Optical Remote Sensing with Coherent Doppler Lidar

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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 received power, $P_r$ is theoretically given by

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

$P_T = $ Transmitted laser power (Watts) for wavelength $\lambda$, range $R$ and time $t$,
- $R =$ range (meters)
- $\beta =$ aerosol backscatter coefficient ($\text{m}^{-1} \text{sr}^{-1}$),
- $T =$ one-way atmospheric transmission.
- $A_{\text{eff}}$ 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

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

\[ P_r = \frac{A_{\text{eff}} \beta T^2}{2R^2} cE_T \]

\[
\Delta t \frac{c}{2}
\]

20 cm Φ

8 km
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 $\lambda$ is given by:

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

Where $\nu$ is the velocity of the aerosol(s) (e.g. wind speed) and $\theta_v$ 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 2$\mu$m light ($f_{Dopp} = 1.5 \times 10^{14}$ Hz) is 15 MHz.

- The returning illumination has a frequency of

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

- 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:

\[ E_a = A_a \cos(j2\pi f_a t + \varphi_a) \]
\[ E_{LO} = A_{LO} \cos(j2\pi f_{LO} t + \varphi_{LO}) \]
\[ E_{tot} = A_a \cos(j2\pi f_a t + \varphi_a) + A_{LO} \cos(j2\pi f_{LO} t + \varphi_{LO}) \]
The detector actually “sees” optical power or:

\[
|E_{\text{tot}}|^2 = |A_a \cos(j2\pi f_a t + \varphi_a) + A_{\text{LO}} \cos(j2\pi f_{\text{LO}} t + \varphi_{\text{LO}})|^2 \\
= A_a^2 |\cos(j2\pi f_a t + \varphi_a)|^2 + A_{\text{LO}}^2 |\cos(j2\pi f_{\text{LO}} t + \varphi_{\text{LO}})|^2 \\
+ 2A_a A_{\text{LO}} \cos(j2\pi f_a t + \varphi_a) \cos(j2\pi f_{\text{LO}} t + \varphi_{\text{LO}}) \\
\]

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

\[
|E_{\text{tot}}|^2 = A_a^2 |\cos(j2\pi f_a t + \varphi_a)|^2 + A_{\text{LO}}^2 |\cos(j2\pi f_{\text{LO}} t + \varphi_{\text{LO}})|^2 \\
+ 2A_a A_{\text{LO}} \cos(j2\pi f_a t + \varphi_a) \cos(j2\pi f_{\text{LO}} t + \varphi_{\text{LO}}) \\
+ 2A_a A_{\text{LO}} \cos(j2\pi (f_a + f_{\text{LO}}) t + (\varphi_a + \varphi_{\text{LO}})) \\
+ 2A_a A_{\text{LO}} \cos(j2\pi (f_a - f_{\text{LO}}) t + (\varphi_a - \varphi_{\text{LO}}))
\]
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:

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

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

$$P_{sig} = P_a + P_{LO} + 2\sqrt{P_a P_{LO}} \cos(j2\pi (f_a - f_{LO})t + (\varphi_a - \varphi_{LO}))$$
The detector current is then given by:

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

Remember \( f_a - f_{\text{LO}} = f_{\text{Dopp}} + f_{\text{offset}} \sim \text{Mhz} \)

We know \( f_{\text{offset}} \)...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....
Laser & Pulses
Time-bandwidth tradeoffs

“short” pulse
Precise in time/range
Ambiguous in frequency

“long” pulse
Ambiguous in time/range
Precise in frequency

How are the pulses created?
Laser & Pulses
Mini-MOPA (master-oscillator/power-amplifier)

Can also alternate between two wavelengths for DIAL measurement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>9-11 micron</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>0.5-2 mJ</td>
</tr>
<tr>
<td>PRF</td>
<td>300 Hz</td>
</tr>
<tr>
<td>Max Range</td>
<td>18 km</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>45-300 m</td>
</tr>
<tr>
<td>Scanning</td>
<td>Full Hemispheric</td>
</tr>
<tr>
<td>Precision</td>
<td>10 cm/s</td>
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Laser & Pulses: High Resolution Doppler Lidar (HRDL)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>2.02 micron</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>2 mJ</td>
</tr>
<tr>
<td>PRF</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Max Range</td>
<td>3-8 km</td>
</tr>
<tr>
<td>Range Res.</td>
<td>30 m</td>
</tr>
<tr>
<td>Beam rate</td>
<td>2 Hz</td>
</tr>
<tr>
<td>Scanning</td>
<td>Full Hemispheric</td>
</tr>
<tr>
<td>Precision</td>
<td>10 cm/s</td>
</tr>
</tbody>
</table>

Detector:
- LO pump
- TM:LuYAG crystal
- AOM
- PZT
- Seed beam
- Resonance detector
- Output pulse
- Return pulse
- Seed beam
- Pump light
- LO

Telescope Scanner Atmosphere

Laser & Pulses: HRDL

785 nm Fiber Coupled Diode Bars

AOM Qswitch

95% OC 20 cm ROC

PZT 2 µm output

HR Heatsink

M1

Crystal

Atmosphere

Slave

Seed Beam

PZT

785 nm Fiber Coupled Diode Bars

Telescope Scanner

Atmosphere

Output pulse

Return pulse

Seed beam

Pump light

LO
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.

