

Optical Remote Sensing with Coherent Doppler LIDAR

Part 2: Detection, Processing, and Analysis of LIDAR signals

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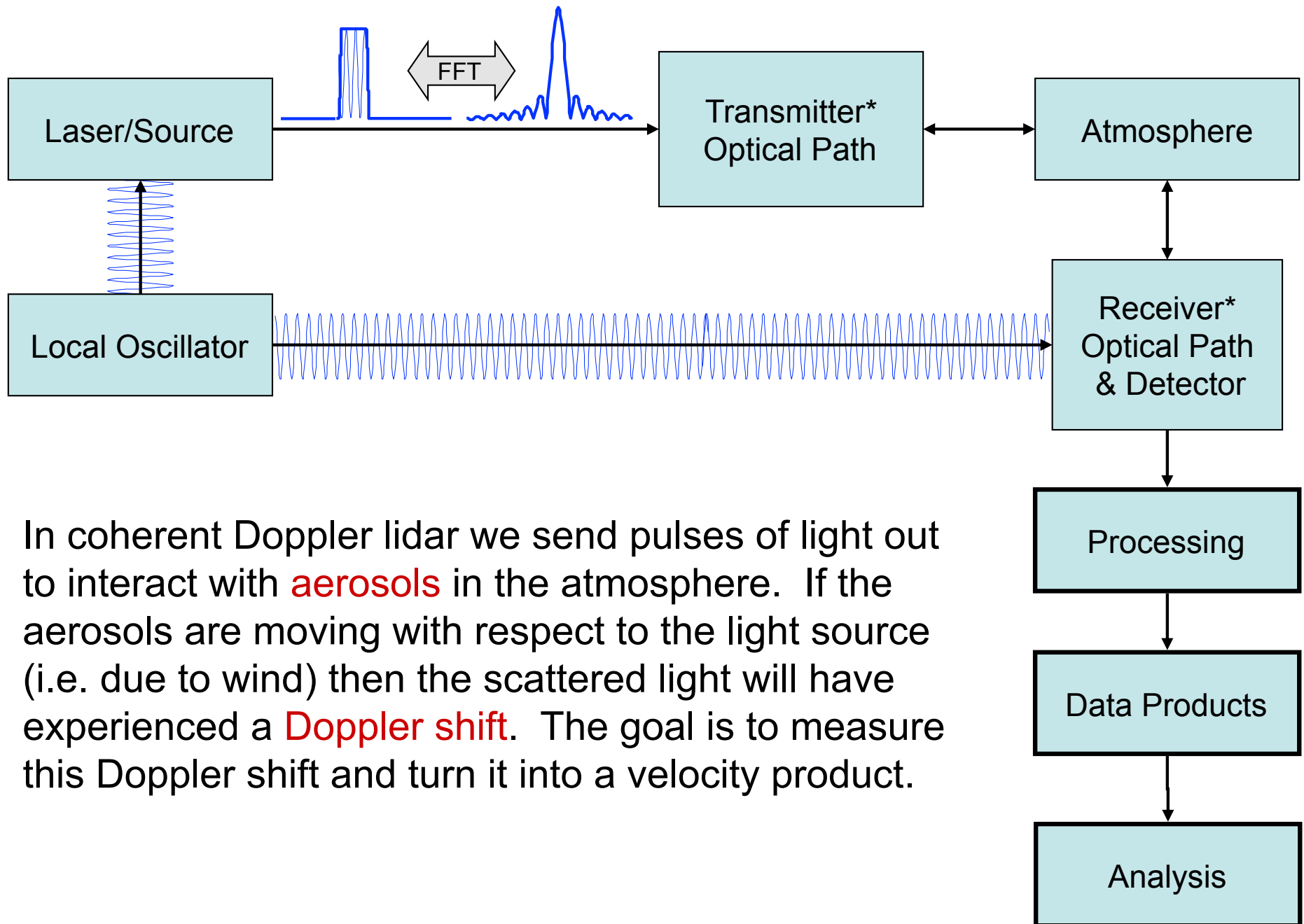
<http://www.esrl.noaa.gov/csd/groups/csd3/>

²Current affiliation: Ball Aerospace

April 4, 2011



Coherent Doppler Lidar



In coherent Doppler lidar we send pulses of light out to interact with **aerosols** in the atmosphere. If the aerosols are moving with respect to the light source (i.e. due to wind) then the scattered light will have experienced a **Doppler shift**. The goal is to measure this Doppler shift and turn it into a velocity product.

* Transmitter & receiver paths usually share common optics

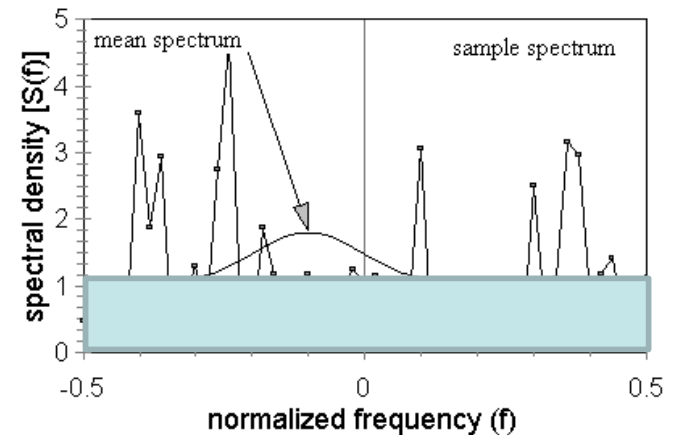
The Coherent Doppler Lidar Equation


The CNR equation can be written explicitly as

$$CNR(R) = \frac{\eta\beta T^2 c E_T}{h\nu B 2R^2} \frac{\pi D^2}{4} \left[1 + \left(\frac{\pi D^2}{4\lambda R} \right)^2 \left(1 - \frac{R}{F} \right)^2 + \frac{D^2}{2\rho_o^2} \right]^{-1}$$

If the focus is at the range of interest, and if there is no turbulence, the CNR equation reduces to:

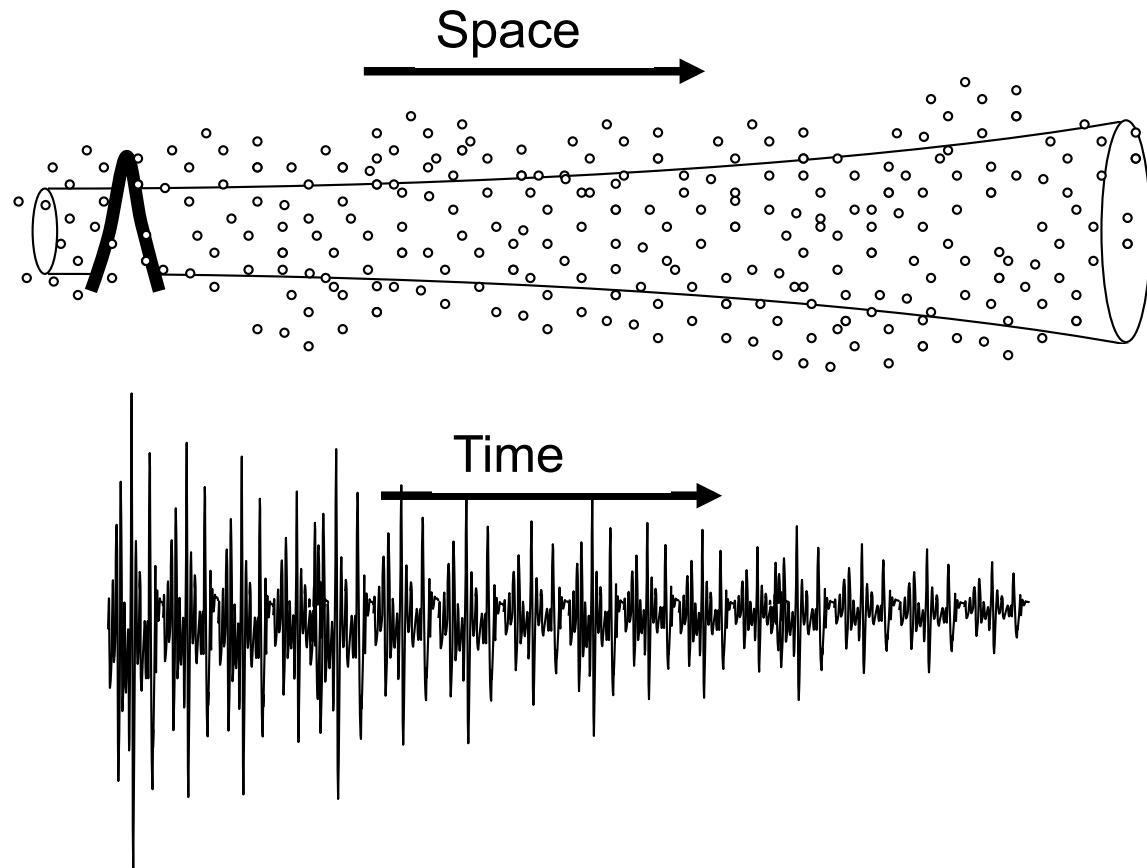
$$CNR(R) = \frac{\eta\beta T^2 c E_T}{h\nu B 2R^2} \frac{\pi D^2}{4}$$



- 
- Coherent Detection
 - Laser
 - Local Oscillator + shift
 - Transmit/Receive paths
 - Atmosphere
 - **Detection & Processing**
 - Analysis and Data products
 - Field Work

Return signal processing

- Return signal mixes with local-oscillator creating the beat frequency + offset signal. $f_{\text{detected}} = f_a - f_{LO} = f_{Dopp} + f_{offse}$
- This beat signal is optically detected, analog filtered, demodulated, and sampled... but not necessarily in that order.



Return signal processing

- This beat signal is optically detected and then...
 - Analog filtered
 - Demodulated (analog or digital)
 - Sampled (one or two channels)

...but not necessarily in that order.

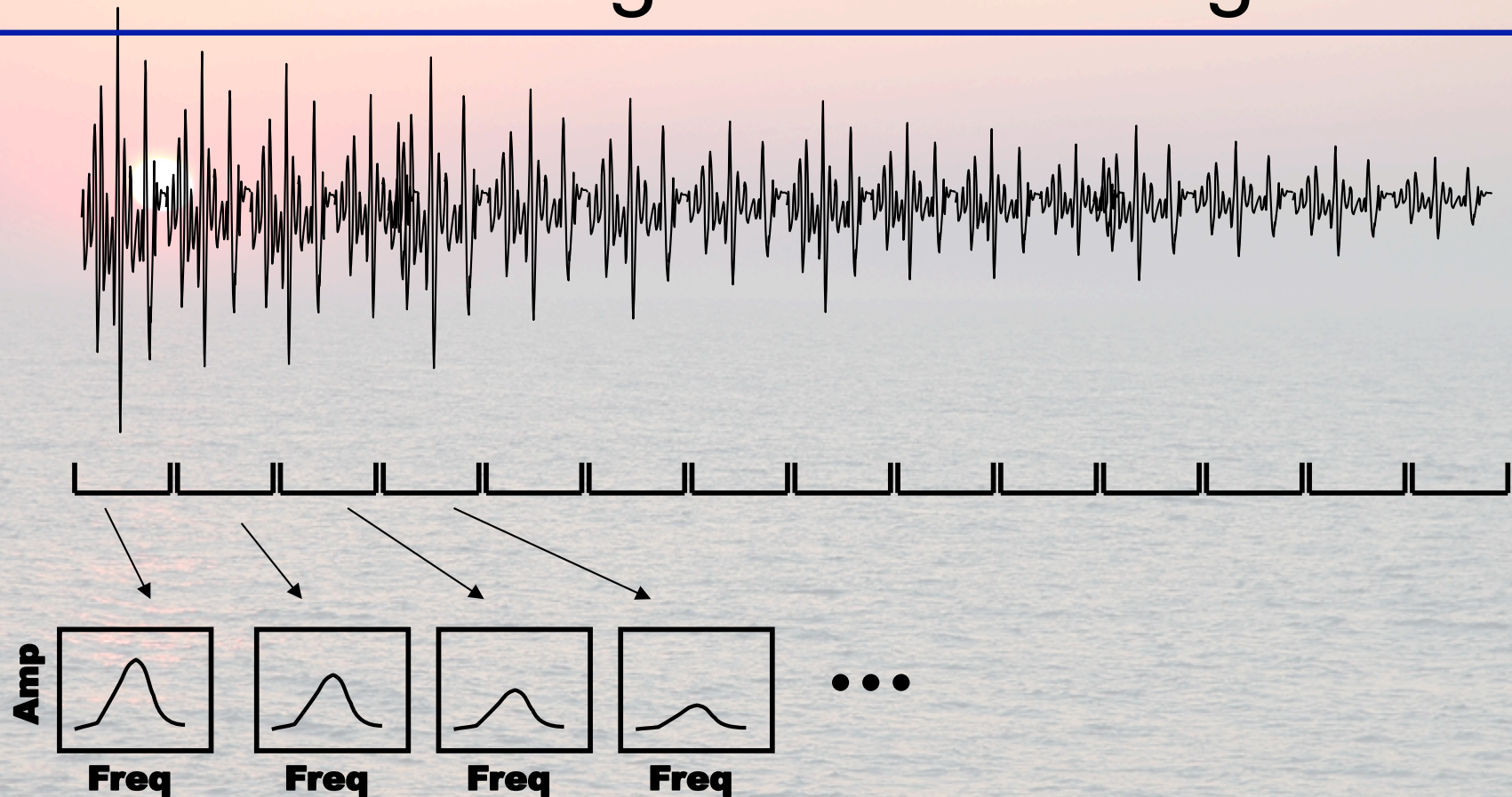
HRDL

- Complex analog demodulation
- Analog filtering (2 channels)
- Sampling – (2 channels)

MOPA

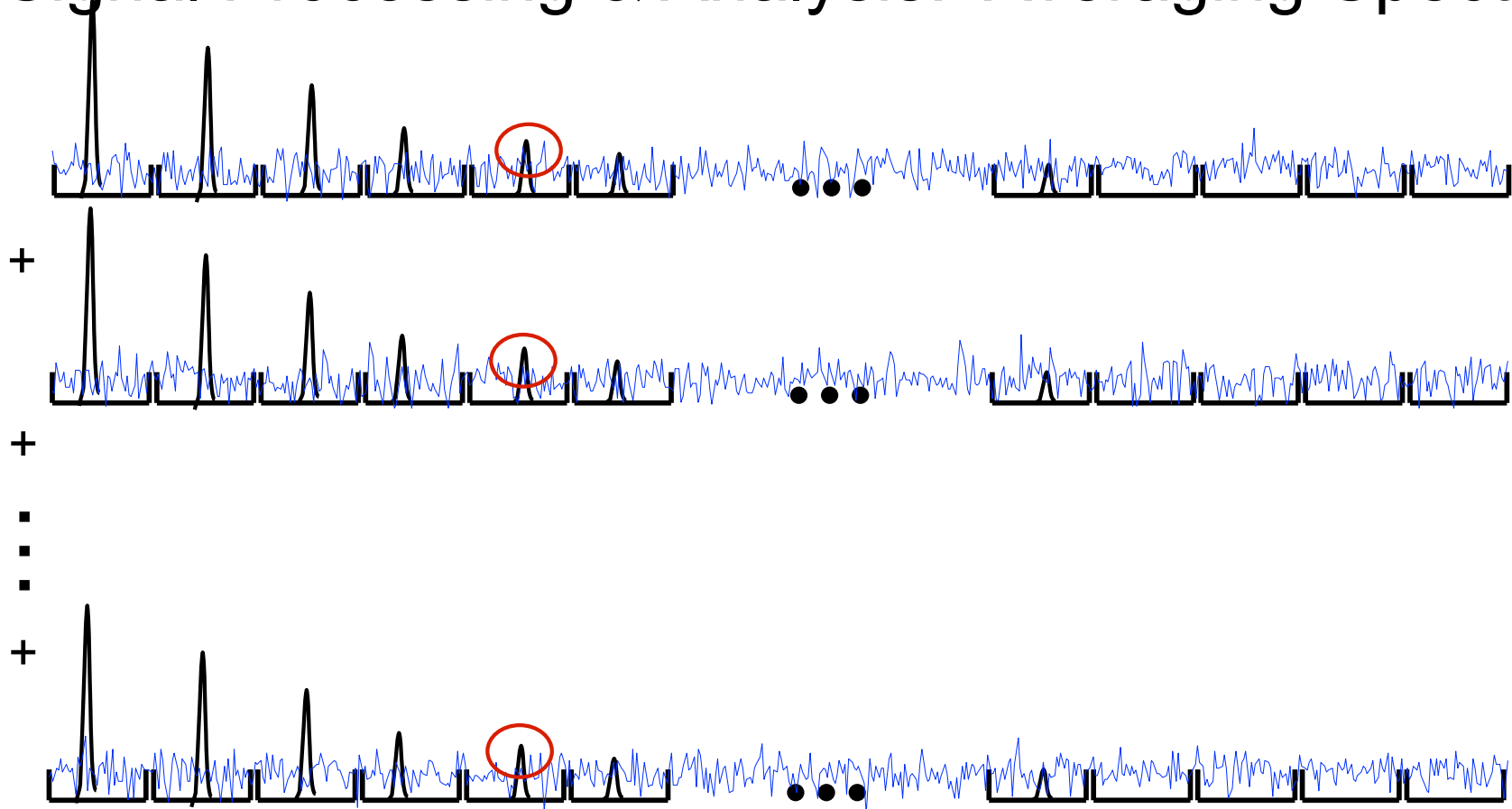
- Analog Filtering
- Sampling
- Digital demodulation

