# Micro-Pulsed Coherent Detection Lidars

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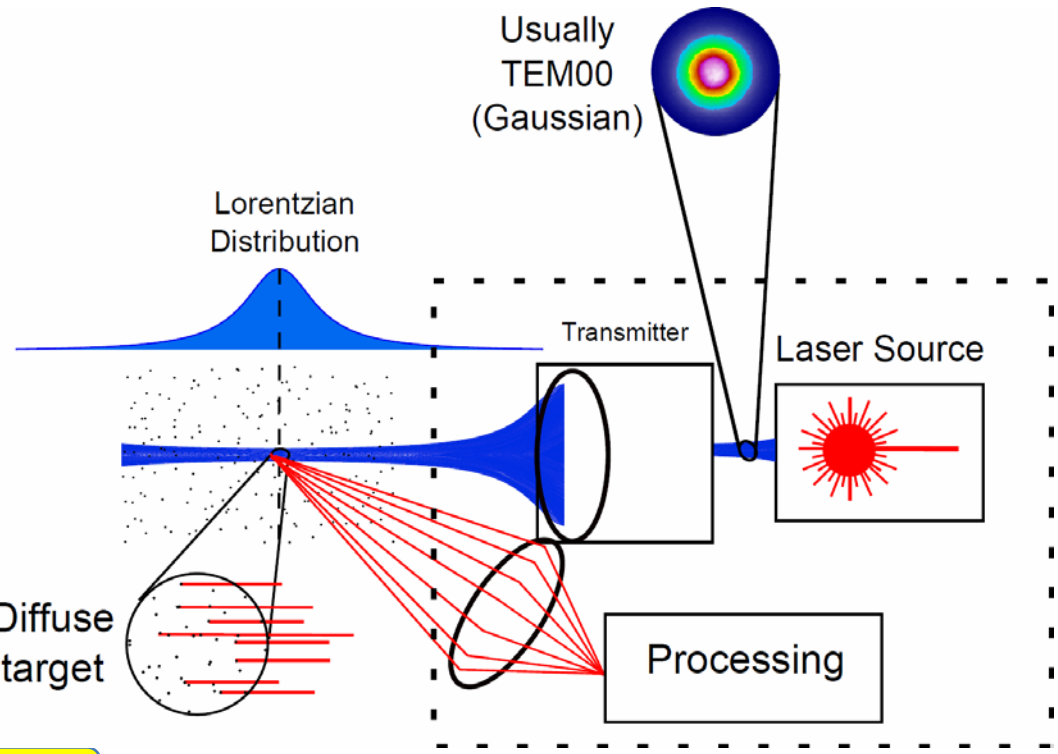
# Light Detection and Ranging (lidar)

Aerosol
and
Rayleigh (molecular)
scattering

$$\propto \frac{1}{\lambda^4}$$




(Elastic or inelastic backscattering)

- **Advantages using (laser) light:**
  - ***High accuracy***
  - ***Small form factor***
  - ***High temporal and spatial resolution***
  - ***Backscatter from tiny objects such as molecules and aerosols***
  - ***Minimal interference with the surrounding***

Coherent Detection Lidars

Direct Detection Lidars

High-Resolution Doppler Lidar
ESRL, NOAA

**Mostly open-space lasers and components**

Water Vapor Differential Absorption Lidar (DIAL)
University of Hohenheim, Germany

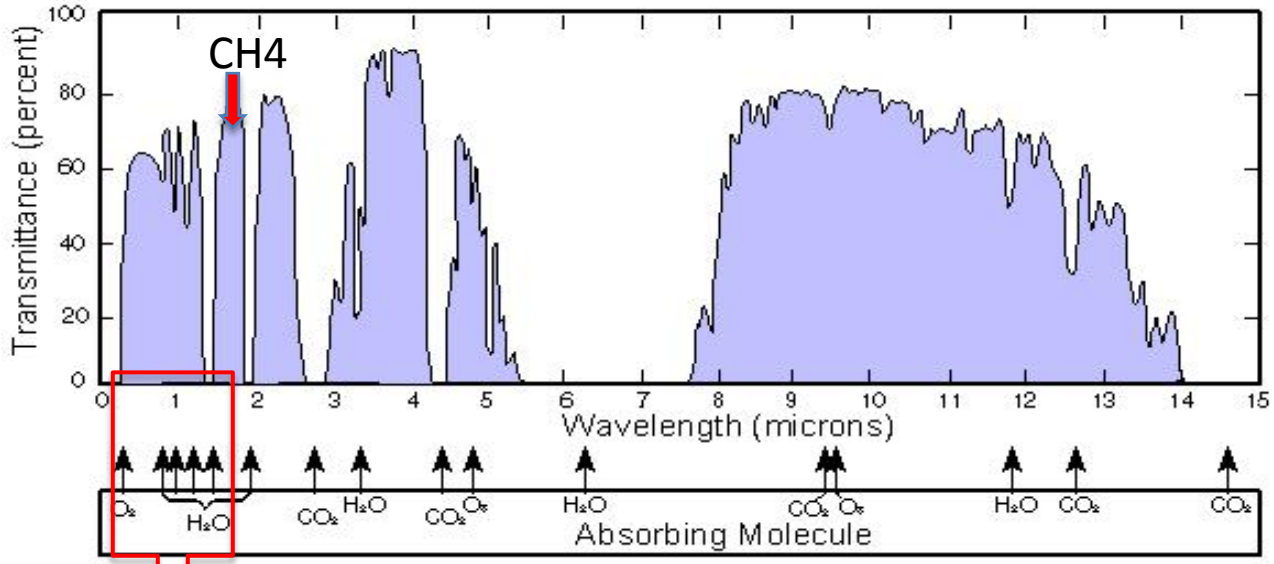
Windcube, Leosphere
Operated by ESRL, NOAA

**Mostly semiconductor and fiber optic lasers and components**

Water Vapor Differential Absorption Lidar (DIAL)
EOL, NCAR

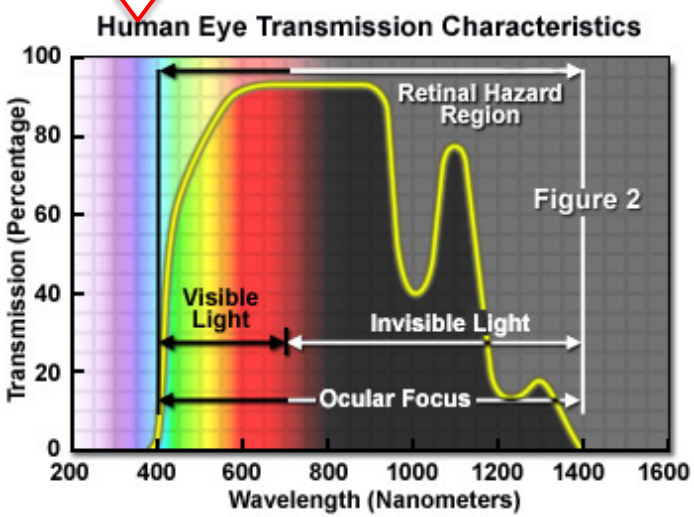
# Atmospheric Transmission/Eye Safety

**Atmospheric Transmission**




(Source: commons.wikimedia.org)

**Eye Safety**

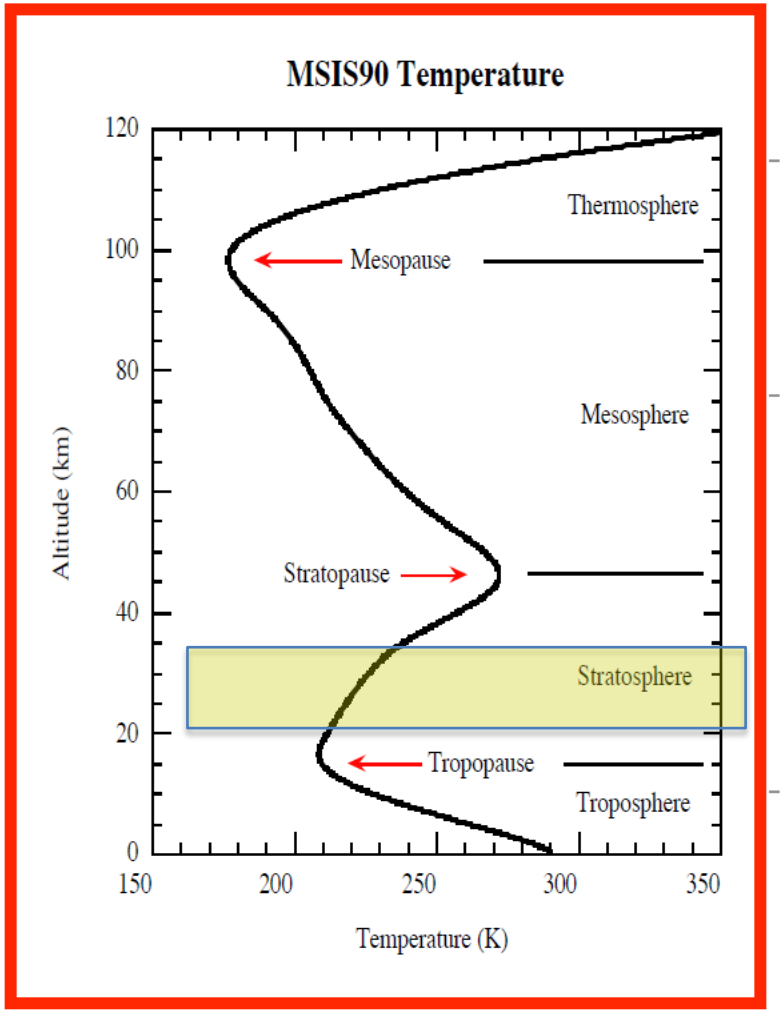


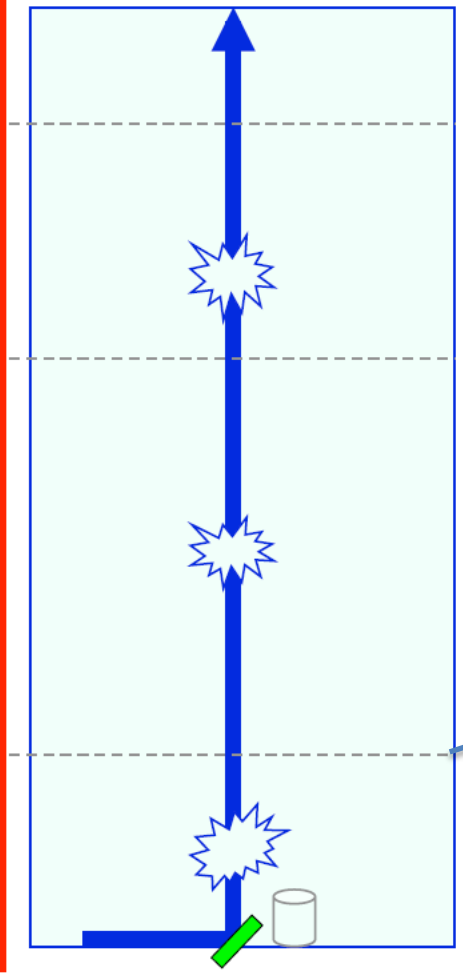

The majority of energy for lambda>1400 nm is absorbed by the cornea

**400-1400 nm is called the ocular focus range**

(Source:http://www.microscopyu.com)

# Scattering processes vs. altitude



**Resonant Fluorescence From Metal Atoms**

**Rayleigh Scattering From Air Molecules**

ABL

**Mie Scattering From Aerosols**

**+Rayleigh scattering**

**Range Determined From Time-of-Flight: $R = c \cdot \Delta t / 2$**

# Lidar Equation

- Mie and Rayleigh backscattering are considered elastic. For these the generalized lidar equation is:

