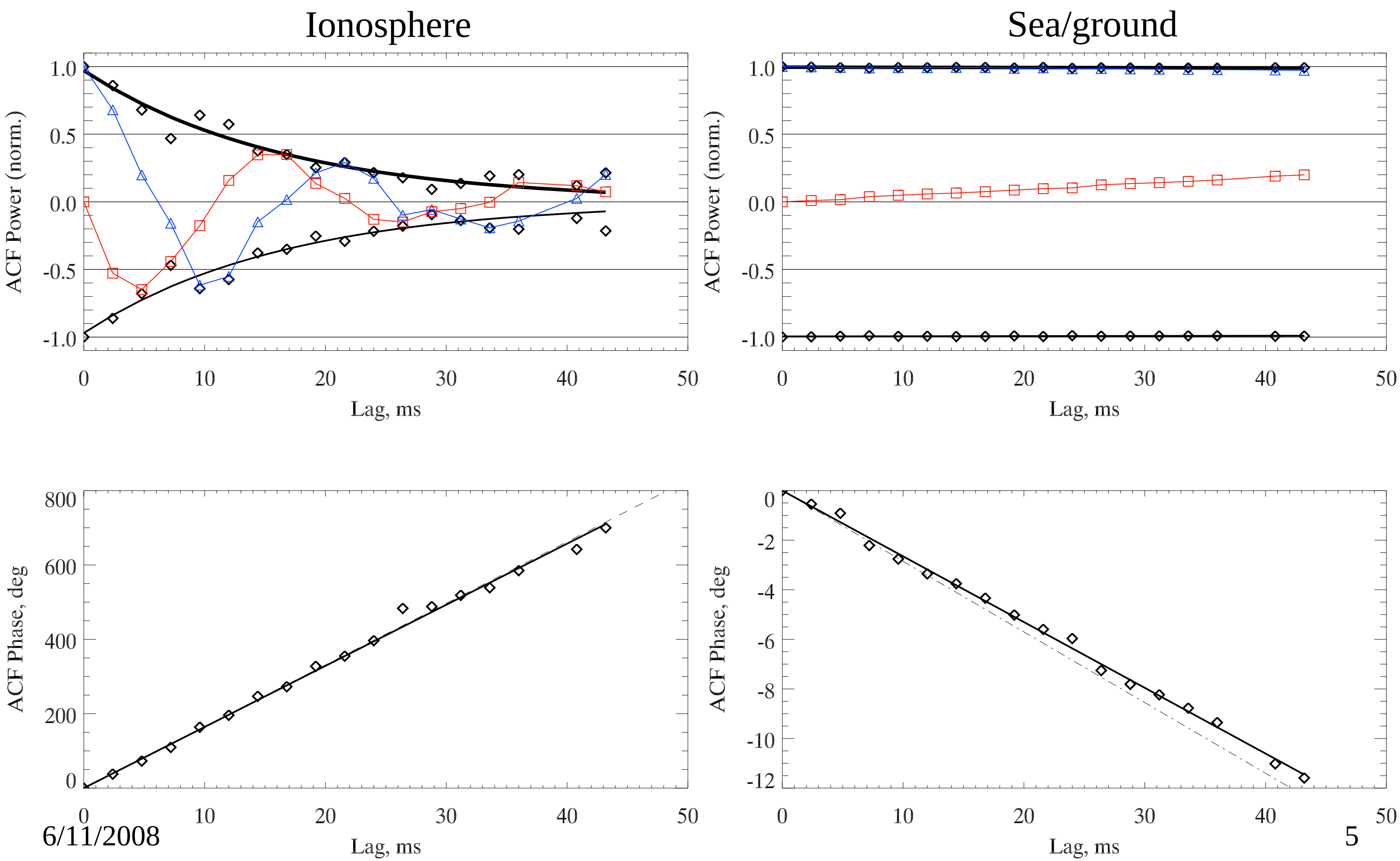
Outline

- Problem formulation
- Mode separation algorithm
  - Basic ideas
  - Mixed scatter criteria
  - Testing against simulated data
  - Application to real data
- Summary and future work

