Optical Remote Sensing with Coherent Doppler Lidar

Part 1: Background and Doppler Lidar Hardware

Mike Hardesty[1], Sara Tucker[2], Alan Brewer[1]
[1]CIRES-NOAA
Atmospheric Remote Sensing Group
Earth System Research Laboratory

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

[2]Current affiliation: Ball Aerospace

April 4, 2011

Remote Troposphere Wind Measurement Techniques

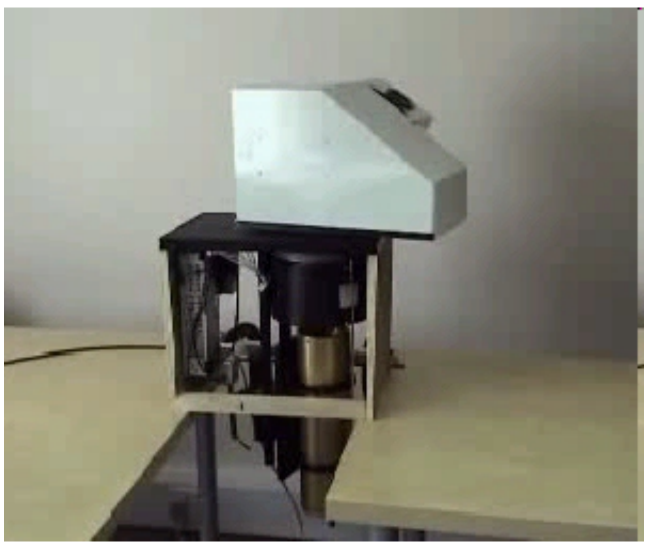
- Doppler lidar provides remote measurement of the radial component of the atmospheric wind
- Highly valuable for clear air, small-scale measurements, turbulence

	Lidar ($\lambda = 2x10^{-6}$ m)	Precipitation Radar ($\lambda=10^{-1}$ m)	Wind Profiler ($\lambda=7.4 \times 10^{-1}$ m)	Cloud/ MoistureFeature tracking
Range Resolution	30 -50 m	0.25 – 1 km	90-120 m	None
Max Range	5-20 km	230-460 km	2.5 - 20 km	Visual range
Transverse resolution	100 μrad	1 degree	4-8 degrees	30 – 70 km (satellite)
Effects of clouds	Opaque, but can see through holes	Don't observe without precipitation	Small cross section	Need for measurement
"Clear" Air performance	Scatters from either aerosols or molecules	Requires bugs, seeds, etc	Needs Refractive index variability	Need contrast in image field

Capability for compact instruments

Wind profiler

Meteorological radar

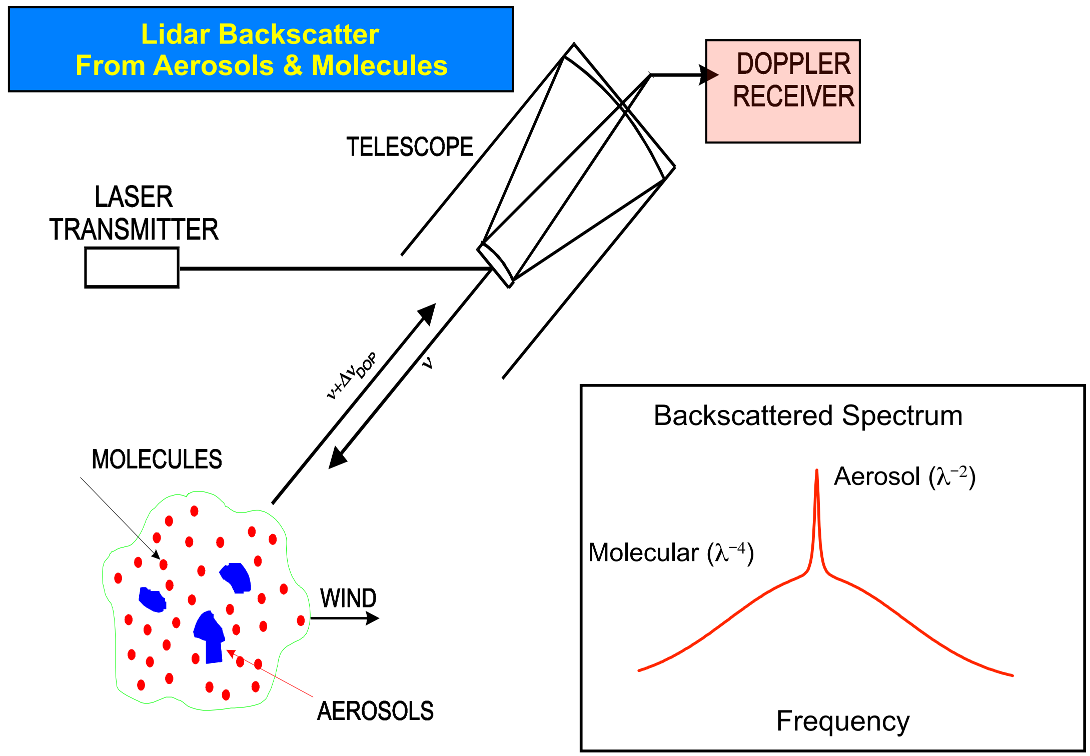


Lidar with scanner

Airborne lidar

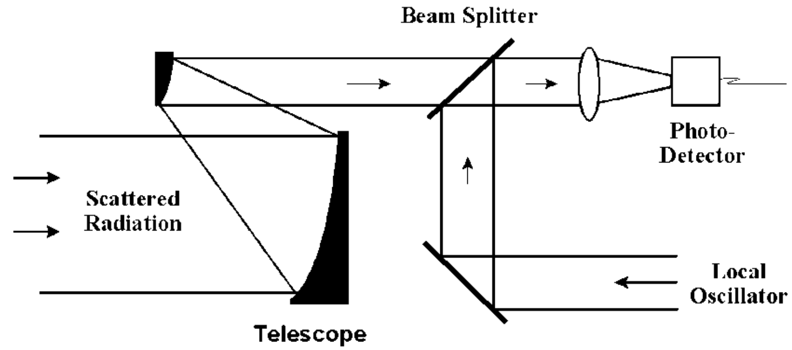
Doppler Lidar Concept

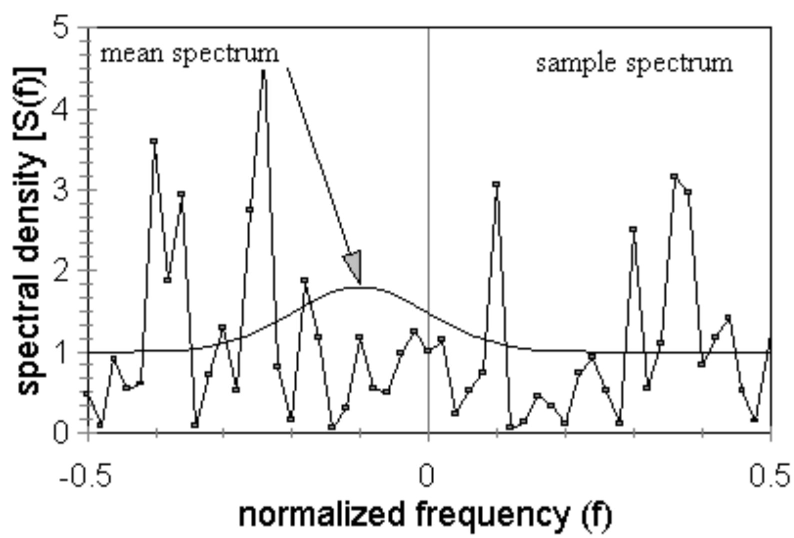
- **Basic requirements**
  - Frequency stable transmitter (~1 m s^{-1}) for coherent detection
  - Doppler receiver to measure frequency shift of the backscattered radiation
- **Doppler receivers**
  - Heterodyne (coherent) detection
  - Direct detection
- **Receivers optimized for aerosol versus molecular returns differ**



Coherent (heterodyne) detection

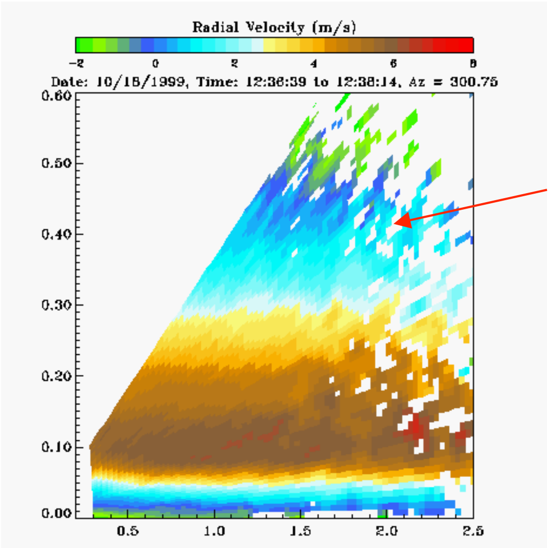
- Mix backscattered radiation with local oscillator laser output
- Produces a “beat” spectrum which is narrowband at radio-frequencies and can be digitally processed
- LO shot noise introduces a noise floor
- Spectral components are random for a single shot
- Background light is not an issue due to narrow bandwidth
- Typically operate in the eyesafe infrared (10 μm, 2 μm 1.5 μm)



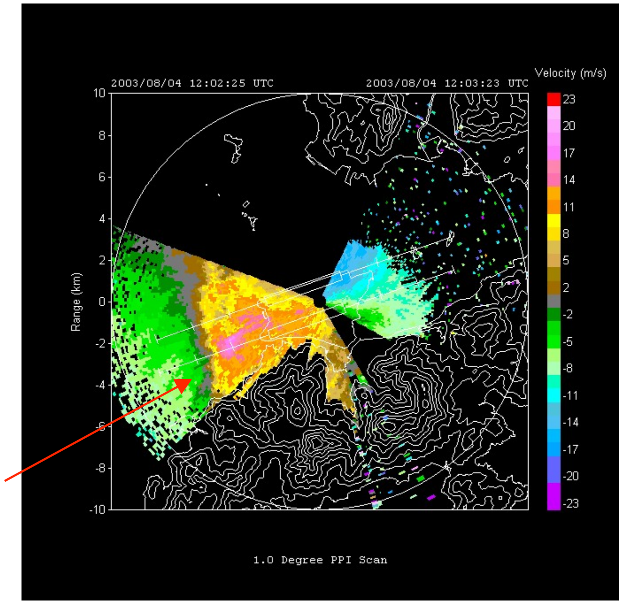


Coherent lidar characteristics

- Used when aerosol loading is significant
- Highly sensitive: a hundred photons are sufficient for estimate
- Threshold effect – need a certain minimum signal level
- Requires diffraction limited transmitter beam and receiver field of view
- 25 years of measurements
- Most, but not all, applications have been low pulse energy, high prf
- NASA/LaRC working on Joule-class transmitters

