Lecture 11: Doppler wind lidar
Why do we study winds?

- Winds are the most important variable studying dynamics and transport in the atmosphere.
- Wind measurements are critical to improvement of numerical weather prediction models.
- They can be used to study planetary atmospheric dynamics.
- Commercial and military aircraft would benefit from clear air wind shear detection as well.
Doppler (Shift) Wind Technique:

Doppler Shift is the apparent frequency change of radiation perceived or emitted by a particle moving relative to the source or receiver of the radiation, compared to when particle at rest.

If the frequency change can be measured, the relative velocity of the source with respect to the receiver can be determined. Note: the directly measured speed is the velocity component along the line of sight of the radiation beam, i.e., the radial velocity.

(1) Coherent (Heterodyne) Detection Doppler Wind Lidar
(2) Direct Detection Doppler Wind Lidar
Coherent Detection Doppler Wind

- **Basic Principle:** the return signal is optically mixed with a local oscillator laser, and the resulting beat signal has the frequency (except for a fixed offset) equal to the Doppler shift due to the moving particles.

- More accurately, the Coherent Detection Doppler Wind lidar should be called "Heterodyne" Detection Doppler Wind lidar.

![Diagram](image)

**Fig. 12.6.** Principle of a heterodyne-detection Doppler lidar.

LO: Local Oscillator; TE: pulsed laser transmitter; LL: Locking Loop
Coherent Detection Doppler Wind

The local oscillator laser has a frequency of $f_{\text{LO}}$.
The pulsed transmitter has a frequency of $f_0 = f_{\text{LO}} + f_{\text{offset}}$.
The return signal (Doppler shifted) has a freq of $f_{\text{Sig}} = f_0 + \Delta f$.

- The optical mixing results in frequencies of $|f_{\text{LO}} \pm f_{\text{Sig}}|$, i.e., sum frequency and beat frequency.
- The sum frequency is well above the frequency cutoff of the detector, but the beat frequency is a low-frequency signal that can be determined with high accuracy.

$$f_{\text{beat}} = |f_{\text{LO}} - f_{\text{Sig}}| = \Delta f + f_{\text{offset}}$$

- Aerosol scattering signal is utilized, owing to its narrow bandwidth and strong signals.
- Accuracy: No bias in principle
- Precision: independent of the wind velocity
Direct Detection Doppler Wind

- **Principle:** no local oscillator is used. Instead, an optical frequency discriminator or spectrum analyzer is used to convert the Doppler frequency shift to a change in optical intensity or power, or to intensity/power spatial distribution, which is in turn directly detected.

- In these direct detection (or incoherent) lidar systems, the return optical signal is filtered or resolved into its spectral components prior to detection. Besides a narrowband lidar transmitter with stable frequency, the main efforts are placed onto the spectral resolved lidar receivers.

- The **optical frequency discriminators** include mainly three (or four) types
  1. Atomic absorption lines, like Na, K, and Fe Doppler lidar, using the resonance fluorescence from the entire line, not just the edge
  2. Edge-filters, like the transmission edge of a molecular absorption line (e.g., iodine I$_2$ absorption lines), or the edge of a transmission fringe of an optical interferometer (e.g., Fabry-Perot etalon)
  3. Fringe pattern imaging of the output of an optical interferometer.
Direction Detection Doppler Wind

- For resonance fluorescence Doppler lidar, the resonance fluorescence from atoms, e.g., Na, K, Fe, in the mesosphere and lower thermosphere is utilized. The atomic absorption lines act as natural frequency analyzers.
- Non-resonance direct detection Doppler lidars utilize aerosol scattering, or molecular scattering, or both.
- The main ideas are

  Intensity ratio (like in Na, K, and Fe Doppler lidar)
  \[ \Rightarrow \text{Frequency shift} \Rightarrow \text{radial velocity (LOS)} \]

  Intensity change (like in HSRL or some Rayleigh Doppler lidar)
  \[ \Rightarrow \text{Frequency shift} \Rightarrow \text{radial velocity (LOS)} \]

  Intensity spatial distribution (like in some Rayleigh Doppler lidar)
  \[ \Rightarrow \text{Frequency shift} \Rightarrow \text{radial velocity (LOS)} \]
The resonance fluorescence Doppler lidar is one kind of direct detection Doppler lidars (DDL). It has been covered in great details in previous lectures.