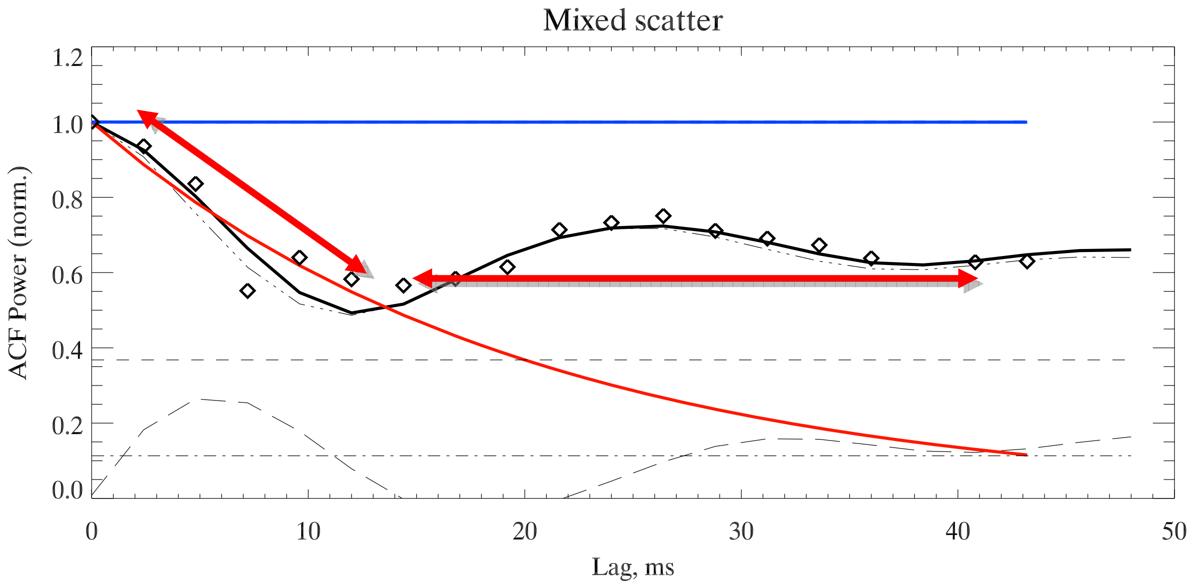
Propagation modes

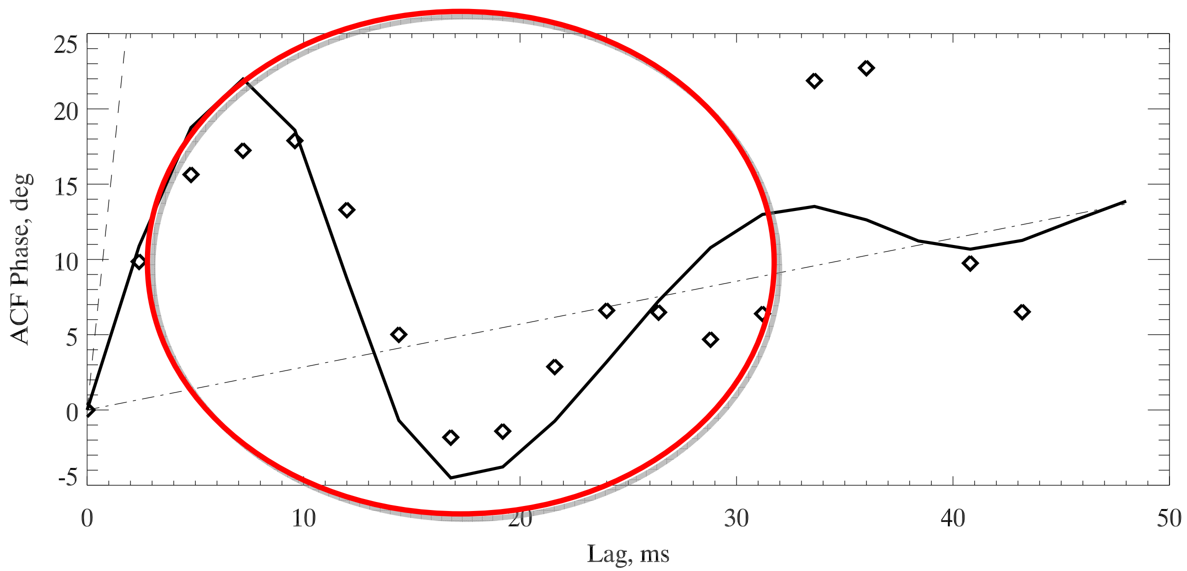


Mixed scatter

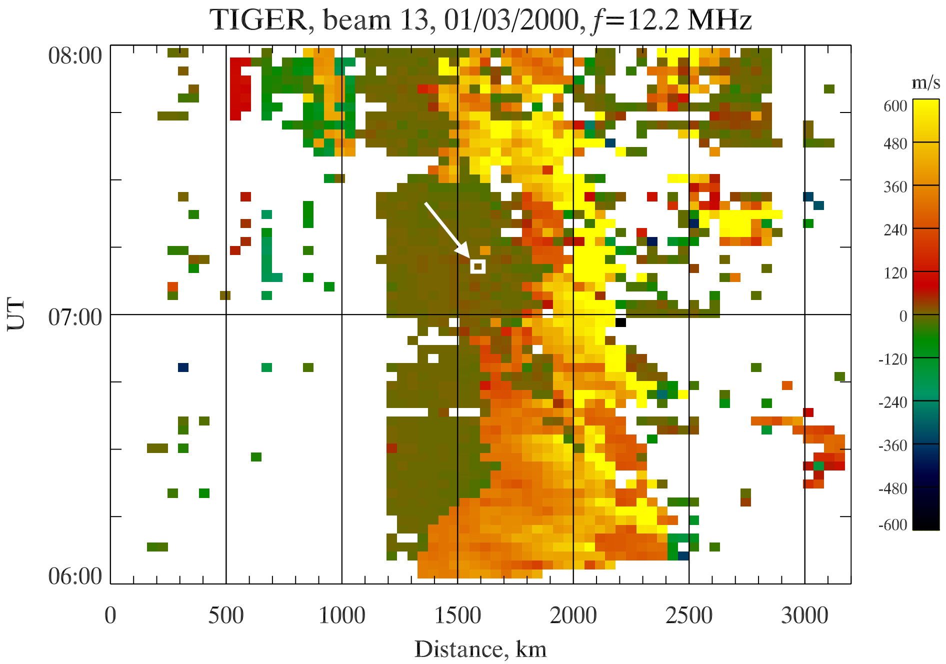


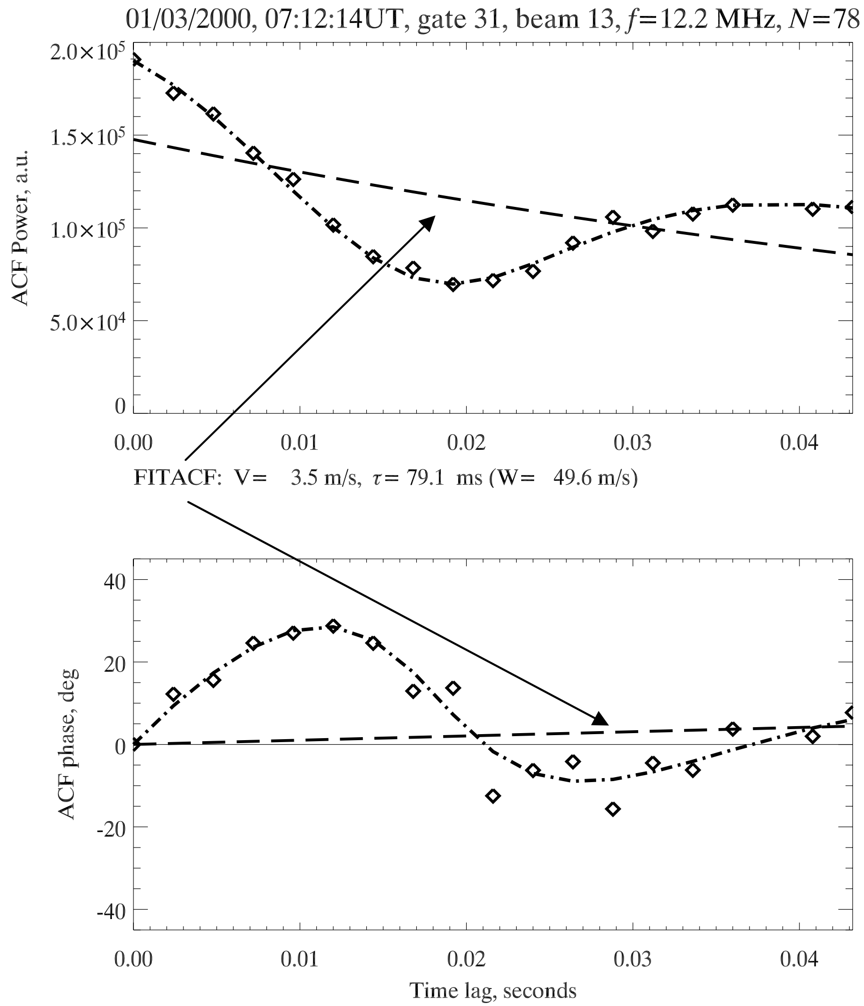
Mixed scatter





Real data


TIGER, beam 13, 01/03/2000, f=12.2 MHz
UT
08:00
07:00
06:00
0 500 1000 1500 2000 2500 3000
Distance, km
m/s
600 480 360 240 120 0 -120 -240 -360 -480 -600

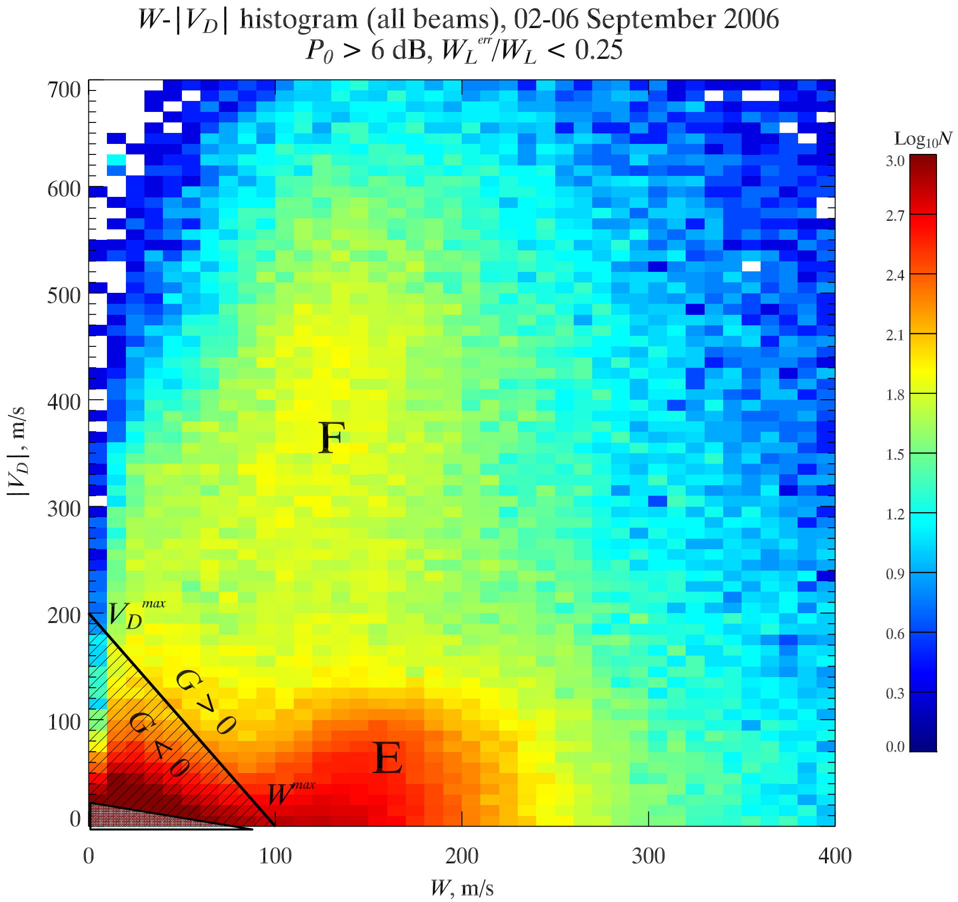

01/03/2000, 07:12:14UT, gate 31, beam 13, f=12.2 MHz, N=78
ACF Power, a.u.
2.0×10^5
1.5×10^5
1.0×10^5
5.0×10^4
0
0.00 0.01 0.02 0.03 0.04
FITACF: V= 3.5 m/s, τ= 79.1 ms (W= 49.6 m/s)
ACF phase, deg
40 20 0 -20 -40
0.00 0.01 0.02 0.03 0.04
Time lag, seconds

It is relatively easy to remove "pure" sea/ground scatter.

