Optical Remote Sensing with Coherent Doppler LIDAR

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

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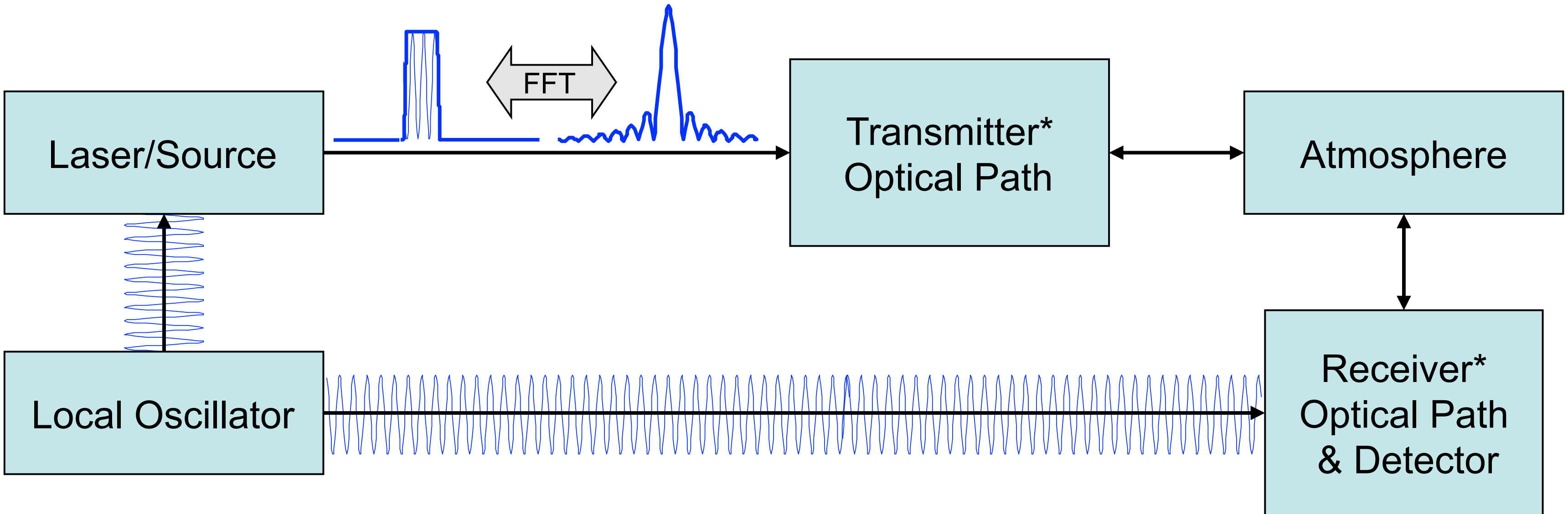
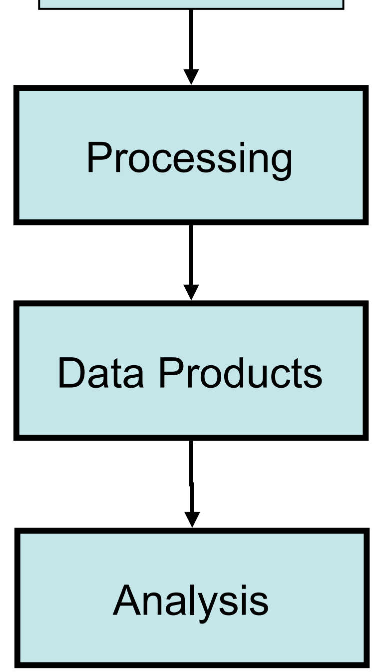
Coherent Doppler Lidar





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

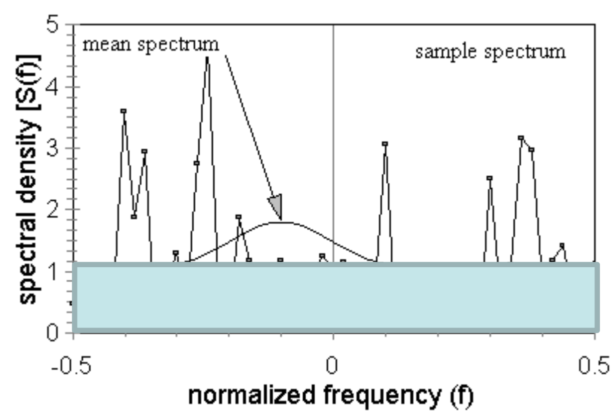
The Coherent Doppler Lidar Equation

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:

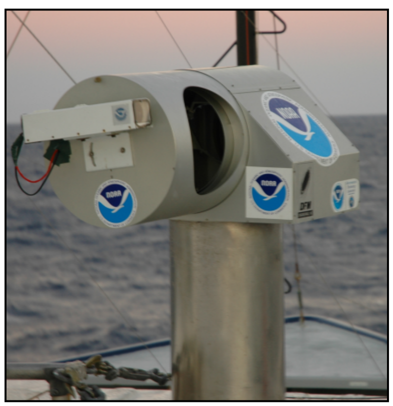
$$CNR(R) = \frac{\eta\beta T^2 c E_T}{h\nu B 2R^2}\frac{\pi D^2}{4}$$

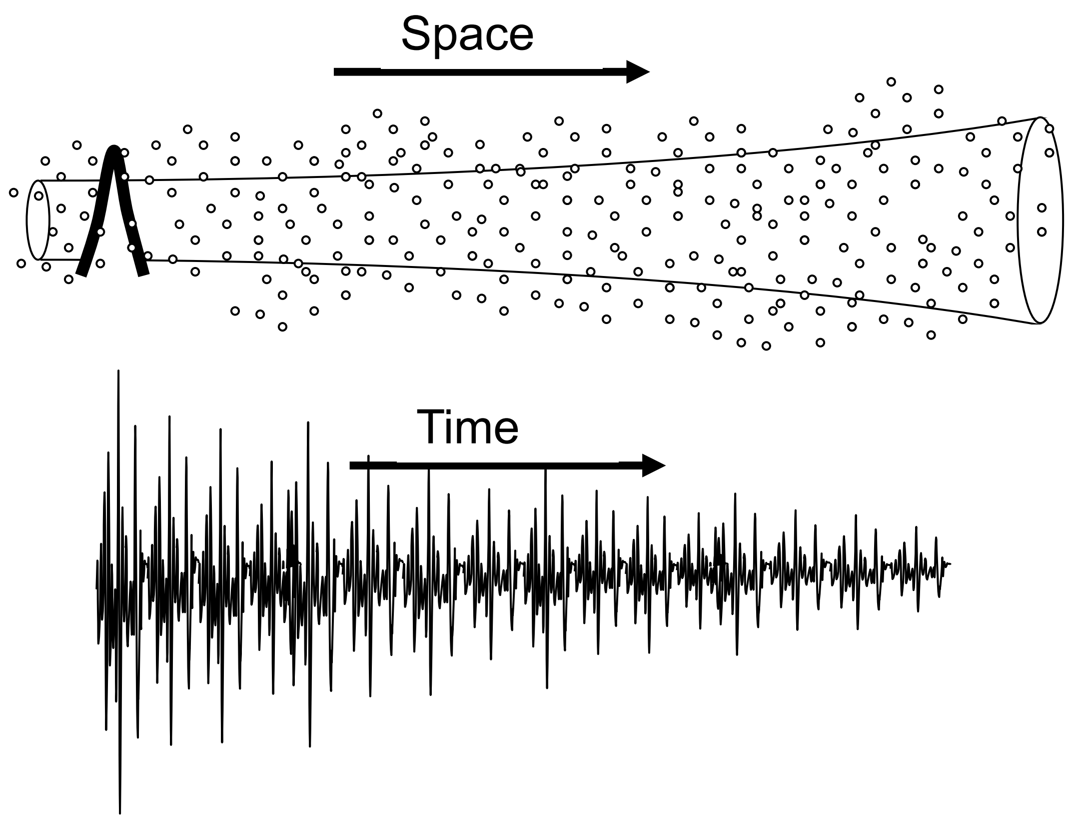


- Coherent Detection
- Laser
- Local Oscillator + shift
- Transmit/Receive paths
- Atmosphere
- **Detection & Processing**
- Analysis and Data products
- Field Work

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.

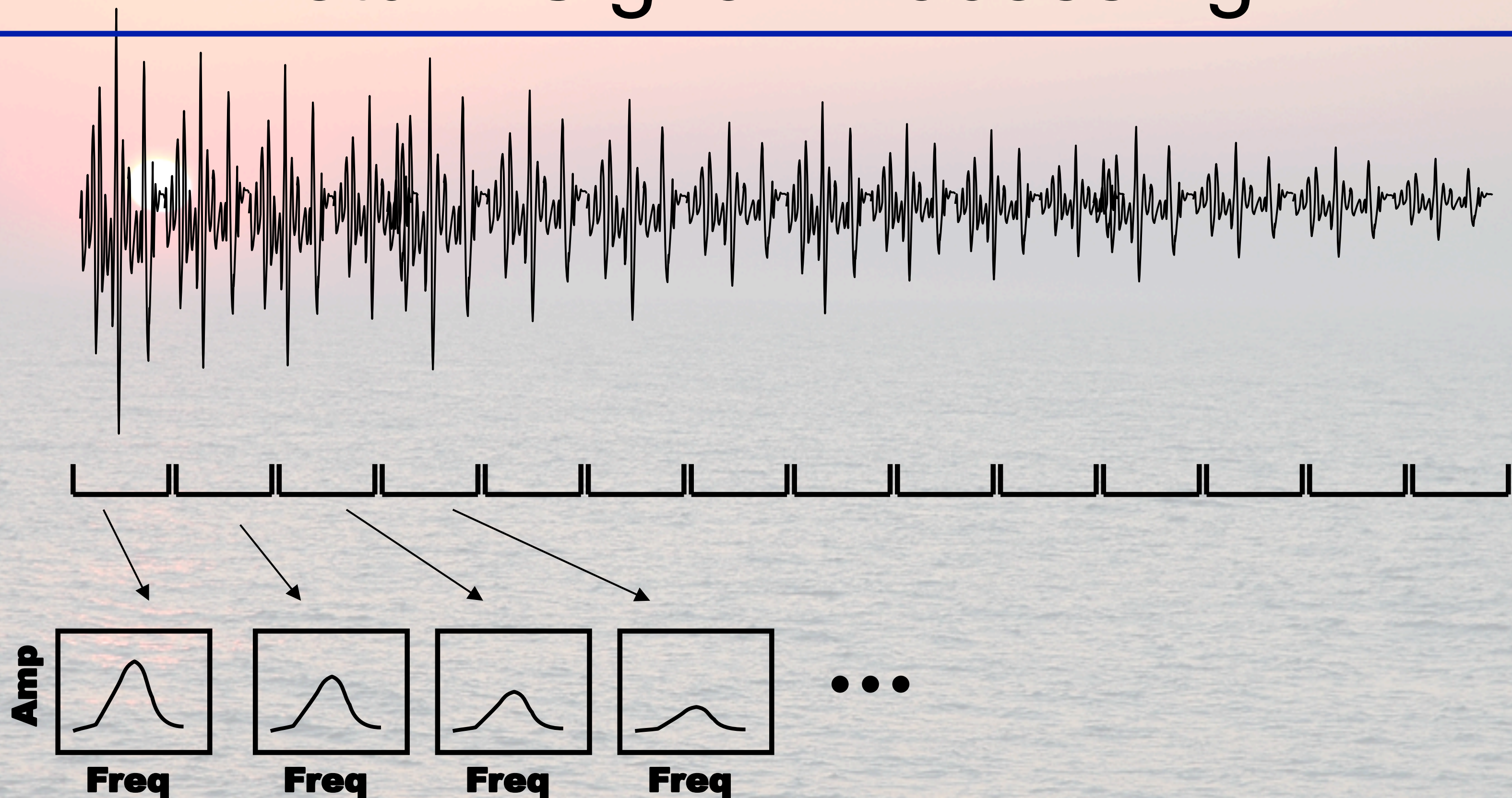
HRDL

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

MOPA

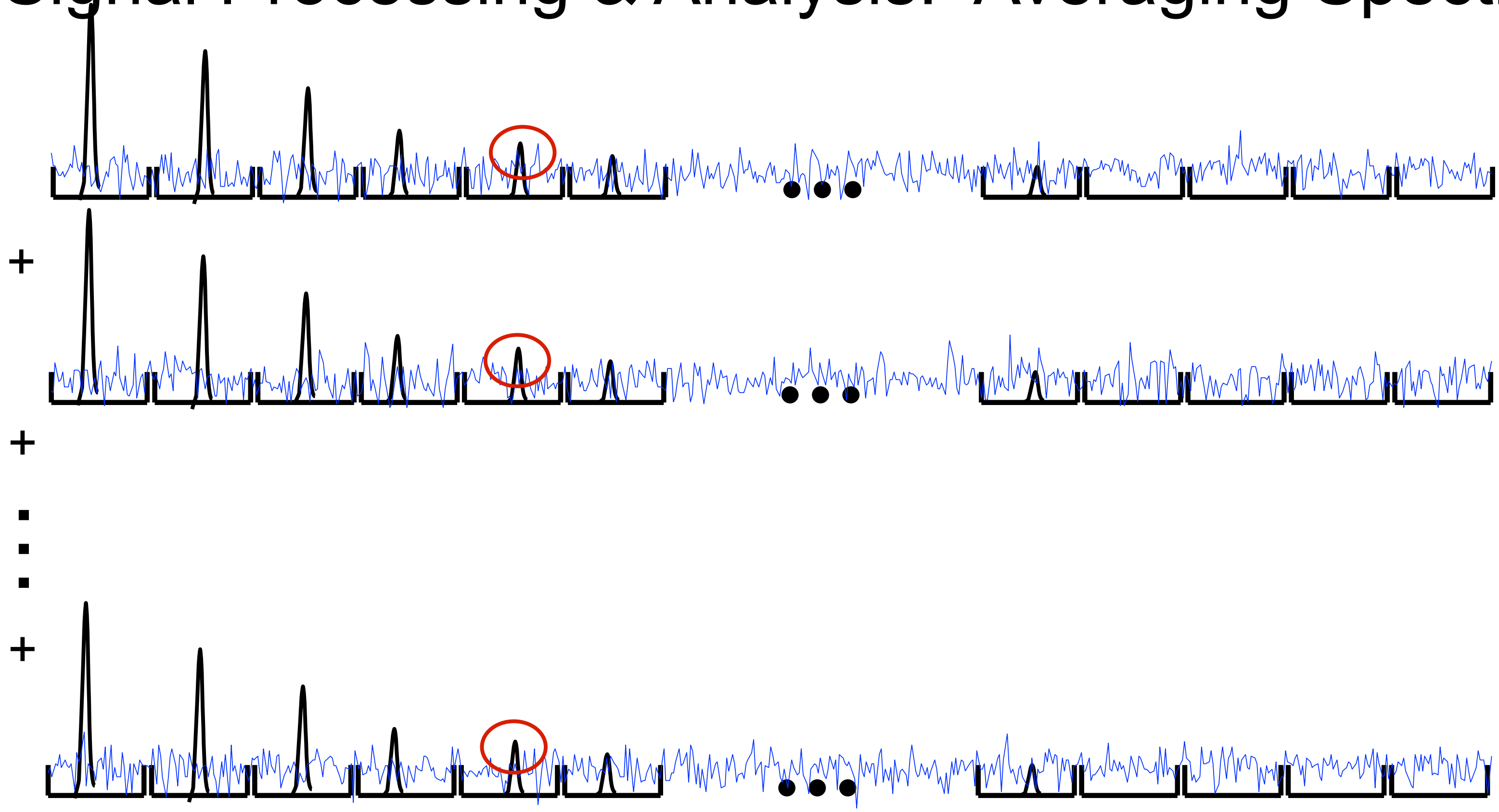
- Analog Filtering
- Sampling
- Digital demodulation

Return Signal Processing

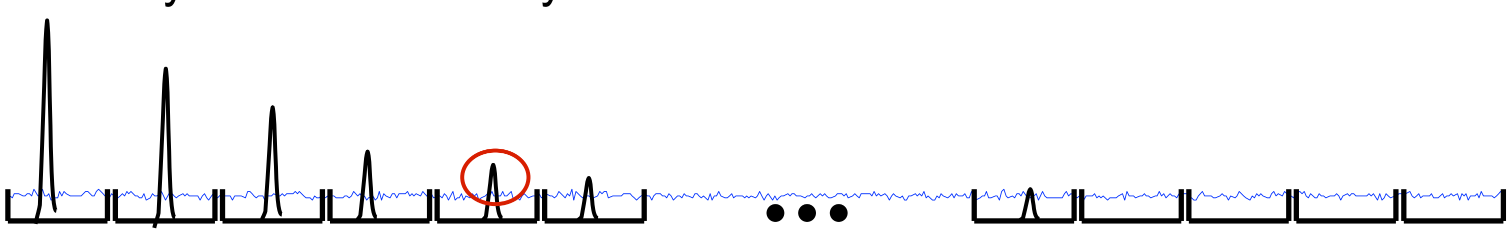


- Break into gates (equal to laser pulse length)
- Find spectrum for each gate
- Average spectra for same range gate from different pulses
- Find frequency peak for each gate to find Doppler shift and intensity as a function of range