![Diagram showing gain curve and frequency range](image-url)
• 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

MW CO₂ Laser @ \( \omega_0 \)
Frequency shift \( \Delta f \)
Pulse mod
18 pass RF discharge optical amplification

Cooled Detector

Transmit/Receive Beamsplitter

\( \lambda/4 \) Waveplate

Aerosols or water droplets

Hemispherical Scanner

Elevation mirror

Tilt mirror

Azimuth axis

CW Laser
Local Oscillator Path
Transmit Beam Path
Atmospheric Return Path
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.

\[ P_r = \frac{A_{\text{eff}} \beta T^2}{2R^2} cE_T \]

$\lambda = 2050$ nm

![Graph showing atmospheric transmission vs. range and backscatter models.](image)
Return signal processing

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>2.05 microns</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>5 mJ</td>
</tr>
<tr>
<td>Receiver Aperture Diameter</td>
<td>9 cm</td>
</tr>
<tr>
<td>PRF</td>
<td>80 Hz</td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Search bandwidth</td>
<td>50 MHz</td>
</tr>
<tr>
<td>Points per gate</td>
<td>64</td>
</tr>
<tr>
<td>Gate Width</td>
<td>96 meters</td>
</tr>
<tr>
<td># pts in FFT</td>
<td>256</td>
</tr>
<tr>
<td># bins in signal BW</td>
<td>11 = 4.3 MHz</td>
</tr>
<tr>
<td># bins in search BW</td>
<td>128 = 50 MHz</td>
</tr>
</tbody>
</table>
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 $\Delta f$. 
The velocity corresponding to the peak frequency is given by:

\[ \nu = \frac{2}{\Delta f \lambda} \]

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

This range gate is after the hard target. For these ranges, the CNR estimate actually reflects a signal bandwidth worth of noise (around the peak noise frequency) ratio, rather than a carrier signal to noise ratio.
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.
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: Whitenened & Averaged spectra for different range gates

Note difference in how the “peak” is chosen after whitening when there is no signal present.
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
• 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

\[ \sigma_v(\tau) \text{ vs } \text{CNR}(\tau), \text{ 0.5 sec. avg.} \]

- 300 ns/45 m
- 400 ns/60 m
- 500 ns/75 m
- 600 ns/90 m
- 1 \mu s/150 m

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

![Turbulence at shear layer](image.png)
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
Chemical distributions (ozone, water vapor, NH3, CO2)
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
The carrier-to-noise ratio (CNR) is found using the following equation:

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

- where $\eta$ is an efficiency factor (less than or equal to unity) describing the noise sources in the photo-detect or signal as well as optical efficiencies,
- $h$ is Plank’s constant (6.626x10^{-34} Joule-sec)
- $\nu$ 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 received power, $P_r$ is theoretically given by

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

$P_T$ = Transmitted laser power (Watts) for wavelength $\lambda$, range $R$ and time $t$,
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- $A_{\text{eff}}$ 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

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

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

Where \(A_{\text{turb}}\) is the coherence area defined by \(\pi \rho_0\).

\(A_{\text{TR}}\) is the transmit/receive area defined by

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

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

Thus \(A_{\text{eff}}\) is defined by

\[
A_{\text{eff}} = \frac{\pi D^2}{4} \left[ 1 + \left( \frac{\pi D^2}{4 \lambda R} \right)^2 \left( \frac{1}{F} - \frac{R}{F} \right)^2 + \frac{D^2}{2 \rho_o^2} \right]^{-1}
\]
The Coherent Doppler Lidar Equation, cont’d

The turbulence parameter $\rho_0$ 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 $1 \times 10^{-16}$ (calm) to $3 \times 10^{-13}$ (quite turbulent)
The Coherent Doppler Lidar Equation, cont’d

The CNR equation can be written explicitly as

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

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

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

The Wideband CNR is then calculated as follows:

\[
P_{\text{sig}} = \sum_{i \in \text{SignalBW}} f_{\text{sig}}(i)
\]

\[
\text{CNR}_{wb} = \frac{P_{f_{\text{sig}}} - N_{wb} P_{ns}}{N_{wb} P_{ns}}
\]

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