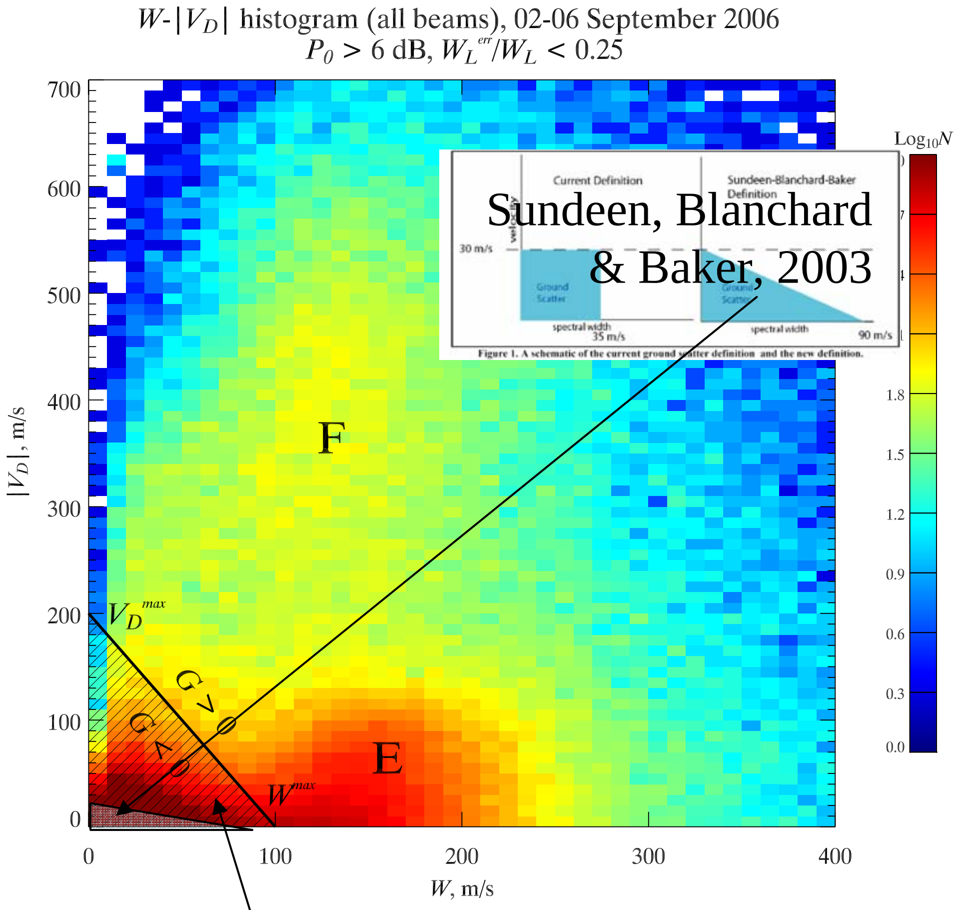
However, mixed scatter is still there!

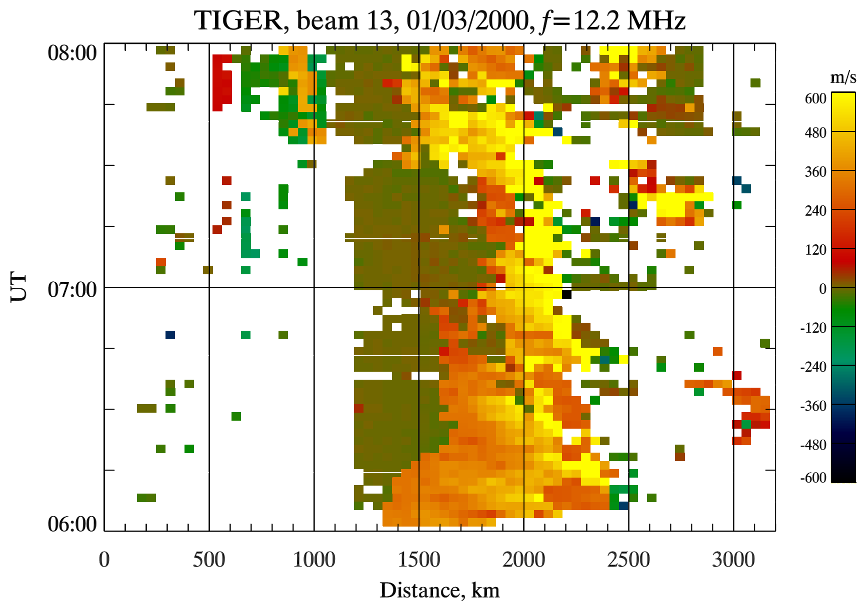
It leads to incorrect estimates of line-of-sight velocity !!!

Empirical mixed scatter criteria



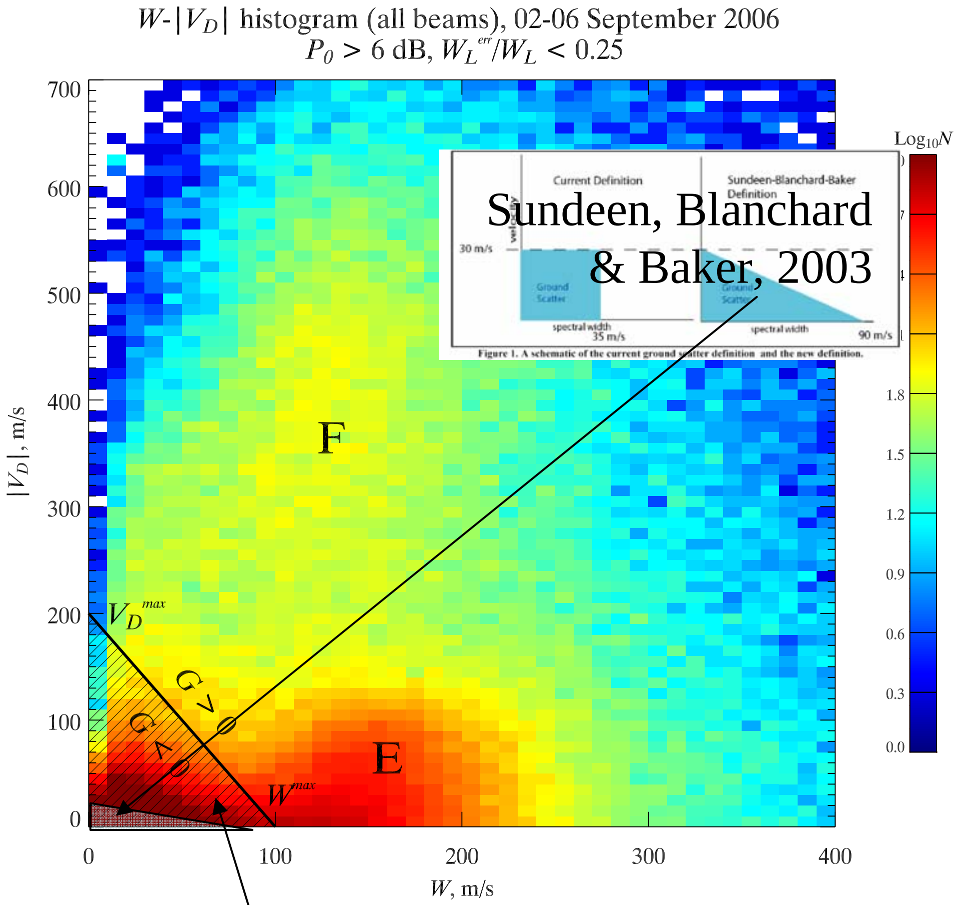
Empirical mixed scatter criteria



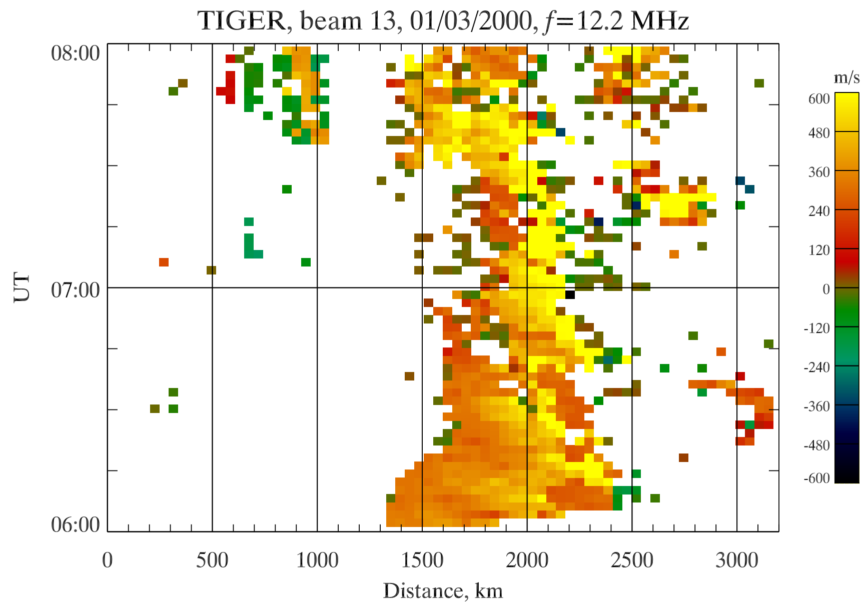


Ponomarenko, Waters & Menk, *AG*, 2007

Empirical mixed scatter criteria



Ponomarenko, Waters & Menk, *AG*, 2007



This does not really help – we just reject some otherwise valid data! There must be some way to actually extract useful information from the contaminated echoes…

