PHYSICS AND ENGINEERING PHYSICS

SuperDARN Pulse Sequences - Optimization and Testing -

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Outline

- ACF introduction and theory.
- FITACF:
  - Theory; known pitfalls; data examples
- [Why] do we need a new pulse sequence?
- The new sequences.
- Data examples.
- Statistics.

Multi-Pulse Theory...

- SuperDARN transmitters send out a series of pulses, which are sampled by the receivers.
- Measure the power and phase of the signal scattered back to the radar from each distance along the beam.
- Determine characteristics of the scattering plasma waves
    - power, velocity, spectral width

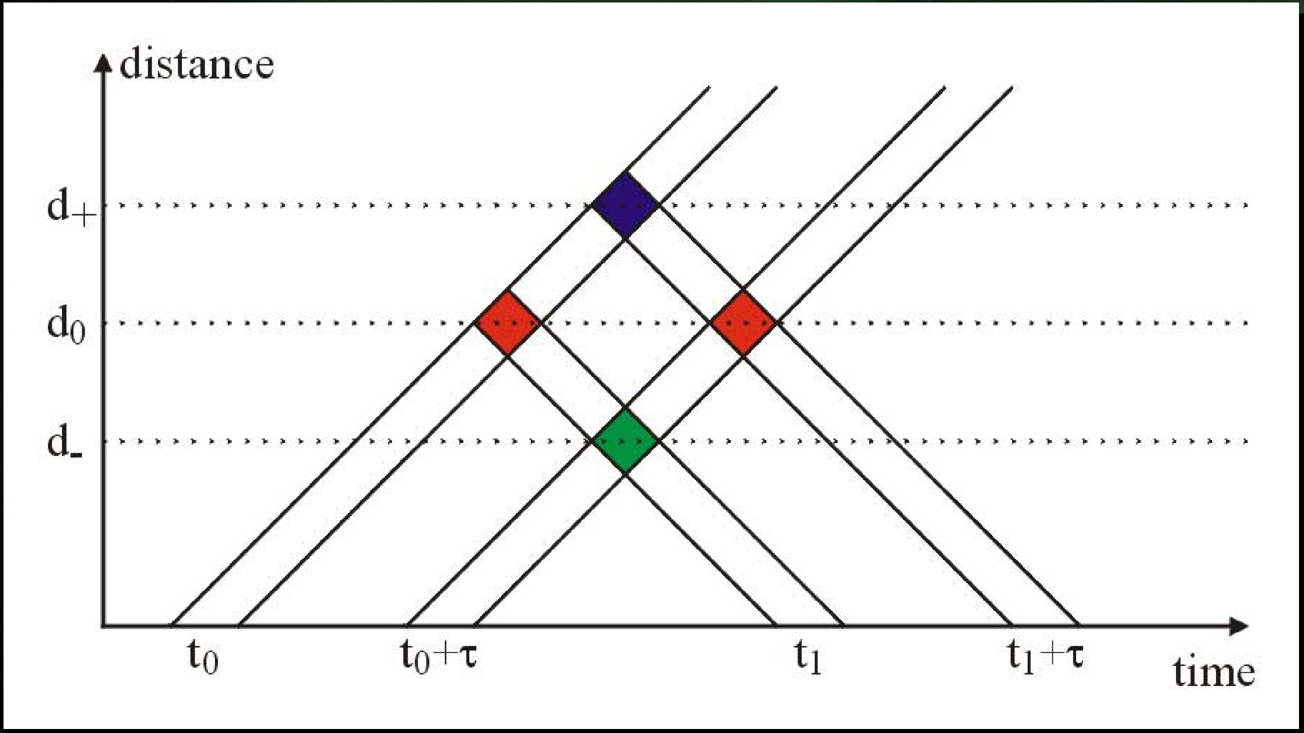
Multi-Pulse Reality...

- It isn't actually that simple. (of course!)

- How do we sort out the returns from different pulses and from different distances?
  - The answer: Complex autocorrelation functions (ACFs).
    - (Indeed!)

2-Pulse Sequence

- We want to know how much the plasma at distance $\mathbf{d_0}$ has moved in time τ.
- We send out 2 pulses, separated by time τ.



2-Pulse Sequence

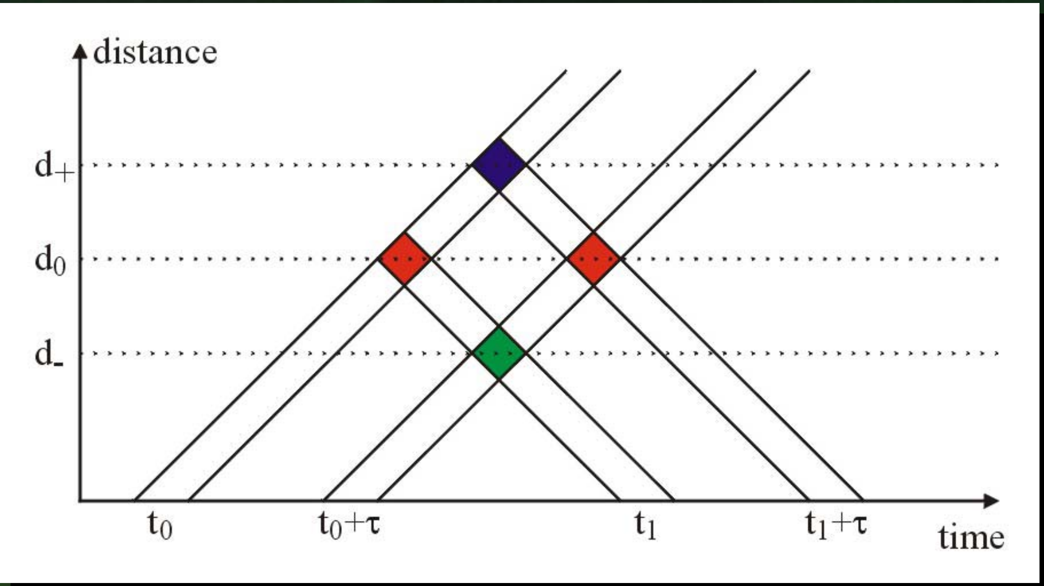
Transmitted pulses:

- p1 at time $\mathbf{t_0}$
- p2 at time $\mathbf{t_0+\tau}$

(Note: $t_1=t_0+2d_0/c$, etc.)

Received pulses:

- p1 from d_0 at time $\mathbf{t_1}$
- p1 from d_+ at time $\mathbf{t_1+\tau}$
- p2 from d_- at time $\mathbf{t_1}$
- p2 from d_0 at time $\mathbf{t_1+\tau}$



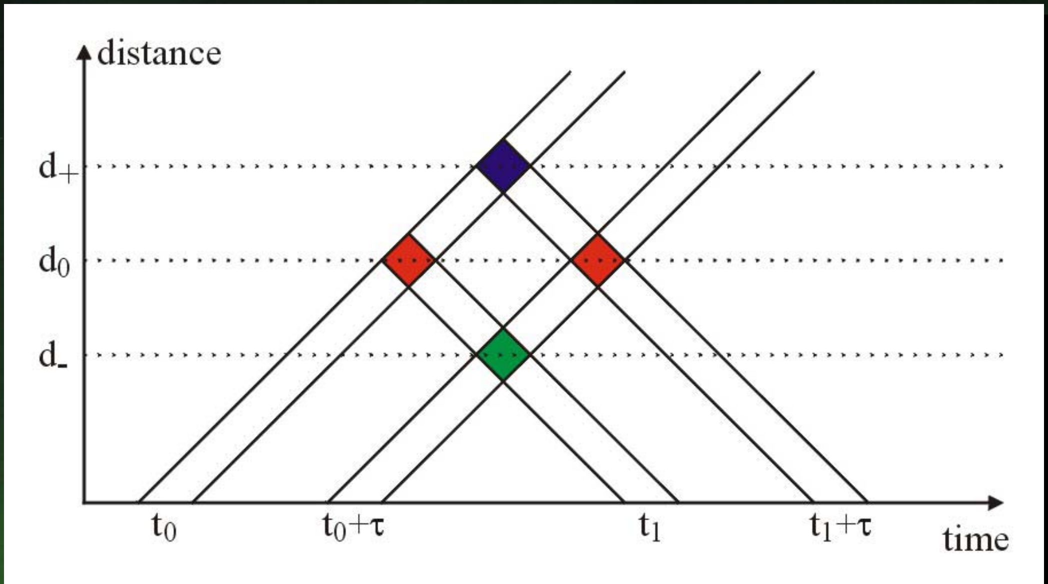
2-Pulse Sequence

Amplitude measured at t_1:

$A(t_1)=A_1(d_0)+A_2(d_-)$

Amplitude measured at $t_1+\tau$:

$A(t_1+\tau)=A_1(d_+)+A_2(d_0)$



ACF at lag τ:

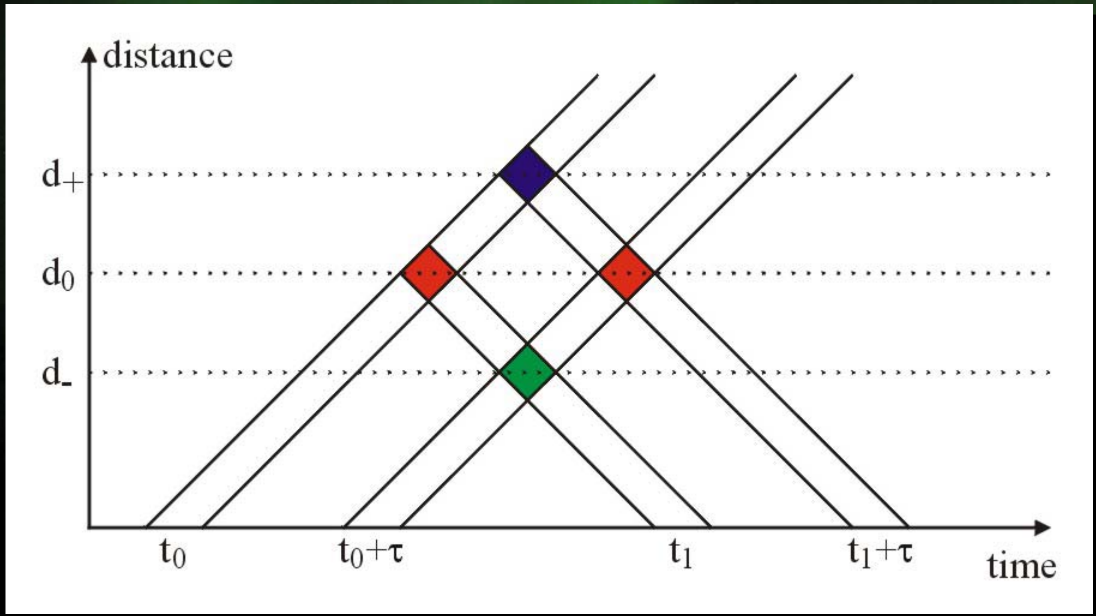
$$A(t_1)\cdot A(t_1+\tau) = (A_1(d_0)+A_2(d_-))\cdot(A_1(d_+)+A_2(d_0))$$

ACF at lag τ

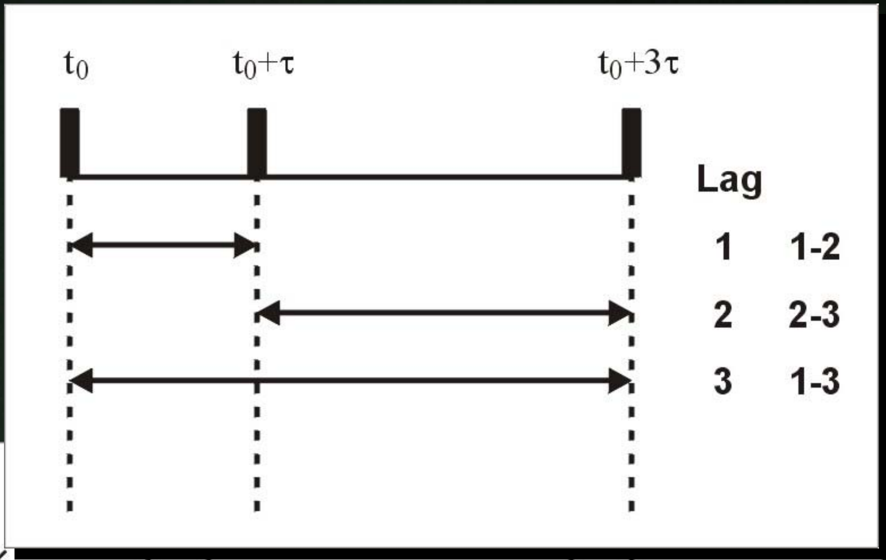
$$\langle A(t_1)\cdot A(t_1+\tau)\rangle = \langle A_1(d_0)\cdot A_2(d_0)\rangle + \langle A_1(d_0)\cdot A_1(d_+)\rangle + \langle A_2(d_-)\cdot A_1(d_+)\rangle + \langle A_2(d_-)\cdot A_2(d_0)\rangle$$

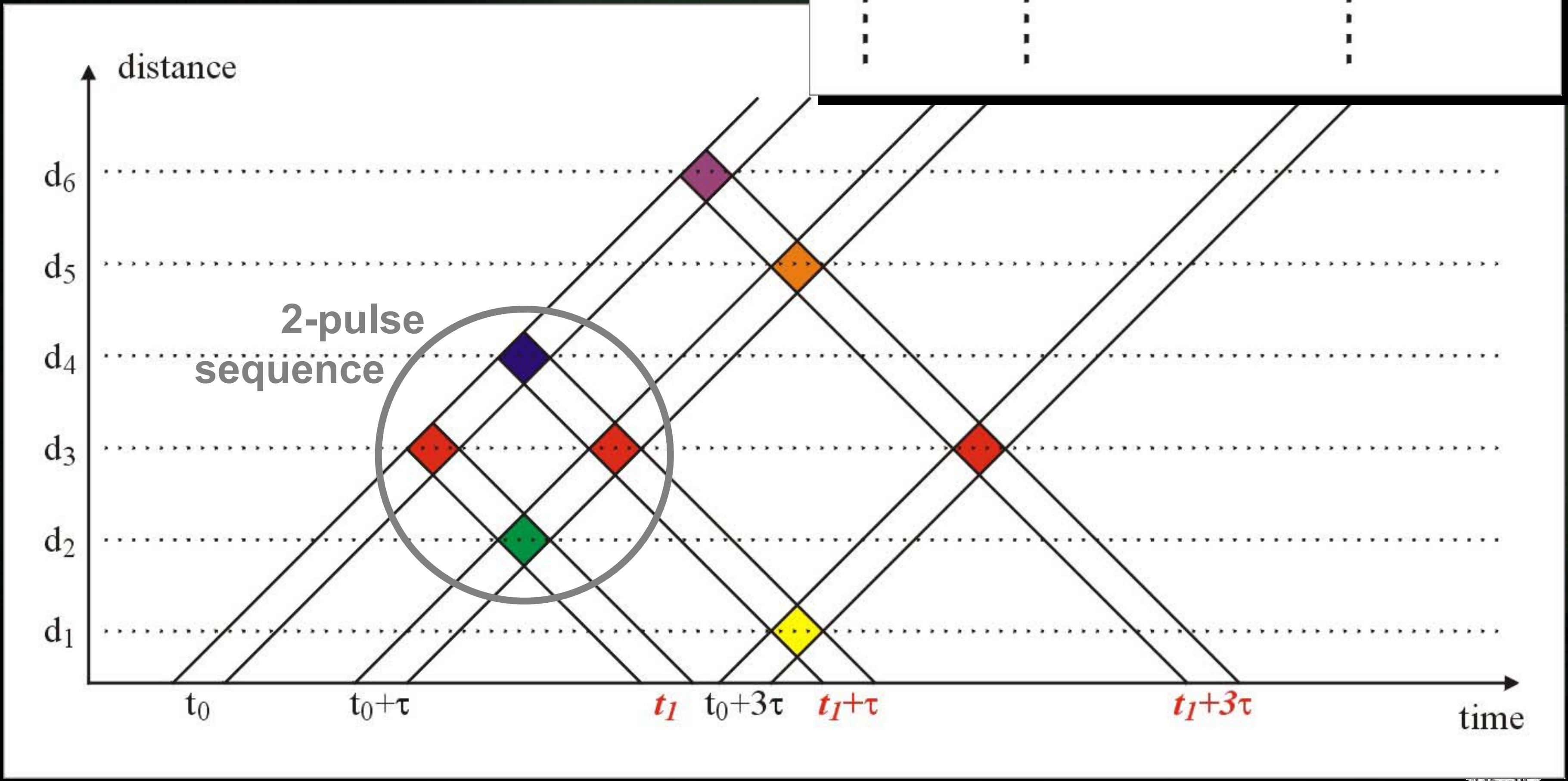
- Average several return signals to minimize uncorrelated signal (phases) from different ranges (⟨ ⟩).
- This works if ionosphere correlated at d_0 over averaging time

$$\langle A(t_1)\cdot A(t_1+\tau)\rangle \sim \langle A_1(d_0)\cdot A_2(d_0)\rangle \sim Ae^{i\omega\tau}$$

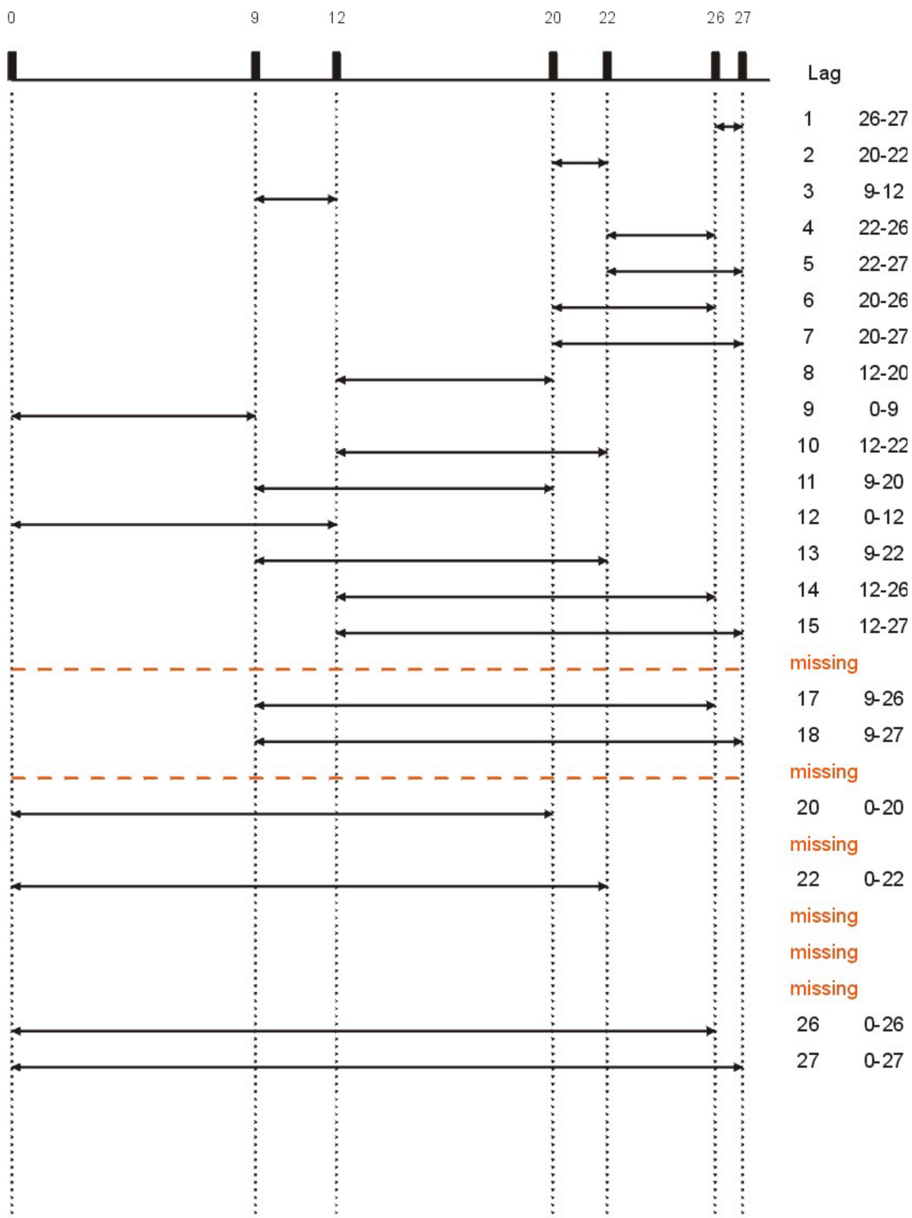


3-Pulse Sequence





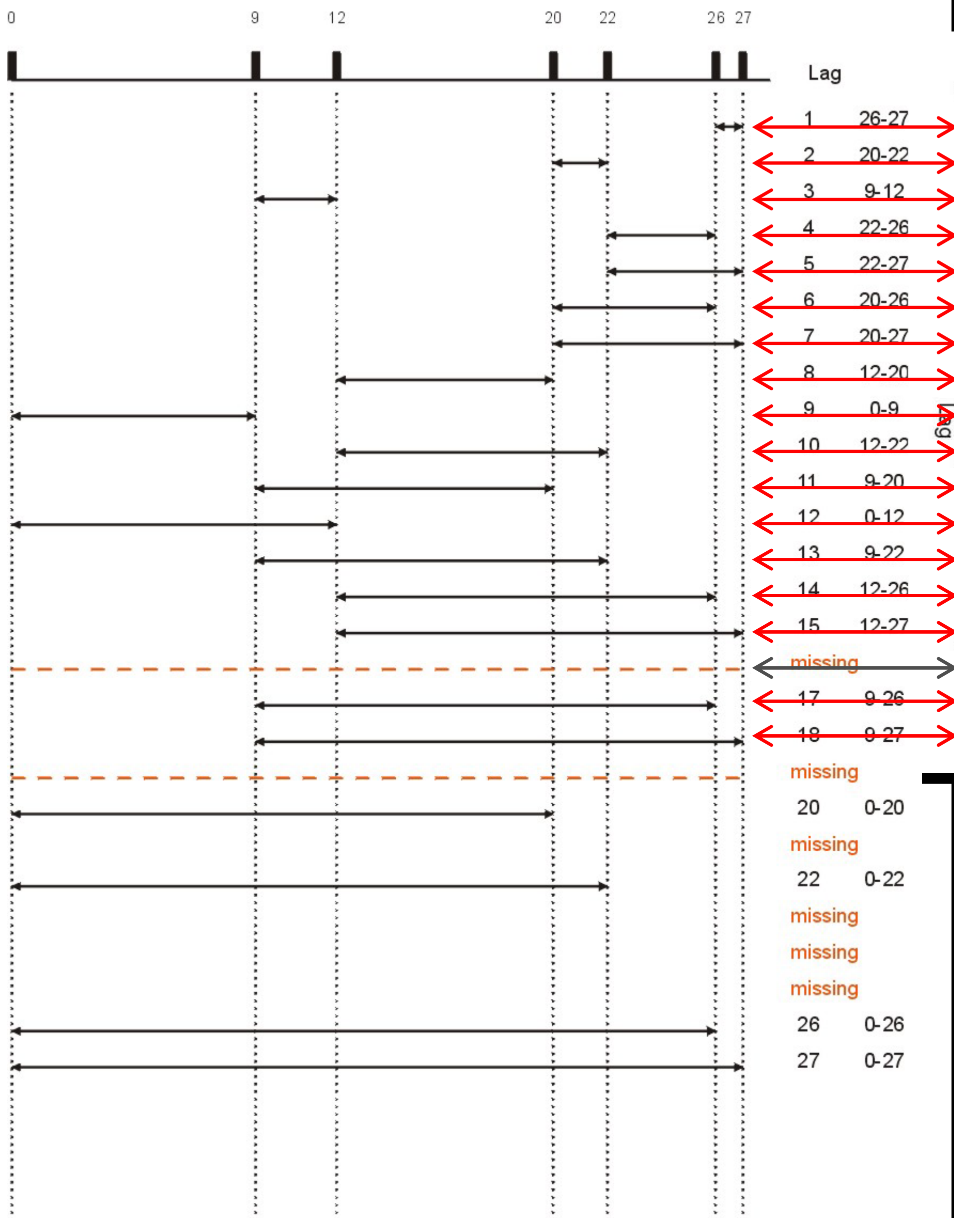
[0, 9, 12, 20, 22, 26, 27]