From intensity ratios (photon count ratios) to derive wind and temperature
Freq Analyzer: Single-Edge Filter

![Diagram of single-edge functional diagram and filter transmission.]

Figure 7.31 Single-edge functional diagram and filter transmission.

- A Fabry-Perot etalon or a molecular absorption line is usually employed as the edge filter. The etalon is locked to the zero-Doppler laser frequency, \( \nu_0 \), such that the frequency of the transmitted laser is matched to the mid-point of the quasi-linear transmission edge of the etalon.

- The intensity ratio of these two channels is a function of the Doppler frequency shift \( \nu_s \).

\[
S = \frac{I_1}{I_2} = \frac{\eta_{bs}}{1 - \eta_{bs}} \frac{R_1}{R_2} T_s = \frac{\eta_{bs}}{1 - \eta_{bs}} \frac{R_1}{R_2} (T_0 - T_m \nu_s / \Delta \nu)
\]
Fig. 7.32  Double-edge functional diagram and filter transmission.

- Two oppositely sloped quasi-linear discriminator edges are used for the two receiver channels in the double-edge design. Usually etalon transmission fringes are used to create the edges. The etalons are locked together (mid-point) to the zero-Doppler transmitted laser frequency $\nu_0$.

- The intensity ratio of the difference between the two signals to the sum is a sensitive function of the Doppler frequency shift $\nu_s$.

$$S = \frac{I_\Delta}{I_\Sigma} = \frac{I_1 - I_2}{I_1 + I_2} = \frac{T_{s_1} - T_{s_2}}{T_{s_1} + T_{s_2}} = \frac{2\nu_s}{\Delta \nu}$$
Doppler Lidar Wind Measurement Concept

Beam is Scanned to Provide 2-3D Spatial Coverage

Return Light is Doppler Shifted by Moving Aerosols

50-80 m pulse transmitted 500 times a second

Portion of Scattered Light Collected By Transmit/Receive Telescope

‘Pencil’ Beam Width 10-30 cm

Pulse Envelope (50-80 m)

Relative wind induces a Doppler frequency shift in the backscattered light; this frequency shift is detected by the sensor

Line of sight (LOS) velocity
Doppler Lidar Wind Measurement Concept

Backscattered Spectrum

Aerosol ($\lambda^{-2}$)

Molecular ($\lambda^{-4}$)

Frequency
**Figure 7.44** Simplified block diagram illustrating the key functionality of direct detection lidar systems. Most systems use a bistatic telescope arrangement (see text).
Transmitter

Laser: Nd:YAG with wavelength of 355nm or 266nm are produced by frequency-tripling and –quadrupling

However, at 266 nm, ozone extinction is high, limiting it to short-range applications. Most current DDL system use 355nm

Typical pulse durations are 5 to 20 nsec resulting in transform-limited spectral bandwidths of 100 to 30MHz FWHM at the fundamental 1064nm wavelength.
1. VAD (velocity-azimuth display)
a conical scan is carried out with the apex of the cone at the lidar scanner
2. DBS (Doppler beam swinging)
four measurements at azimuth-angle intervals of 90°, or three at 120°, or even two at right angles
should be sufficient, along with one measurement in the vertical.
VAD Technique

Fig. 12.9. Example of sine fitting of the radial wind velocity simulated with the use of the VAD technique.

If we fit this to a function of type

\[ v_r = a + b \cos(\theta - \theta_{\text{max}}) \]  \hspace{1cm} (12.10)

with offset \( a \), amplitude \( b \), and phase shift \( \theta_{\text{max}} \), we immediately get the three-dimensional wind vector

\[ u = (u, v, w) = (-b \sin \theta_{\text{max}} / \cos \varphi, -b \cos \theta_{\text{max}} / \cos \varphi, -a / \sin \varphi). \]  \hspace{1cm} (12.11)
DBS Technique

This Doppler beam swinging, or DBS, technique is faster and simpler both in the hardware and in the data evaluation algorithm, but lacks the goodness-of-fit information as a measure for the reliability of the results.