Barthes et al, RSc 1998

4.1. Summary of the MUSIC Method

Let us now write the ACF as a sum of M damped sine waves.

$$C_n = C(n\tau_0) = \sum_{i=1}^{M} A_i z_i^{n\tau_0} \qquad (10)$$

with

$$z_i = e^{-\alpha_i + j\omega_i} \qquad (11)$$

Let $\mathbf{Y}_n$ be the vector built with p consecutive observations organized in reverse order :

$$\mathbf{Y}_n = [C_n, C_{n-1}, \cdots, C_{n-p+1}]^T \qquad (12)$$

The $p{\times}p$ autocorrelation matrix $\mathbf{R}_p$ is defined as the expectation of $\mathbf{Y}_n\mathbf{Y}_n^+$, where the plus sign denotes the transpose of the complex conjugate. In the presence of damping, the matrix cannot be calculated by the usual method using both direct and reverse order in the C_n series that constitute the $\mathbf{Y}_n$ vector. The matrix is simply calculated as

$$\mathbf{R}_p = E\{\mathbf{Y}_n\mathbf{Y}_n^+\} = \frac{1}{N-p+1}\sum_{n=p-1}^{N-1}\mathbf{Y}_n\mathbf{Y}_n^+ \qquad (13)$$

where $E\{\ \}$ is the mathematical expectation operator and N is the length of the data record (the number of points in the ACF). It can be shown that if C_n is given by (10) and if $\mathbf{R}_p$ is estimated with the above equation (13), the rank of $\mathbf{R}_p$ is equal to M, which means that only M eigenvalues λ_i, $i \in [1,p]$, are nonzero values. The M eigenvectors $\mathbf{V}_i$ associated with these eigenvalues span the signal subspace. The signal has only projection in this subspace:

$$\mathbf{R}_p = \sum_{i=1}^{M} \lambda_i \mathbf{V}_i \mathbf{V}_i^+ \qquad (14)$$

The other eigenvectors ($\mathbf{V}_{M+1}..\mathbf{V}_p$) define the noise subspace (only the noise has projection in this subspace). Owing to the properties of the autocorrelation matrix, these two vector subspaces are orthogonal. Let $\mathbf{Z} = [z^0, z^1, ..., z^{p-1}]^T$ be a vector belonging to the signal subspace. The scalar product between this vector and each of the noise vectors is equal to zero. This property is used to derive the polynom of MUSIC:

$$\sum_{i=M+1}^{p}\left|\mathbf{Z}^+\mathbf{V}_i\right|^2 = \mathbf{Z}^+.\sum_{i=M+1}^{p}\mathbf{V}_i\mathbf{V}_i^+.\mathbf{Z} = \mathbf{Z}^+.\mathbf{Q}\mathbf{Z} \qquad (15)$$

The roots of this polynom z_i give through relation (11)

Problems with *Barthes et al* 1998 approach

- Purely empirical mixed scatter criteria
  - Phase error 0.30 rad
  - Power error 0.15R(0)

- Too complex and computationally expensive

Basic ideas

- Two-component ACF consisting of ionospheric (large *W* and *V*) and ground/sea scatter small *W* and *V*)

$$R(\tau) = R^{ion} e^{-\alpha_1 \tau + i\omega_1 \tau} + R^{gr} e^{-\alpha_2 \tau + i\omega_2 \tau}$$

This saves computation resources

- Simultaneous estimate of all parameters via fitting the above complex function to complex ACFs

This allows to avoid dealing with 2π skips and to easier interpret fitting errors.

Selection criterion

It would be reasonable to use some sort of a theoretically justified criterion to distinguish between mixed and single-component scatter echoes. The natural candidate for this is the statistical fluctuation level

$$\sigma_R = R(0)/\sqrt{N_a}$$

which is used in FITACF to determine the “bad lag” power threshold. However, for the mixed scatter the ground/sea component contribute very little to the overall fluctuation level.

N_a is a number of <u>independent</u> time series!

$$\sigma_R^{mix} = \sigma_R^{ion} + \sigma_R^{gr}$$

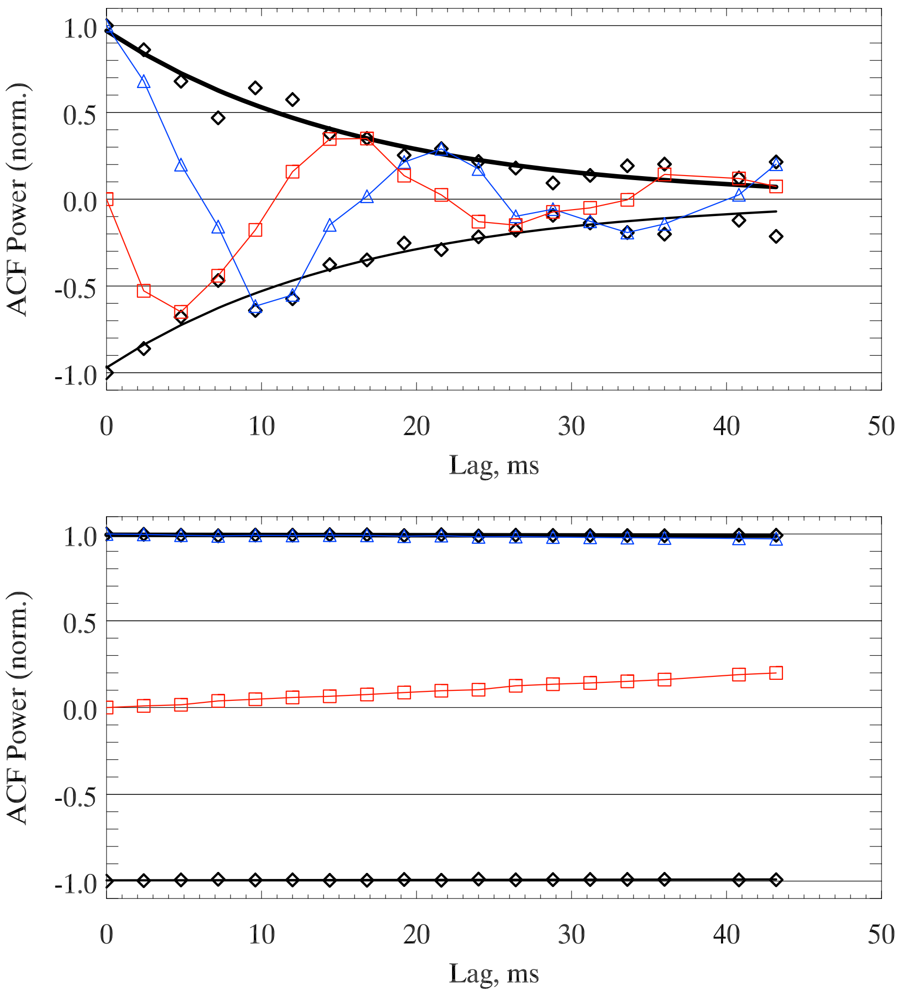
$$\tau^{gr} \sim \Delta t_{\text{int}} \geq 1-10 \text{ s}$$

$$\tau^{ion} \leq \tau_{\max} << \Delta t_{\text{int}}$$

$$\sigma_R^{ion} >> \sigma_R^{gr}$$

$$\sigma_R^{mix} \approx \sigma_R^{ion} \leq R^{mix}(0)/\sqrt{N_a}$$

The overall fluctuation magnitude decreases with increasing contribution from the ground/sea component!