Solid angle

$$E_R = \eta E_T \beta(\lambda, z) T^2(\lambda, z) G(z) \frac{A}{z^2} \Delta z$$

$E_T$ : Transmit signal energy

$E_R$: Receive signal energy

$\eta$: Lidar efficiency

$\beta(\lambda,z)$: Backscatter coefficient

$T(\lambda,z)$: One-way atmospheric transmission

$G(z)$: Geometrical probability of backscatter receiption

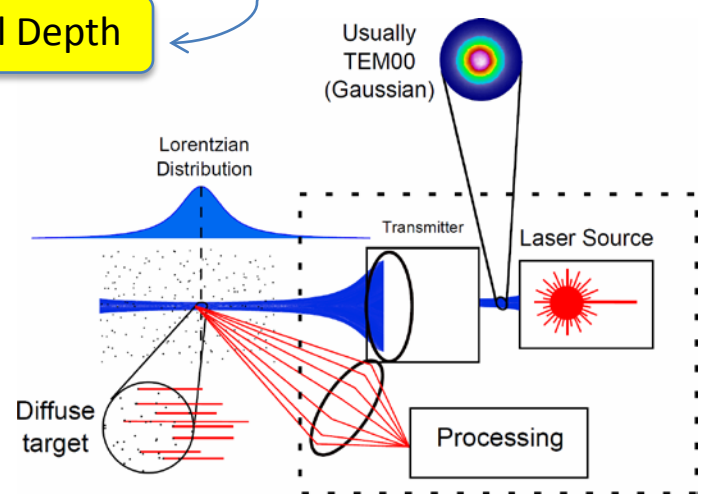
$A$: Apperture area

$\Delta z \left( = \frac{c\tau}{2} \right)$ : Range gate

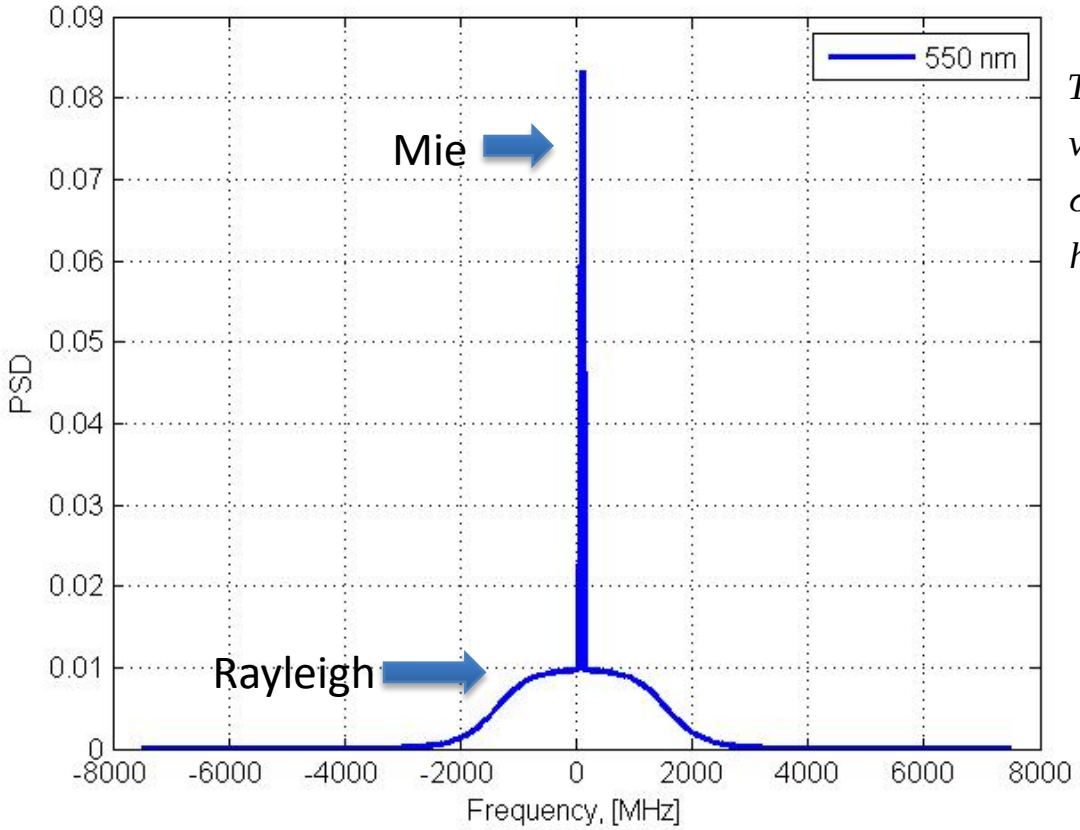
$$T = T_{Mie} T_{Rayleigh} T_{absorption}$$

$$T = \exp\left( -\int_0^z N(z)\sigma(\lambda, z) dz \right)$$

Optical Depth



# Simulations are done based on the US standard atmospheric model




$T = 289\ K$, temperature

$v = 25$ m/s, mean wind speed

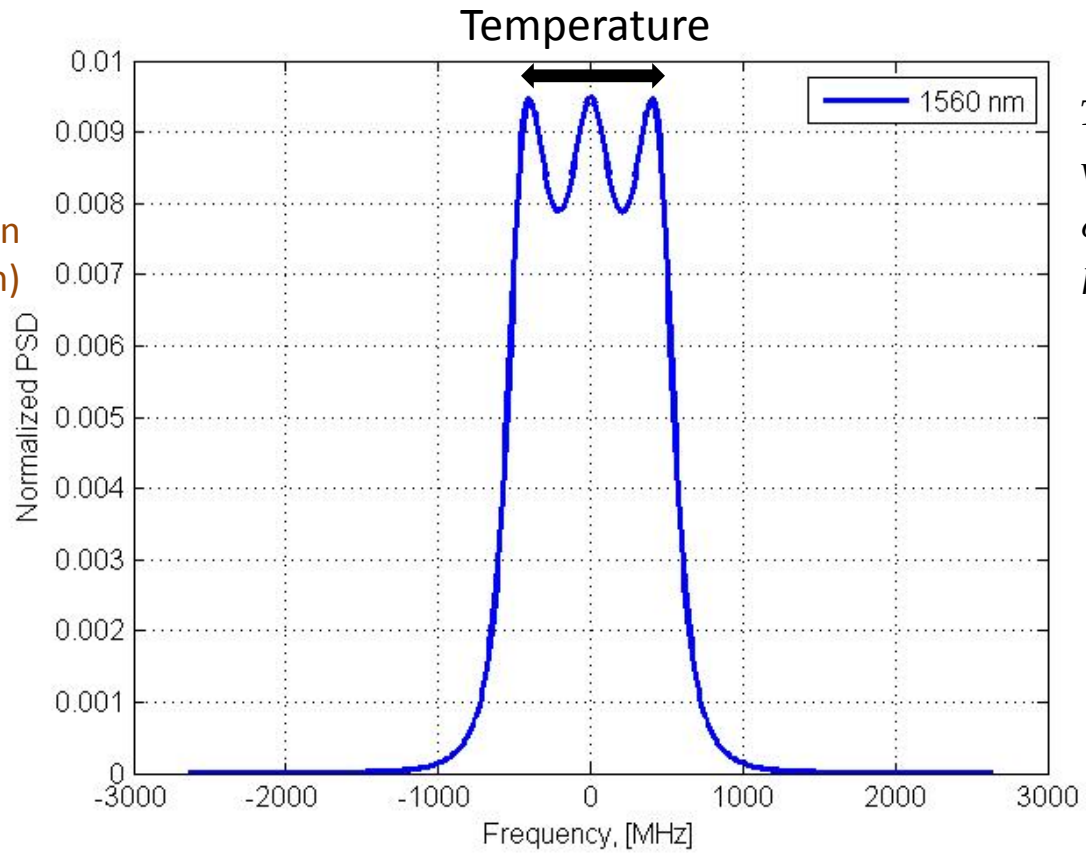
$\sigma_v = 2.5$ m/s, std of wind speed

$h = 1$ km, height

The Rayleigh backscatter thermal broadening for this wavelength has the popular Gaussian (Maxwell) distribution with standard deviation of:

# Simulations are done based on the US standard atmospheric model

Hydrodynamic region
(1560 nm: h< 5.8 km)




$T = 289\ K$, temperature

$v = 0$ m/s, mean wind speed

$\sigma_v = 0$ m/s, std of wind speed

$h = 1$ km, height

- If the wavelength is longer than the mean free path between the molecules the molecular backscatter is called Rayleigh-Brillouin backscatter and features Brillouine peaks.

- The separation between Brillouin peaks (resulting from acoustic waves) is a function of the temperature.

- Depending on the laser wavelength and the mean-free path between the atmospheric molecules the signal backscatter can be in different regimes.

U.S. Standard atmospheric model

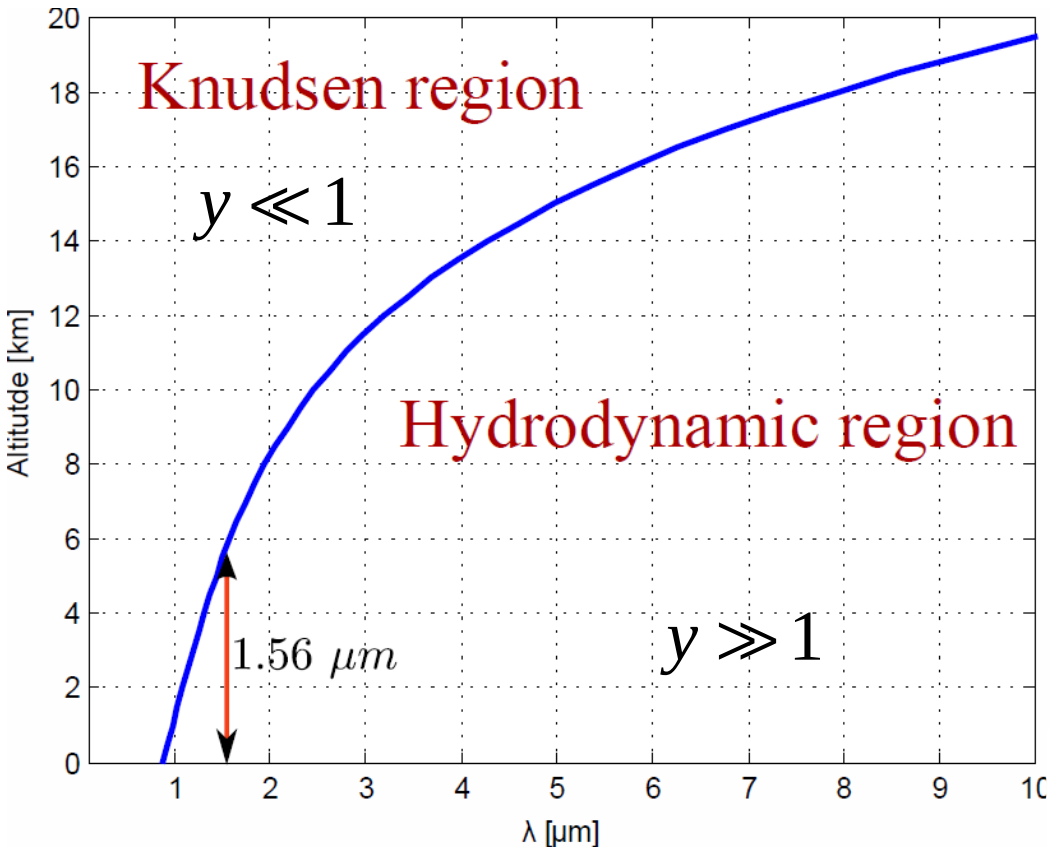
$$y = \frac{\lambda\left(T + 111P\right)}{4.34T^2}$$

