Optical Remote Sensing with Coherent Doppler Lidar

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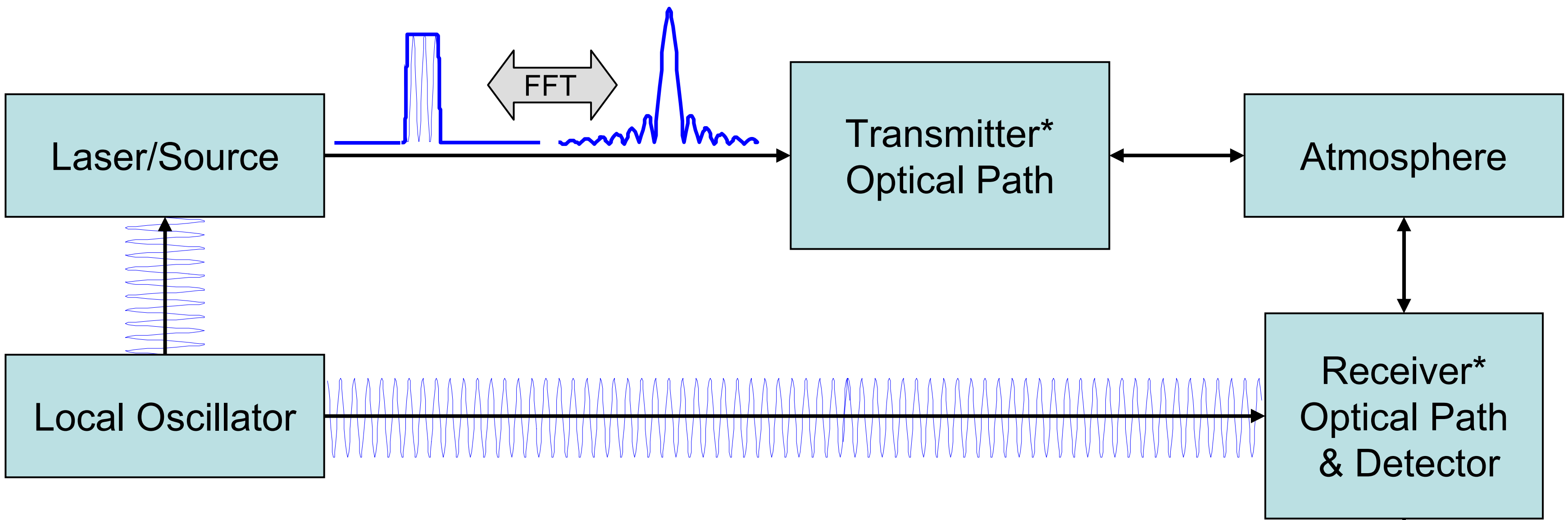
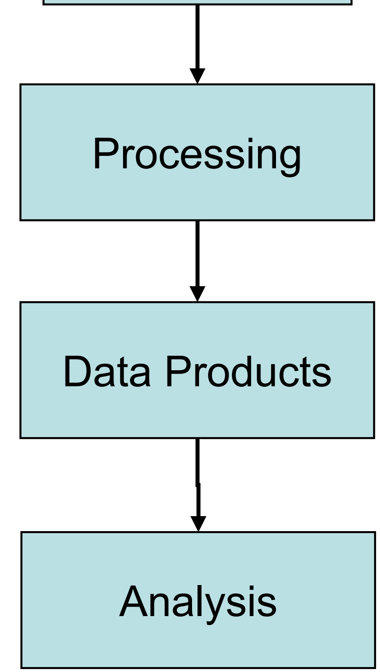
Coherent Doppler Lidar





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

Coherent Doppler Lidar: Return Power

The received power, P_r is theoretically given by

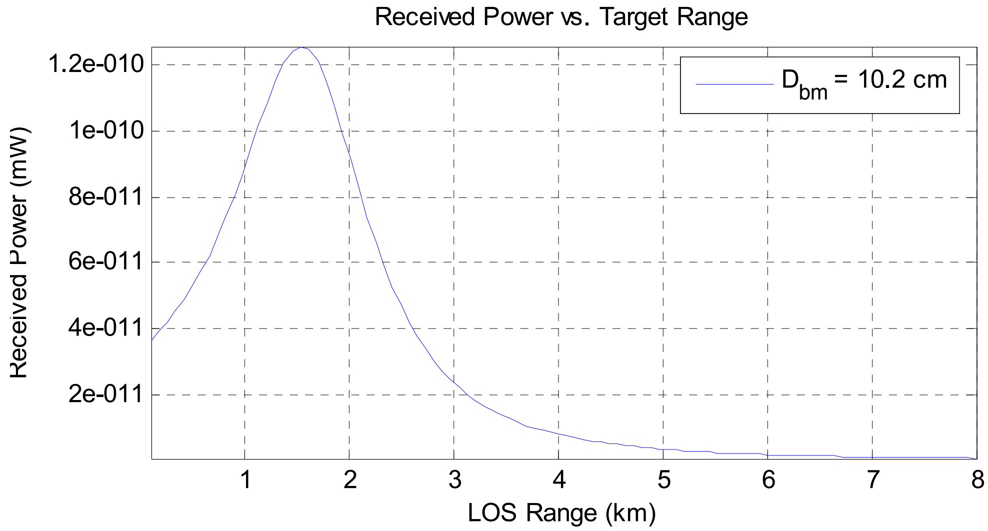
$$P_r = \int_0^\infty \frac{A_{eff}\beta T^2}{R^2} P_T\left(\lambda, t - \frac{2R}{c}\right) dr$$

P_T = Transmitted laser power (Watts) for wavelength λ, range R and time t,

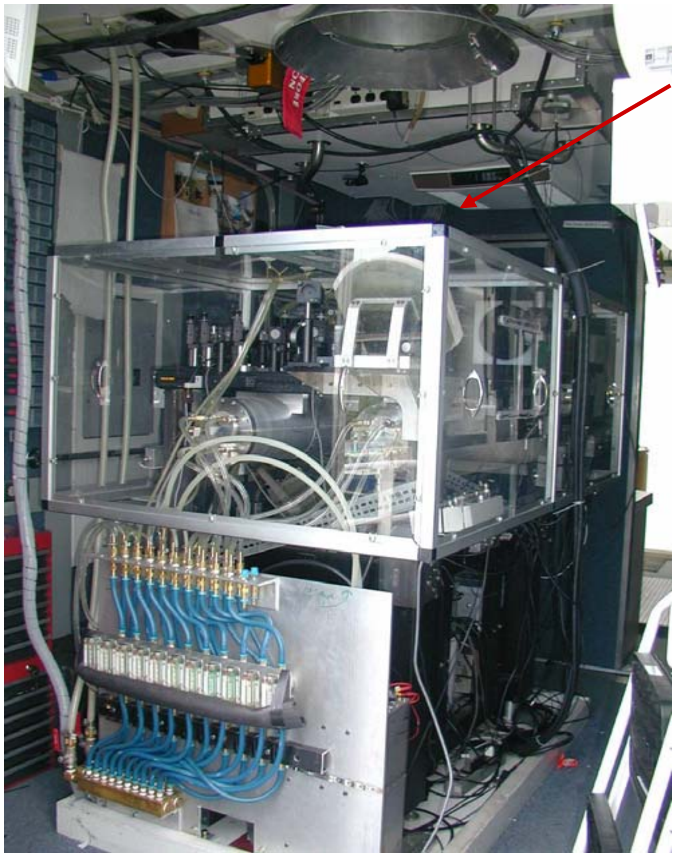
- R = range (meters)
- $\beta =$ aerosol backscatter coefficient ($m^{-1}\ sr^{-1}$),
- T = one-way atmospheric transmission.
- A_{eff} is the effective antenna area of the transceiver for a target at range R.

For aerosol targets distributed in range (relative to the pulse length) the received power at the lidar P_r can be approximated as

$$P_r = \frac{A_{eff}\beta T^2}{2R^2} cE_T$$

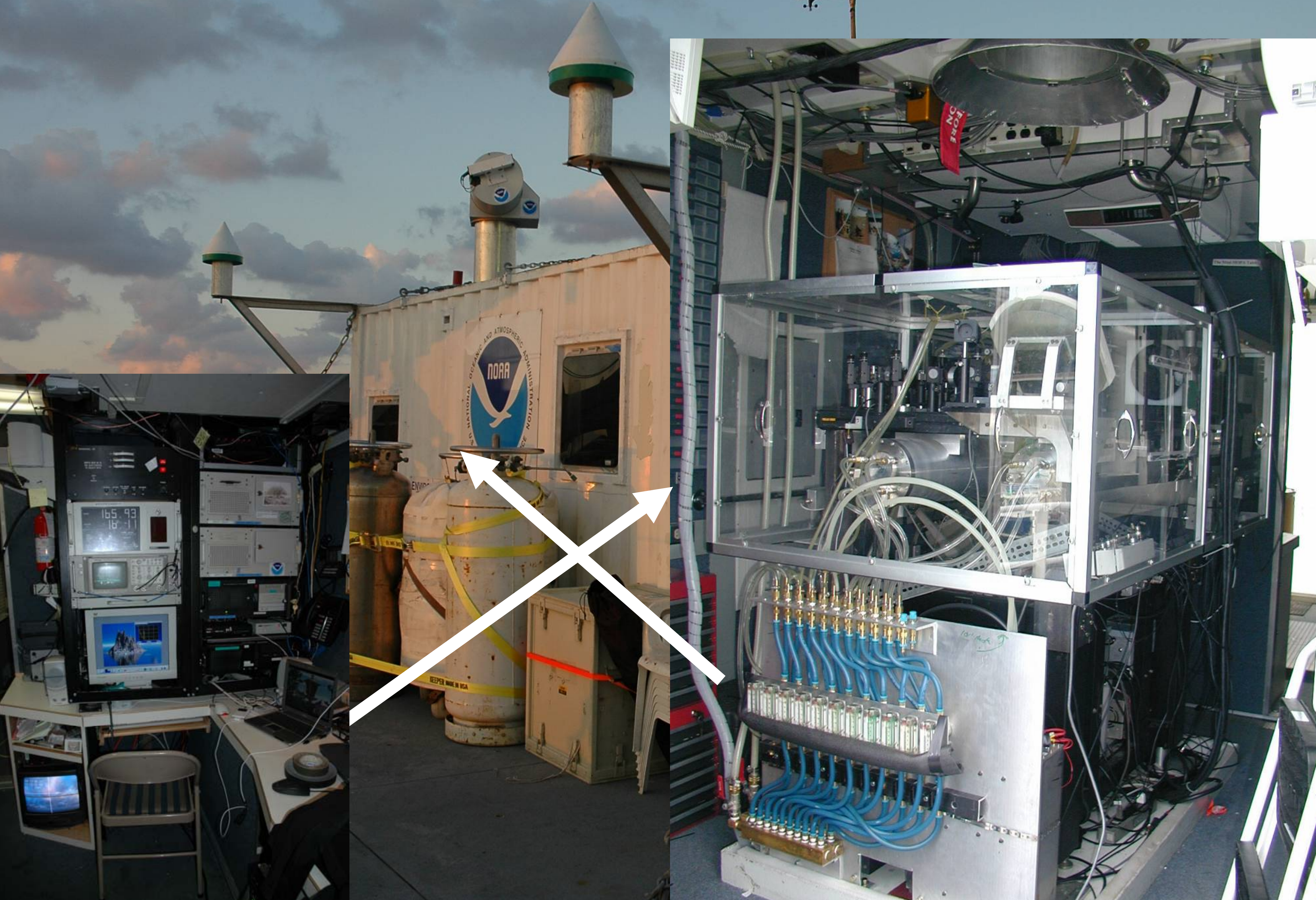


NOAA ESRL Lidars



- Mini-MOPA
- HRDL
- OPAL
- TOPAZ
- DABUL
- Fish Lidars
- TUV
- CODI
- TEAC0
- ABAeL

mini-MOPA Lidar

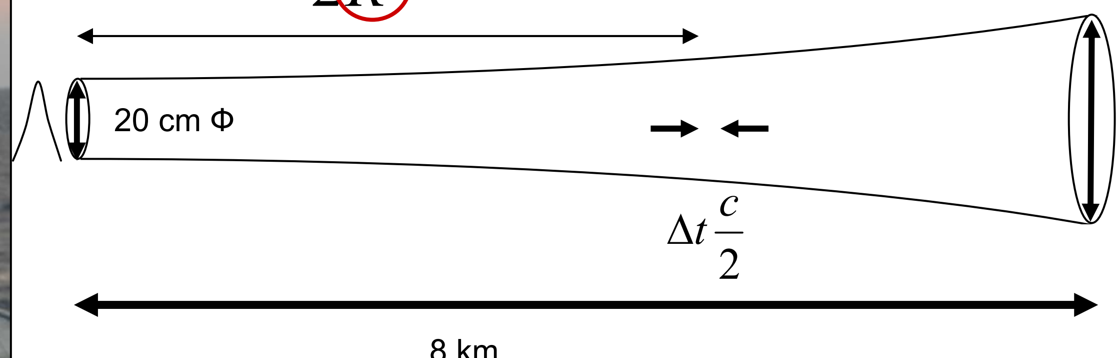


Coherent Doppler Lidar

Lidar measurement volume:

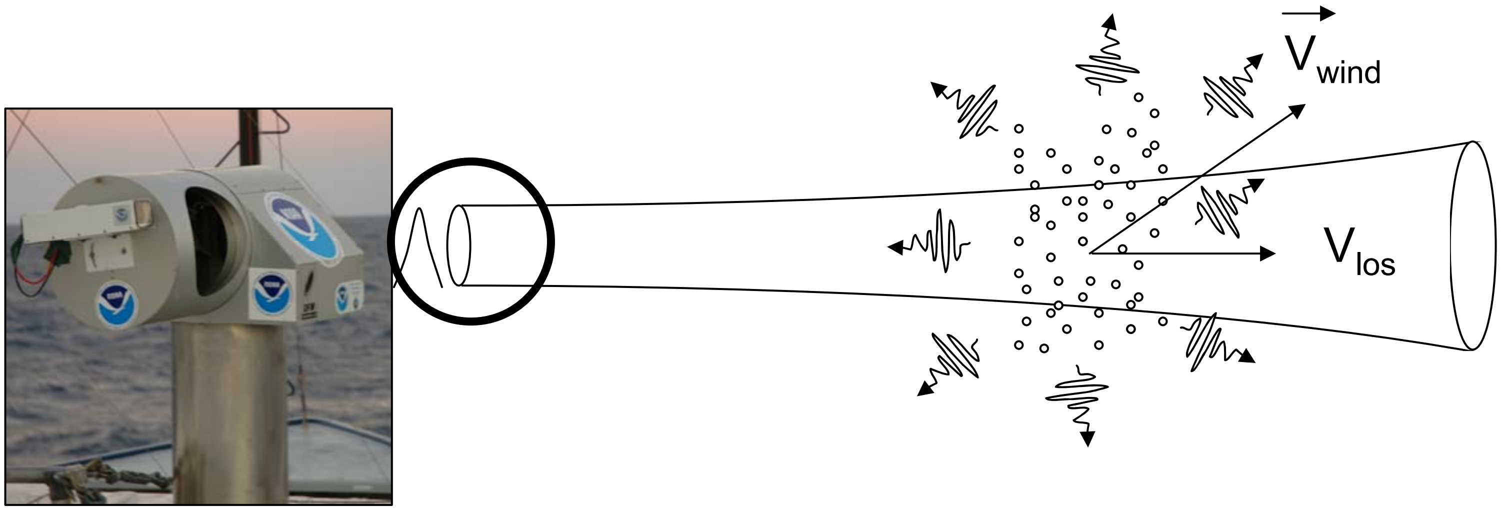
- Diffraction limited divergence (60 μrad)
- “Spotlight” beam can measure to within a few meters of the surface (no side lobes)
- 30-150 m measurement volume along the beam (Instrument dependent)

$$P_r = \frac{A_{eff} \beta T^2}{2R^2} c E_T$$



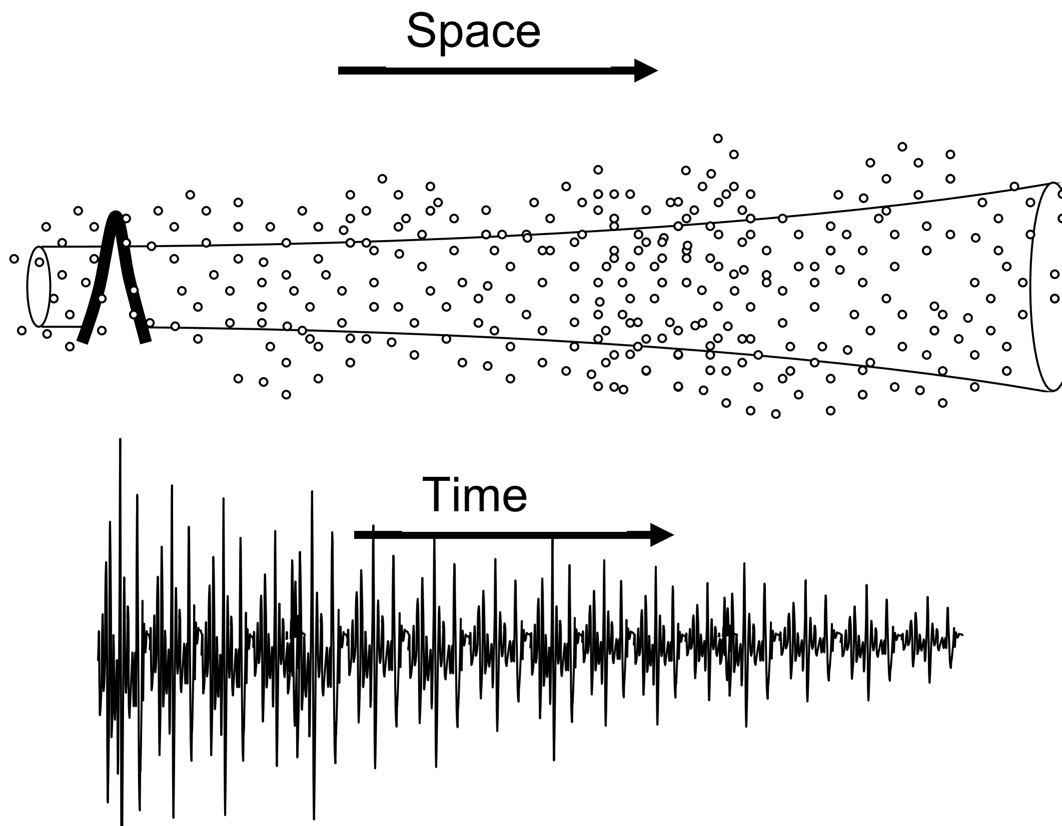
Light Scattering : ~2 μm & 10 μm

- The targets are aerosol particles
- The light scatters off the aerosol in all directions
- Part of the scattered light is detected - β
- The wind carries the aerosol scattering targets
- Doppler measurement is made to determine wind speed along the line of site



Light scatters from distributed target:

- For distributed aerosol
- As the pulse propagates out, a continuous signal is scattered back to the telescope and detected



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

Coherent Detection: The Doppler shift

- The Doppler shift for illumination of wavelength λ is given by:

$$\Delta f = \frac{2v\cos\theta_v}{\lambda} = \frac{2\upsilon v\cos\theta_v}{c}$$

  Where v is the velocity of the aerosol(s) (e.g. wind speed) and θ_v is the angle between the wind direction and the lidar line of sight (LOS)

  For a 15 m/s wind speed, the Doppler shift for 2μm light (f_{Dopp} = 1.5x10^{14} Hz) is 15 MHz.