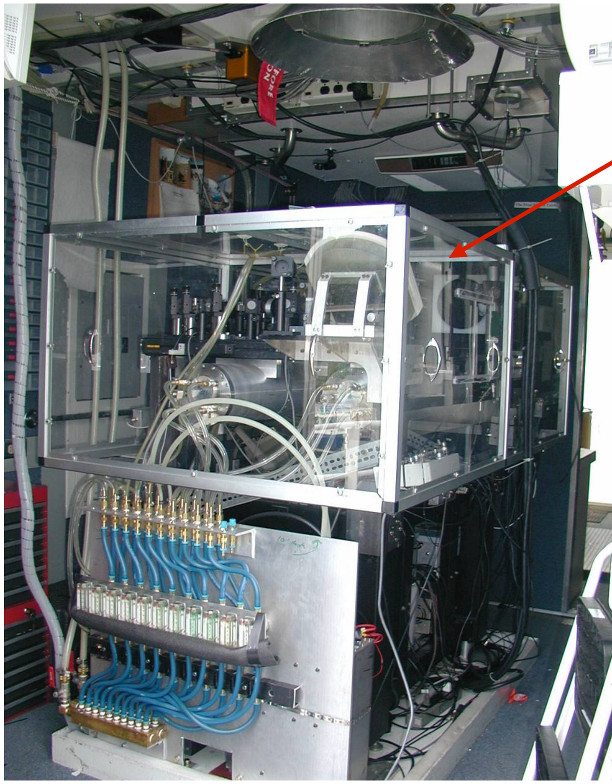


Stable boundary layer mapping

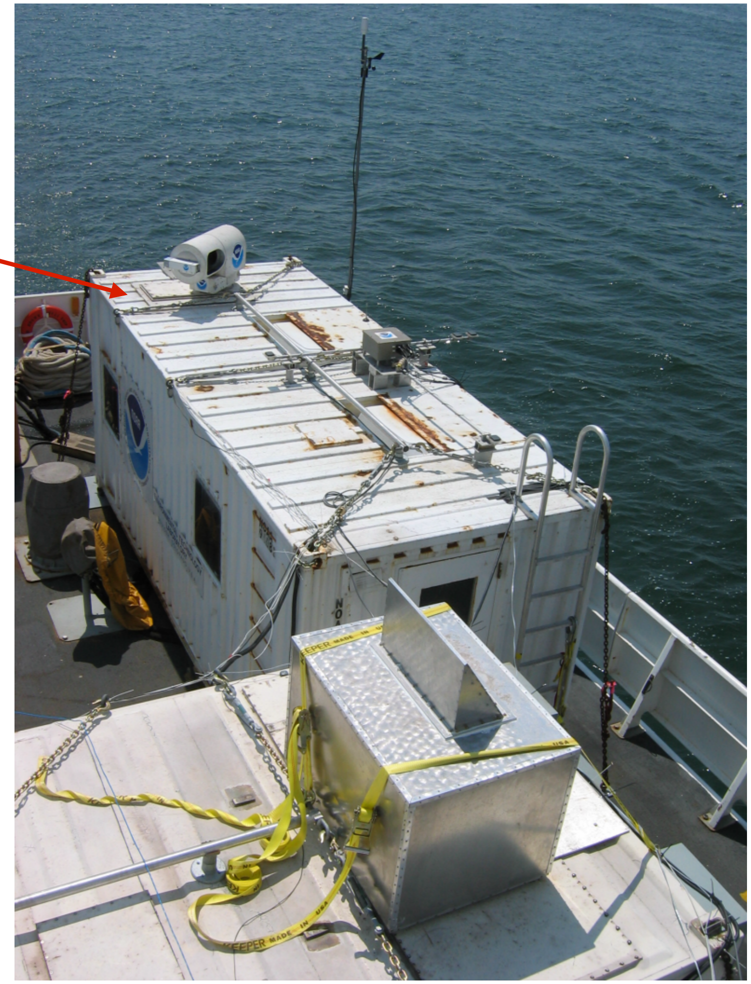


Hong Kong Airport Wind Shear

NOAA ESRL Lidars



- Mini-MOPA
- HRDL
- OPAL
- TOPAZ
- ABDIAL
- DABUL
- Fish Lidars
- CODI
- TEAC0
- ABAEL
- Halo (new)

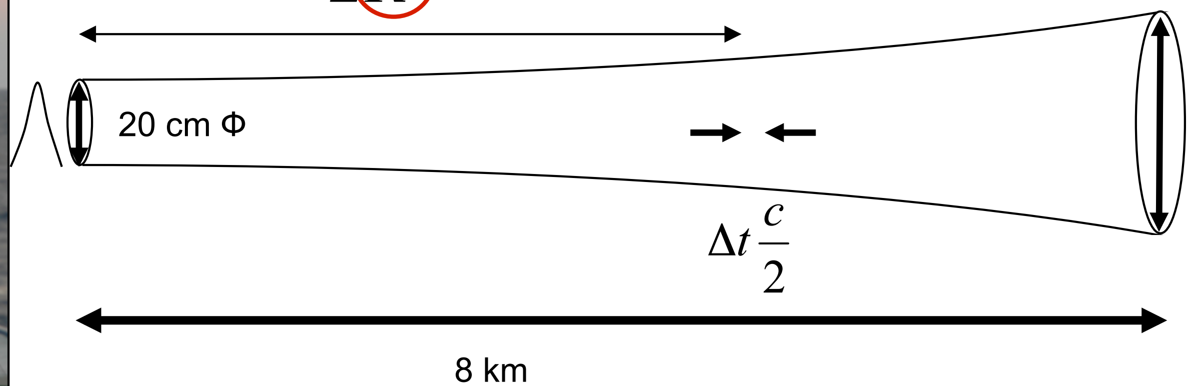


Coherent Doppler Lidar

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 (range resolution) along the beam (Instrument dependent)

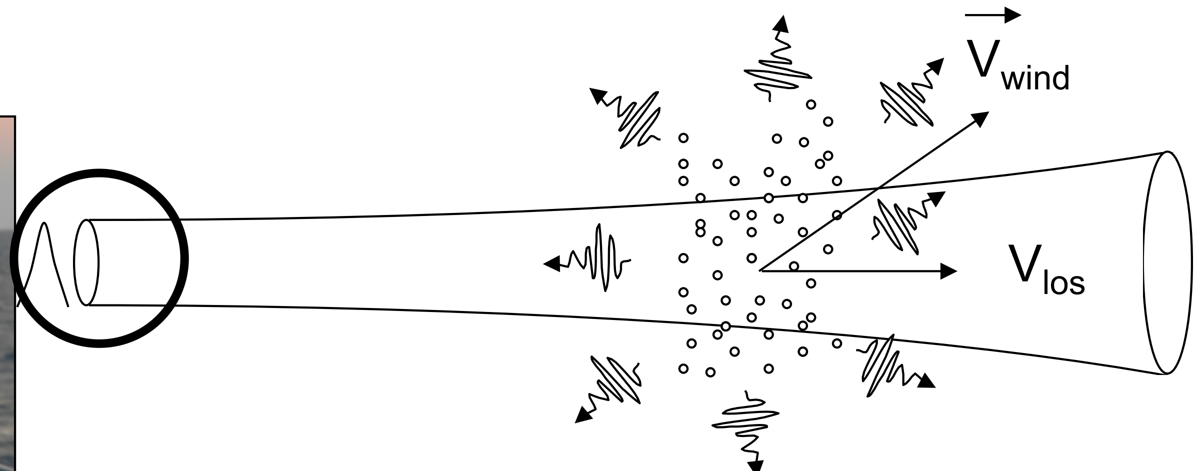
$$P_r = \frac{A_{eff}\beta T^2}{2R^2} cE_T$$



Coherent Doppler Lidar

Light Scattering : ~2 μm & 10 μm

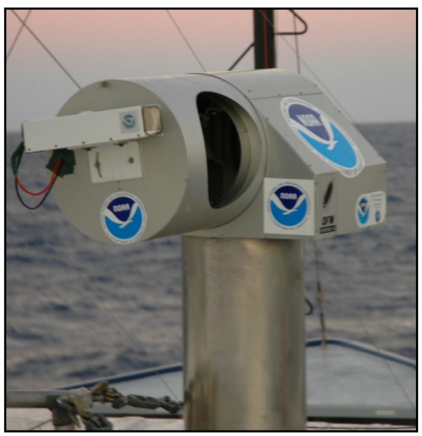
- The targets are aerosol particles
- The light scatters off the aerosol in all directions
- Part of the scattered light is detected – backscatter, β
- The wind carries the aerosol scattering targets
- Doppler measurement is made to determine wind speed along the line of sight

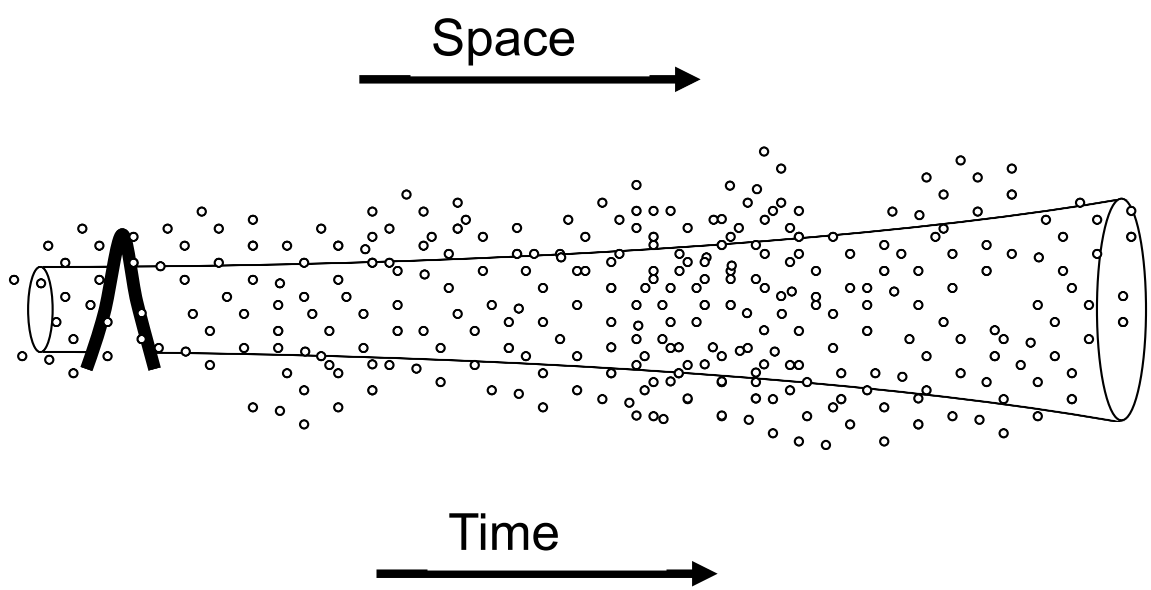


Coherent Doppler Lidar

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
- Transmit/Receive paths
- Atmosphere
- Detection & Processing
- Analysis and Data products
- Field Work