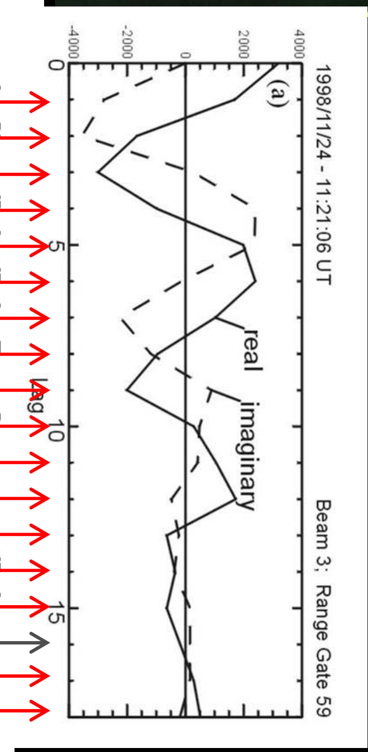


Current SuperDARN Pulse Sequence

- 7 pulses
- 2.4 ms τ
- .3 ms pulse length (45 km range gate)
- no repeated lags
- first missing lags at 16τ and 19τ
- by Schiffler

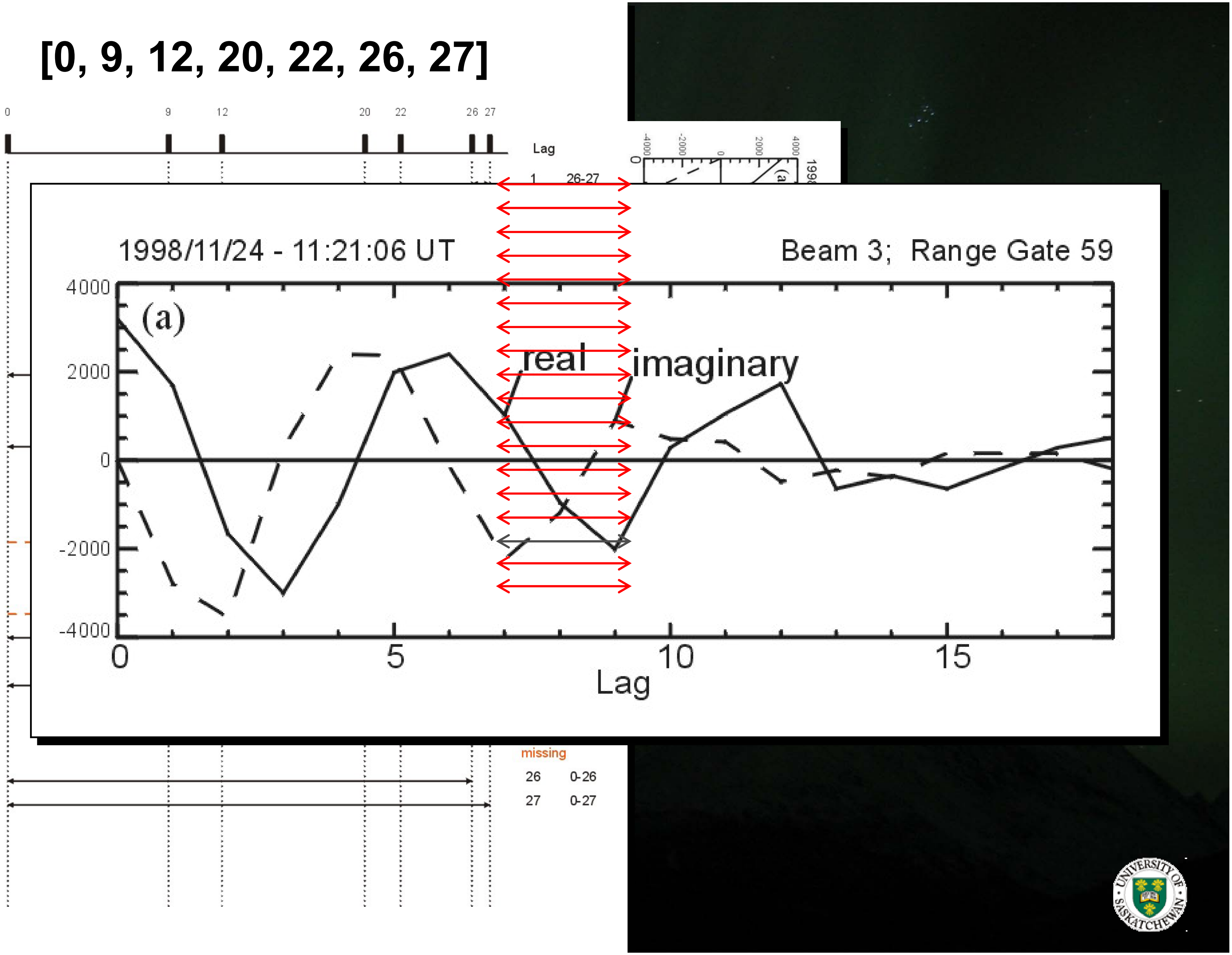
[0, 9, 12, 20, 22, 26, 27]





ow Do We
t From a
g Table
an ACF?

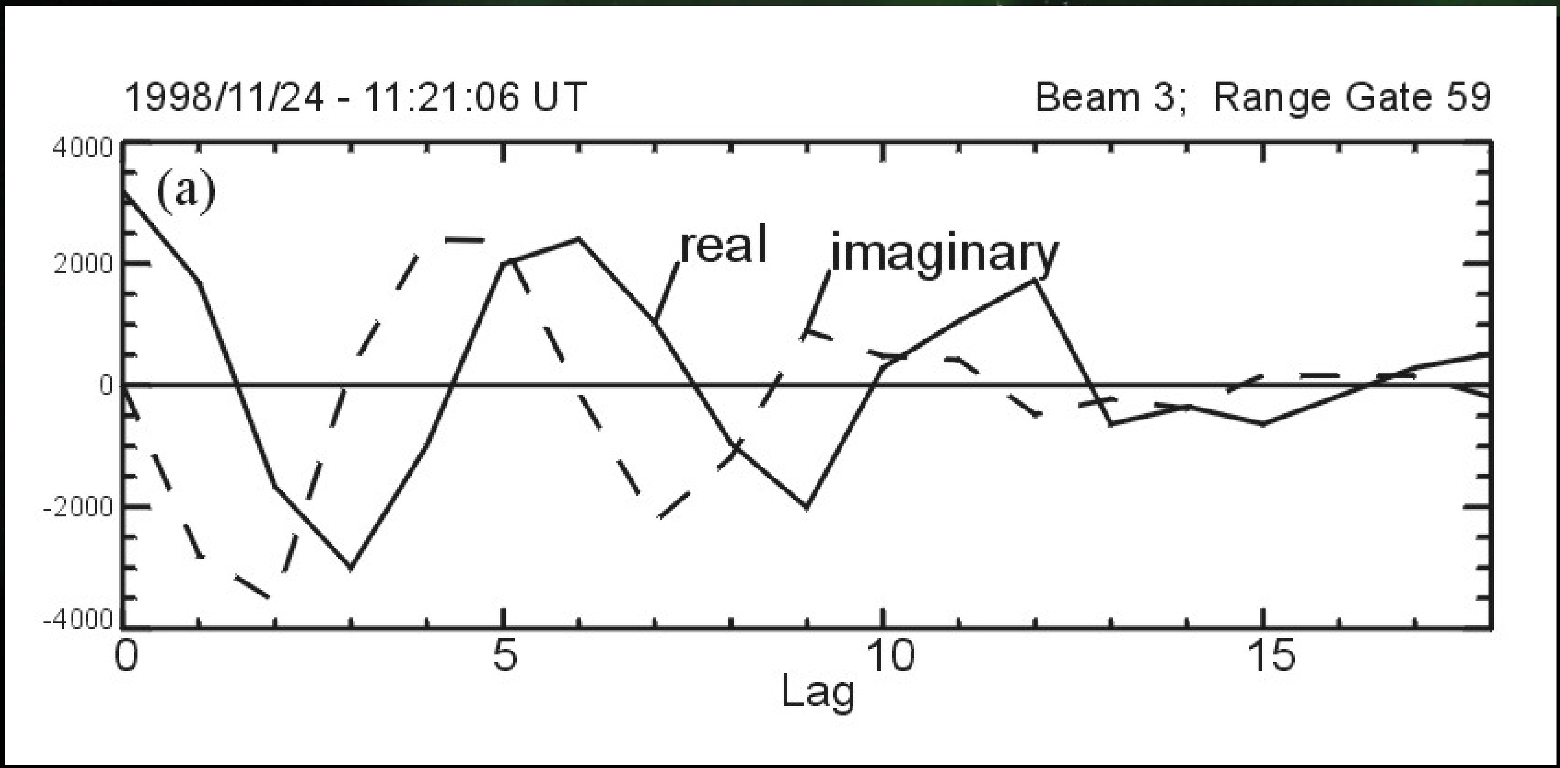
[0, 9, 12, 20, 22, 26, 27]



What the Radars Measure
- What's in a .dat file? -

Real and imaginary contribution for each lag.

(in phase & quadrature voltages)



FITACF

- Fourier transform of ACF gives spectrum (Wiener-Khinchin theorem)

but ...

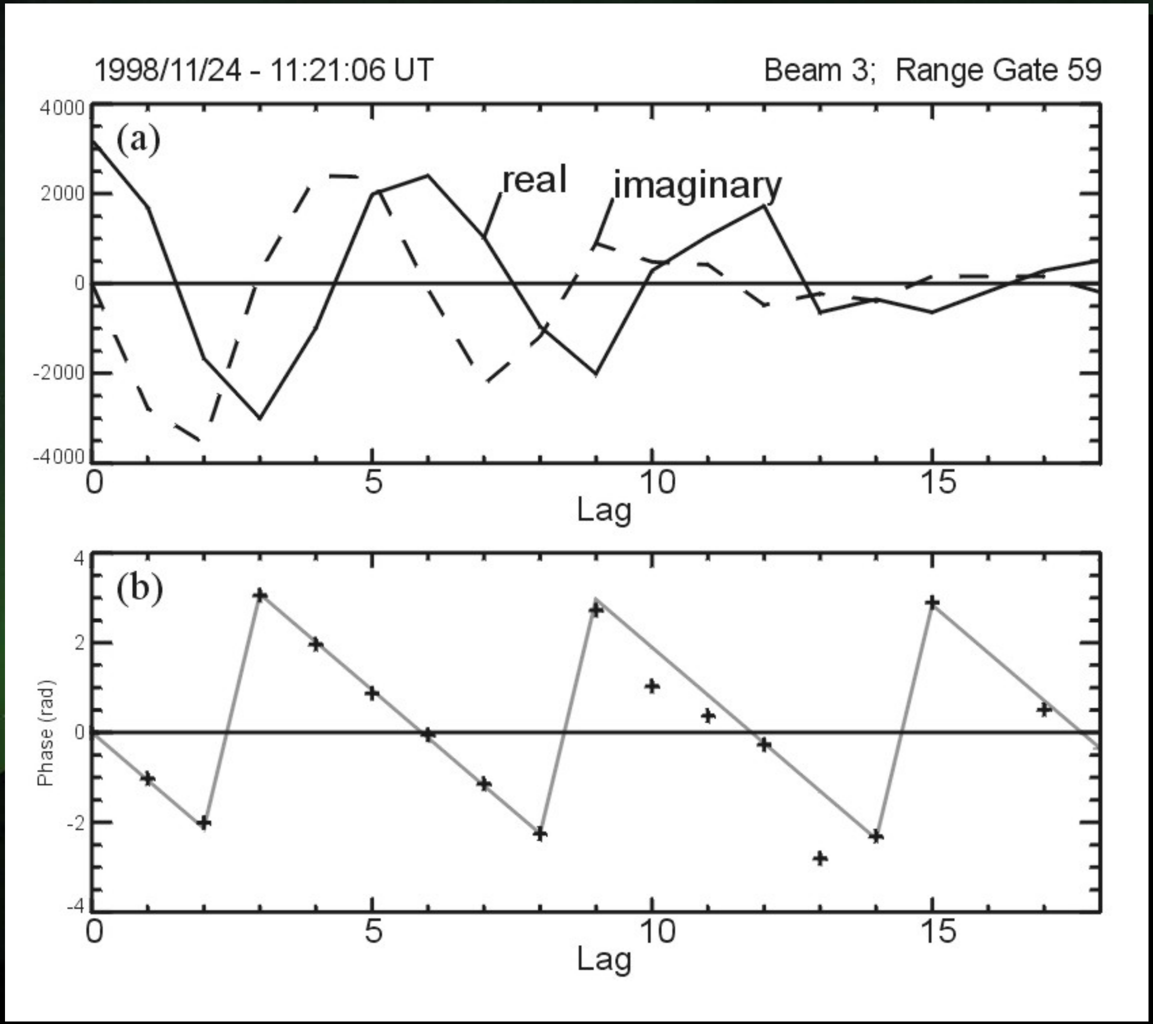
- FITACF estimates spectral parameters without Fourier transforming the ACF:
  - mean doppler velocity
  - spectral width
  - backscattered power

Φ - The Phase of the ACF

- ACF is of the form: $Ae^{i\Phi}$

$$\Phi = \text{atan}(Im/Re)$$

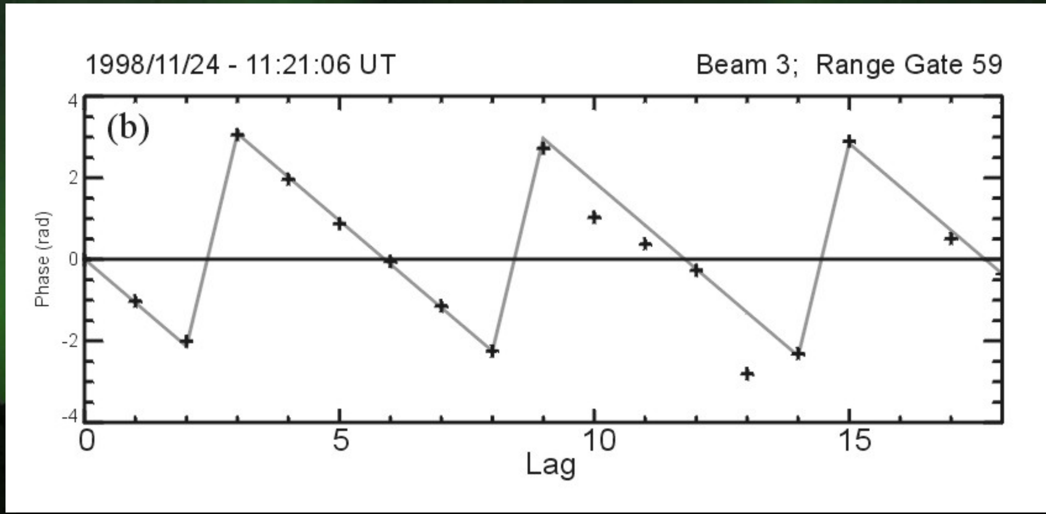
- phase varies linearly with lag between ±π
- note 2π jumps



Getting Velocity from Φ

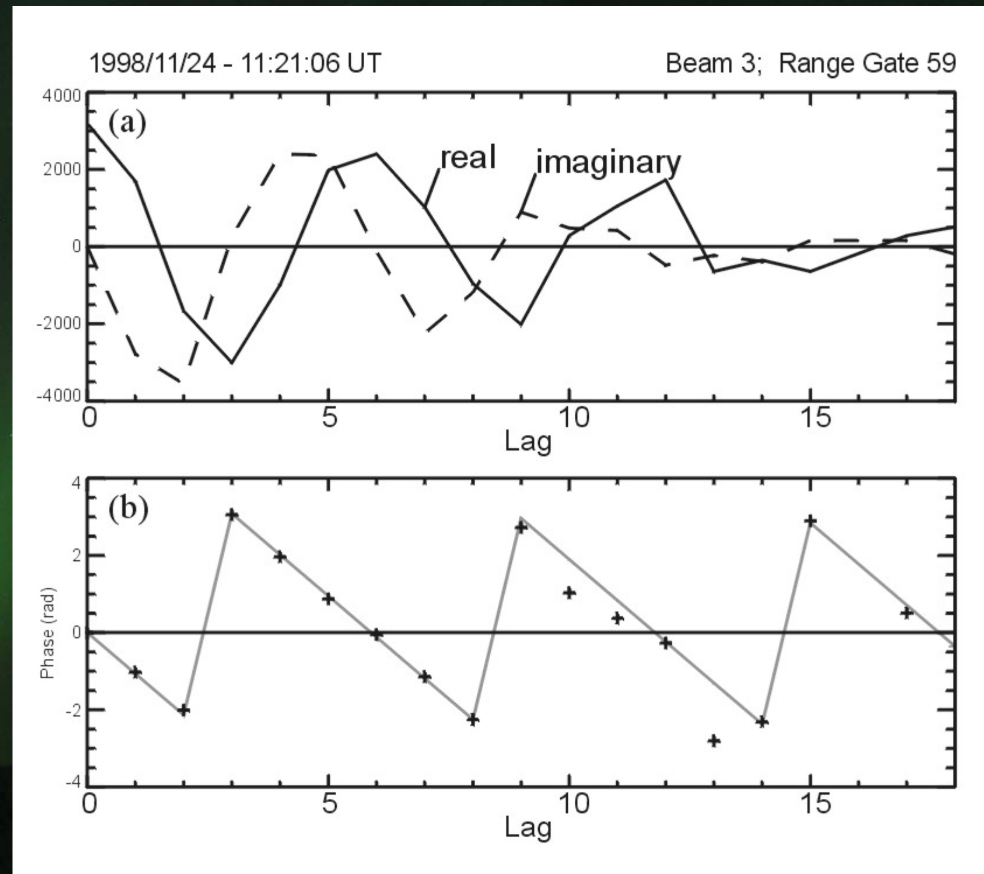
- If there is a dominant velocity (spectral peak) then doppler velocity $\langle \omega_D \rangle$ depends linearly on phase.
- Gain accuracy of vel. over Fourier method (sampling).

$$\Phi = \langle \omega_D \rangle k\tau,$$
$$\langle v_D \rangle = c\langle \omega_D \rangle / (4\pi\, f_{radar})$$



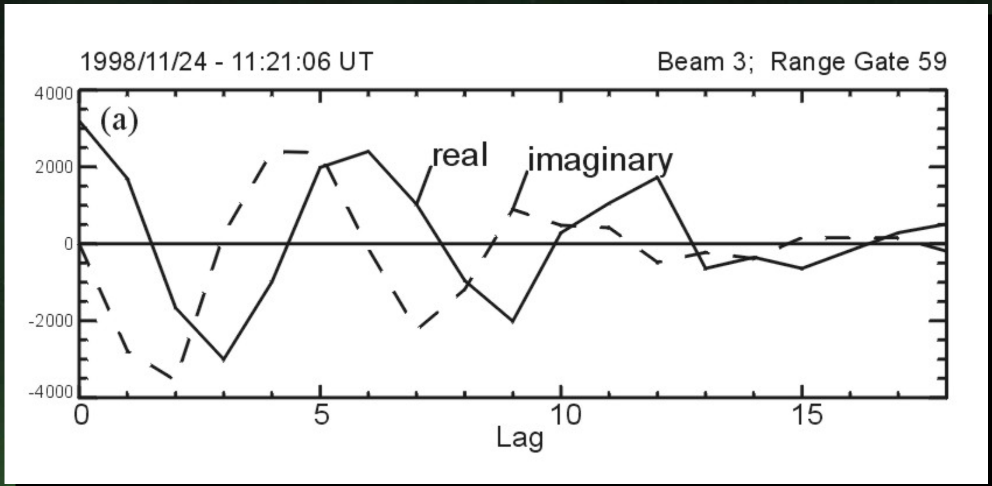
Decay of the ACF

- In nature, plasma structure in sampling volume changes with time.
- Over time, plasma is less well correlated.
- ∴ ACFs become less correlated with increasing lag.
- Manifested in decay of ACF envelope.



Spectral Width - Decay of the ACF

- Rate of decay of ACF determines the FITACF estimate of spectral width.
- Can be fitted with a Lorentzian or a Gaussian function:
  - ***width_l***
  - ***width_s***

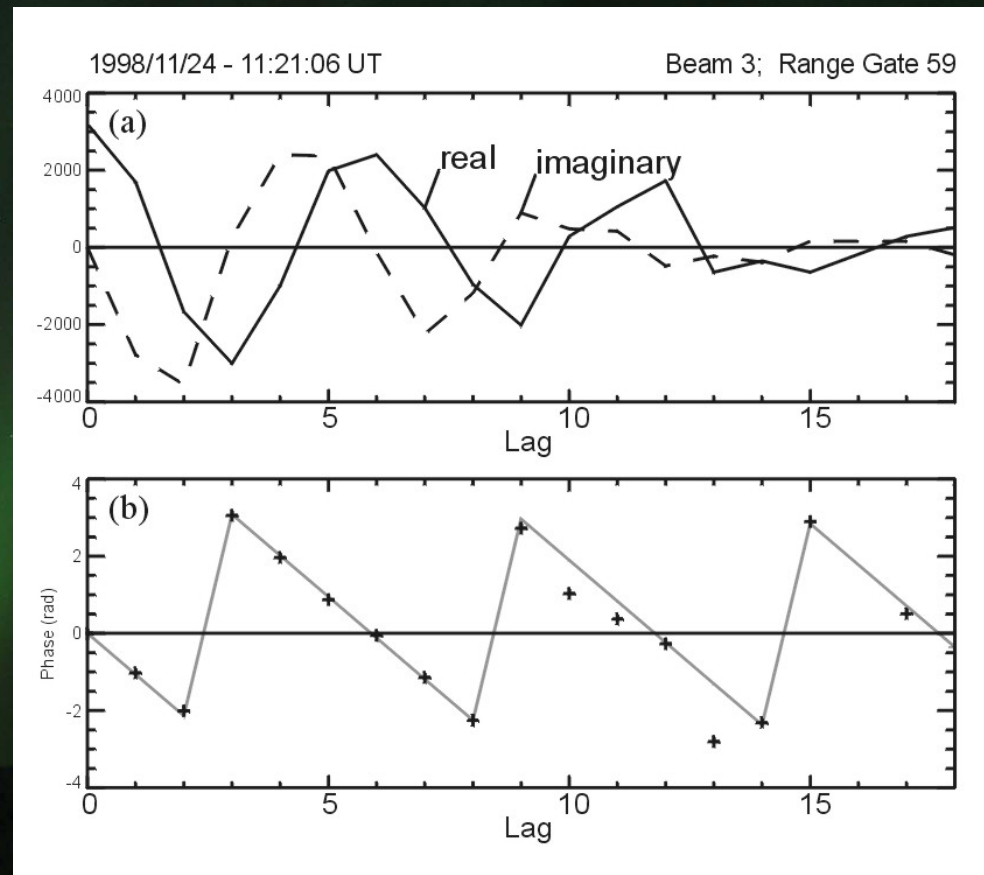


$$\Delta v = 2\beta c \,/\, (4\pi\, f_{radar})$$

For a Lorentzian fit the characteristic decay $1/\beta$ is related to spectral width Δv.

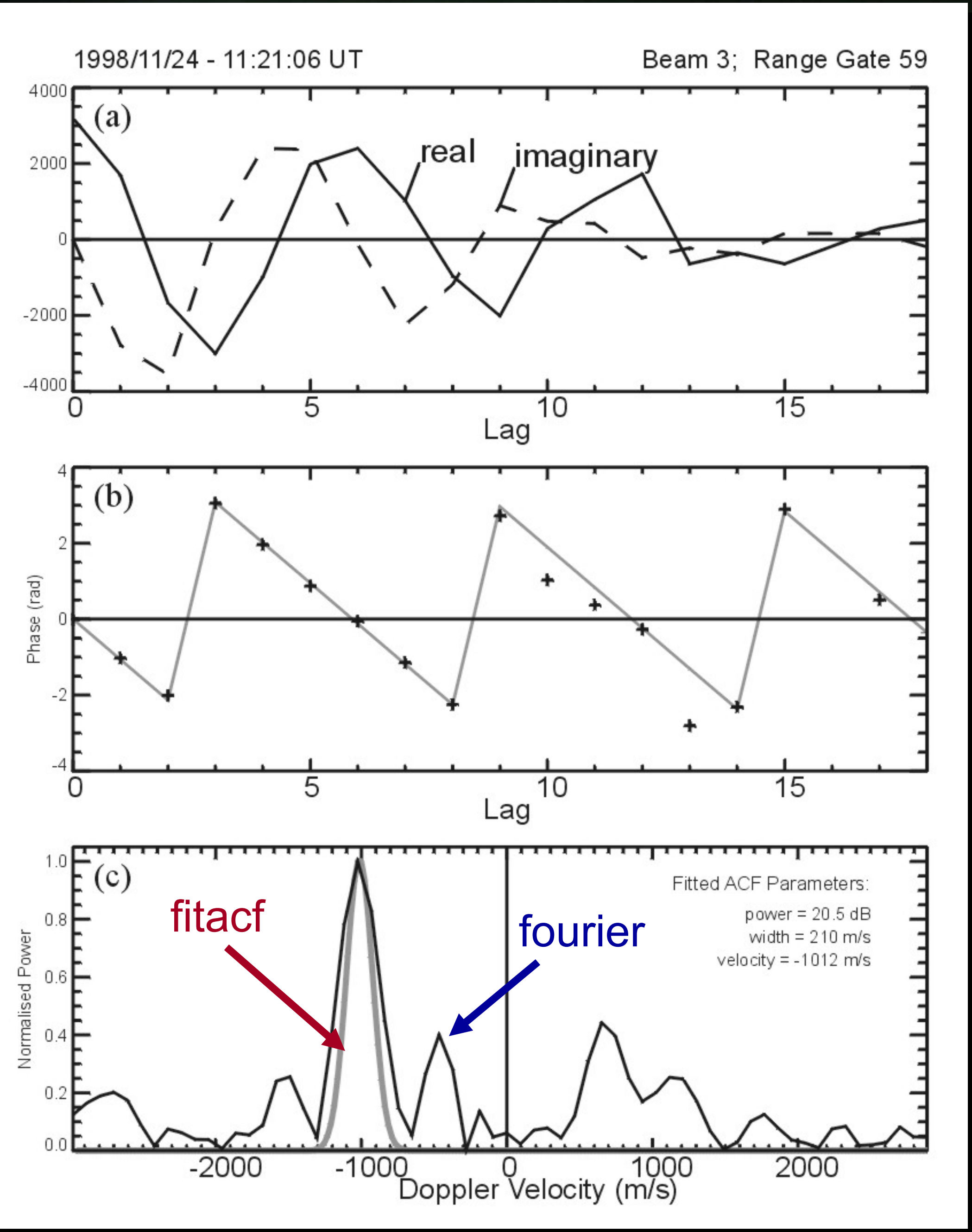
Backscattered Power

- Measured power at lag 0 (where Im=0) is related to spectral power:
  - ***pwr_0***
- The value of fitted ACF (Lorentzian or Gaussian) at lag 0 gives fitted backscattered power:
  - ***pwr_l***
  - ***pwr_s***



What's in a .fit file:

- Fitted values of velocity, power, and width, defining fitted spectrum.
- For single-peaked spectra this is very good!
- (Recall that Fourier transform of ACF gives actual spectrum.)