Fitting error?

It makes sense to use fitting error to estimate the fluctuation level. Because we apply fitting to real and imaginary parts of ACF, one would expect that

$$\sigma_R \approx 2\delta_R^{\mathrm{fit}}$$

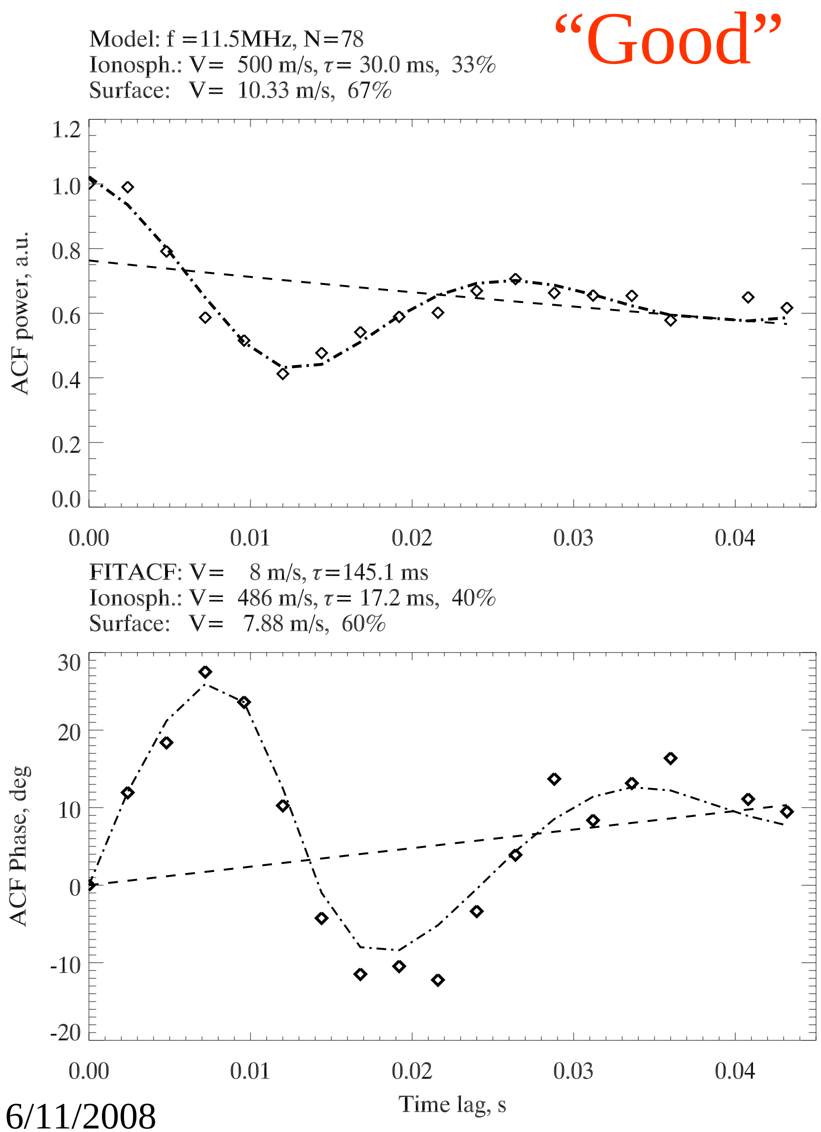
Therefore, ACF should be marked as *mixed* if both ionospheric and ground power exceed the above level

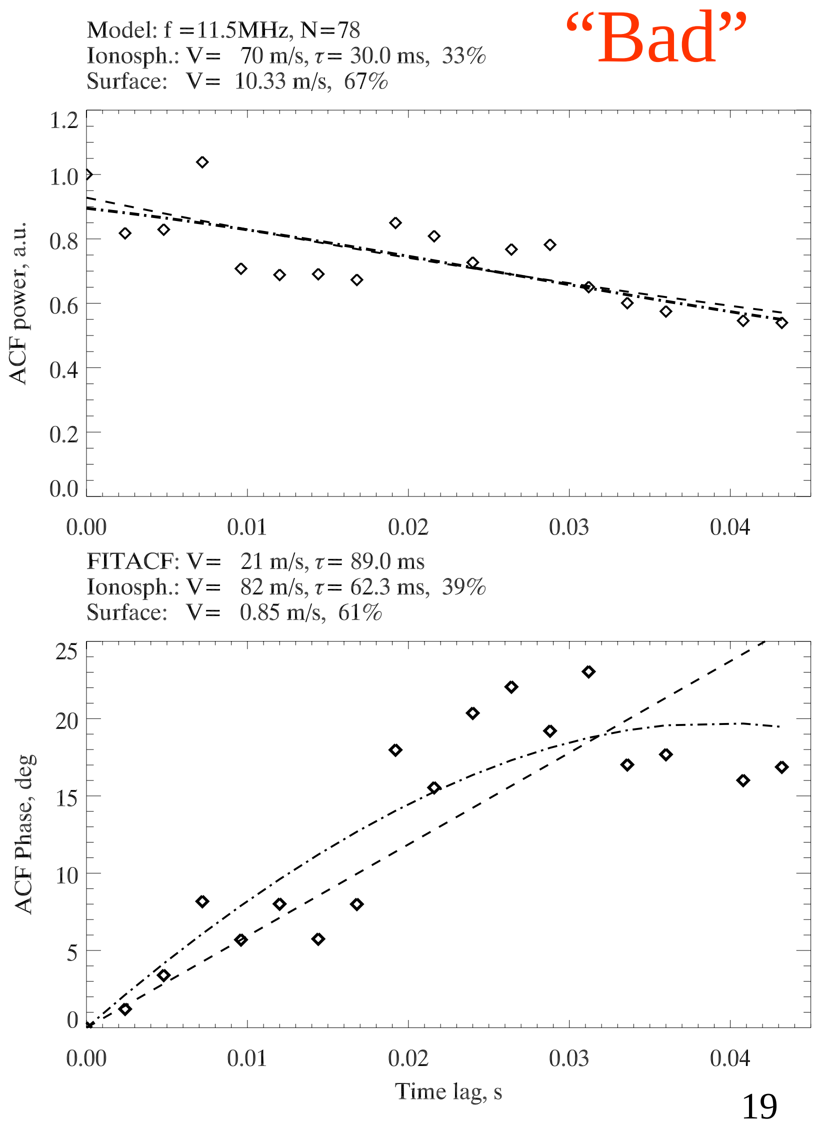
$$R^{\mathrm{ion,gr}}(0) > 2\delta_R^{\mathrm{fit}}$$