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 two light beams of slightly different frequencies…

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 PO 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

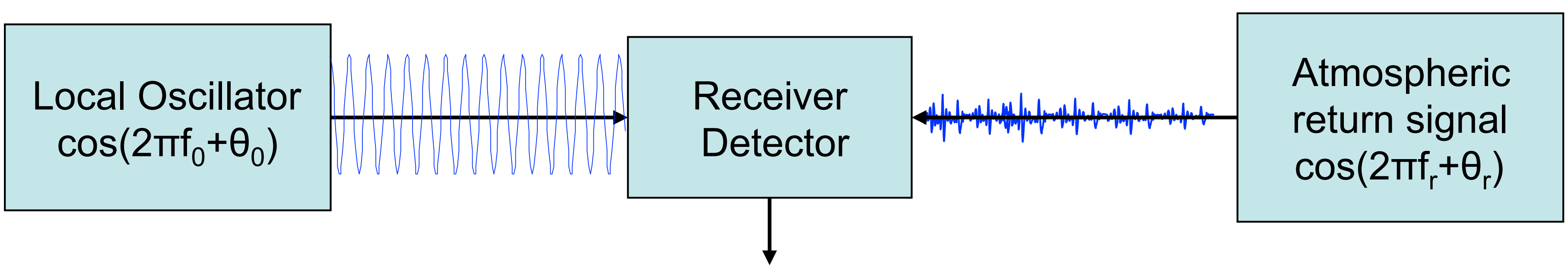
The atmospheric return signal and the signal from the local oscillator are both incident on the detector.

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:

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

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

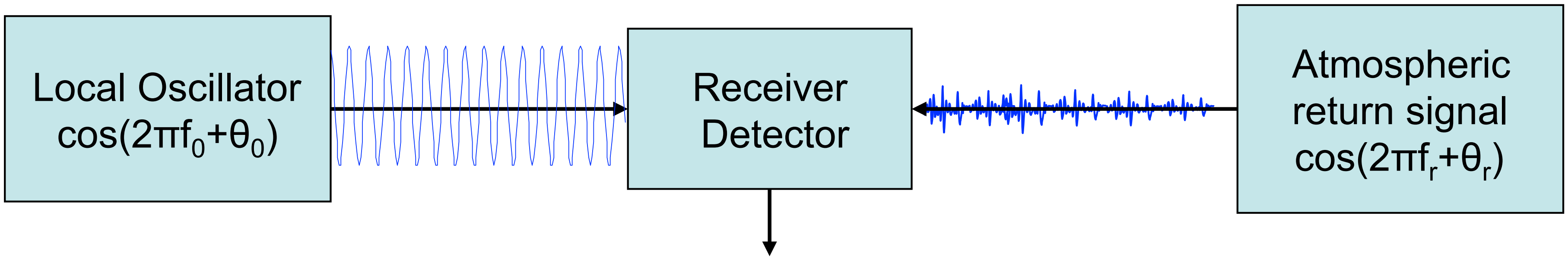
$$+2A_a A_{LO}\cos\left(j2\pi f_a t + \varphi_a\right)\cos\left(j2\pi f_{LO} t + \varphi_{LO}\right)$$

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

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

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

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

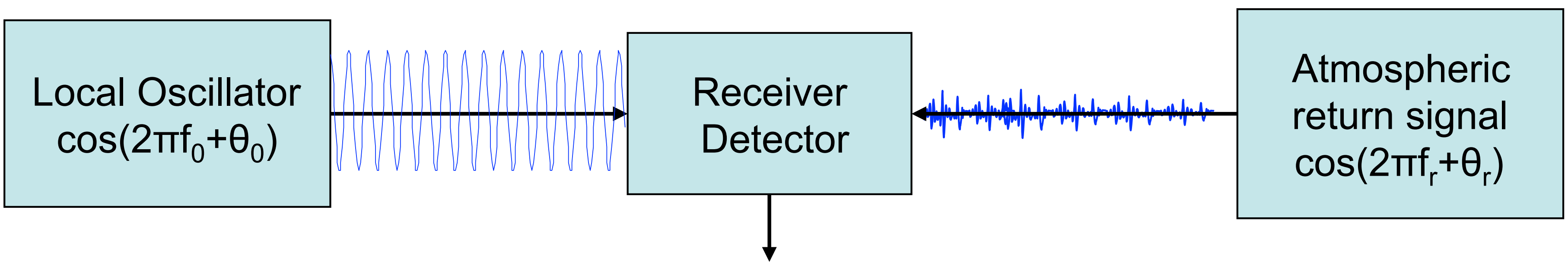


Coherent Detection

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:

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

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

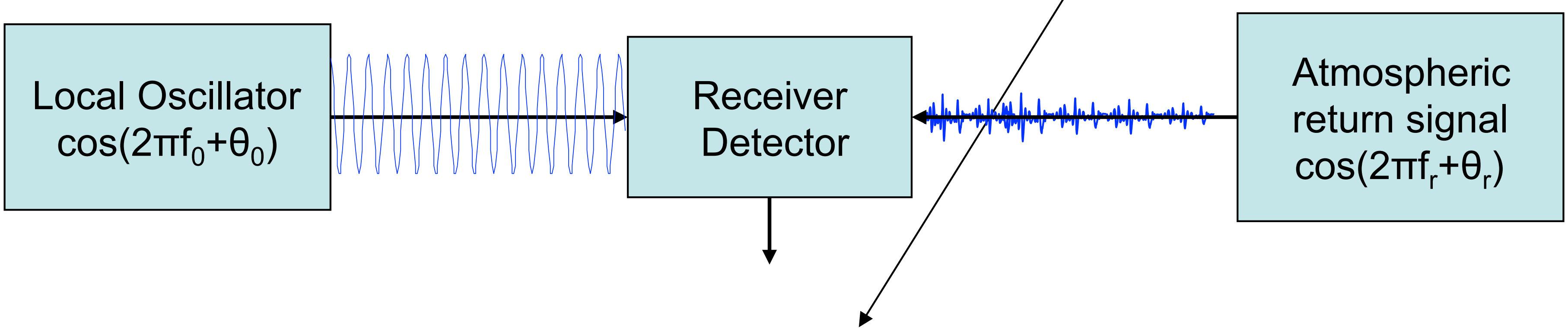


$$P_{sig} = P_a + P_{LO} + 2\sqrt{P_a P_{LO}} \cos\left(j2\pi\left(f_a - f_{LO}\right)t + \left(\varphi_a - \varphi_{LO}\right)\right)$$

Coherent Detection

The detector current is then given by:

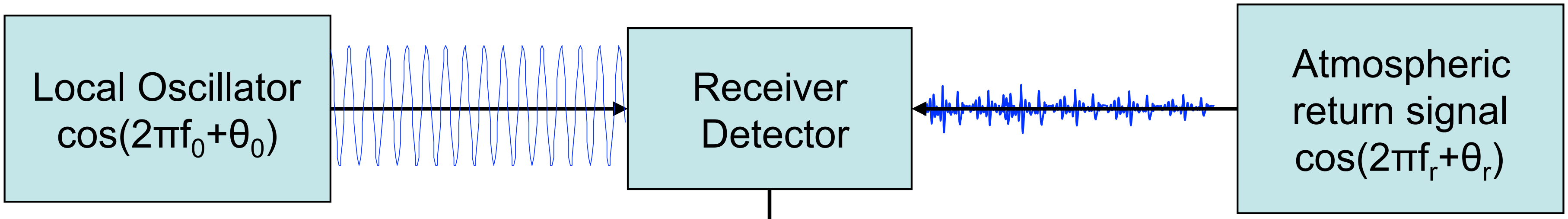
$$i_{sig} = \left(\frac{\eta e P_{sig}}{h\upsilon}\right) = i_a + i_{LO} + 2\sqrt{i_a i_{LO}}\cos\left(j2\pi\left(f_a - f_{LO}\right)t + \left(\varphi_a - \varphi_{LO}\right)\right)$$



Remember $f_a - f_{LO} = f_{Dopp} + f_{offse} \sim$ MHz

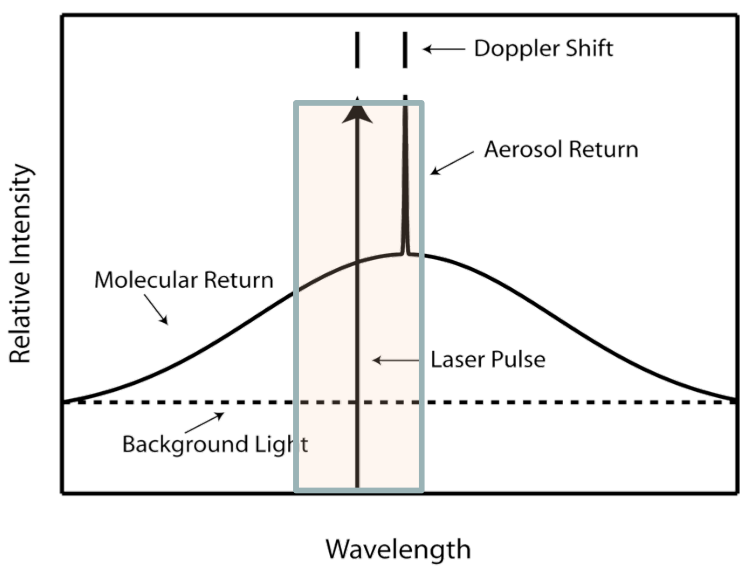
We know f_{offset}…so we can find the Doppler shift frequency.