What's in a .fit file?
- Summary -

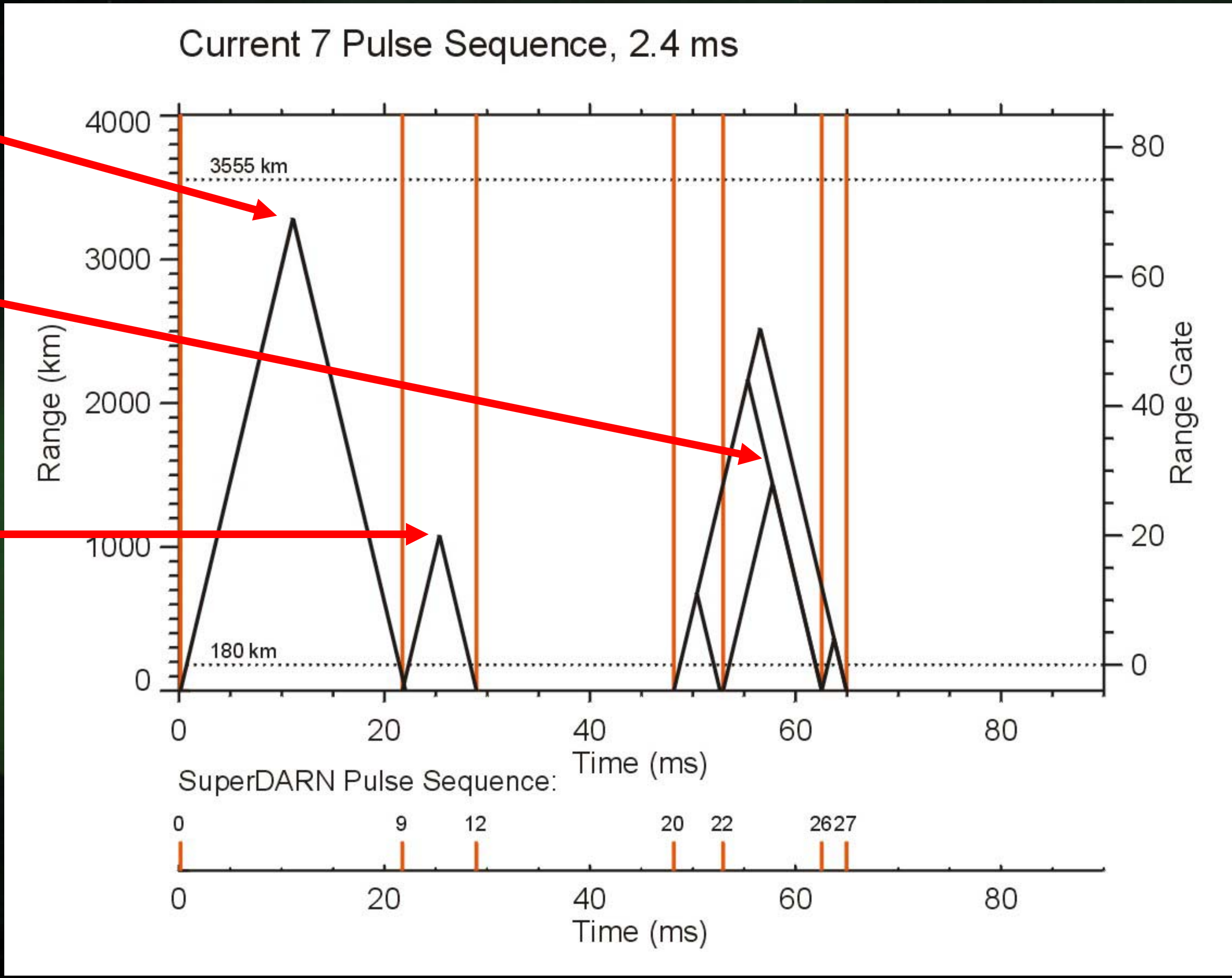
- Backscattered Power:
  - Lag 0 power (fitted*)
- Doppler Velocity:
  - Rate of change of ACF phase, $\Phi = \langle \omega_D \rangle k\tau$ ($k \in \Im$)
  - $\langle v_D \rangle = c\langle \omega_D \rangle / (4\pi\ f_{radar})$
- Spectral Width:
  - Rate of decay of ACF envelope (fitted)

Pitfalls and Bad Lags

- In all cases, can ***NOT*** receive when Tx on.
- Often, ACFs are bad when no Lag 0.
  - Must not be transmitting when receiving first echoes from a pulse (Lag 0).
- First few lags crucial to ACF fitting technique.
- Cross-range noise:
  - Self-correlated echoes come from 2 different ranges at the same time.
  - Compare Lag 0 power at possible ranges. If power is much stronger in one range gate, then dominant signal assumed to be from there.

Tx On & Cross-Range Noise

- no lag 0 power
- cross-range noise ex.
- (note that lag 3 returns from RG~20 when Tx on)

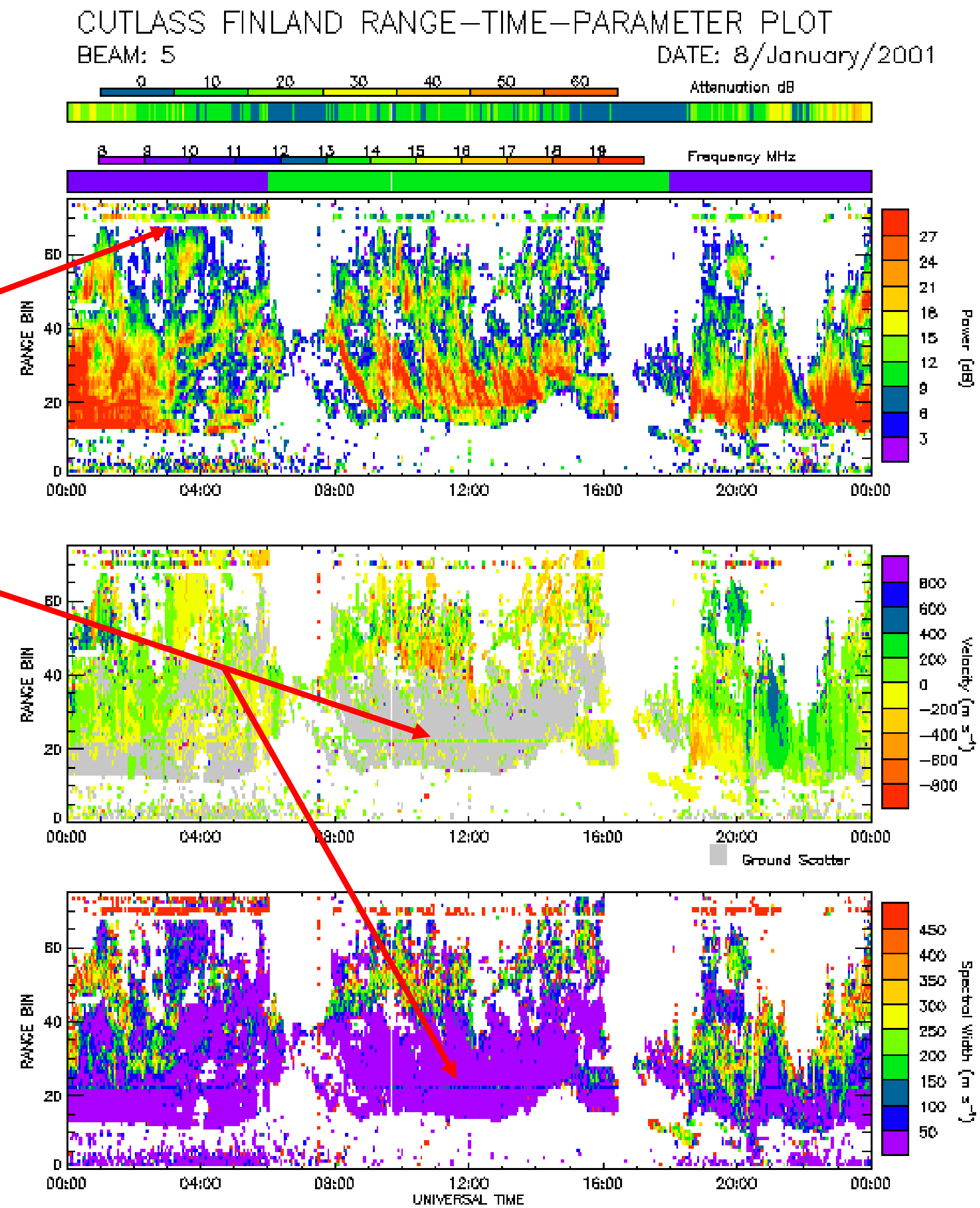


Pitfalls and Bad Lags

- In general, data disregarded if:
  - Rx off due to Tx on
  - Power is similar or weaker than simultaneous returns from another range gate
  - Unphysical ACF (often HF interference)

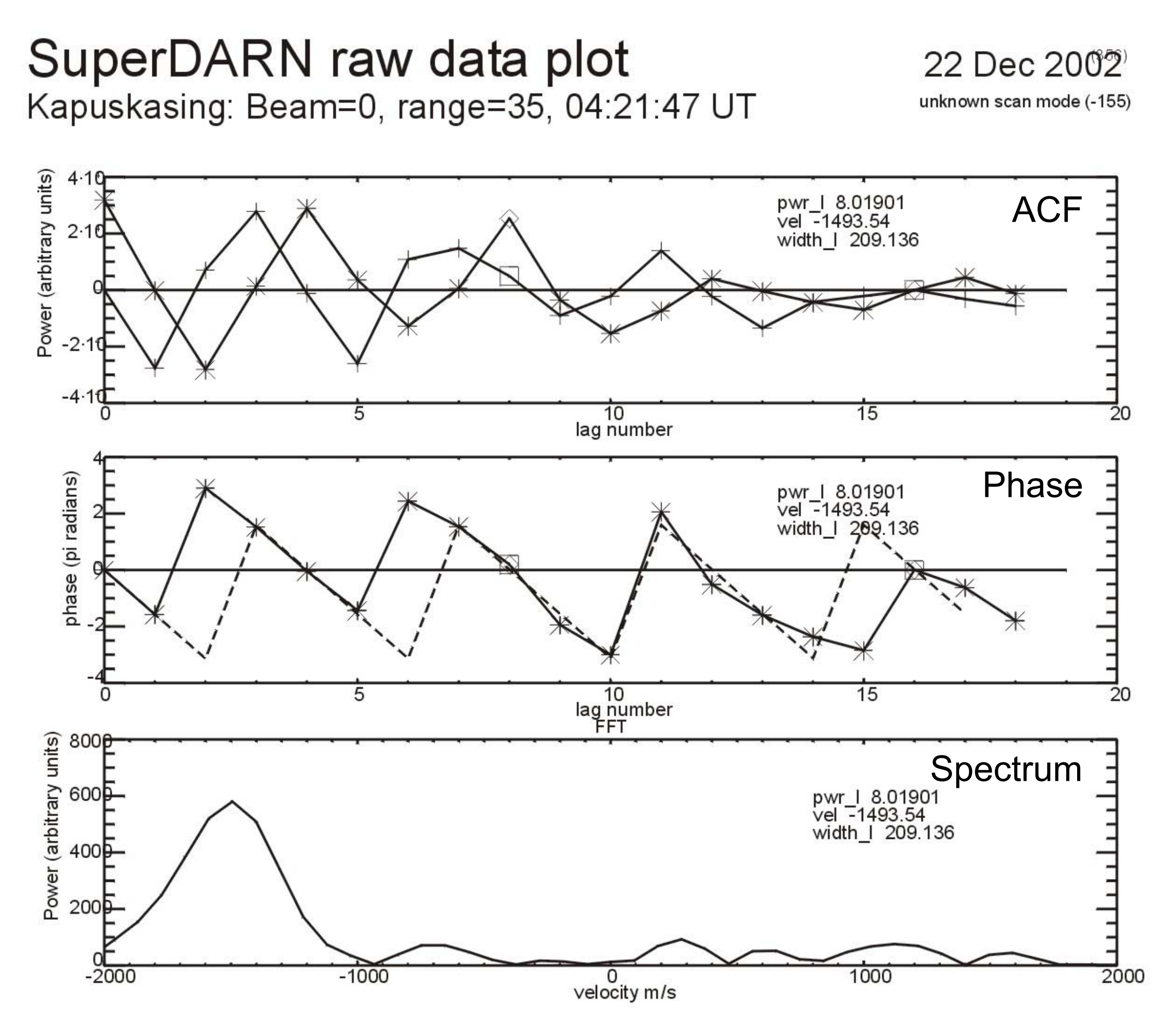
Bad Lags in Real Data

- RG 68 – missing Lag 0
  - (Tx pulse 2; Rx pulse 1)
- RG 20 – Missing 3τ
  - (Tx pulse 12; Rx pulse 9)
  - Seems to be a critical lag; perhaps where ACF often has first 2π jump?
- probable cross-range noise at far ranges (only when lots of other scatter at near ranges)



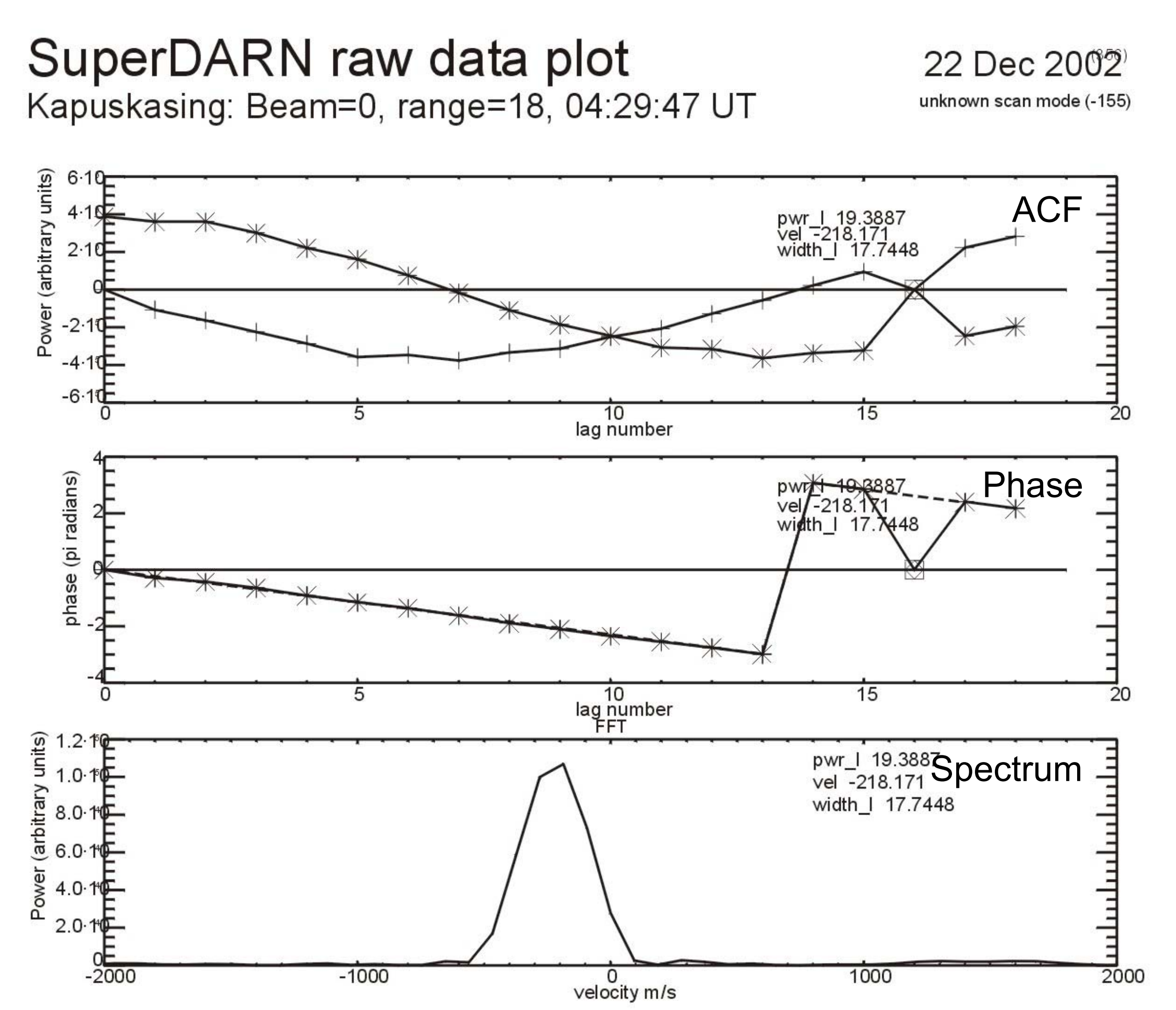
Some Real ACFs – *High Velocity*

- rapid phase change
- moderate decay of ACF envelope
- fitted par's:
  - pwr = 8.0
  - vel = -1490
  - wid = 209



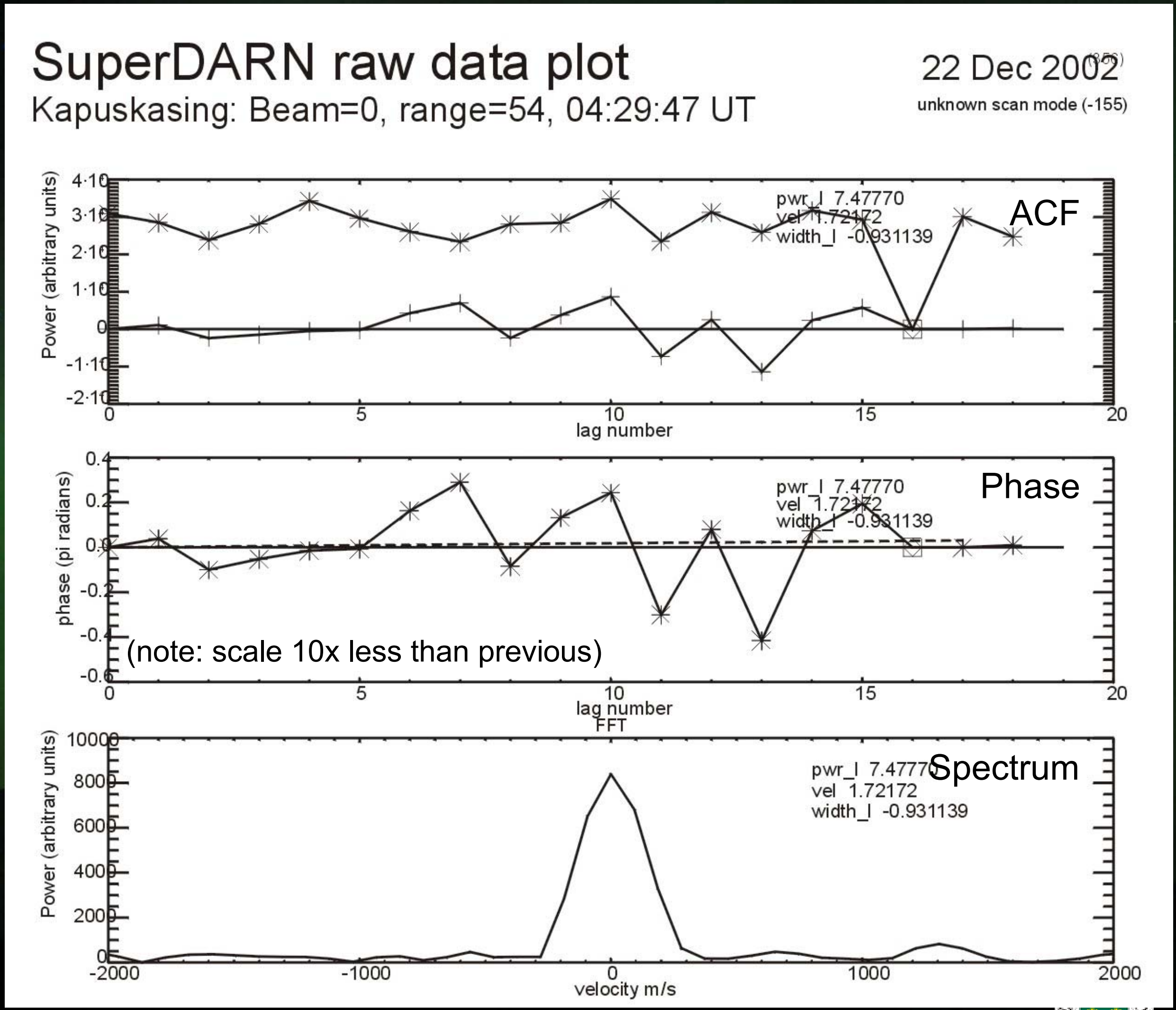
Some Real ACFs – *Low Velocity*

- slow phase change
- slower decay of ACF envelope
- fitted par's:
  - pwr = 19.4
  - vel = -218
  - wid = 17.7



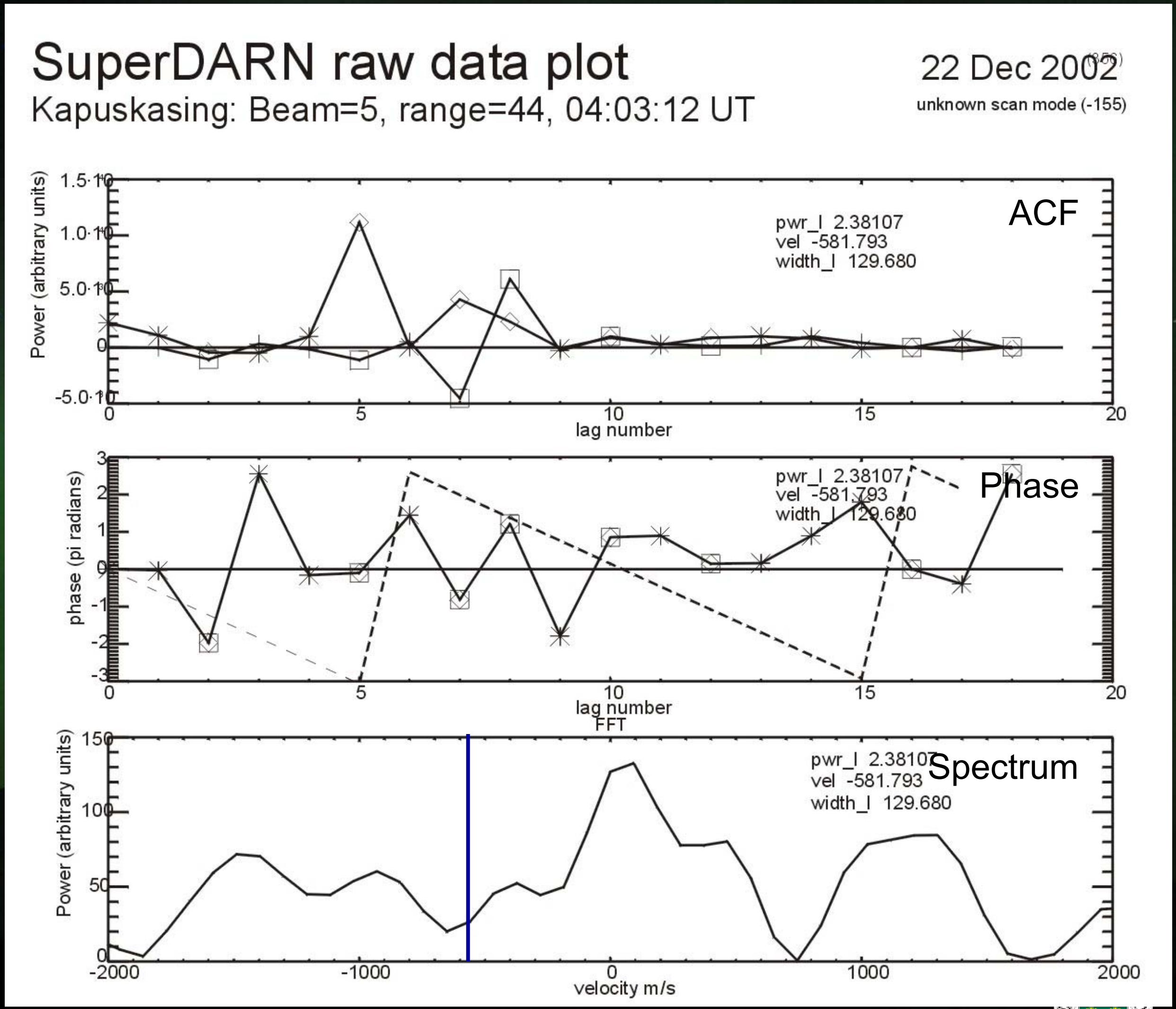
Some Real ACFs – *Ground Scatter*

- basically no phase change
  (ground not moving!)
- no decay of ACF envelope
  (ground correlated!)
- possible real vel. imbedded
- fitted par's:
  - pwr = 7.5
  - vel = -1.7
  - wid = -0.9



Some Real ACFs - *Bad*

- low power
- bad linear fit to phase
- very poor ACF and spectrum
- fitted(*!*) par's:
  - pwr = 2.4±1.9 (< 3dB)
  - vel = -582±170
  - wid = 130±140



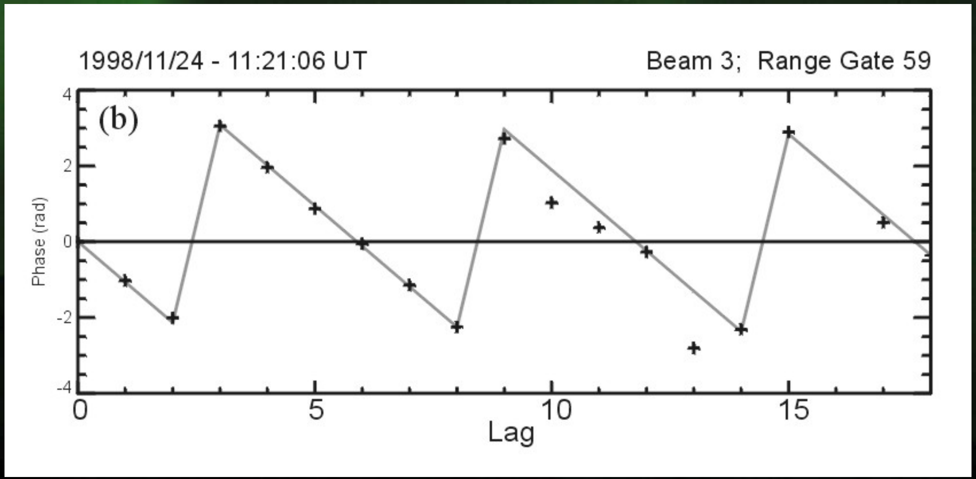
So if it's already working, why would we want to change it?