Simulated ACFs

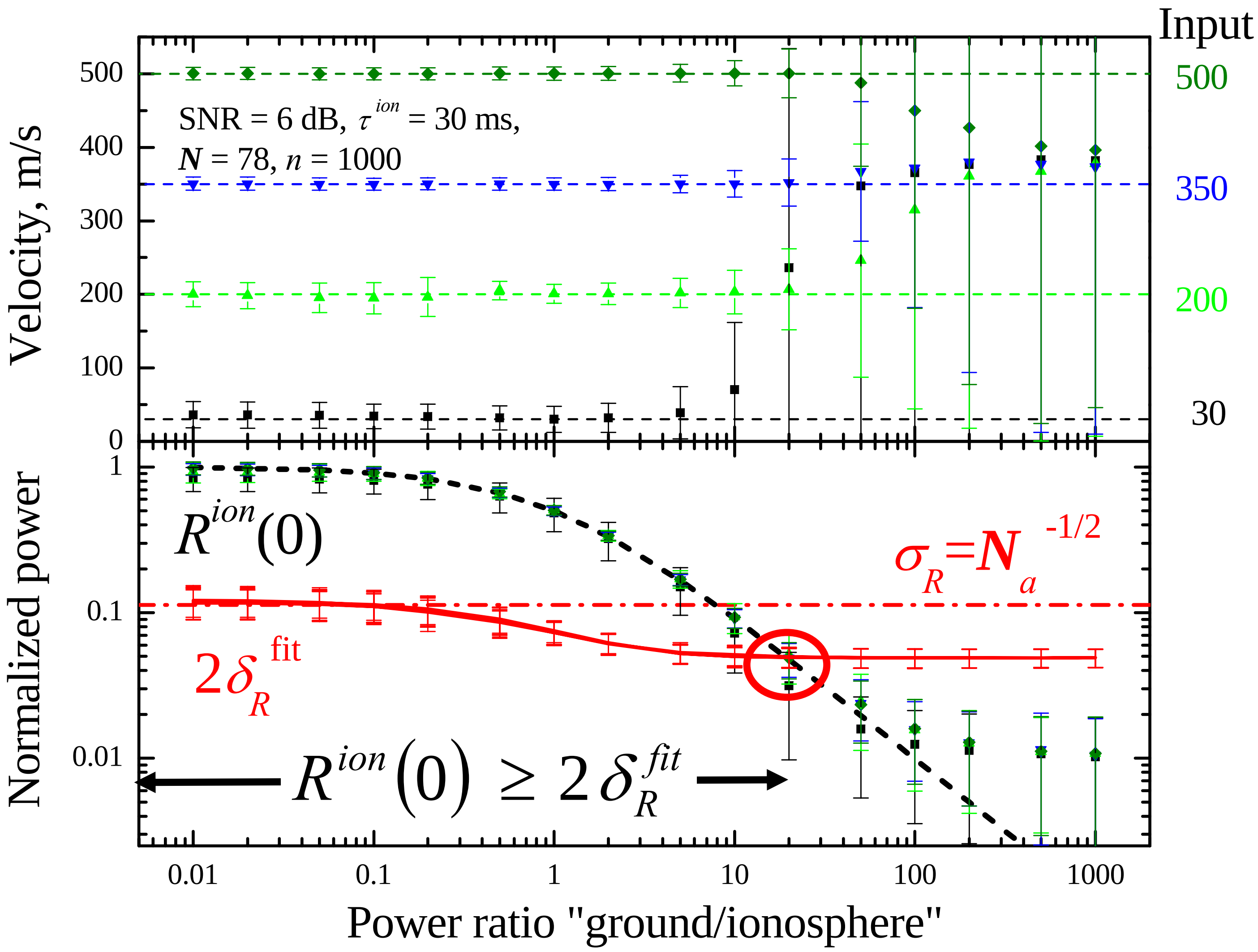
- Signal components
  - Ionospheric scatter with large *W* and *V*
  - Ground scatter with small *W* and *V*
  - White noise
- Variable parameters
  - *V, W* for the ionospheric component
  - ionosphere/ground power ratio
  - signal-to-noise ratio