Coherent Detection



$$f_{detected} = f_a - f_{LO} = f_{Dopp} + f_{offset} \sim \text{MHz}$$

We assume that f_{LO} is the same at 20+km (or 66.7 μs – at least) as it was when we sent the pulse out – Not always true for UV sources



Rayleigh vs. Mie scattering

Also consider the spread of frequencies in the return signal – f_{Dopp} is **not** a single frequency.

Spectrum of f_{Dopp} is a function of transmitted pulse spectrum and atmospheric turbulence

Optical and bandpass filters limit background light and shot noise

- Coherent Detection
- Laser & pulses
- Transmit/Receive path
- Atmosphere
- Detection & Processing
- Analysis and Data products
- Field Work

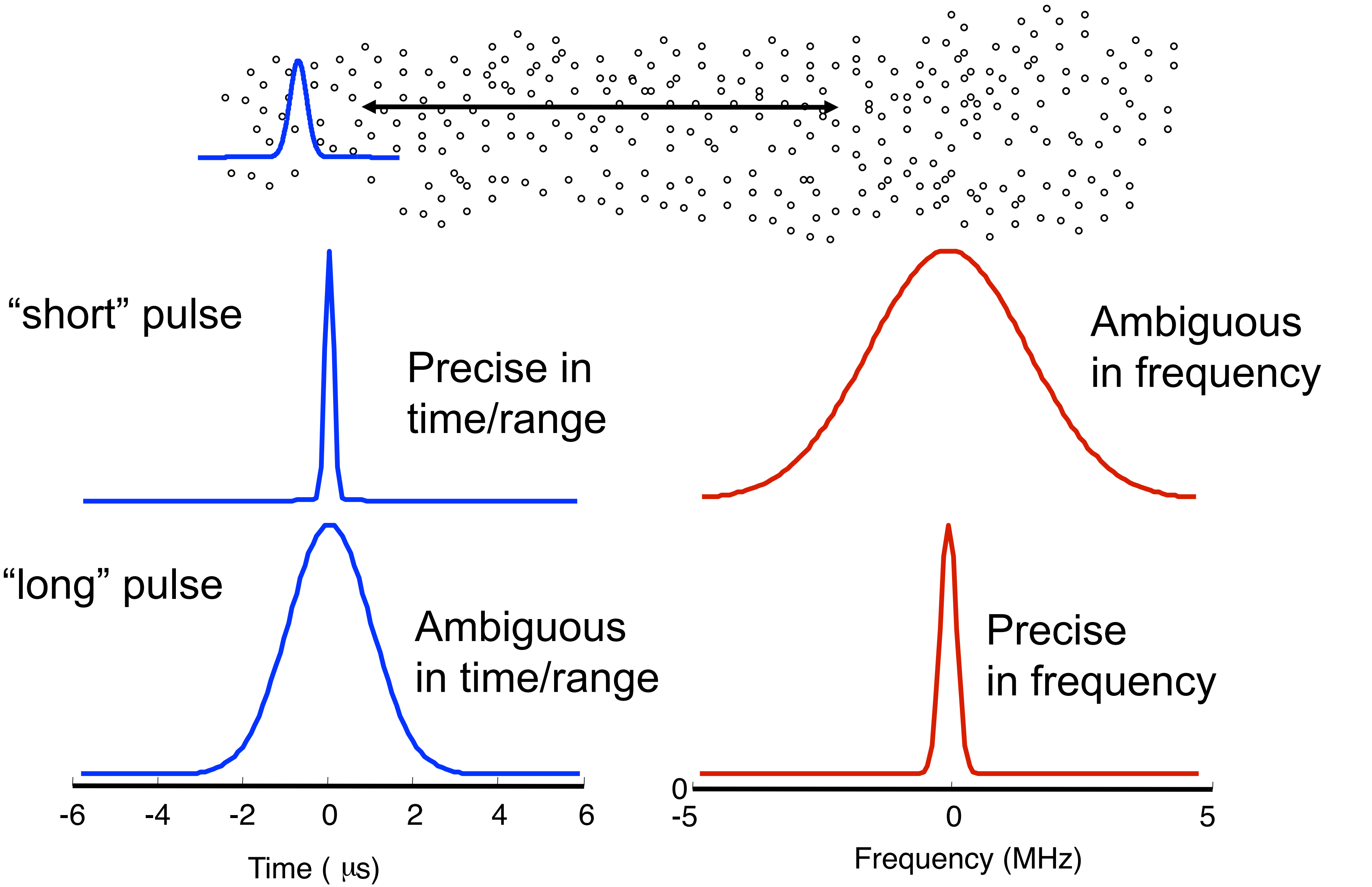
Laser & Pulses
Ideal Laser/Transmitter Requirements

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

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

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

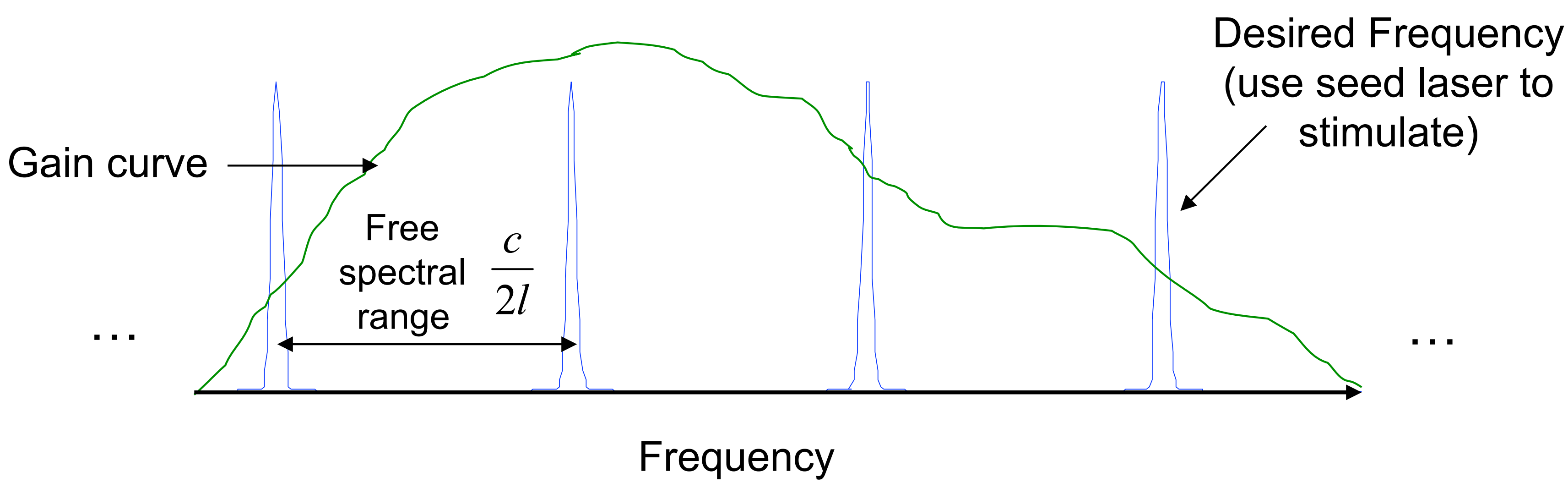
Laser & Pulses
Time-bandwidth tradeoffs



How are the pulses created?

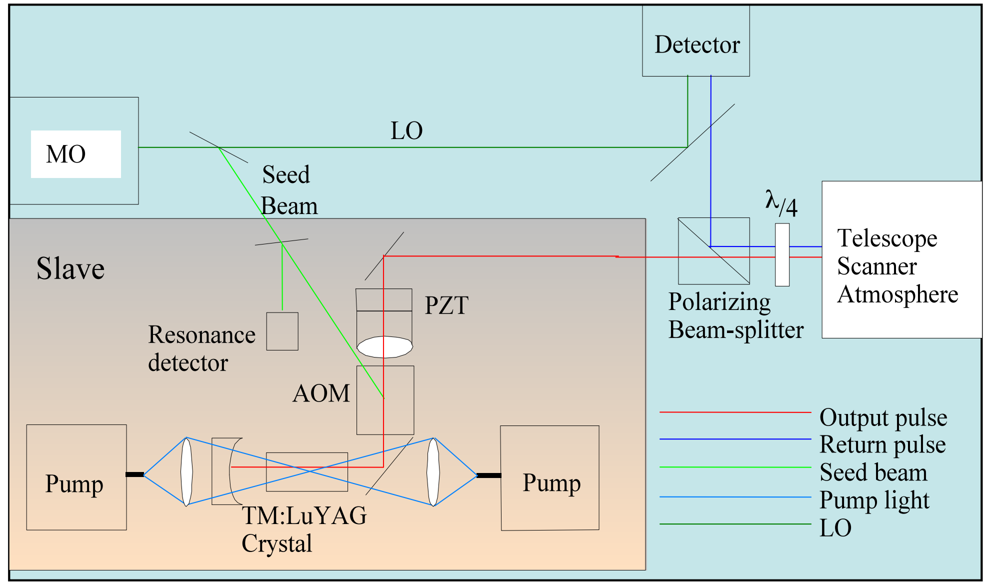
Transmitter frequency stabilization; Use same laser for injection seeding and LO

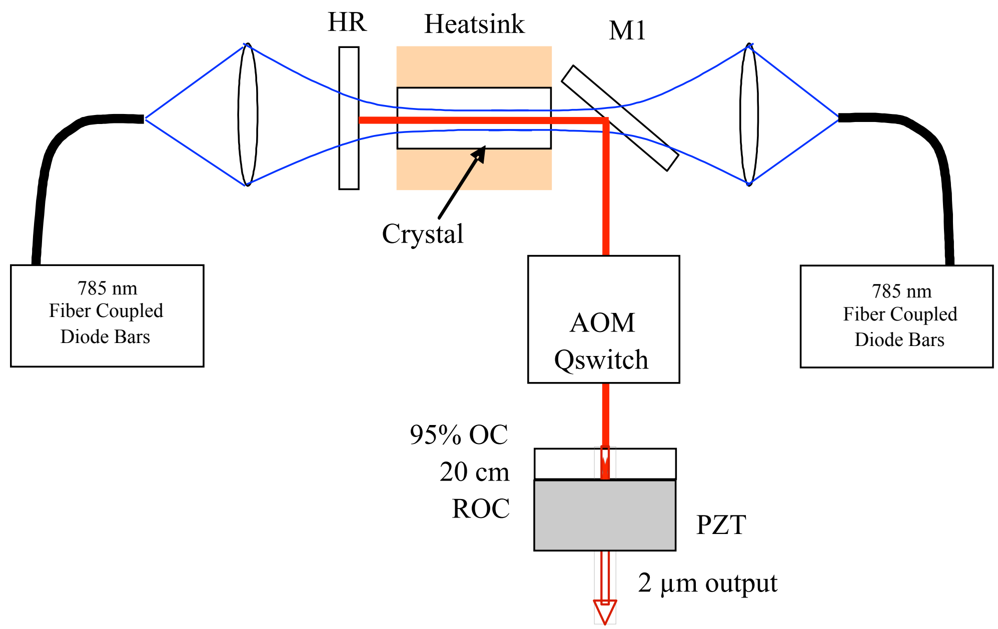
- Continuous wave – always available for heterodyne detection of return pulses from the atmosphere.
- Stable – especially over pulse separation times.
- Need a way to shift the frequency of the pulses relative to the LO (or the other way around) – we use AOMs for this.
- Sometimes the same source as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