- Improve ACF accuracy
  – number of points in the ACF could be increased (decrease τ)
- Increase maximum (alias) velocity
  – determined by lag separation τ

Maximum ('Alias') Velocity

- Velocity determined from slope of ACF phase Φ, which varies between $\pm\pi$
- Therefore, $\omega_{max} = \pi/\tau$

$$v_{max} = c/(4\tau \cdot f_{radar})$$



Maximum ('alias') Velocity

Examples:

τ=2.4 ms; f_{radar}=18.0 MHz → v_{alias} = 1734 m/s

τ=2.4 ms; f_{radar}=14.4 MHz → v_{alias} = 2170 m/s

τ=2.4 ms; f_{radar}=10.2 MHz → v_{alias} = 3064 m/s

τ=1.5 ms; f_{radar}=14.4 MHz → v_{alias} = 3470 m/s

τ=1.5 ms; f_{radar}=10.2 MHz → v_{alias} = 4900 m/s

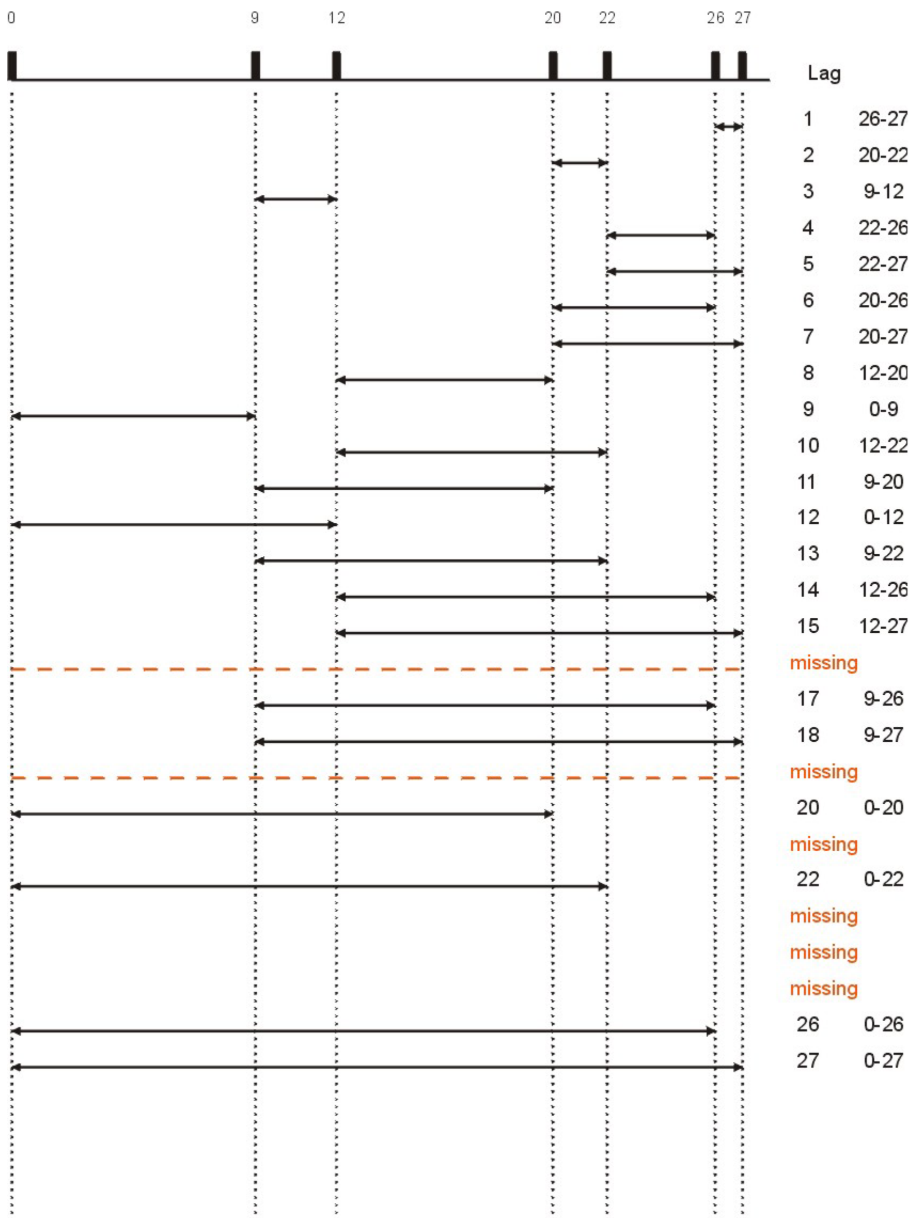
Optimizing New Sequence

- No repeated lags.
- Minimize number of inherently missing lags.
- Long lag between first 2 pulses to get Lag 0 power at all ranges.
- Minimize τ to maximize number of points in ACF.
- Minimize missing lags due to Tx-on/Rx-off conflicts.

Tested Pulse Sequences

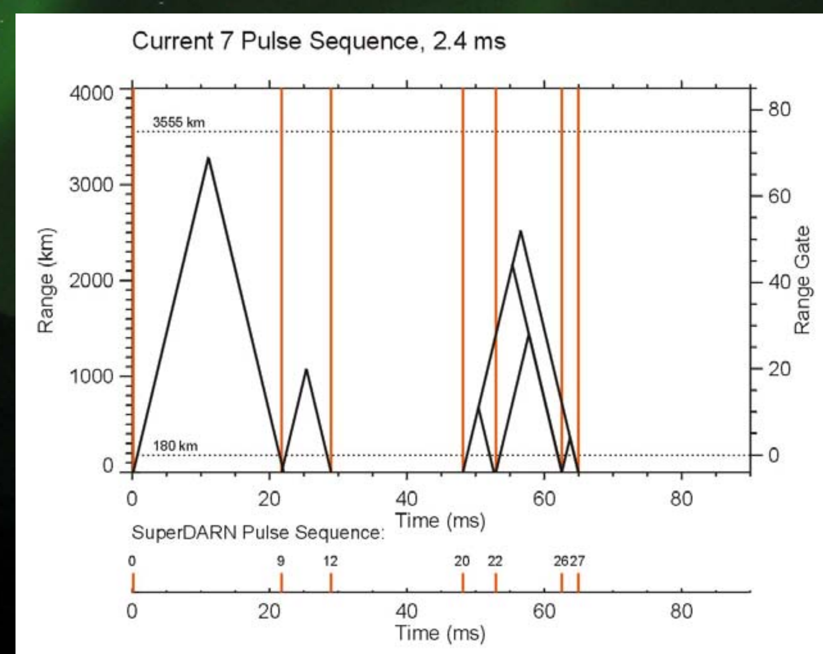
- Current 7-pulse:
  - [0, 9, 12, 20, 22, 26, 27], 2400 μs
- Ray's 8-pulse:
  - [0, 19, 28, 31, 39, 41, 45, 46], 1200 μs
- 'kat_scan' 8-pulse:
  - [0, 14, 22, 24, 27, 31, 42, 43], 1500 & 1800 μs
- 9-pulse:
  - [0, 16, 26, 27, 34, 46, 49, 51, 55], 1500 μs

[0, 9, 12, 20, 22, 26, 27]

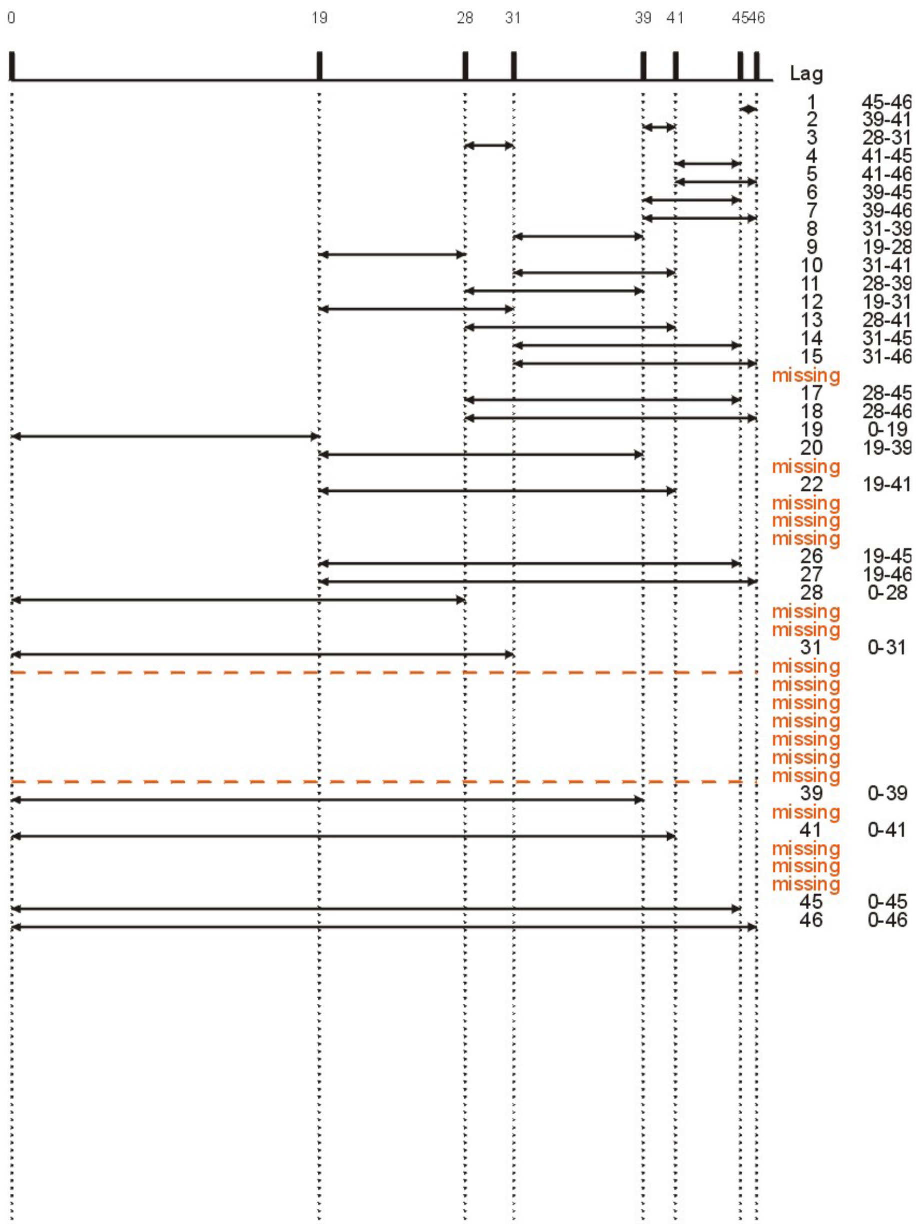


Current Sequence

- 7 pulses, τ = 2400 μs
- first missing lags at 16τ and 19τ

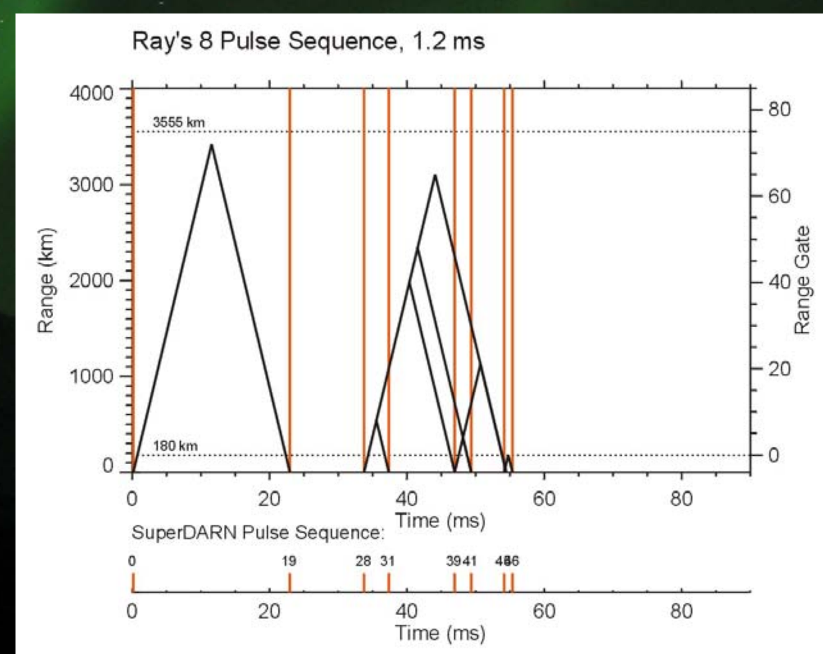


[0, 19, 28, 31, 39, 41, 45, 46]

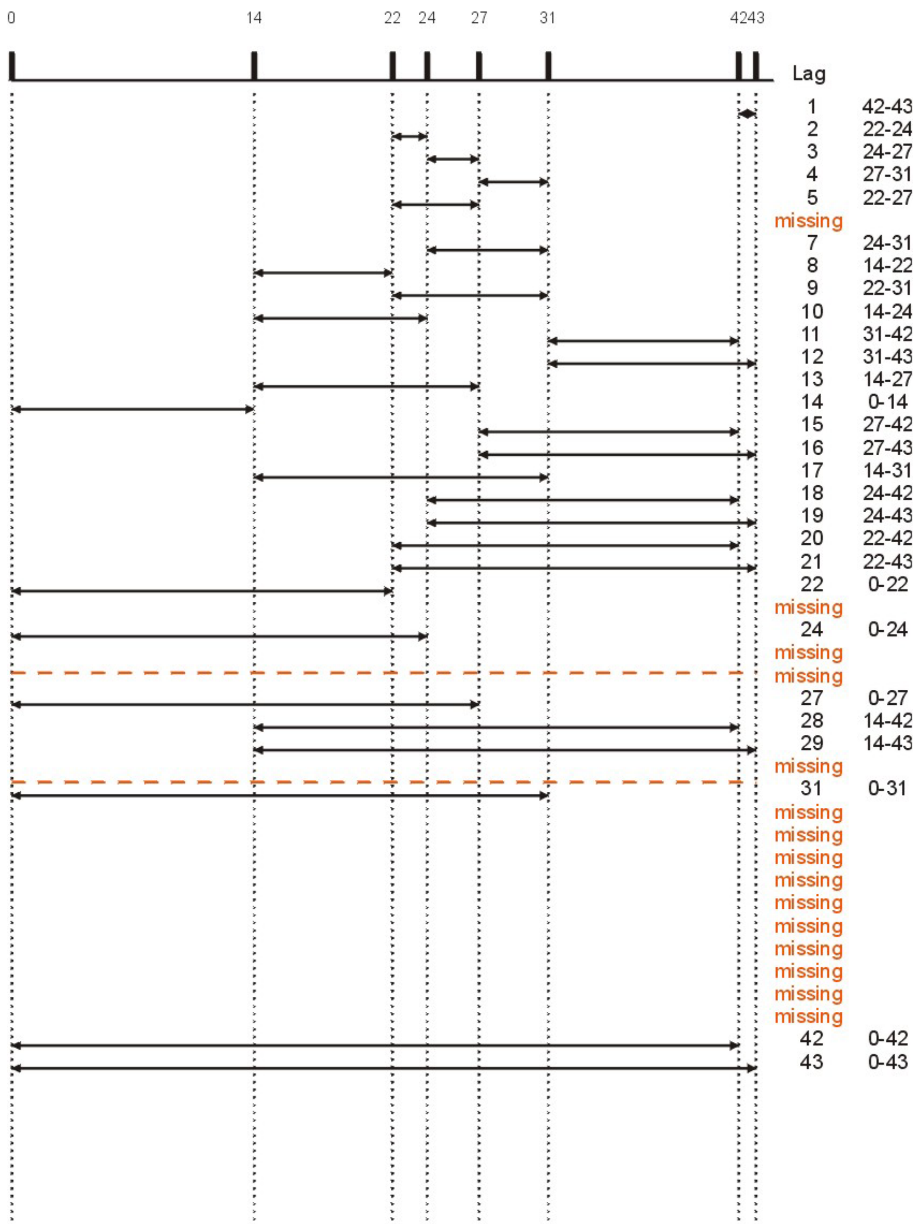


Ray's Sequence

- 8 pulses, τ = 1200 μs
- added 19τ to current pulse sequence and halved τ
- many missing lags

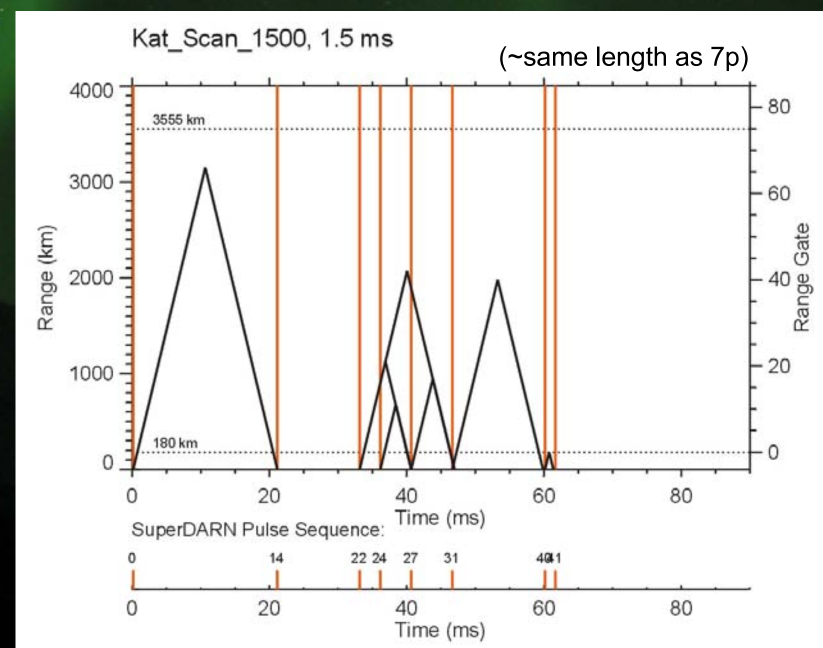


[0, 14, 22, 24, 27, 31, 42, 43]

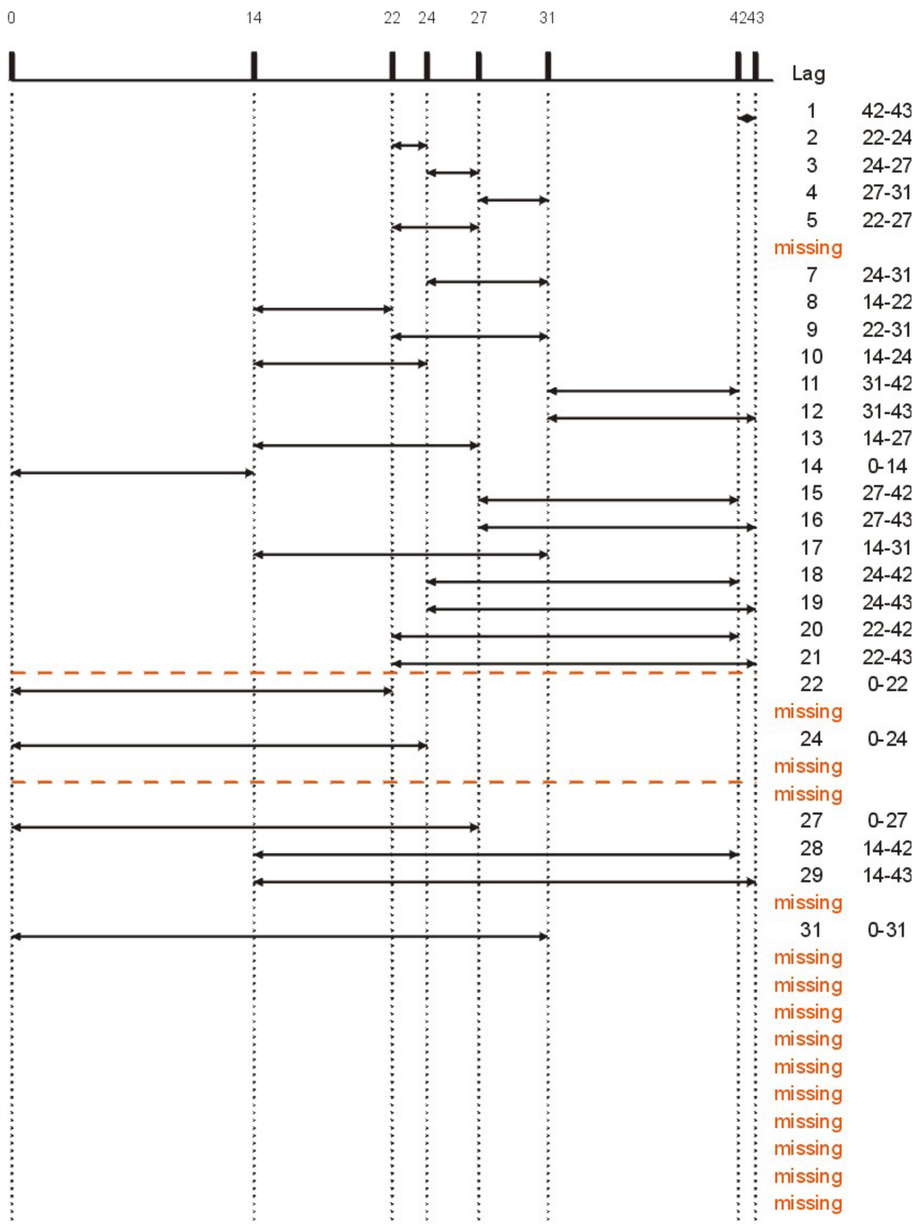


‘kat_scan 1500’