Return Signal Processing

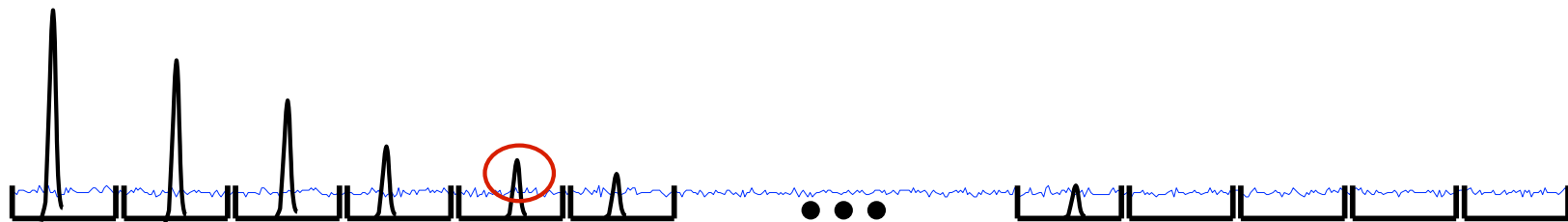


- Break into gates (equal to laser pulse length)
- Find spectrum for each gate
- Average spectra for same range gate from different pulses
- Find frequency peak for each gate to find Doppler shift and intensity as a function of range

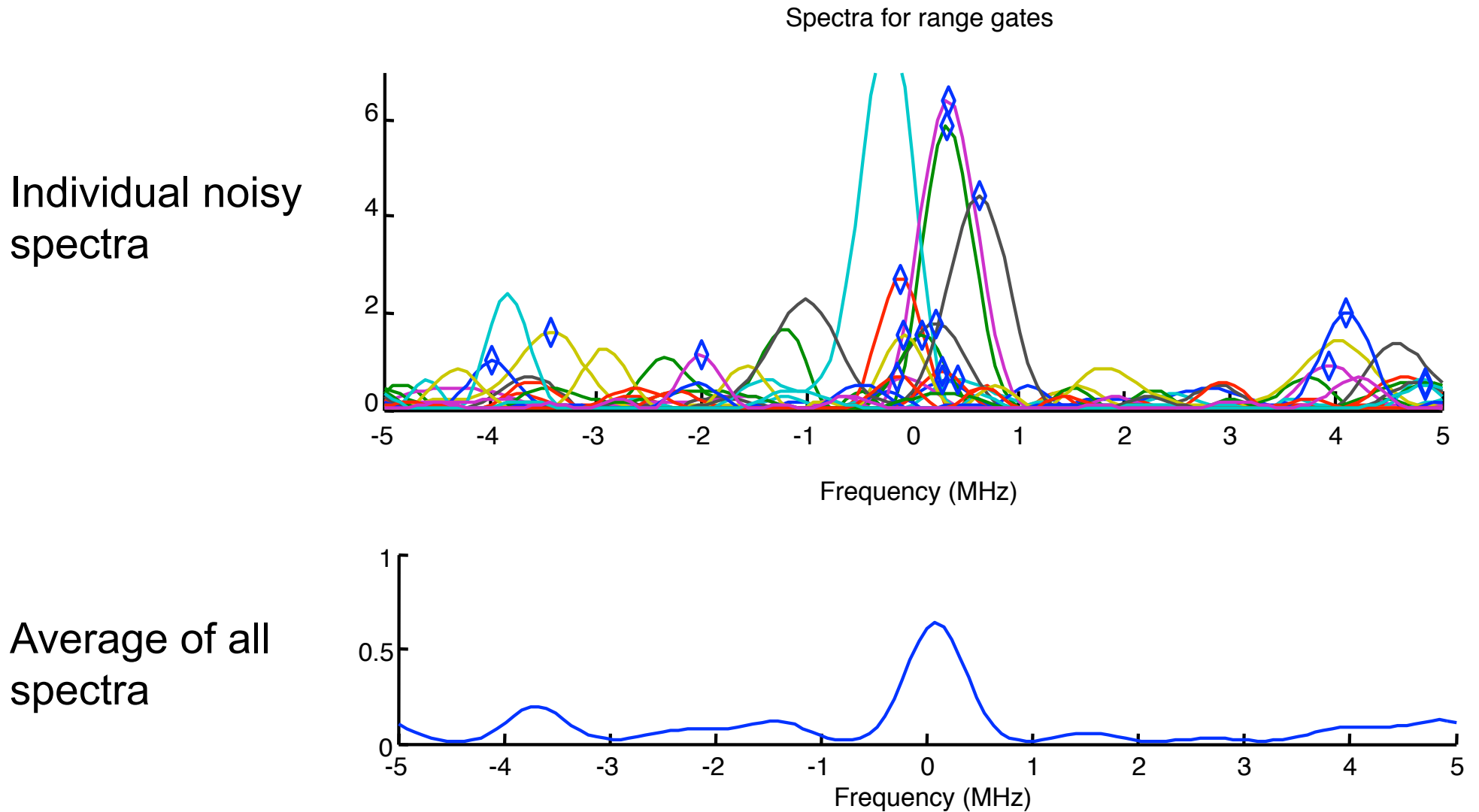
Signal Processing & Analysis: Averaging Spectra



- Average the spectra and THEN estimate the frequency/velocity
- Why not the other way around?



Signal Processing & Analysis: Averaging Spectra

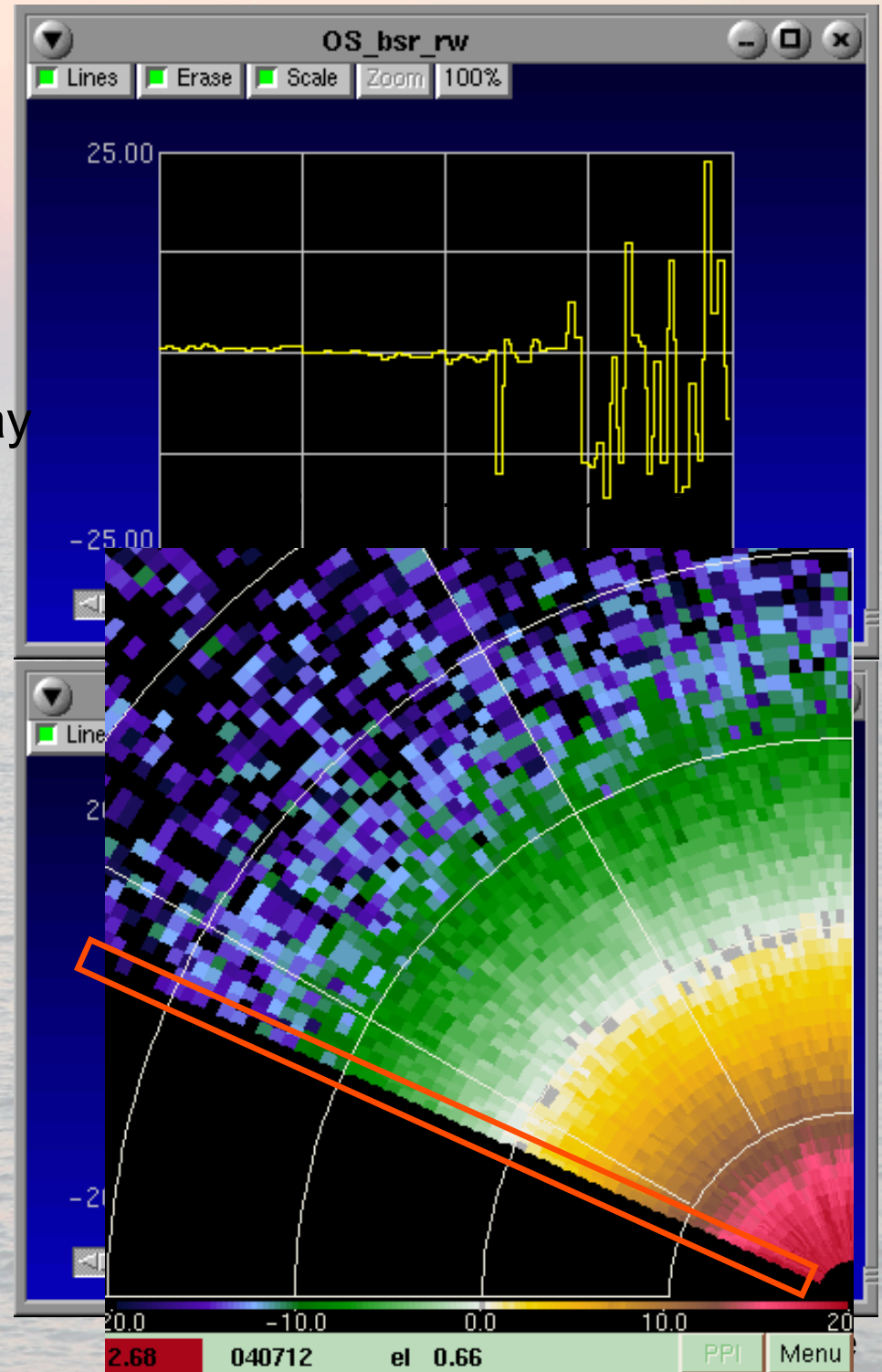
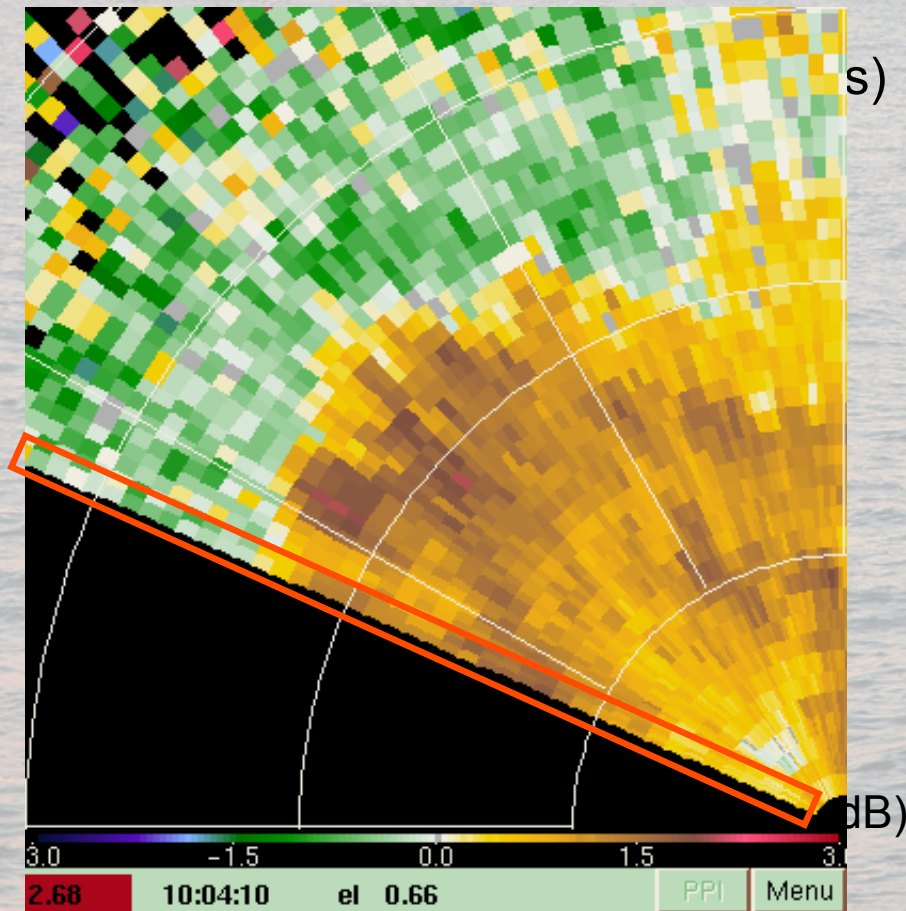


Result: Average CNR does NOT change
-but velocity estimate *precision* improves

Example Data

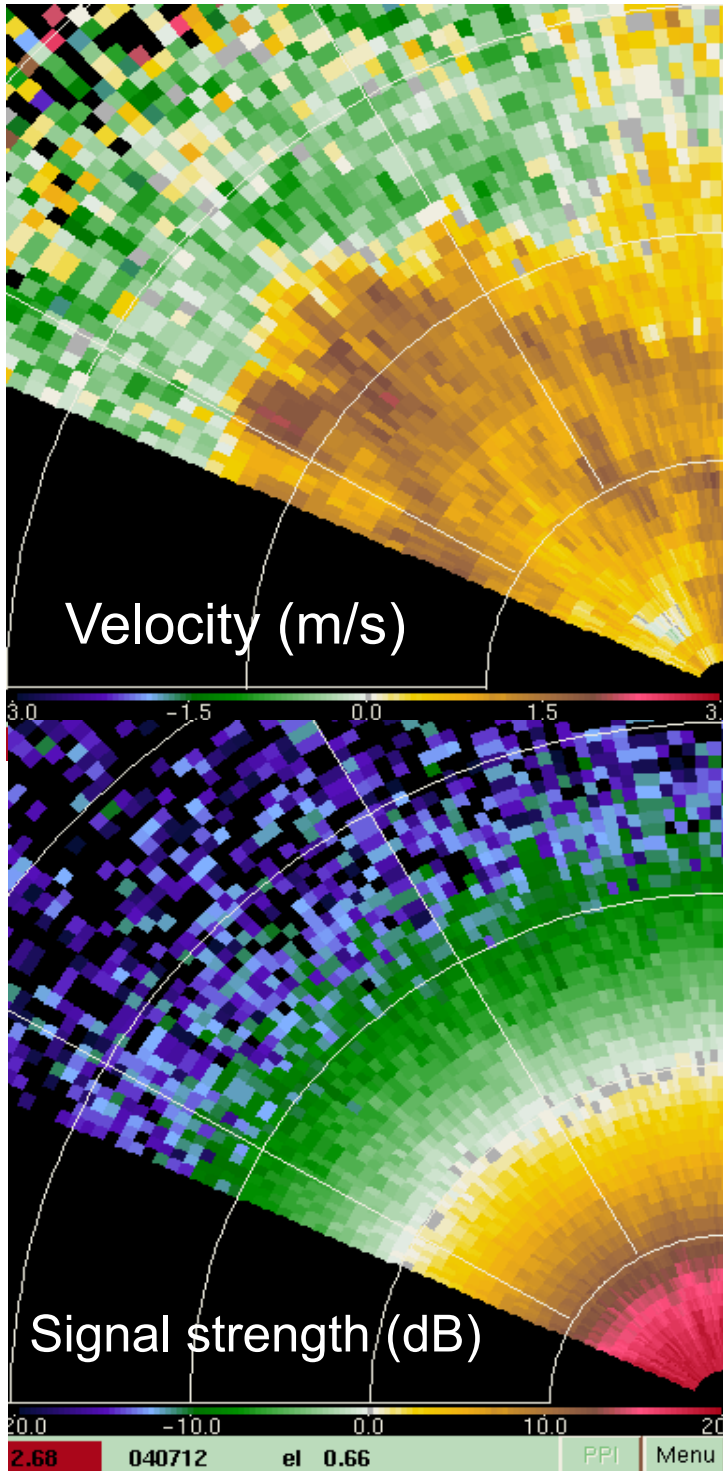
Single beam range resolved estimates: 150m / 2X sec
Color code and combine single beam results into scanning display

Velocity (m/s)

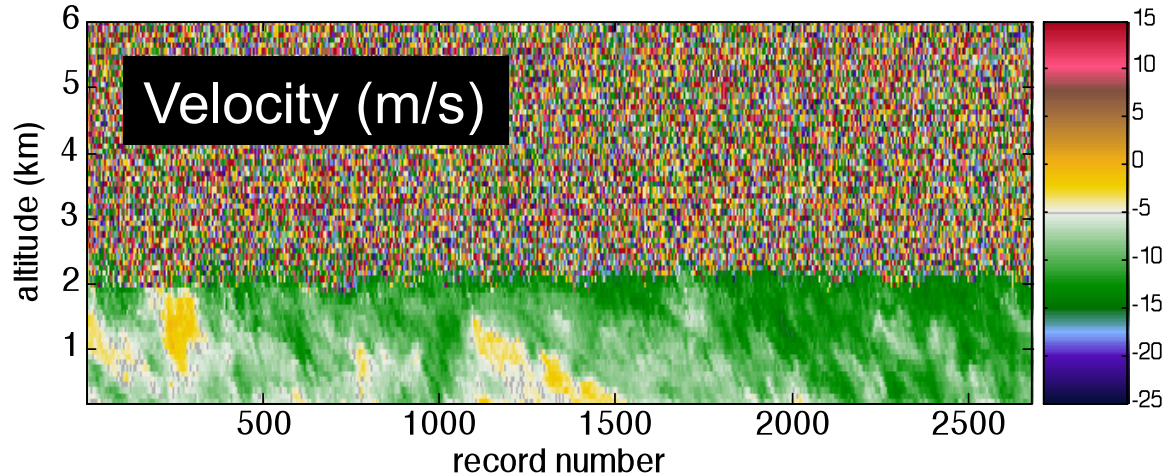


Doppler lidar data displays

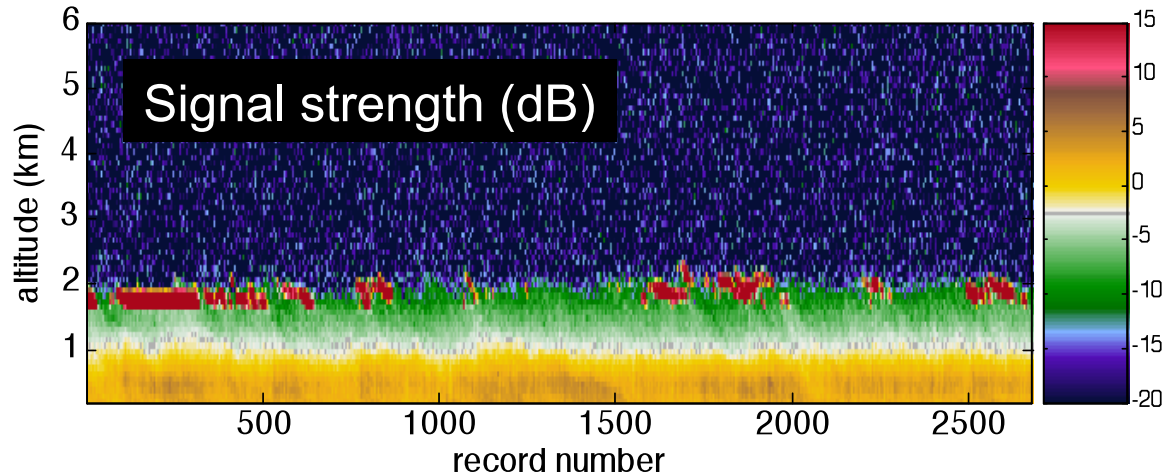
- Depend on scan type
- versus range or altitude
- colormap: Cool = toward the lidar
Warm = away from the lidar



MOPA:GW031030_1352, File 8. Velocity Estimate



MOPA:GW031030_1352, File 8. wbSNR



Signal Processing: Real Data Example

This data comes from an instrument called the Twin Otter Doppler Wind Lidar (TODWL). It flies in an aircraft and points down at the earth.