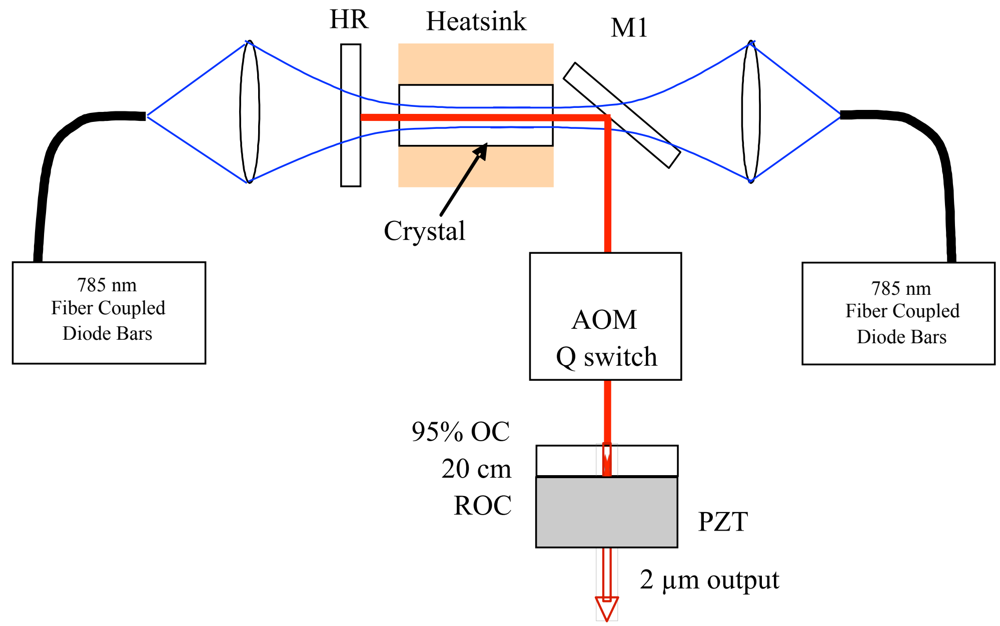
Laser & Pulses: High Resolution Doppler Lidar (HRDL)

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

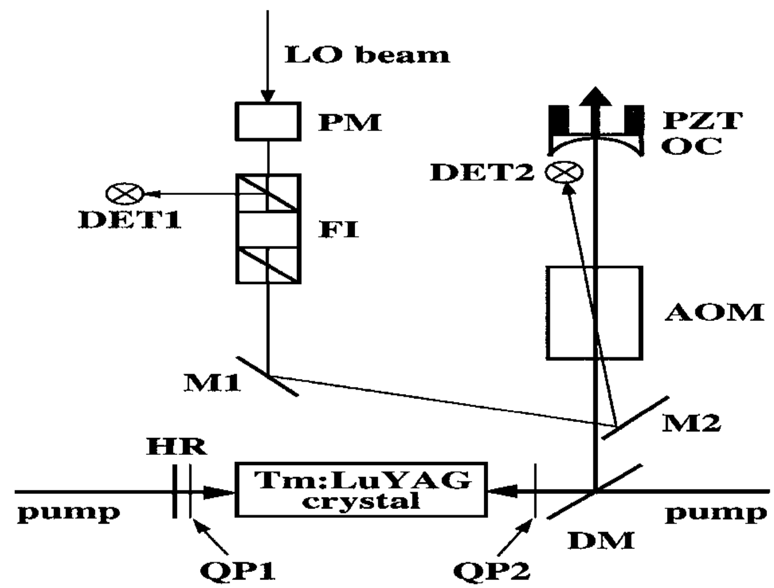


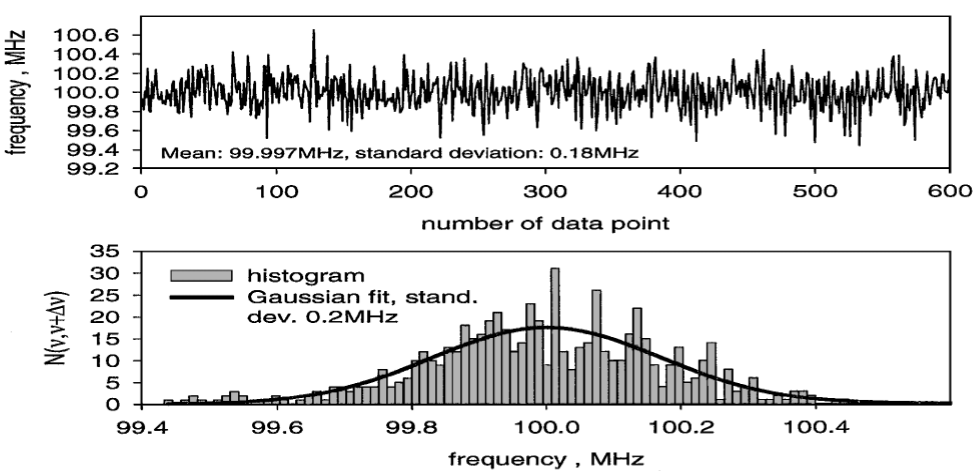


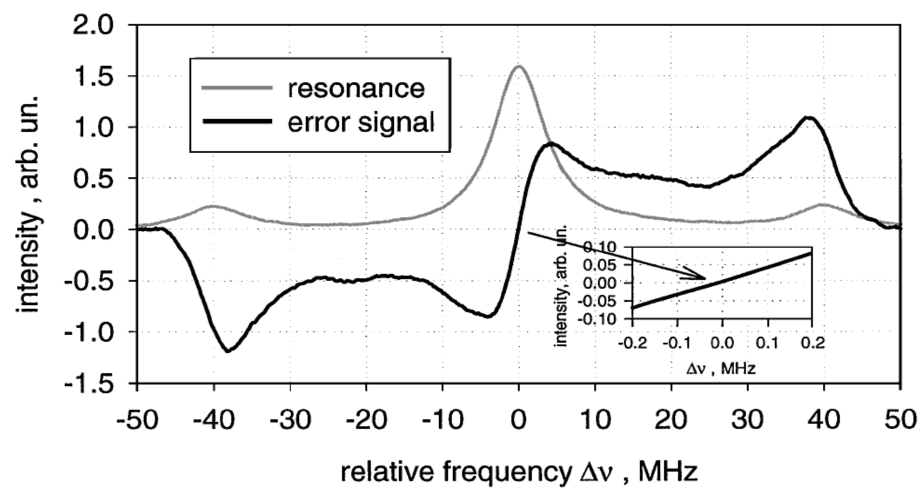
HRDL Frequency Stabilization



Pound-Drever-Hall Stabilization

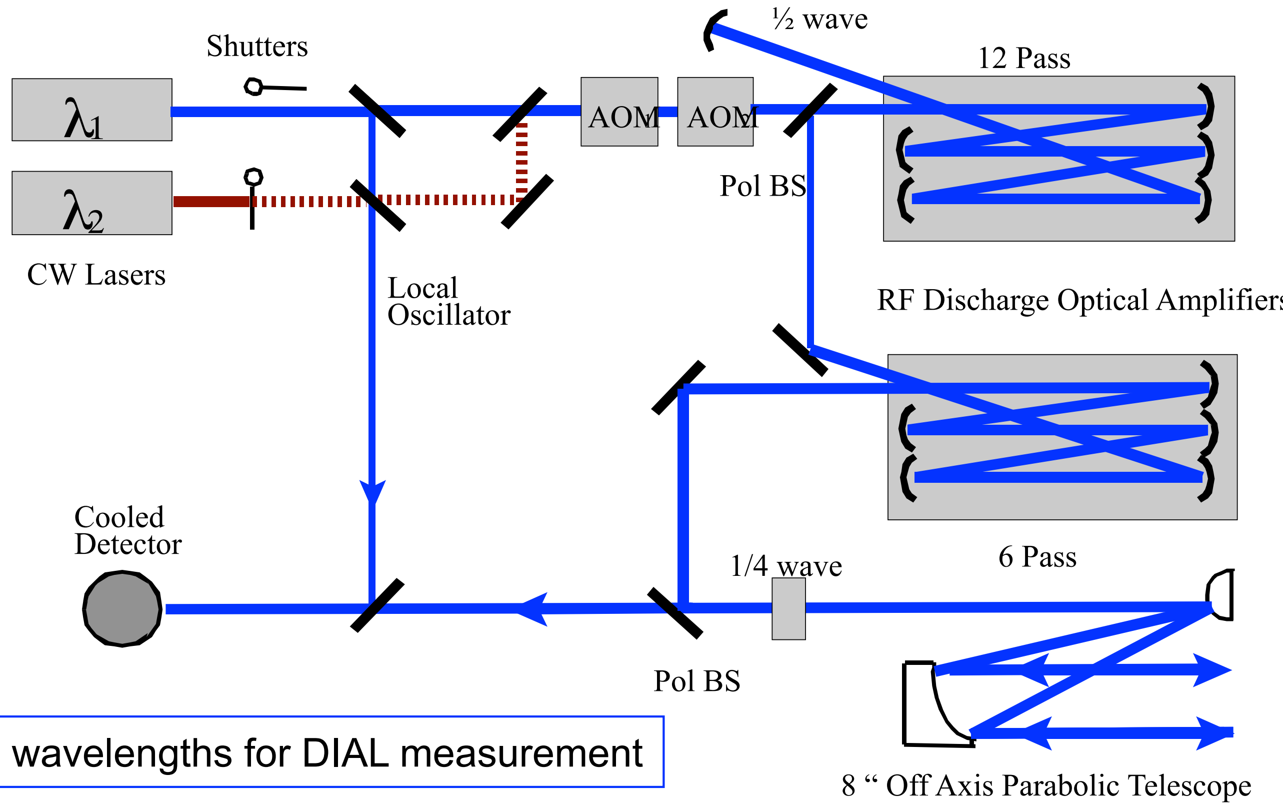






Wulfmeyer et al, Opt. Lett. 25 1228-1230

Laser & Pulses Mini-MOPA (master-oscillator/ power-amplifier)