- 8 pulses, τ = 1500 μs
- lag 1 separated from rest of sequence
- except for 6τ, missing lags behaviour nearly identical to current 7-pulse sequence

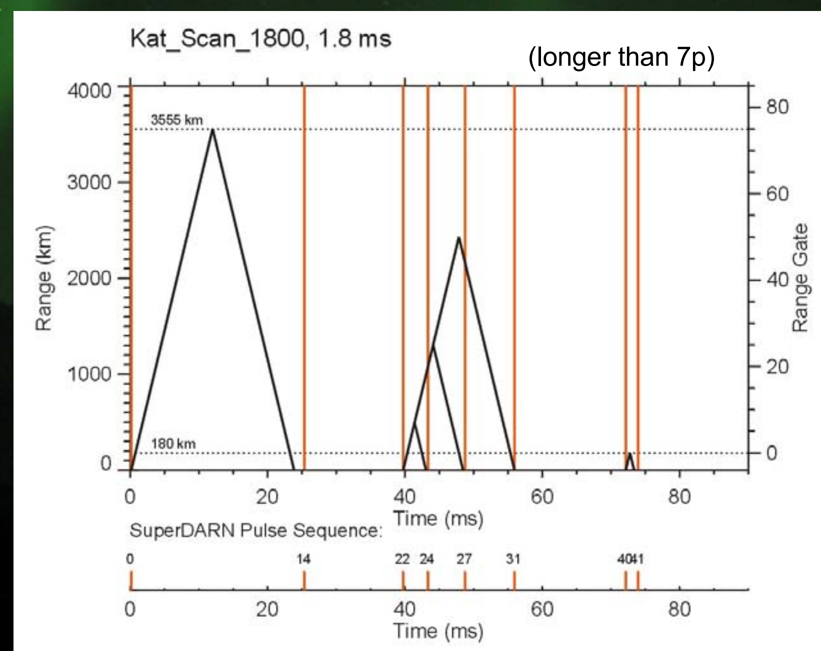


[0, 14, 22, 24, 27, 31, 42, 43]

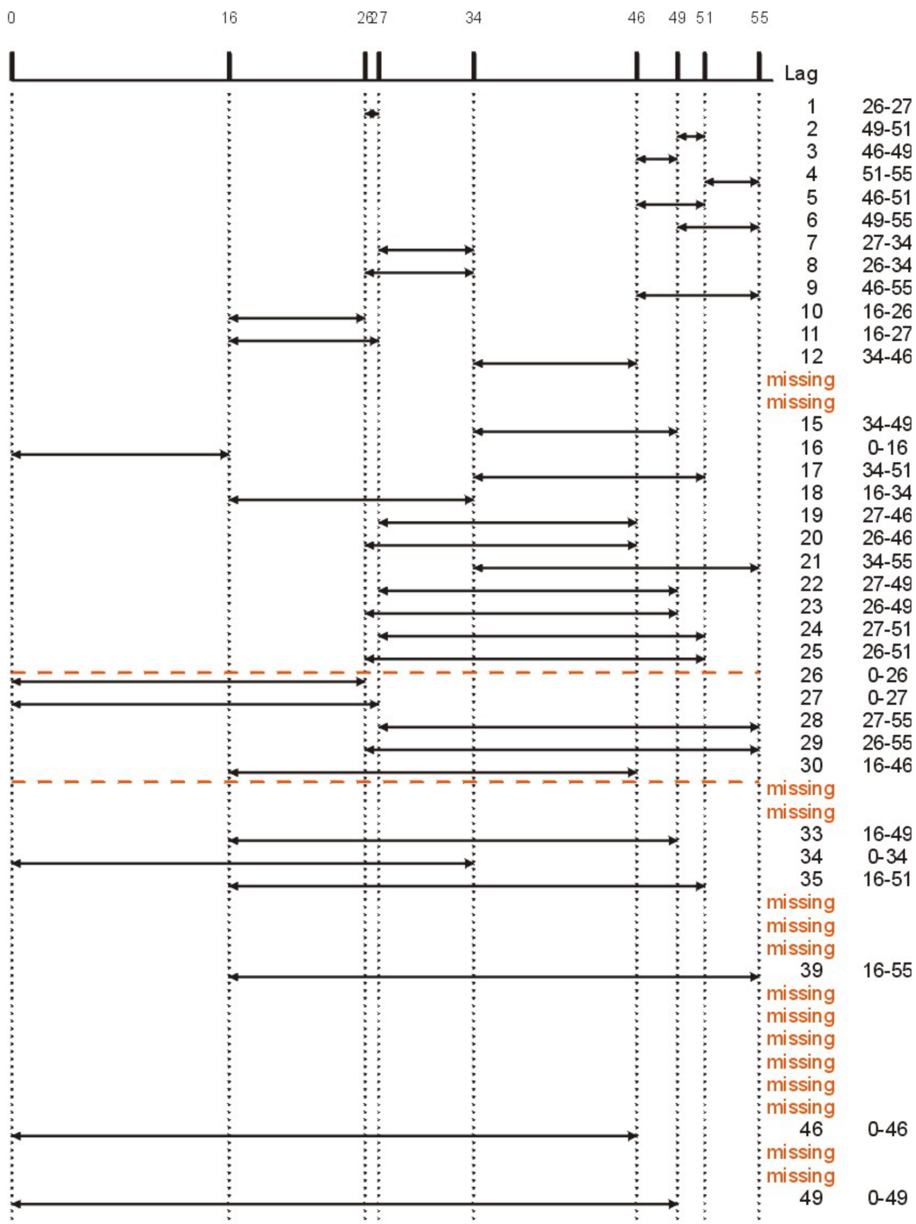


‘kat_scan 1800’

- 8 pulses, τ = 1800 μs
- lag 0 determination possible at all ranges

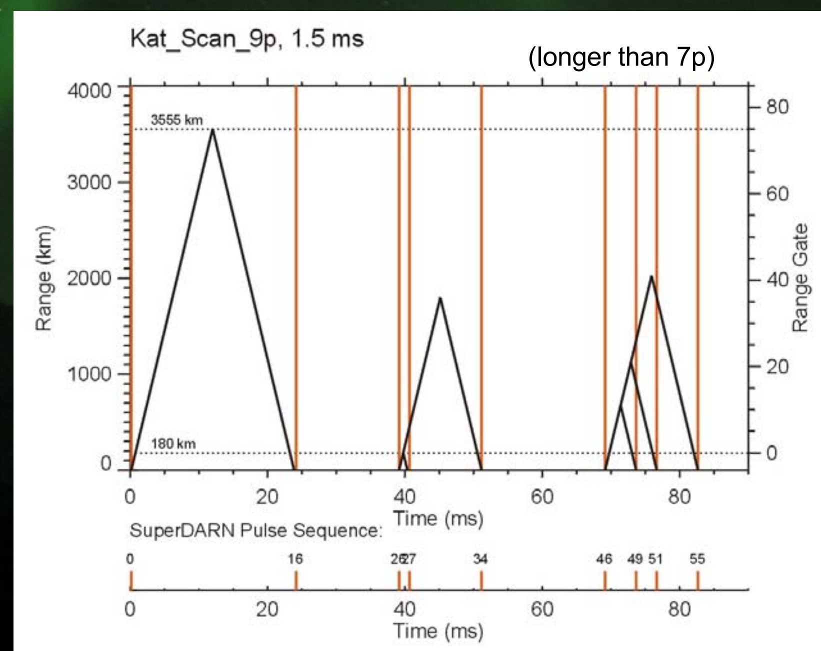


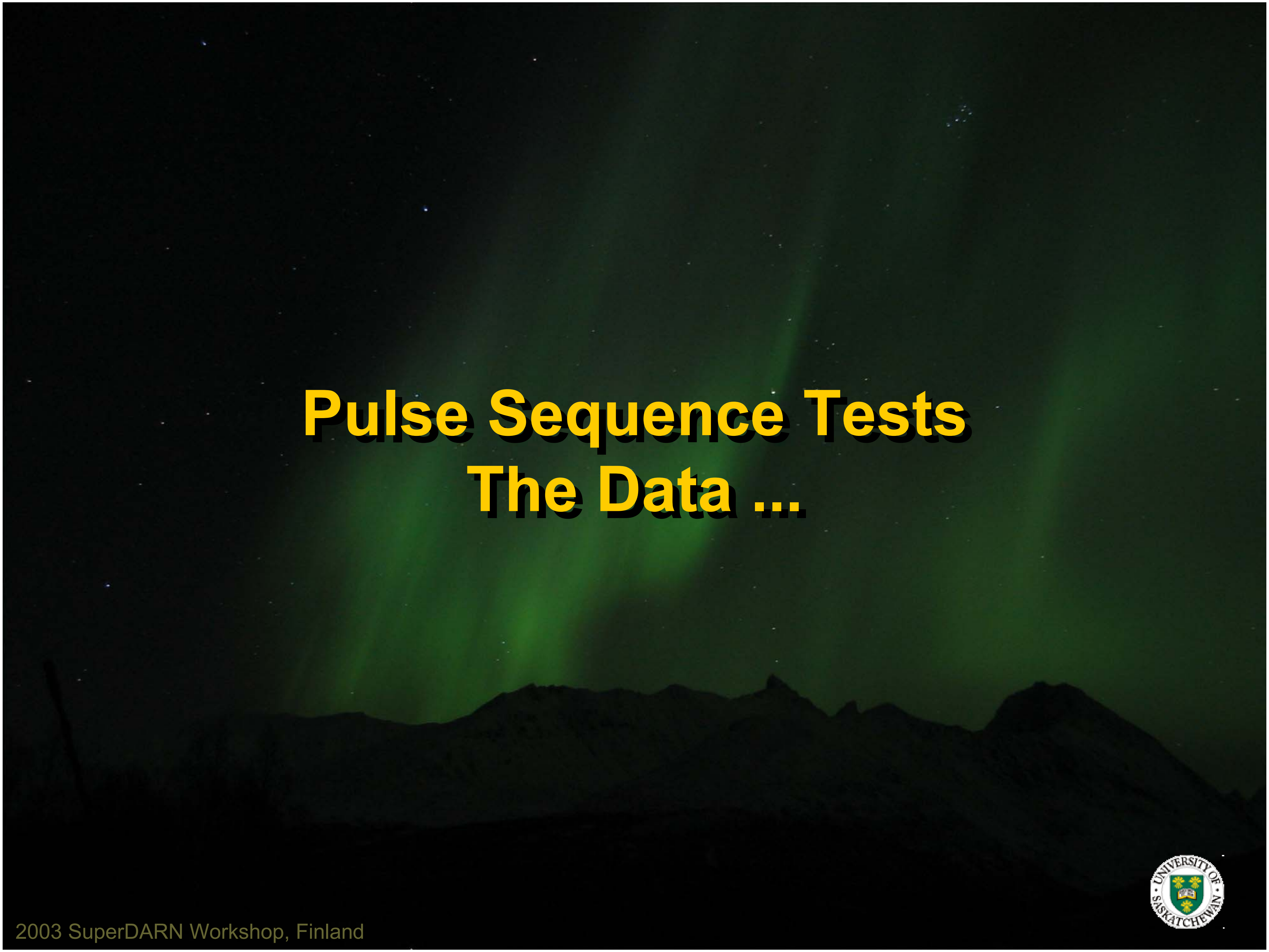
[0, 16, 26, 27, 34, 46, 49, 51, 55]

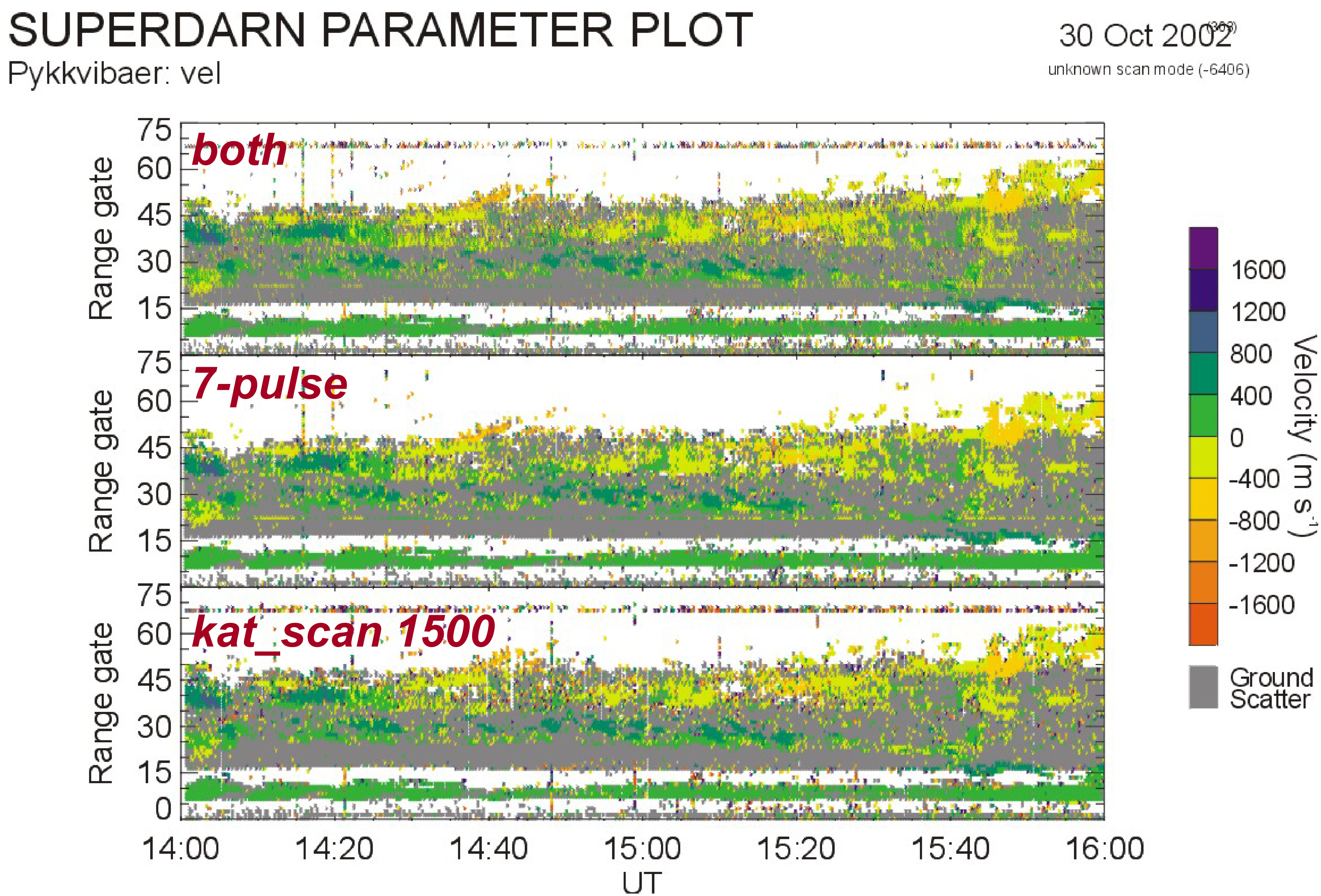


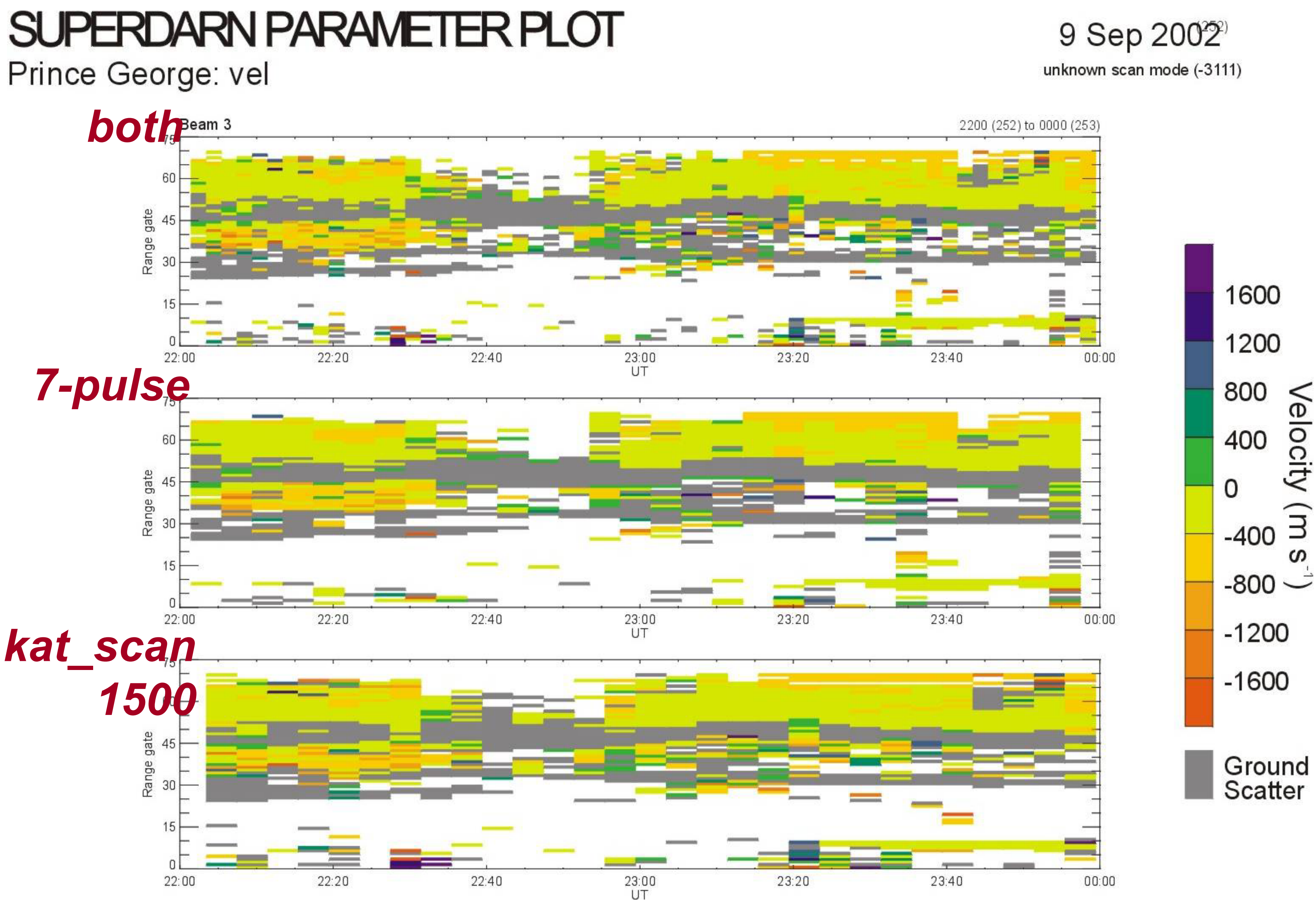
kat_scan_9p

- 9 pulses, τ = 1500 μs
- lag 0 determination possible at all ranges
- longer pulse train; fewer averages




Pulse Sequence Tests
The Data ...


SUPERDARN PARAMETER PLOT
Pykkvibaer: vel
30 Oct 2002 (303)
unknown scan mode (-6406)
both
7-pulse
kat_scan 1500
Range gate
75
60
45
30
15
0
14:00
14:20
14:40
15:00
15:20
15:40
16:00
UT
1600
1200
800
400
0
-400
-800
-1200
-1600
Velocity (m s-1)
Ground Scatter

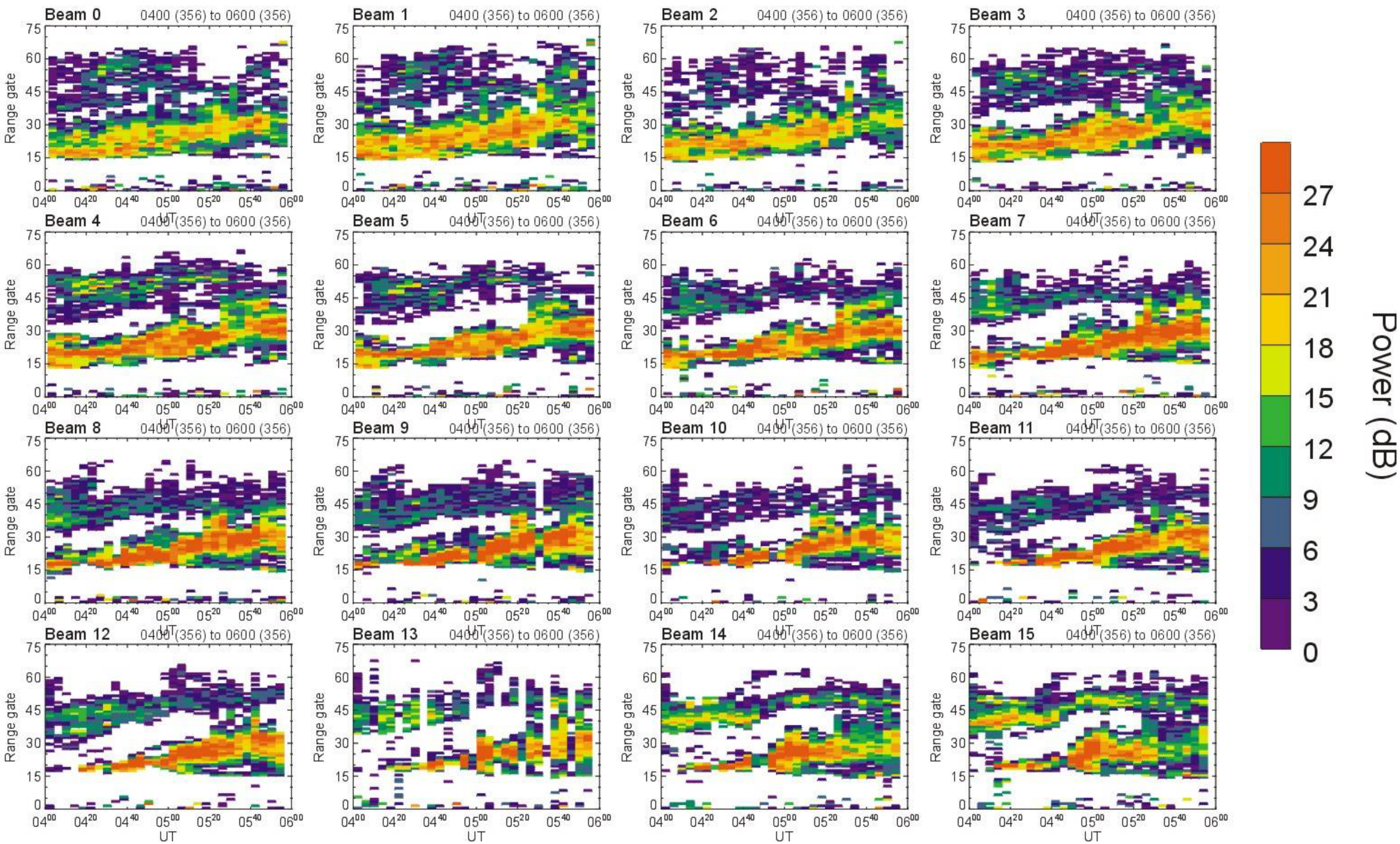

SUPERDARN PARAMETER PLOT
Prince George: vel
9 Sep 2002 (252)
unknown scan mode (-3111)
both
Beam 3
2200 (252) to 0000 (253)
7-pulse
kat_scan
1500
Range gate
75
60
45
30
15
0
22:00
22:20
22:40
23:00
23:20
23:40
00:00
UT
Velocity (m s-1)
1600
1200
800
400
0
-400
-800
-1200
-1600
Ground Scatter

SUPERDARN PARAMETER PLOT

Kapuskasing: pwr_l *7-pulse*

22 Dec 2002 (356)

unknown scan mode (-155)