- The returning illumination has a frequency of

$$f_{return} = f + f_{Dopp} = 1.50000015\text{x}10^{14}\text{ Hz.}$$

- Cutoff frequencies of our detectors are around GHz.
- How can we detect such small Doppler shifts in frequencies way above detection limit?

Coherent Detection
Detecting Doppler Shifts

We can't detect the frequency of light - but we can detect the "beat" (i.e. difference) signal between to light beams of slightly different frequency…

So, we create two beams: a local oscillator (LO) and a power oscillator (PO). The Local oscillator has frequency f_{LO}.

We make sure that the PO has a known frequency offset (i.e. f_{offset} = 10 MHz, 100 MHz) from that of the LO, or $f_{PO} = f_{LO} + f_{offset}$.

This LO beam goes out into the atmosphere. The light that returns (scattering off of aerosols) may have been Doppler shifted by f_{Dopp} for a total frequency offset of

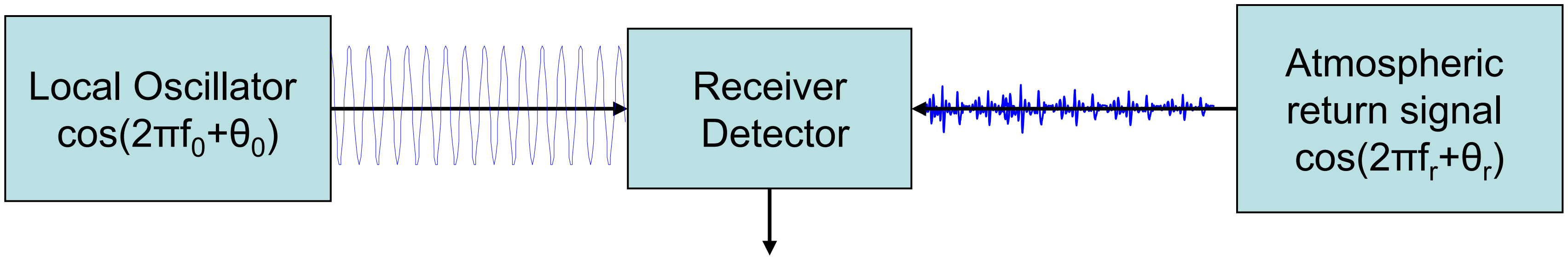
$$f_a = f_{Dopp} + f_{offset} + f_{LO}$$

Coherent Detection

The atmospheric return signal and the signal from the local oscillator are both incident on the detector.

Their electric fields add to create the total electric field incident on the detector:

$$E_a = A_a \cos\left(j2\pi f_a t + \varphi_a\right)$$
$$E_{LO} = A_{LO} \cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)$$
$$E_{tot} = A_a \cos\left(j2\pi f_a t + \varphi_a\right) + A_{LO} \cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)$$



Coherent Detection

The detector actually "sees" optical power or:

$$\left|E_{tot}\right|^2 = \left|A_a \cos\left(j2\pi f_a t + \varphi_a\right) + A_{LO}\cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)\right|^2$$

$$= A_a{}^2\left|\cos\left(j2\pi f_a t + \varphi_a\right)\right|^2 + A_{LO}{}^2\left|\cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)\right|^2$$

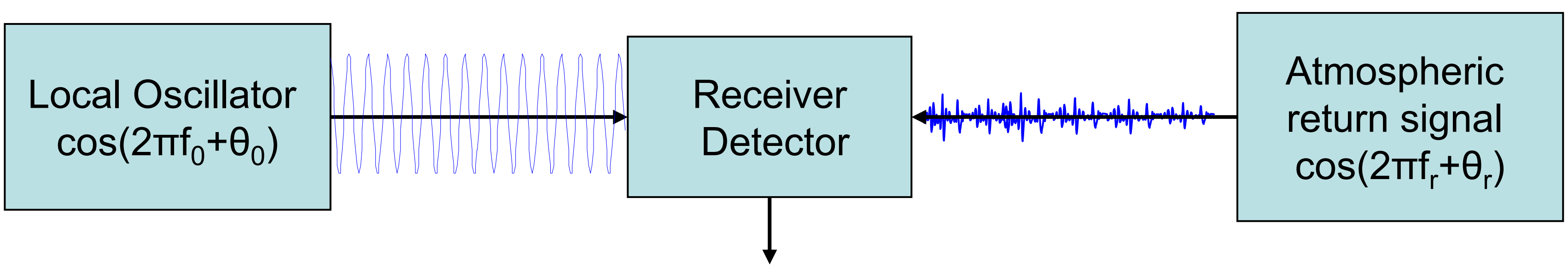
$$+ 2A_a A_{LO}\cos\left(j2\pi f_a t + \varphi_a\right)\cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)$$

The product of cosines leads to a sum and a difference:

$$\left|E_{tot}\right|^2 = A_a{}^2\left|\cos\left(j2\pi f_a t + \varphi_a\right)\right|^2 + A_{LO}{}^2\left|\cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)\right|^2$$

$$+ 2A_a A_{LO}\cos\left(j2\pi\left(f_a + f_{LO}\right)t + \left(\varphi_a + \varphi_{LO}\right)\right)$$

$$+ 2A_a A_{LO}\cos\left(j2\pi\left(f_a - f_{LO}\right)t + \left(\varphi_a - \varphi_{LO}\right)\right)$$

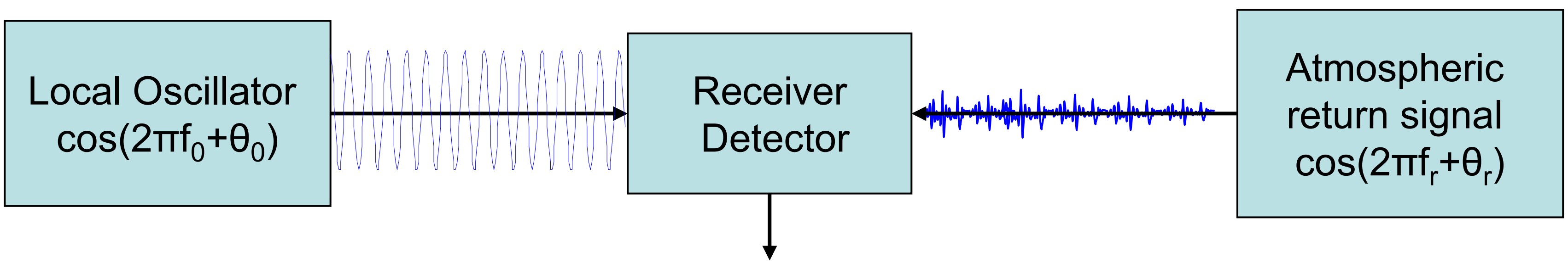


Coherent Detection

The high frequency (i.e. the sum of LO and atmospheric frequencies) is too high to detect. The other terms contribute to a DC offset, and the difference frequency is what gives us our signal:

$$|E_{tot}|^2 = |A_a|^2 + |A_{LO}|^2 + A_a A_{LO} \cos\left(j2\pi\left(f_a - f_{LO}\right)t + \left(\varphi_a - \varphi_{LO}\right)\right)$$

In terms of power - the optical power on the detector is given by:

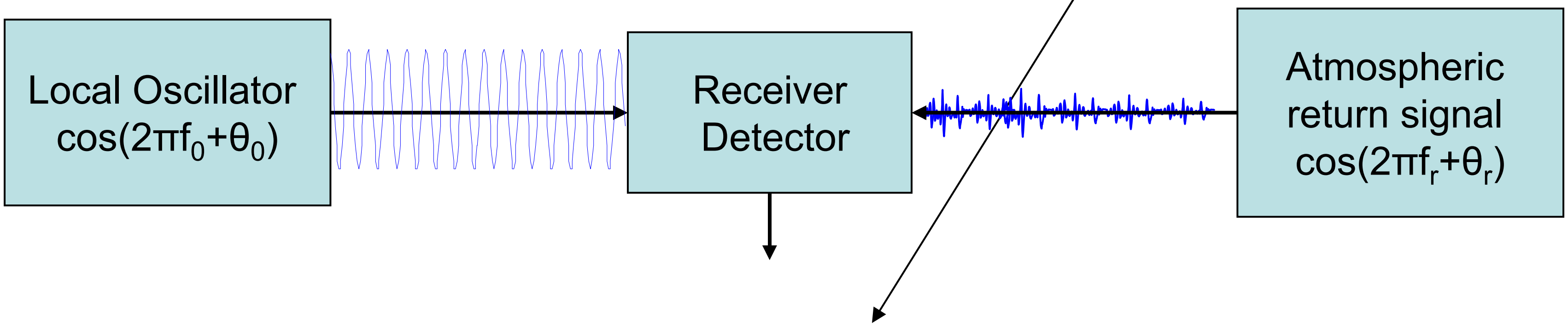


$$P_{sig} = P_a + P_{LO} + 2\sqrt{P_a P_{LO}} \cos\left(j2\pi\left(f_a - f_{LO}\right)t + \left(\varphi_a - \varphi_{LO}\right)\right)$$

Coherent Detection

The detector current is then given by:

$$i_{sig} = \left(\frac{\eta e P_{sig}}{h\upsilon} \right) = i_a + i_{LO} + 2\sqrt{i_a i_{LO}} \cos\left(j2\pi \left(f_a - f_{LO} \right) t + \left(\varphi_a - \varphi_{LO} \right) \right)$$



Remember $f_a - f_{LO} = f_{Dopp} + f_{offset}$ ~ Mhz

We know f_{offset}…so we can find the Doppler shift frequency.

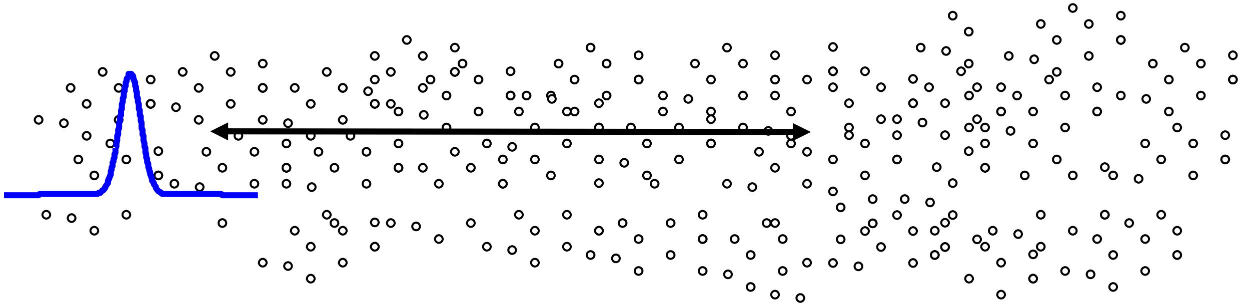
Laser & Pulses
Laser/Transmitter Requirements

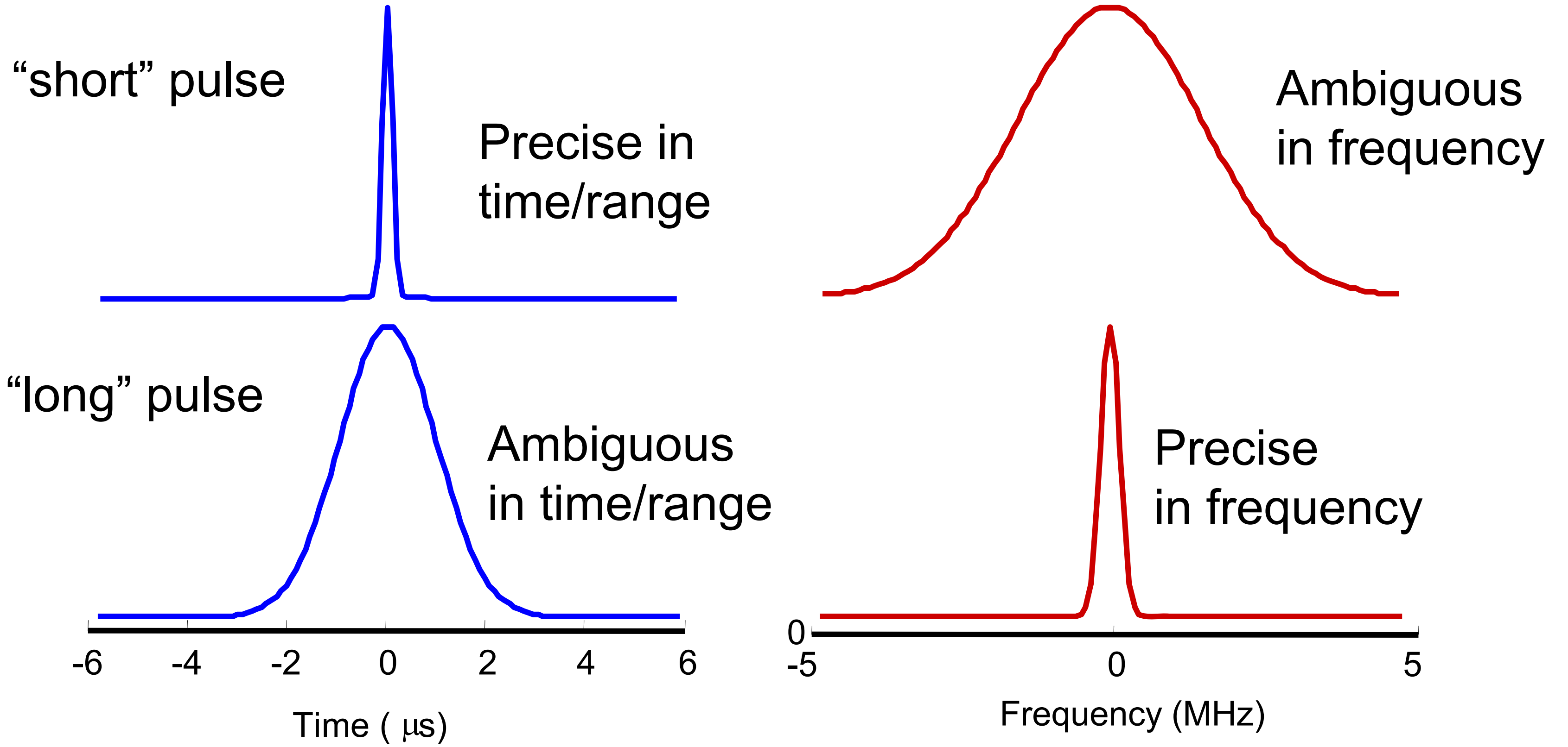
- Narrow bandwidth (i.e. ~1 Mhz)
- Q-switched or modulated
- Low atmospheric absorption
- High pulse repetition frequency (PRF)
- 1-8 mJ per pulse
- Eyesafe

Tradeoffs between:
- short pulses
- pulse bandwidth
- PRF
- average power

A fun intro to lasers….
http://www.colorado.edu/physics/2000/lasers/index.html

Laser & Pulses
Time-bandwidth tradeoffs

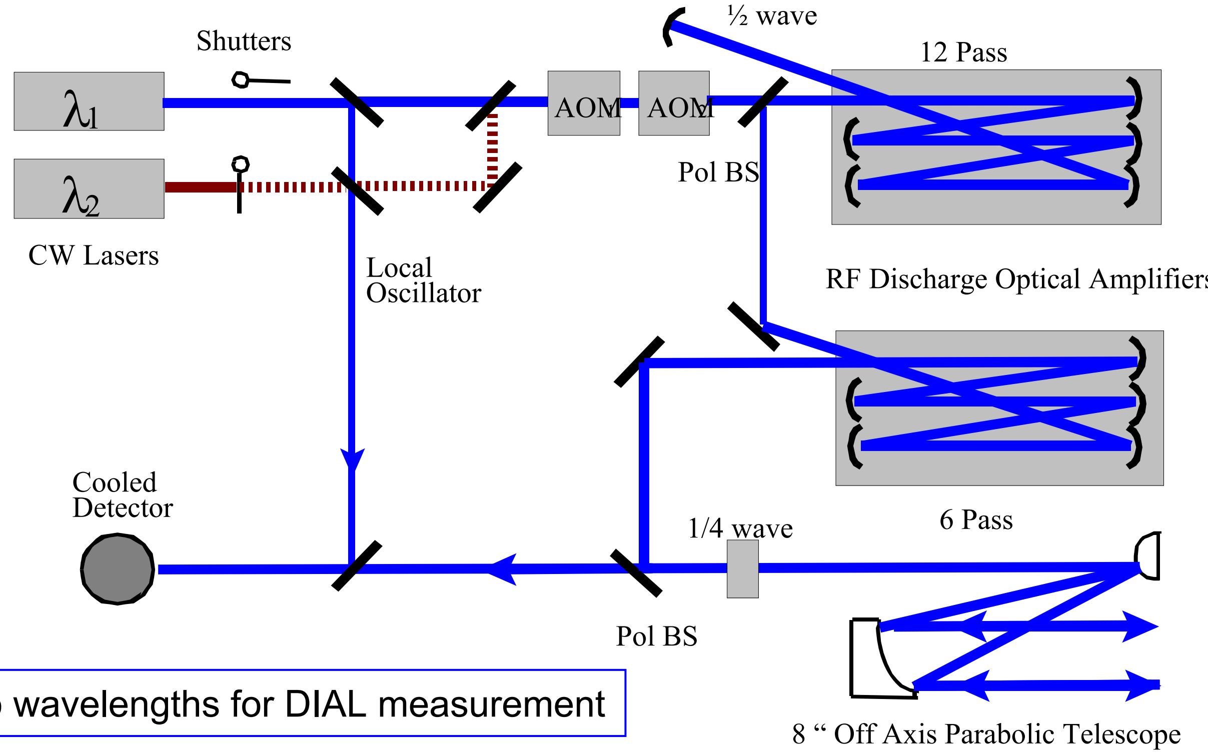




How are the pulses created?