“Good” and “bad” mixed ACFs

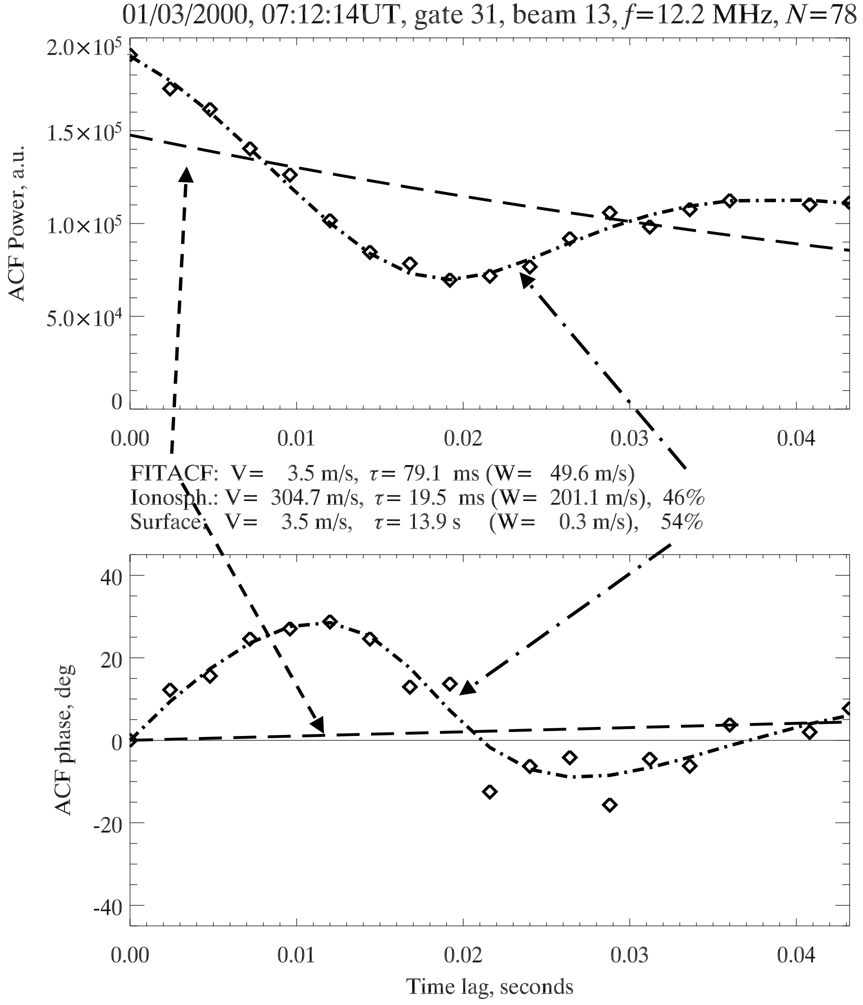


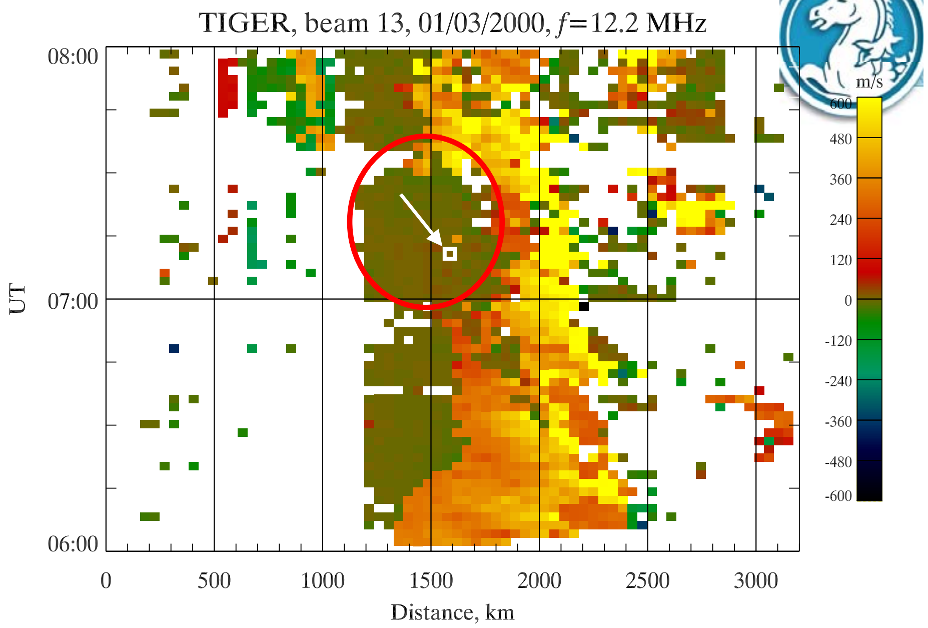


Testing and new mixed scatter criteria

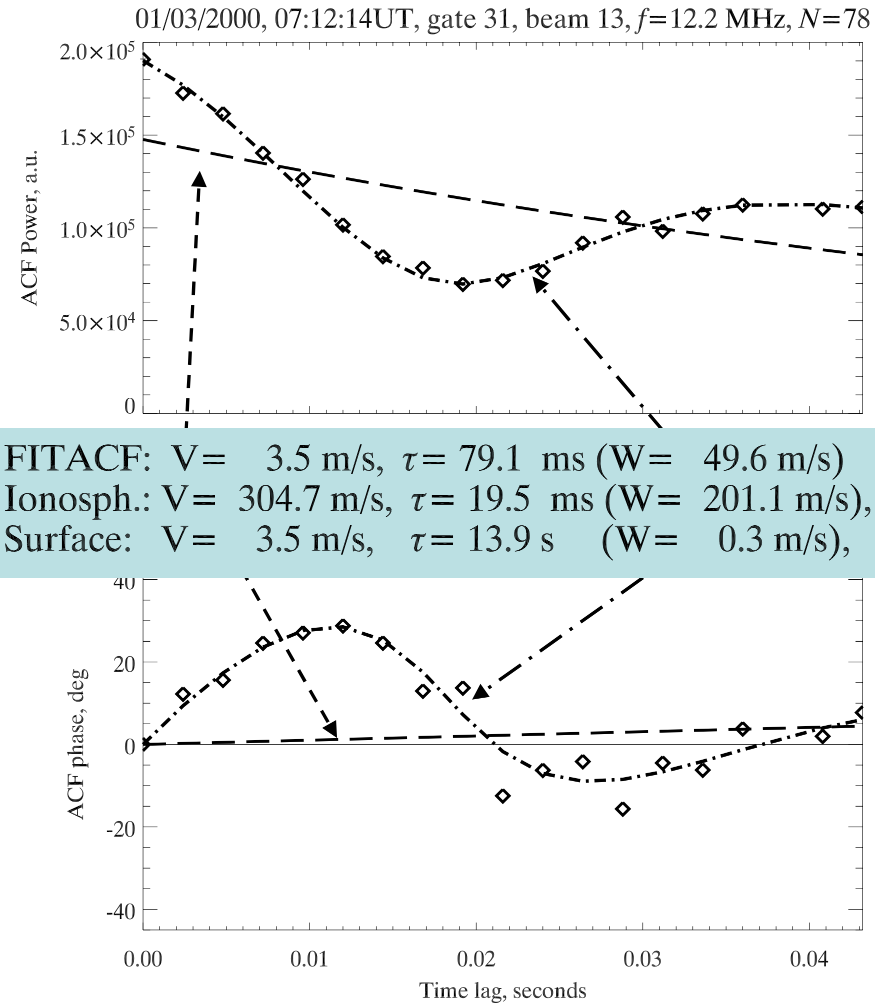


Real data


01/03/2000, 07:12:14UT, gate 31, beam 13, f=12.2 MHz, N=78
ACF Power, a.u.
FITACF: V= 3.5 m/s, τ= 79.1 ms (W= 49.6 m/s)
Ionosph.: V= 304.7 m/s, τ= 19.5 ms (W= 201.1 m/s), 46%
Surface: V= 3.5 m/s, τ= 13.9 s (W= 0.3 m/s), 54%
ACF phase, deg
Time lag, seconds


TIGER, beam 13, 01/03/2000, f=12.2 MHz
UT
Distance, km
m/s

Real data



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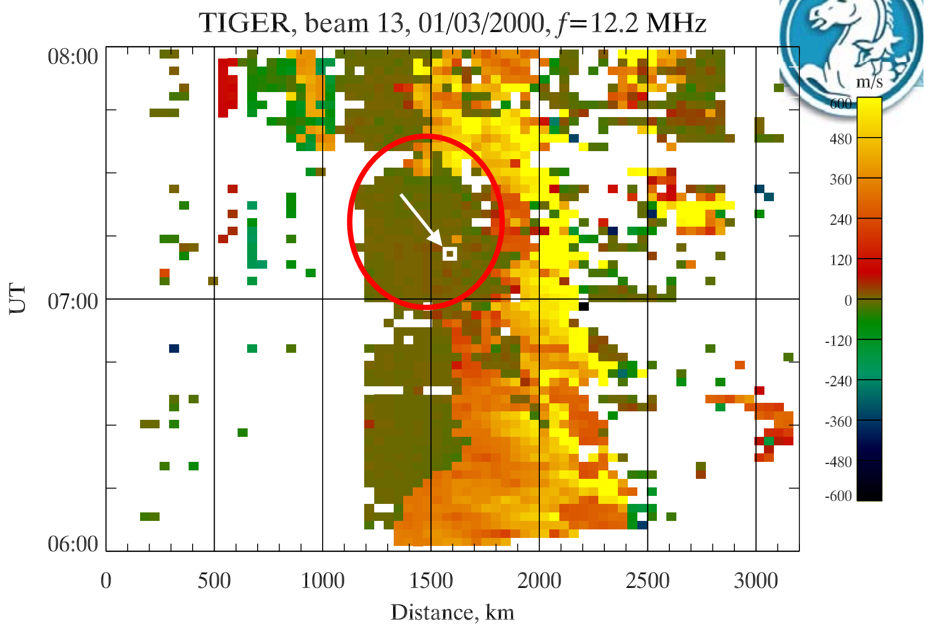
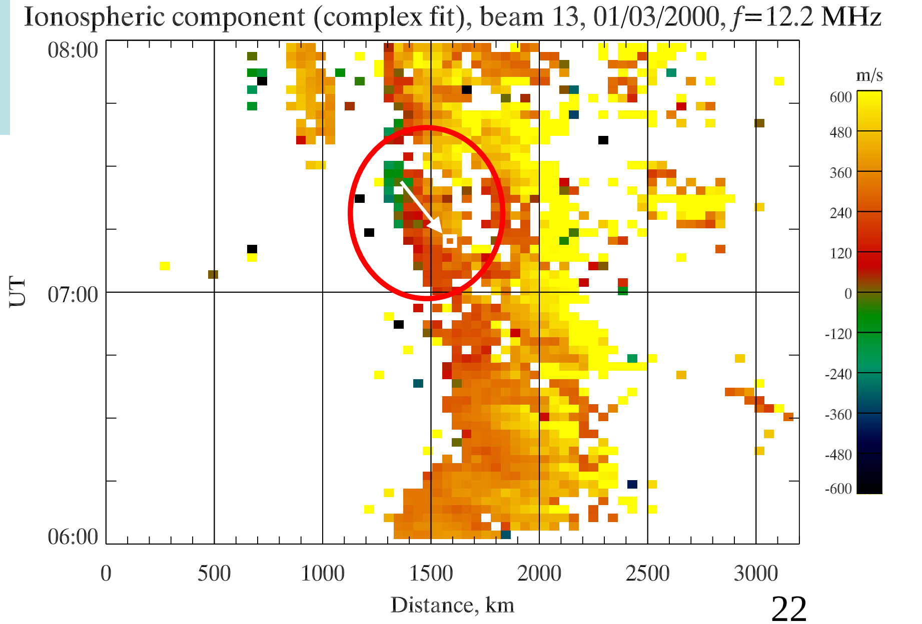
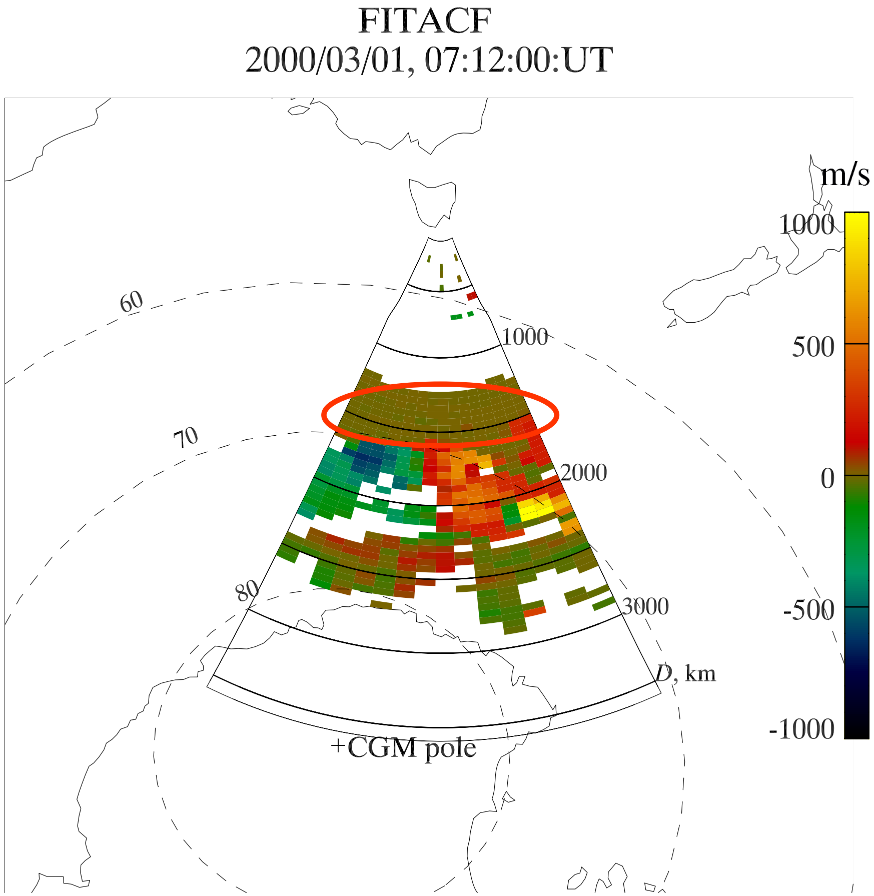
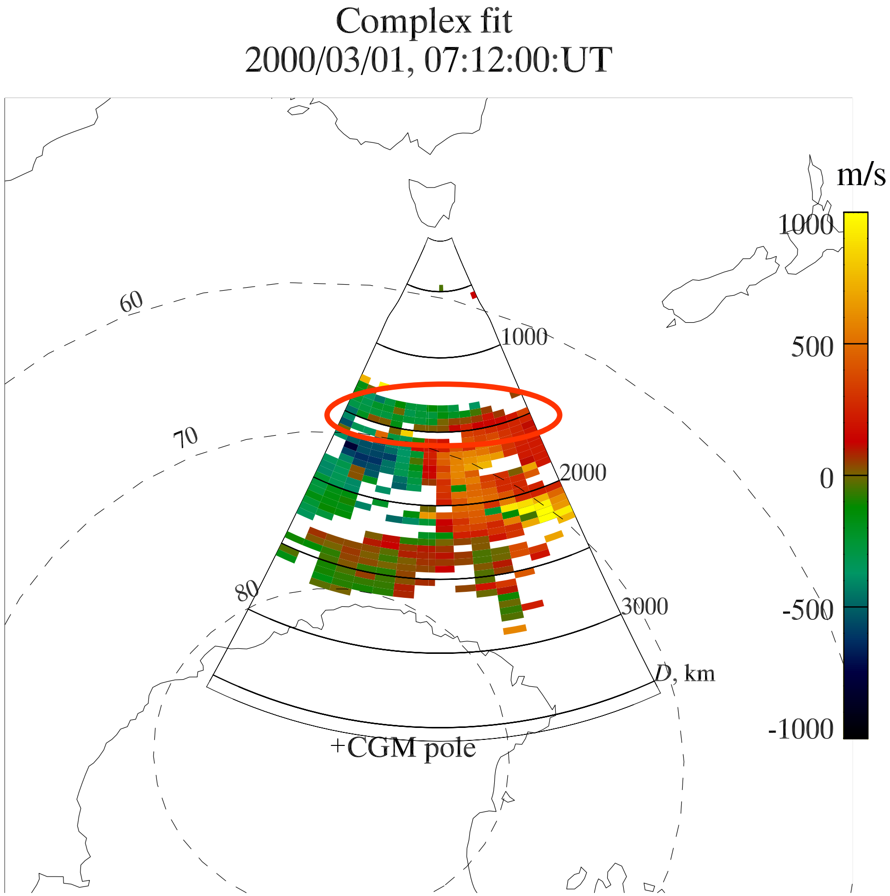