\[
\begin{align*}
    u &= -(v_r2 - v_r1 \sin \varphi)/\cos \varphi, \\
    v &= -(v_r3 - v_r1 \sin \varphi)/\cos \varphi, \quad \text{and} \\
    w &= -v_r1.
\end{align*}
\]
Fig. 1. Block diagram of the optical layout for a lidar when the edge technique is used. The normalized edge signal, the ratio of the detector outputs, is measured for the outgoing and backscattered laser signals for each pulse. BS’s, beam splitters; M1, M2, mirrors; AMP’s, amplifiers.
Because of two-way path in lidar remote sensing, the backscattered return signal is Doppler shifts twice by a moving scattering with speed of $v$:

$$\Delta v = \left(\frac{2v}{\lambda}\right)$$

The Doppler shift is determined from a differential measurement of the frequency of the outgoing laser pulse and the laser return backscattered from the atmosphere.
A small fraction of the laser signal is picked off from the outgoing beam. This laser signal is split between an edge filter detector (DET 2) and an energy monitor detector (DET 1).

The backscattered photons are also split between the edge filter and the energy monitor detectors.
Receiver (double-edge)
The aerosol spectrum corresponds to Doppler shifts from Brownian motion of aerosol particles and has a width of 0.7 kHz to 0.7 MHz for aerosol particles with radii from 0.01 to 1 mm.

The edge filter width is approximately 50-100 MHz.
Double-edge for molecular backscattering

The two edge filter channels (labeled ‘Edge 1’ and ‘Edge 2’) are located in the wings of the molecular broadened spectrum at a position which has equal sensitivity to Doppler shifts for molecular backscattered signal.

molecular-scattered spectrum (~3.3 to 4GHz FWHM)

Free Spectral Range (FSR) of edge filter is ~12GHz

The reference channel (‘Locking Filter’) is located such that the outgoing laser frequency appears on the edge of the ‘Locking’ fringe.

Monitoring the outgoing laser frequency actively ‘lock’ the etalon to the laser frequency to maintain the symmetric arrangement of the filters about the outgoing laser frequency.
Spectral Resolution Requirements

Molecular backscattering:
1. For $\lambda = 355\text{nm}$, a Fabry–Perot etalon with a plate separation, $d$, of order 12.5mm, and with an overall finesse of order 6 to 8.

2. To ensure that there is no spectral wrapping (or aliasing) of the molecular signal through the different orders of the etalon
   
   $\text{FSR} = \frac{c}{2d} = \sim 12\text{GHz}$

3. The finesse ($\mathcal{F}$) of 7 to 8 results in a resolution, $\Delta v = \frac{\text{FSR}}{\mathcal{F}}$ or approximately 1.6GHz FWHM, which sufficiently resolves the 3.3 to 4GHz FWHM molecular spectrum