Laser & Pulses Mini-MOPA

(master-oscillator/ power-amplifier)

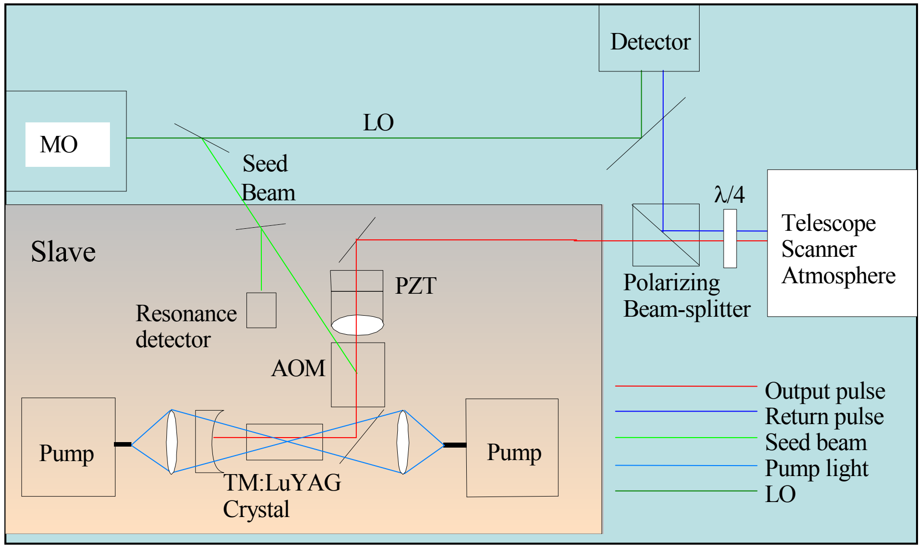


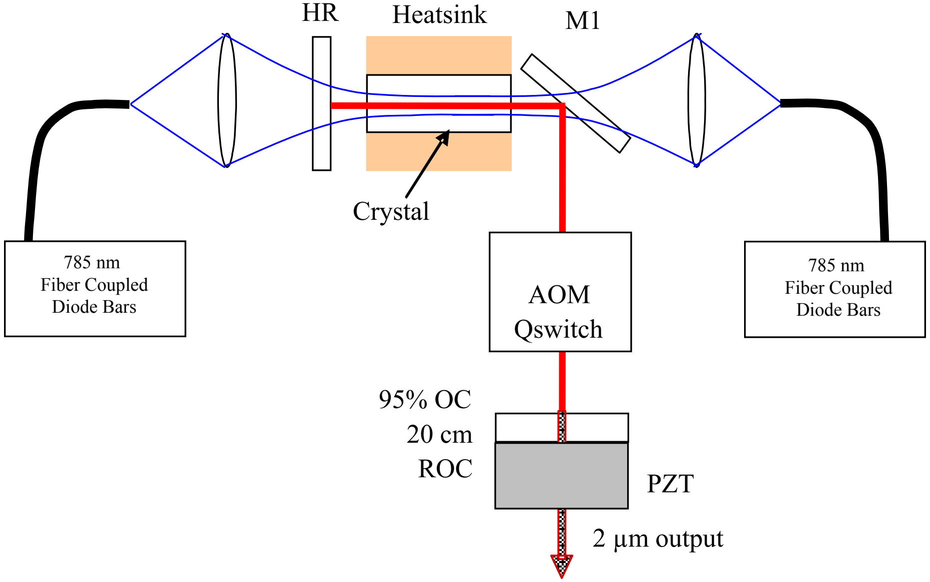
Can also alternate between two wavelengths for DIAL measurement

Wavelength	9-11 micron
Pulse Energy	0.5-2 mJ
PRF	300 Hz
Max Range	18 km
Range Resolution	45-300 m
Scanning	Full Hemispheric
Precision	10 cm/s

Laser & Pulses: High Resolution Doppler Lidar (HRDL)

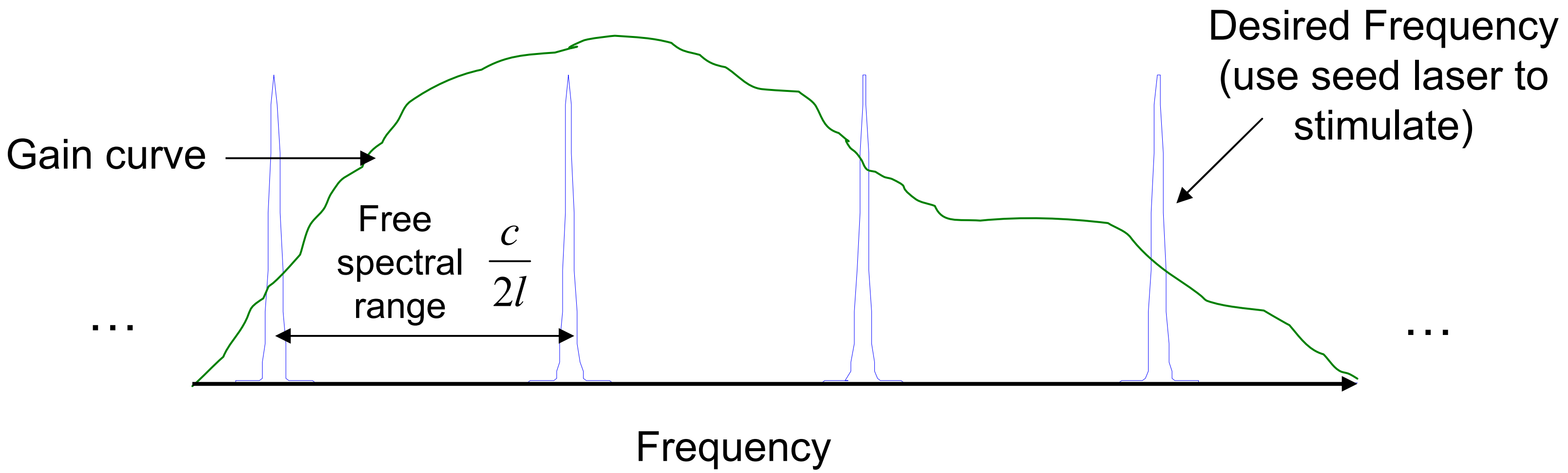
Wavelength	2.02 micron
Pulse Energy	2 mJ
PRF	200 Hz
Max Range	3-8 km
Range Res.	30 m
Beam rate	2 Hz
Scanning	Full Hemispheric
Precision	10 cm/s





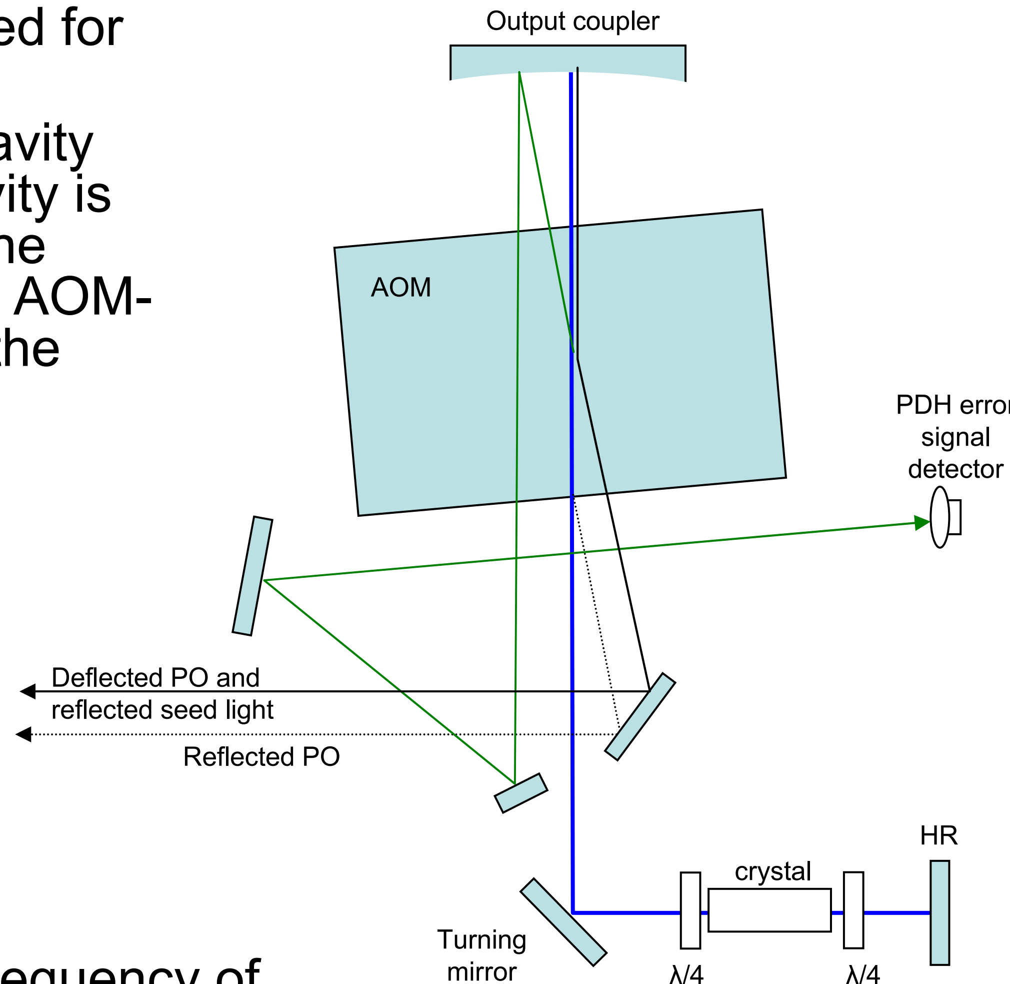
Local Oscillator + shift: LO Requirements

- Continuous wave – always available for heterodyne detection of return pulses from the atmosphere.
- Stable – especially over pulse separation times.
- Need a way to shift the frequency of the pulses relative to the LO (or the other way around) – we use AOMs for this.
- Sometimes the same source as the PO – sometimes a seed for the PO.



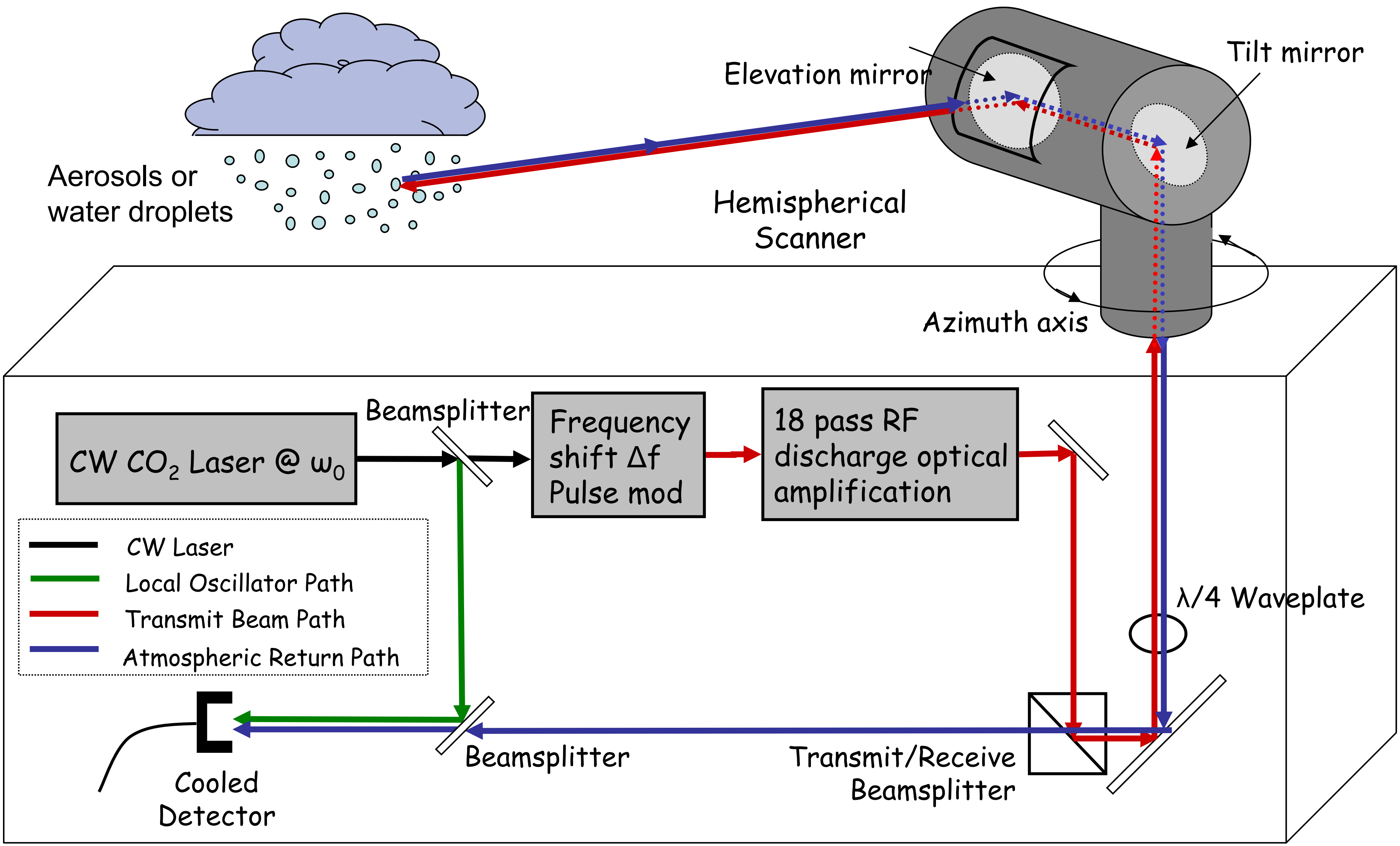
Local Oscillator & Seed: HRDL

- The LO is a separate laser seed for the PO
- The LO is “injected” into the cavity using the AOM angle. The cavity is then adjusted to optimize for the frequency of the LO PLUS the AOM-induced frequency offset and the AOM is turned off.
- At this time, the PO light in the cavity has already started the stimulated emission process – now all the photons emit at the same frequency and phase – and the pulse is formed.

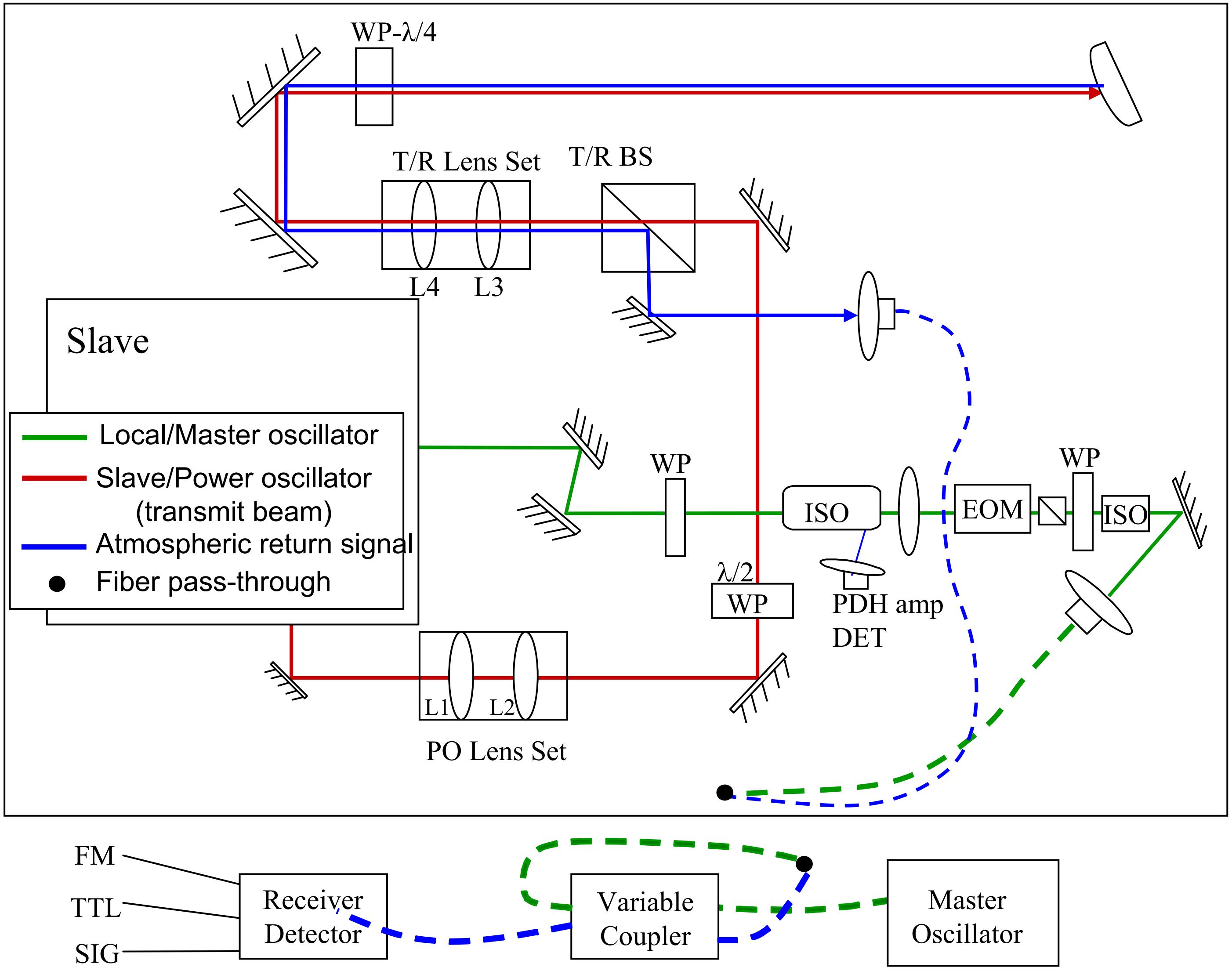


- The AOM causes the center frequency of the pulse to be 100 Mhz higher than the LO seed light.