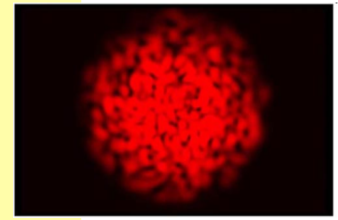


Can also alternate between two wavelengths for DIAL measurement

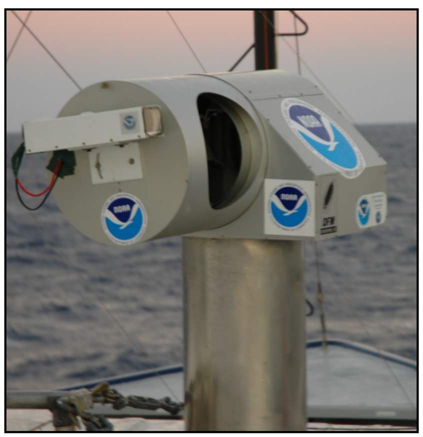
Wavelength	9-11 micron
Pulse Energy	0.5-2 mJ
PRF	300 Hz
Max Range	18 km
Range Resolution	45-300 m
Scanning	Full Hemispheric
Precision	10 cm/s

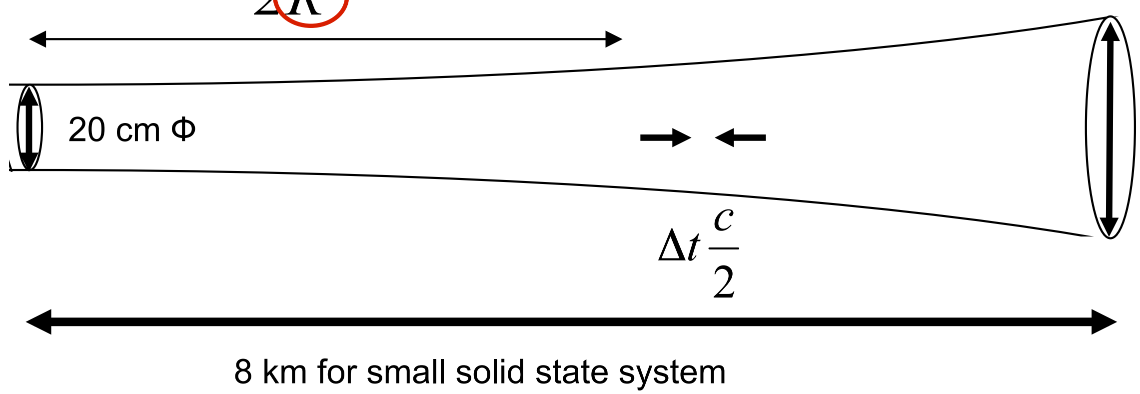
Spatial Coherence

- Want maximum spatial coherence (large speckle size) at the receiver for best mixing efficiency
- Aerosol target in the atmosphere looks like a partially coherent source at the receiver
- To maximize transverse coherence the area illuminated at the target should be as small as possible (Van Cittert – Zernike Theorem)
- To minimize bandwidth, pulse must be temporally coherent



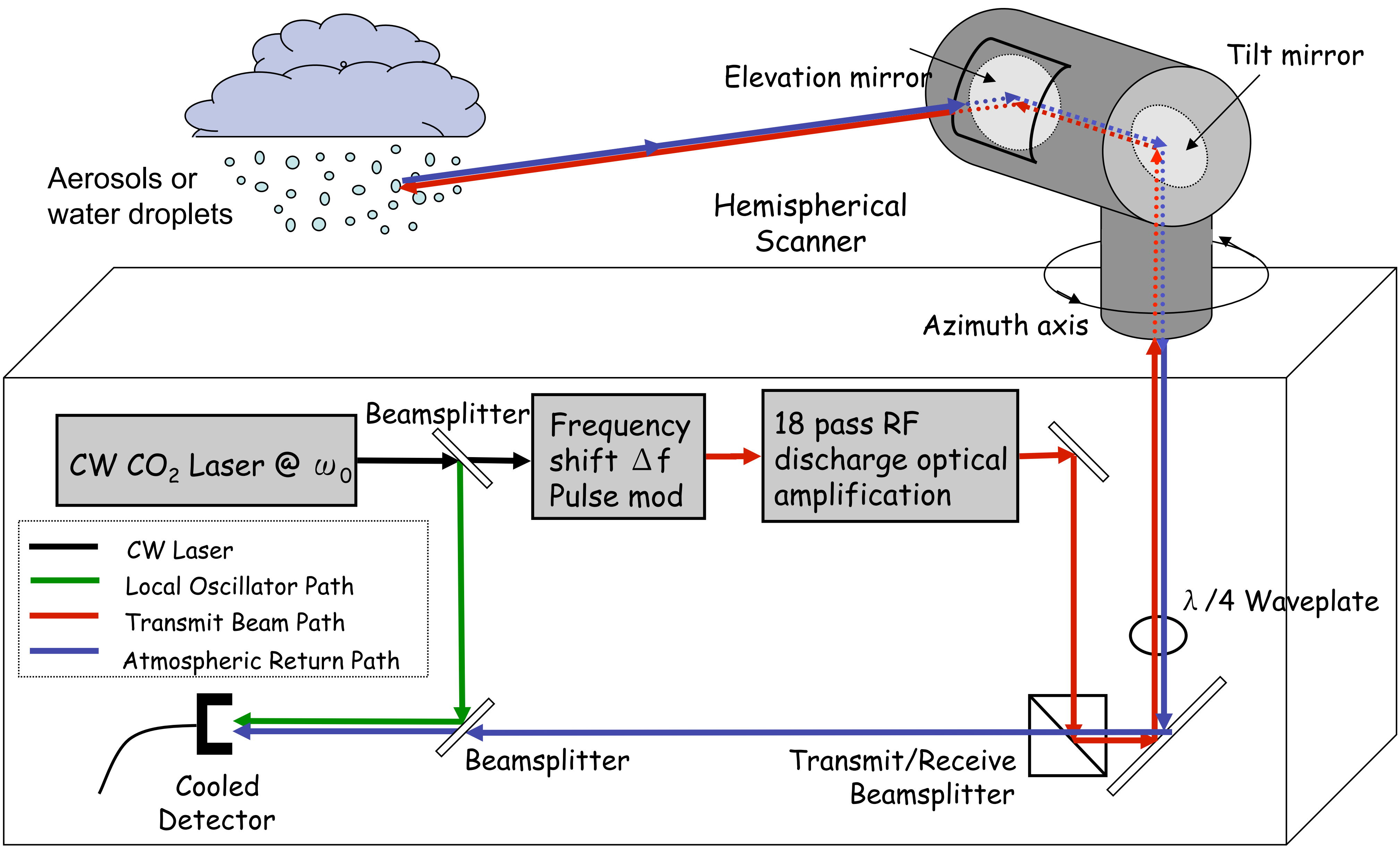
$$P_r = \frac{A_{eff}\beta T^2}{2R^2} cE_T$$



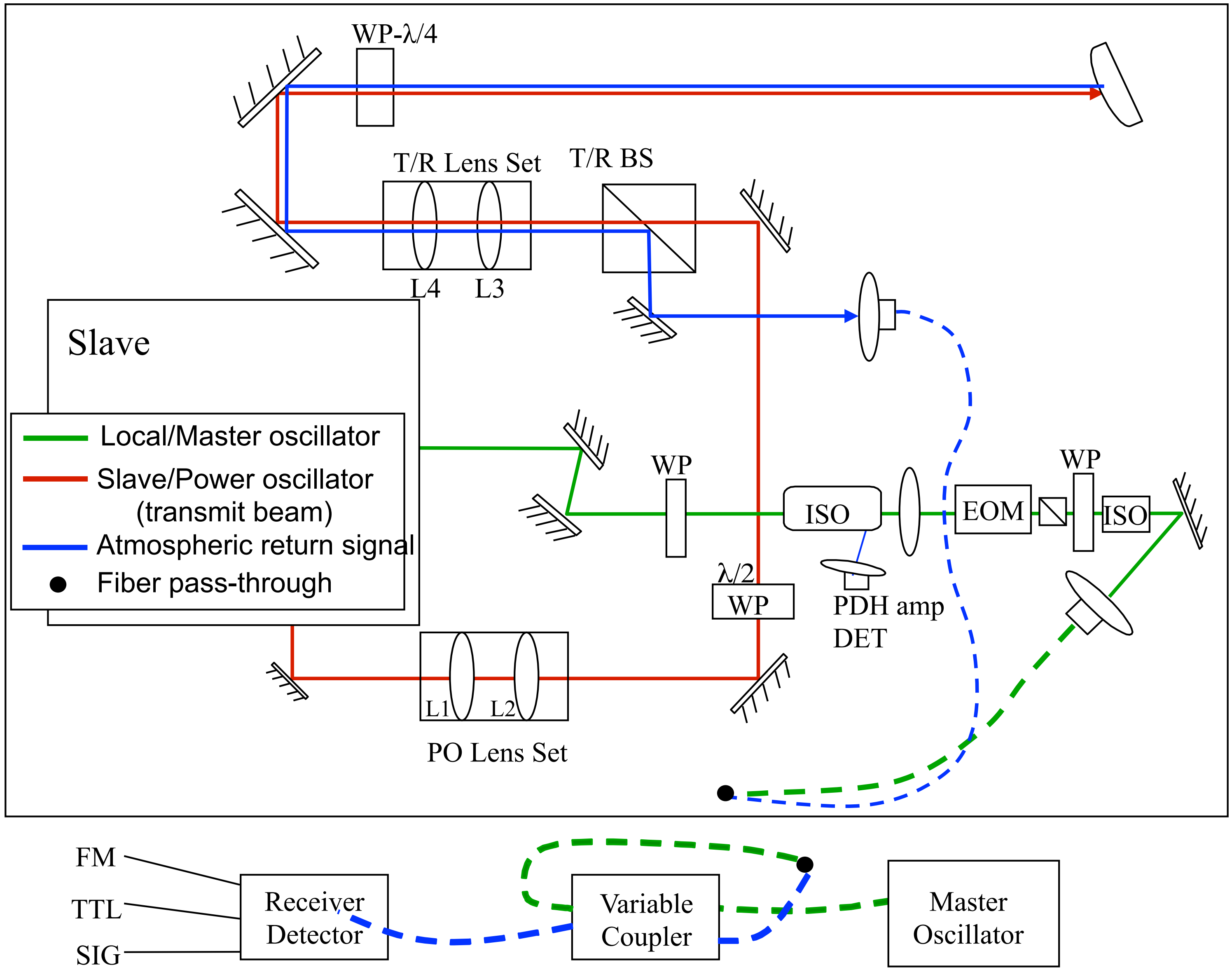


- Coherent Detection
- Laser
- **Transmit/Receive paths**
- Atmosphere
- Detection & Processing
- Analysis and Data products
- Field Work