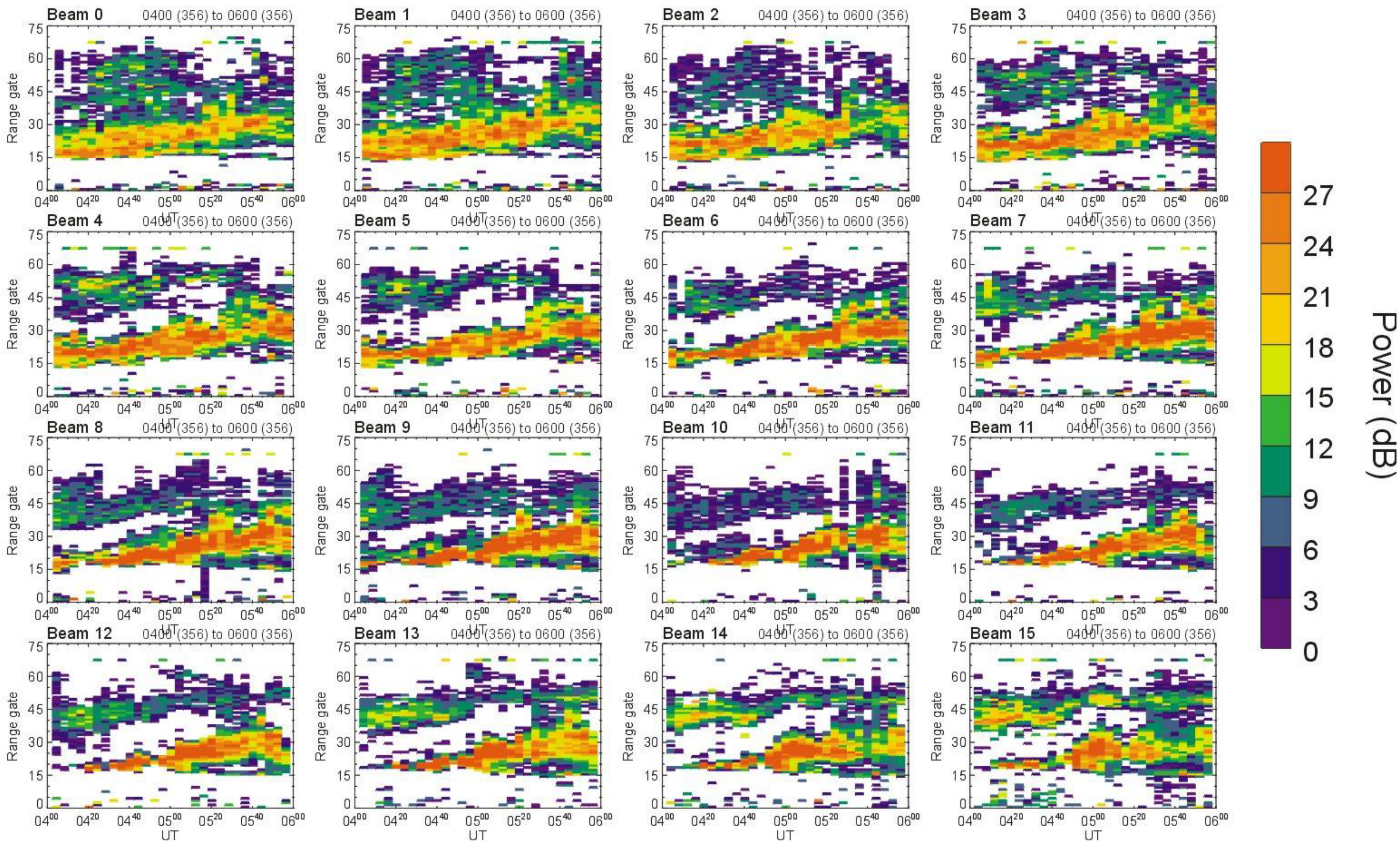
SUPERDARN PARAMETER PLOT

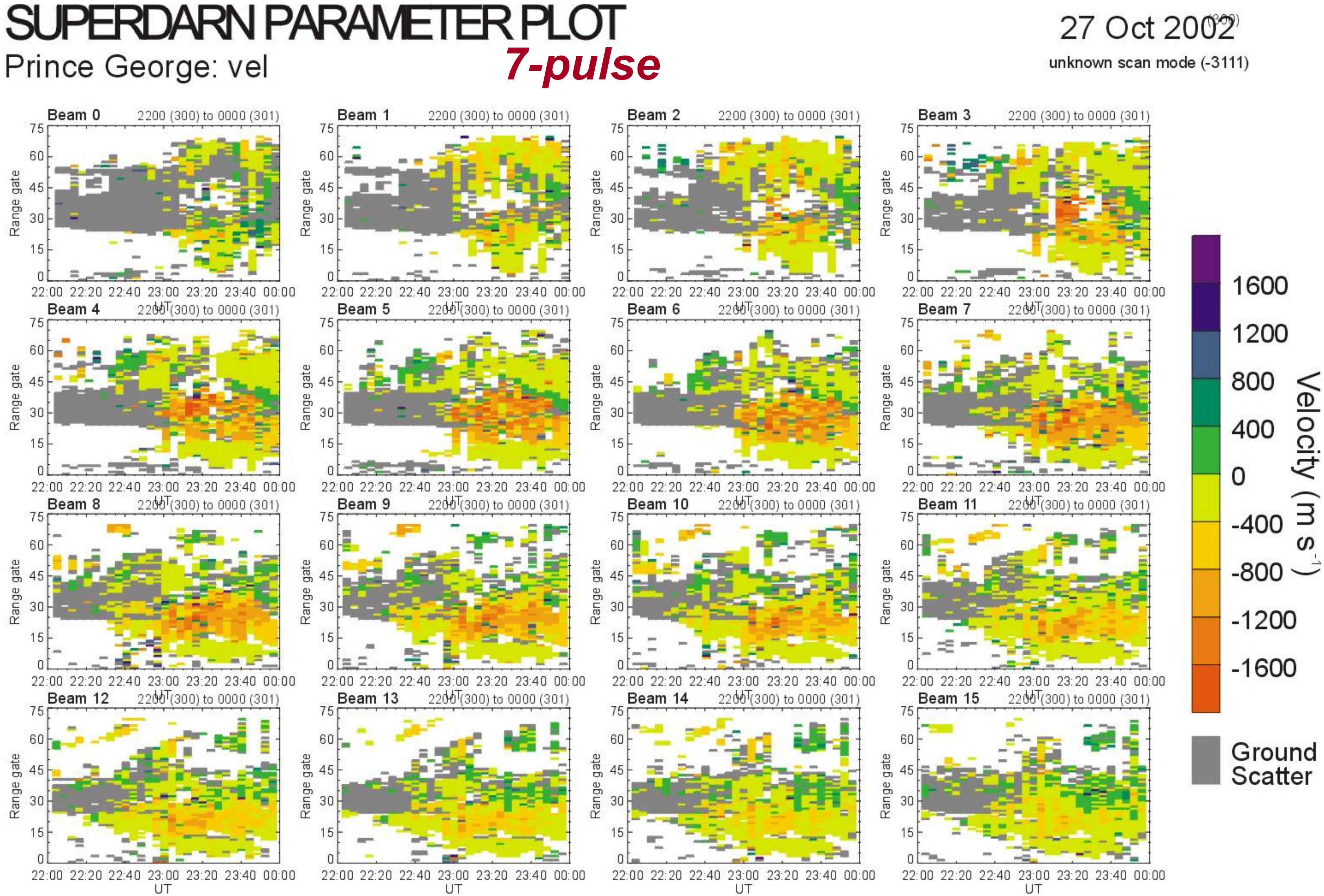
Kapuskasing: pwr_l

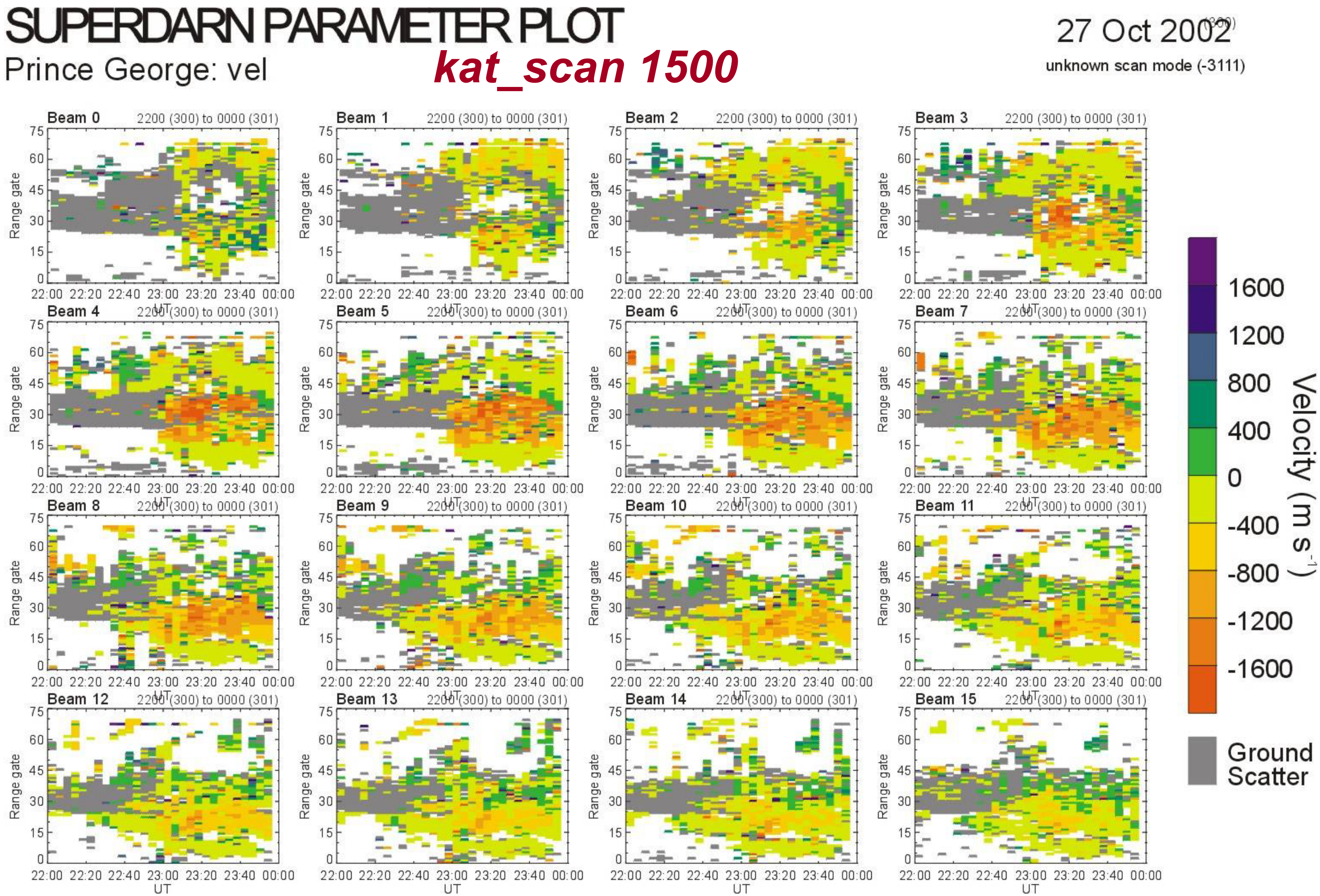
kat_scan 1500

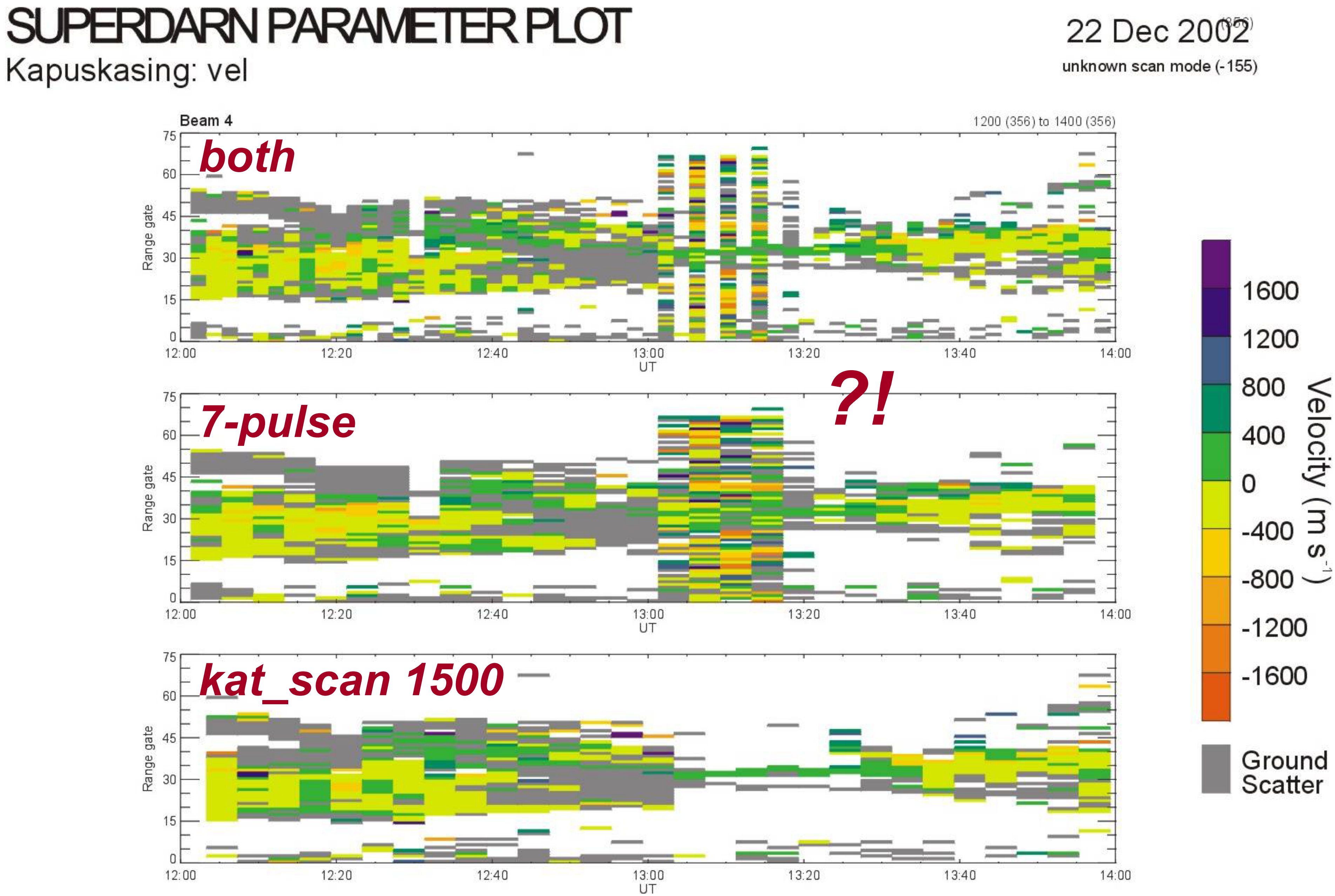
22 Dec 2002 (356)

unknown scan mode (-155)

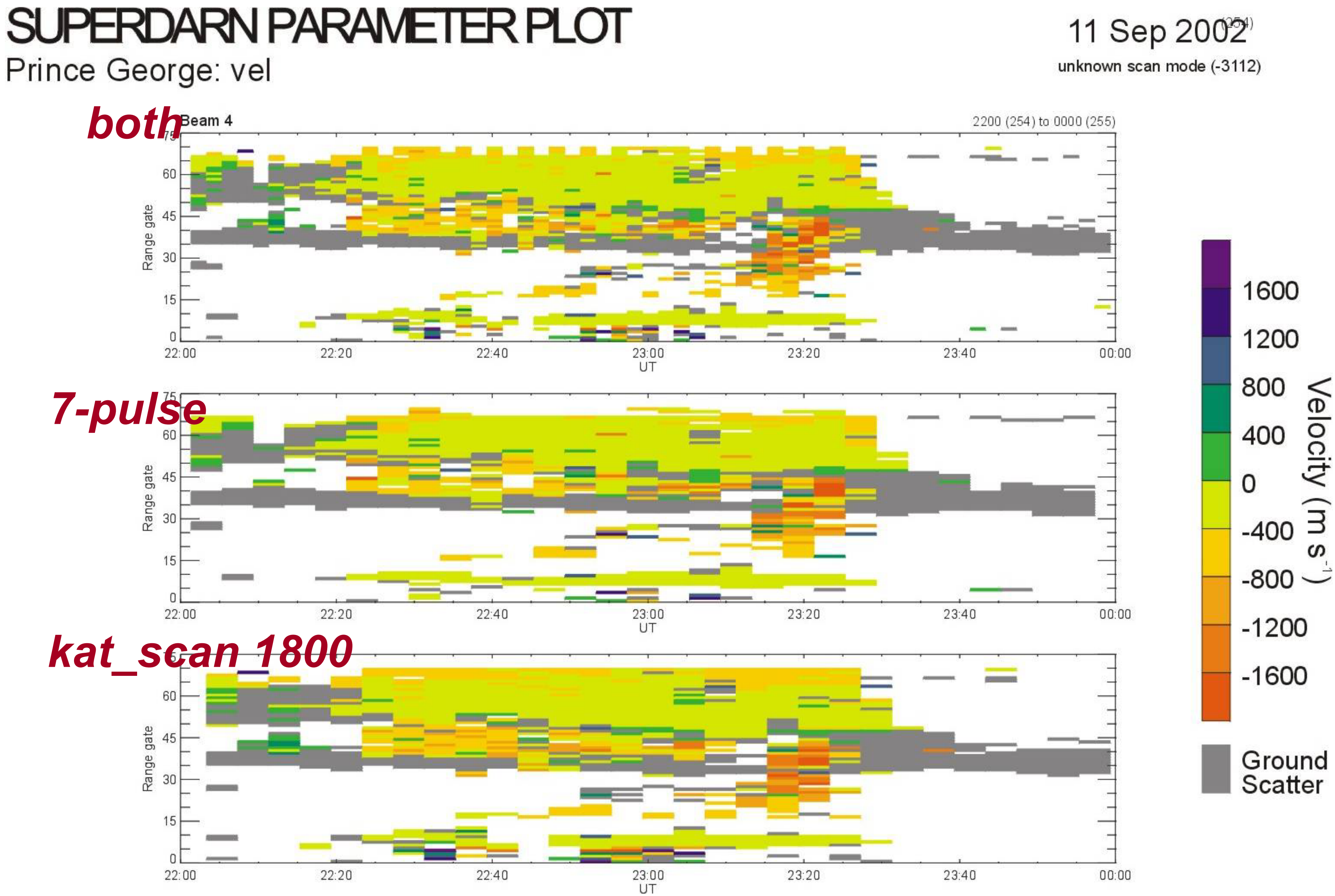



SUPERDARN PARAMETER PLOT
Prince George: vel
7-pulse
27 Oct 2002 (300)
unknown scan mode (-3111)
Beam 0 2200 (300) to 0000 (301)
Beam 1 2200 (300) to 0000 (301)
Beam 2 2200 (300) to 0000 (301)
Beam 3 2200 (300) to 0000 (301)
Beam 4 2200 (300) to 0000 (301)
Beam 5 2200 (300) to 0000 (301)
Beam 6 2200 (300) to 0000 (301)
Beam 7 2200 (300) to 0000 (301)
Beam 8 2200 (300) to 0000 (301)
Beam 9 2200 (300) to 0000 (301)
Beam 10 2200 (300) to 0000 (301)
Beam 11 2200 (300) to 0000 (301)
Beam 12 2200 (300) to 0000 (301)
Beam 13 2200 (300) to 0000 (301)
Beam 14 2200 (300) to 0000 (301)
Beam 15 2200 (300) to 0000 (301)
Range gate
0 15 30 45 60 75
22:00 22:20 22:40 23:00 23:20 23:40 00:00
UT
Velocity (m s-1)
1600 1200 800 400 0 -400 -800 -1200 -1600
Ground Scatter


SUPERDARN PARAMETER PLOT
Prince George: vel
kat_scan 1500
27 Oct 2002 (300)
unknown scan mode (-3111)
Beam 0
Beam 1
Beam 2
Beam 3
Beam 4
Beam 5
Beam 6
Beam 7
Beam 8
Beam 9
Beam 10
Beam 11
Beam 12
Beam 13
Beam 14
Beam 15
2200 (300) to 0000 (301)
Range gate
UT
Velocity (m s-1)
1600
1200
800
400
0
-400
-800
-1200
-1600
Ground Scatter



SUPERDARN PARAMETER PLOT
Kapuskasing: vel
22 Dec 2002 (356)
unknown scan mode (-155)
Beam 4
1200 (356) to 1400 (356)
both
7-pulse
?!
kat_scan 1500
Range gate
0
15
30
45
60
75
12:00
12:20
12:40
13:00
13:20
13:40
14:00
UT
1600
1200
800
400
0
-400
-800
-1200
-1600
Velocity (m s-1)
Ground Scatter



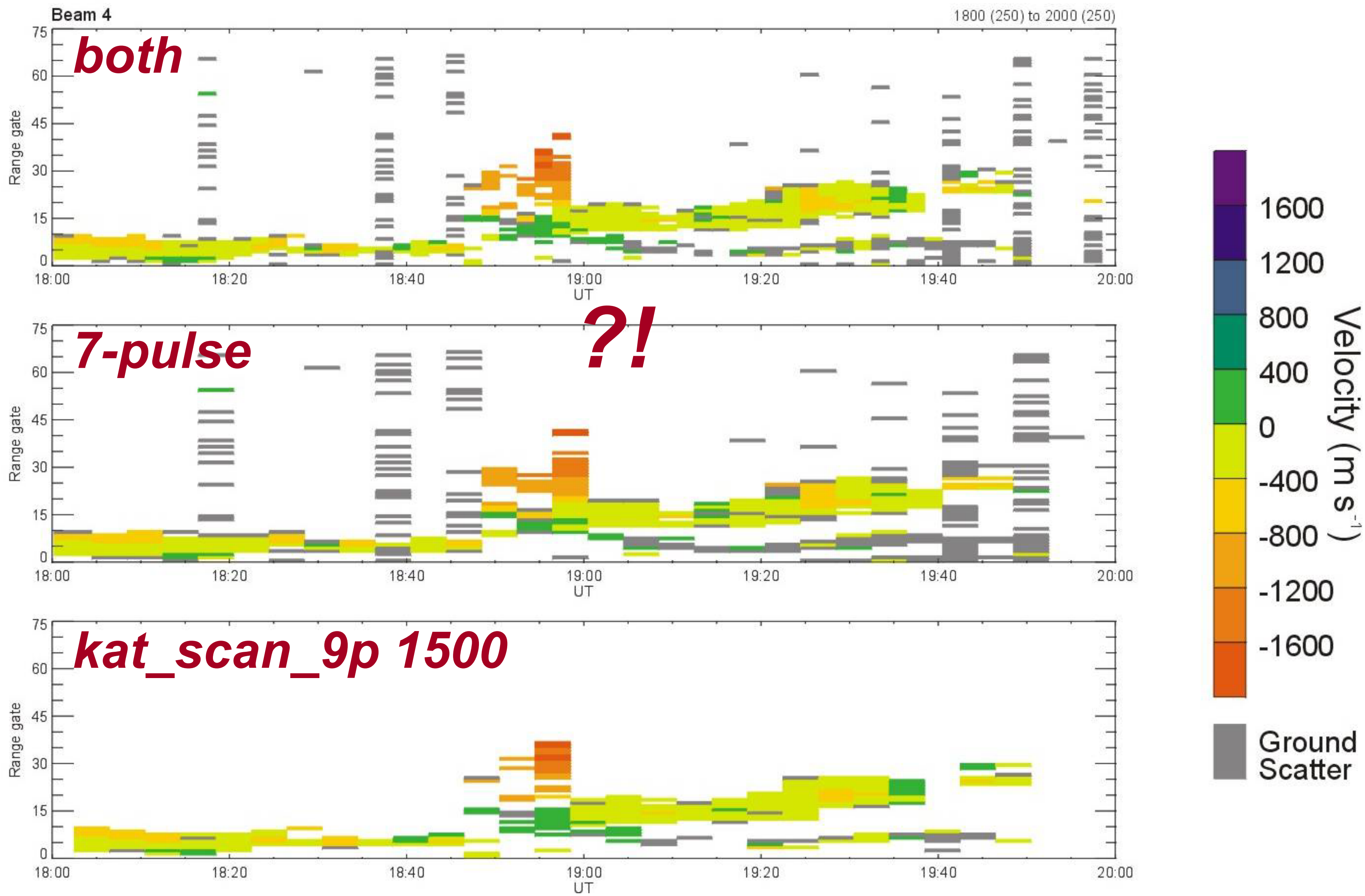
SUPERDARN PARAMETER PLOT
Prince George: vel
11 Sep 2002 (254)
unknown scan mode (-3112)
both
Beam 4
2200 (254) to 0000 (255)
7-pulse
kat_scan 1800
Range gate
75
60
45
30
15
0
22:00
22:20
22:40
23:00
23:20
23:40
00:00
UT
1600
1200
800
400
0
-400
-800
-1200
-1600
Velocity (m s^{-1})
Ground Scatter