Mini-MOPA (master-oscillator/power-amplifier) system



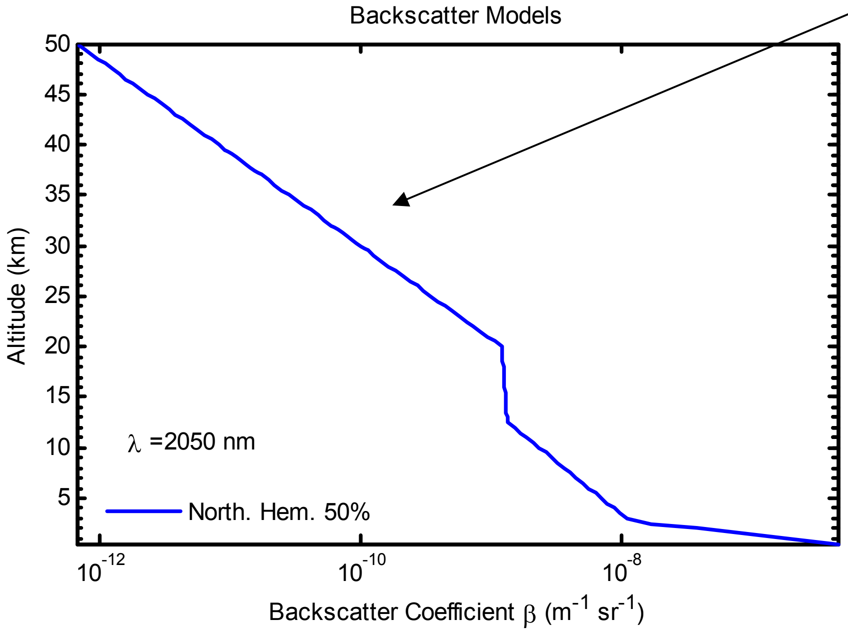
High Resolution Doppler Lidar (HRDL) system

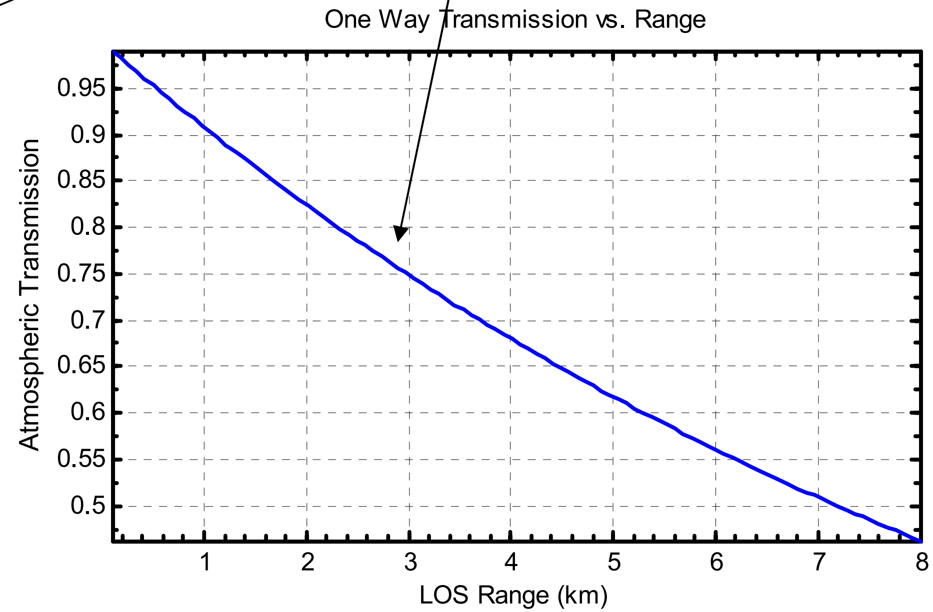


Atmospheric Return

- Continuous return from distributed target
- Atmosphere affects the amount of return signal according to the amount of aerosols (backscatter), extinction, and turbulence.

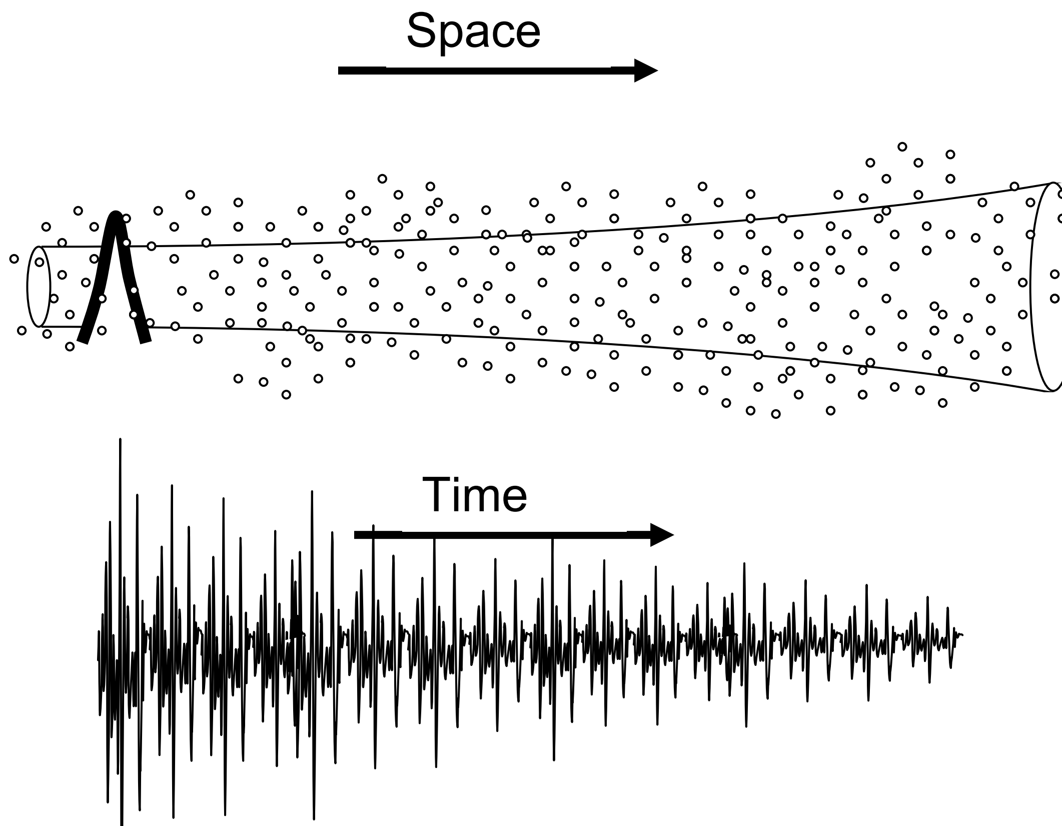
$$P_r = \frac{A_{eff}\,\beta\,T^2}{2R^2}\,cE_T$$



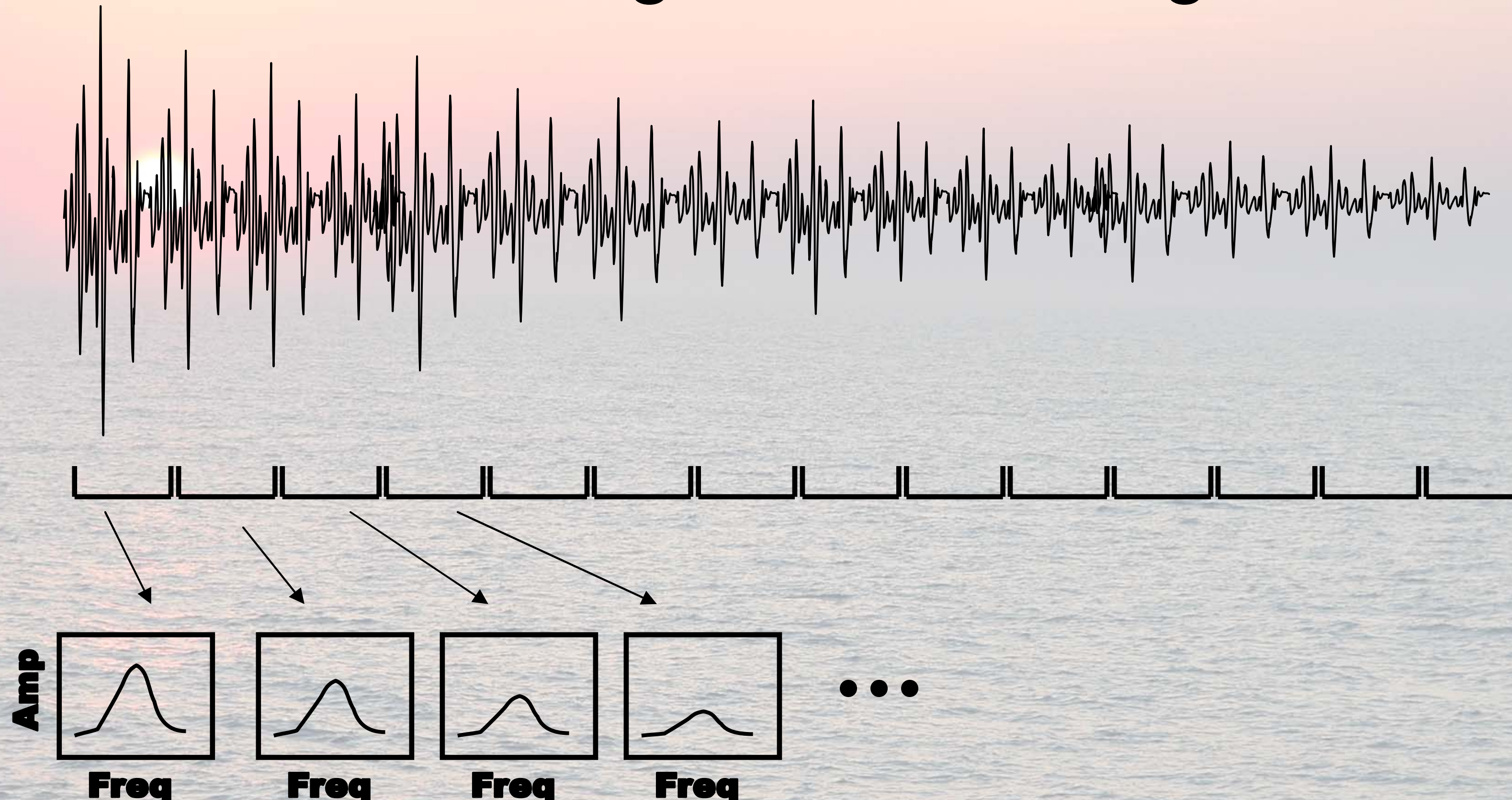


Return signal processing

- Return signal mixes with local-oscillator creating the beat frequency + offset signal.
- This signal is detected, filtered, and sampled.



Return Signal Processing



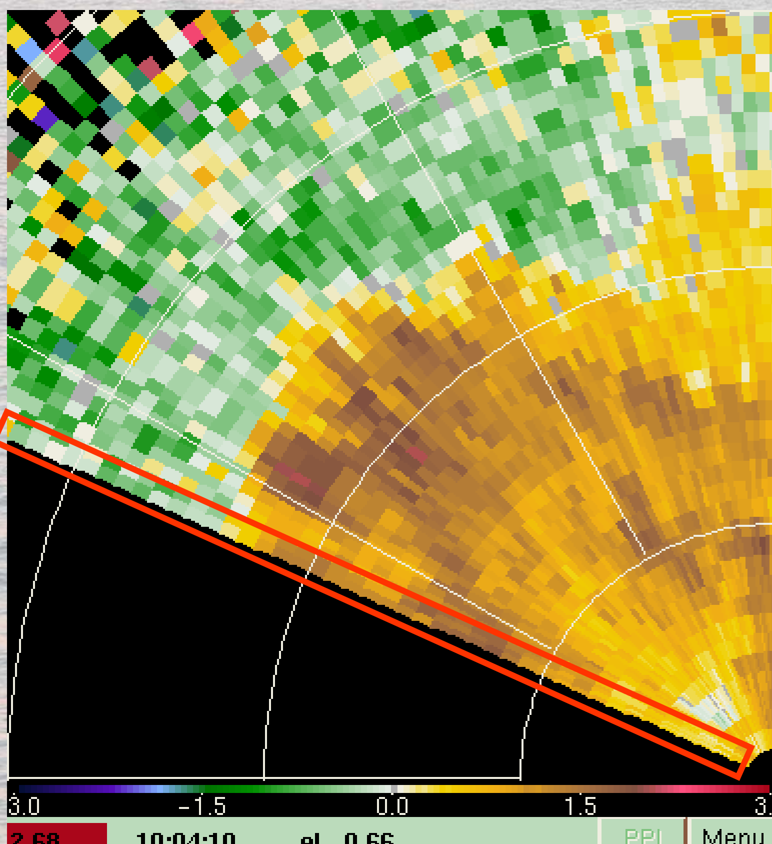
- Break into gates (equal to pulse length (150m typical))
- Find spectrum for each gate
- Average spectra for same range gate from different pulses
- Find frequency peak for each gate to find Doppler shift and Intensity as a function of range

Example Data

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

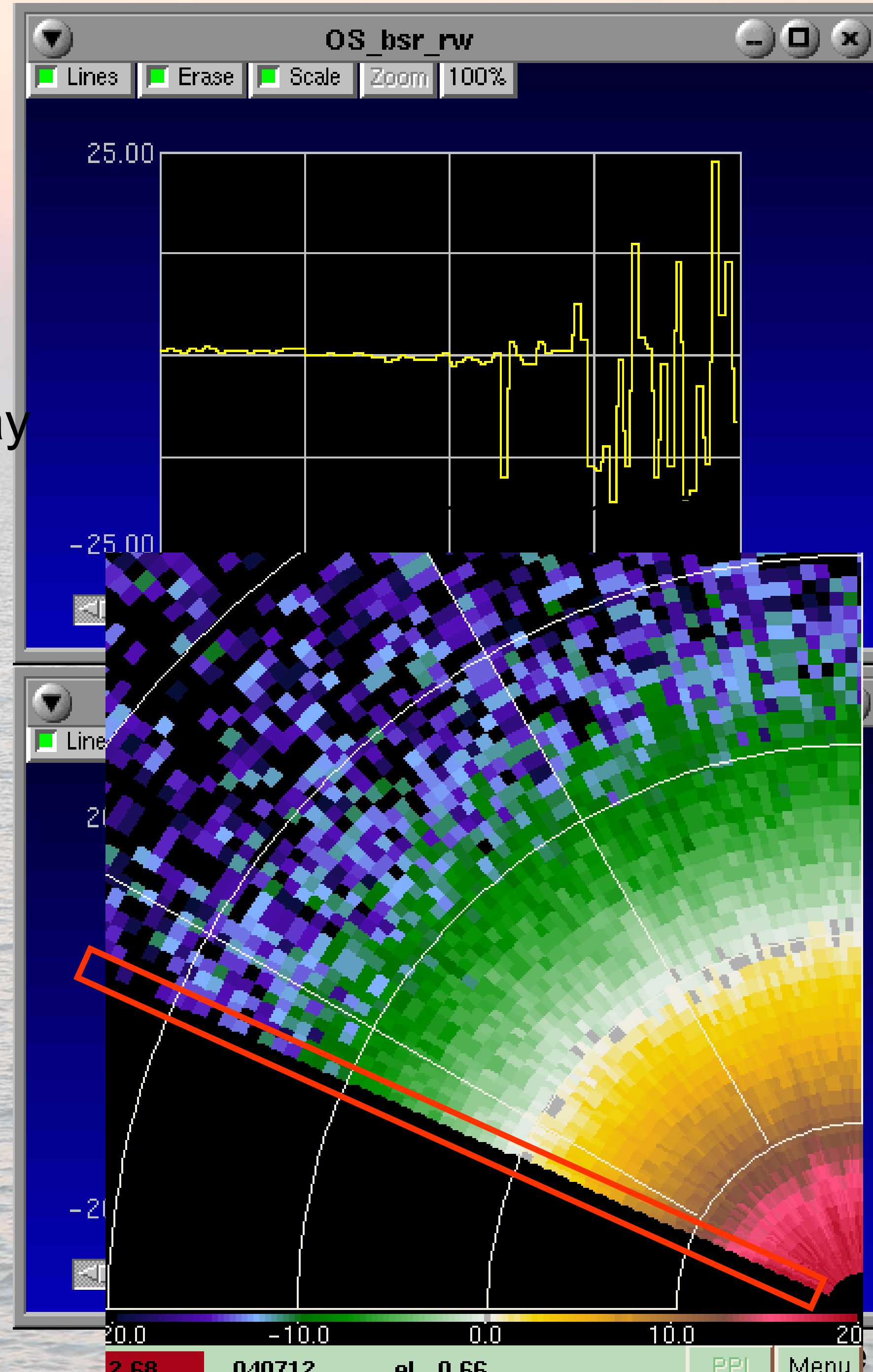
Color code and combine single beam results into scanning display

Velocity (m/s)



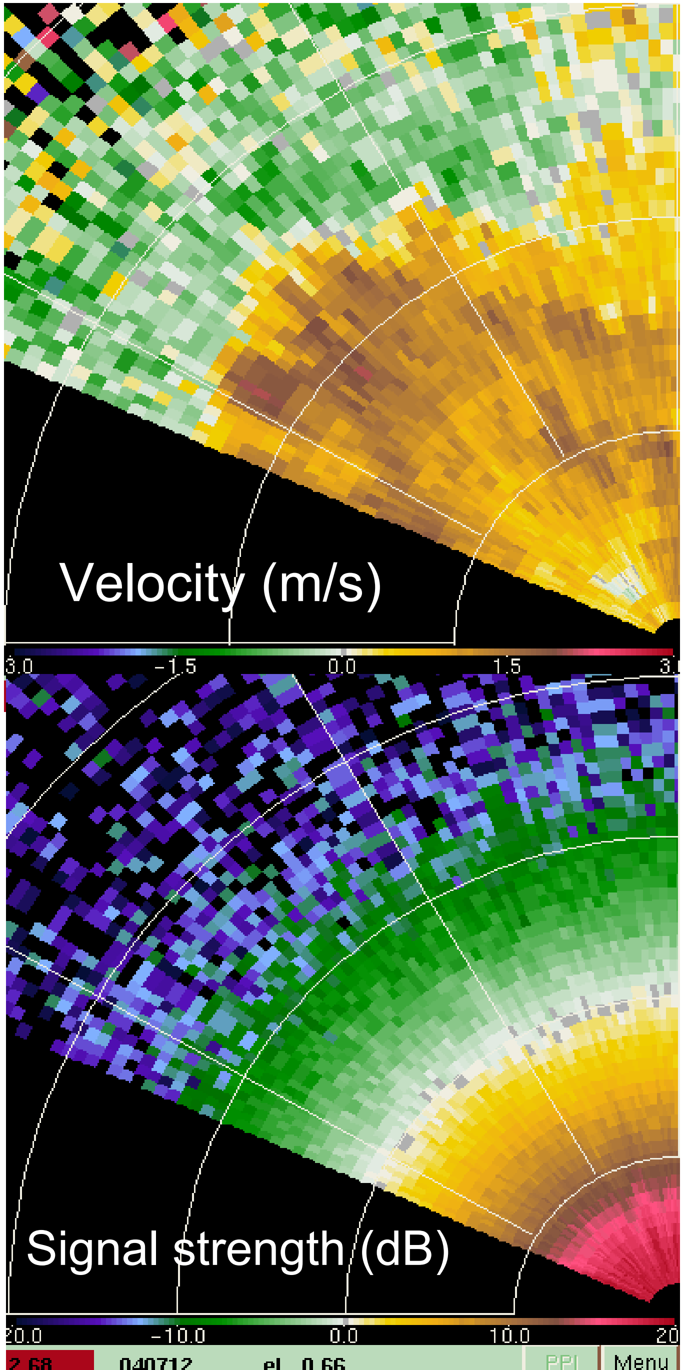
s)