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



High Resolution Doppler Lidar (HRDL) system

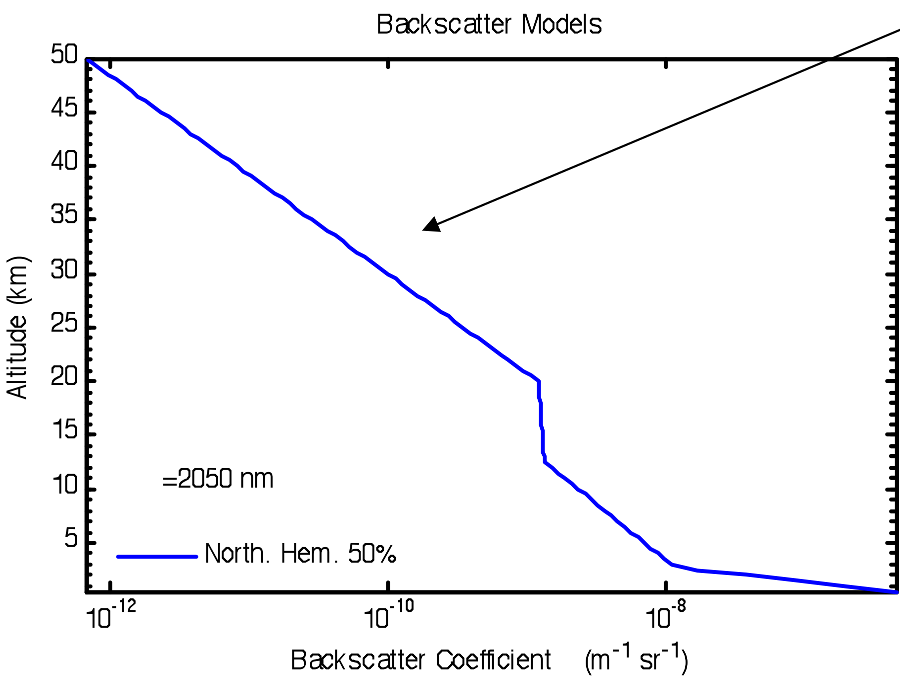


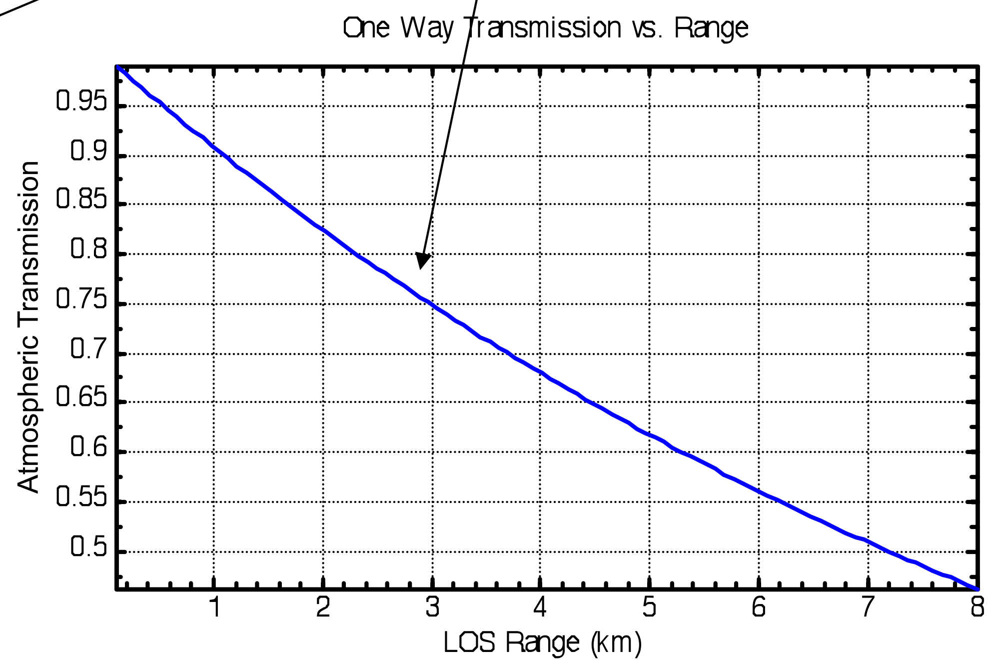
- Coherent Detection
- Laser
- Transmit/Receive paths
- **Atmosphere**
- Detection & Processing
- Analysis and Data products
- Field Work

Atmospheric Return

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

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





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 (6.626x10^{-34} Joule-sec)
- *v* 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.

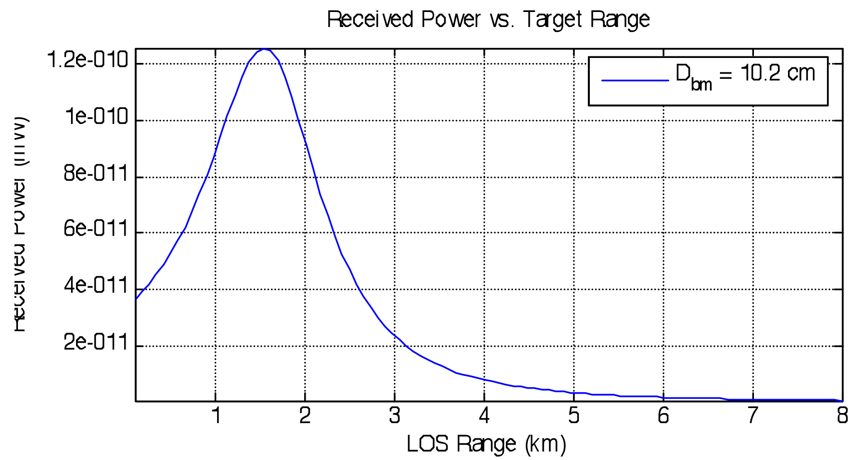
The Coherent Doppler Lidar Equation, cont'd

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)
- β = 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

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

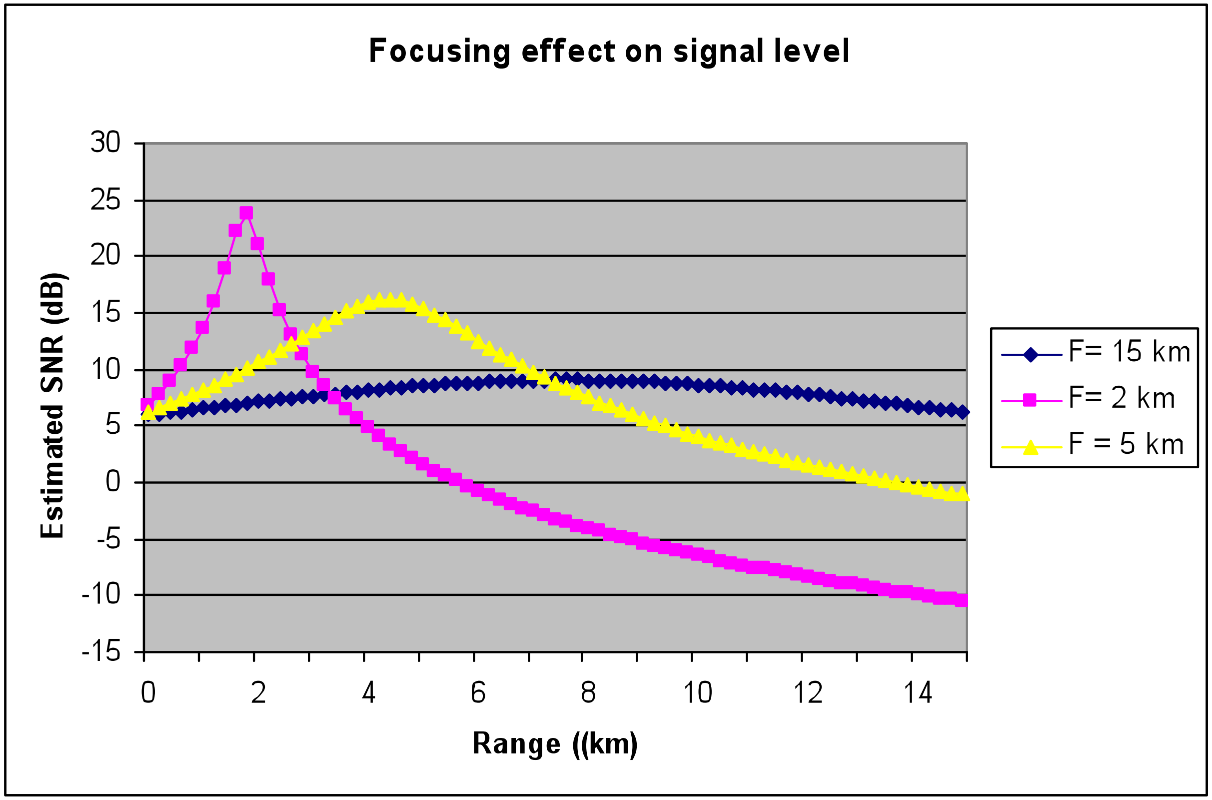
D_b is the transmitted, $1/e^2$ intensity, untruncated, Gaussian beam diameter in meters, F is the focus of the transmitter optics.