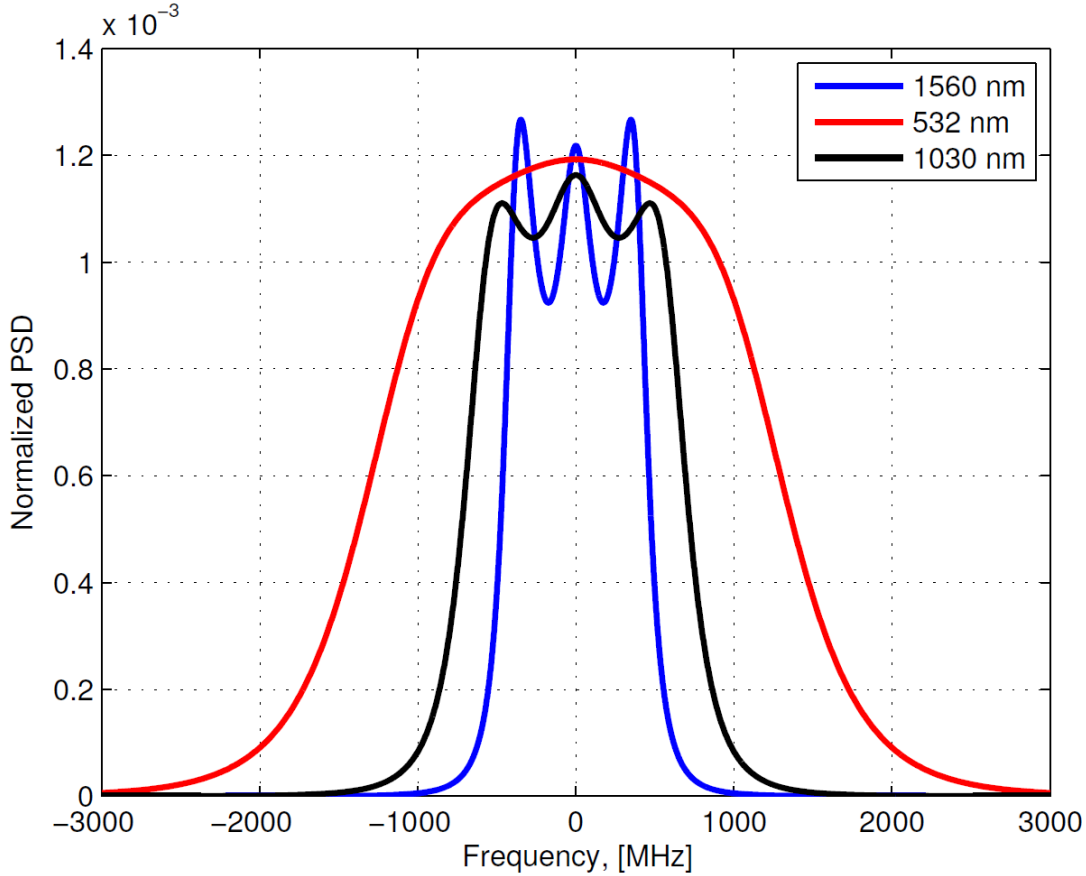
$y$ : Normalized collisional frequency

$\lambda$ : Wavelength [nm]

$P$ : Pressure [Pa]

$T$ : Temperature [K]






**Comparison of the SRBS spectra for different wavelengths associated with the same atmospheric conditions.**

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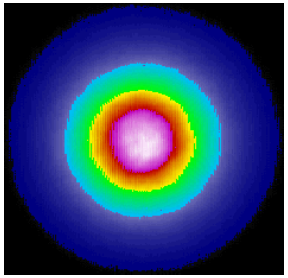
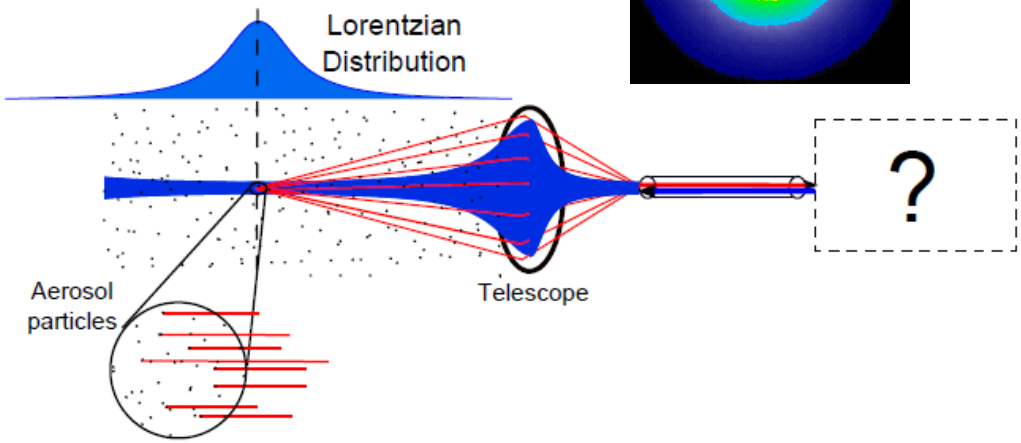
# CW vs. pulsed lidars

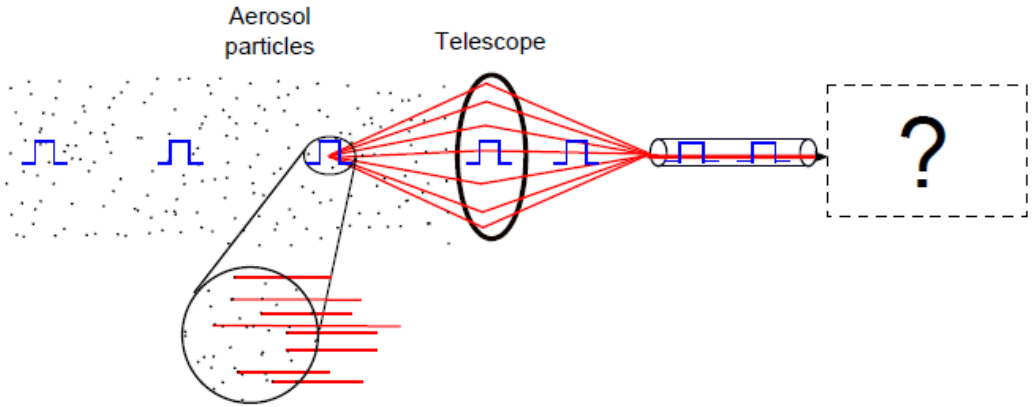
- In CW lidars ranging is achieved through focusing the laser beam which has the following properties,
  - **The beam cross section has a Gaussian light intensity distribution**
  - **The longitudinal light intensity is Lorentzian**

Transverse mode (TEM)00 of laser light



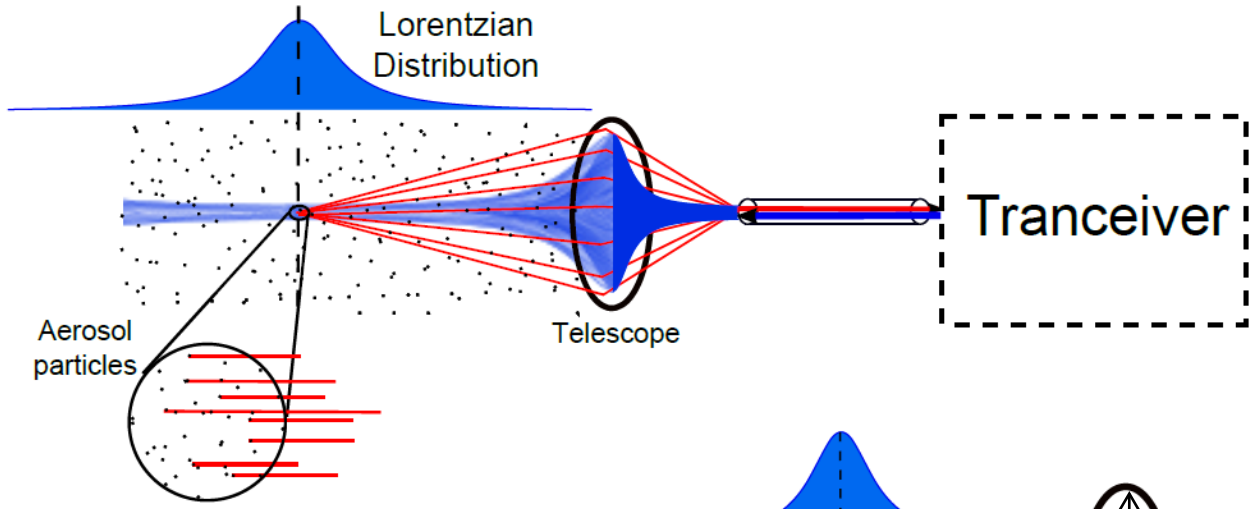



- In pulsed lidar ranging is achieved through range gating, i.e., through time windowing the recorded time series to isolate the range of interest.



# CW lidar and ranging

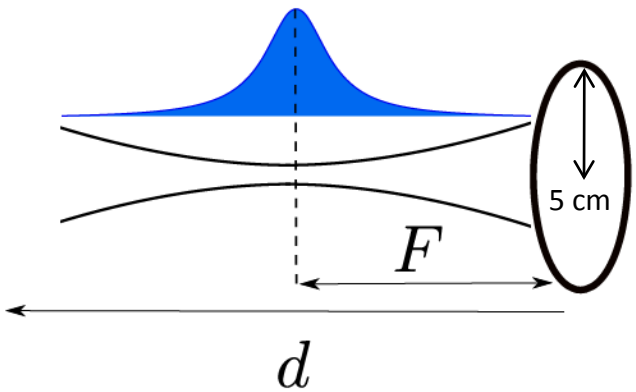
➢In CW lidars ranging is achieved through focusing the laser beam which has the following properties,