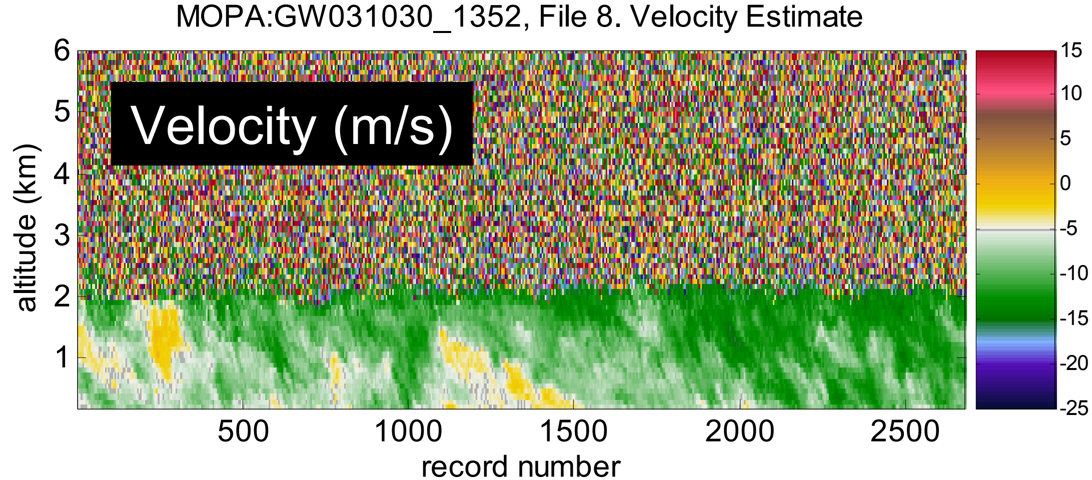
dB)

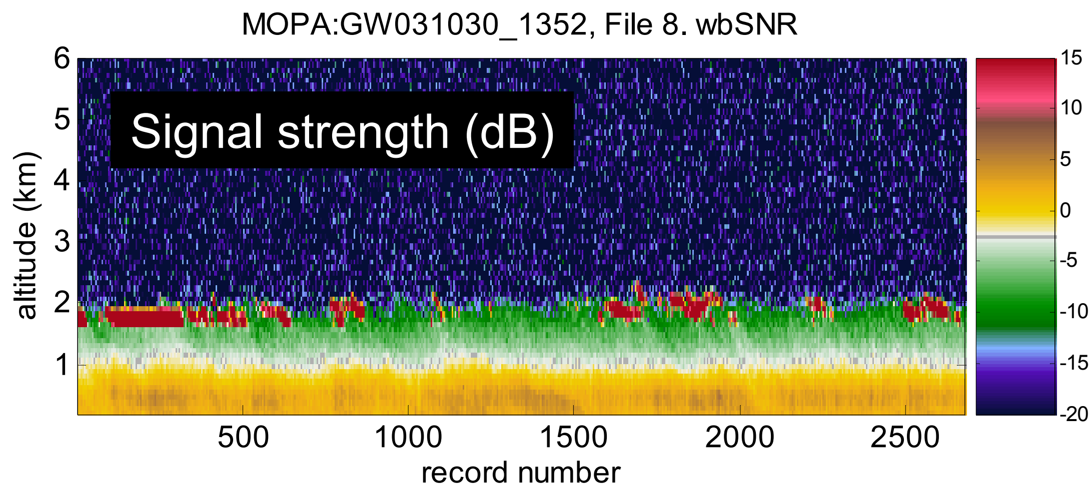


Doppler lidar data displays

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







Signal Processing: Real Data Example

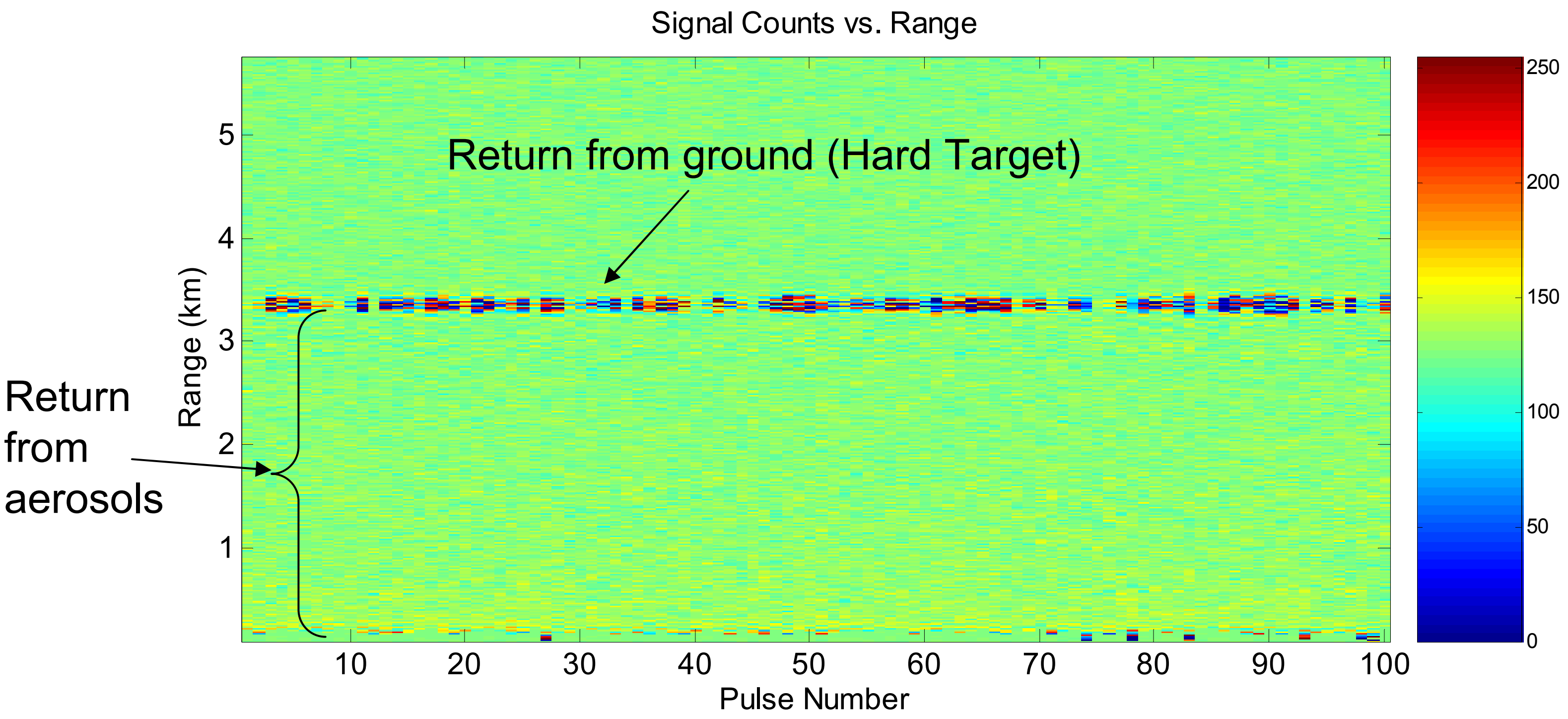
This data comes from an instrument called the Twin Otter Doppler Wind Lidar (TODWL). It flies in an aircraft and points down at the earth.

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.

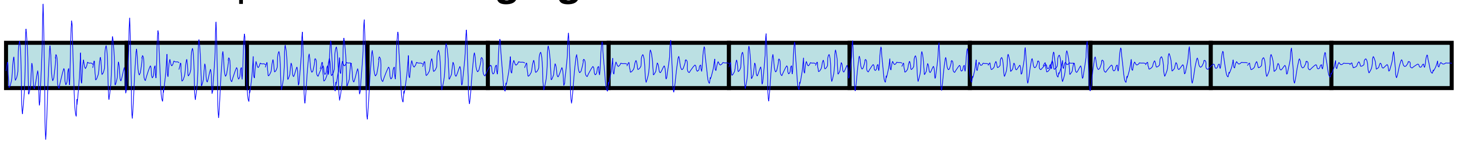
Goal: Calculate velocity and CNR versus range for this data set.

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

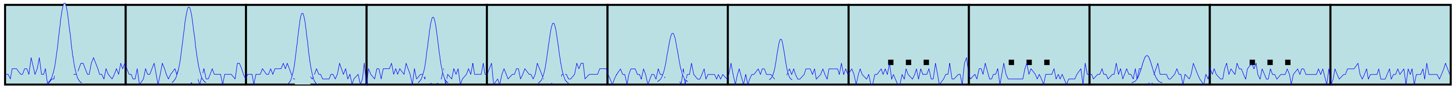


Return Signal Processing: Steps for processing example data

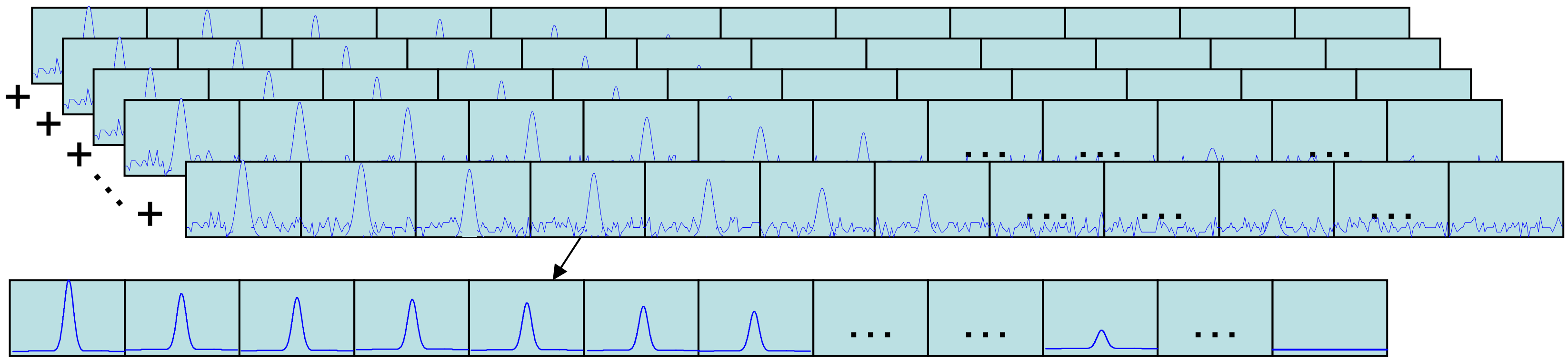
1. Divide each pulse into ***range gates***



2. Find the ***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



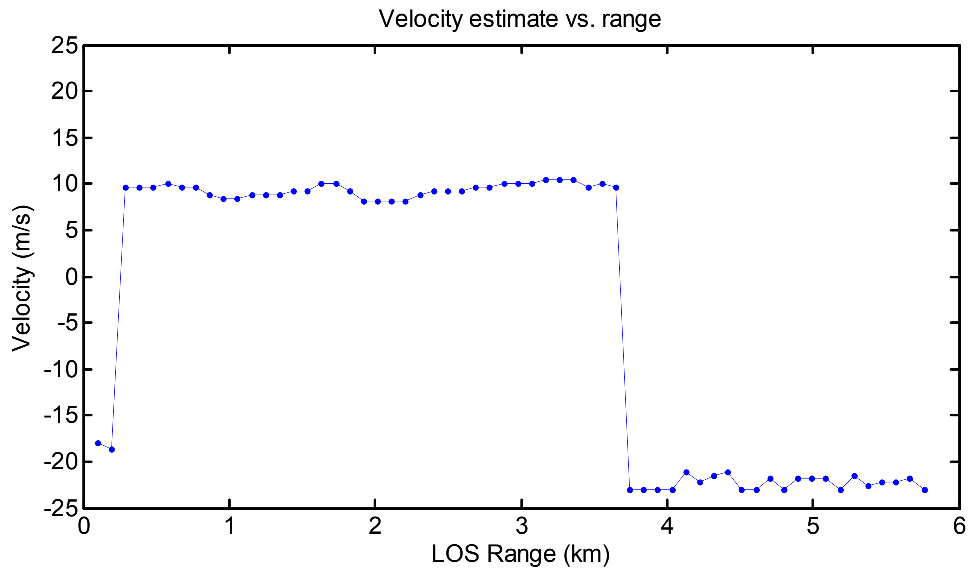
4. The frequency axis should be 0 to 50 MHz.

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.

Return Signal Processing: Steps for processing example data

The ***velocity*** corresponding to the peak frequency is given by:

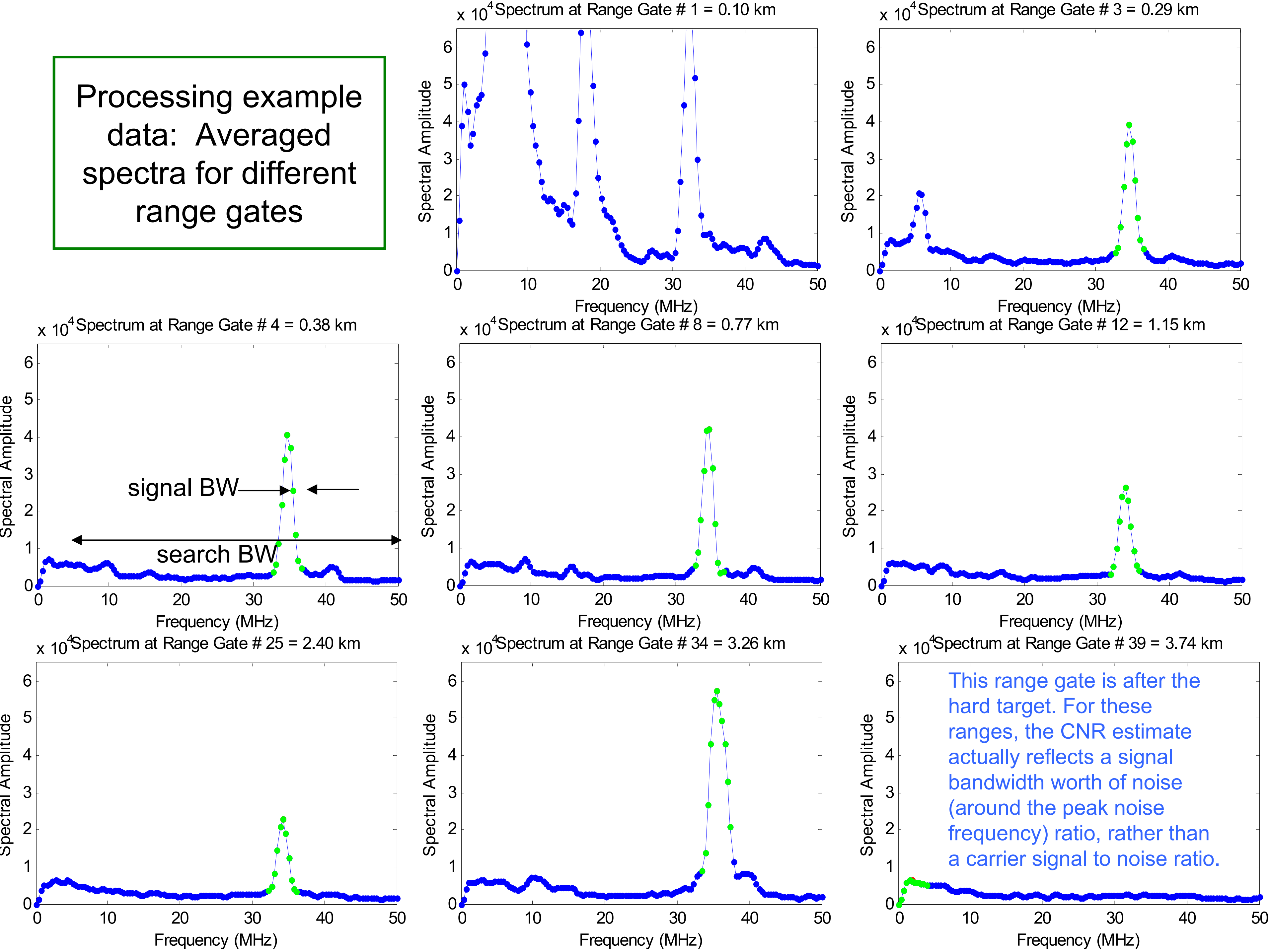
$$v = \frac{2}{\Delta f \lambda}$$



Questions related to processing

- What happens to the bandwidth when the range gate is shortened/lengthened?
- Why can't the range gate be shorter than the pulse length?
- What happens to the noise floor when you average the spectra?
- What happens to the velocity estimates if you average only 10 pulses worth of spectra per beam? How about 100?
- Does the peak intensity value change much when you average the spectra?
- Notice that the noise floor in this example is not flat (white). How does this affect the velocity estimates when there is no return signal?