Signal Processing & Analysis: Averaging Spectra

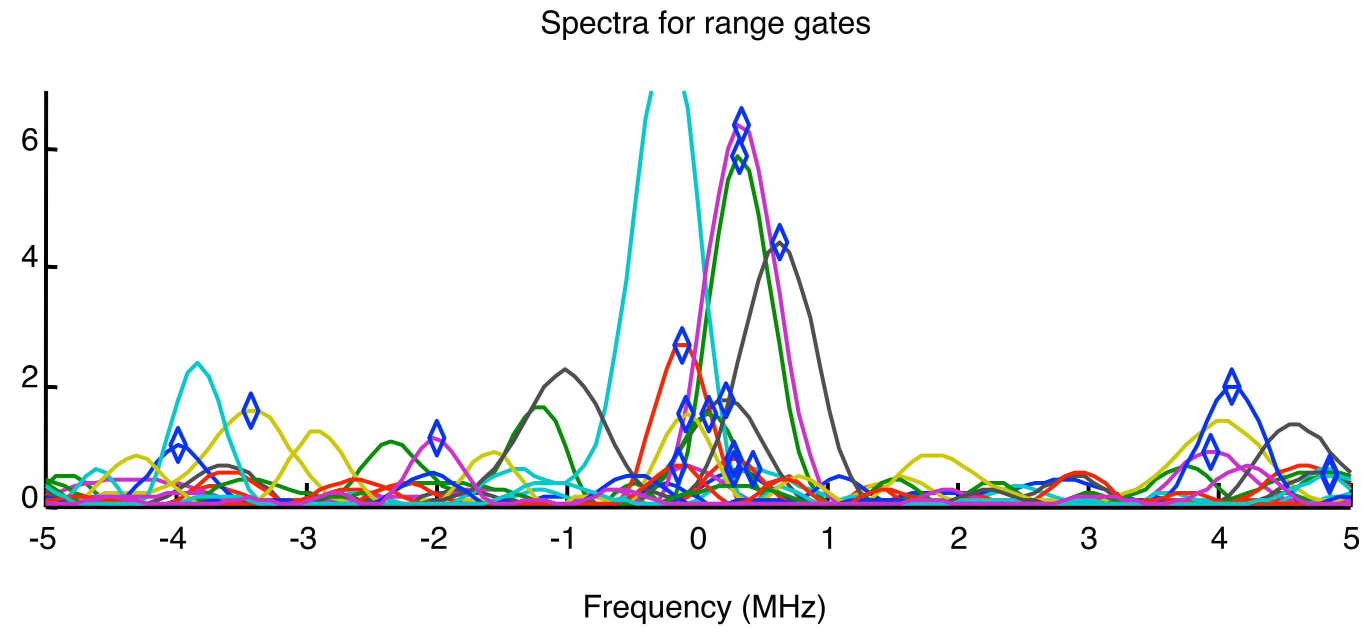


- Average the spectra and THEN estimate the frequency/velocity
- Why not the other way around?

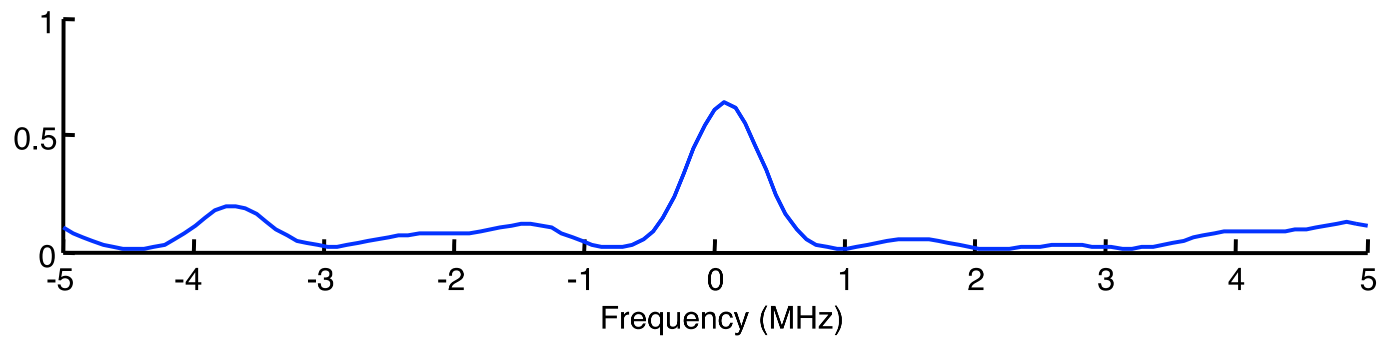


Signal Processing & Analysis: Averaging Spectra

Individual noisy spectra



Average of all spectra



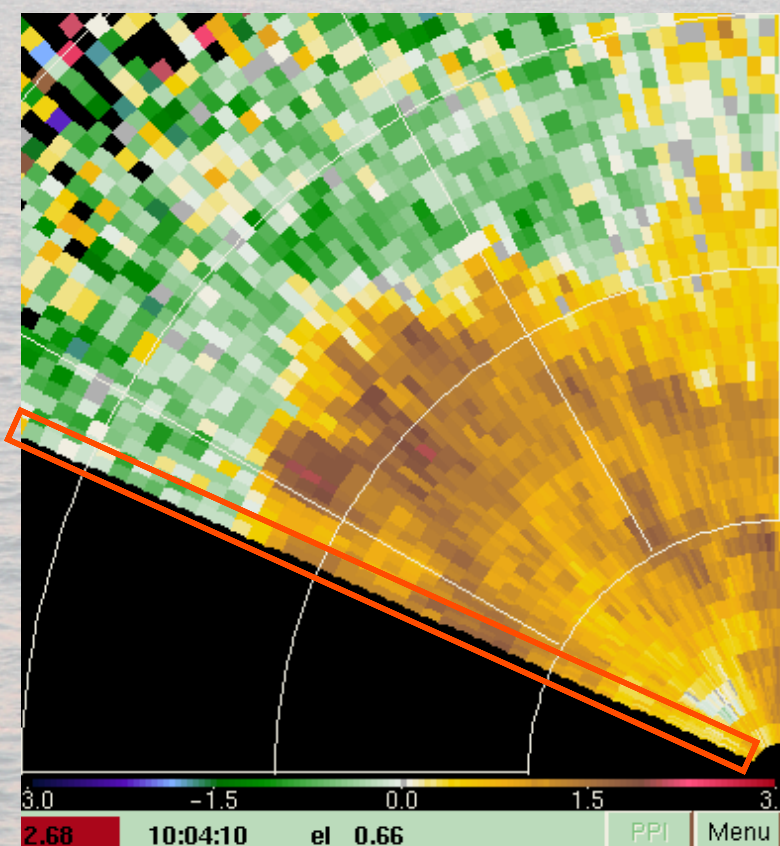
Result: Average CNR does NOT change
-but velocity estimate *precision* improves

Example Data

Single beam range resolved estimates: 150m / 2X sec

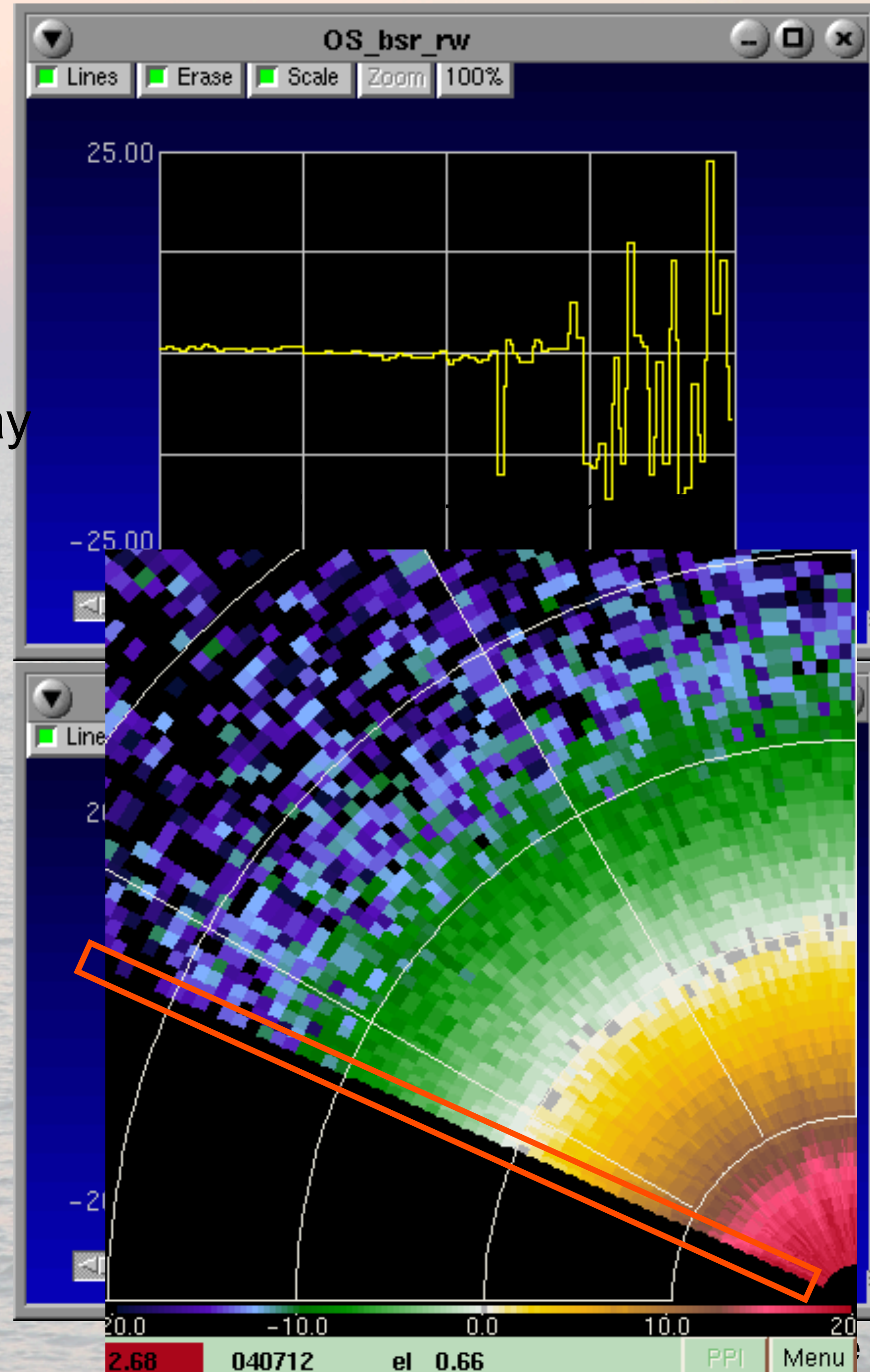
Color code and combine single beam results into scanning display

Velocity (m/s)



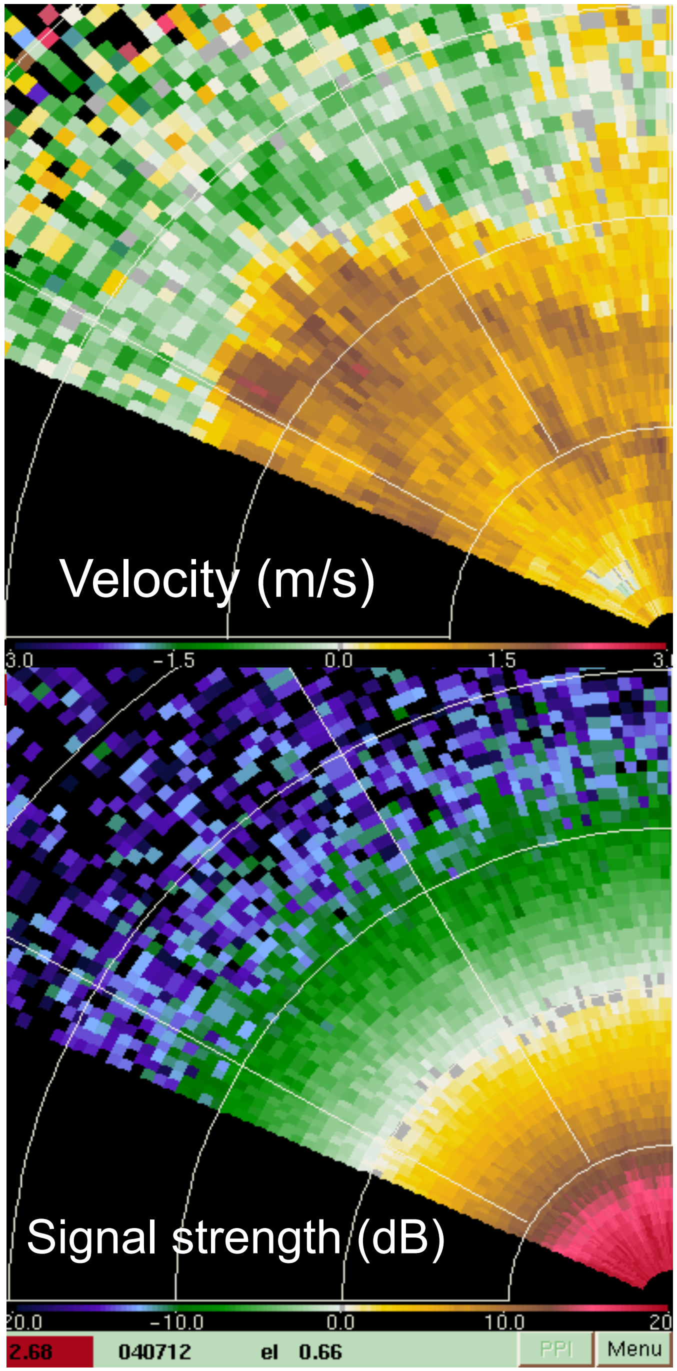
s)

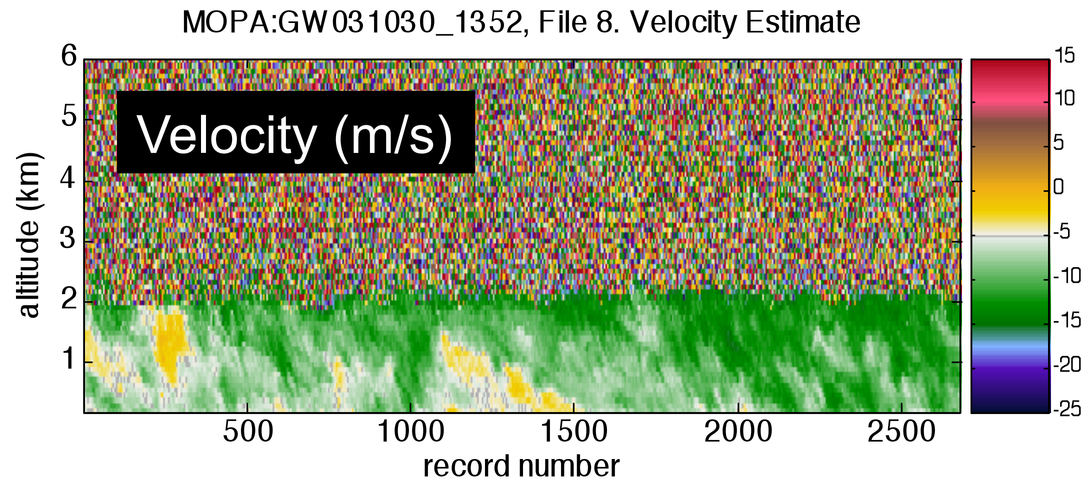
dB)