Fan diagrams

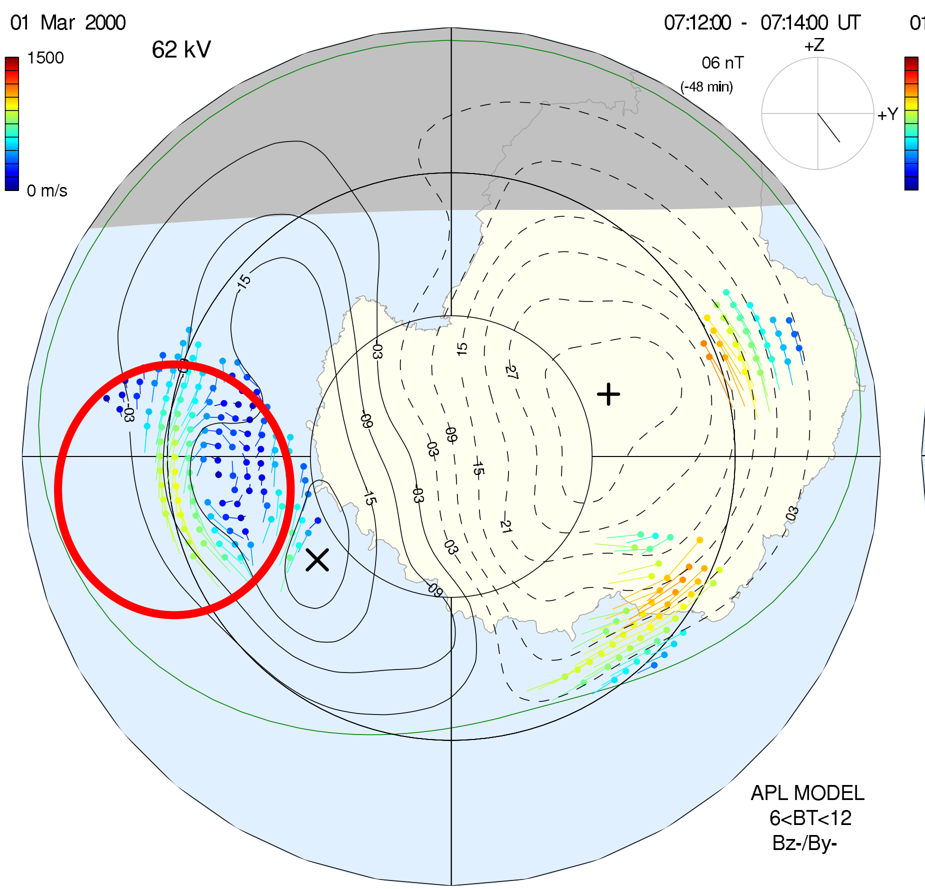


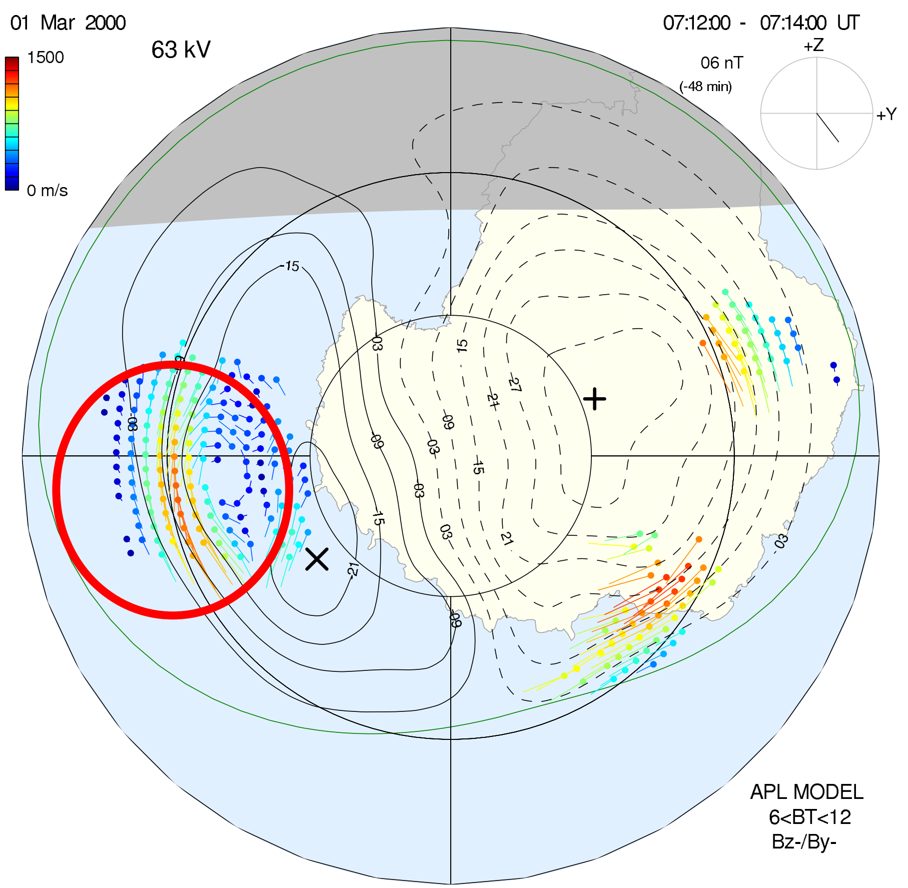


Convection maps

FITACF

Complex fit





Conclusions

- Well… It actually works! We achieved:
  - Expanded spatial coverage
  - Correct estimates of velocity magnitude
  - Physically justified criteria for mixed scatter
  - Nothing prevents us from increasing the number of components, but this will result in less stable soultions

Remaining problems:

  - Spectral width estimates are larger compared with FITACF

Future directions

- The new technique should be complimentary to the single-component model currently used in FITACF. We need to develop criteria allowing to decide when one model is better than the other. This can be done based on fitting errors scaled by respective degrees of freedom for the single- and two-component models.

Acknowledgments

- Mike Ruohoniemi for a stimulating discussion at SDARN’07
- Kile Baker for being a tough but constructive referee