- The beam cross-section has a Gaussian light intensity distribution

$$\Delta = F - d$$

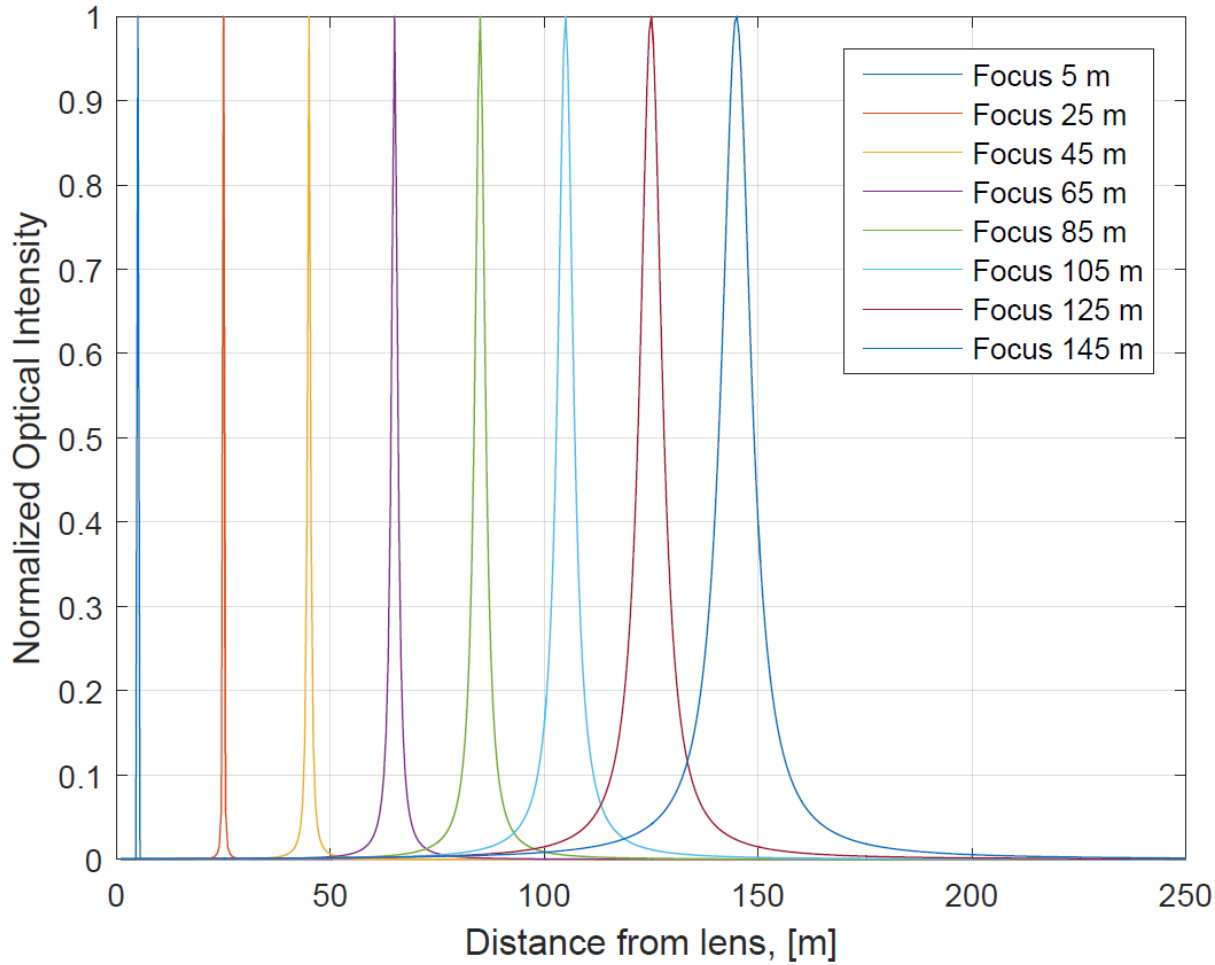
$$\Gamma = \frac{\lambda F^2}{\pi r^2}$$




- The longitudinal light intensity is Lorentzian

$$\text{Optical Intensity} = \frac{\Gamma / \pi}{\Delta^2 + \Gamma^2}$$

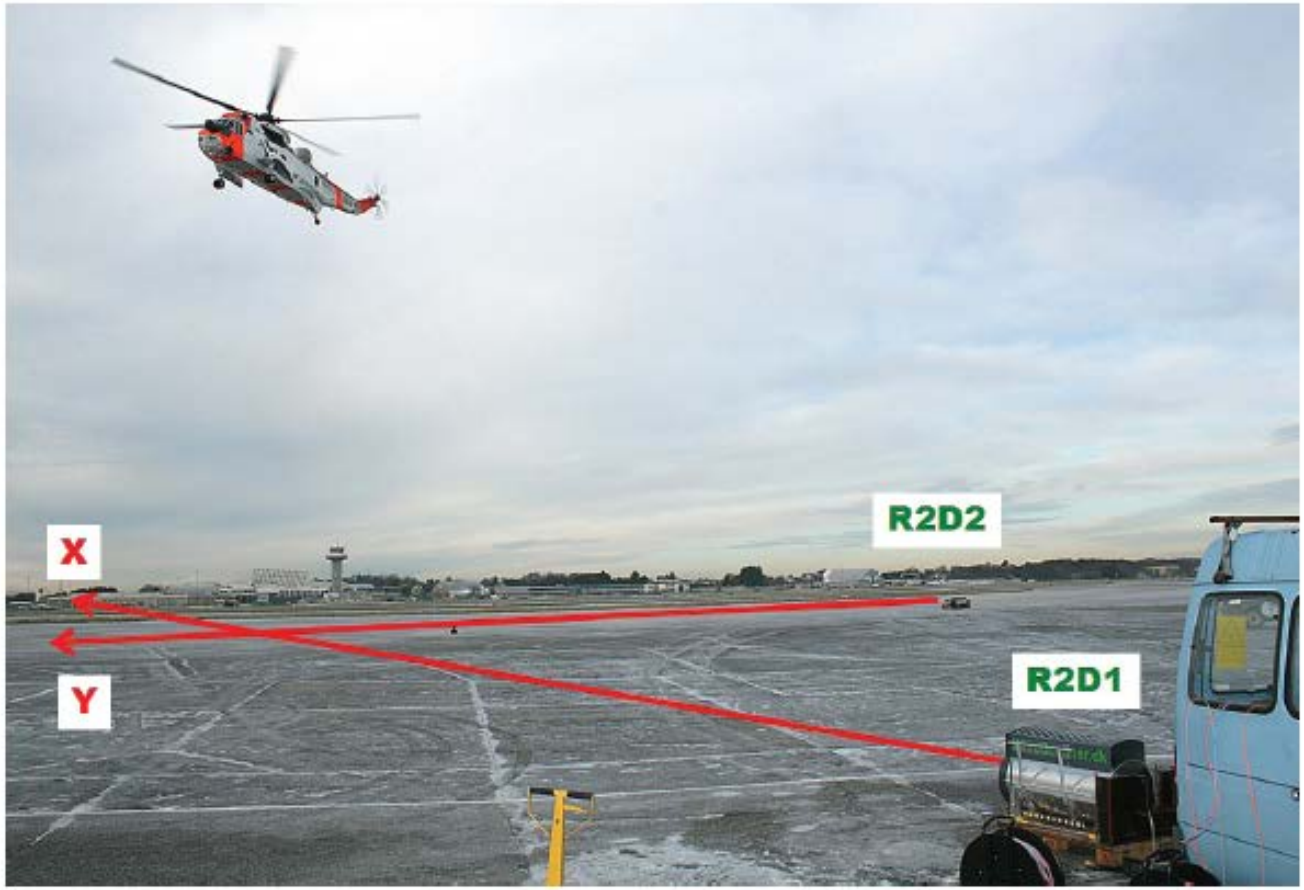
# Introduction, CW vs. pulsed CDLs




Telescope Diameter= 10 cm

FWHM@45 m= 0.8 m
FWHM@145 m= 8 m

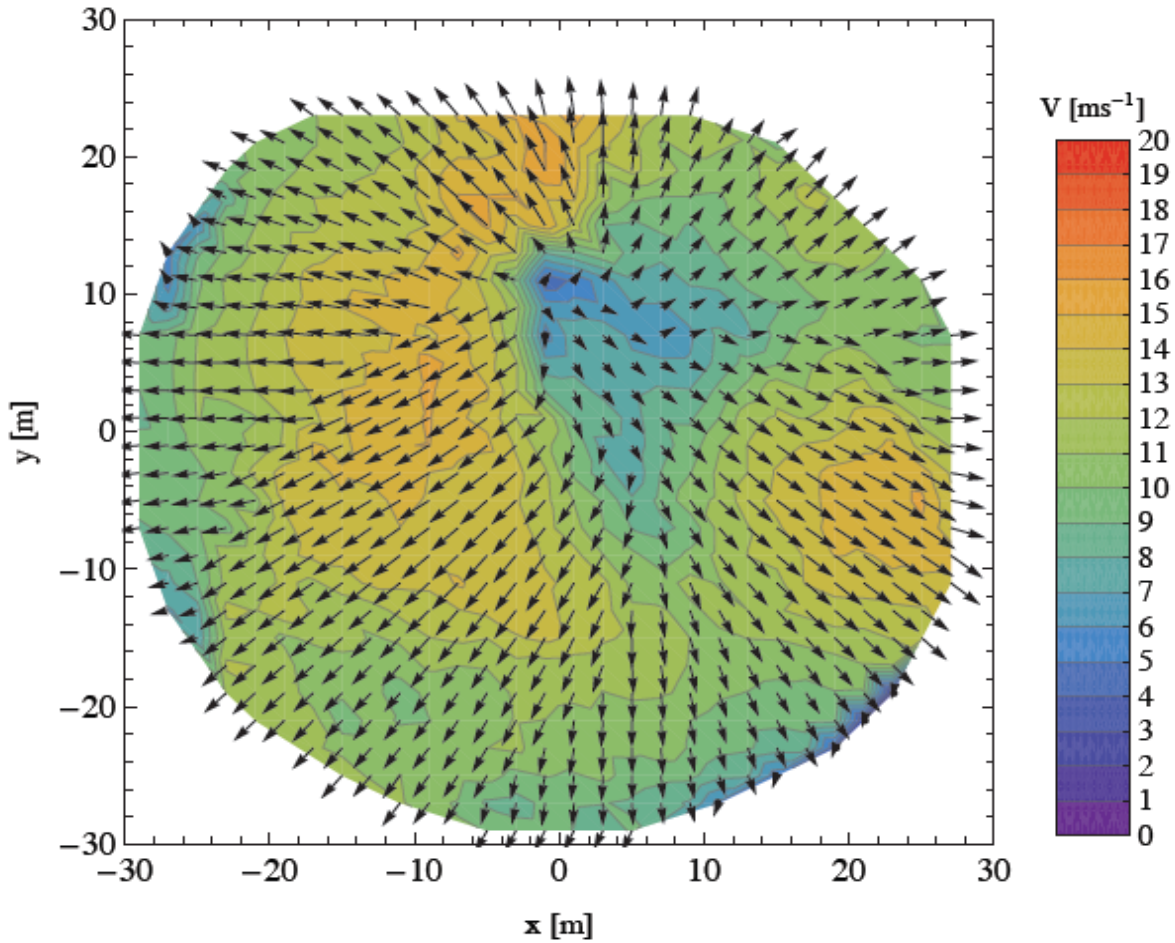
# Introduction, CW application example




Mikael Sjoholm, et al. "Helicopter downwash measured by continuous-wave Doppler lidars with agile beam steering." 16th International Symposium for the Advancement of Boundary-Layer Remote Sensing

The experimental setup for scanning a horizontal plane below the helicopter.