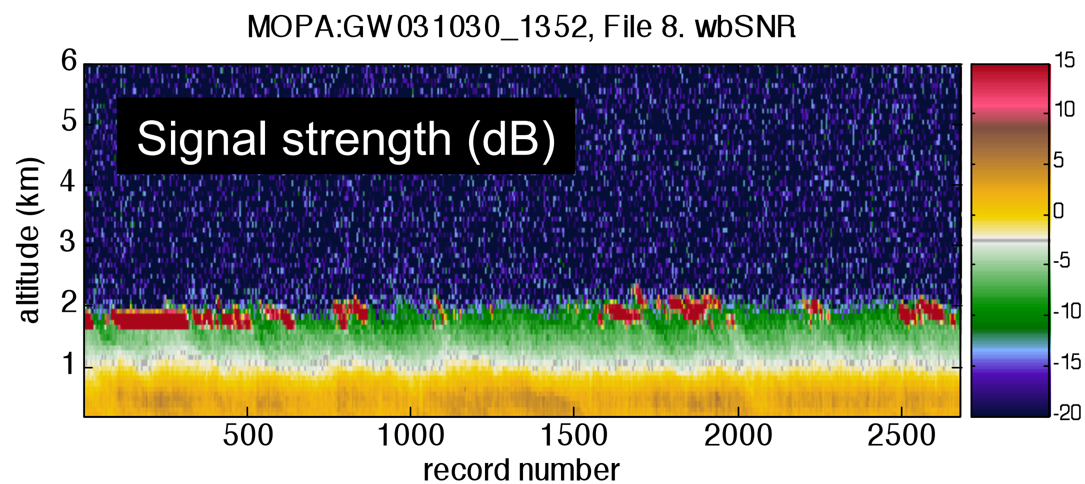


Doppler lidar data displays

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







Signal Processing: Real Data Example

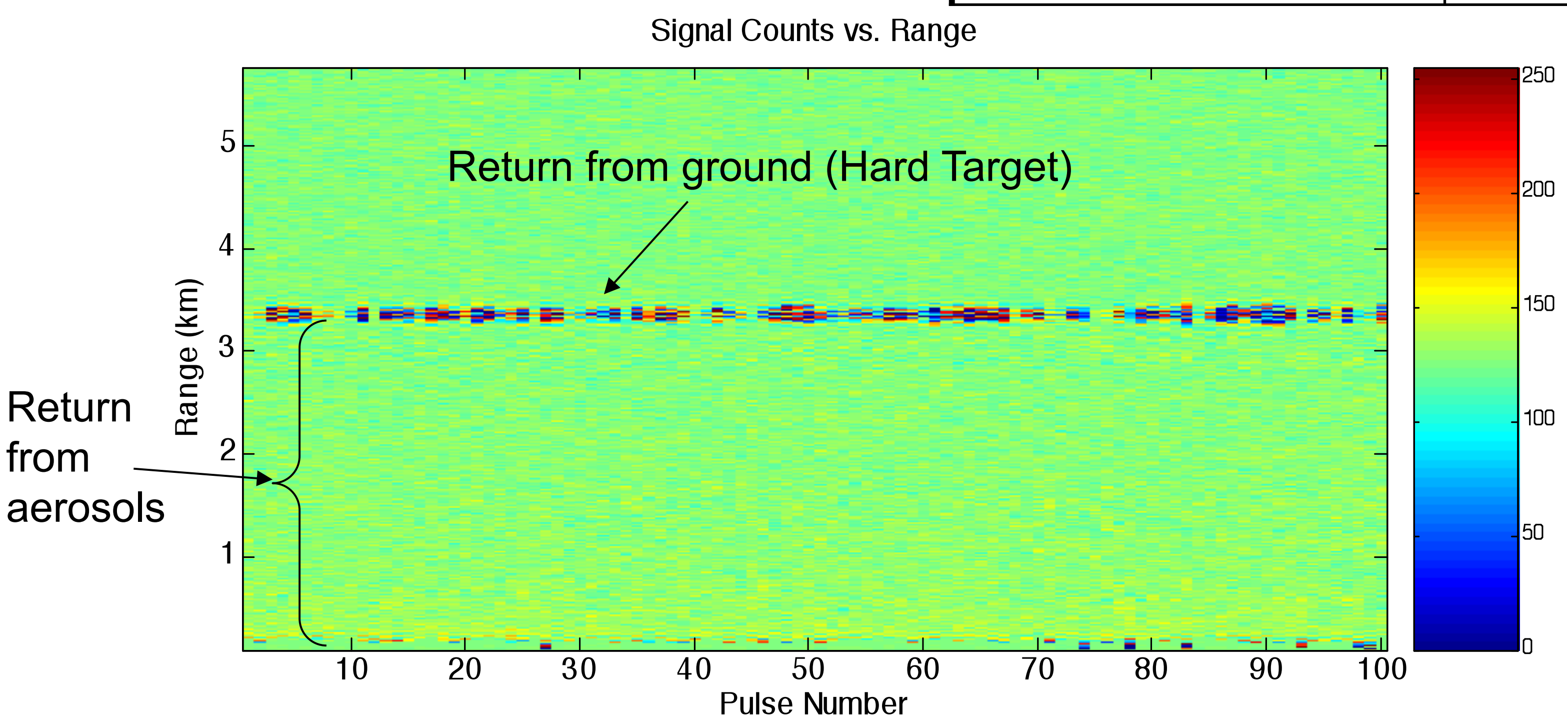
This data comes from an instrument called the Twin Otter Doppler Wind Lidar (TODWL). It flies in an aircraft and points down at the earth.

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.

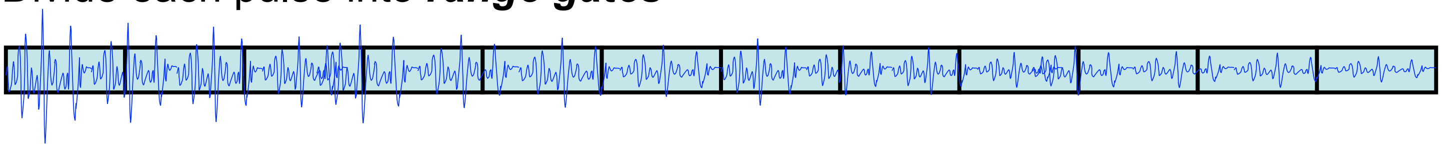
Goal: Calculate velocity and CNR versus range for this data set.

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

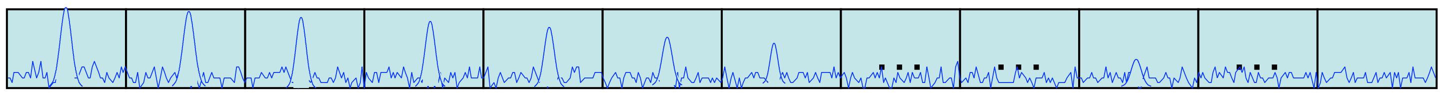


Return Signal Processing: Steps for processing example data

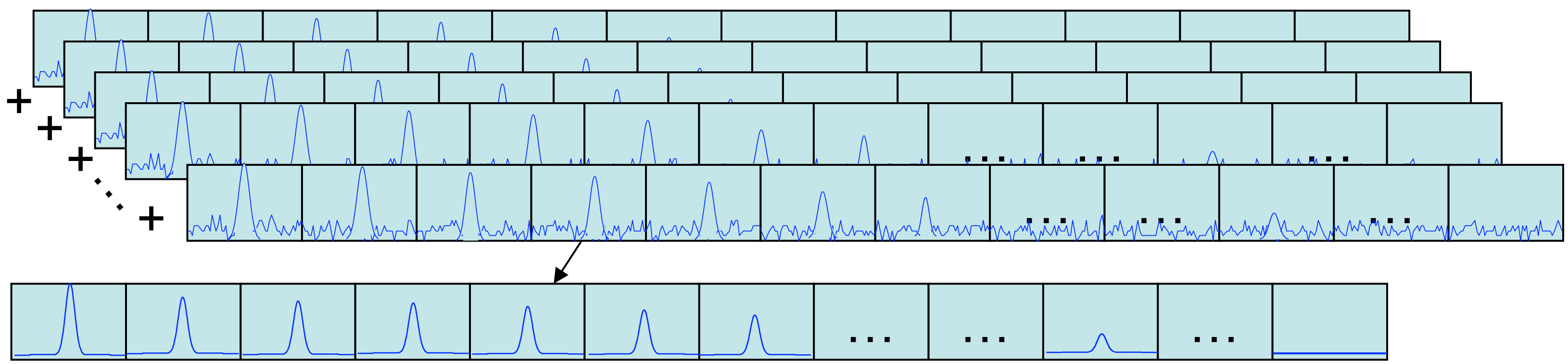
1. Divide each pulse into ***range gates***



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)



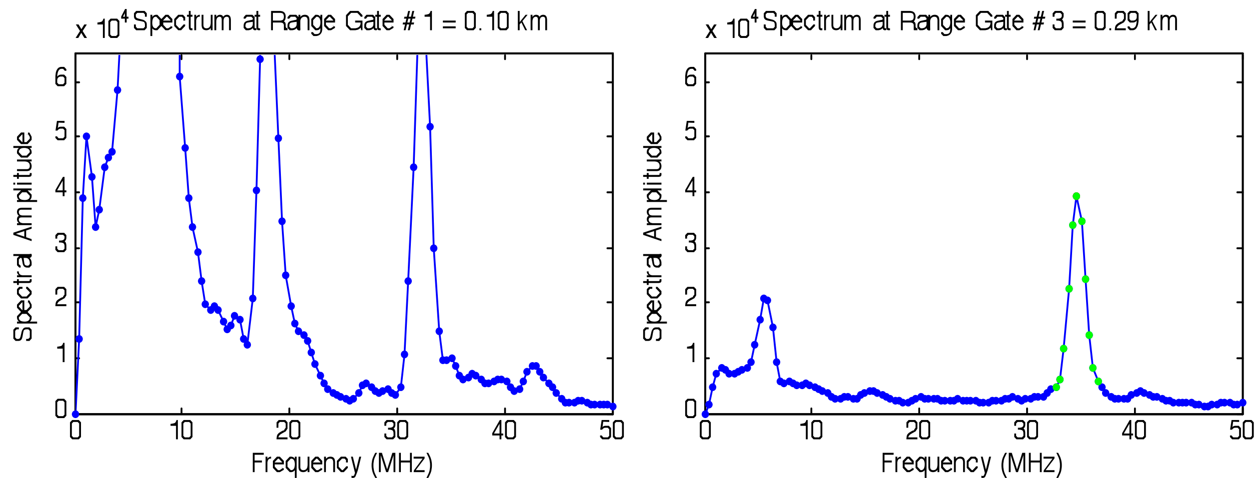
3. ***Average*** the spectrum for each range gate, with the spectra from the same range gate in all the other N pulses

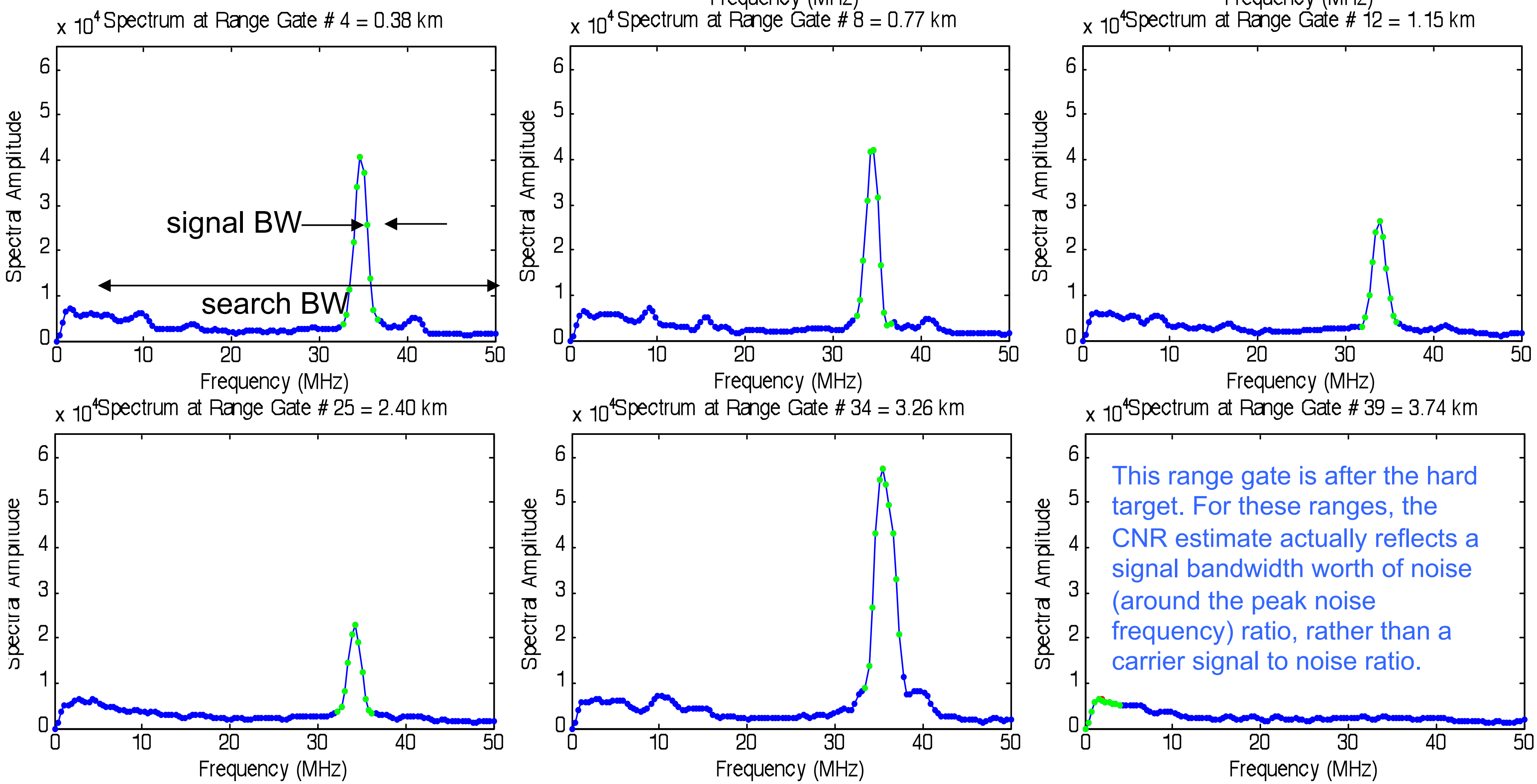


4. The frequency axis should be 0 to 50 MHz.

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.

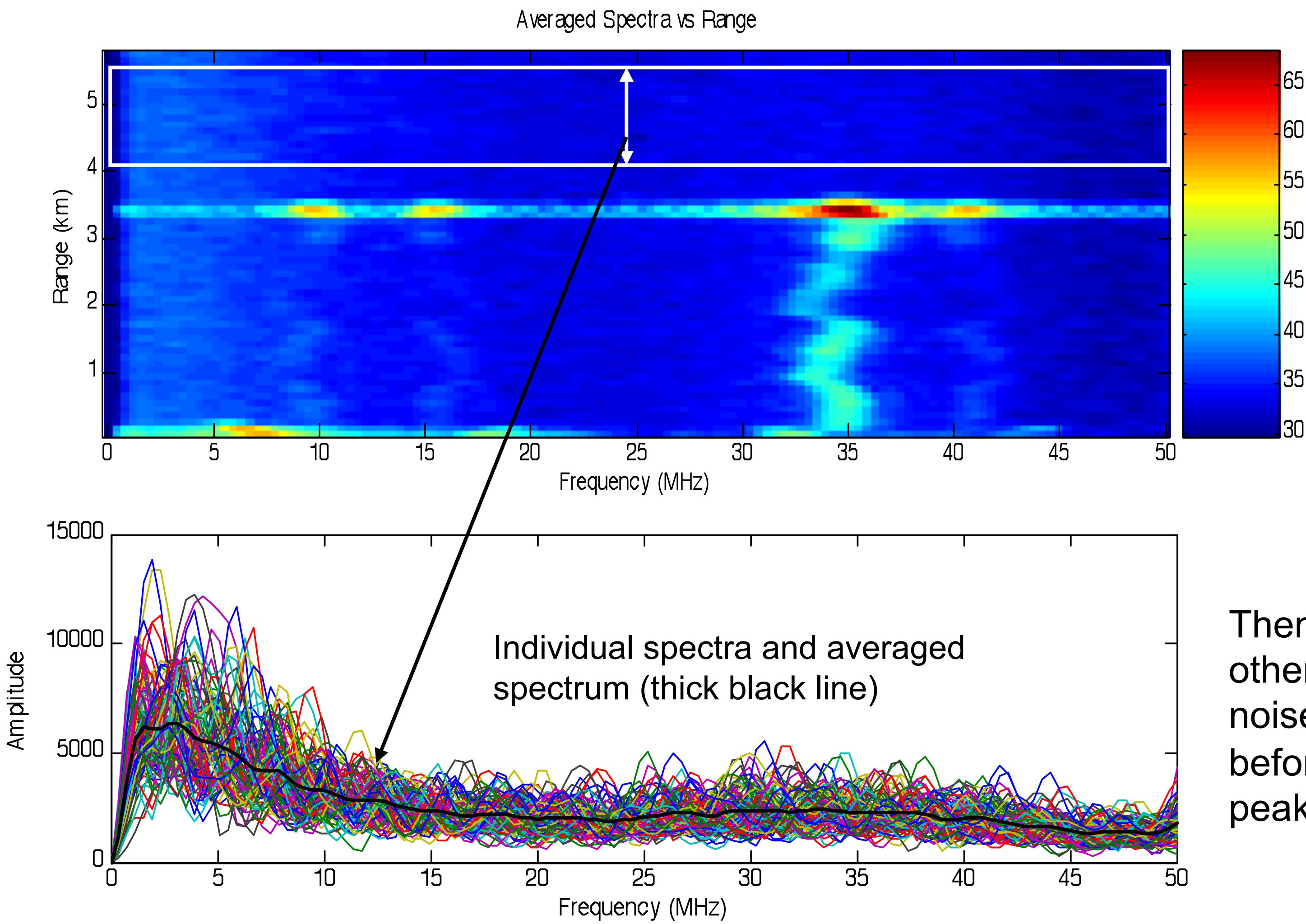
Processing example data: Averaged spectra for different range gates