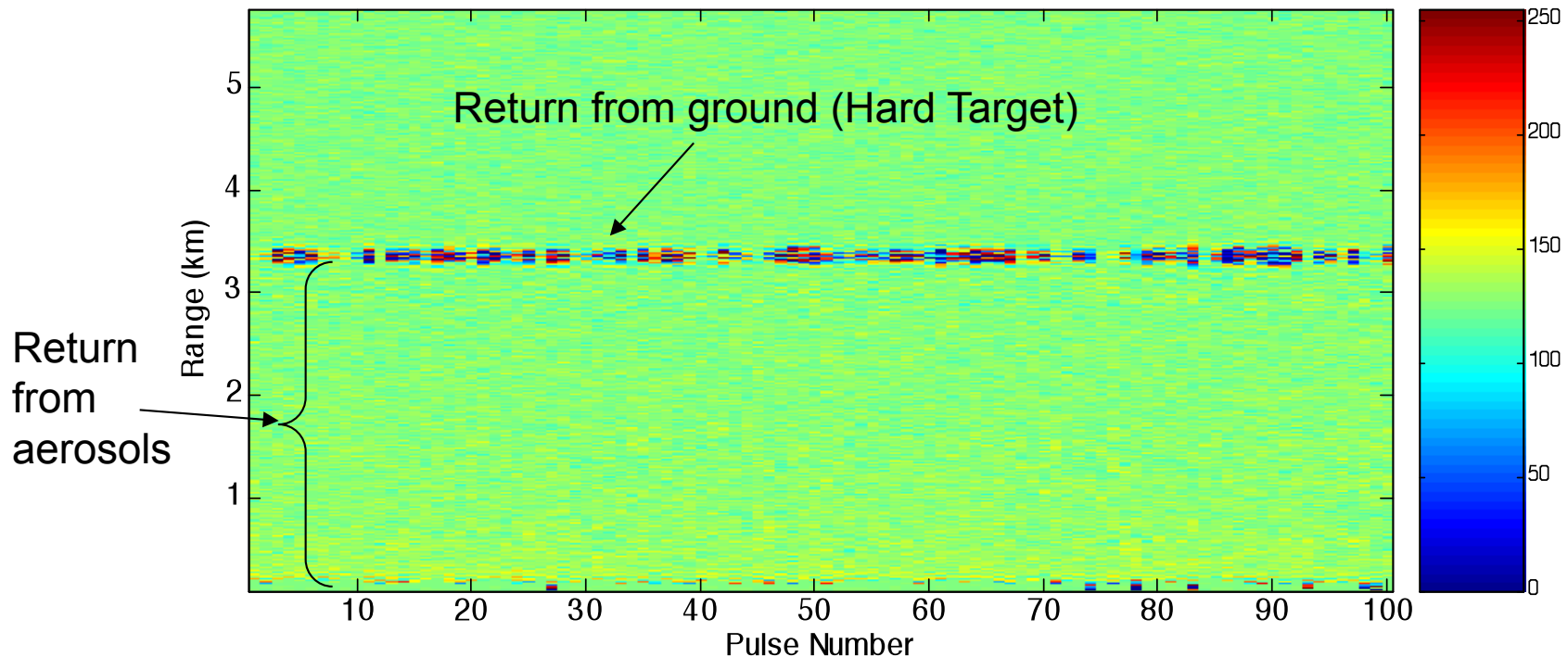
The figure below contains a visual plot of the raw data (3900 samples per pulse) signal counts vs. range and pulse #.

Range for this plot (and all other plots we'll show here) is line-of-sight (LOS) range.

Goal: Calculate velocity and CNR versus range for this data set.

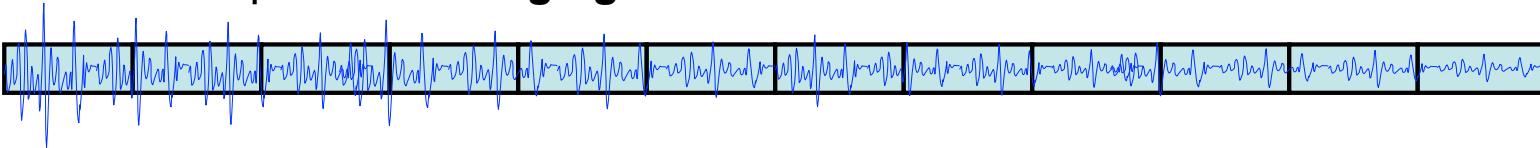
TODWL Parameters	Value
Wavelength	2.05 microns
Energy/pulse	5 mJ
Receiver Aperture Diameter	9 cm
PRF	80 Hz
Sampling Rate	100 MHz
Search bandwidth	50 MHz
Points per gate	64
Gate Width	96 meters
# pts in FFT	256
# bins in signal BW	11 = 4.3 MHz
# bins in search BW	128 = 50 MHz

Signal Counts vs. Range

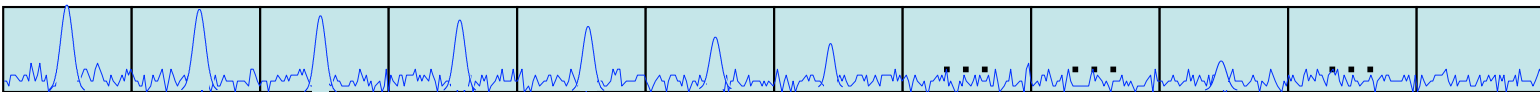


Return Signal Processing: Steps for processing example data

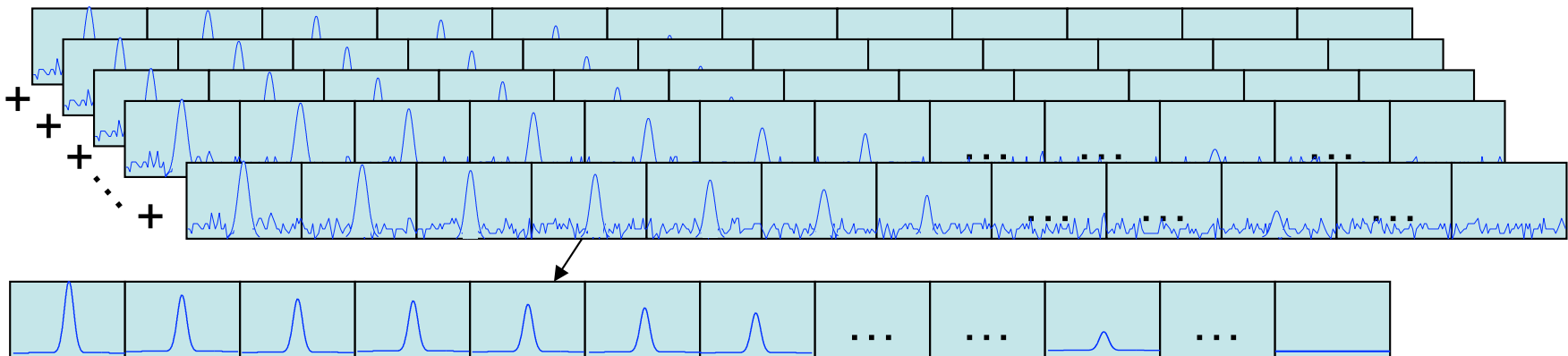
1. Divide each pulse into **range gates**



2. Find the **power spectrum** for each range gate of each pulse. (Spectrum is the squared magnitude of the FT of the data – not just the FT)

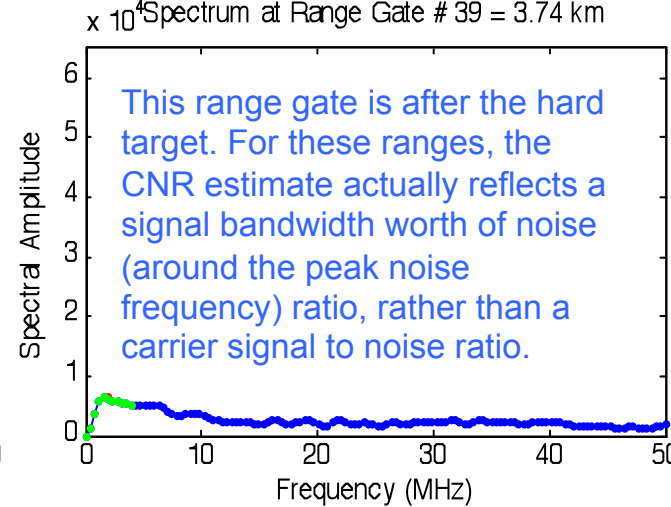
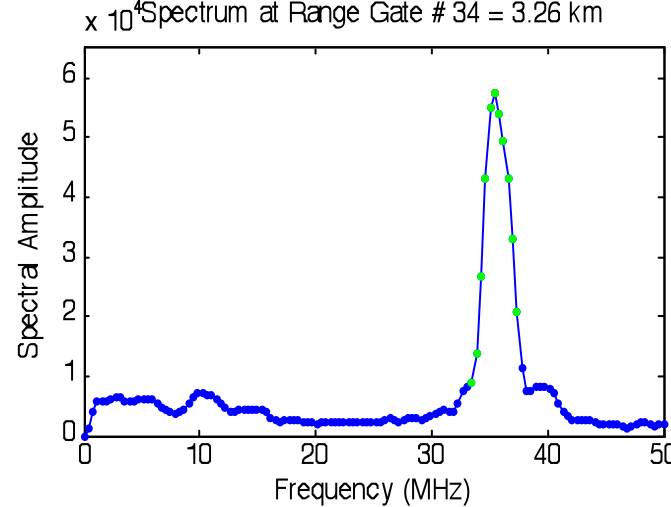
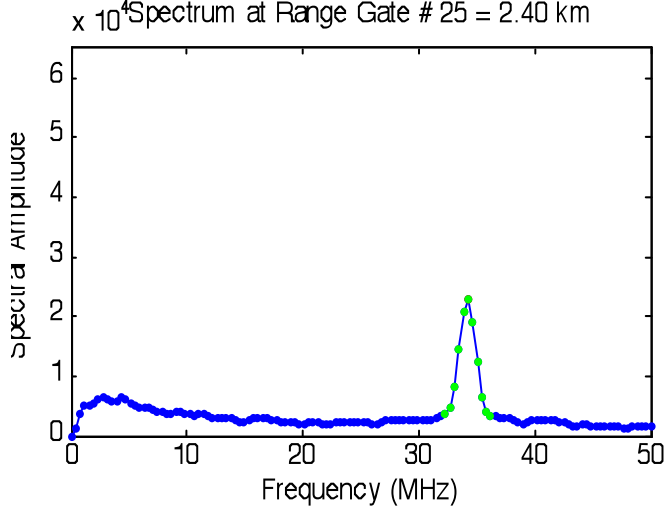
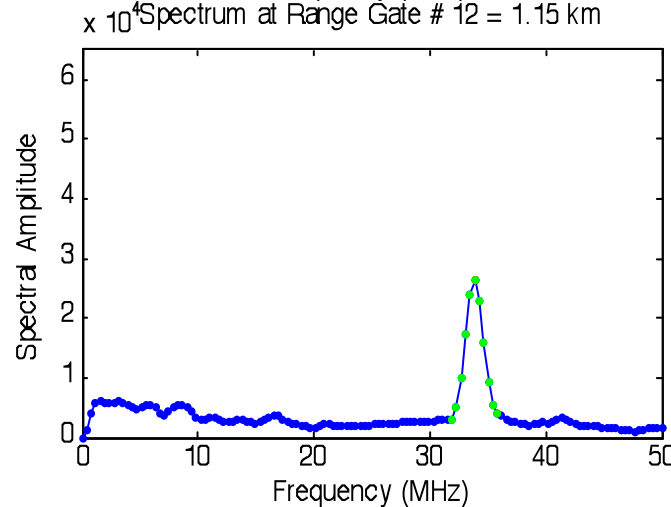
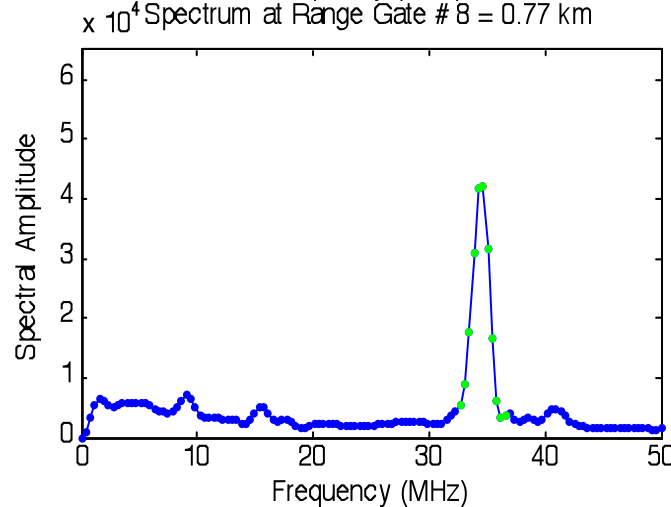
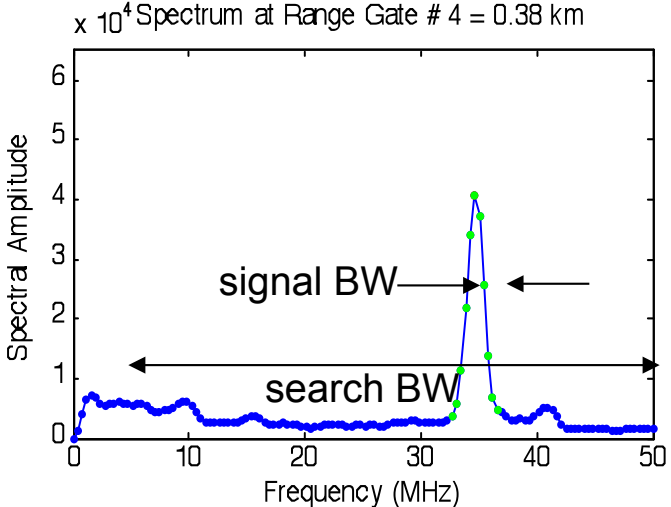
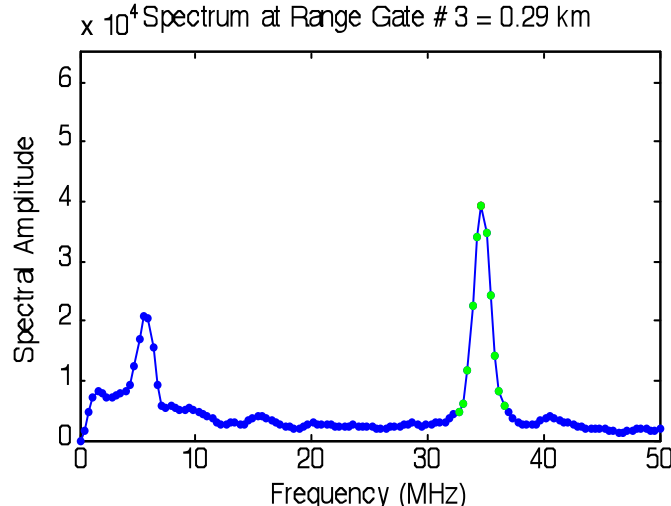
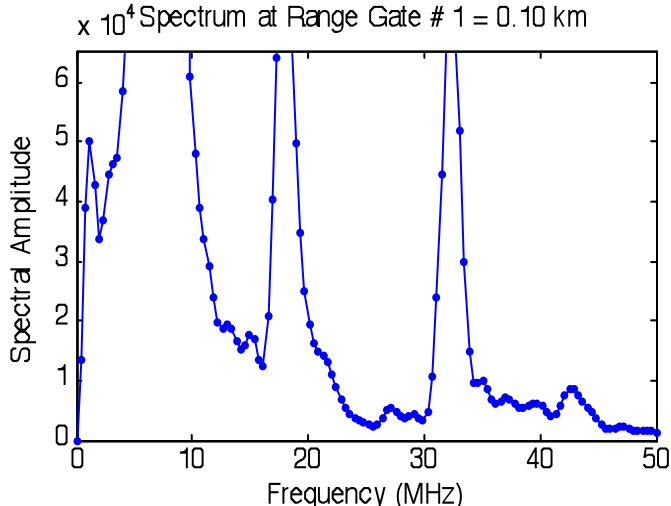


3. **Average** the spectrum for each range gate, with the spectra from the same range gate in all the other N pulses