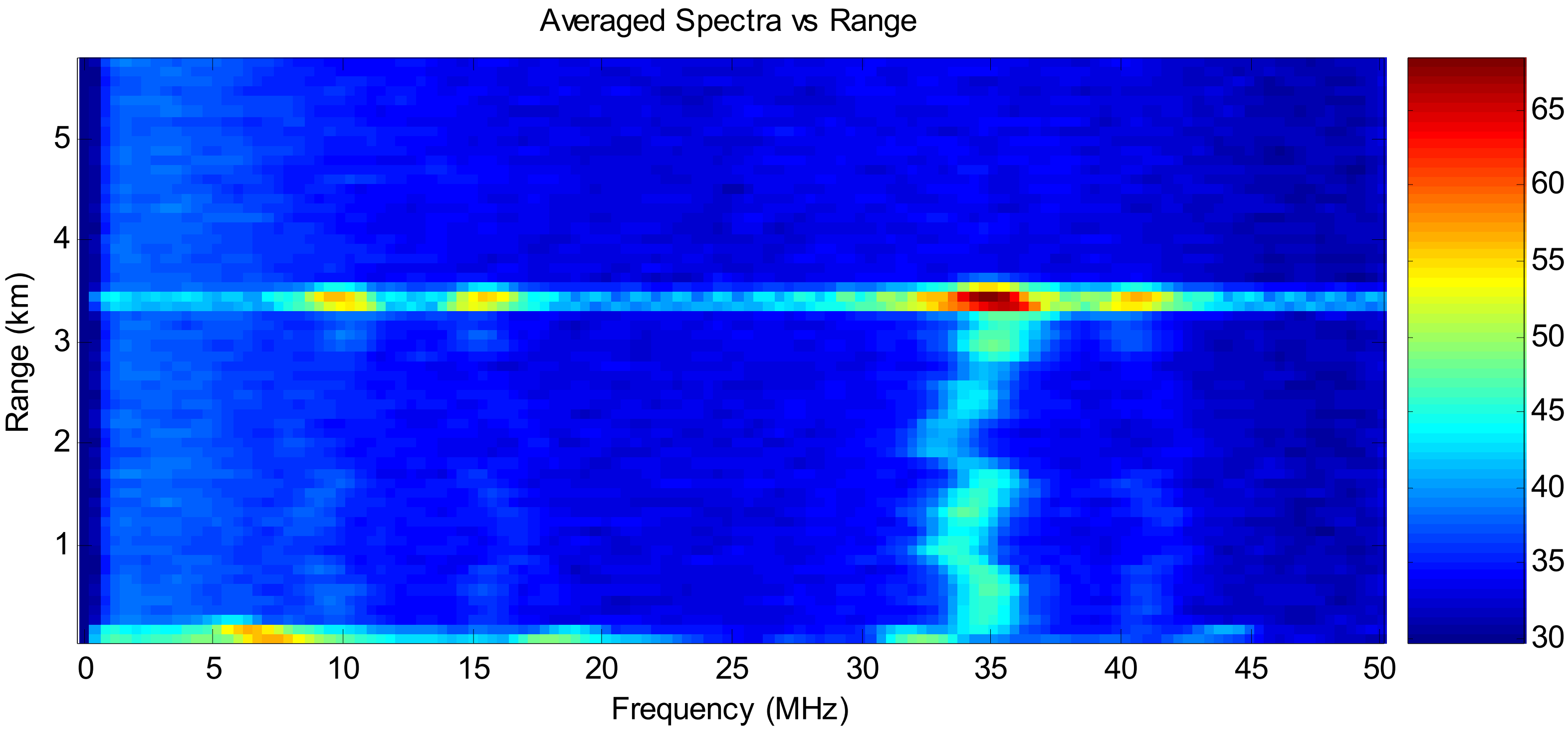
Processing example data: Averaged spectra for different range gates



Return Signal Processing: Processing example data (velocity)

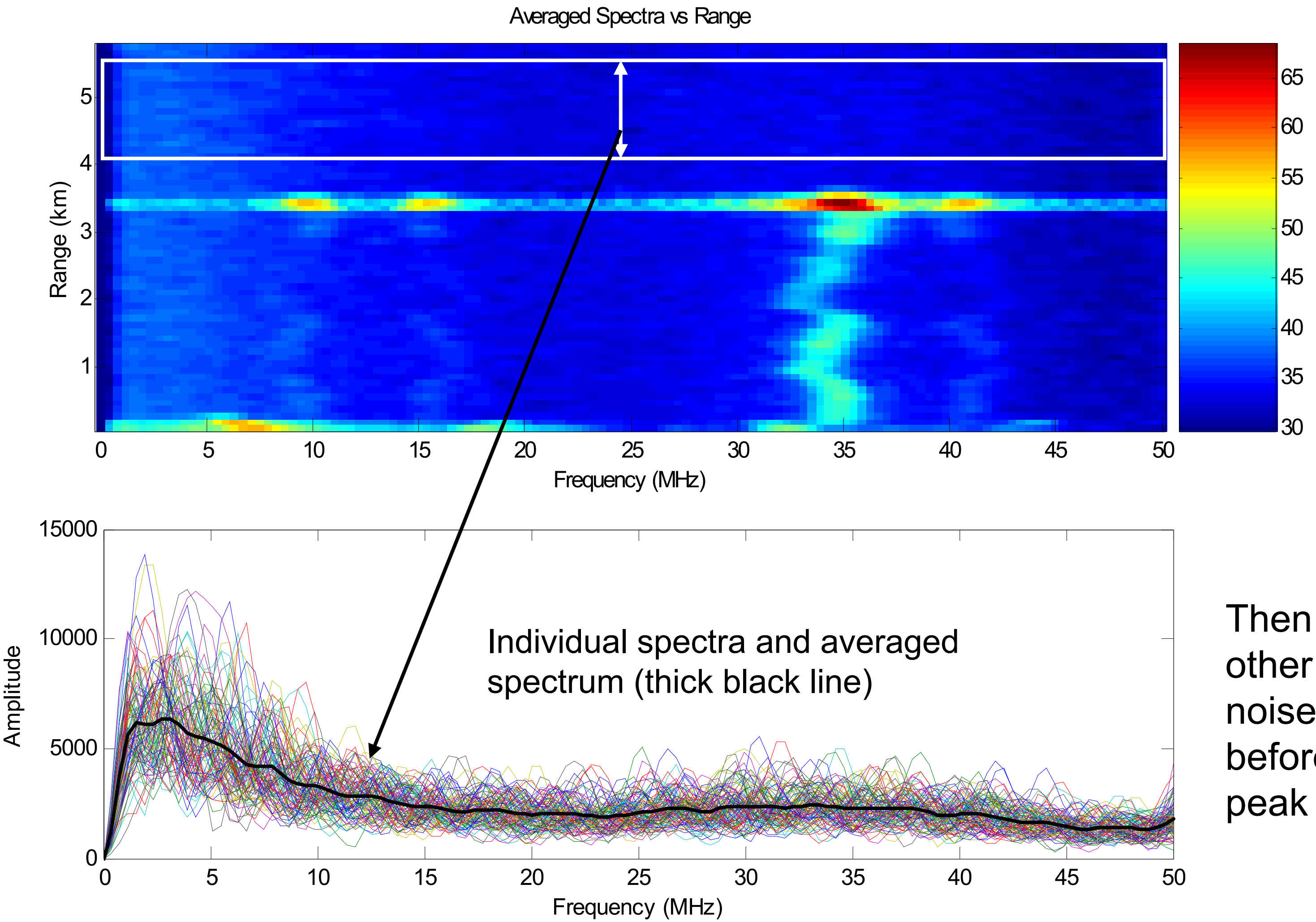
The figure below contains a visual plot of the 128 point spectra for each range gate (plotted against range). Note the effects of aliasing manifested as a "mirroring" of the peak locations at each range. Also note the fact that the noise "floor" is not uniform.

Range gate values indicate the maximum range in each gate. Gates are 96 meters long so the first range gate is listed as 96 m, the second as 192 m, and so on.



Return Signal Processing: Processing example data – Noise floor whitening

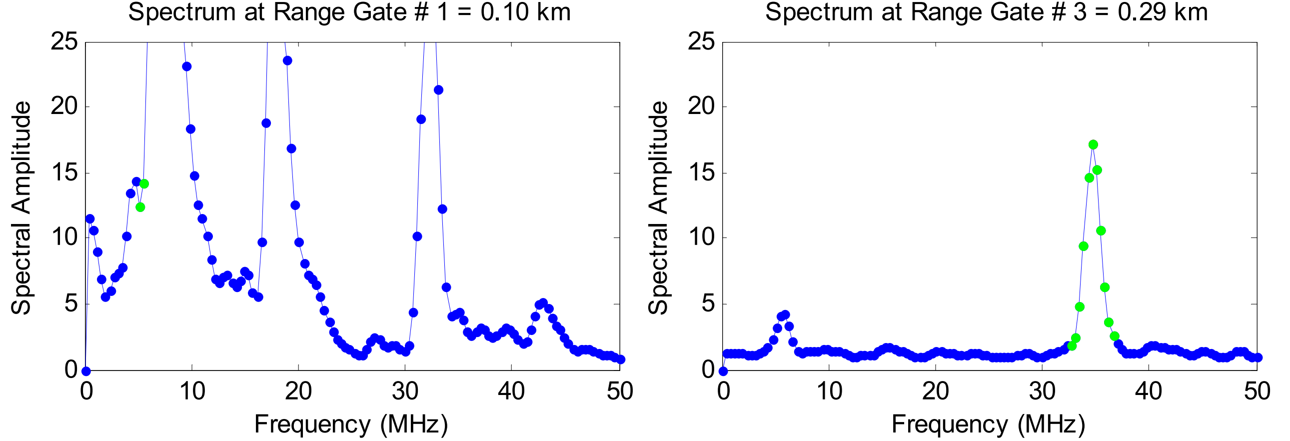
Notice the increased signal levels in lower frequencies. We need to flatten/whiten the noise floor.

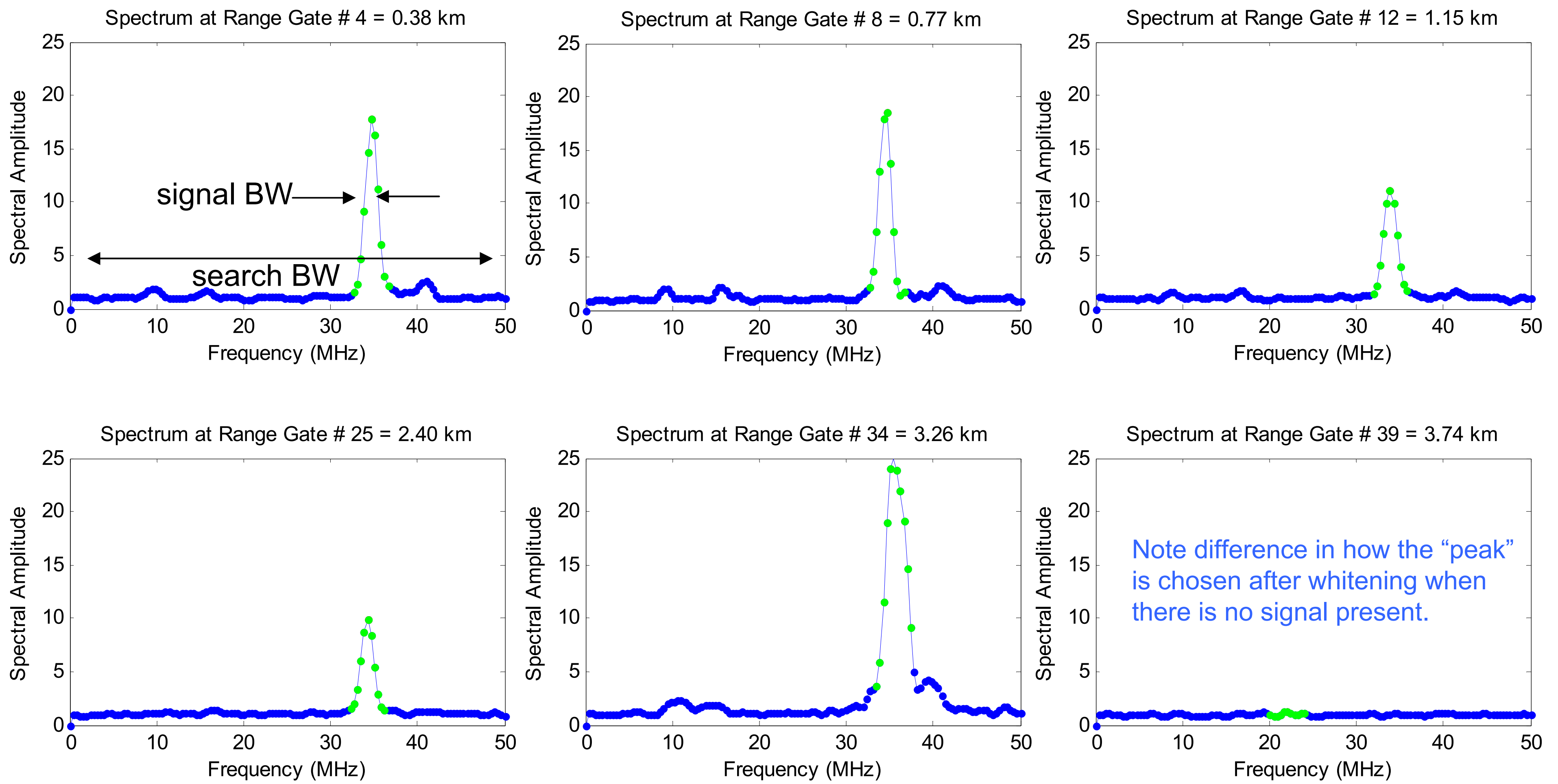


Find the average spectrum in an area where there is no return signal. This is the estimated spectral noise floor

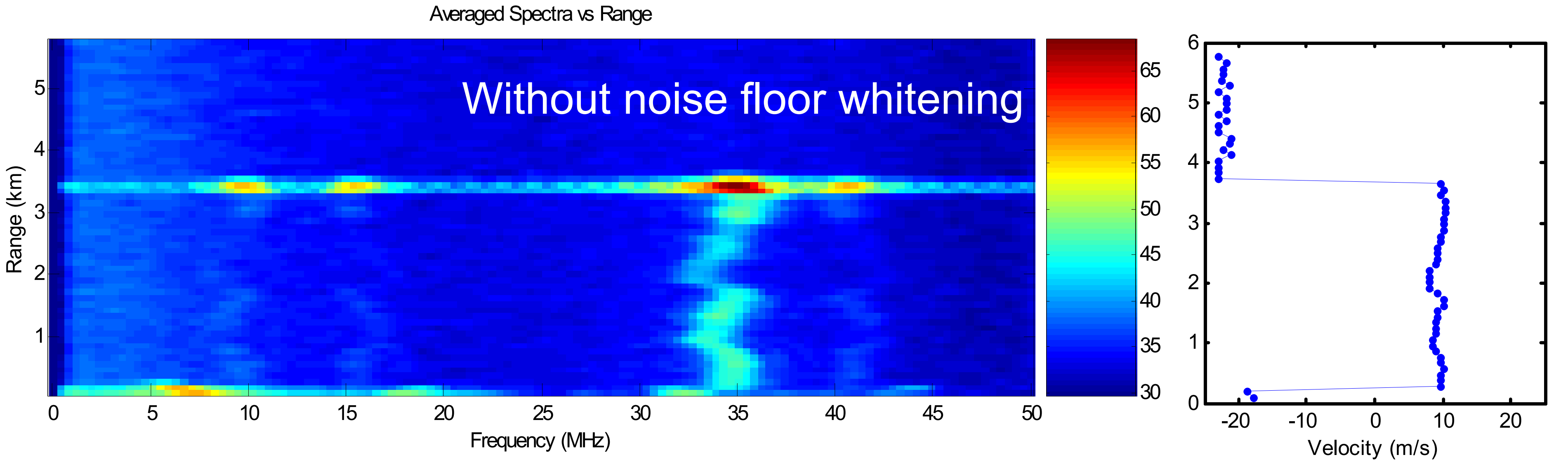
Then divide all of the other spectra by this noise floor estimate before estimating the peak frequency.

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

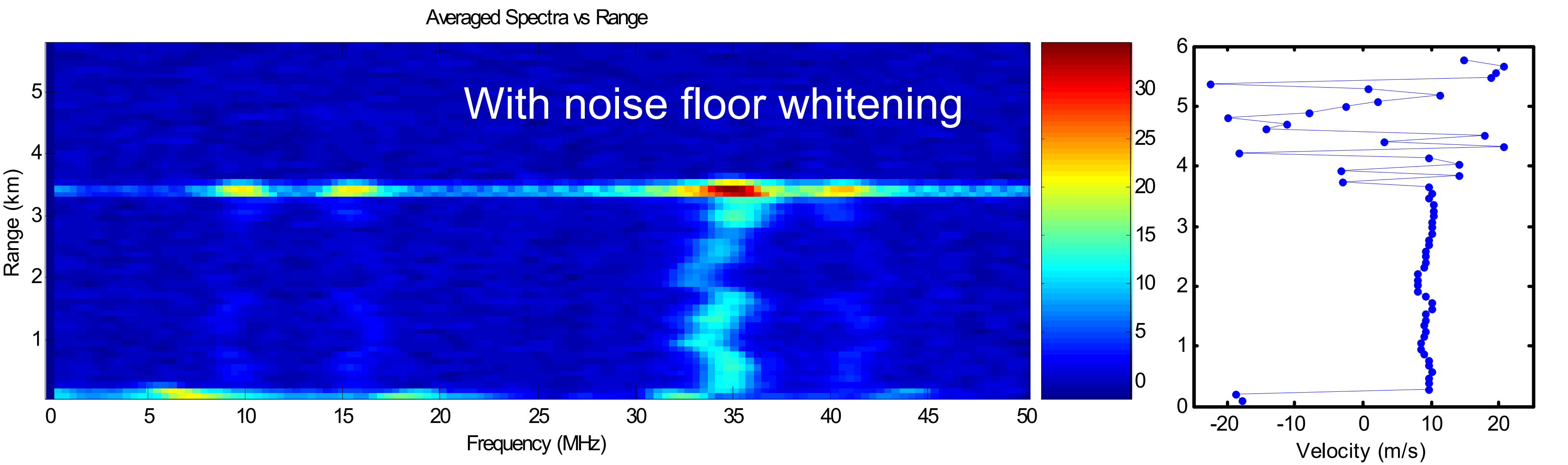




Return Signal Processing: Processing example data – noise floor whitening

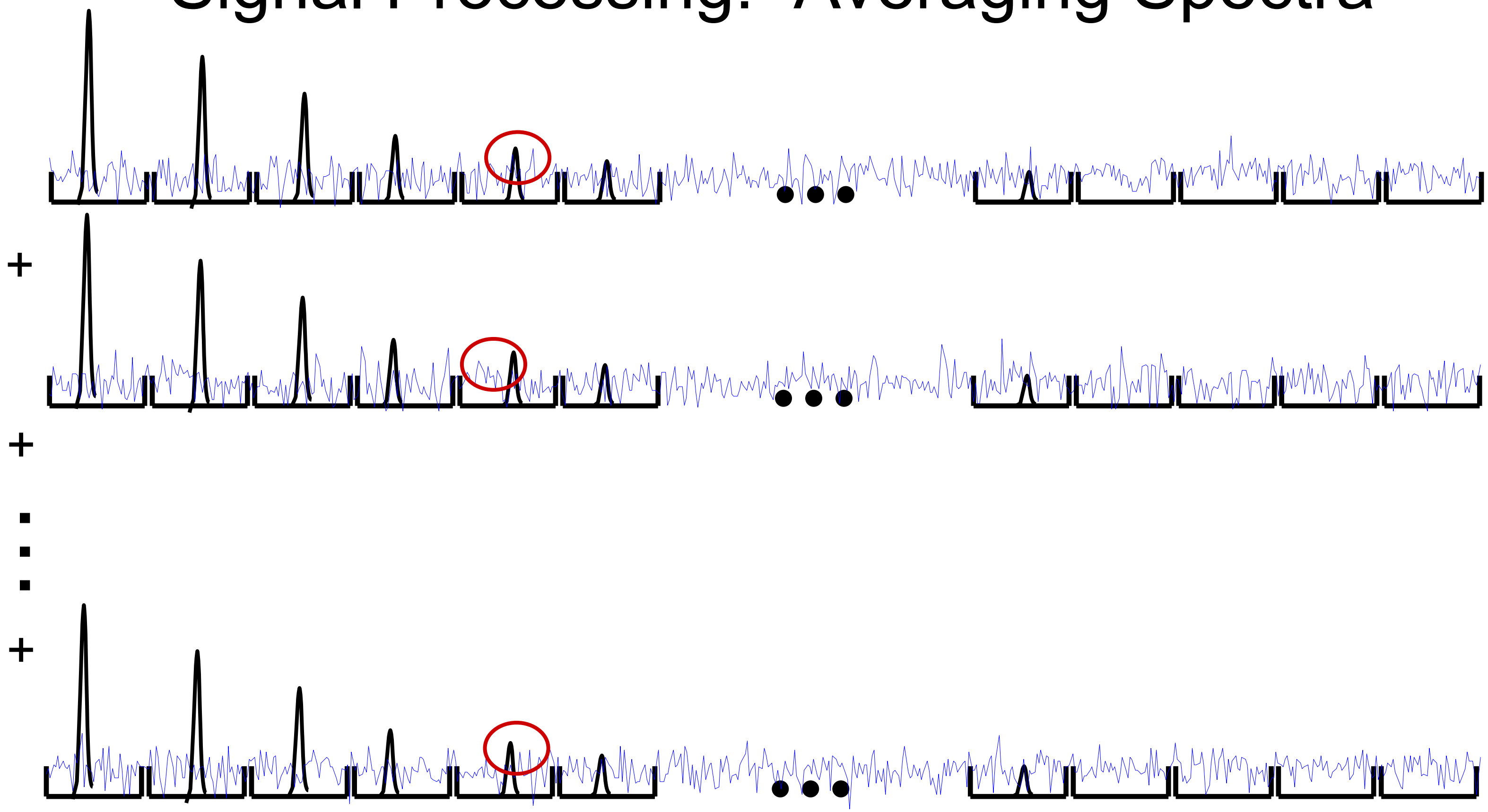


Note that when the noise floor is not flat, then velocity estimates in areas of low signal will be biased toward the noise floor peaks.