Return Signal Processing: Processing example data – Noise floor whitening

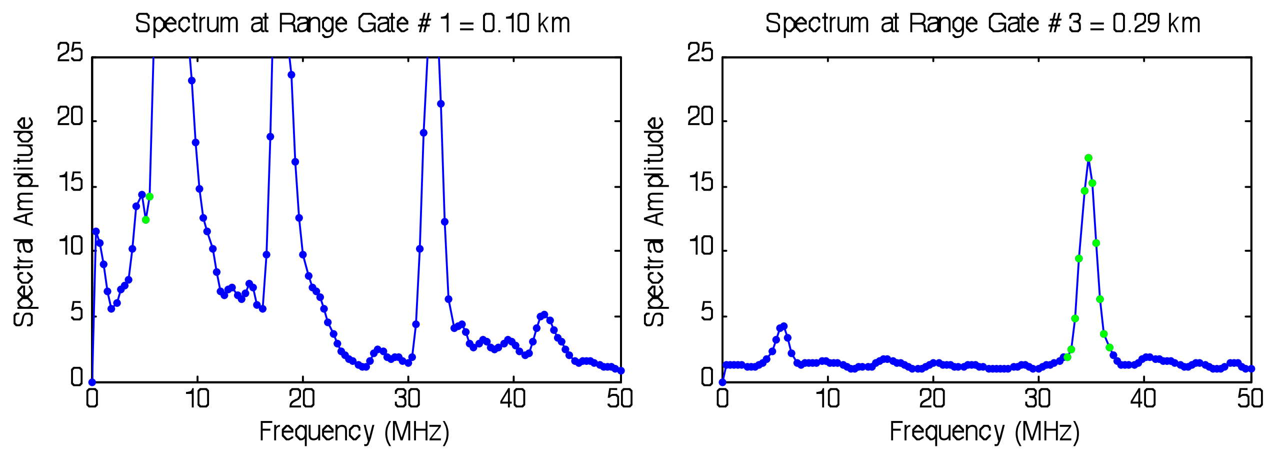
Notice the increased signal levels in lower frequencies. We need to flatten/whiten the noise floor.

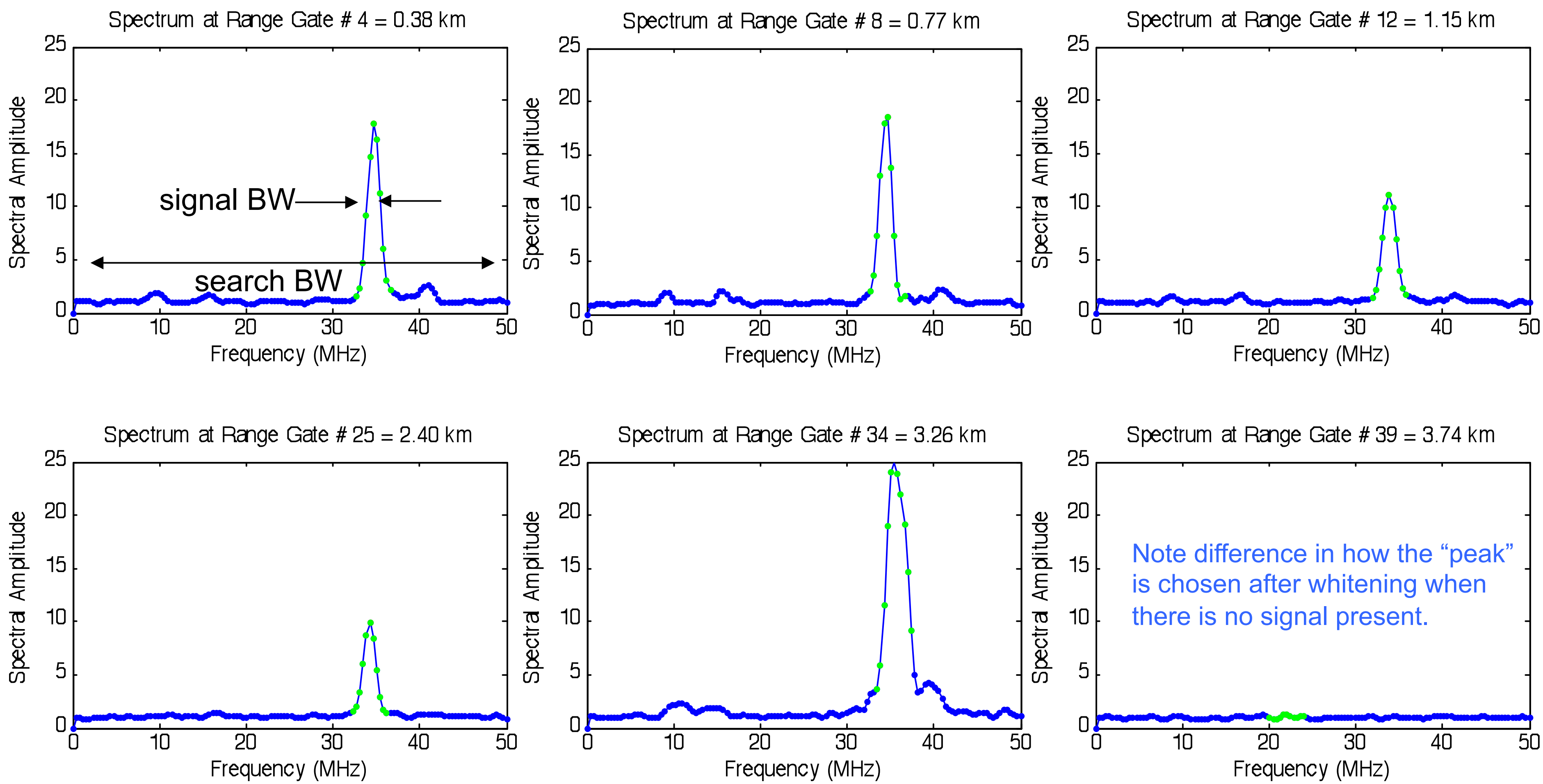


Find the average spectrum in an area where there is no return signal. This is the estimated spectral noise floor

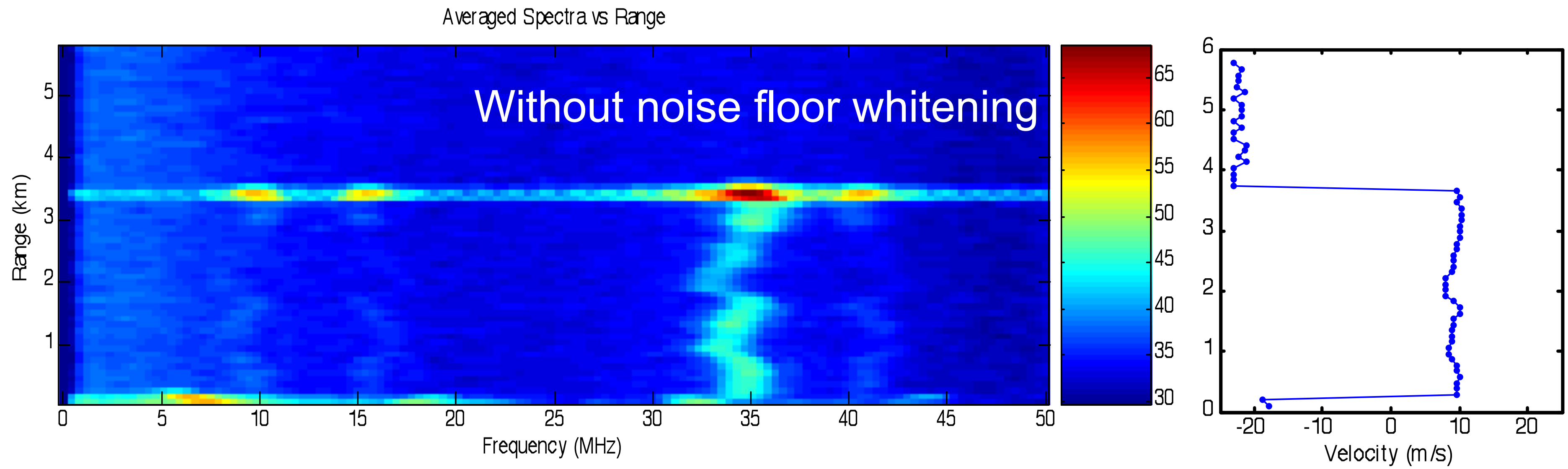
Then divide all of the other spectra by this noise floor estimate before estimating the peak frequency.

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

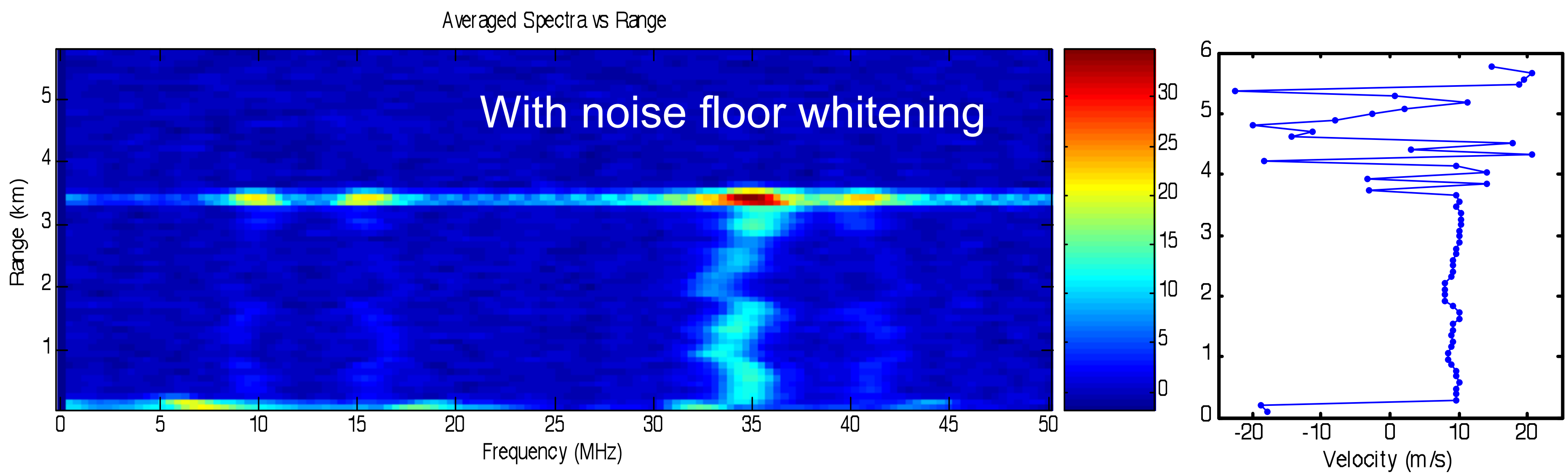




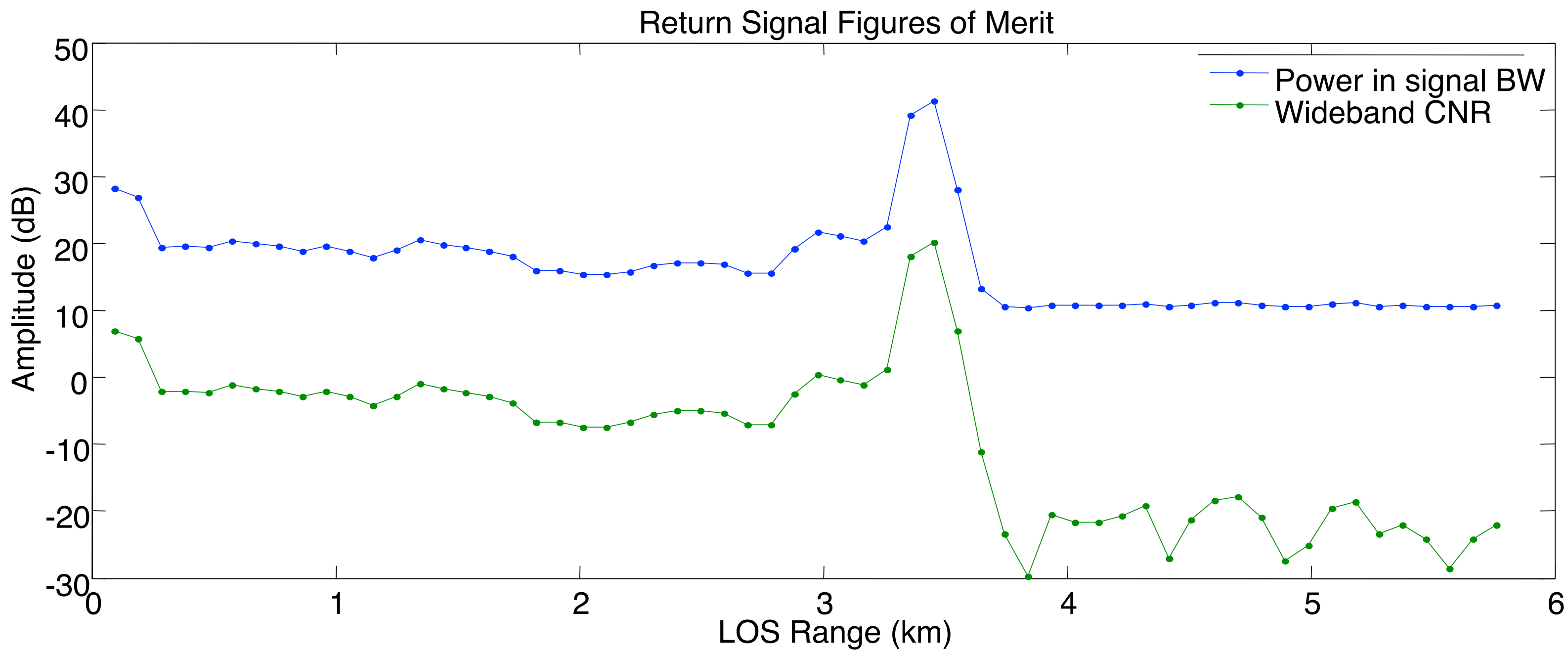
Return Signal Processing: Processing example data – noise floor whitening



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.



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.