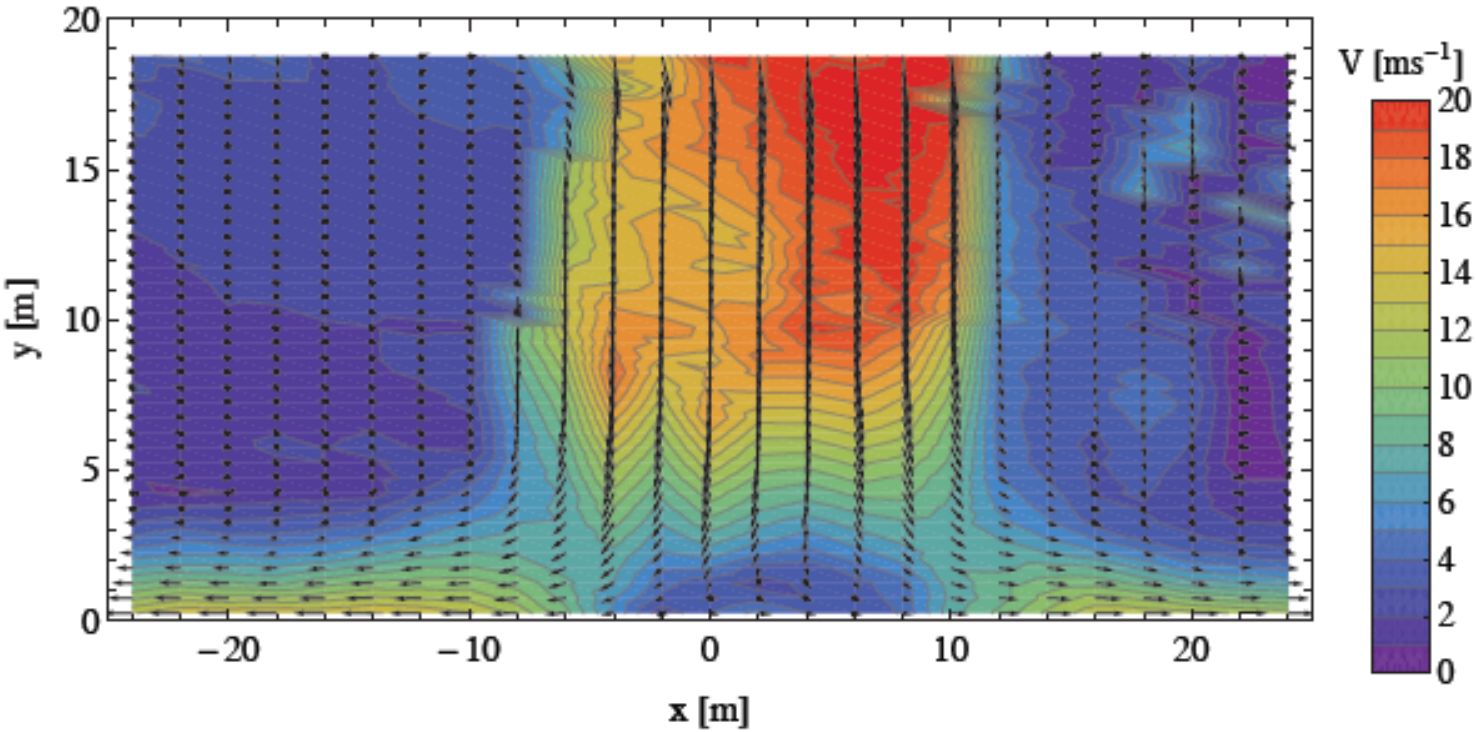
# Introduction, CW application example




Mikael Sjoholm, et al. "Helicopter downwash measured by continuous-wave Doppler lidars with agile beam steering." 16th International Symposium for the Advancement of Boundary-Layer Remote Sensing

The retrieved 2D wind field in a horizontal plane close to ground.

# Introduction, CW application example




Mikael Sjoholm, et al. "Helicopter downwash measured by continuous-wave Doppler lidars with agile beam steering." 16th International Symposium for the Advancement of Boundary-Layer Remote Sensing

The retrieved 2D wind field in a vertical plane below the helicopter.

# Signal modeling, CW CDL

The transmit and receive signal may be modeled as,

$$s(t) = \sqrt{2P}\cos\left[2\pi f_c t + \theta(t)\right] + L_R(t)$$

$$r(t) = k\sqrt{2P}\sum_{l=0}^{L-1}\alpha_l \cos\left[2\pi\left(f_c \pm \Delta f_l\right)t + \theta(t) + \phi_l\right]$$

- $k$ is a proportionality constant
- $f_c$ is the laser frequnecy (carrier frequency)
- $\theta(t)$ is the laser phase noise described by a Weiner process (Lorentzian spectral shape)
- $L_R$(t) is the laser relative intensity noise (RIN) having a peak at the relaxation oscillation frequency
- $\alpha_l$s are backscatter coefficients associated with aerosol particles (independant Gaussian rvs)
- $\Delta f_l$ is the Doppler shift associated with the movement of the $l$th particle ($\Delta f_l$s are independant Gaussian rvs)
- $\phi_l$ is the phase factor associated with the $l$th particle, modeled as a uniformly distributed rv
- all rvs are independant

# Signal modeling

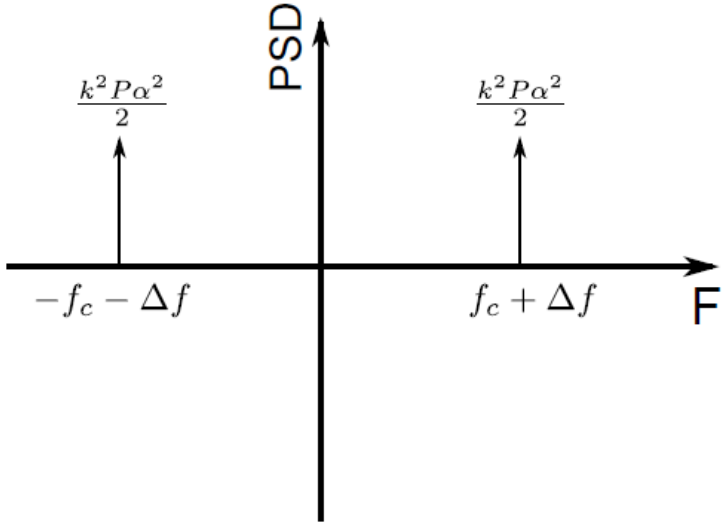
- For simplicity and without lack of generality lets adopt a receive signal model associated with the reflection from a single moving hard target where the effect of phase noise has been neglected.

$$r(t) = k\sqrt{2P}\alpha\cos\left[2\pi\left(f_c + \Delta f\right)t + \phi\right]$$

- If somehow a CTFT could be carried out on the optical received signal

$$R(F) = \frac{k\sqrt{2P}\alpha}{2}e^{j\varphi}\delta(F + f_c + \Delta f) + \frac{k\sqrt{2P}\alpha}{2}e^{-j\varphi}\delta(F - f_c - \Delta f) \Rightarrow$$

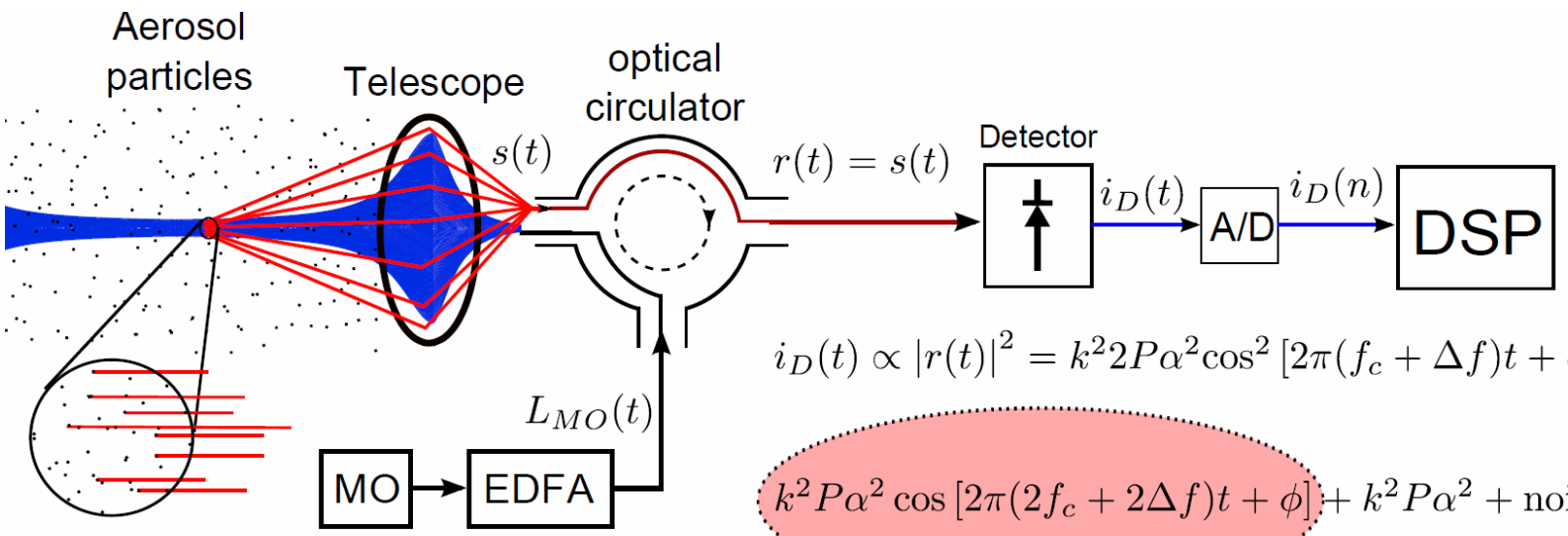
$$\left|R(F)\right|^2 = \frac{k^2P\alpha^2}{2}\delta(F + f_c + \Delta f) + \frac{k^2P\alpha^2}{2}\delta(F - f_c - \Delta f)$$



# Why coherent detection (heterodyning)?

- The optical signal needs to be converted into an electrical current for further processing -> a photodiode (square-law detector is used).

- Due to numerous advantages digital signal processing (DSP) algorithms provide, the received signal needs to be digitized for estimating the Doppler shift.

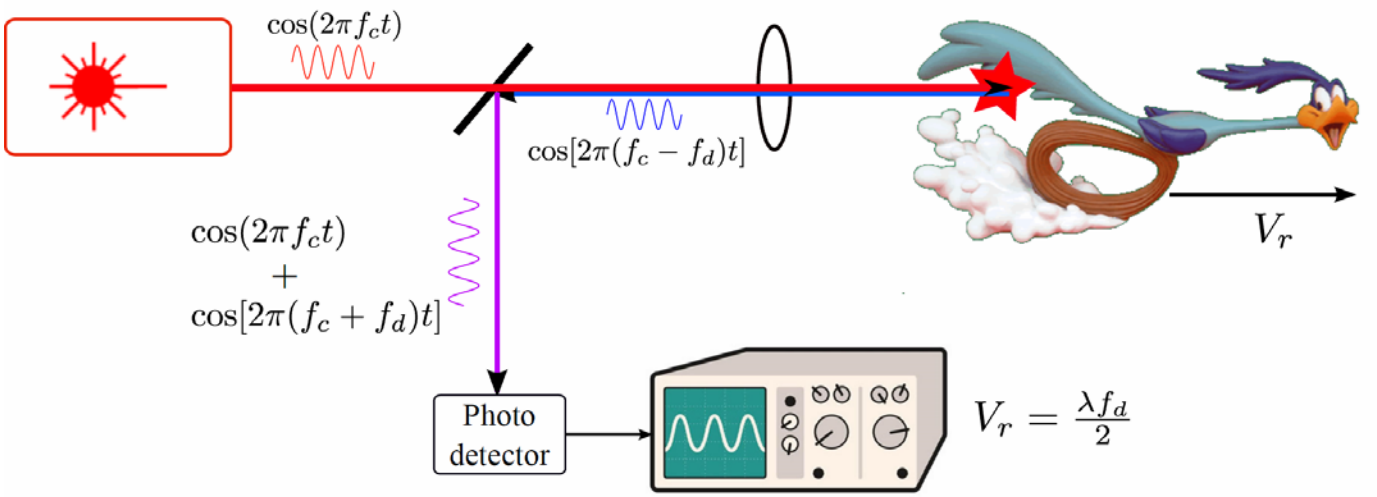



$$i_D(t) \propto |r(t)|^2 = k^2 2P\alpha^2 \cos^2\left[2\pi(f_c + \Delta f)t + \phi\right] + \text{noise} =$$

$$k^2 P\alpha^2 \cos\left[2\pi(2f_c + 2\Delta f)t + \phi\right] + k^2 P\alpha^2 + \text{noise}$$