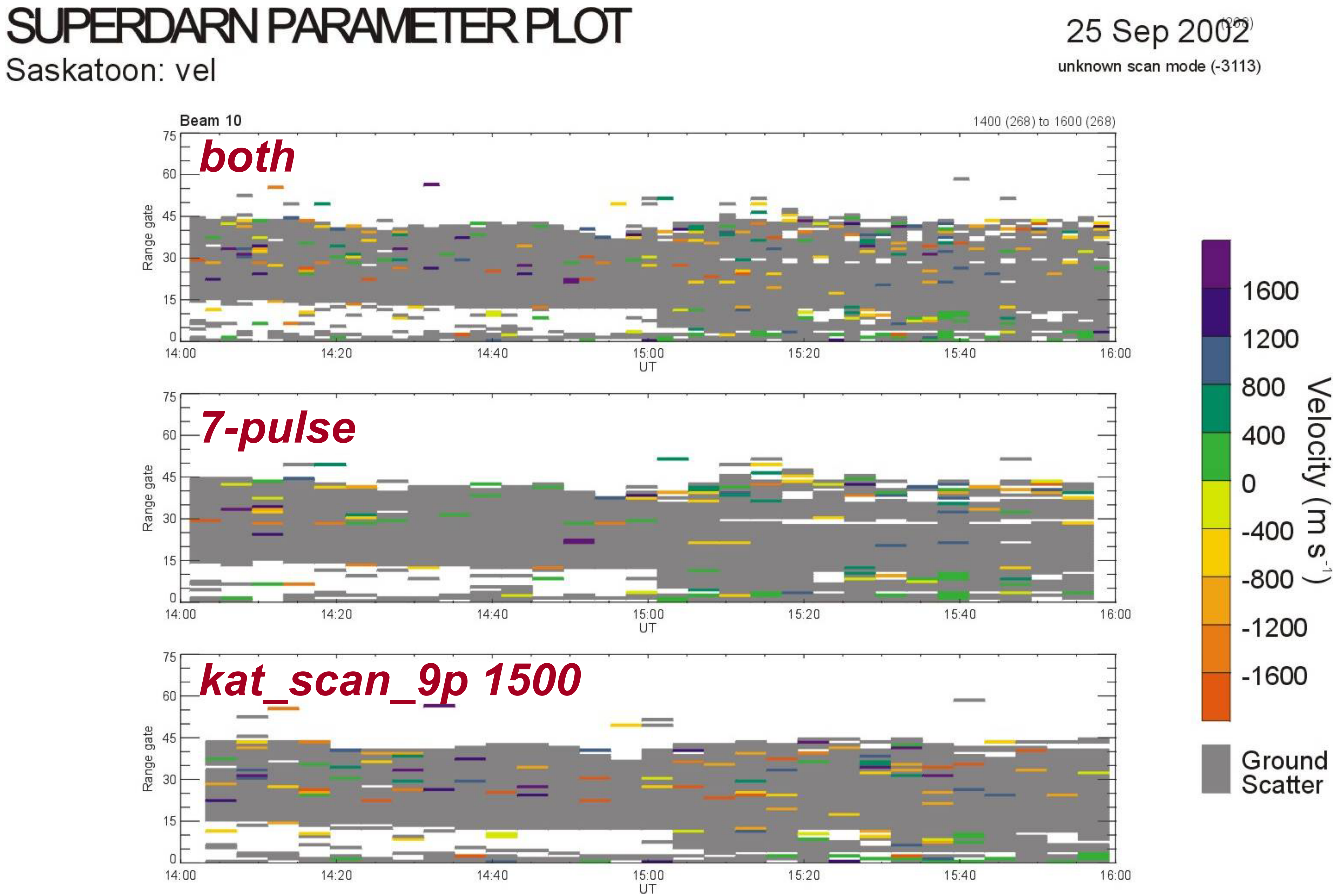
SUPERDARN PARAMETER PLOT

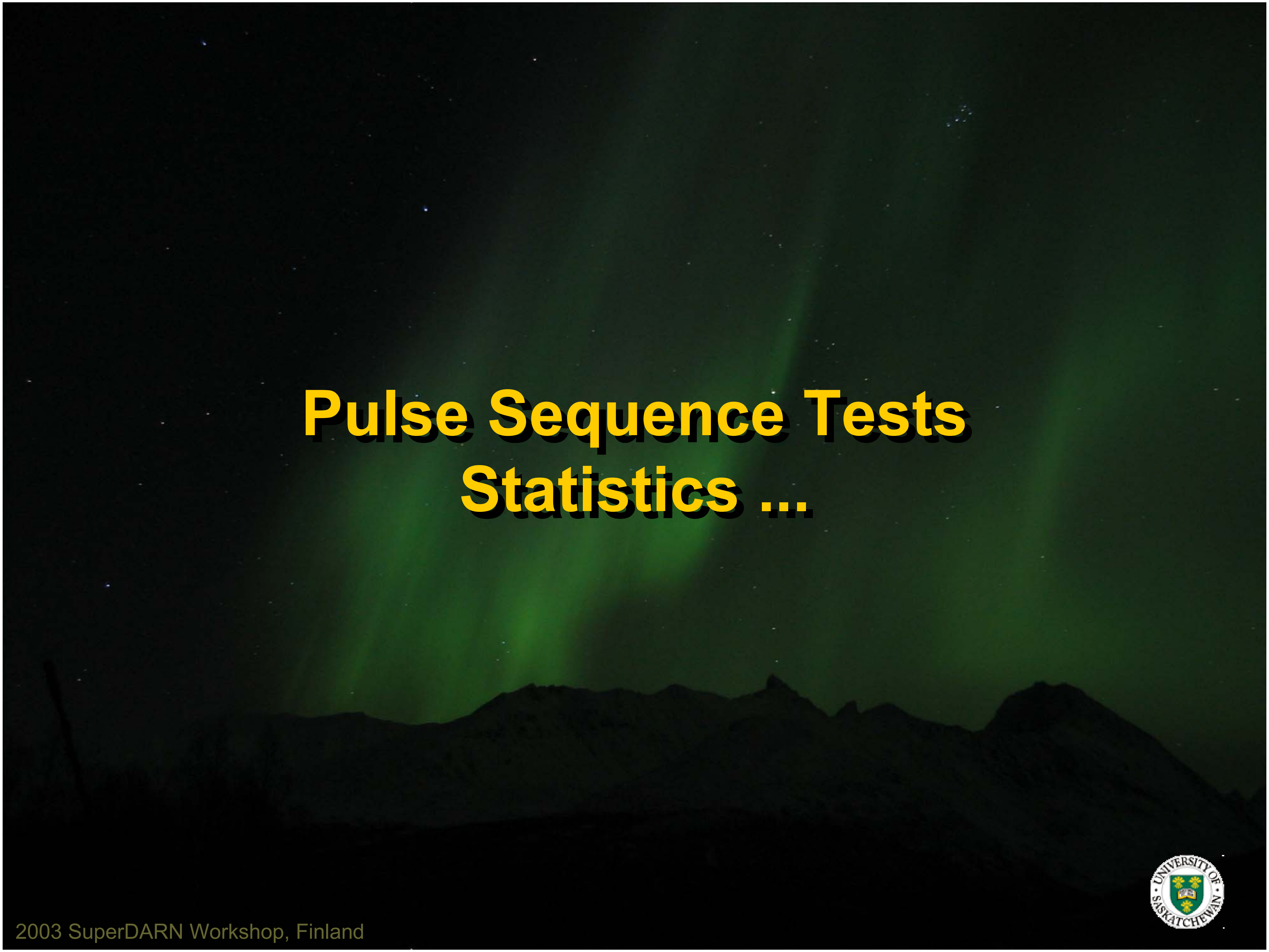
Saskatoon: vel

7 Sep 2002

unknown scan mode (-3113)




SUPERDARN PARAMETER PLOT
Saskatoon: vel
25 Sep 2002 (268)
unknown scan mode (-3113)
Beam 10
1400 (268) to 1600 (268)
both
7-pulse
kat_scan_9p 1500
Range gate
UT
Velocity (m s-1)
Ground Scatter

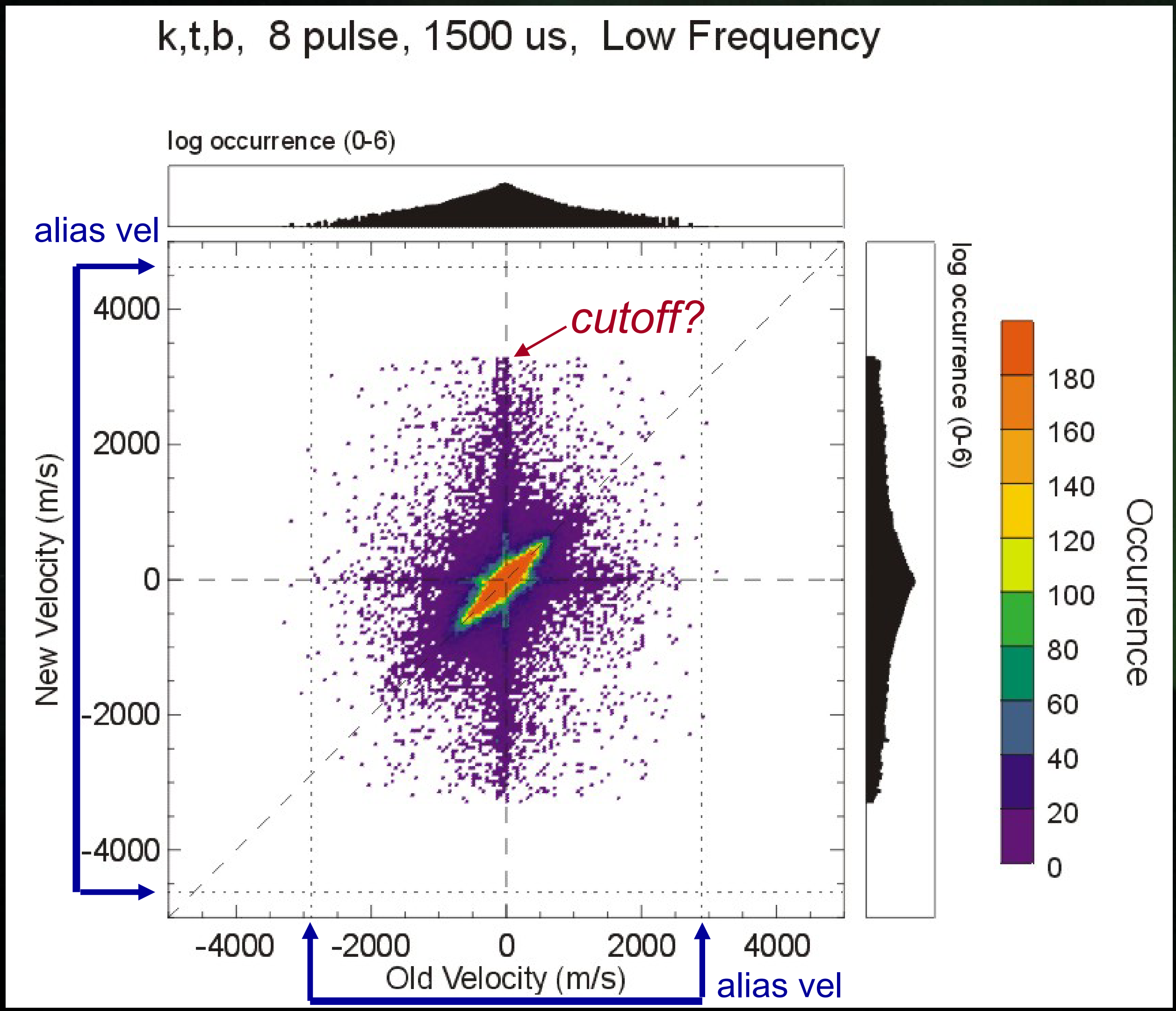


Pulse Sequence Tests
Statistics ...

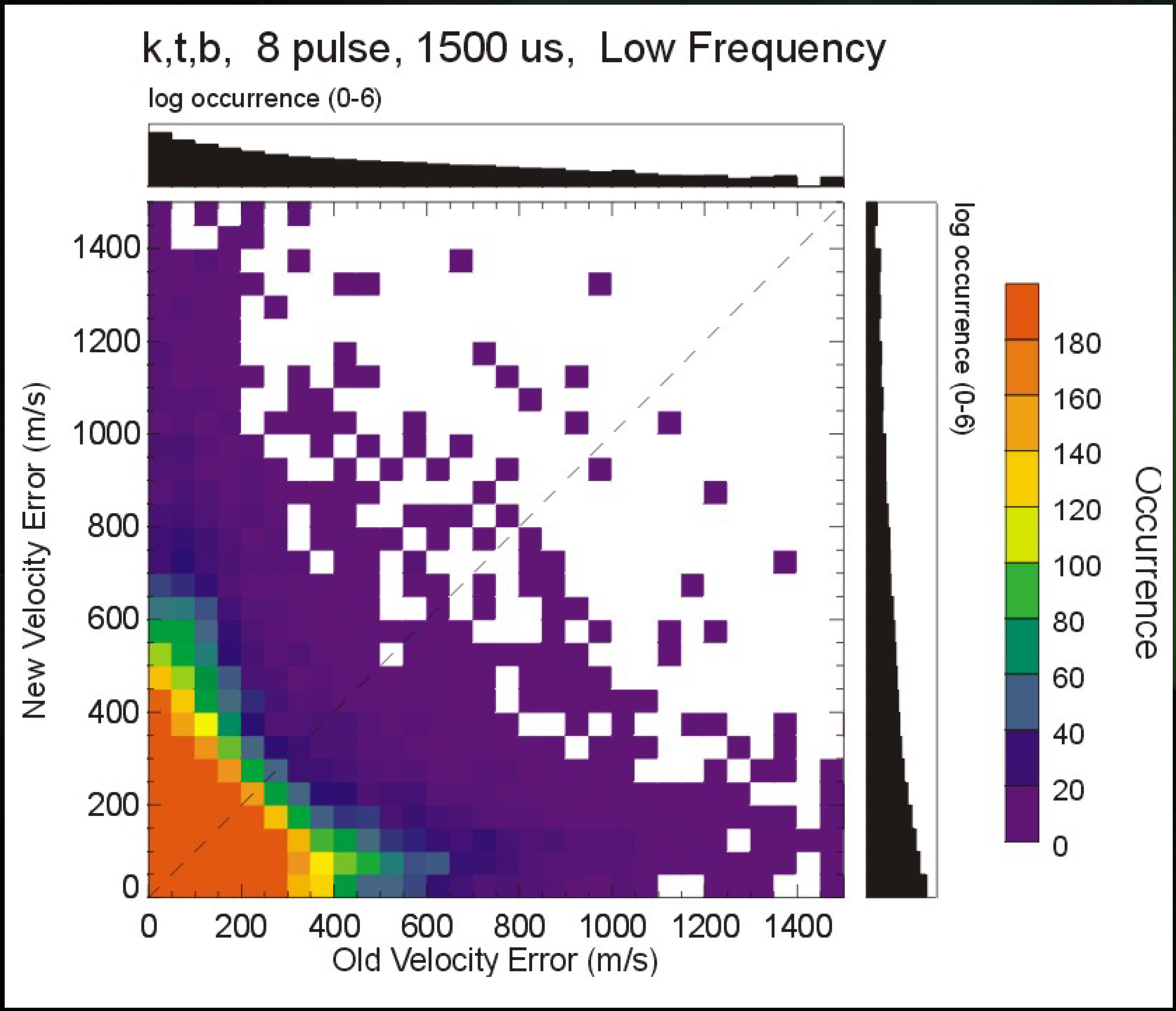
Pulse Sequence Statistics

- CUTLASS:
  - camp beam 5*, alternating pseq's
- All other SD radars:
  - interleaved full scans, alternating pseq's
- Data Selection Criteria:
  - same beam in successive scans
  - ionospheric scatter in both samples
  - 'qflag' good in both samples