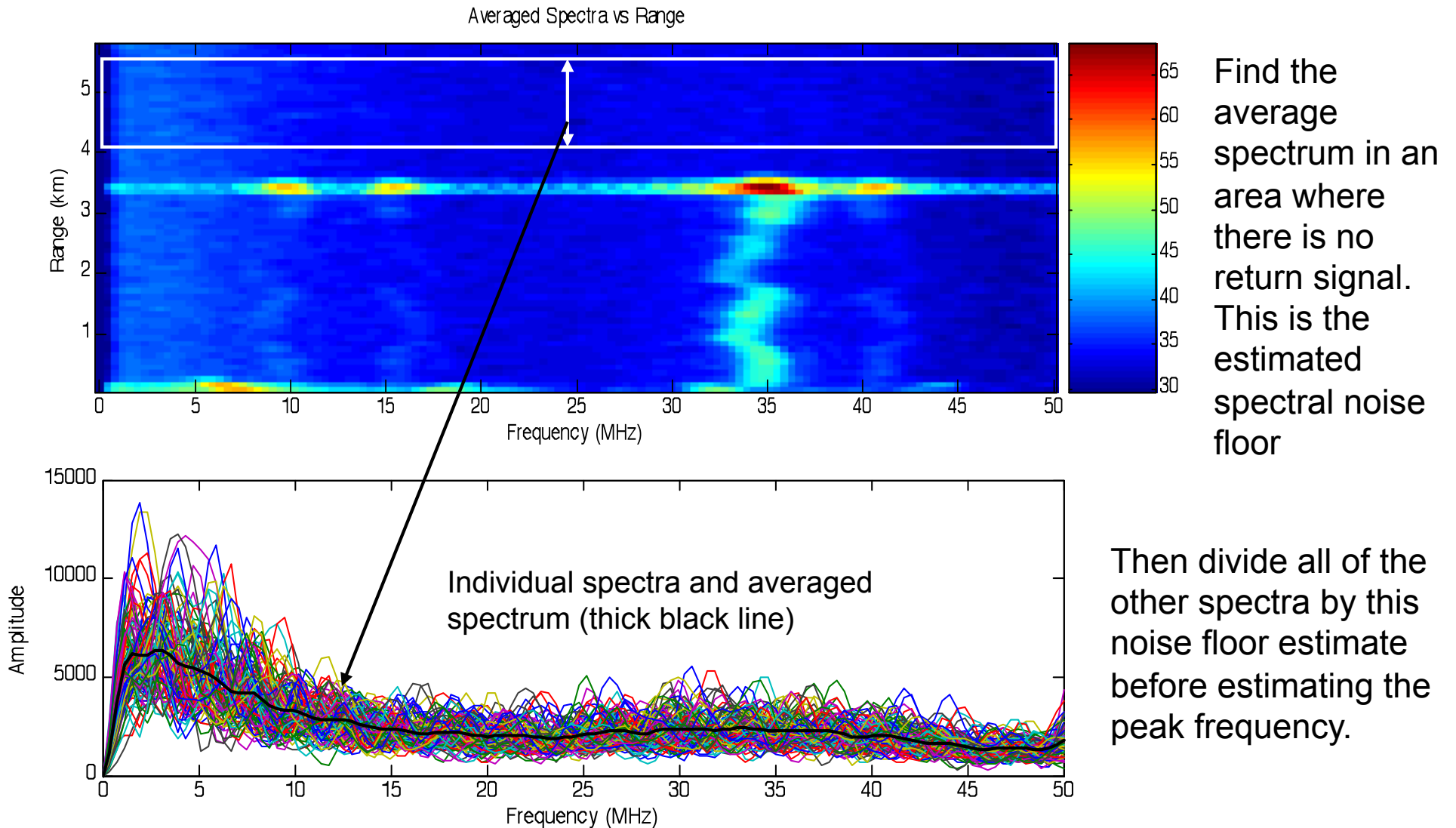
4. The frequency axis should be 0 to 50 MHz.
5. Find the **peak** in the spectrum at each range gate. This gives the measured frequency. Find the offset from the center by subtracting 25 MHz to get the Doppler induced offset Δf .

Processing example data: Averaged spectra for different range gates

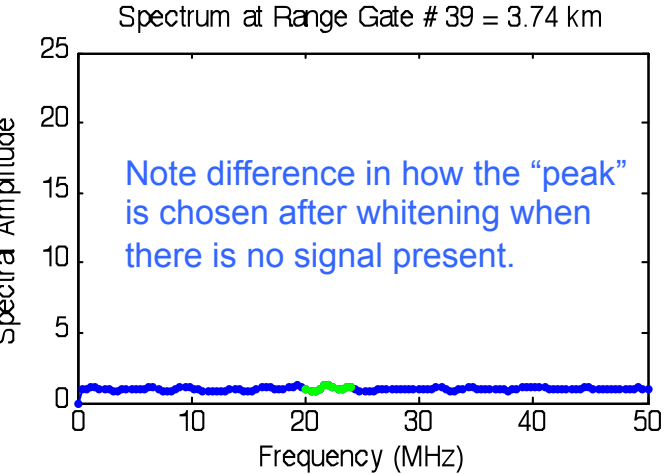
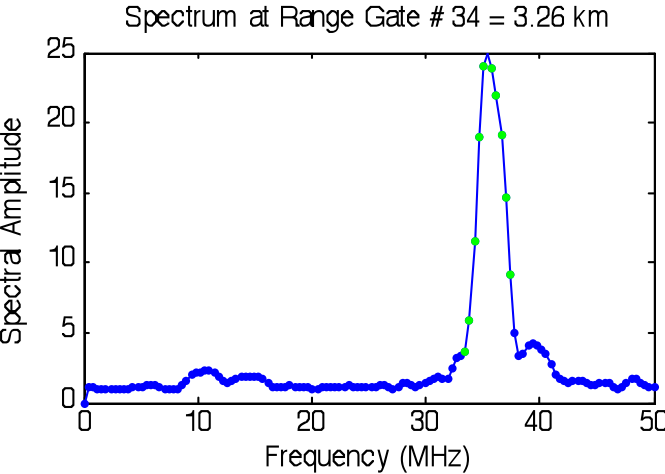
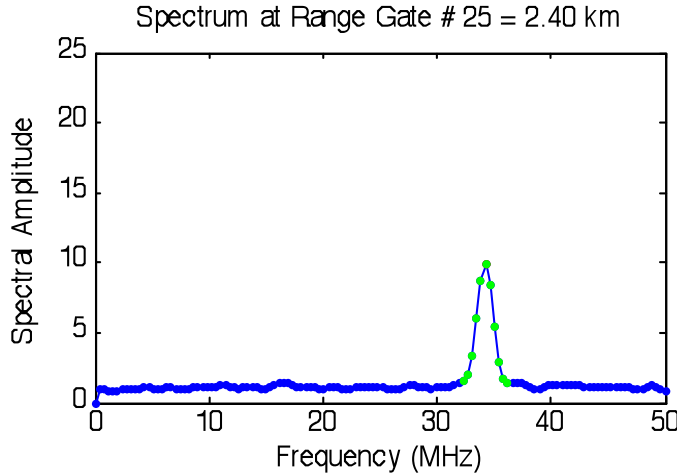
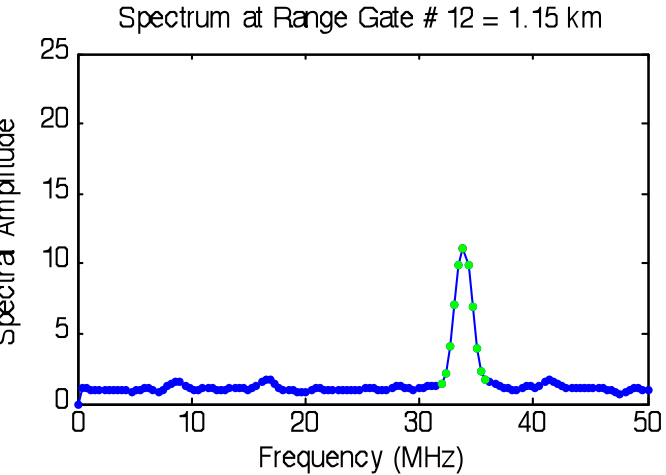
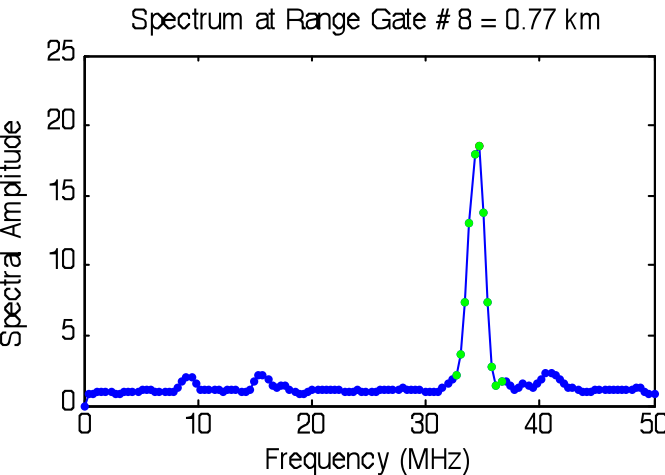
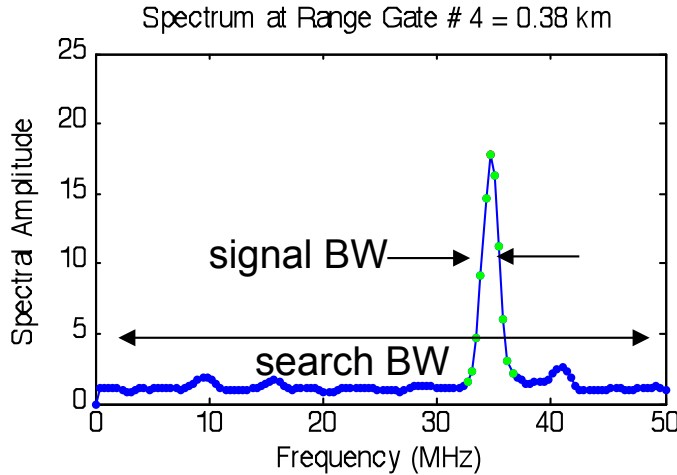
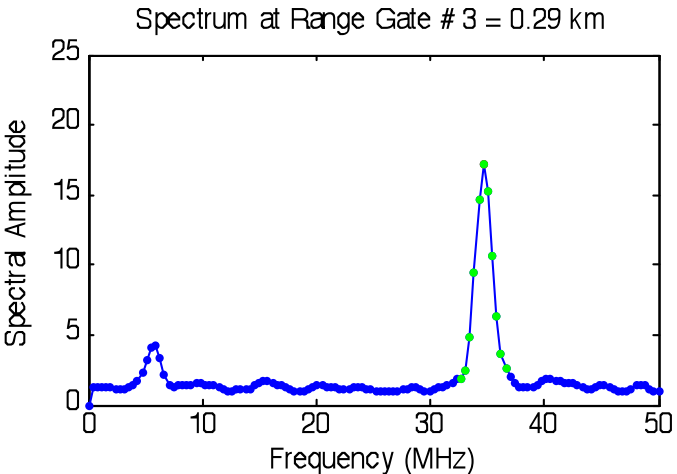
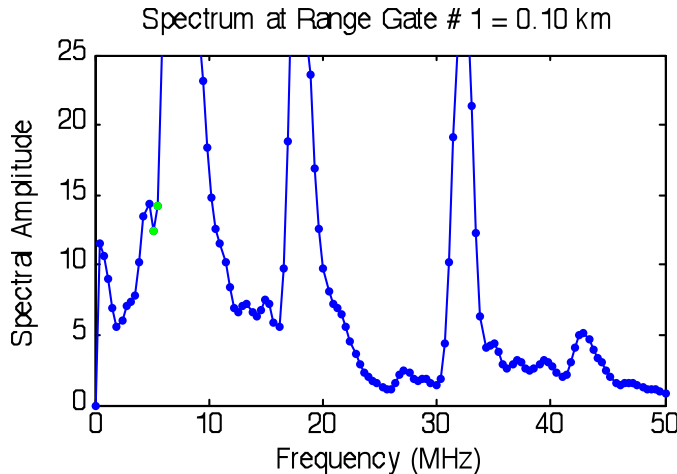


Return Signal Processing: Processing example data – Noise floor whitening

Notice the increased signal levels in lower frequencies. We need to flatten/whiten the noise floor.

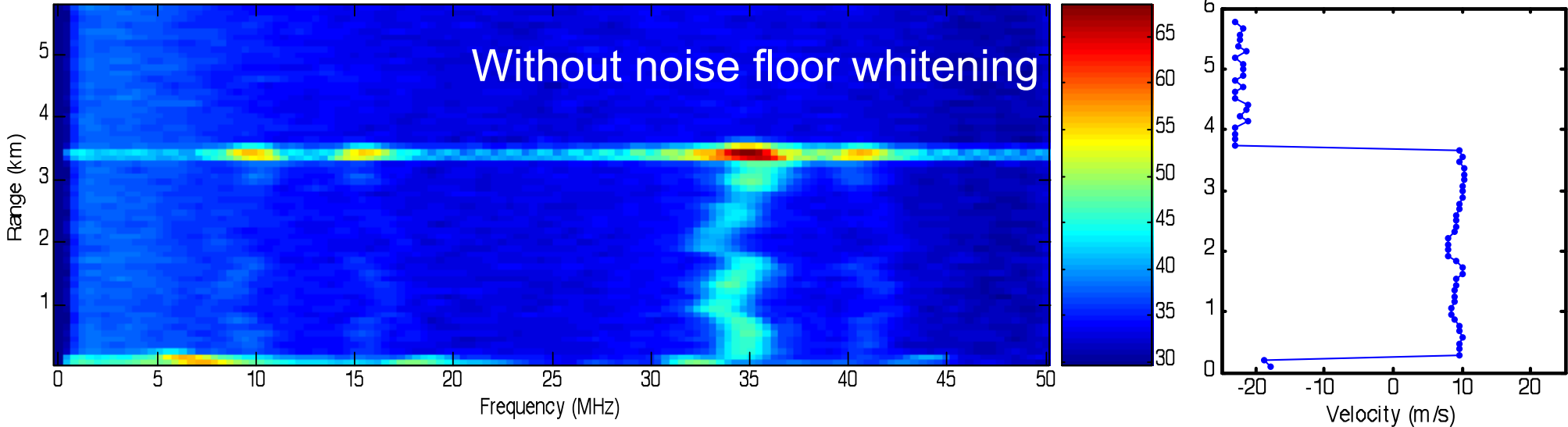


Processing example data: *Whitened & Averaged* spectra for different range gates



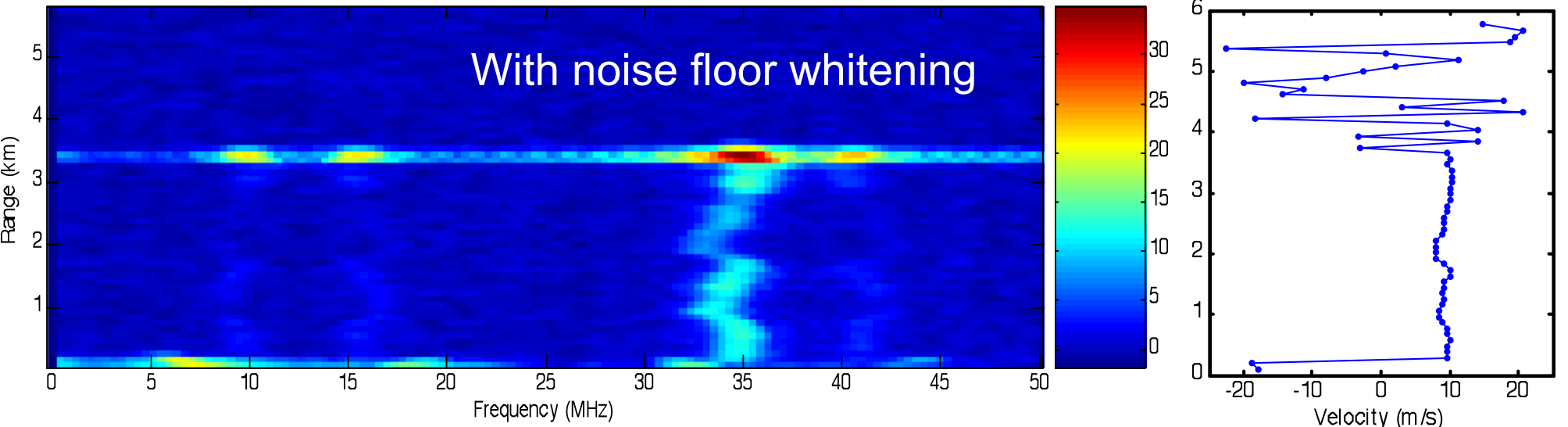
Return Signal Processing: Processing example data – noise floor whitening

Averaged Spectra vs Range

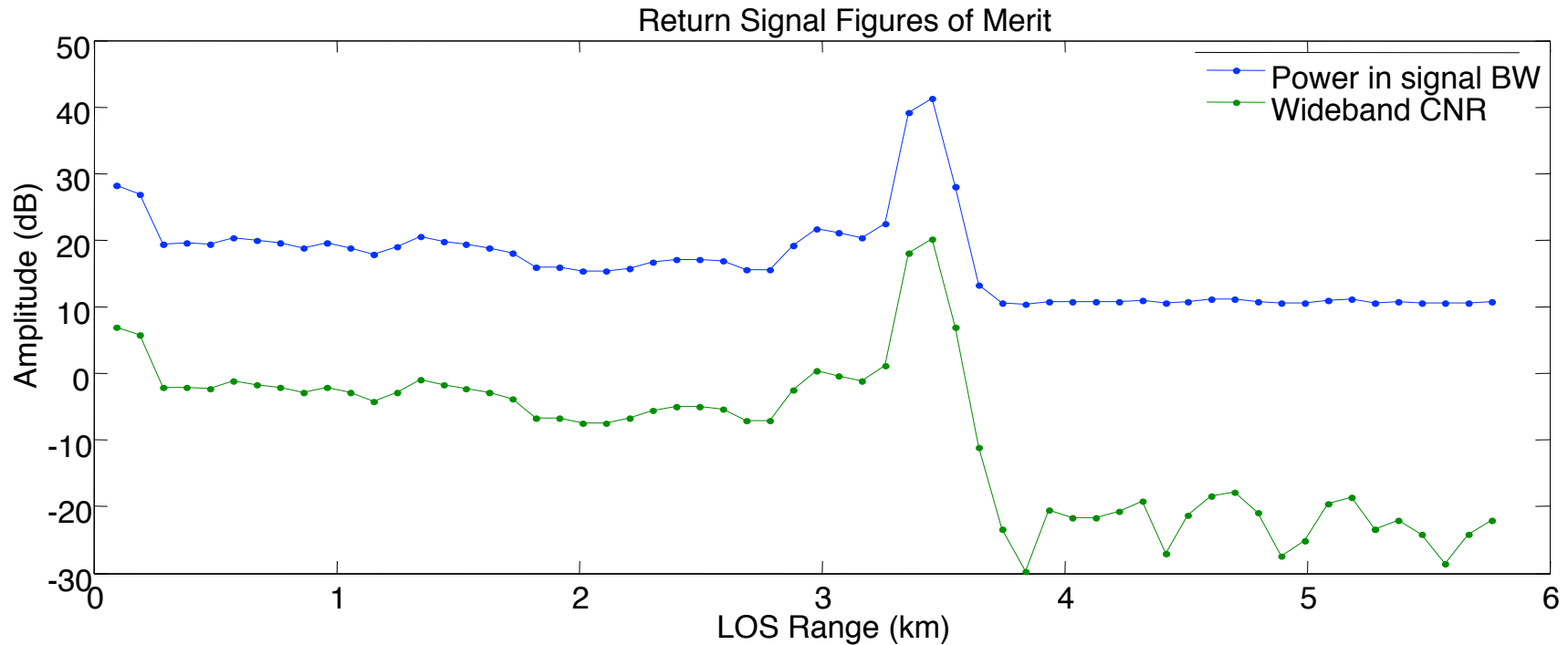


Note that when the noise floor is not flat, then velocity estimates in areas of low signal will be biased toward the noise floor peaks.