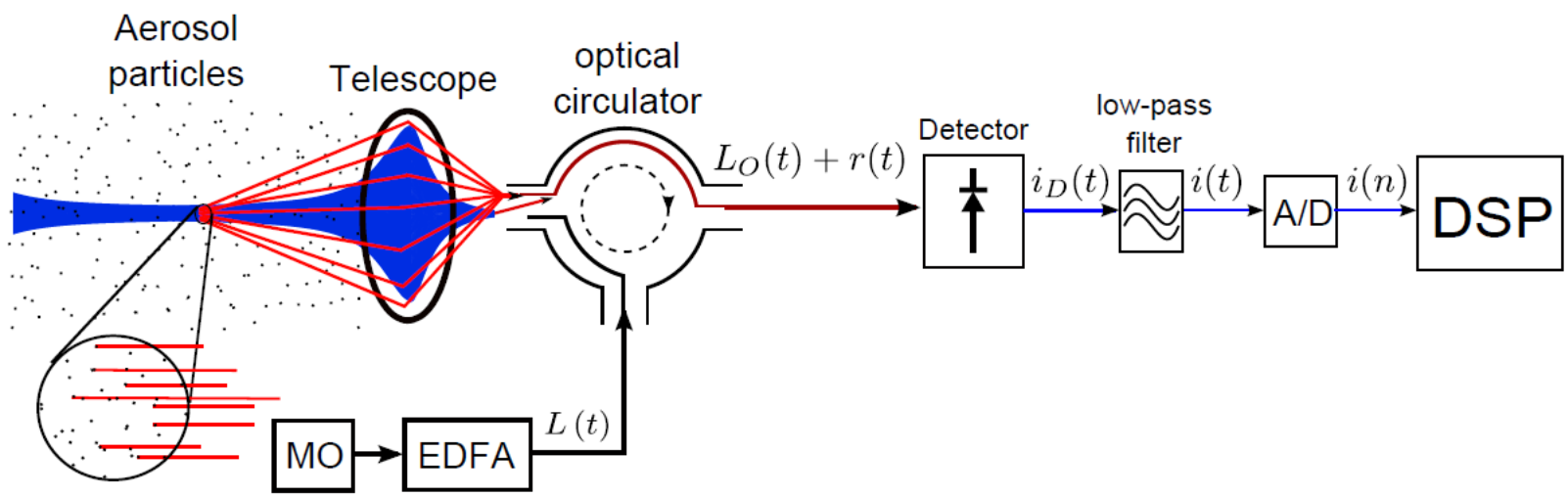
?

# Coherent detection lidars (CDL):




- **Share many similarities with Radars and wireless/wired/optical communications.**
- **In atmospheric science, conventionally used to measure wind-induced Doppler shift (Mie scattering).**
- **Highly sensitive; provides a carrier-to-noise (CNR) of unity per photon per unit bandwidth.**
- **Can be built on open-space optics, fiber-based, or a combination. All-fiber 1550 nm CDLs have become widely employed due to:**
  - **Compact, robust, and cost-effective lasers and fiber amplifiers**
  - **Wide selection of fiber-optic components made available by the optical communication industry.**

# Homodyne receivers, real-mixing




- The simplest homodyne receiver is a direct down-conversion configuration with real (in-phase) mixing.

- In such systems, the received signal is mixed with a portion of the reflected LO signal from the end facet of the delivery fiber right before the telescope. The amount of LO power can be adjusted by controlling the polished fiber-end angle!

- Ground-based ZephIR and airborne LAMS (EOL, NCAR) lidars have a similar system set-up.

# Homodyne receivers, real-mixing

- The beating (mixing) process is carried out by the photodetector.

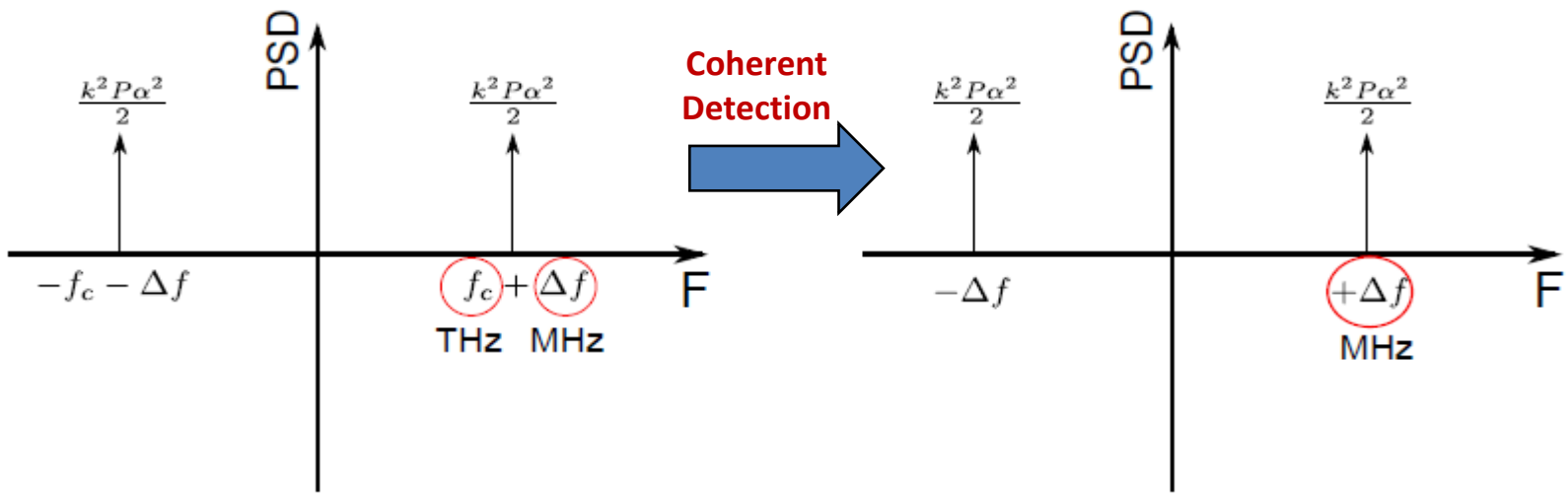
$$i_D(t) = \alpha \left| r(t) + L(t) \right|^2 + \eta_{sn}(t) + \eta_{th}(t) + \eta_{1/f}(t) \Rightarrow$$

$$i_D(t) = \alpha \left[ r(t)^2 + L(t)^2 + 2L(t)r(t) \right] + \eta_{sn}(t) + \eta_{th}(t) + \eta_{1/f}(t).$$

- After proper filtrering and signal conditioning,

$$\boxed{i_D(t) = \alpha\sqrt{2P}\cos\left(2\pi\Delta f t + \phi\right)} +$$

$$\eta_{\mathrm{dc}} + \eta_R(t)^2 + \eta_{sn}(t) + \eta_{th}(t) + \eta_{1/f}(t)$$



# Coherent Detection Efficiency, Noise Behaviour

- **The dominant noise is the detector's shot noise; a white Gaussian noise. The DC offset, 1/f, and RIN are colored noise.**
- **The unwanted noise terms may be suppressed by proper signal processing or high-quality components.**
- **There is only so much one may do to improve the noise behavior.**

If the dominant noise source is the shot-noise, then

$$CNR = \frac{\eta \lambda P_R}{h_p c B},$$

where

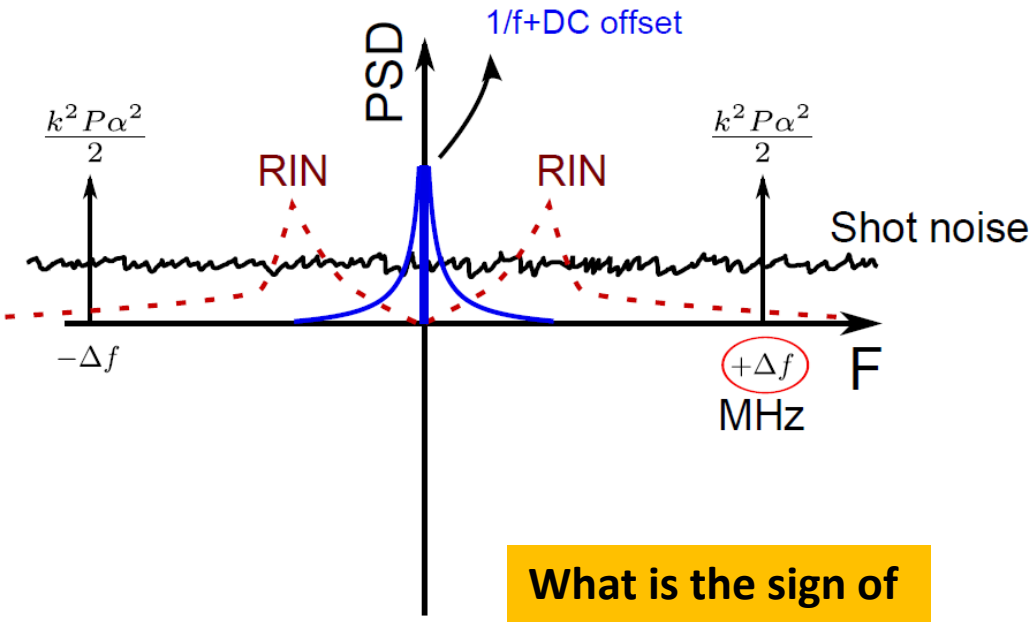
$P_{LO}$ : LO power

$\eta_{Det.}$ : Detector efficiency ( $\approx 1$)