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

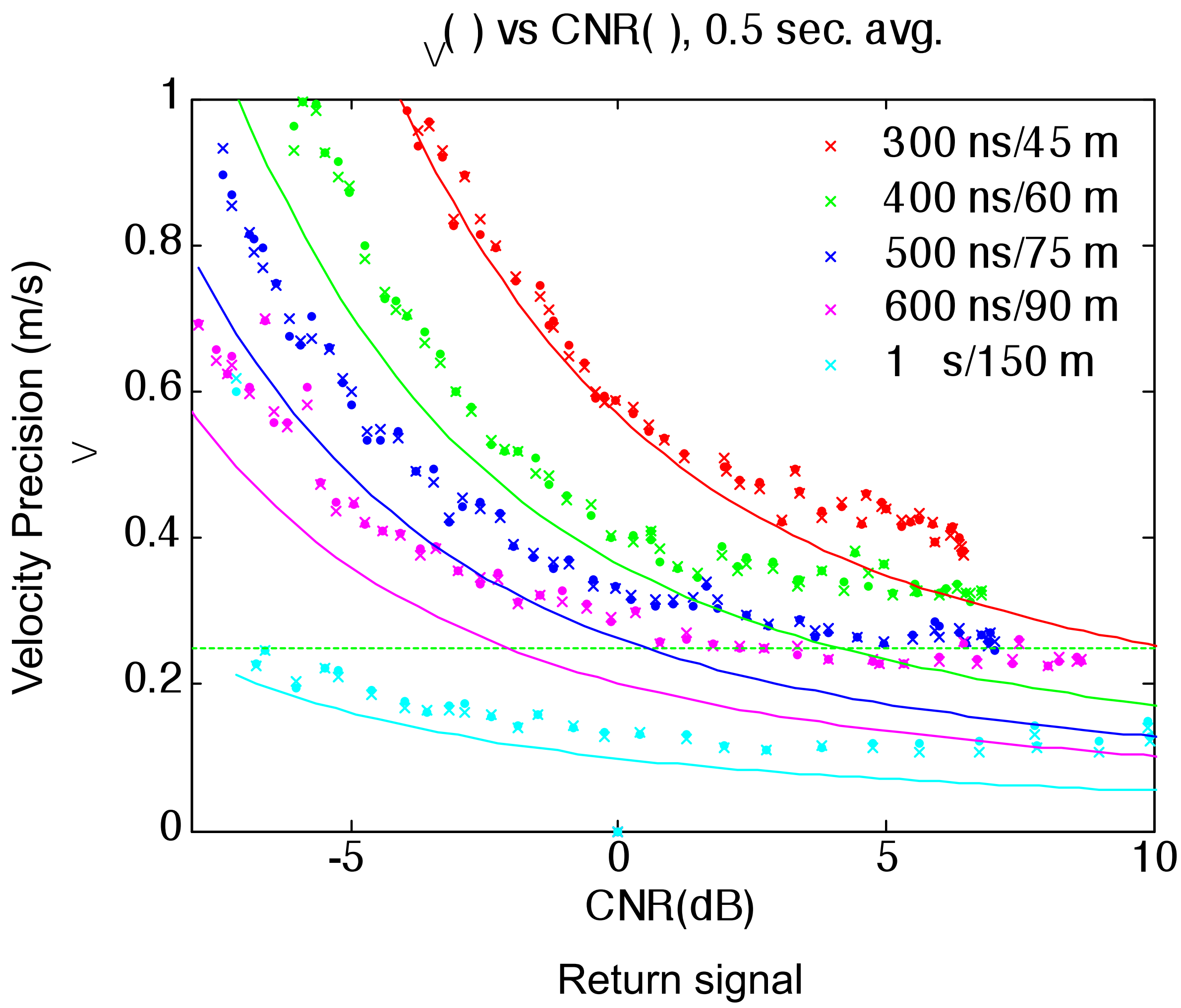
The Wideband CNR is then calculated as follows:

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

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} = NFFT/2 = 128). The N_{wb}/NFFT/2 is equivalent to the signal BW to total search BW ratio.

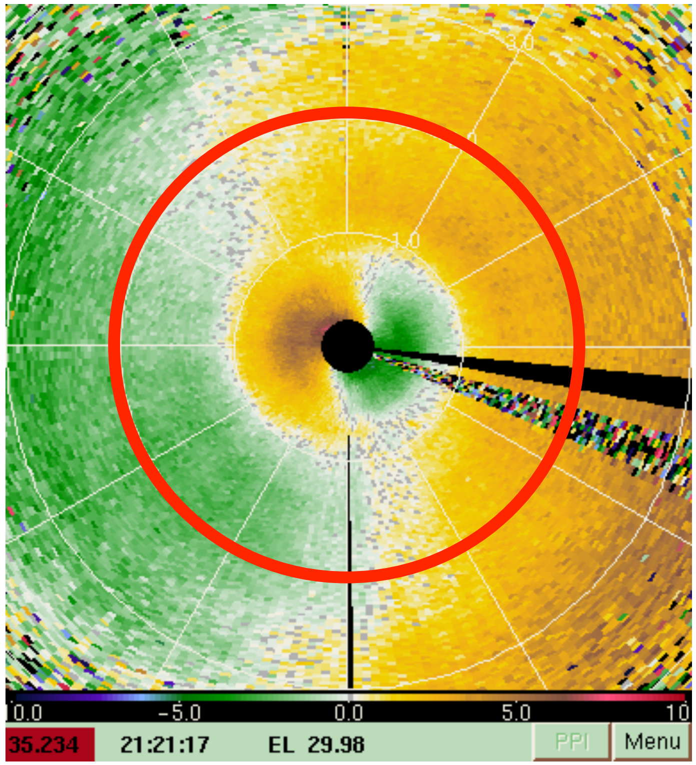
- Coherent Detection
- Laser
- Local Oscillator + shift
- Transmit path
- Atmosphere
- Receiver/Detection
- Processing
- **Analysis and Data products**
- Field Work

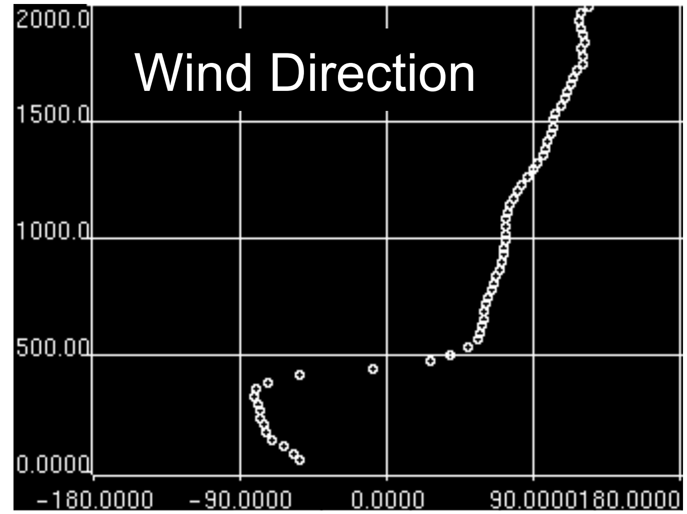
Velocity precision vs CNR and various pulse widths from mini-MOPA

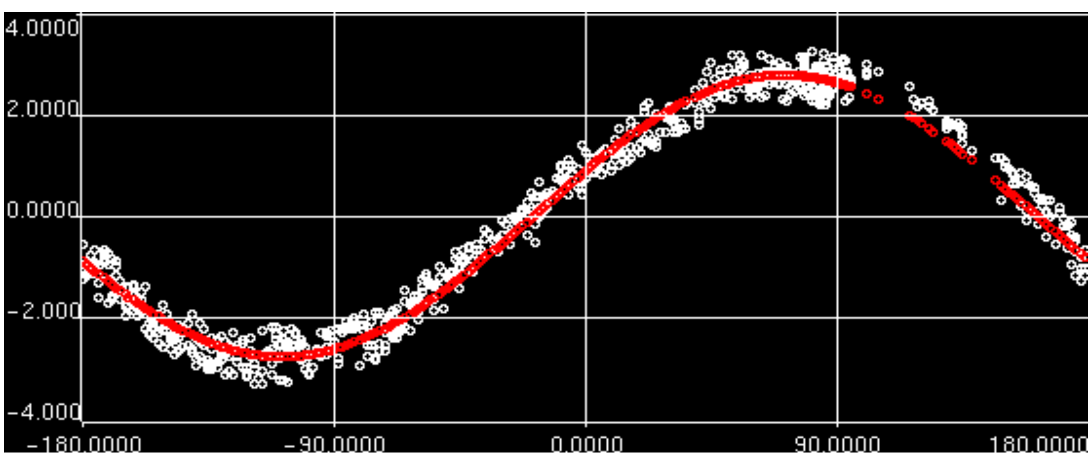


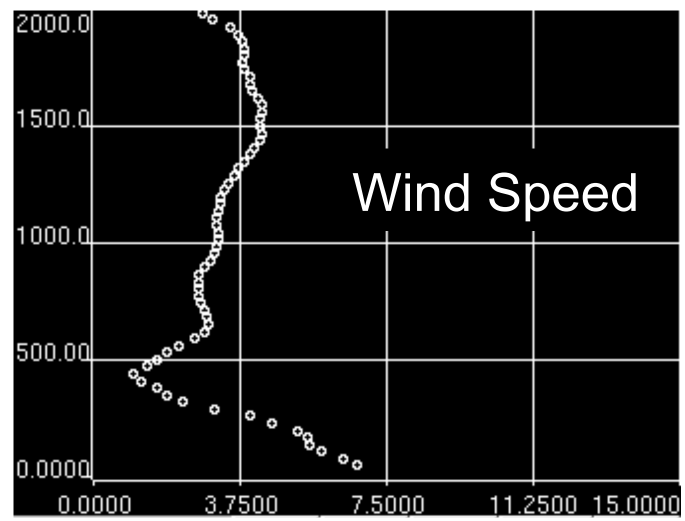
Tradeoffs between:
- detection bandwidth and CNR
- range gate length (range precision)
- velocity precision
- time resolution

Doppler Lidars: Calculating wind profile from PPI scans



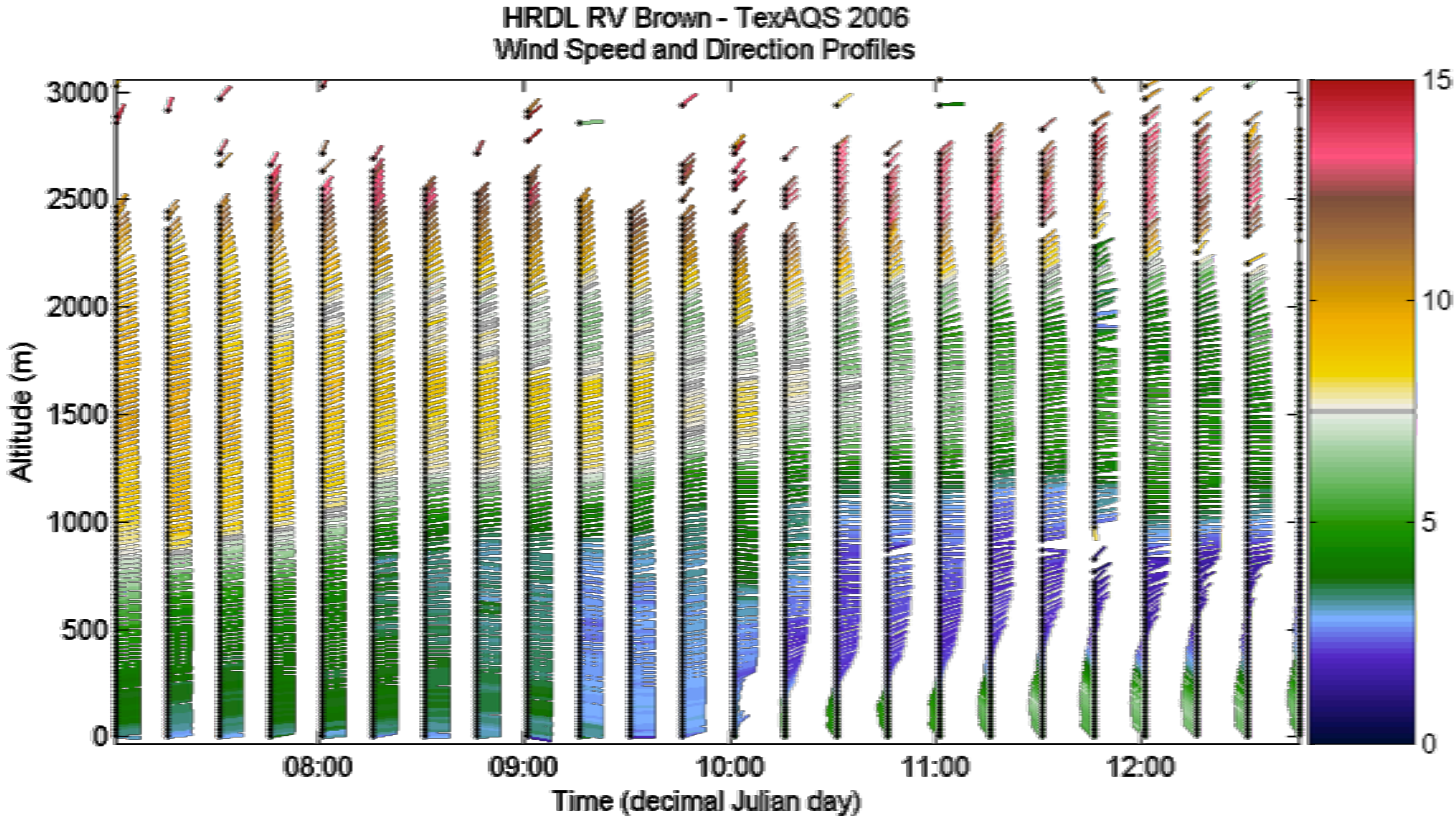






Wind Profiles

- 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.

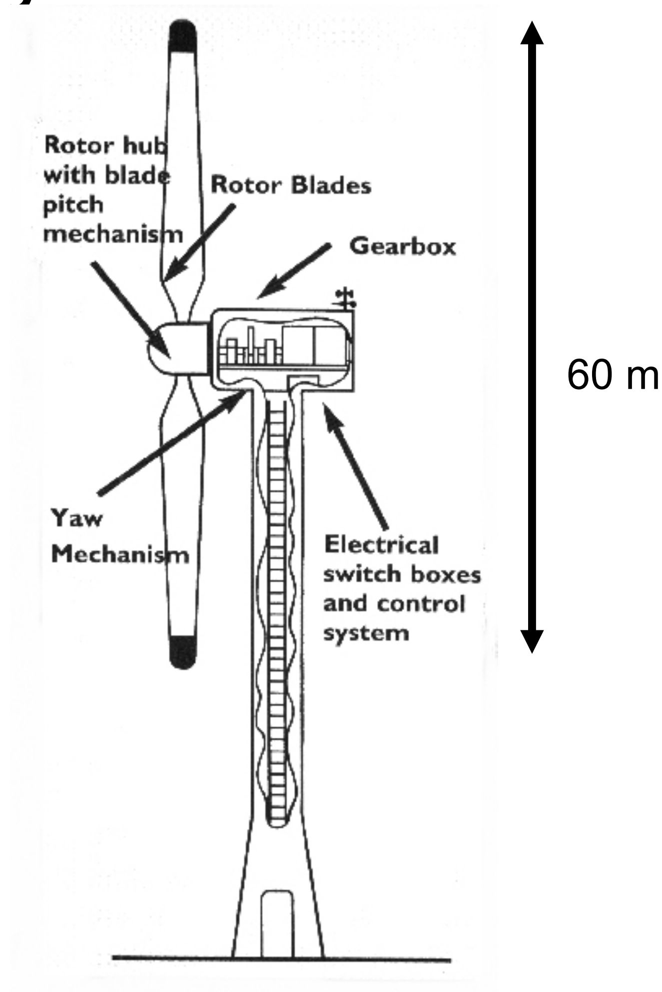
Wind Profiles: Uses

- 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

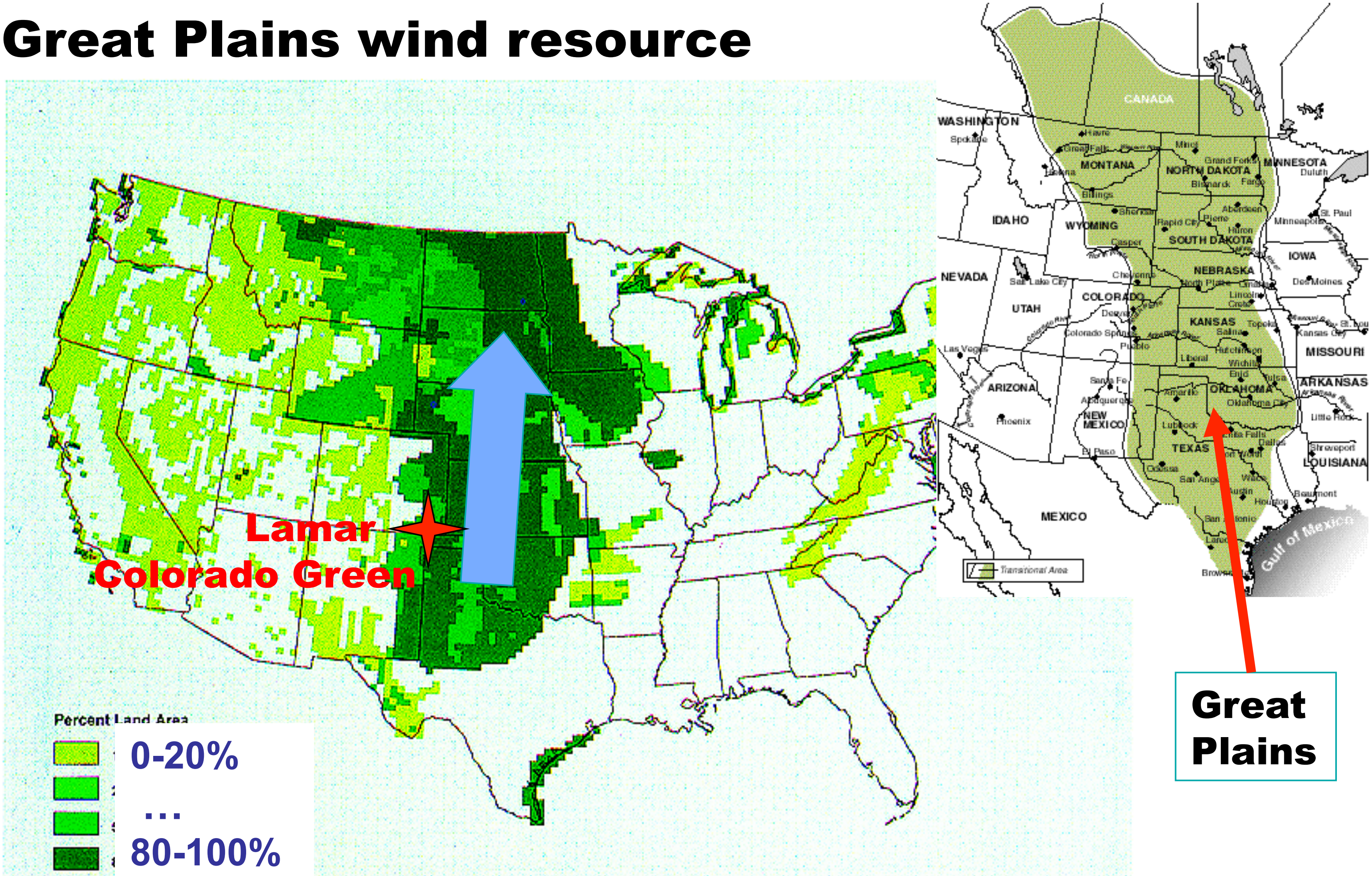
- Coherent Detection
- Laser
- Transmit path
- Atmosphere
- Receiver/Detection
- Processing
- Analysis and Data Products
- **Field Work**