Averaged Spectra vs Range



Return Signal Processing: Processing example data (CNR)




To calculate CNR of real data, first sum the values in the frequency bins within the signal bandwidth (+/- 5 bins from the peak frequency) of the spectrum for the given range gate.

$$P_{f_{sig}} = \sum_{k \in \text{SignalBW}} f_{sig}(k)$$

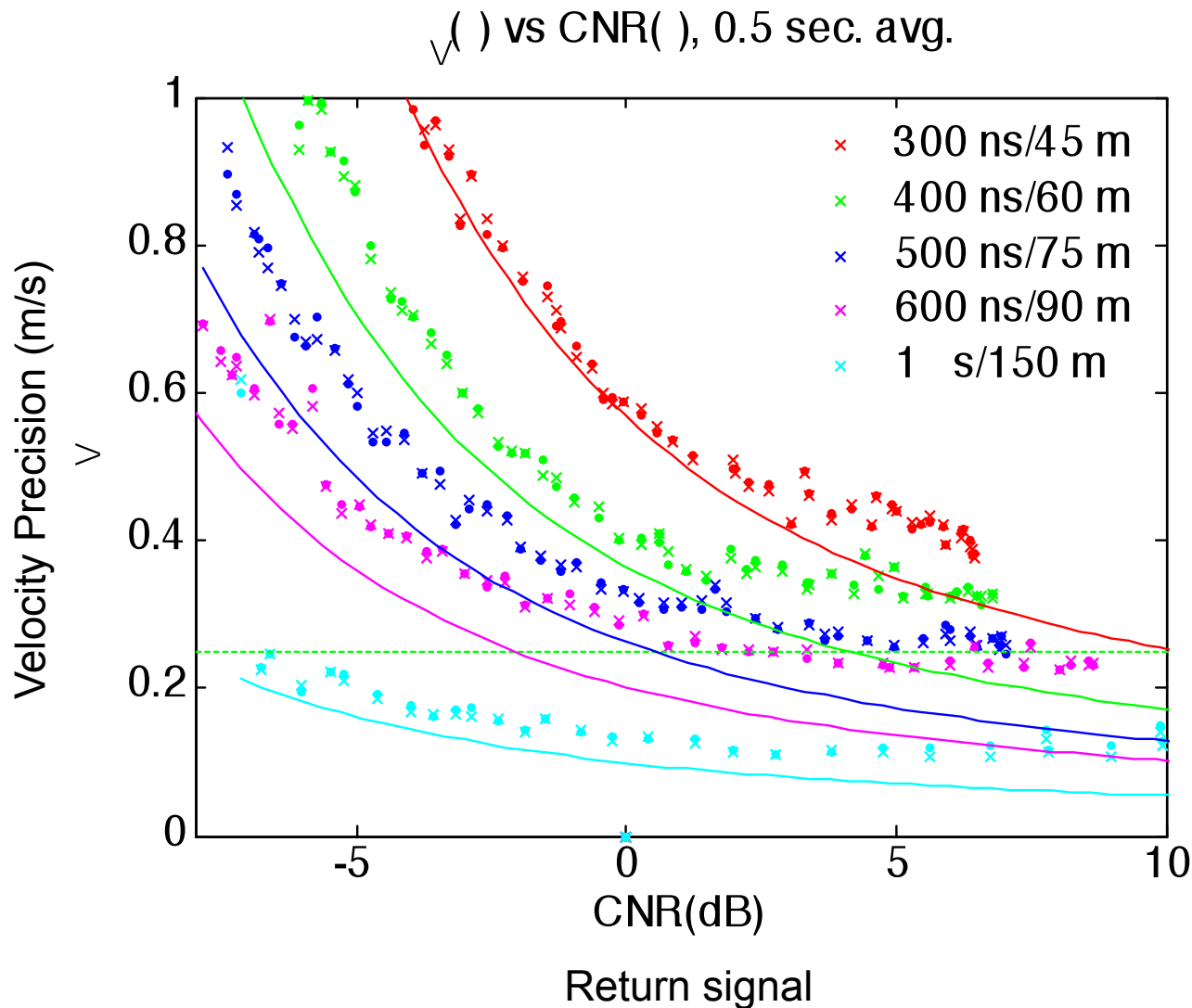
The Wideband CNR is then calculated as follows:

$$CNR_{wb} = \frac{P_{f_{sig}} - N_{sigBW} P_{ns}}{N_{wb} P_{ns}}$$

Where P_{ns} is the average noise power, N_{sigBW} is the number of bins in the signal bandwidth and N_{wb} is the number of bins in the spectrum ($N_{wb} = \text{NFFT}/2 = 128$). The $N_{wb}/\text{NFFT}/2$ is equivalent to the signal BW to total search BW ratio.

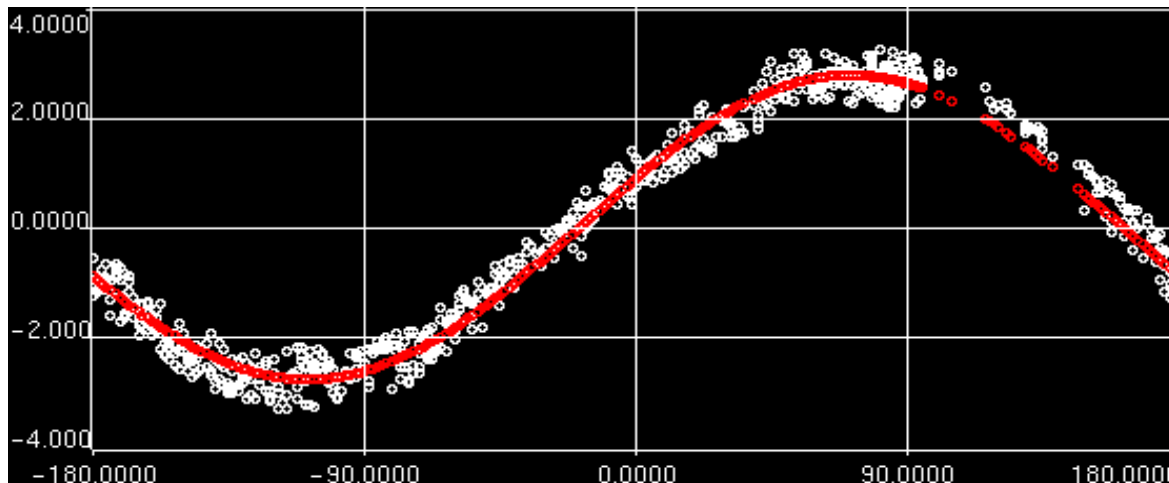
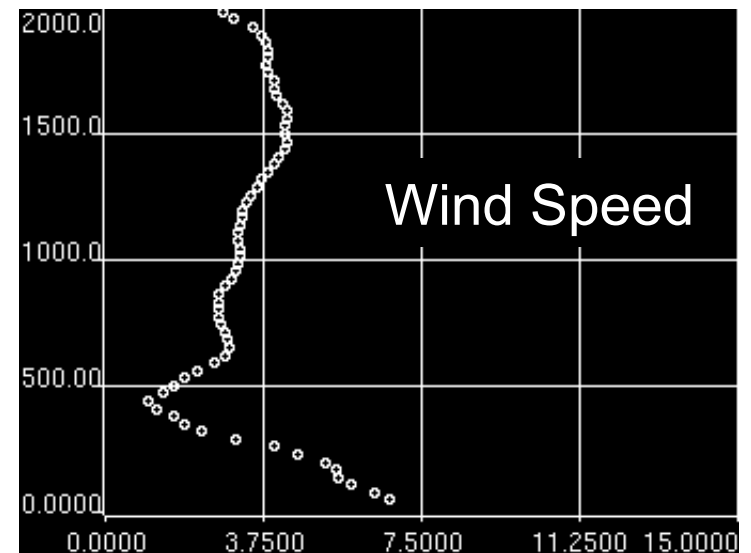
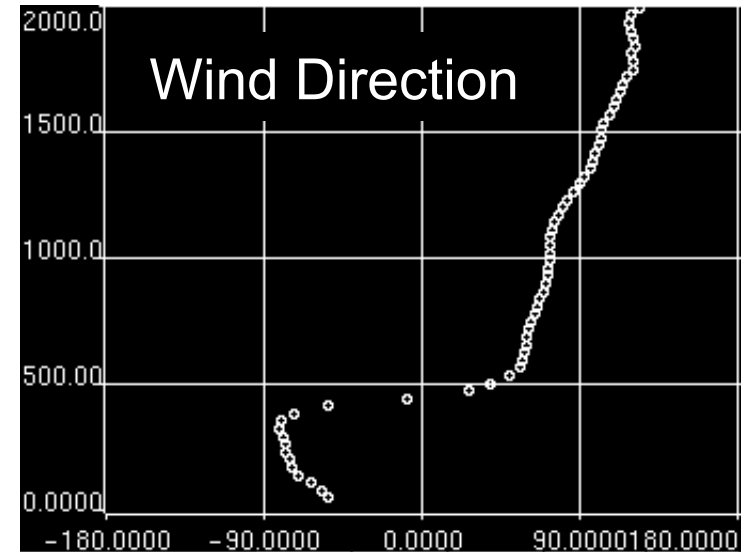
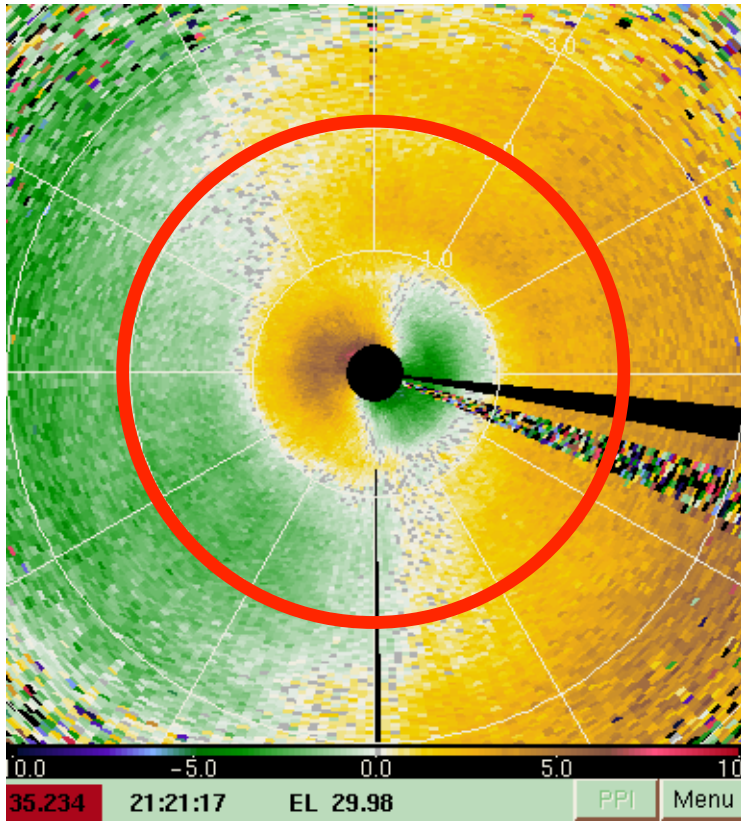
- 
- A sunset over the ocean with a list of technical steps overlaid. The sun is low on the horizon, casting a warm glow over the water and sky. The sky is filled with scattered clouds, some of which are illuminated by the setting sun. The water in the foreground is dark blue with small waves.
- Coherent Detection
 - Laser
 - Local Oscillator + shift
 - Transmit path
 - Atmosphere
 - Receiver/Detection
 - Processing
 - **Analysis and Data products**
 - Field Work

Velocity precision vs CNR and various pulse widths from mini-MOPA



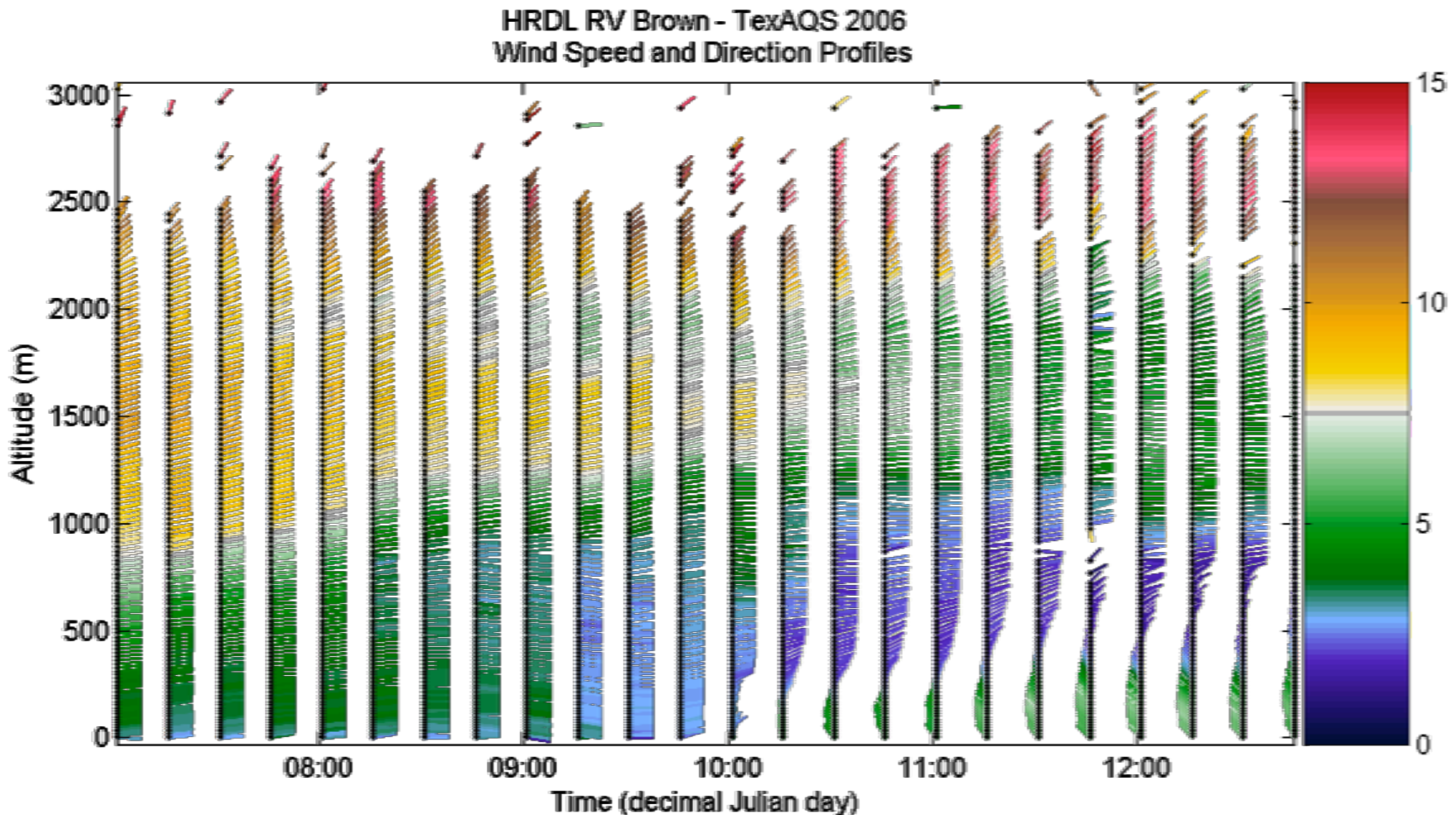
- Tradeoffs between:
- detection bandwidth and CNR
 - range gate length (range precision)
 - velocity precision
 - time resolution

Doppler Lidars: Calculating wind profile from PPI scans



Wind Profiles

- The dot is “now” (profile time).
- Wind is coming *from* the direction corresponding to the line angle.
- Color indicates wind speed according to the colorbar.



Wind Profiles: Info

- Down to 5 m above the surface/water – variable separation increasing with altitude to 30 m.
- Precision for wind speed estimates
 - LOS estimates < 20 cm/s
 - Profiles – depends on turbulence, usually better than LOS estimates.
- Precision for wind direction: usually depends on wind speed.