$h_p$ : Plank's constant

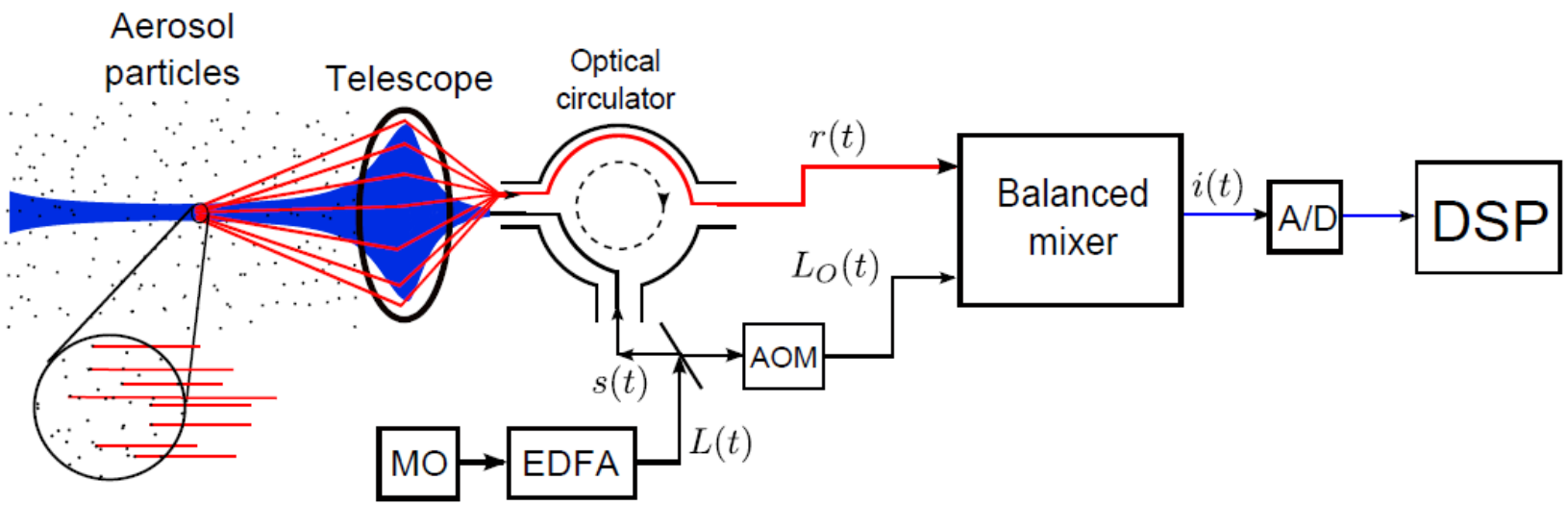
$B$ : Detector's bandwidth

$c$ : Speed of light

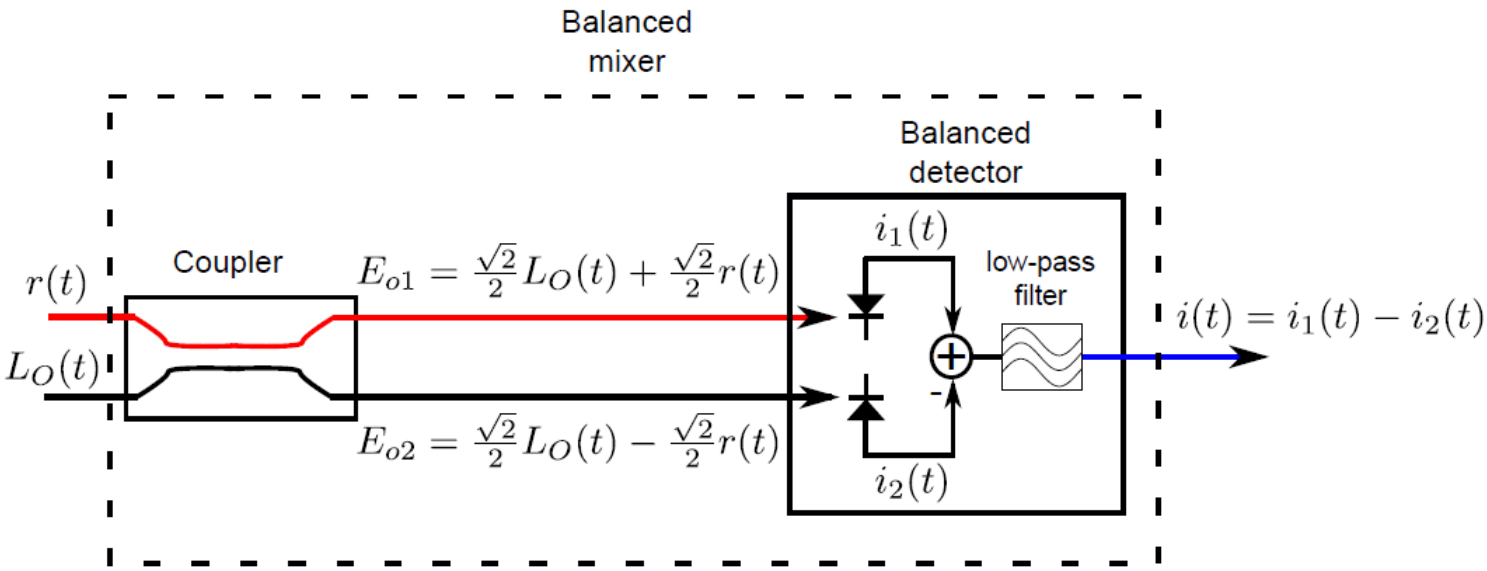



**What is the sign of Doppler shift?**

# Coherent Detection, Heterodyne Receiver



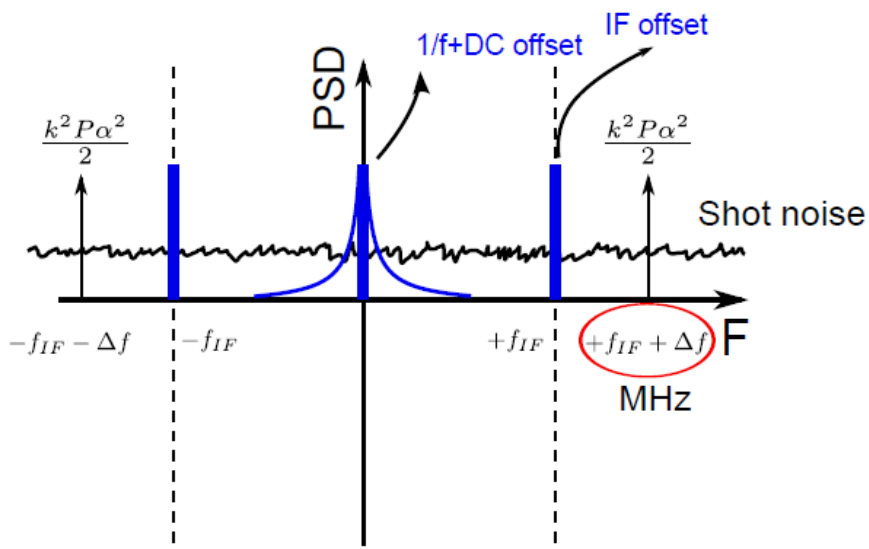

- In heterodyne receivers, the Doppler shift is down-converted to the intermediate band. Why?
- To perform this, either the frequency of the transmit signal or LO is shifted by IF, e.g., 27 MHz used in ZephiR based Windscanner.

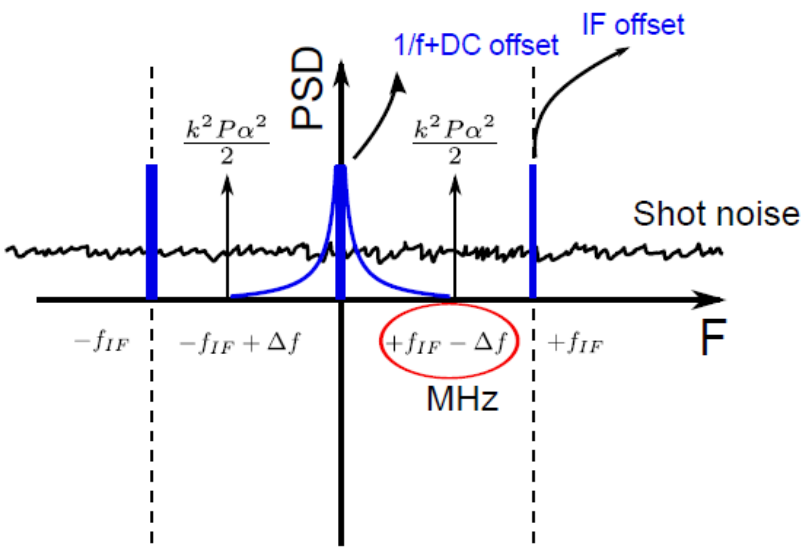



- If only one detector is used half the signal power, i.e., 3 dB is lost.

- A balanced detector needs to be used so not only all signal power is used but also the effect of DC noise as well as laser's RIN noise can be ideally removed. This in effect can improve the SNR significantly.

- Its performance is characterized through common mode rejection ratio (CMRR), i.e., the common mode signals from the LO path are removed.



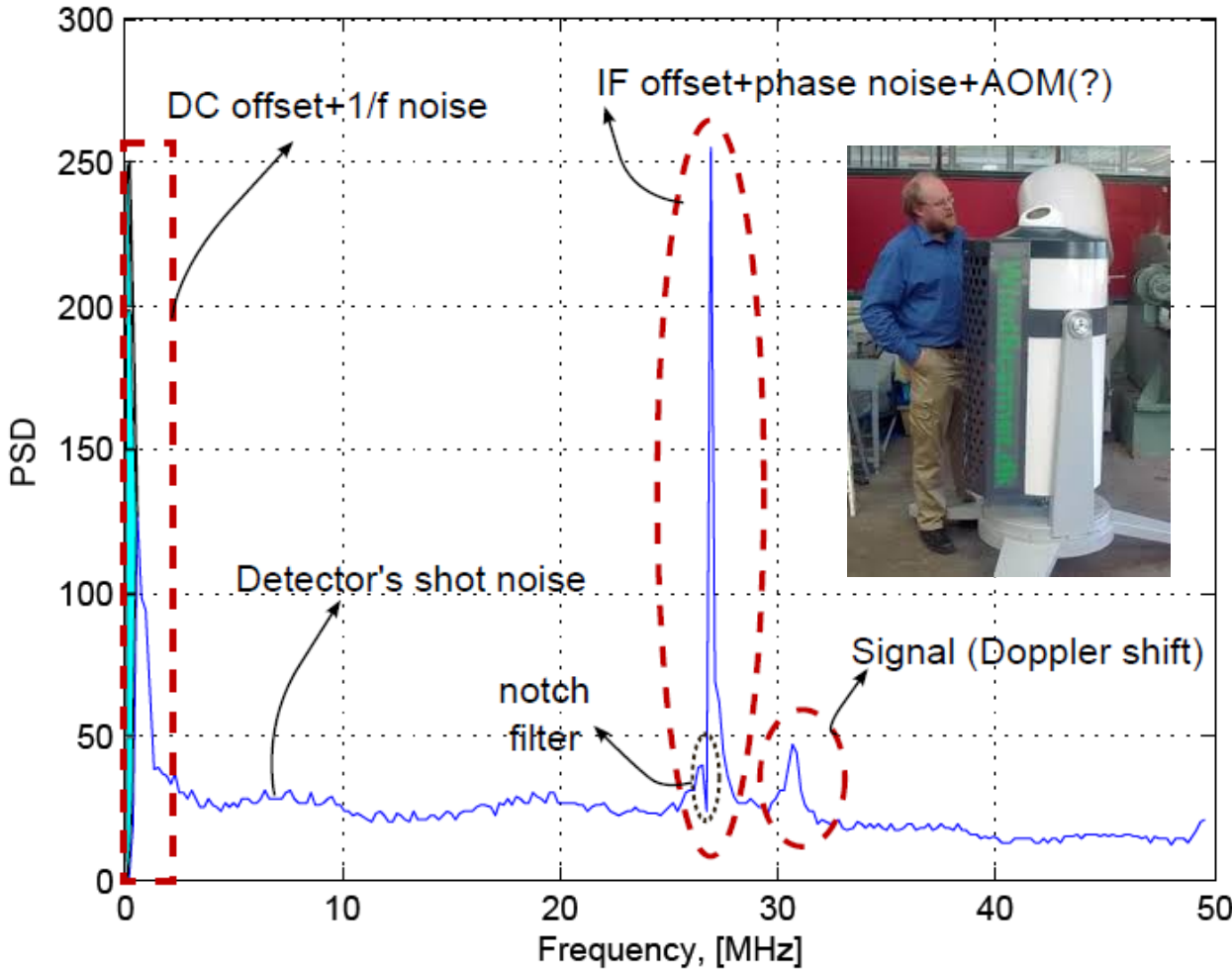




- Due to the presence of IF, one needs to employ an A/D with much wider BW if the same radial velocity range is sustained.
- The price of A/D doesn't increase linearly with respect to the BW.
- Due to the reflections from the optical surfaces as well as the optical circulator cross-talk, a strong signal component appears around the IF frequency which can saturate the following stages.