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



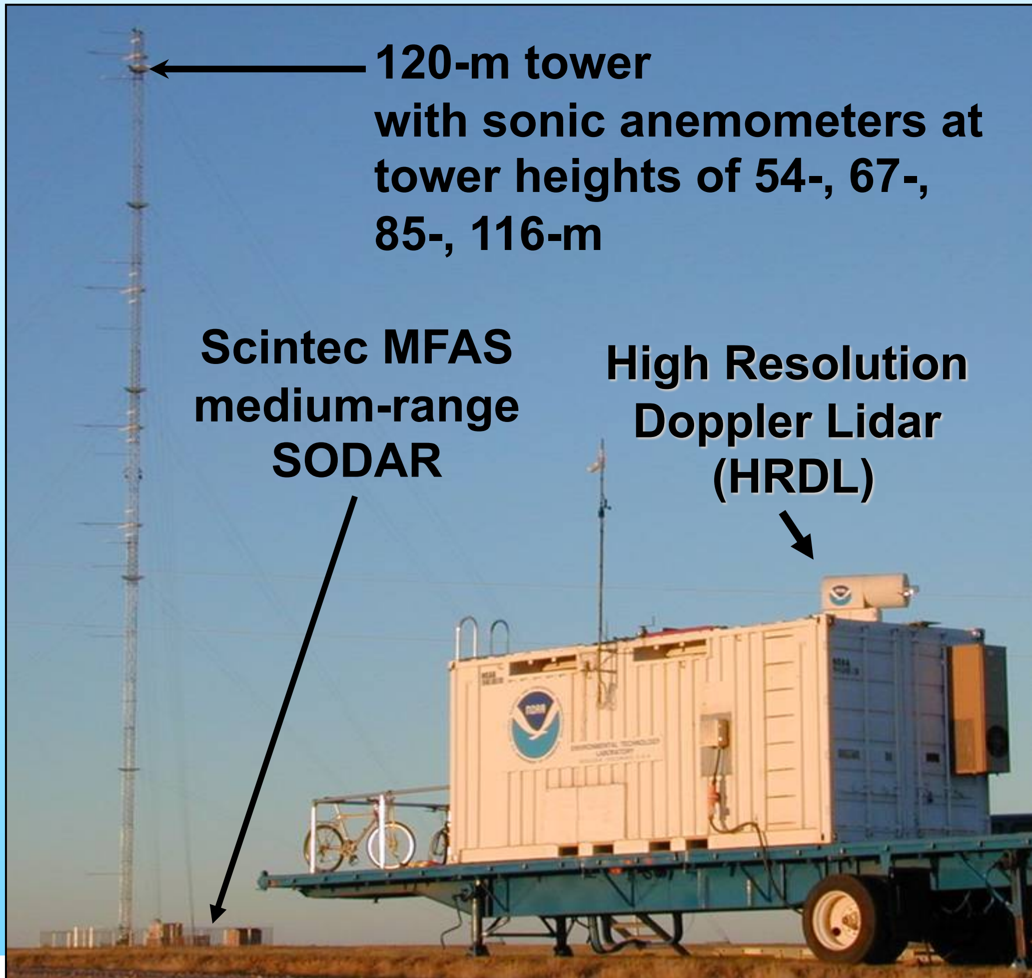
Great Plains wind resource



"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 W m^{-2} per year

Instrumentation – Lamar, Colorado,

NREL-ESRL Low-Level Jet Study

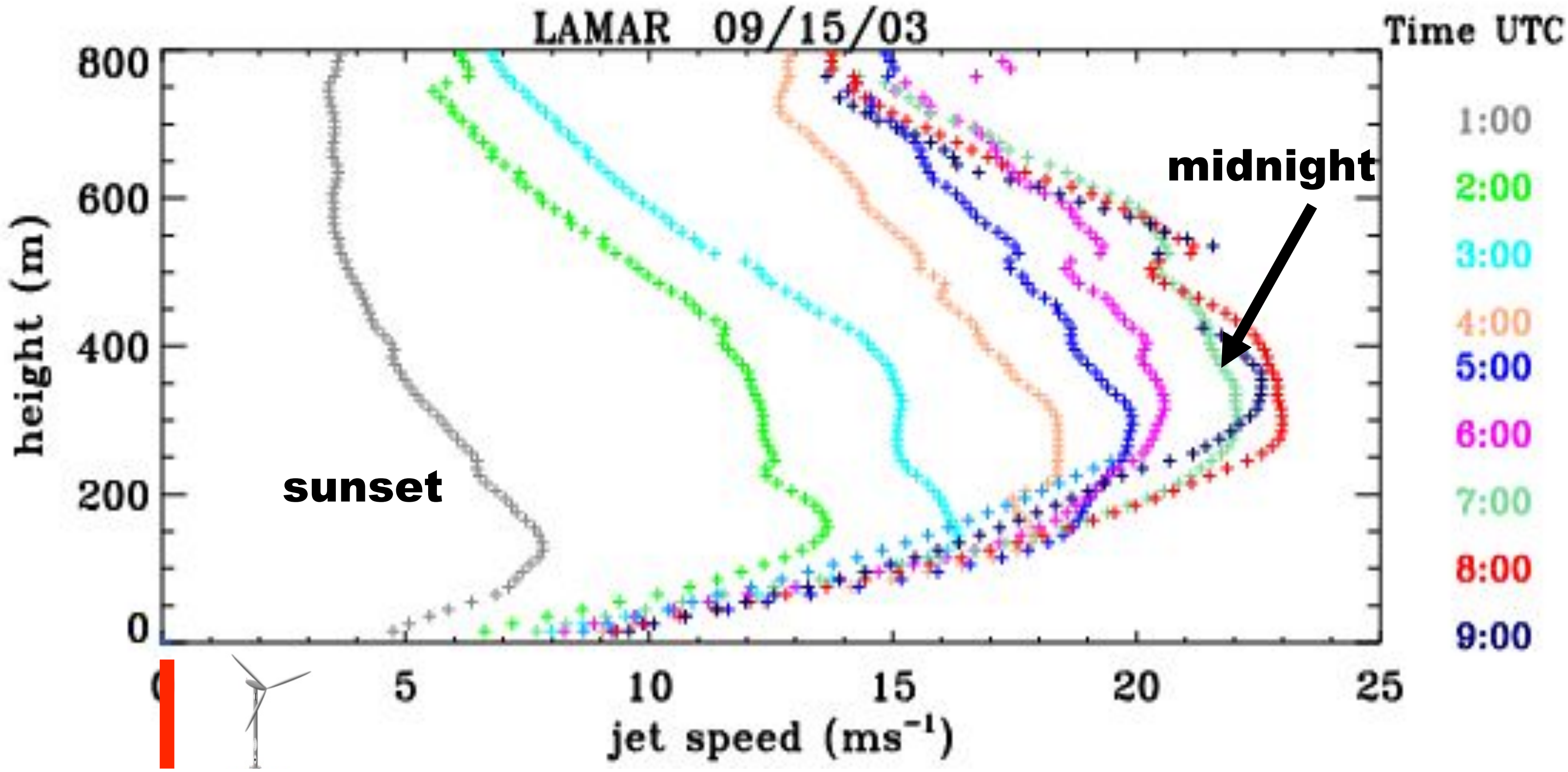


HRDL technical parameters	
Wavelength	2.02 μm
Pulse energy	1.5 mJ
Pulse rate	200/s
Range resolution	30 m
Velocity resolution	~ 0.1 m/s
Time resolution	0.5 s
Minimum range	0.2 km
Maximum range	3 km
Beam width range cm	6 to 28