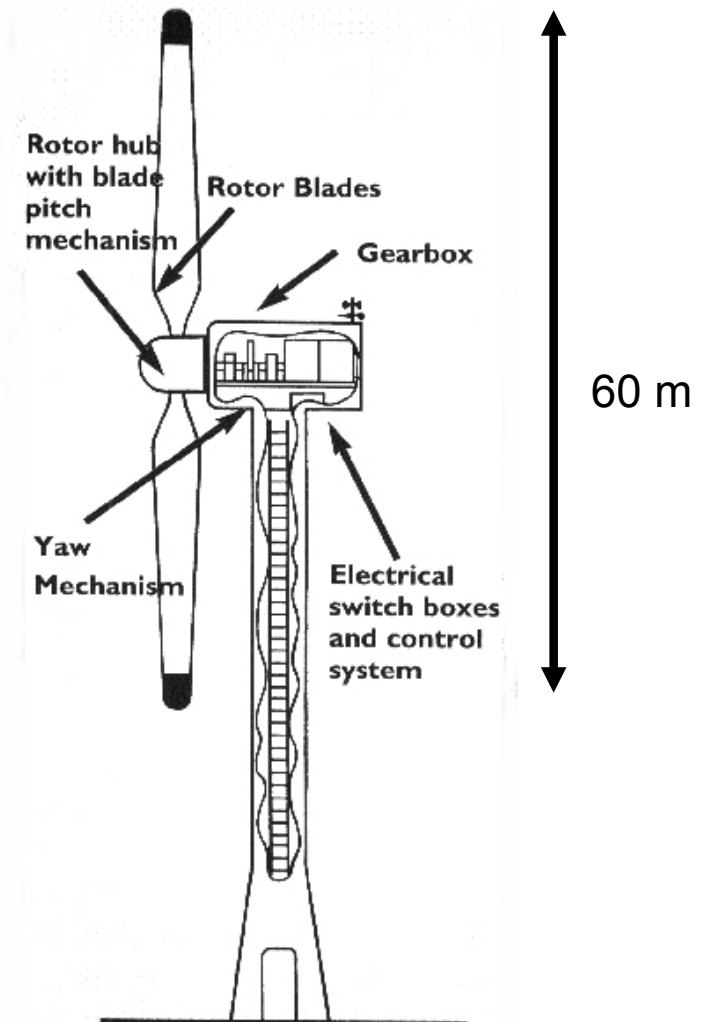
Wind Profiles: Uses

- Observation of
 - sea-breeze/land-breeze conditions,
 - low level jet
 - shear & mixing
 - diurnal cycles
- Help in understanding changes in atmospheric conditions
- Previously sheared layers started mixing down. From which direction did the stuff in that layer come?
- Diurnal cycles: patterns in wind speed and direction at all altitudes

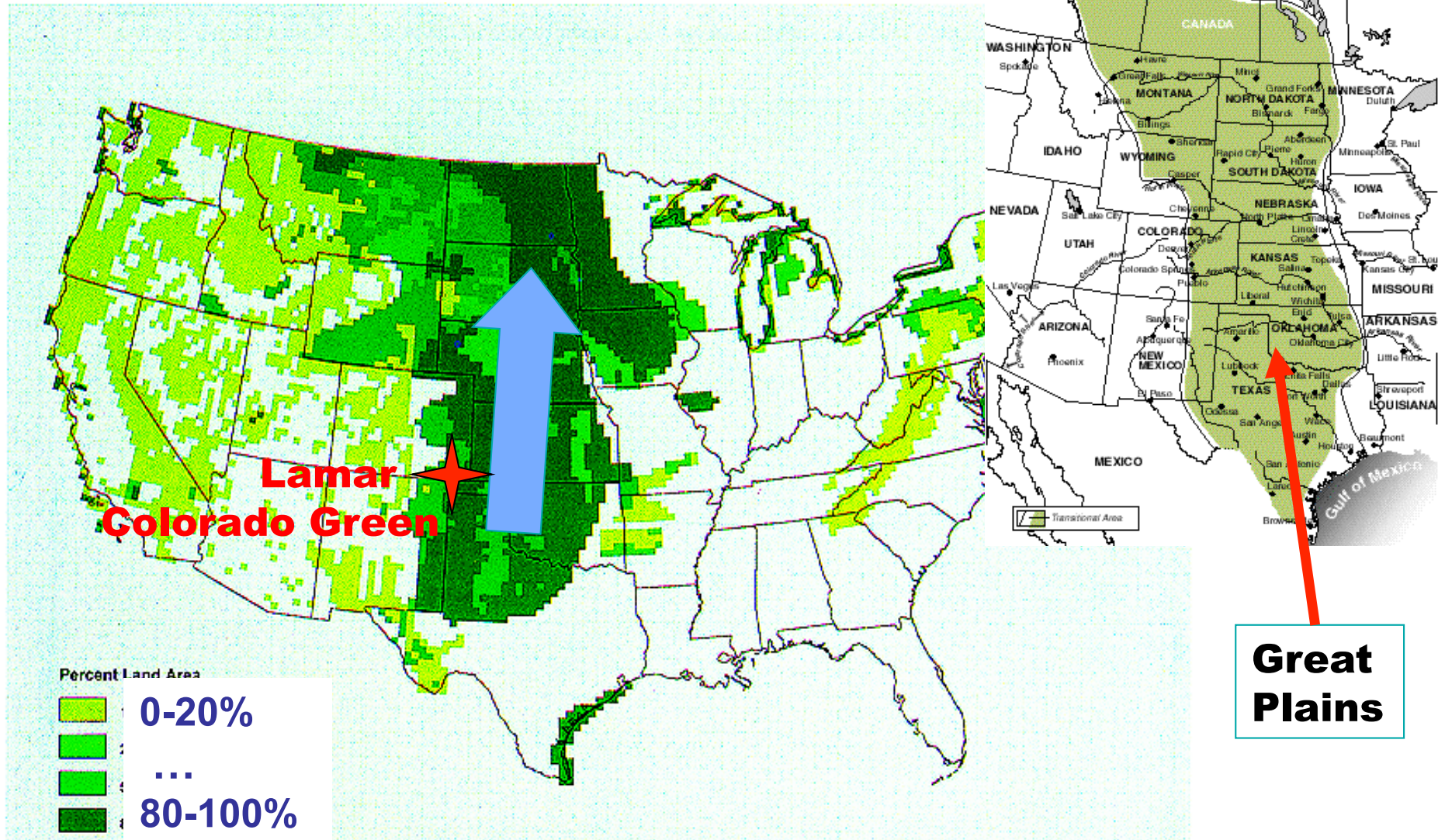
- 
- Coherent Detection
 - Laser
 - Transmit path
 - Atmosphere
 - Receiver/Detection
 - Processing
 - Analysis and Data Products
 - **Field Work**

Improving Wind Turbine Performance and Reliability

- Wind turbines are getting larger as the demand for alternative energy increases
- As wind turbines get larger, effects of wind shear and turbulence on efficiency and reliability becomes an important issue
- Doppler lidar ideal for investigating these effects

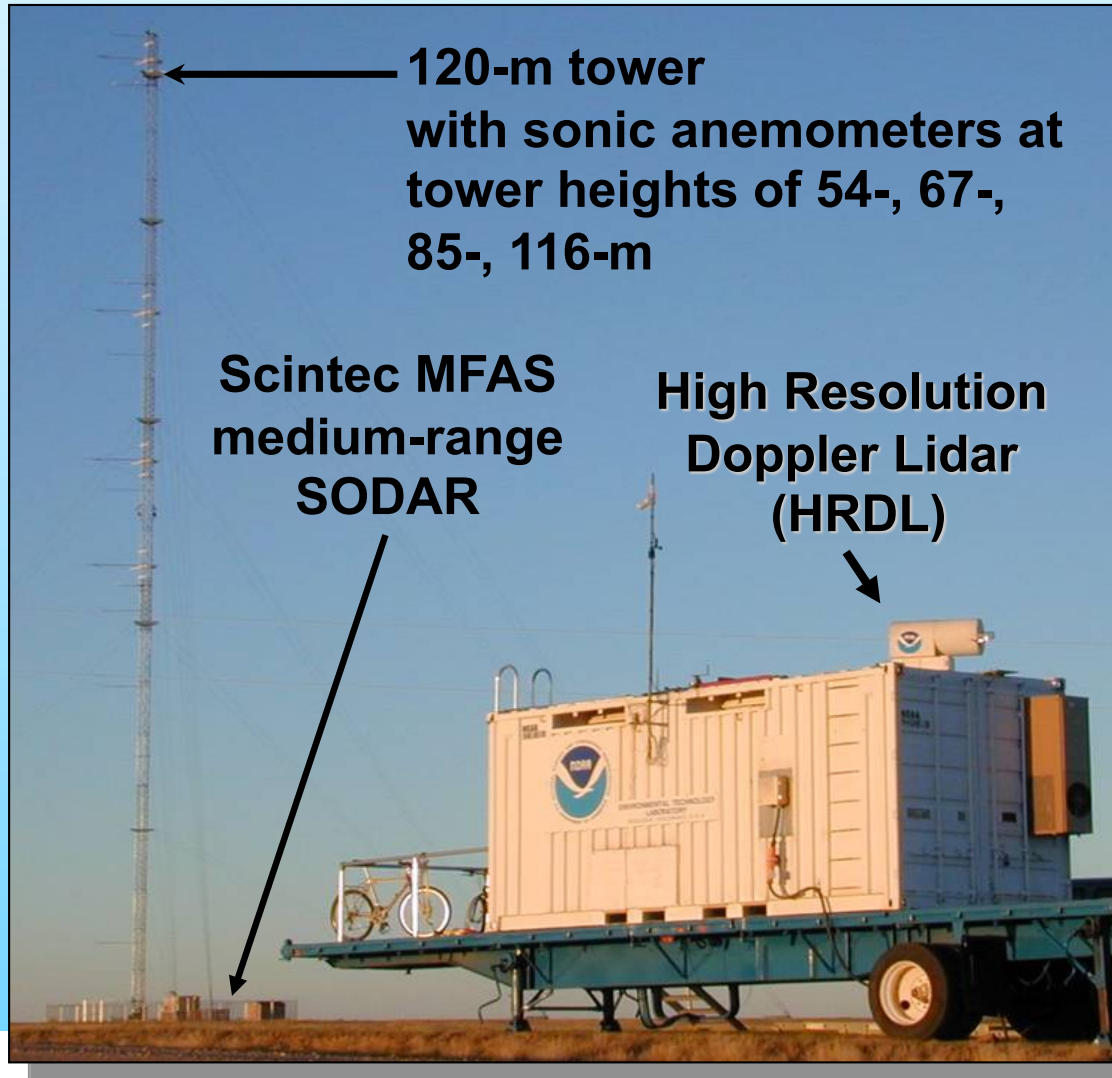


Great Plains wind resource



“Percent of the land area estimated to have Class 3 or higher wind power in the contiguous United States” (NREL site) Class 3 = $300-400 \text{ W m}^{-2}$ per year

Instrumentation – Lamar, Colorado, *NREL-ESRL Low-Level Jet Study*



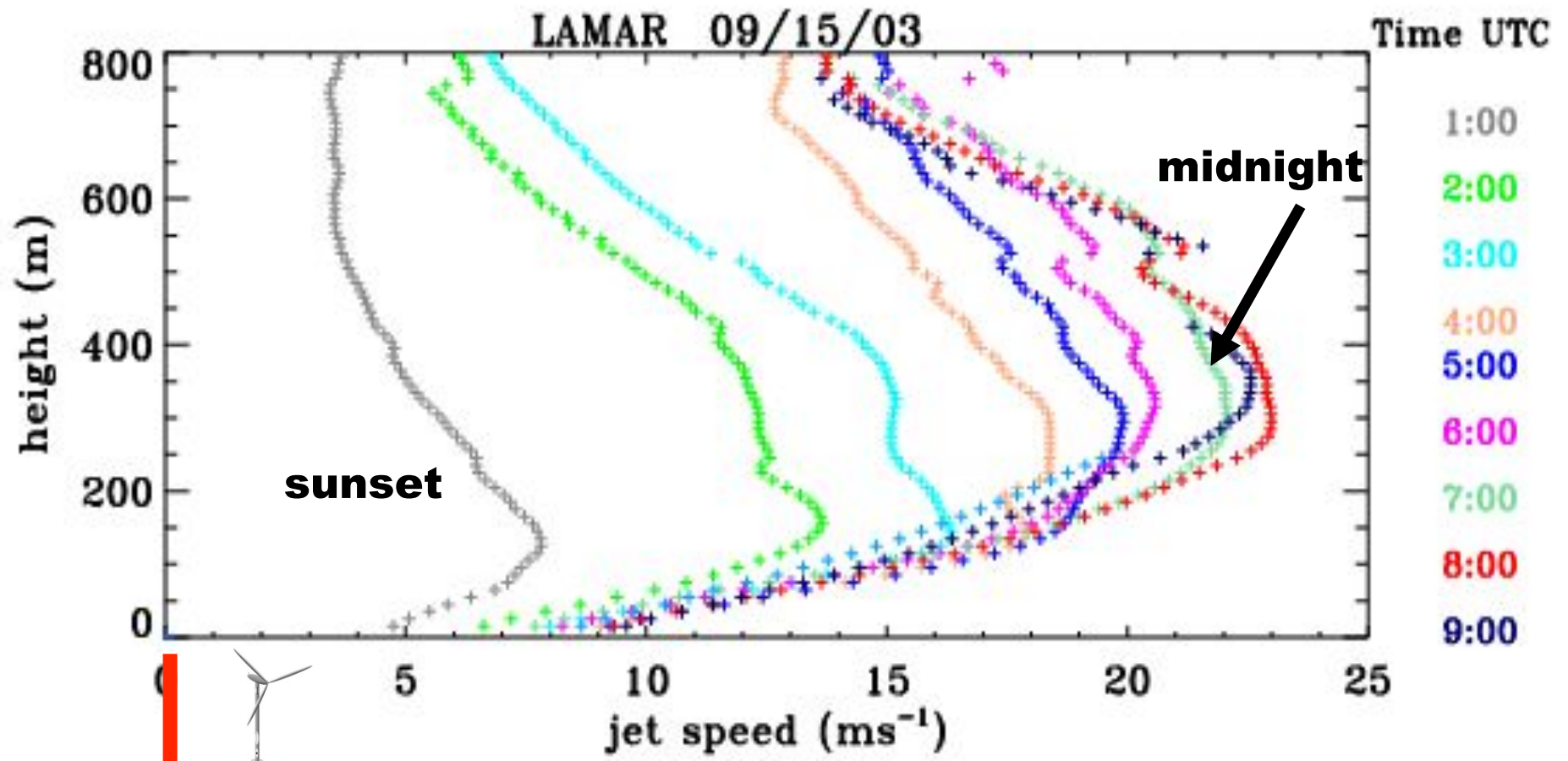
HRDL technical parameters	
Wavelength	2.02 μm
Pulse energy	1.5 mJ
Pulse rate	200/s
Range resolution	30 m
Velocity resolution	~ 0.1 m/s
Time resolution	0.5 s
Minimum range	0.2 km
Maximum range	3 km
Beam width range cm	6 to 28



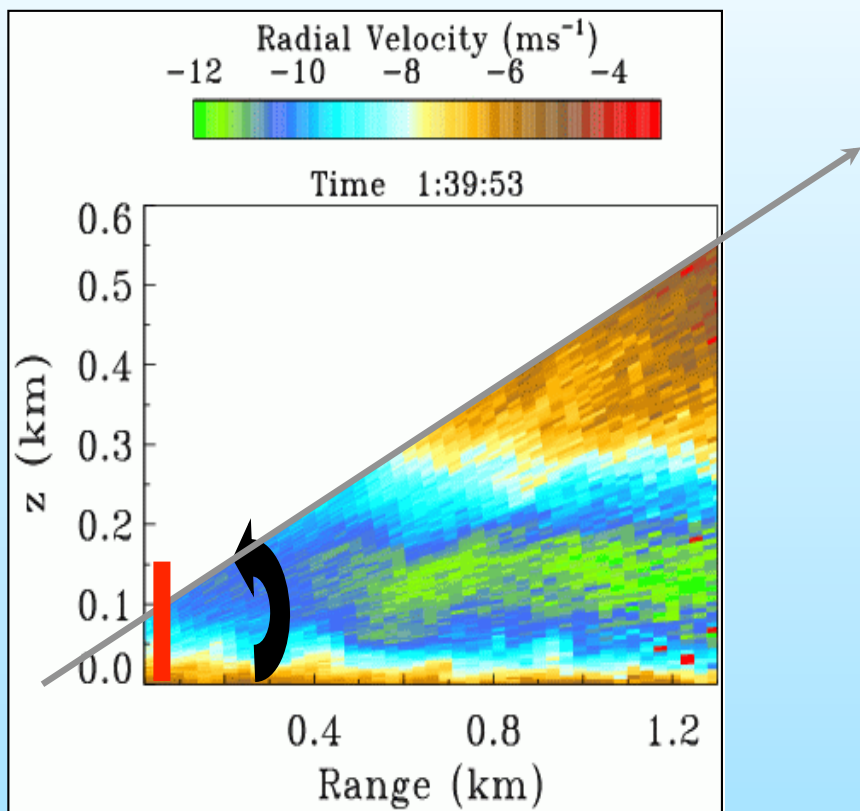
Lamar, Colorado

ESRL-NREL collaboration – September 2003

Doppler Lidar wind profiles

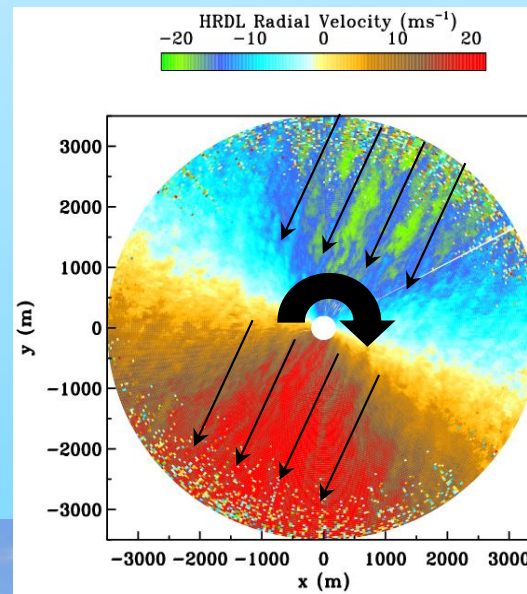
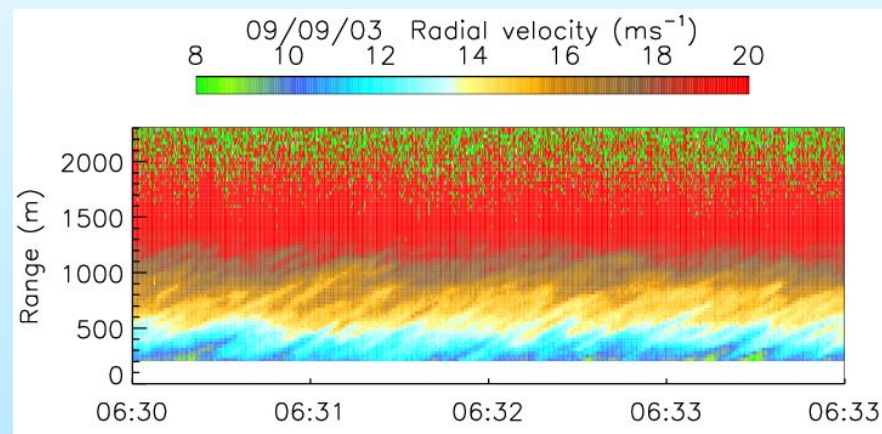