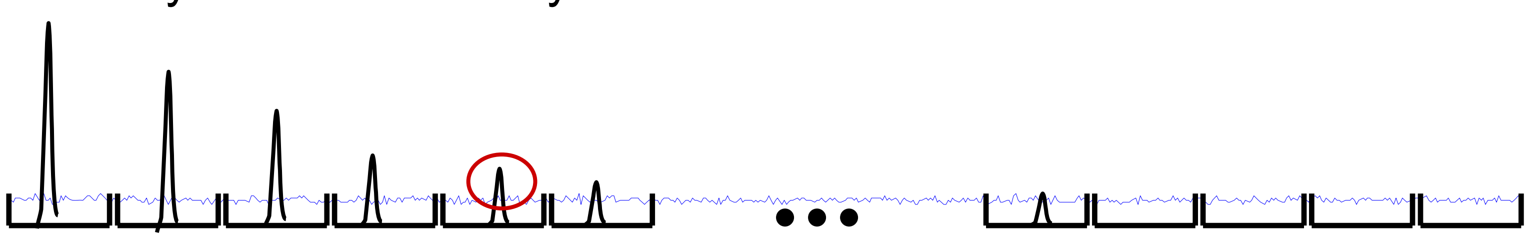


- Coherent Detection
- Laser
- Local Oscillator + shift
- Transmit path
- Atmosphere
- Receiver/Detection
- Processing
- Analysis and Data products

Signal Processing: Averaging Spectra

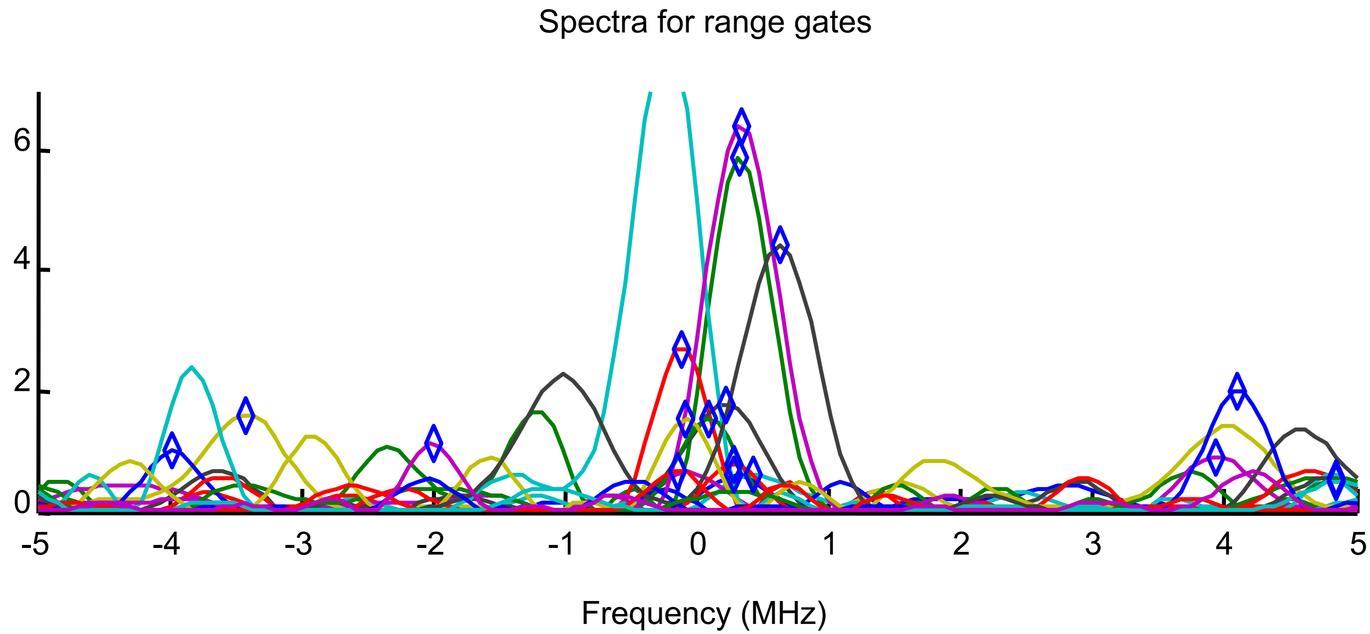


- Average the spectra and THEN estimate the frequency/velocity
- Why not the other way around?

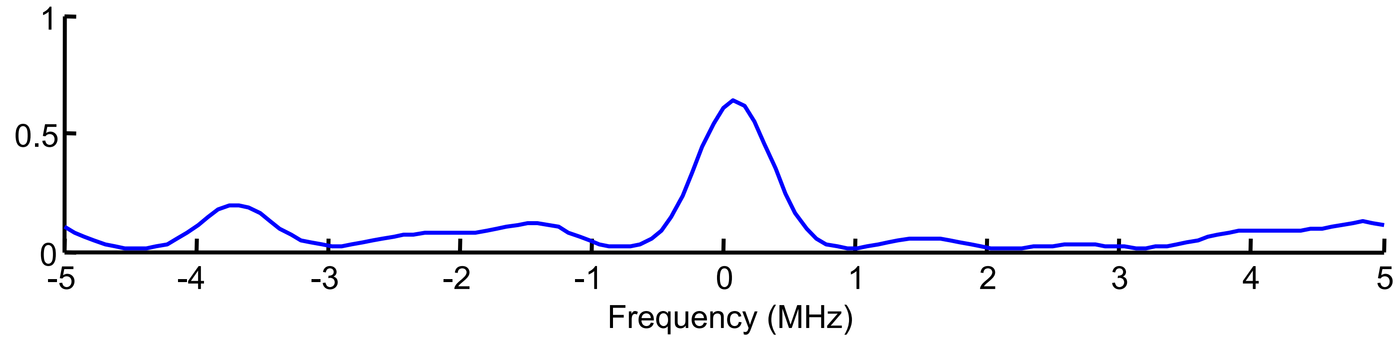


Signal Processing: Averaging Spectra

Individual noisy spectra

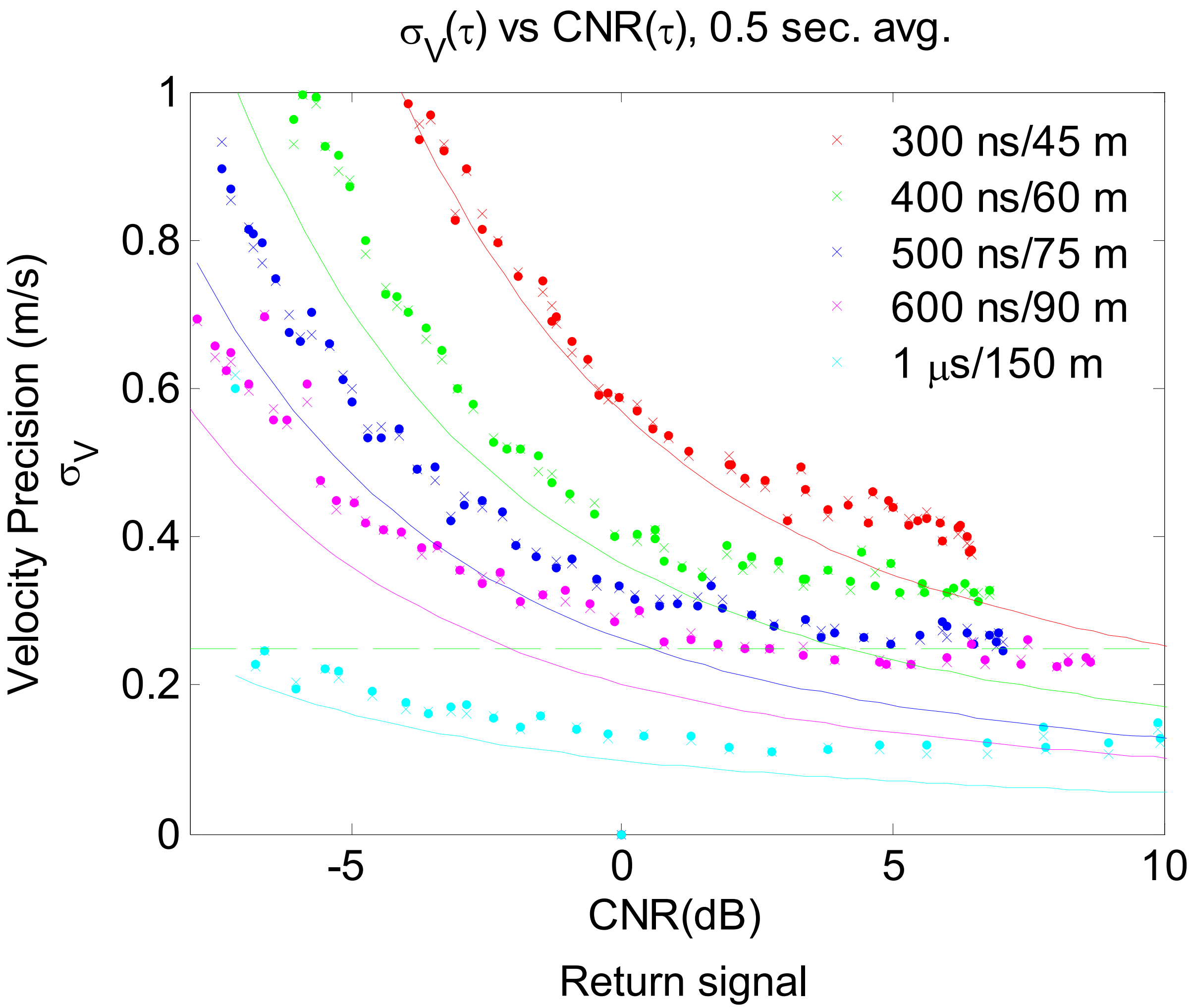


Average of all spectra



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

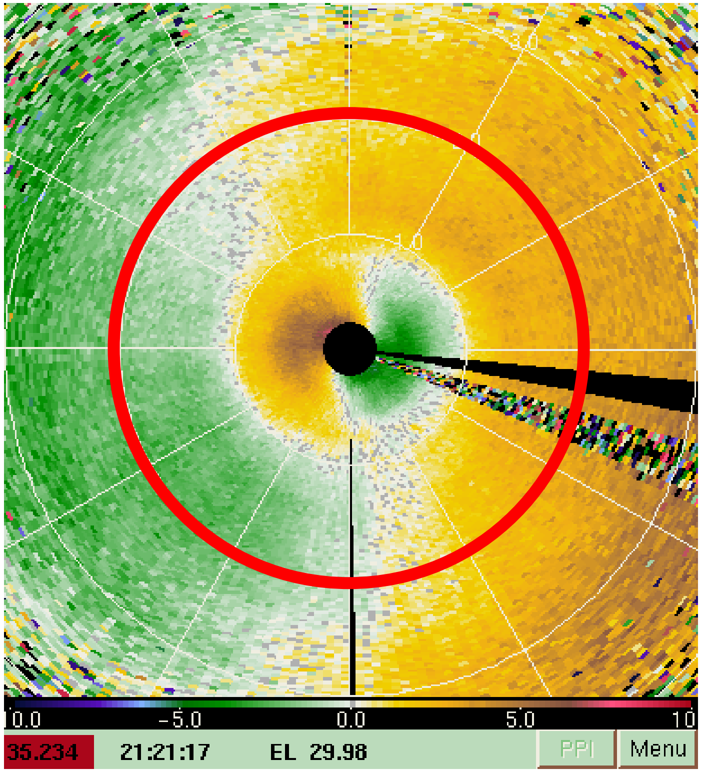
Velocity precision vs CNR and various pulse widths from mini-MOPA

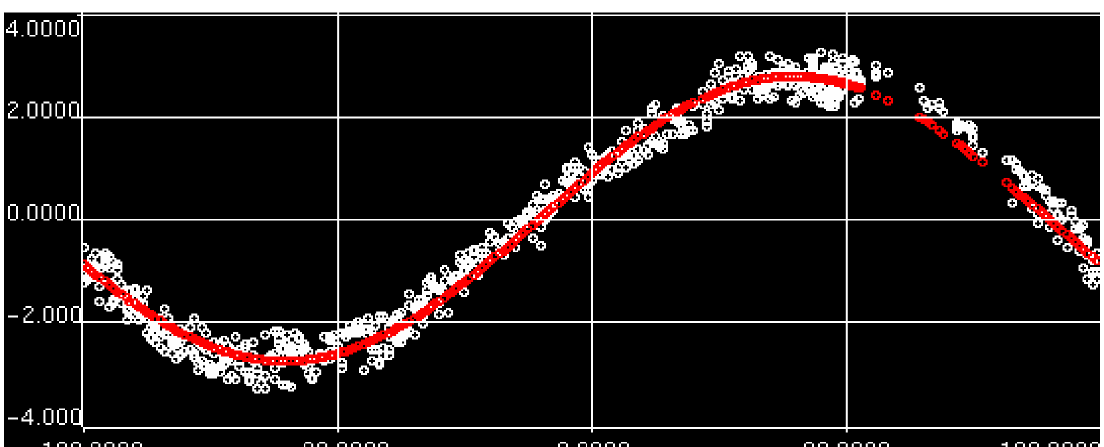


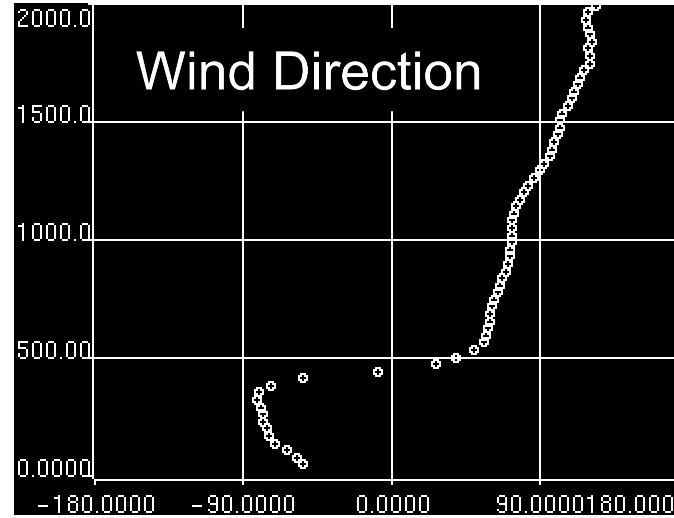
Tradeoffs between:

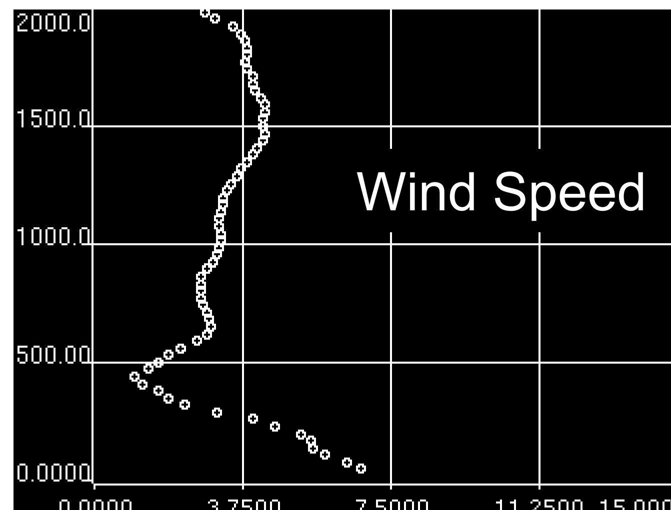
- detection bandwidth and CNR
- range gate length (range precision)
- velocity precision
- time resolution