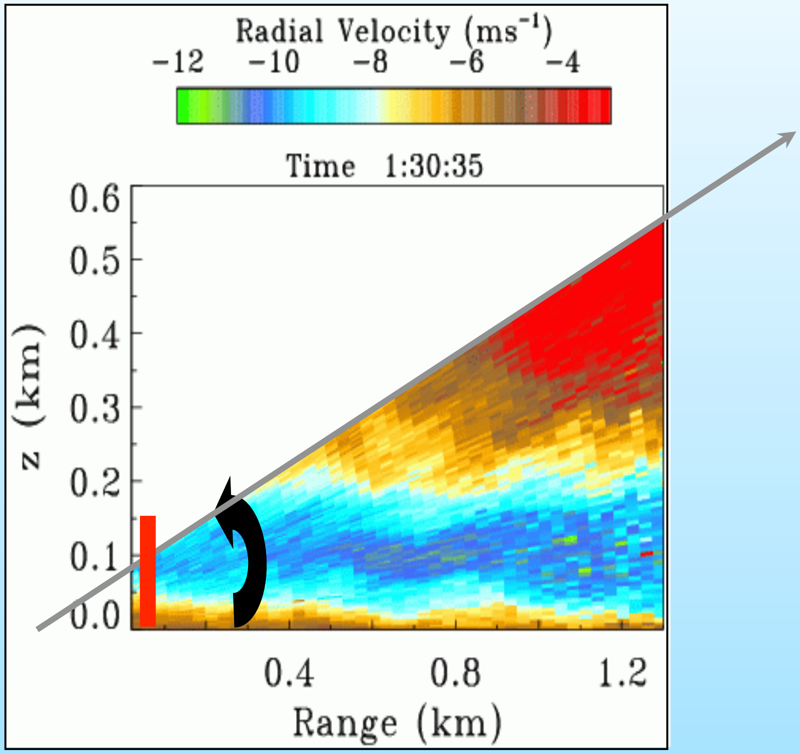
Lamar, Colorado

ESRL-NREL collaboration – September 2003

Doppler Lidar wind profiles

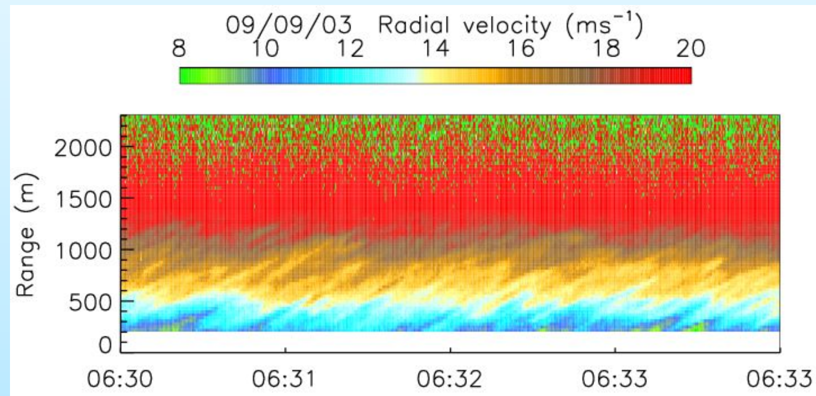


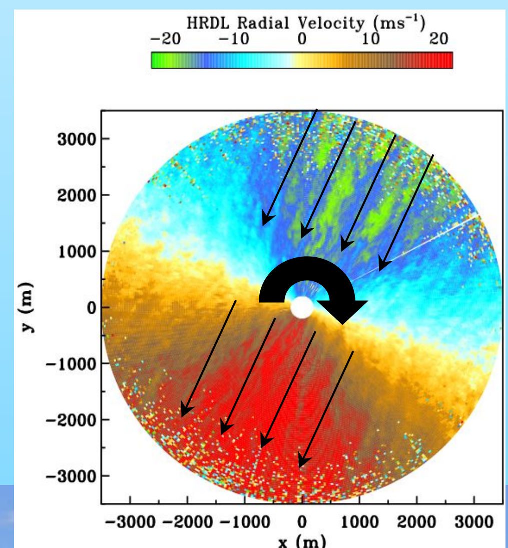
HRDL measurements



Vertical-slice scans

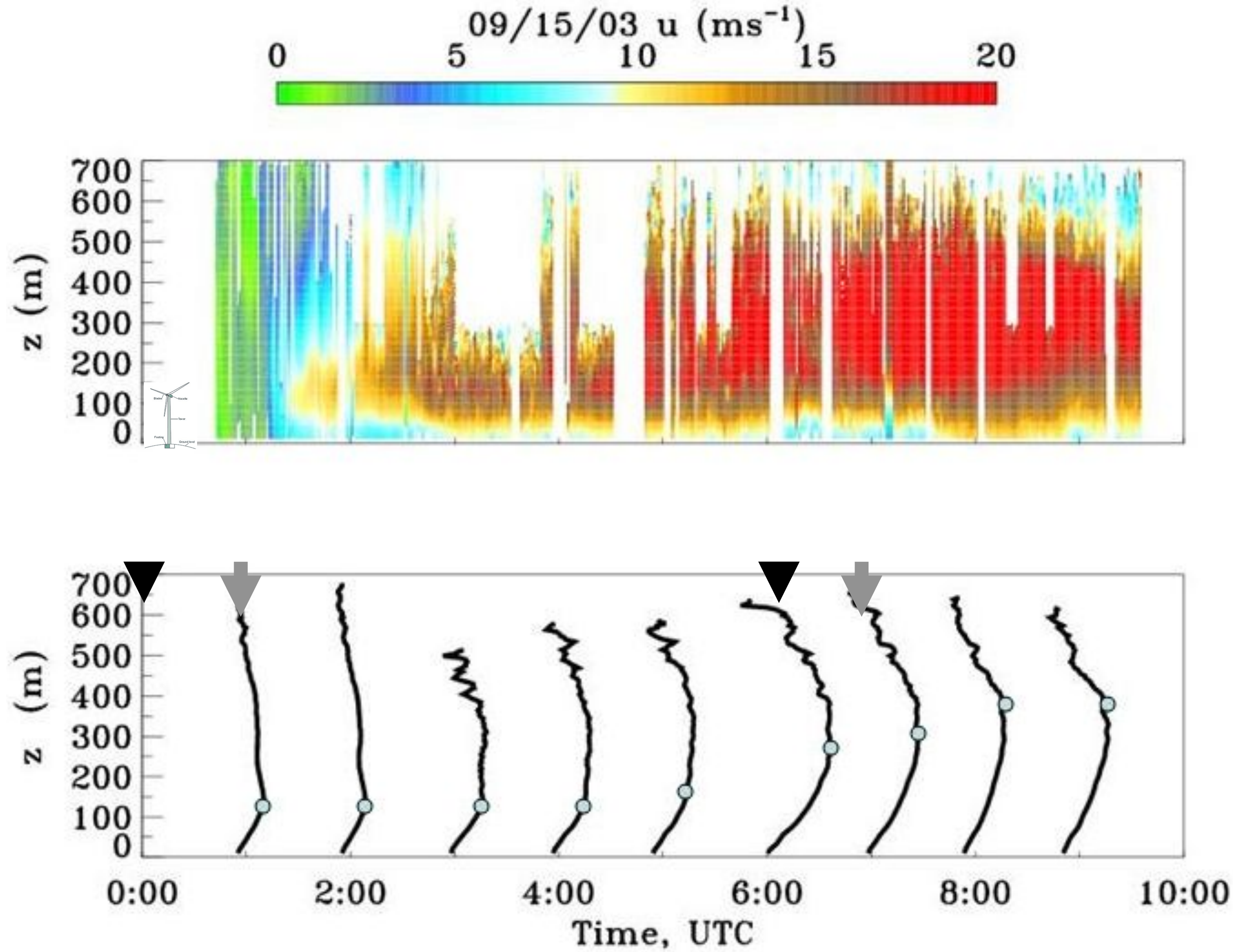
Fixed-beam scans



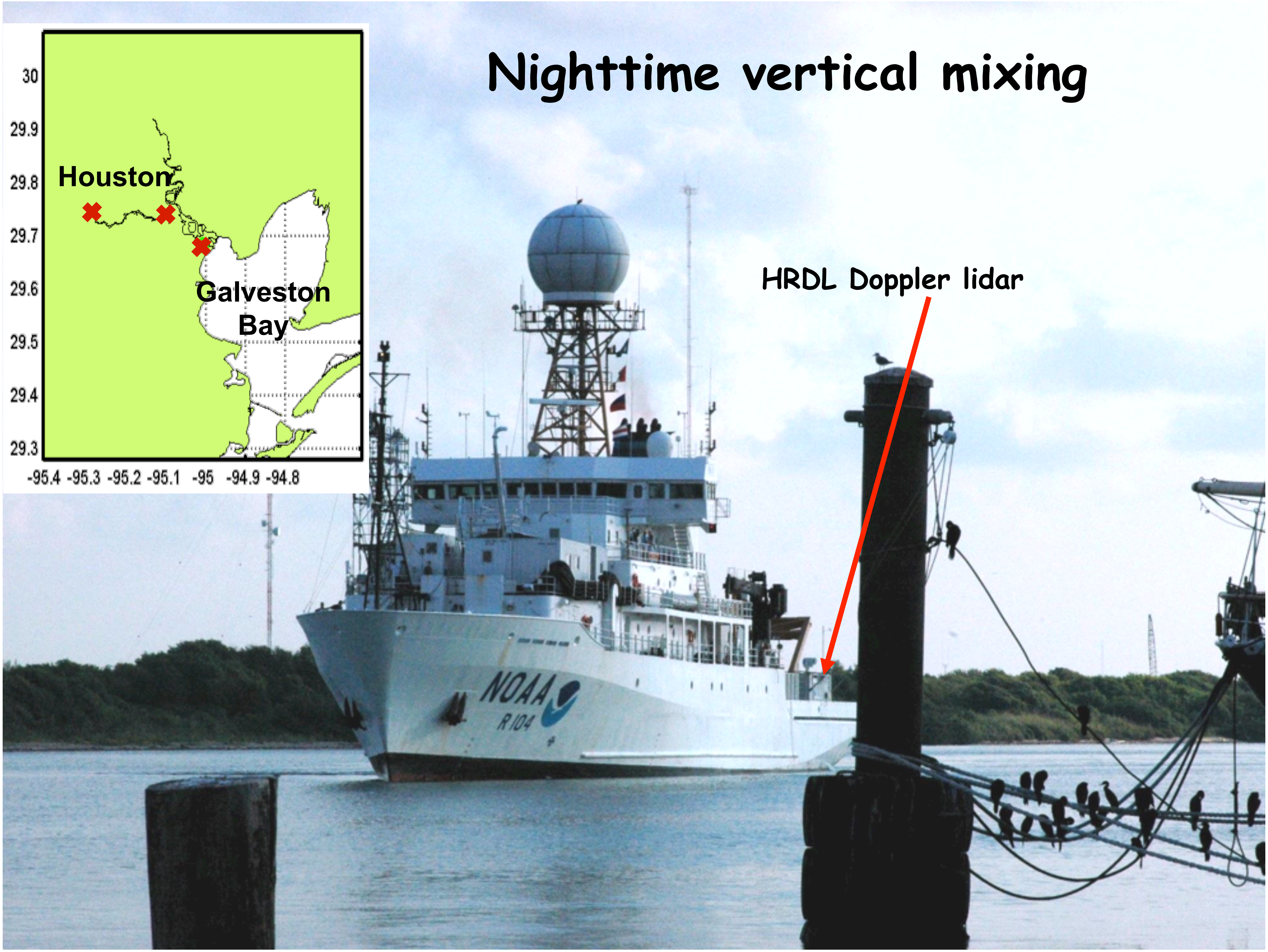


Conical scans

Documenting evolution of LLJ through the night



Nighttime vertical mixing



Motion Compensation

CO

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

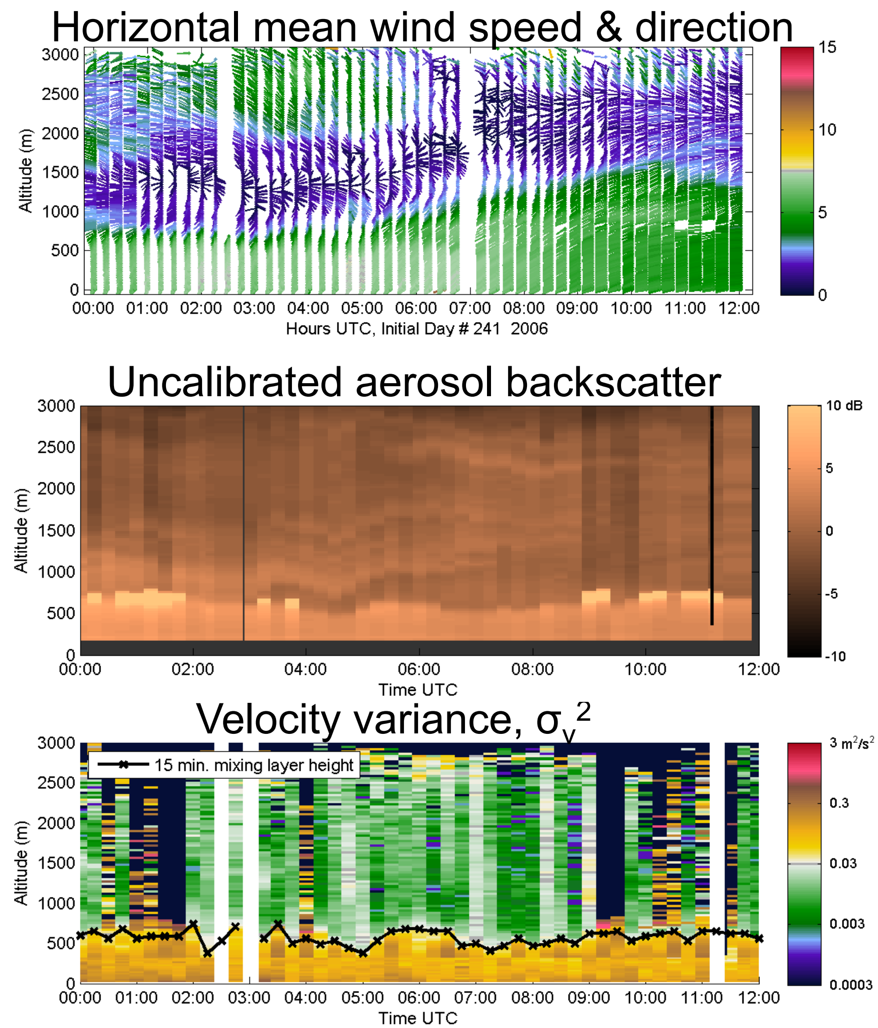
HRDL: Boundary Layer Mixing height

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.

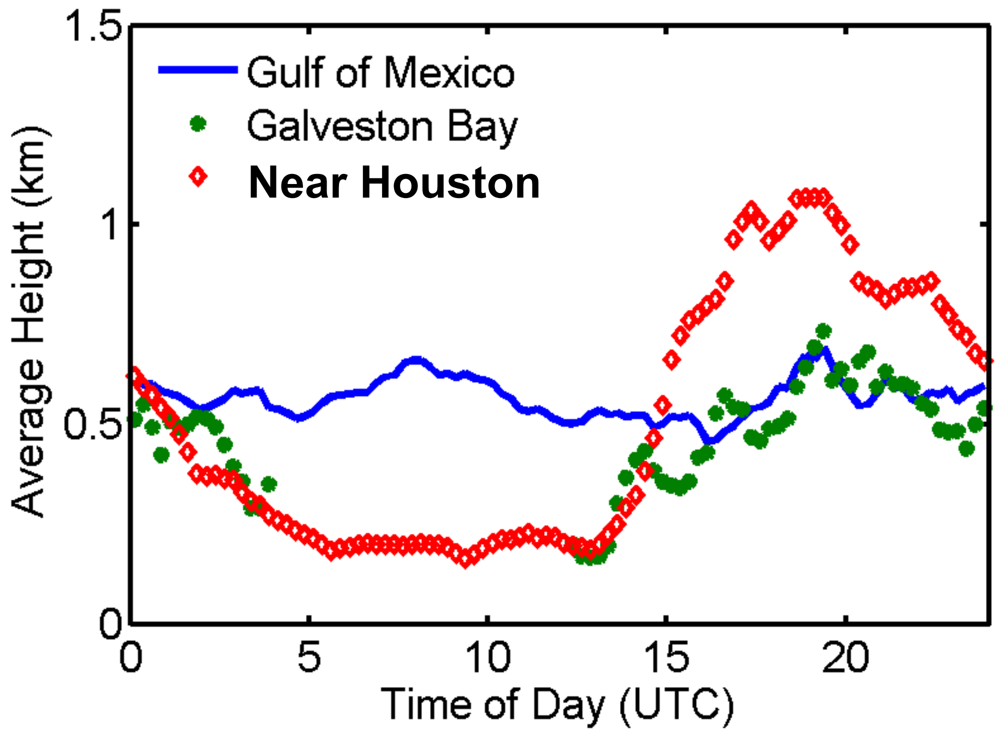
- **Combine height information from**
  - **σ_V^2 (turbulence) profiles**
  - **mean wind (shear) profiles, and**
  - **aerosol backscatter profiles**

to generate MH estimate once every 15 minutes.



Doppler Lidar mixing height and location

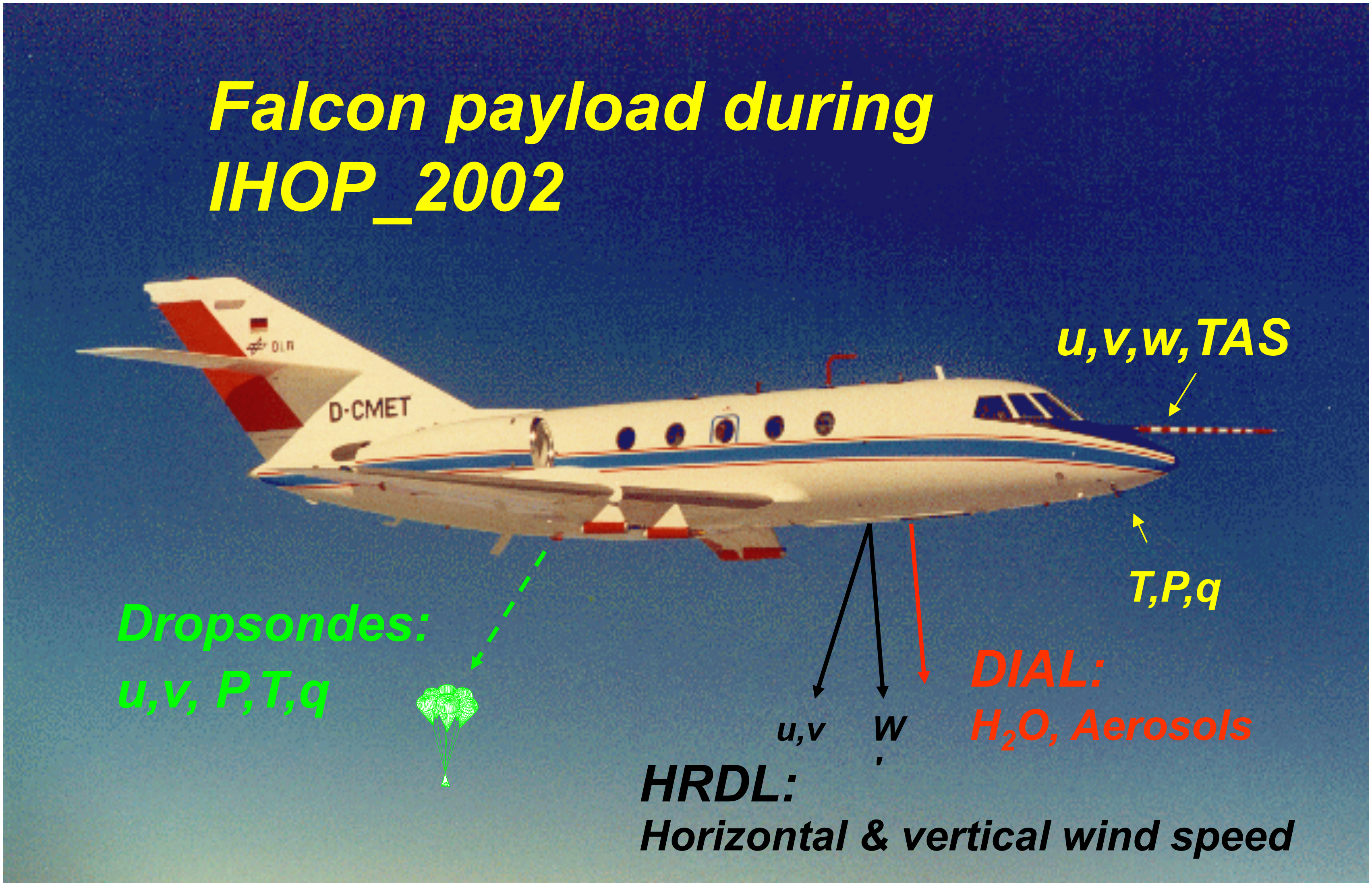
- **Little diurnal variation in the Gulf of Mexico (except during rare offshore flow)**
- **Strong diurnal variation near Houston – sea-breeze observed.**
- **Small variations over Galveston Bay (mixture of land and Gulf influences)**



Measuring wind and moisture fields from aircraft

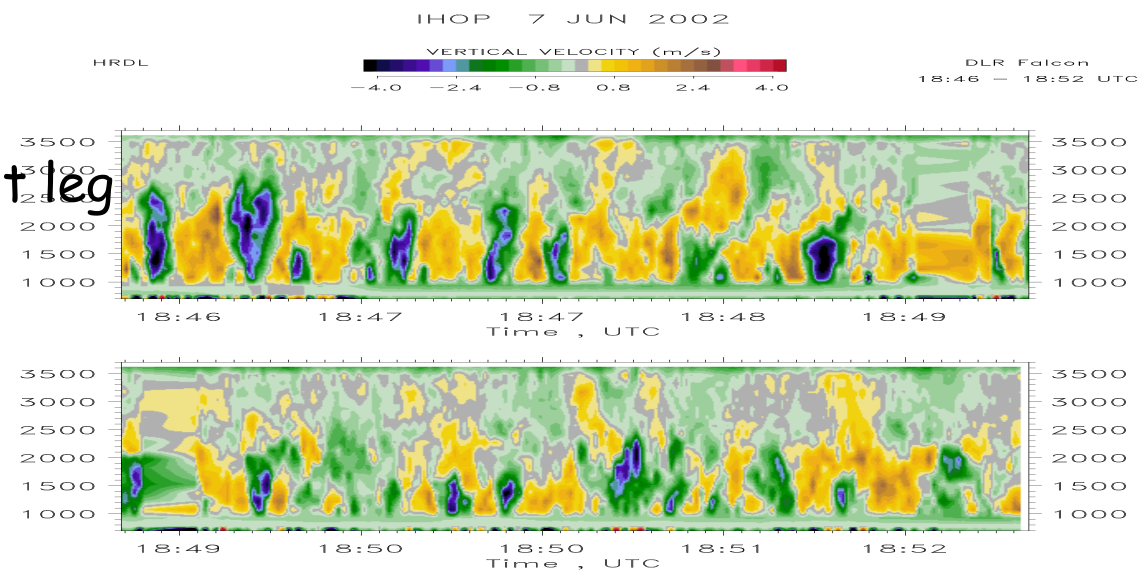
International H_2O Project: US Great Plains