HRDL measurements



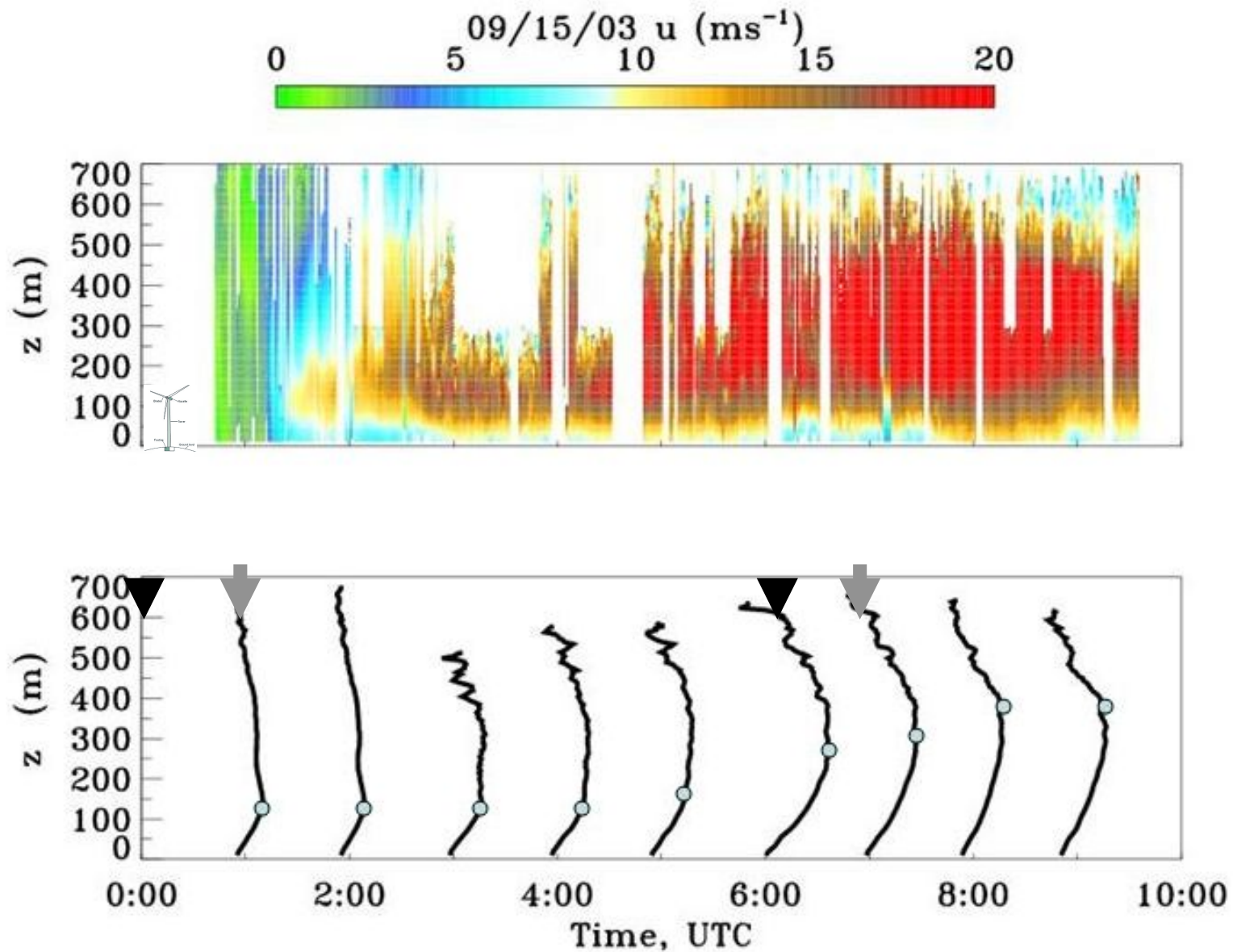
Vertical-slice scans

Fixed-beam scans

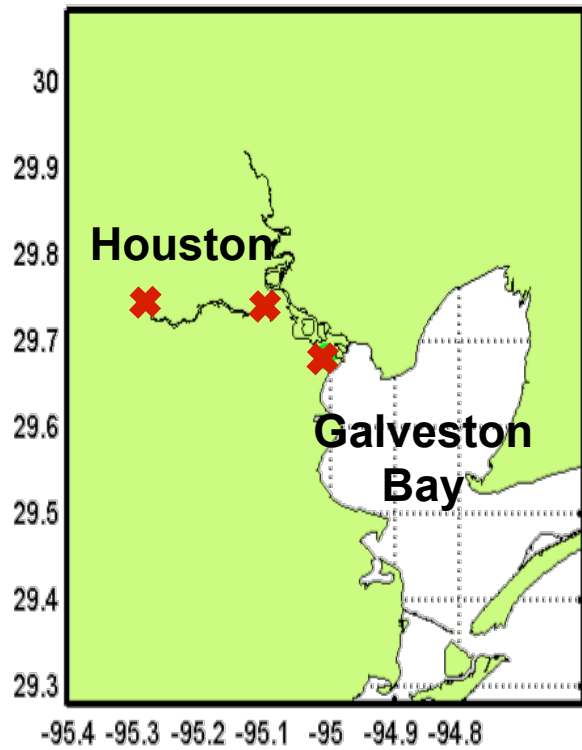


Conical scans

Documenting evolution of LLJ through the night



Nighttime vertical mixing



Motion Compensation



CO

- GPS base INU
- Estimates of orientation, angular rates, position, velocity, and acceleration at 20 Hz.
- Static precision 0.15°
- Hemispheric beam scanner
 - Motion comp calculation
 - Maintain "world frame" scan parameters
 - Tilt axis for Zenith Star

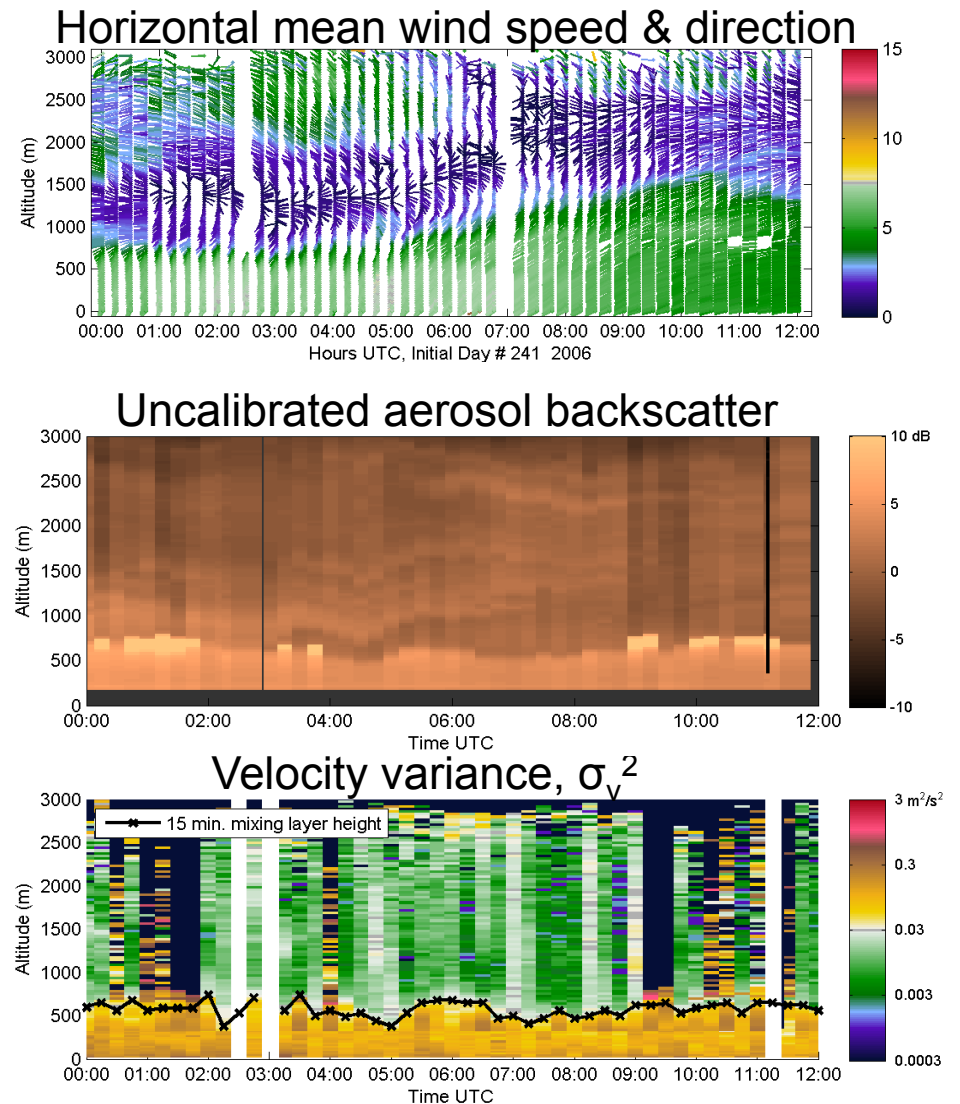


HRDL: Boundary Layer Mixing height

TexAQS 2006 HRDL Data Products

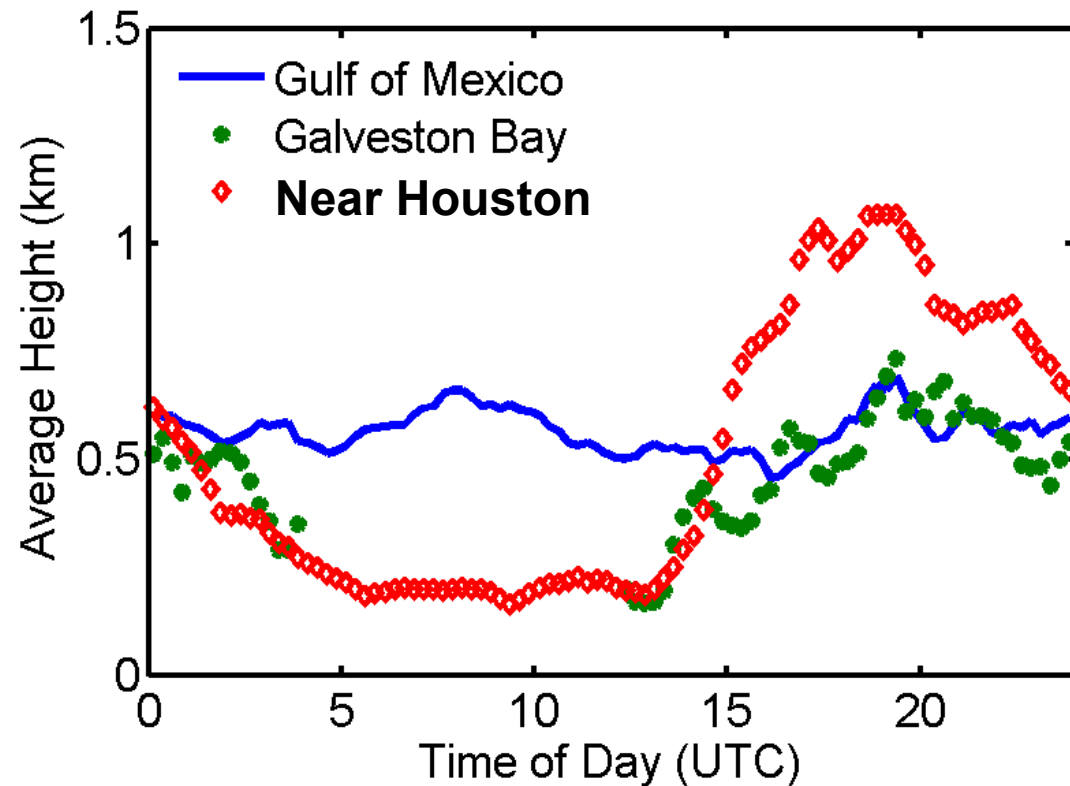
Mixing height: Defined as the height of the layer of the atmosphere in turbulent connection with the surface of the earth.

- **Combine height information from**
 - σ_v^2 (turbulence) profiles
 - mean wind (shear) profiles, and
 - aerosol backscatter profiles
- to generate MH estimate once every 15 minutes.**



Doppler Lidar mixing height and location

- Little diurnal variation in the Gulf of Mexico (except during rare offshore flow)
- Strong diurnal variation near Houston – sea-breeze observed.
- Small variations over Galveston Bay (mixture of land and Gulf influences)