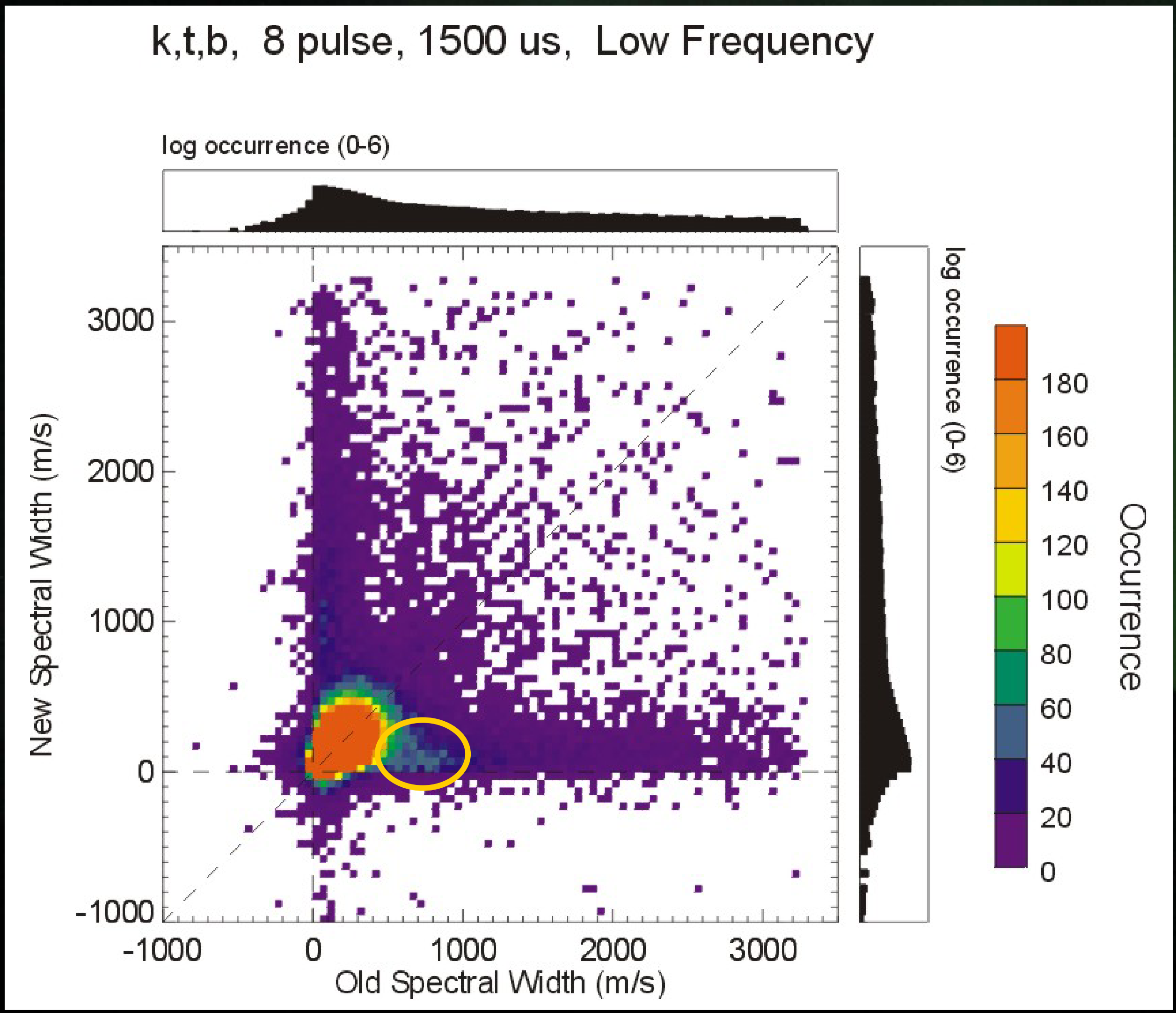
Old vs. New Velocity



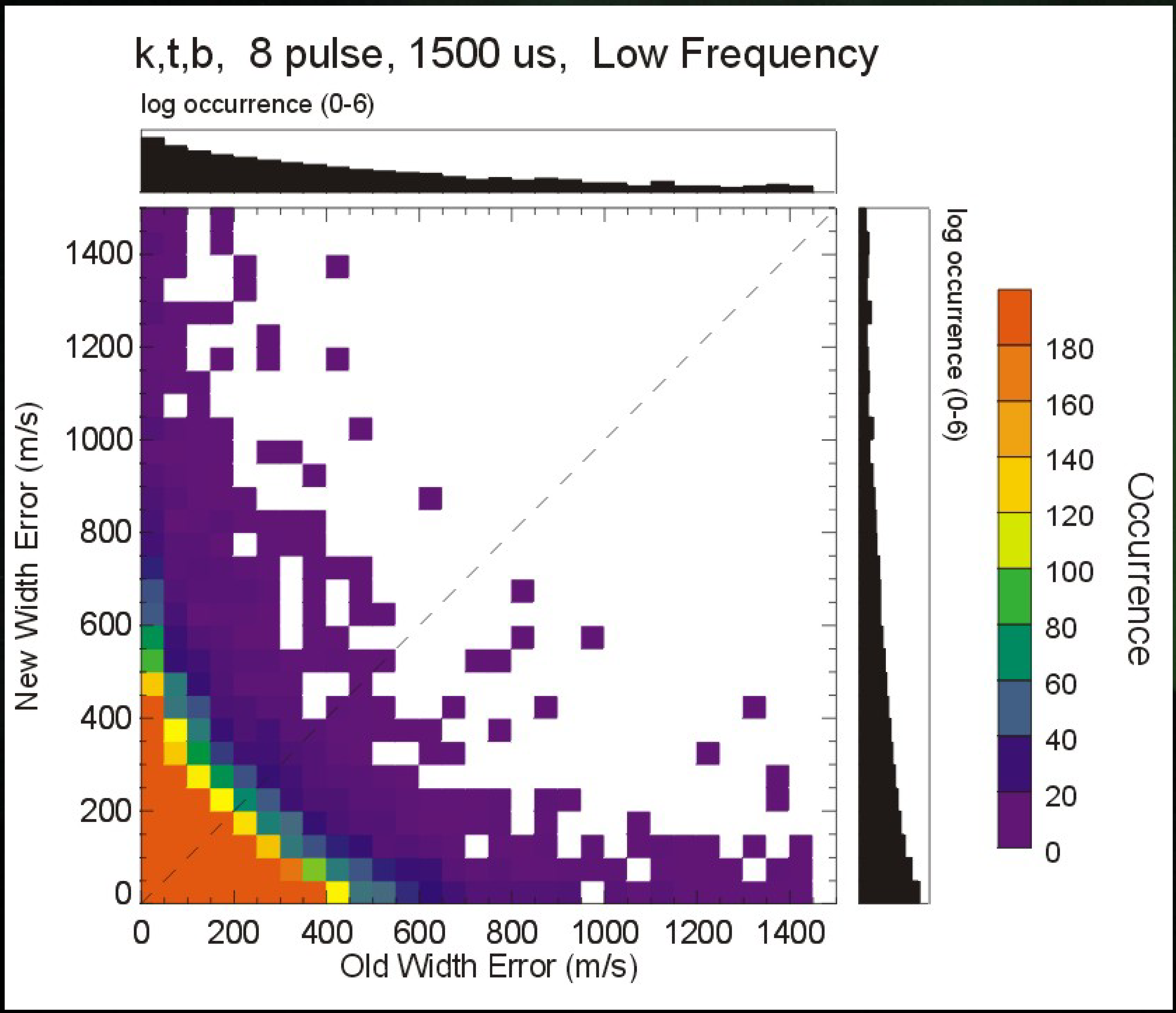
Old vs. New Velocity Error



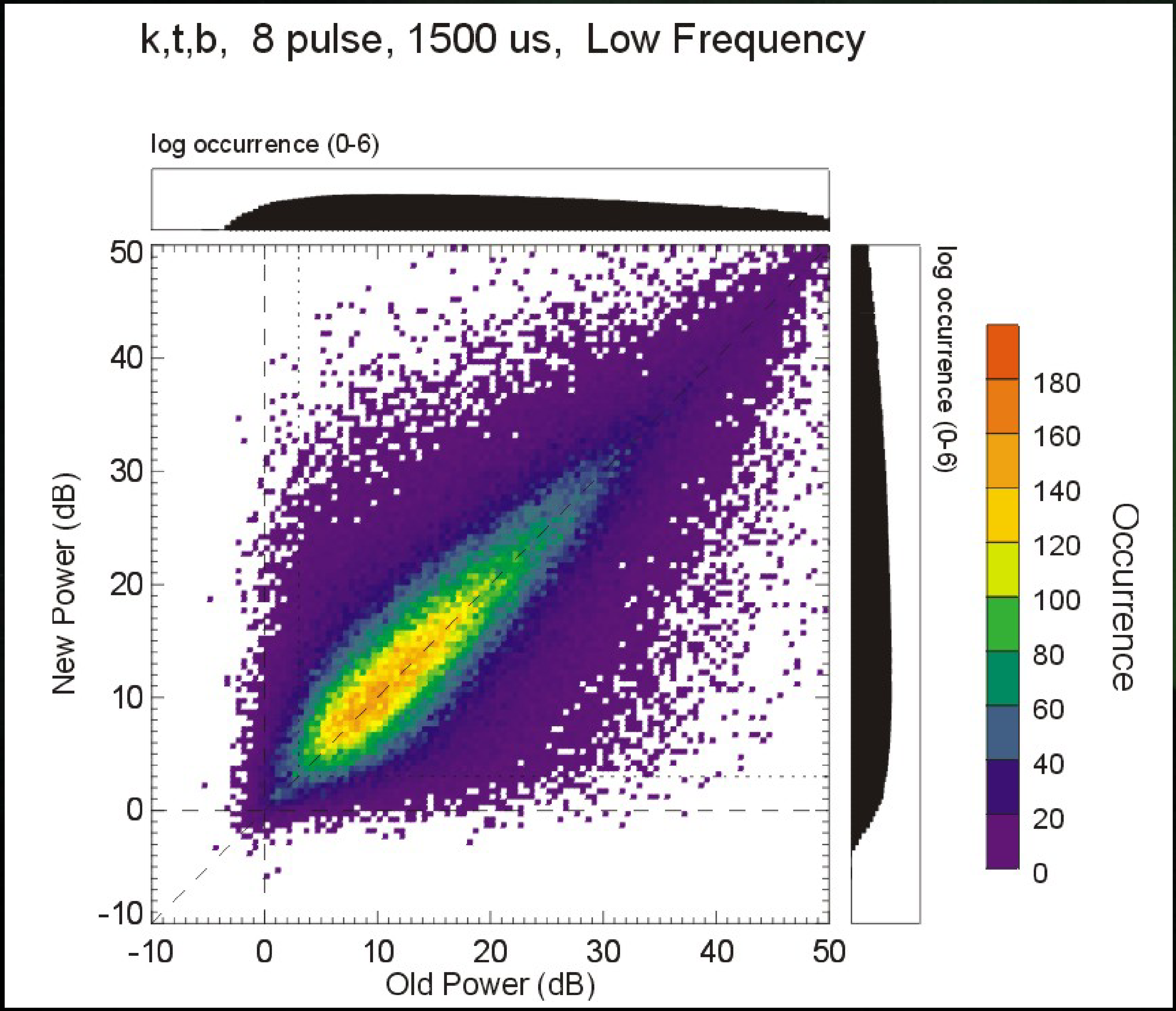
Old vs. New Spectral Width



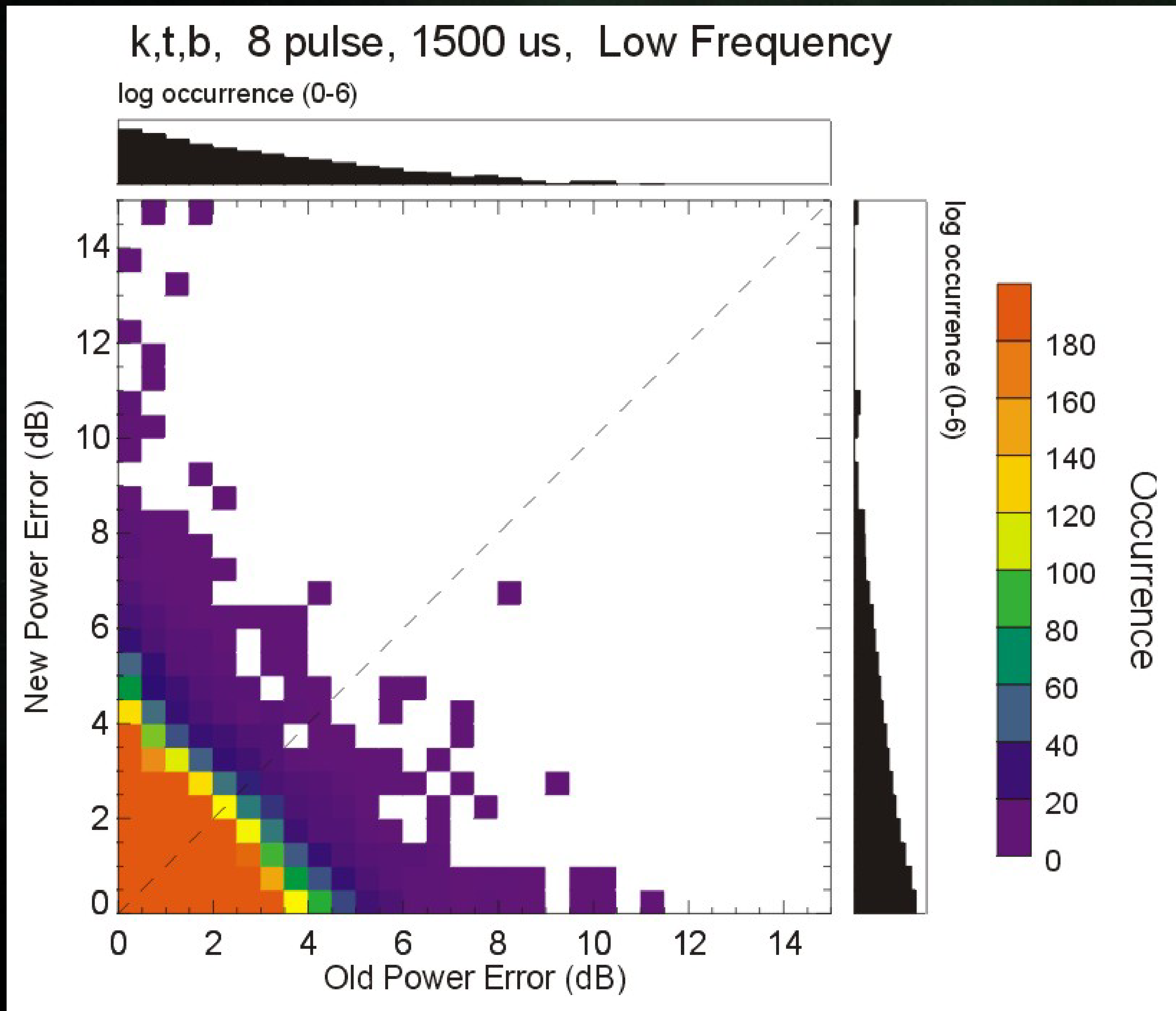
Old vs. New Width Error



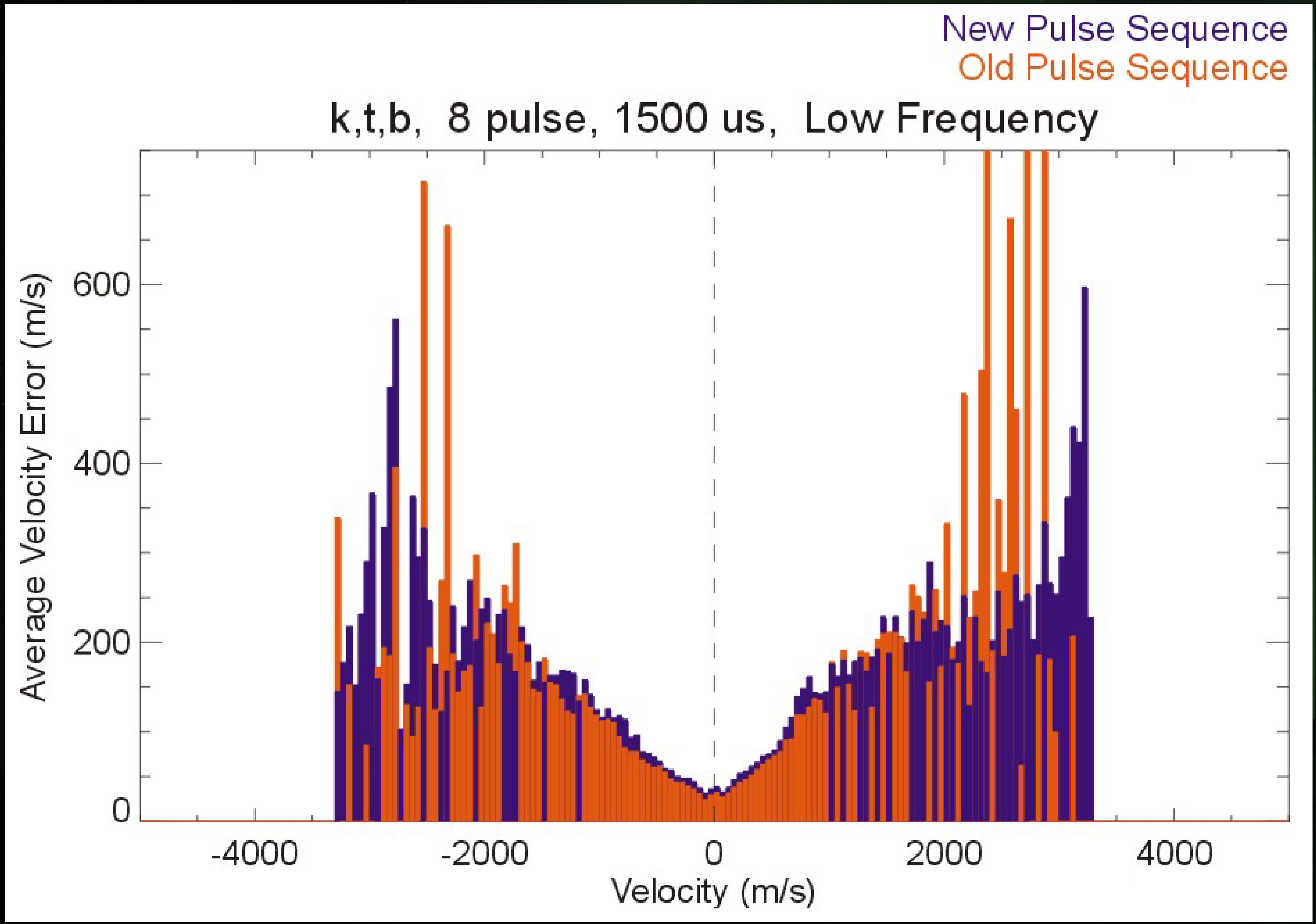
Old vs. New Power



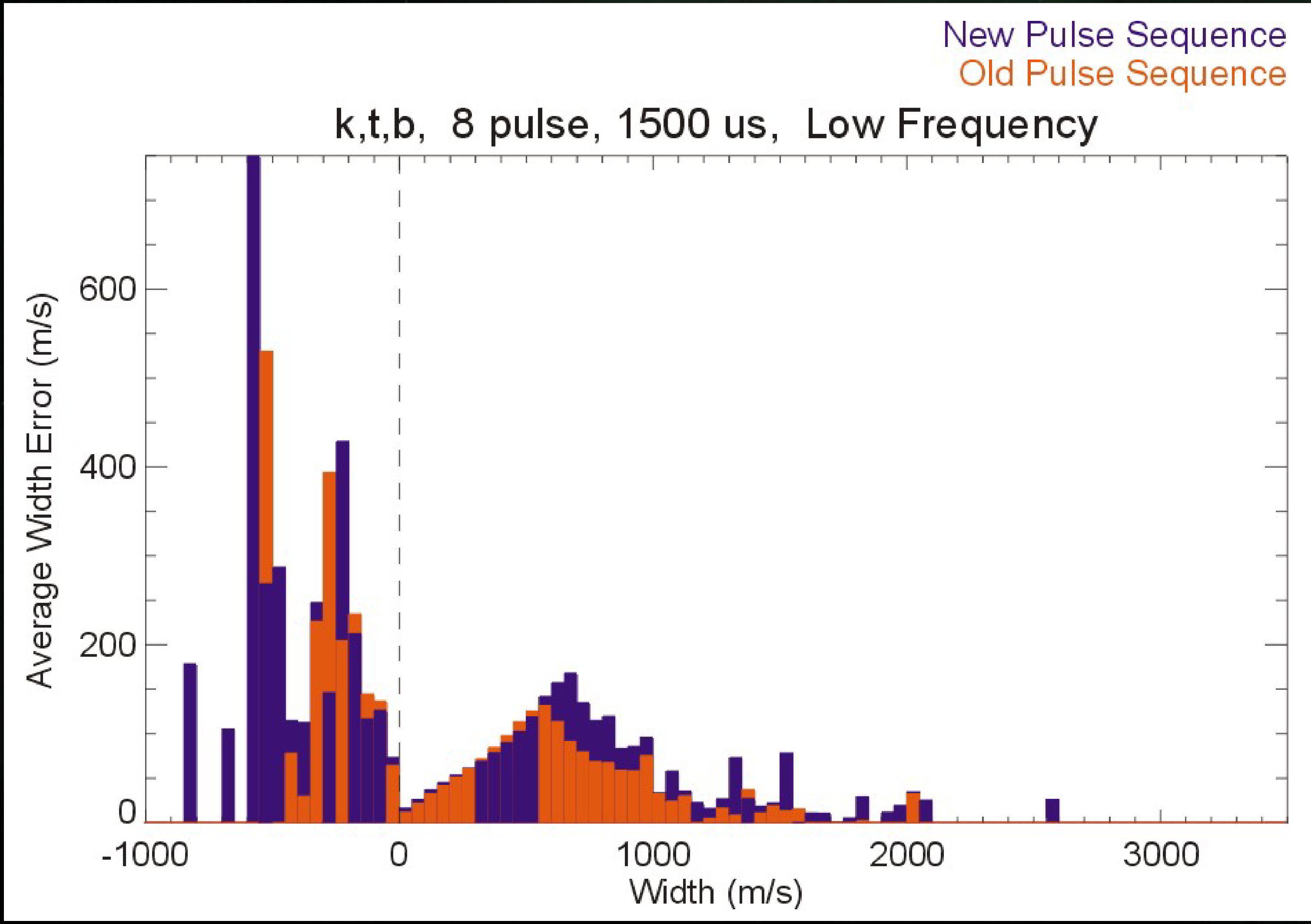
Old vs. New Power Error



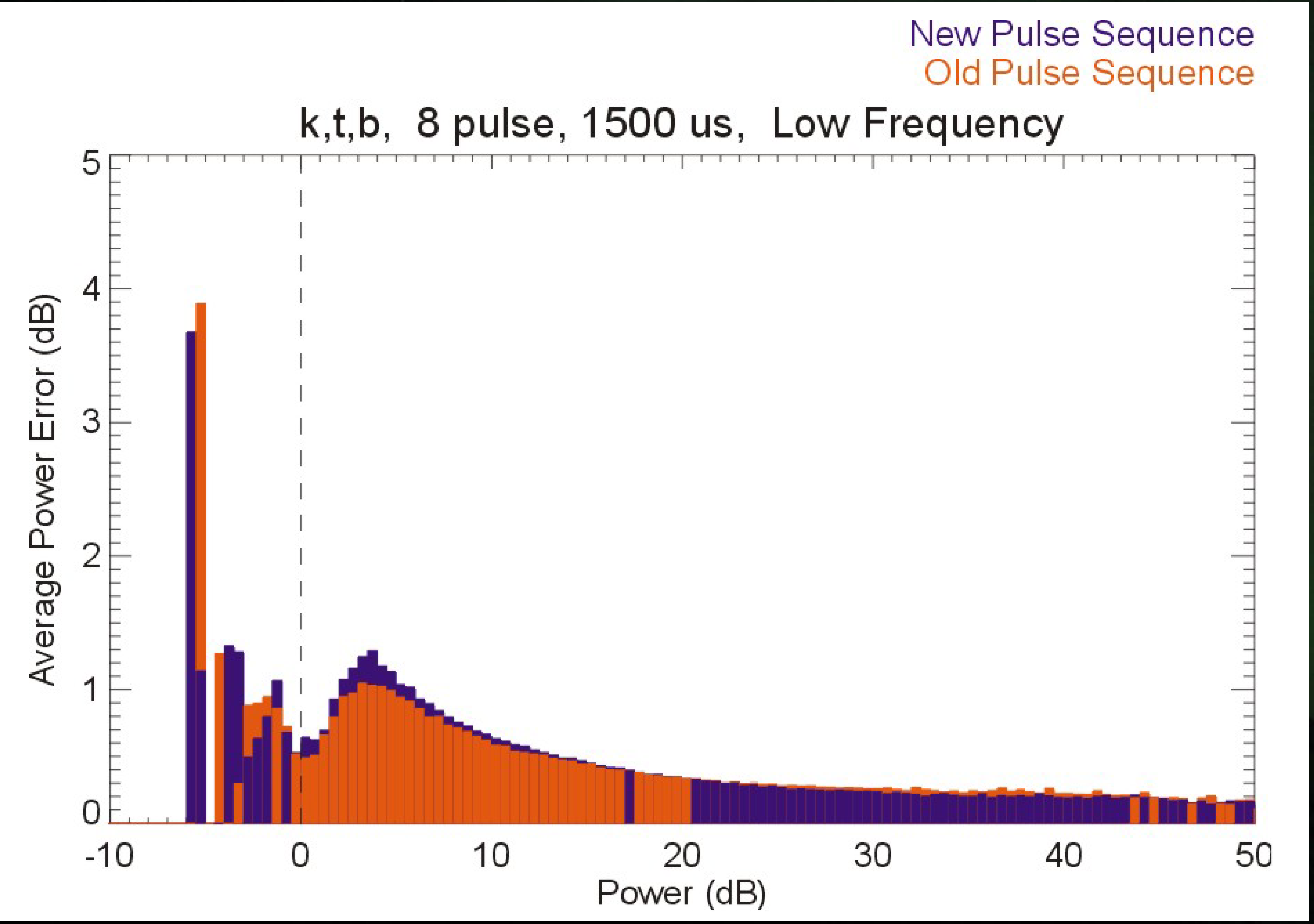
Average Velocity Error



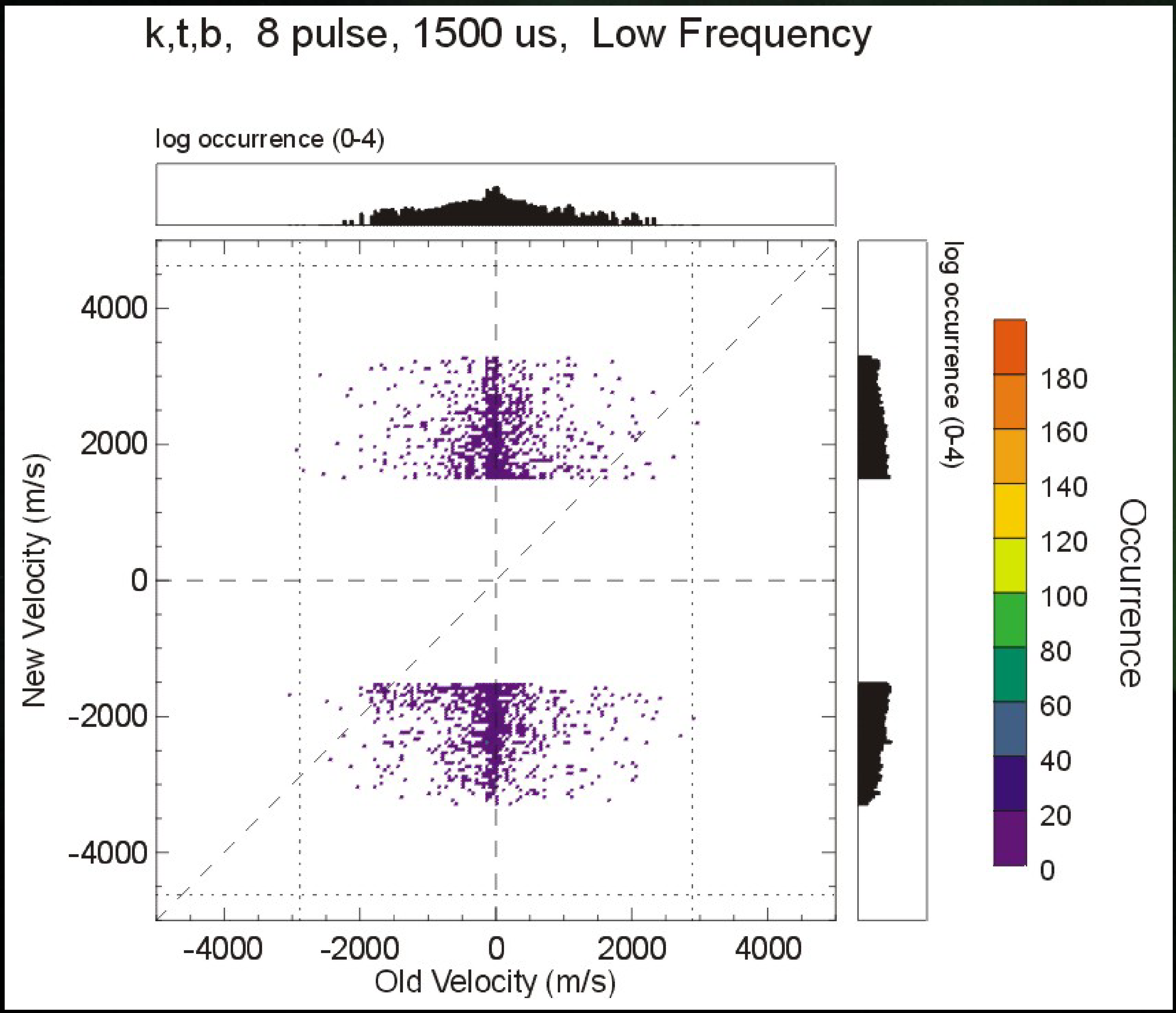
Average Width Error



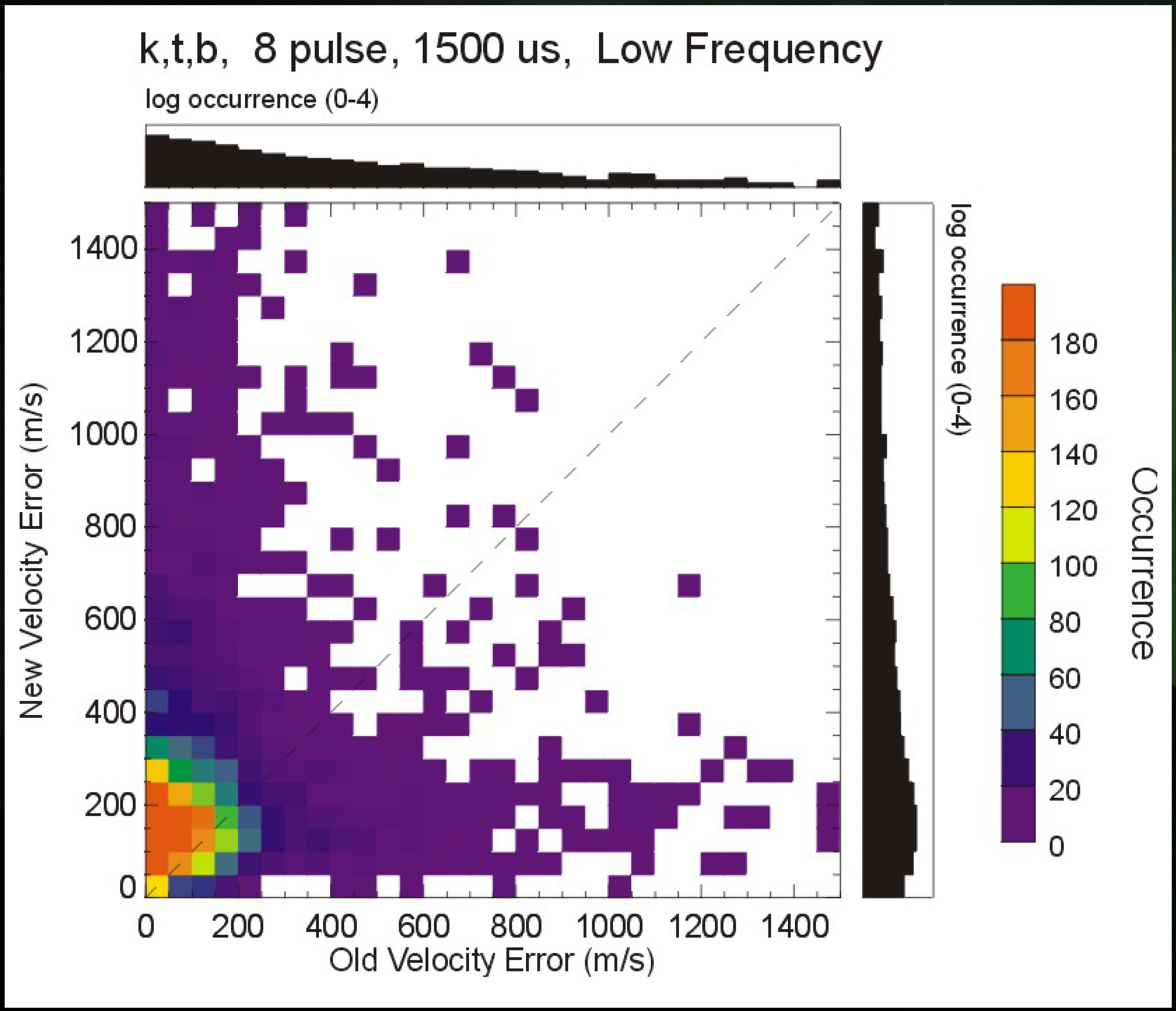
Average Power Error



Old vs. New Velocity - Cutoff



Old vs. New Velocity Error - Cutoff



FITACF Summary

- FITACF cleverly determines mean velocity, power, and width of spectrum.
- Current pulse sequence works well, but there is always room for improvement.

Conclusions

- Data examples show clear differences between pulse sequences:
  - effect of bad lags
  - persistent differences b/w fitted parameters
- Higher velocities measured by new pulse sequences.
- Better determination of ACFs with more samples
  - to me seems to be more important than velocity aliasing (but mostly moderate velocities measured during these tests ~ several hundred m/s flows)

Future Work

- Test for high flows
  - e.g., þykkvibær/Stokkseyri zonal beams.
- Stereo test:
  - measurements from same region.
  - possible stereo badlags problems?
- Statistics for only high flow events.
- % ground/iono scatter.
- Case study of ACFs of pseqs.
- Re-evaluate errors, ground scatter definition, etc.