Doppler Lidars: Calculating wind profile from PPI scans

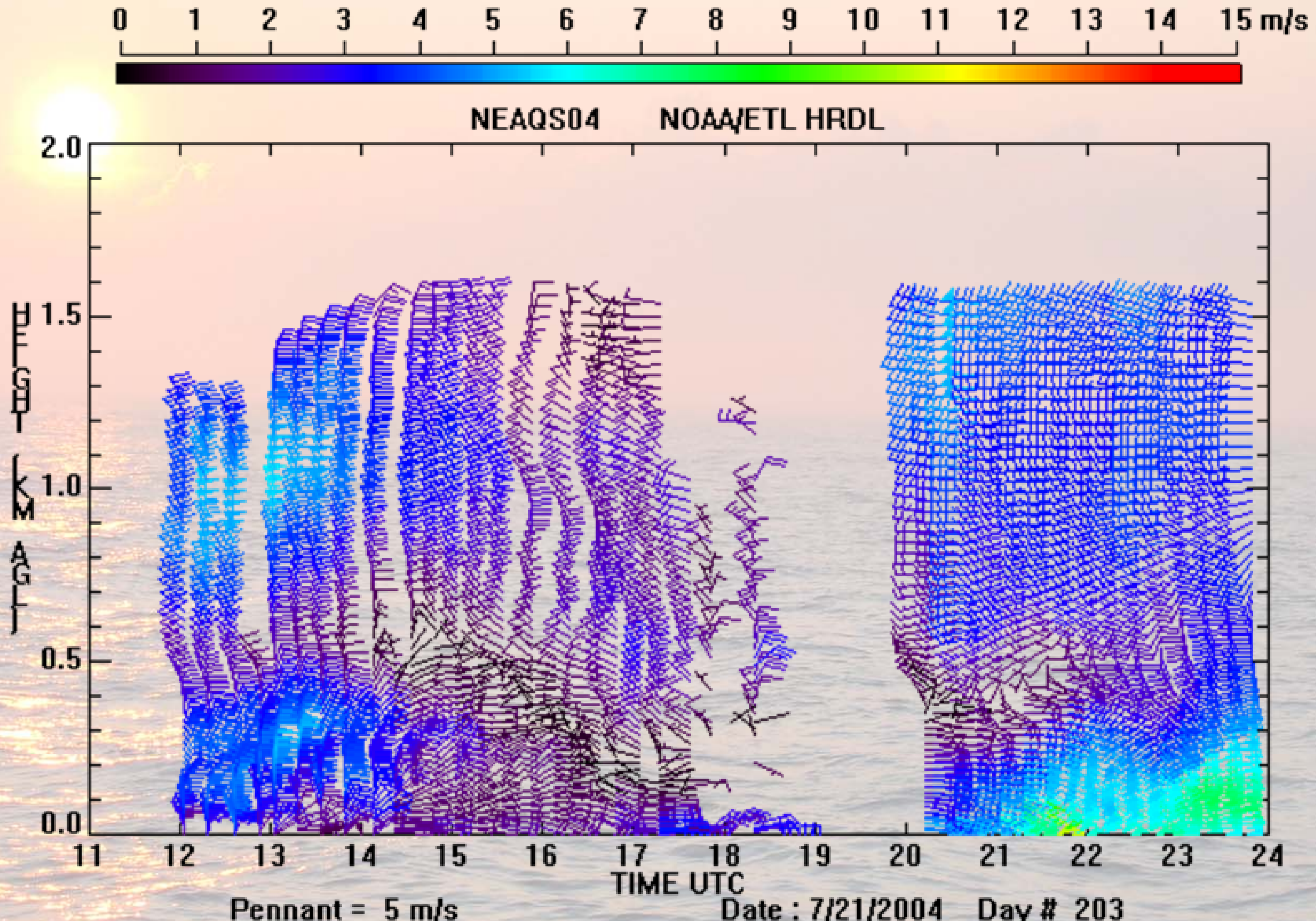






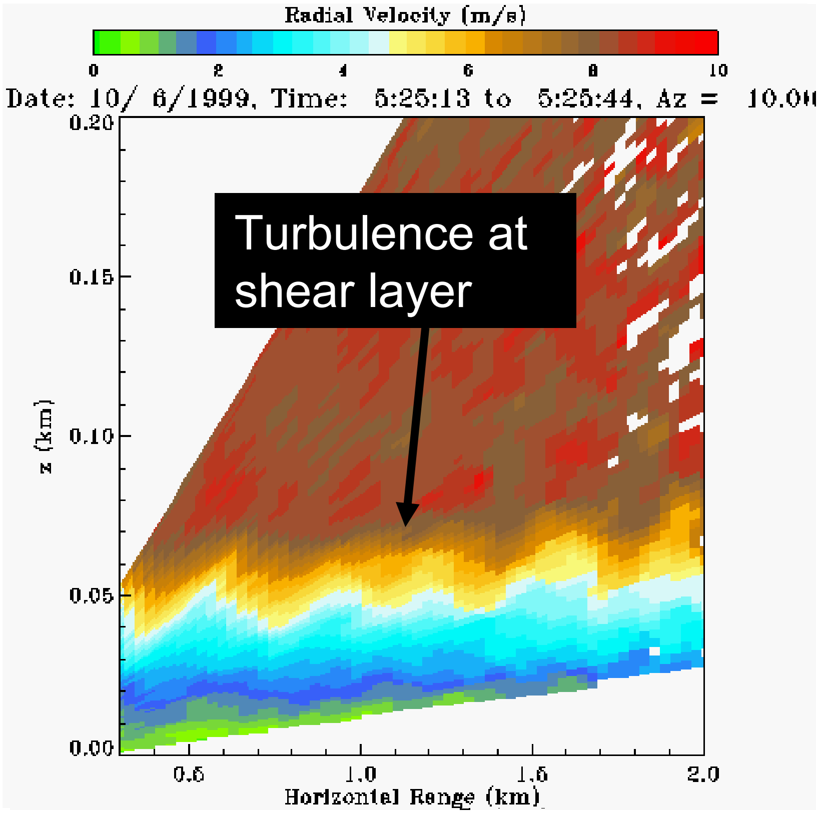


Combine profiles into 12 hour displays



5m – 30 m vertical / 15 minute resolution

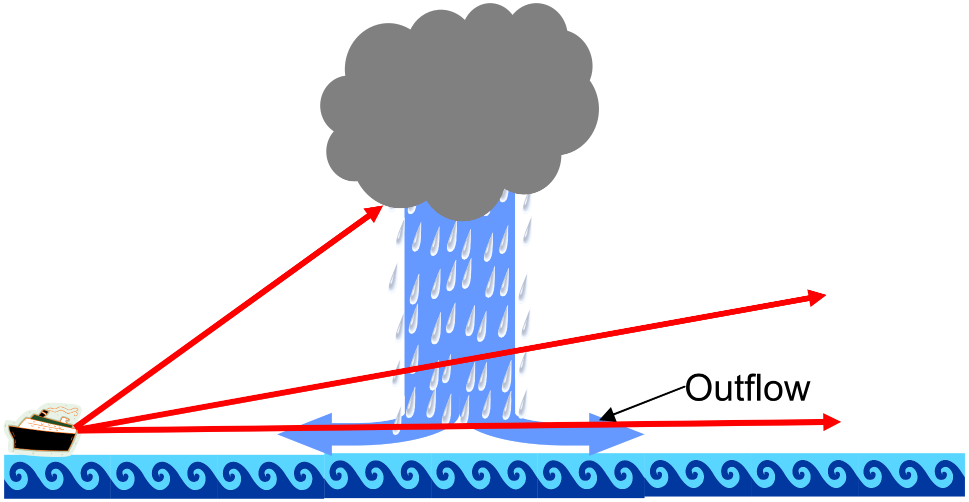
Turbulence Measurements

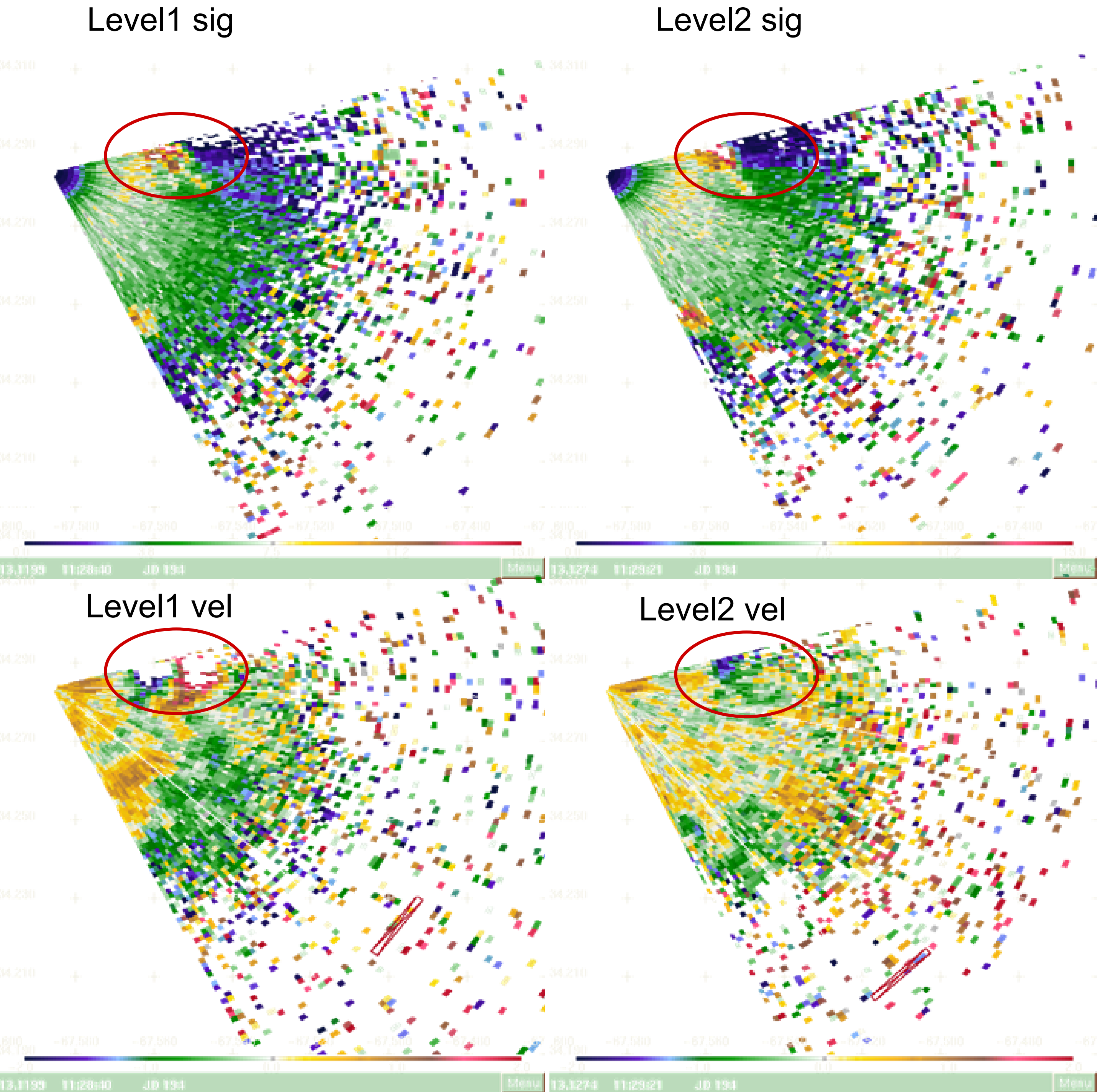


Objectives

- Profiles of turbulence
- Study mixing process
- Parameterization of sub scale processes for model improvement

Observations of thunderstorm outflows





Frame 8

11:28:40

MISCELLANEOUS

NOAA/ESRL Lidar Field Work

Carrier to Noise Ratio (CNR)

What does ETL Optical Remote Sensing Division do ?

- Investigate and implement new technology for improving observations of the atmosphere and ocean
- Demonstrate application of 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

Basic Lidar measurements

- Chemical distributions (ozone, water vapor, NH_3, CO_2)
- Cloud properties
- Aerosol measurements
- Low level mean winds
- Residual winds
- Turbulence, general dynamics

Instruments have been mounted on research ships for sea based operation

Challenges include:

- Sea salt corrosive environment
- High vibration
- Platform motion & orientation
- Low frequency accelerations – stability issues
- Big waves and leaky seatainers

Motion Compensation

Appendix: The Coherent Doppler Lidar Equation

The carrier-to-noise ratio (CNR) is found using the following equation:

$$CNR = \frac{\left\langle \left| i_{het} \right|^2 \right\rangle}{\left\langle \left| i_N \right|^2 \right\rangle} = \frac{\eta P_r}{h \nu B}$$

- where η is an efficiency factor (less than or equal to unity) describing the noise sources in the photo-detector signal as well as optical efficiencies,
- *h* is Plank's constant (6.626×10^{-34} Joule-sec)
- ν is the optical frequency (Hz.)
- *B* is the receiver bandwidth determined by the receiver electronics.
  - In HRDL's case, *B* is 50 MHz. - In MOPA's case, *B* is 10 MHz
- *Rule of thumb:* We need about one coherent photon per inverse BW to get 0 dB CNR – i.e. Coherent Doppler Lidar is quite sensitive.

The Coherent Doppler Lidar Equation, cont'd

The received power, P_r is theoretically given by

$$P_r = \int_0^{\infty} \frac{A_{eff} \beta T^2}{R^2} P_T\left(\lambda, t - \frac{2R}{c}\right) dr$$

P_T = Transmitted laser power (Watts) for wavelength λ, range R and time t,

- R = range (meters)
- $\beta =$ aerosol backscatter coefficient (m^{-1} sr^{-1}),
- T = one-way atmospheric transmission.
- A_{eff} is the effective antenna area of the transceiver for a target at range R.

For aerosol targets distributed in range (relative to the pulse length) the received power at the lidar P_r can be approximated as

$$P_r = \frac{A_{eff} \beta T^2}{2R^2} c E_T$$

The Coherent Doppler Lidar Equation, cont'd

The effective area is effected by the Gaussian beam expansion and transmitter focus parameters as well as turbulence and is given by

$$\frac{1}{\langle A_{eff} \rangle} = 2\left(\frac{1}{A_{TR}} + \frac{1}{A_{turb}} \right)$$

Where A_{turb} is the coherence area defined by $\pi\rho_{0.}$

A_{TR} is the transmit/receive area defined by

$$\frac{1}{A_{TR}} = \frac{2}{\pi D^2} + \frac{\pi D^2}{8\lambda^2}\left(\frac{1}{F} - \frac{1}{R} \right)^2$$

D_b is the transmitted, 1/e[2] intensity, untruncated, Gaussian beam diameter in meters, F is the focus of the transmitter optics.

Thus A_{eff} is defined by

$$A_{eff} = \frac{\pi D^2}{4}\left[1 + \left(\frac{\pi D^2}{4\lambda R} \right)^2 \left(1 - \frac{R}{F} \right)^2 + \frac{D^2}{2\rho_o^2} \right]^{-1}$$

The Coherent Doppler Lidar Equation, cont'd

The turbulence parameter ρ_0 is given by

$$\rho_o = \left[1.45 k^2 \int_0^{\infty} C_n^2 (R') \left(1 - \frac{R'}{R} \right)^{\frac{5}{3}} dR' \right]^{-\frac{3}{5}}$$

For constant refractive turbulence (C_n^2) level, The above equation reduces to

$$\rho_o = \left[1.45 k^2 C_n^2 \frac{3}{8} R \right]^{-\frac{3}{5}}$$

Typical C_n^2 levels are between $1X10^{-16}$ (calm) to $3X10^{-13}$ (quite turbulent)

The Coherent Doppler Lidar Equation, cont'd

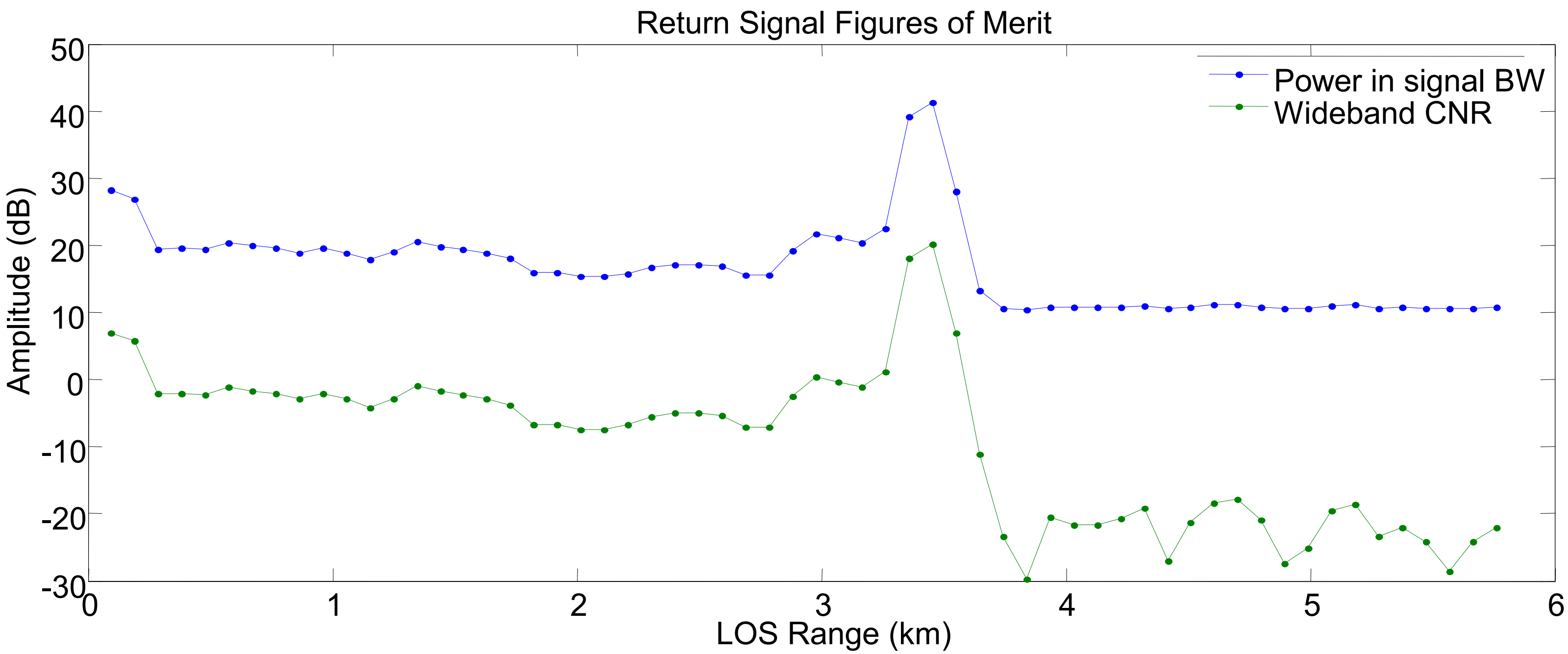
The CNR equation can be written explicitly as

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

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

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

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.

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

The Wideband CNR is then calculated as follows:

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

Where P_{ns} is the average noise power, N_{BW} 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.