Measuring wind and moisture fields from aircraft



International H₂O Project: US Great Plains

IHOP Measurement Configuration

Falcon payload during IHOP_2002



Dropsondes:
u,v, P,T,q

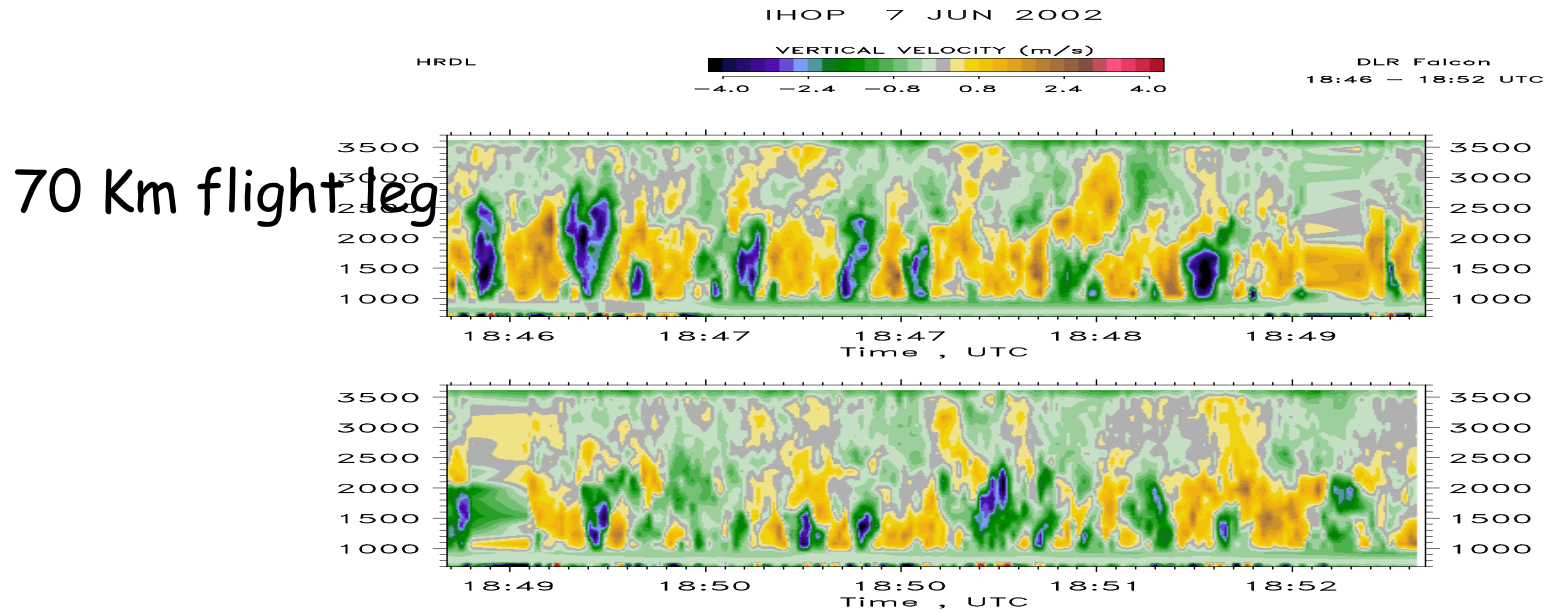


u,v
W

DIAL:
H₂O, Aerosols

HRDL:
Horizontal & vertical wind speed

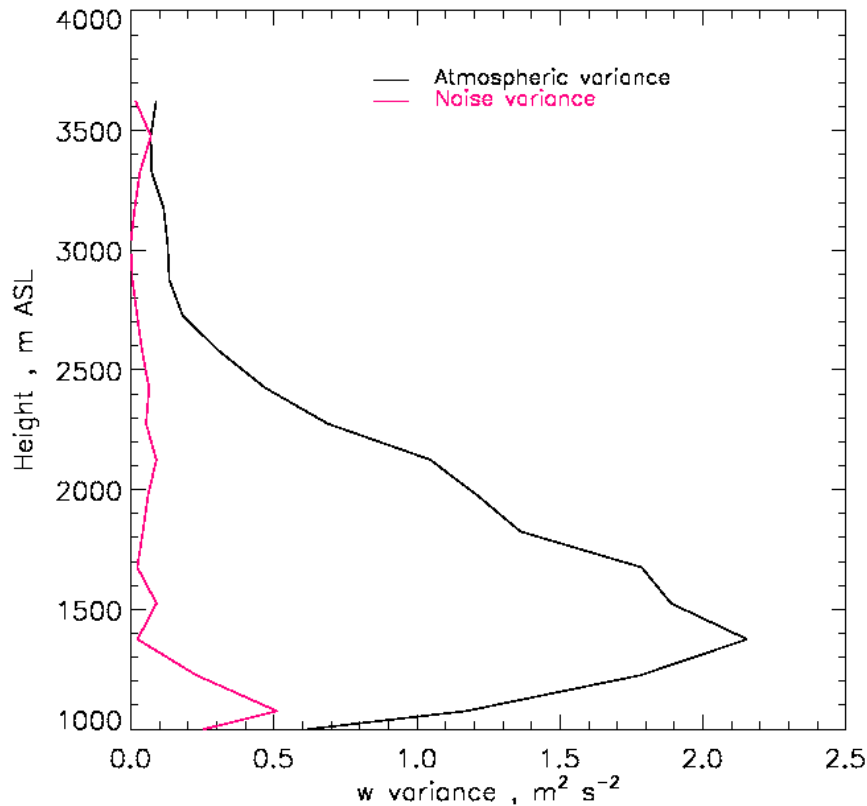
Vertical velocity measurements



Vertical velocity variance and skewness

IHOP 06/07/02

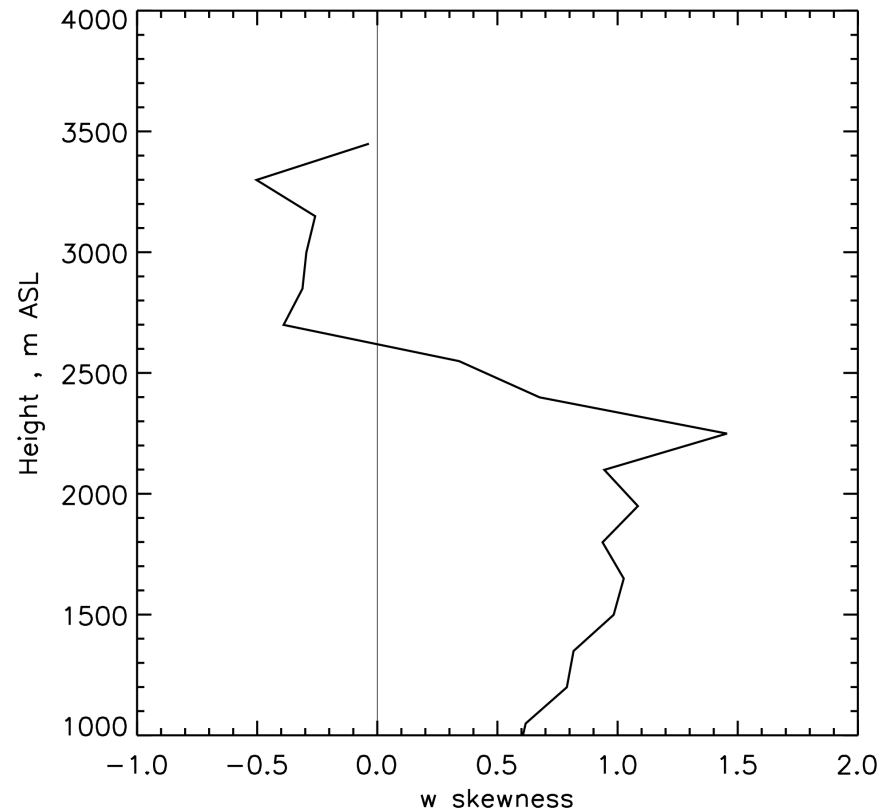
HRDL 18:46 – 18:52 UTC



Estimated errors in the vertical velocity variance ~ 15-30% dominated by sampling error

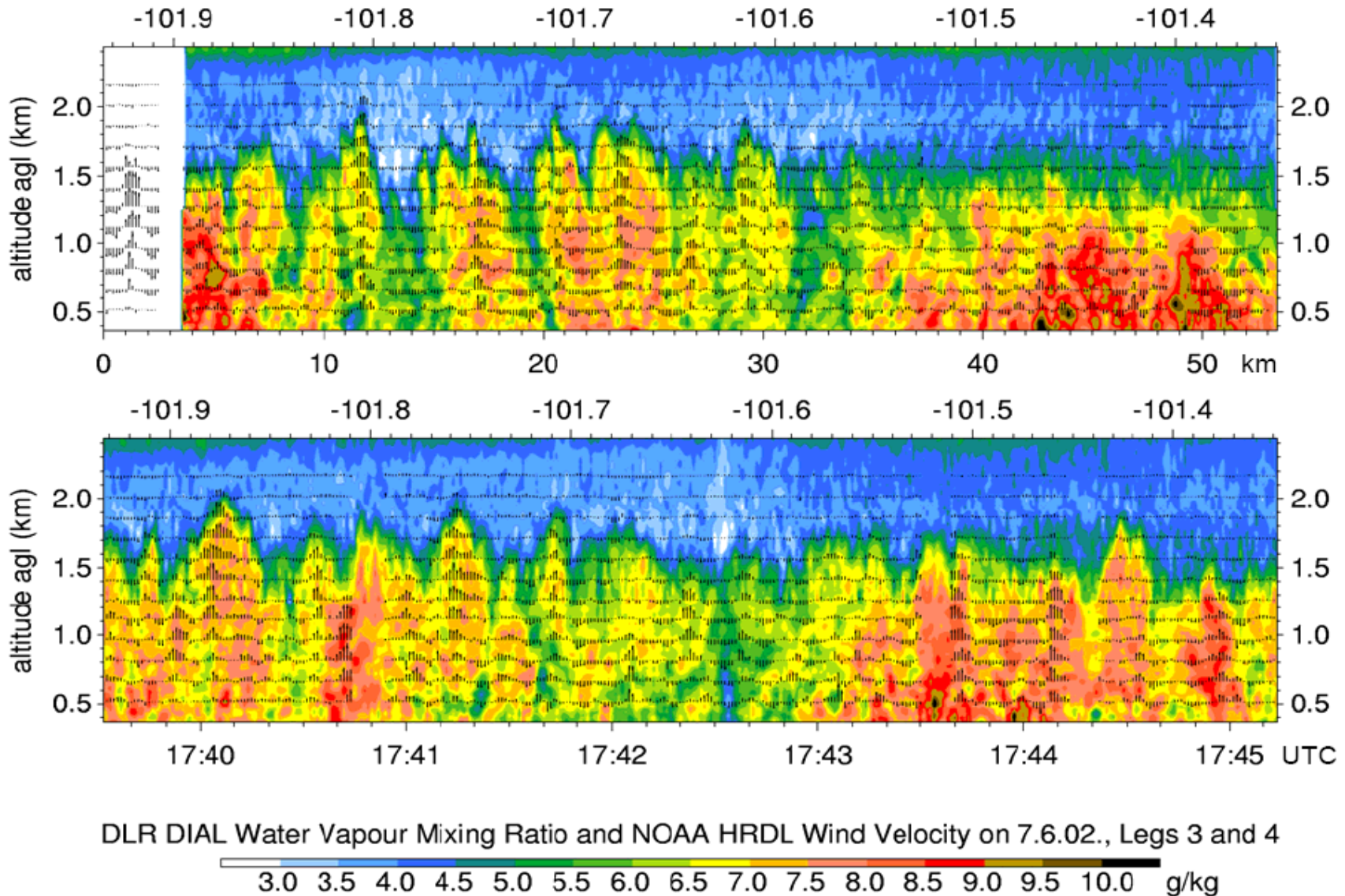
IHOP 06/07/02

HRDL 18:46 – 18:52

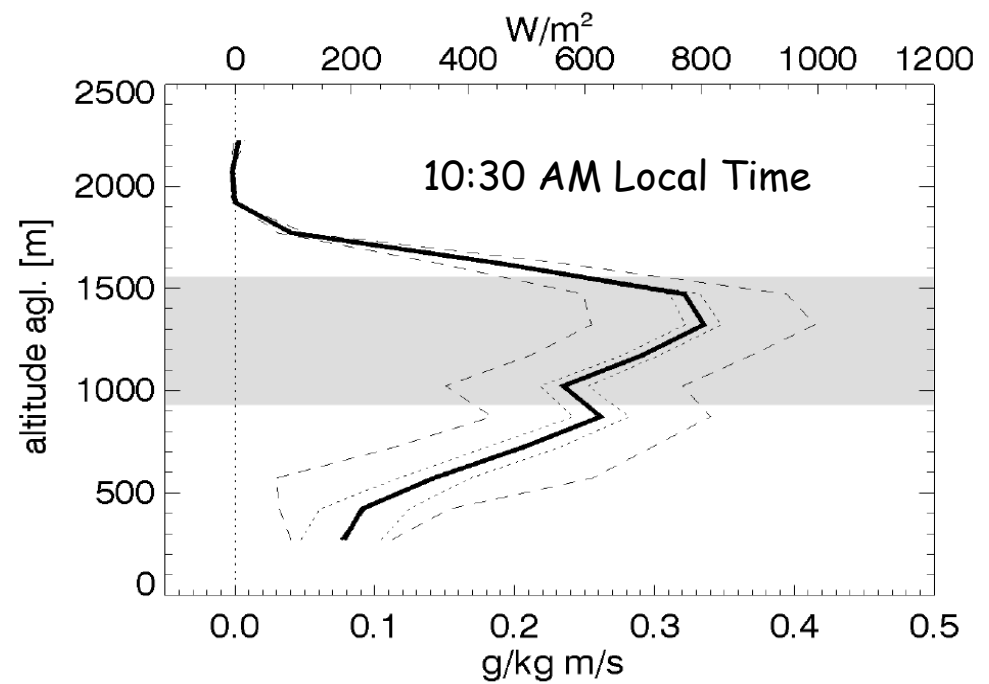
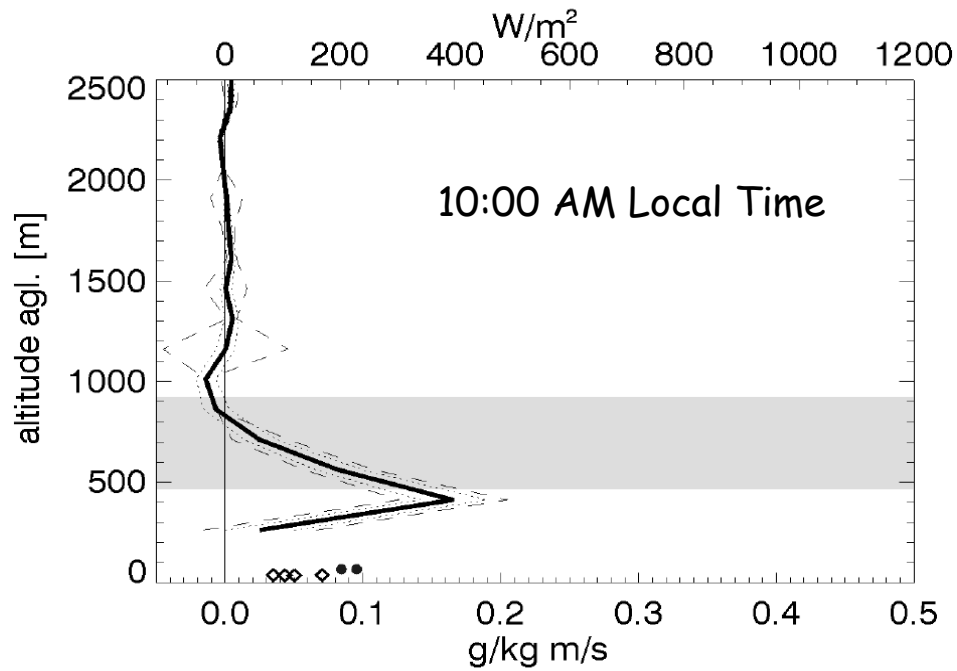


Skewness indicates convective boundary layer

Simultaneous water vapor and winds

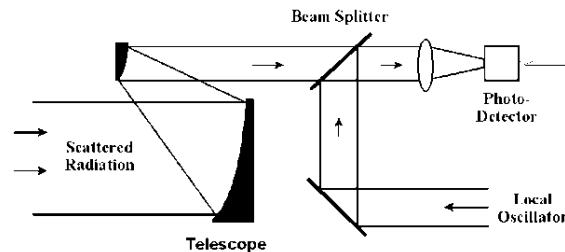


Moisture flux profiles



Summary of Key Points

- Coherent Doppler lidar systems employ aerosols (clouds, dust, pollution) as scattering mechanism
 - Typically applied in the lower troposphere and boundary layer
 - Aerosol backscattered signal is narrow band (few m s^{-1} BW)
- Radiation from a local oscillator laser is “mixed” with the atmospheric return on the face of the detector



- Efficient mixing enhances signal to noise ratio due to narrow noise bandwidth, but necessitates stringent design specifications on transmitter and receiver

Summary (2)

- Transmitter requirements
 - Narrowband pulse (ideally transform limited)
 - Single longitudinal mode
 - Spatial coherence (ideally TEM00 Gaussian mode)
 - Want to produce the smallest spot at the range of interest
 - Typically linearly polarized laser output changed to circularly polarized (enables use of polarization beam splitter as T/R switch)
- Atmospheric propagation
 - Atmospheric turbulence reduces coherence, impacts sensitivity
 - Focusing impacts range sensitivity curve, produces flat near-field response
- Receiver issues
 - LO mixed with backscattered signal on the detector face
 - LO size matched to backscattered signal spot
 - Receiver field of view matched to spot size at the range of interest (diffraction limited)

Summary (3)

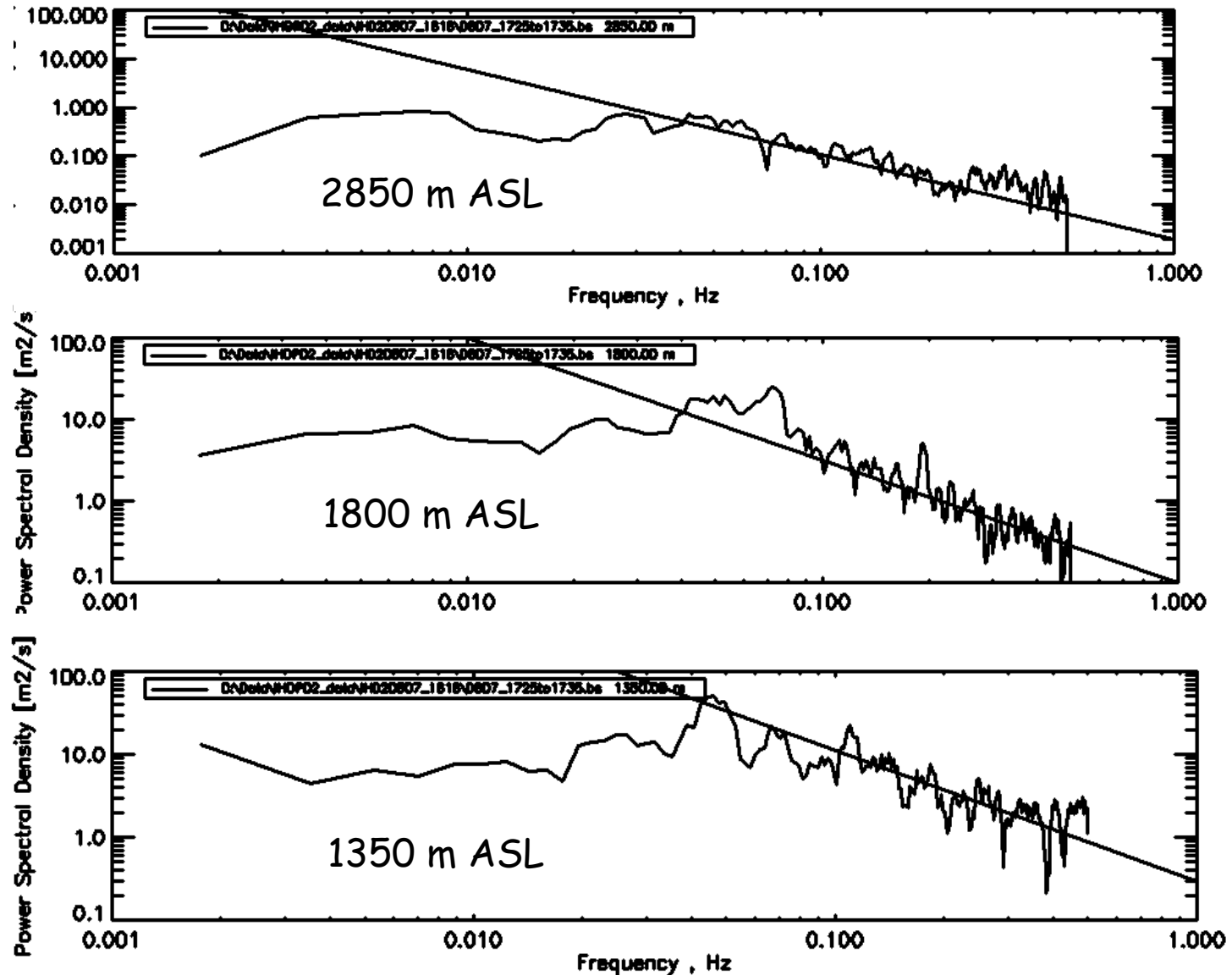
- Signal processing
 - Detector output is digitized and band-pass filtered (bandpass matched to maximum Doppler shift - ~ 100 MHz at $2 \mu\text{m}$)
 - Apply spectrum analysis for each range gate to produce Doppler estimate
 - Apply multiple pulse averaging to reduce noise in spectrum (but must average in spectral domain)
 - Apply noise whitening to eliminate spurious spectral peaks
 - Can make measurements at wideband $\text{CNR} < -20$ dB (just a few photons)
- Applications
 - Systems can be compact (e.g., 10 cm optics), suitable for ground, air and ship platforms
 - Scanner enables rapid mapping of 3 dimensional wind field
 - Velocity-azimuth display technique for measurement of average 3-dimensional wind
 - Horizontal and vertical velocity variance to characterize turbulence and mixing

Questions?

Vertical Velocity Spectra

- Smaller scales are filtered out due to finite pulse volume

- Small impact on the measurements except near the surface



What does the NOAA/CSD/Optical Remote Sensing Group do ?

- Investigate and implement new technology for improving **observations of the atmosphere and ocean**
- Demonstrate and apply new measurement techniques for:
 - Air quality
 - Chemical distribution
 - Dynamics for mixing/transport
 - Improving and assessing weather forecast model performance
 - Parameterization of sub grid scale processes (turbulent mixing, complex terrain)
 - Providing new observations for data assimilation.
 - Cal/val forecast models
 - Understanding climate forcing mechanisms
 - Clouds / aerosol indirect effect on climate
 - Sources and sinks of important species (CO₂, O₃, H₂O)
 - Ocean / atmosphere energy exchange