Aerosol backscattering:
1. significantly higher spectral resolution is required to properly resolve the narrow aerosol signal spectral width (following the laser width).
2. A Fabry–Perot etalon of plate separation, $d$, of order 70mm and finesse ($\mathcal{I}$) of order 40 or higher. This 2.1GHz FSR etalon provides a resolution $\Delta n$ of about 50 MHz.
<table>
<thead>
<tr>
<th>Requirements</th>
<th>Aerosol Channel</th>
<th>Molecular Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technique</td>
<td>Fringe imaging</td>
<td>Fringe image (FI) or double edge (DE)</td>
</tr>
<tr>
<td>Number of subpupils</td>
<td>1</td>
<td>1 (FI); 3 (DE)</td>
</tr>
<tr>
<td>Working aperture of etalon subpupil</td>
<td>40 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Acceptance angle</td>
<td>$\pm 2.2 \text{ mrad}$ for FI</td>
<td>$\pm 1.9/5.3 \text{ mrad}$ (DE/FI)</td>
</tr>
<tr>
<td>Optical path difference</td>
<td>70 mm</td>
<td>12.5 mm</td>
</tr>
<tr>
<td>Free spectral range</td>
<td>2.1 GHz</td>
<td>12.0 GHz</td>
</tr>
<tr>
<td>Plate flatness before Coating (at $\lambda = 355 \text{ nm}$)</td>
<td>$&lt;\lambda/150 \text{ rms}$</td>
<td>$&lt;\lambda/50 \text{ rms}$</td>
</tr>
<tr>
<td>Plate flatness after Coating (at $\lambda = 355 \text{ nm}$)</td>
<td>$&lt;\lambda/120 \text{ rms}$</td>
<td>$&lt;\lambda/40 \text{ rms}$</td>
</tr>
<tr>
<td>Plate relative alignment (at $\lambda = 355 \text{ nm}$)</td>
<td>$&lt;0.1 \mu\text{rad}$</td>
<td>$&lt;0.5 \mu\text{rad}$</td>
</tr>
<tr>
<td>Mirror reflectivity/finesse</td>
<td>$\sim 95%; F_{\text{REF}} = 61$</td>
<td>$\sim 75%; F_{\text{REF}} = 11$</td>
</tr>
<tr>
<td>Overall finesse (including defect finesse)</td>
<td>41</td>
<td>7.7</td>
</tr>
<tr>
<td>Transmission fringe FWHM resolution</td>
<td>52 MHz</td>
<td>1.6 GHz</td>
</tr>
<tr>
<td>Overall $T$ of etalon at transmission peaks</td>
<td>80%</td>
<td>$&gt;87%$</td>
</tr>
<tr>
<td>Edge 1 step height</td>
<td>–</td>
<td>0 nm</td>
</tr>
<tr>
<td>Locking step height</td>
<td>–</td>
<td>$27 \pm 1 \text{ nm}$ (for DE)</td>
</tr>
<tr>
<td>Edge 2 step height</td>
<td>–</td>
<td>$77 \pm 1 \text{ nm}$ (for DE)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\delta \nu$ from Edge 1 of 1.8 GHz</td>
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<tr>
<td></td>
<td></td>
<td>$\delta \nu$ from Edge 1 of 5.2 GHz</td>
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</table>
NASA/GSFC mobile wind lidar

Goddard Lidar Observatory for Winds (GLOW) (Gentry and Chen, 2001)

Figure 1 - The mobile Doppler lidar system is mounted in a modified delivery van. The 45 cm clear aperture azimuth-over-elevation scanner is mounted on the roof to allow full sky access.
Optical layout of GLOW lidar

Figure 2 - Optical layout of the GLOW lidar system. The molecular receiver is shown in the dashed box.
Receiver

Energy Monitors
Fabry-Perot Etalon
Edge Detectors
Beam Collimator
Locking Detector
Vertical profiles of photons and winds

Figure 1 – Photocounts detected in the molecular receive for the two edge channels, EDG1 and EDG2 and the energy monitor, EM. The range resolution is 250m and 300 shots are averaged.

Figure 2 – a) A color plot of one minute radial wind profiles obtained with the GLOW lidar system on the afternoon of September 25, 2000. b) Same profiles overlaid in a plot of altitude vs velocity.
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<th><strong>Table 1. Satellite Lidar System Simulation Parameters</strong></th>
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<tr>
<td>Altitude (km)</td>
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<td>Scan pattern</td>
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<tr>
<td>Spatial resolution (km (\times) km)</td>
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<td>Vertical resolution (km)</td>
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<td>Shots averaged</td>
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<tr>
<td><strong>Laser</strong></td>
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<tr>
<td>Wavelength (nm)</td>
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<tr>
<td>Energy (J)</td>
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<tr>
<td>Spectral width (MHz)</td>
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<tr>
<td><strong>Receiver</strong></td>
</tr>
<tr>
<td>Telescope diameter (m)</td>
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<tr>
<td>Field of view (mrad)</td>
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<tr>
<td>Optical efficiency(^a)</td>
</tr>
<tr>
<td>Beam splitter</td>
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<tr>
<td>Transmission/reflectance</td>
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<td>Detector</td>
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<td>Quantum efficiency (%)</td>
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<td><strong>Etalon</strong></td>
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<td>Spacing (cm)</td>
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<td>Free spectral range (GHz)</td>
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<tr>
<td>Spectral width (FWHH, GHz)</td>
</tr>
<tr>
<td>Effective finesse</td>
</tr>
<tr>
<td>Etalon separation (GHz)</td>
</tr>
</tbody>
</table>

\(^a\)The optical efficiency does not include the beam splitter transmission/reflectance or the etalon transmission.