Thus A_{eff} is defined by

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

Focusing effects in coherent lidar

- Must choose system focus based on sensitivity threshold
- Many low energy systems operate near threshold so this is an important design issue



Received power

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

Effective receiver area

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

The Coherent Doppler Lidar Equation, cont'd

The turbulence parameter ρ_0 is given by

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

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

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

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

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

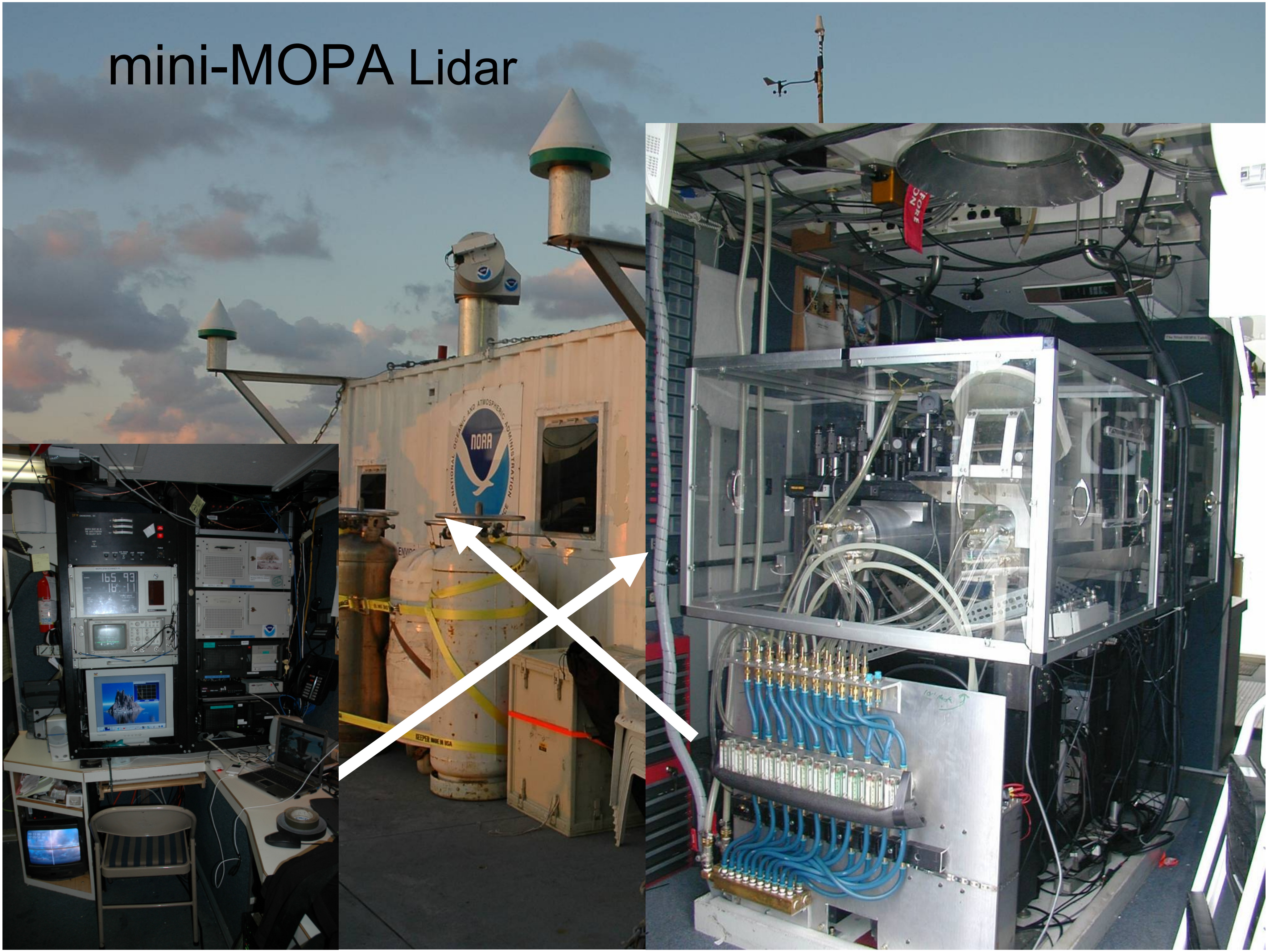
If the focus is at the range of interest, and if there is no turbulence, the CNR equation reduces to:

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

Next lecture…

- Coherent Detection
- Laser
- Transmit/Receive paths
- Atmosphere
- Detection & Processing
- Analysis and Data products
- Field Work

mini-MOPA Lidar



Coherent Doppler Lidar: Return Power

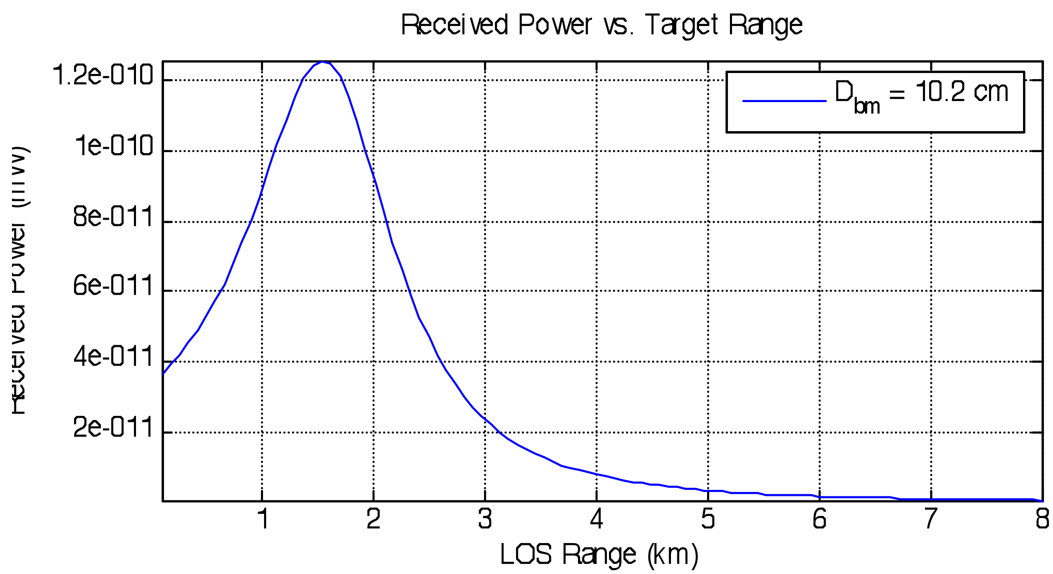
The received power, P_r is theoretically given by

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

- P_T = Transmitted laser power (Watts) for wavelength λ, range *R* and time *t*.
- *R* = range (meters)
- β = 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*.

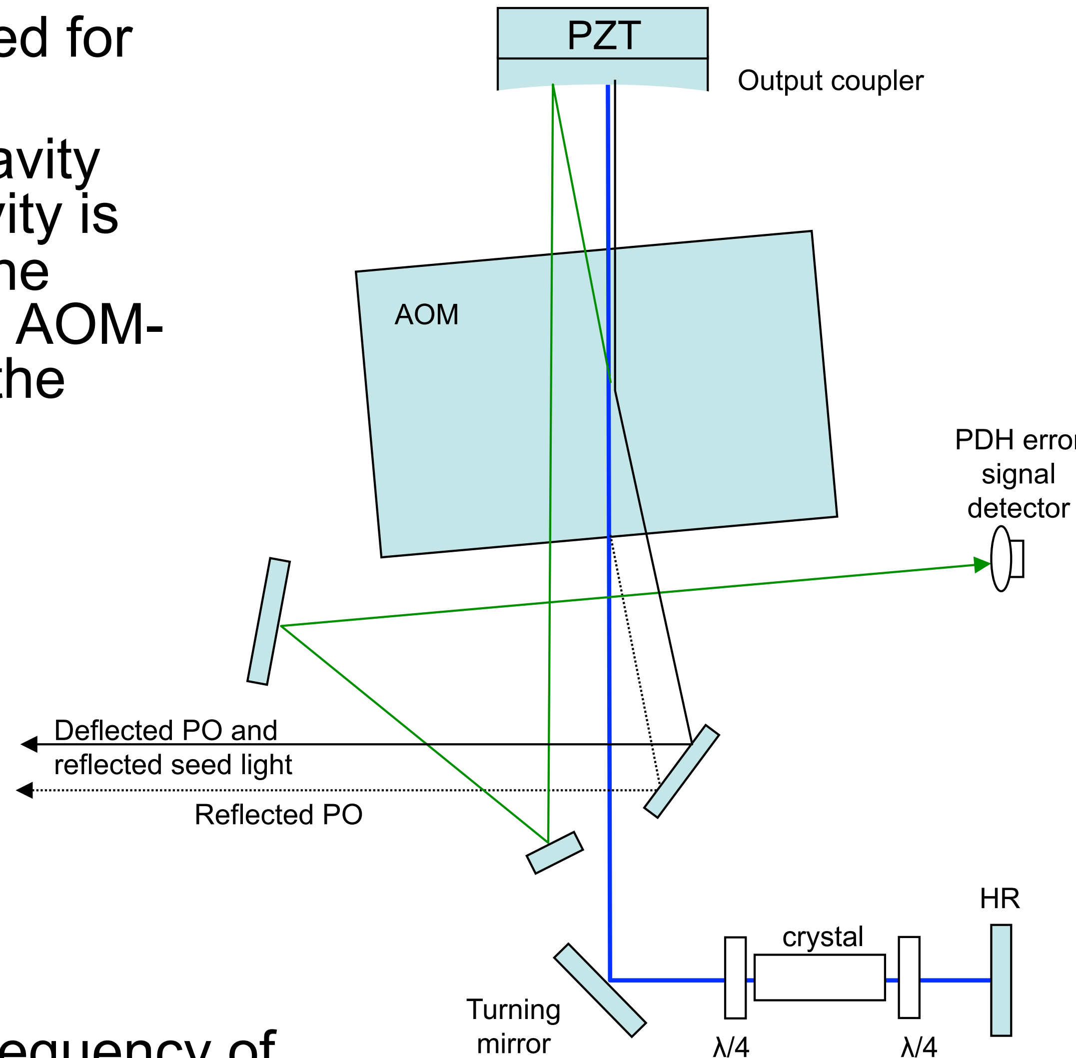
For aerosol targets distributed in range (relative to the pulse length) the received power at the lidar P_r can be approximated as

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



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.



IR vs. UV in heterodyne detection

Property	**IR**	**UV**
Linewidth/ Temporal Coherence	kHz → 10s of km and longer (100 km)	Old: GHz → meters New: MHz → 100's m
Scattering/BW	Mie – pulse transform limited	Rayleigh (very wide) & Mie
Detection noise	Shot noise limited by LO power	LO Shot noise + Rayleigh scattering
Aerosol sampling BW (SNR $\propto$1/BW) $\Delta f = \frac{2v}{\lambda}$	2µm: 25 m/s needs 50 MHz BW	355nm: 25 m/s needs ~300 MHz
Refractive Turbulence	Some effect (less for longer λ)	Stronger effect (less spatial coherence)