IHOP Measurement Configuration

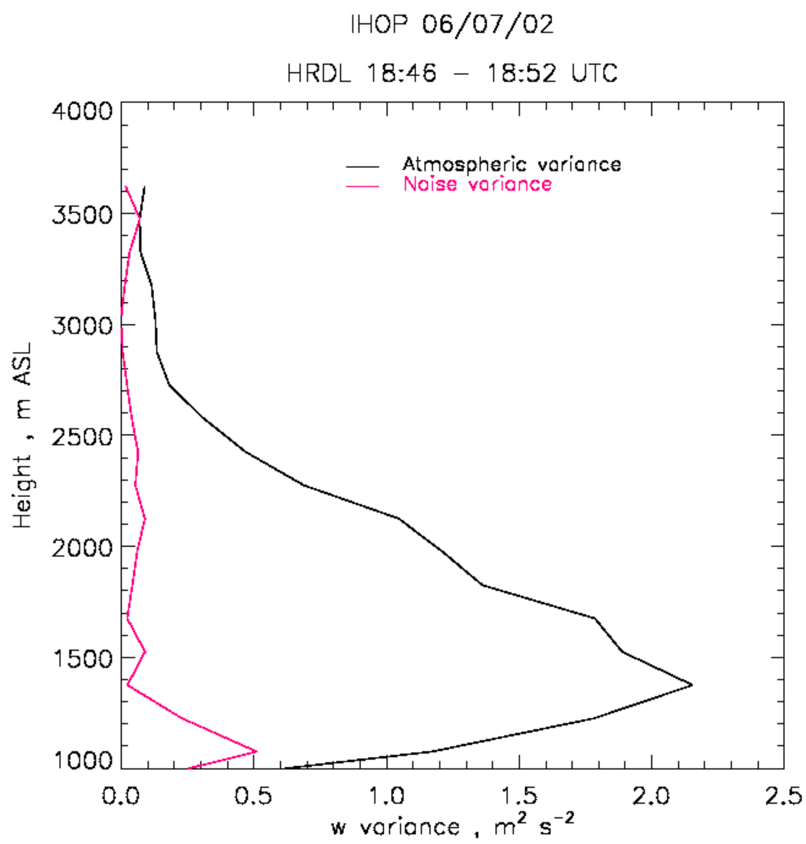


Vertical velocity measurements

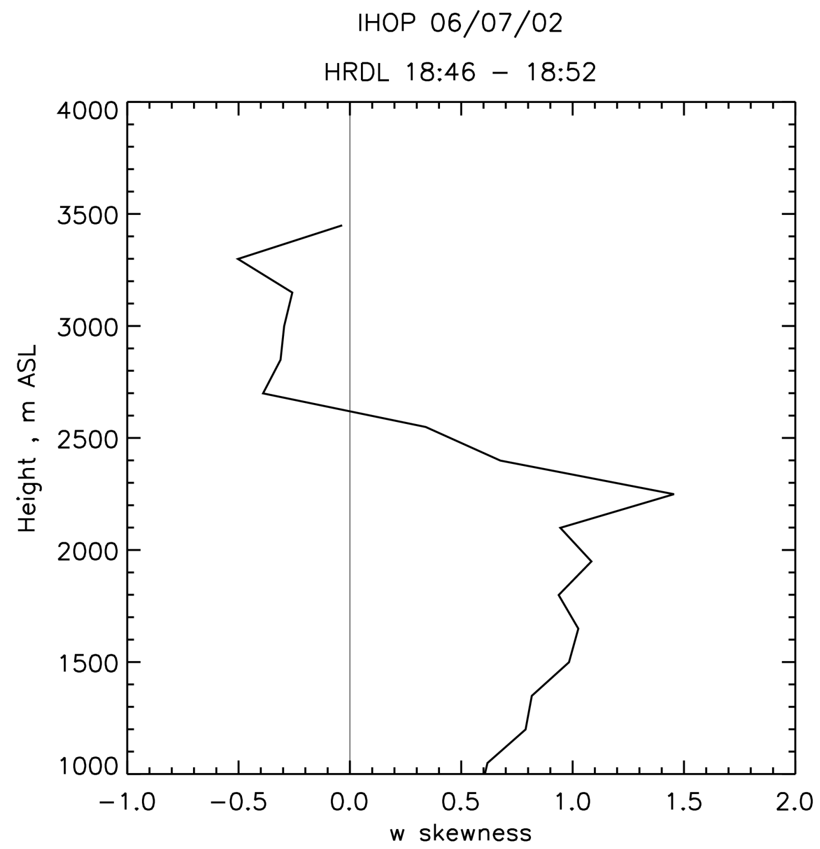
70 Km flight leg



Vertical velocity variance and skewness

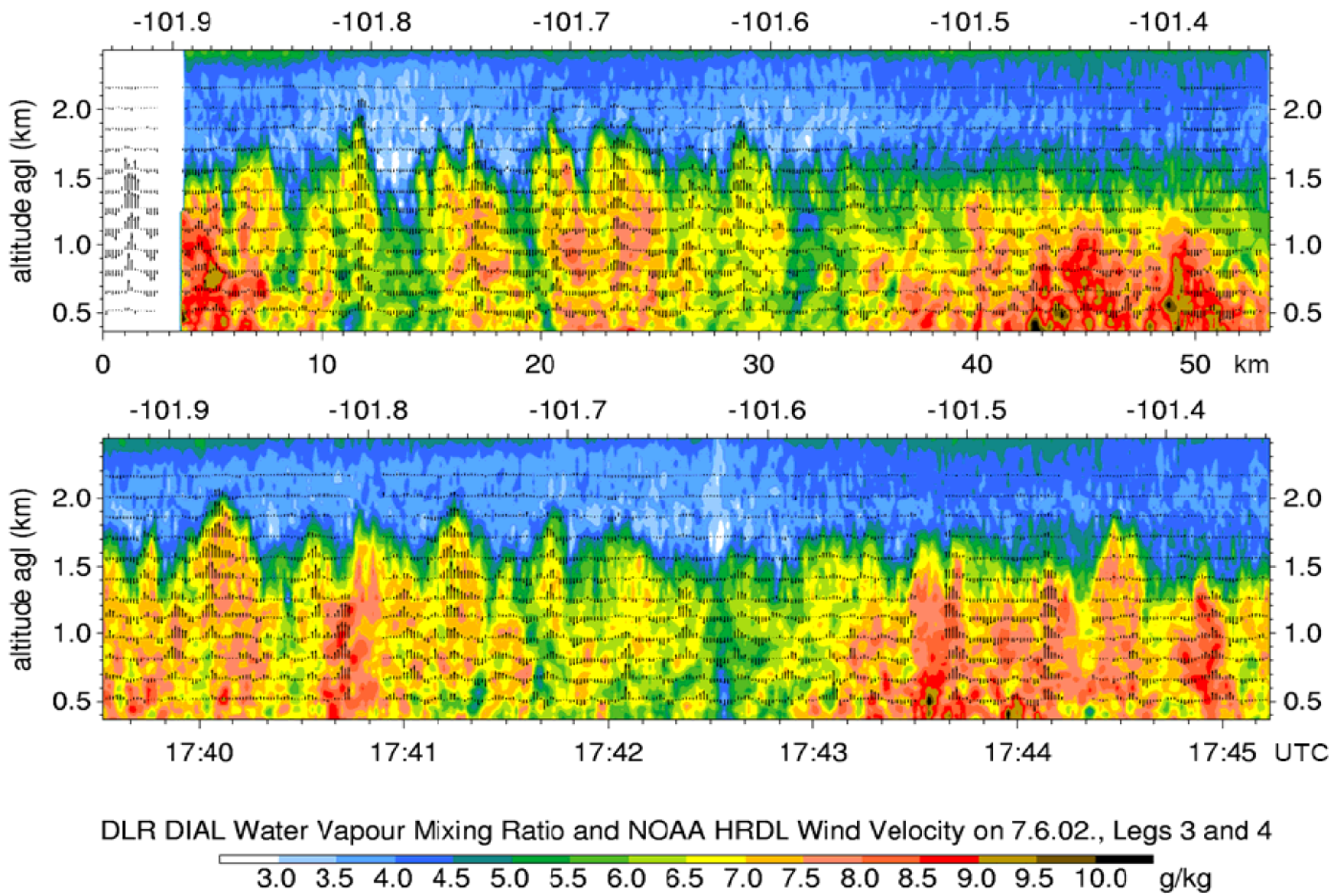


Estimated errors in the vertical velocity variance ~ 15-30% dominated by sampling error

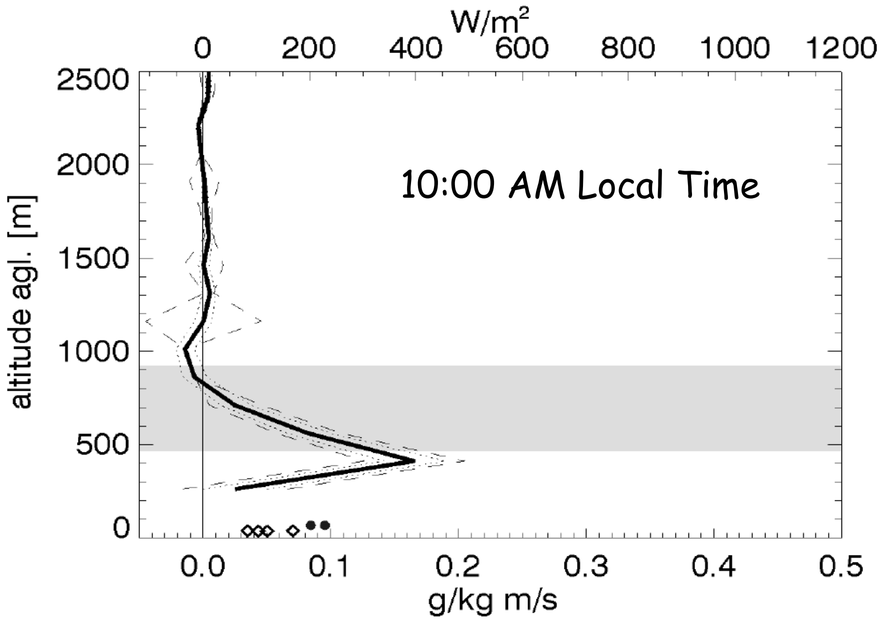


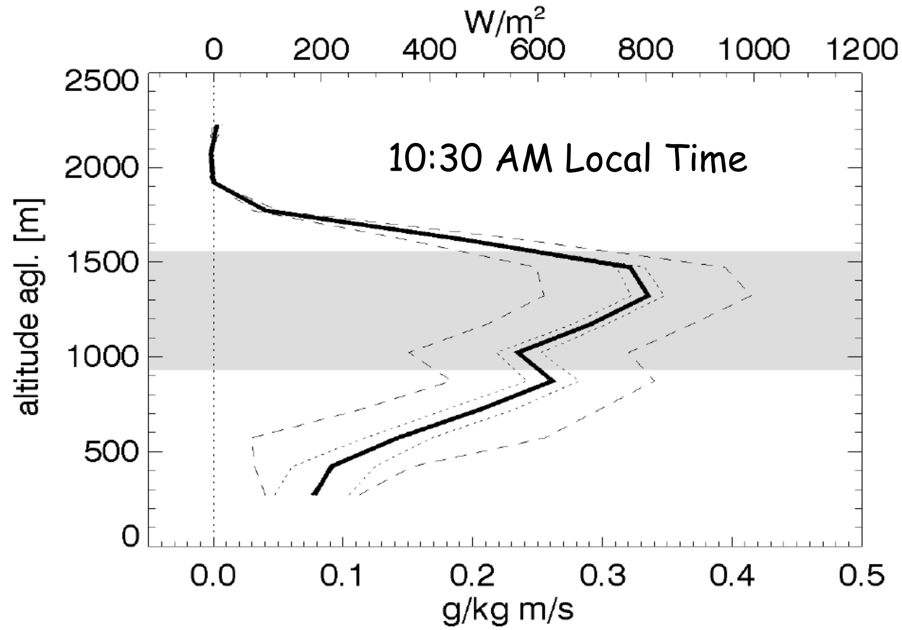
Skewness indicates convective boundary layer

Simultaneous water vapor and winds



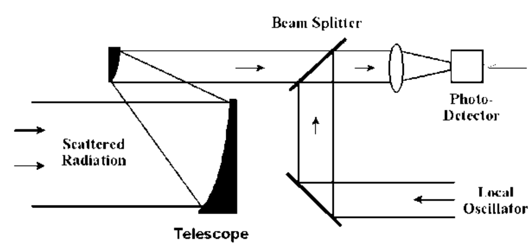
Moisture flux profiles





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)

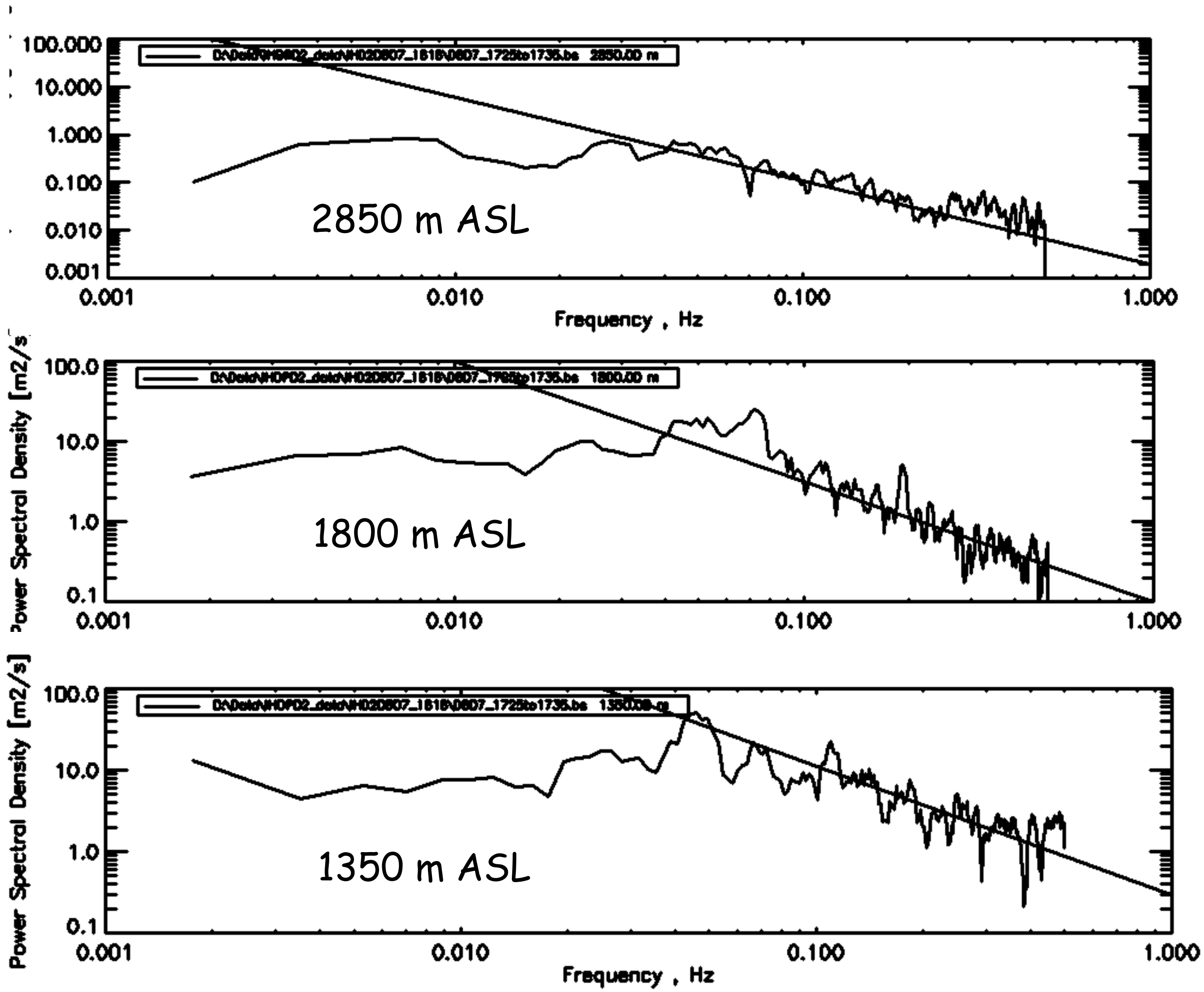
Summary (3)

- Signal processing
  - Detector output is digitized and band-pass filtered (bandpass matched to maximum Doppler shift - ~100 MHz at 2 μm)
  - 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 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, H20)
    - Ocean / atmosphere energy exchange