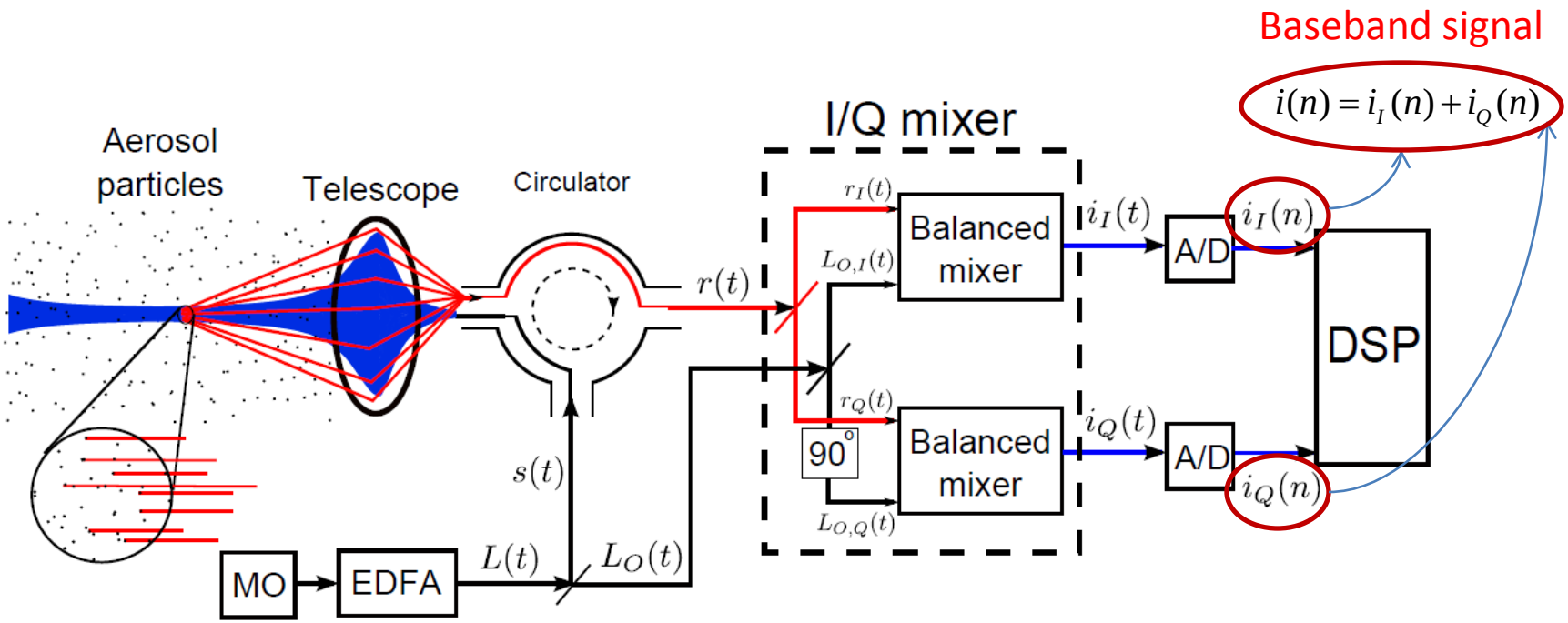
# CW CDL, Example Spectra

- Laser phase noise and additional AOM drifts contribute to the noise component around the IF.

- Temperature dependency of the laser phase noise and the notch filter makes it difficult to remove the IF offset.



# CW CDL, Image-Reject Homodyne



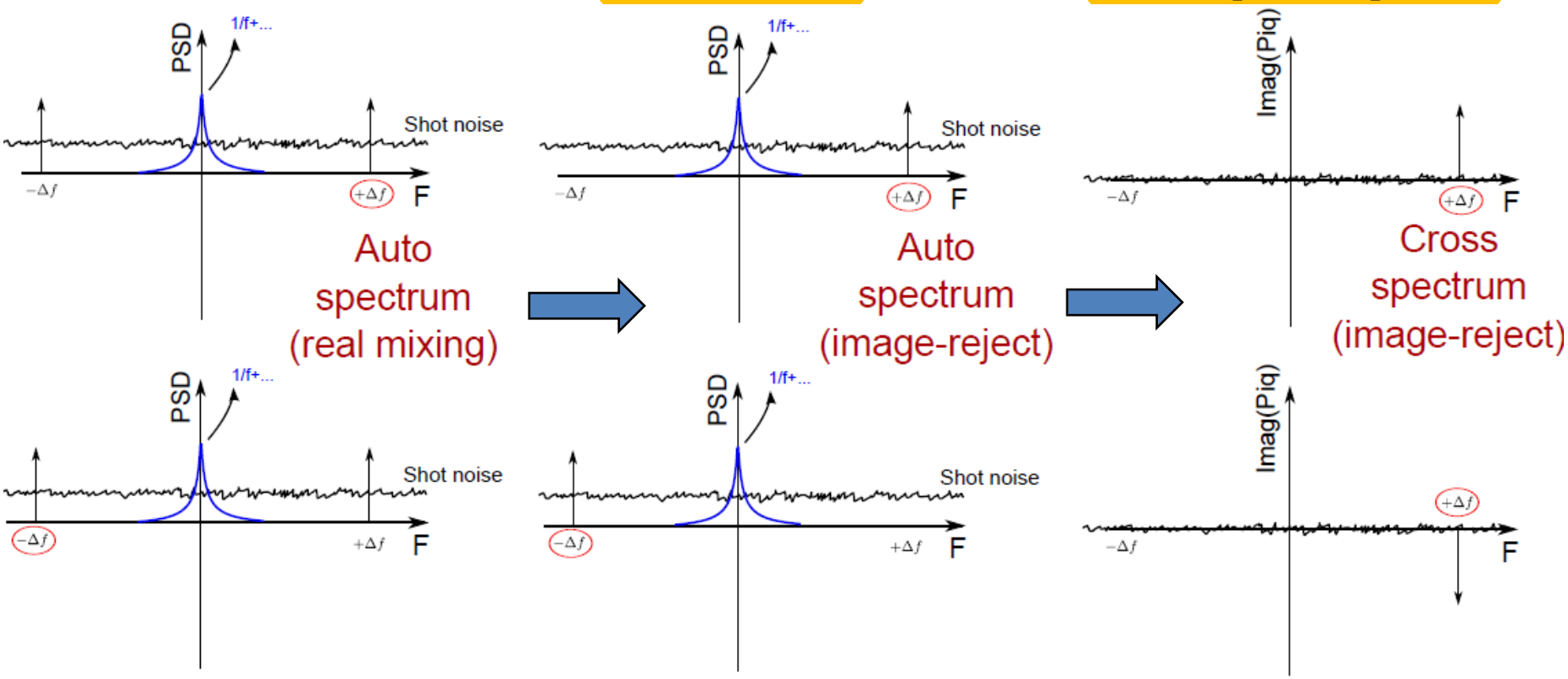

➢To resolve the sign ambiguity one may use a concept popular in wireless communications called homodyne image-reject receivers, also known as homodyne with complex mixing, I/Q or quadrature detection.

➢It can be shown that by mixing the received signal once with the local oscillator and once with its phase shifted replica (90 degree), the sign ambiguity can be resolved.

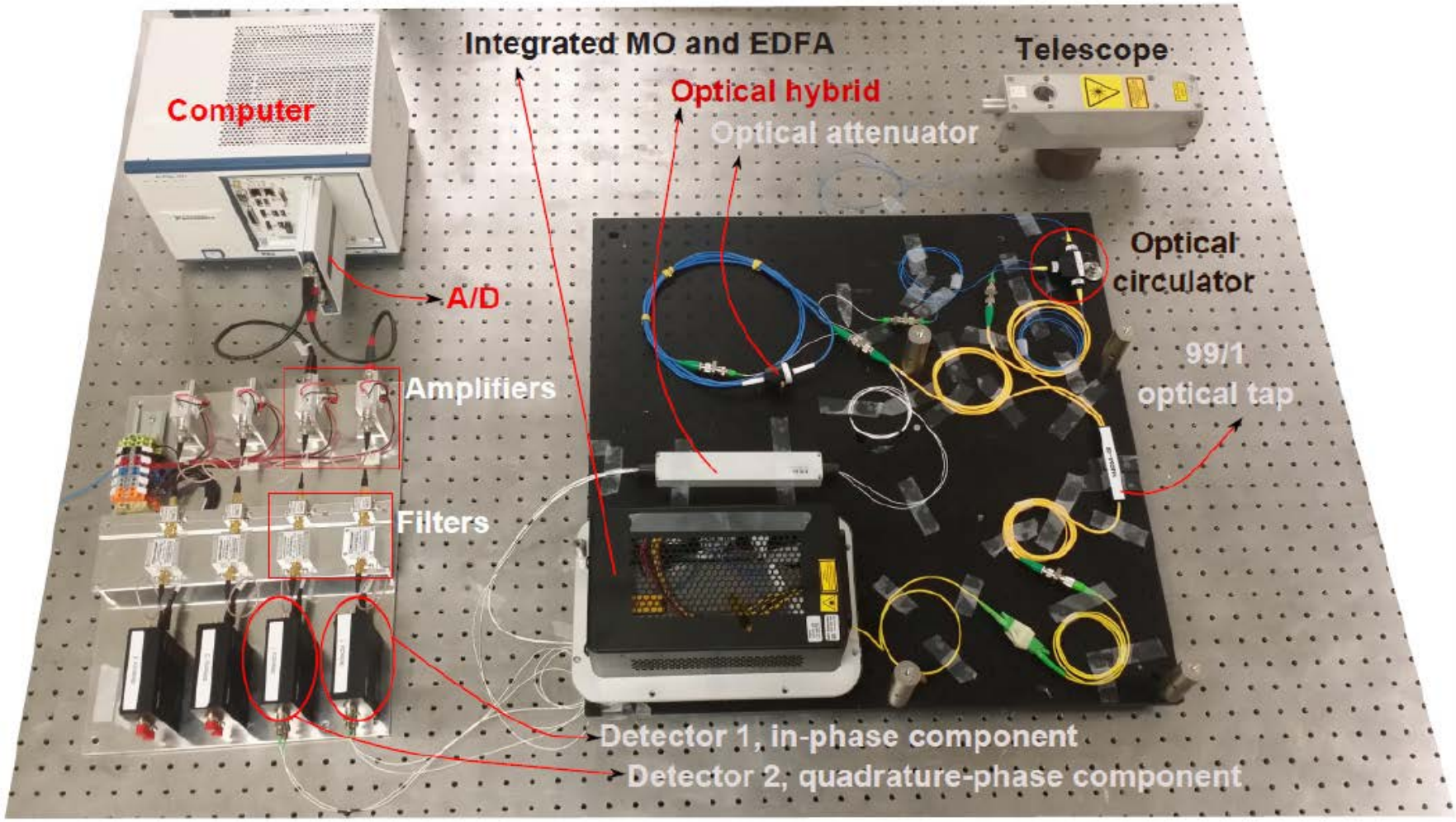
- To eliminate/suppress the noise sources present in the signal, a cross-correlation approach can be employed.
- The cross-correlation benefits from the fact that the noise sources in in-phase and quadrature-phase paths are independent.
- The information is ideally contained in the imaginary part of the cross-spectra unless there is a significant gain/phase imbalance.

$$I(f) = \Im[i(t)] \rightarrow$$
$$P_I(f) = \mathrm{E}\left[I(f)\overline{I(f)}\right]$$

$$I_I(f) = \Im[i_I(t)], I_Q(f) = \Im\left[i_Q(t)\right] \rightarrow$$
$$P_{I_I I_Q}(f) = \mathrm{E}\left[I_I(f)\overline{I_Q(f)}\right]$$

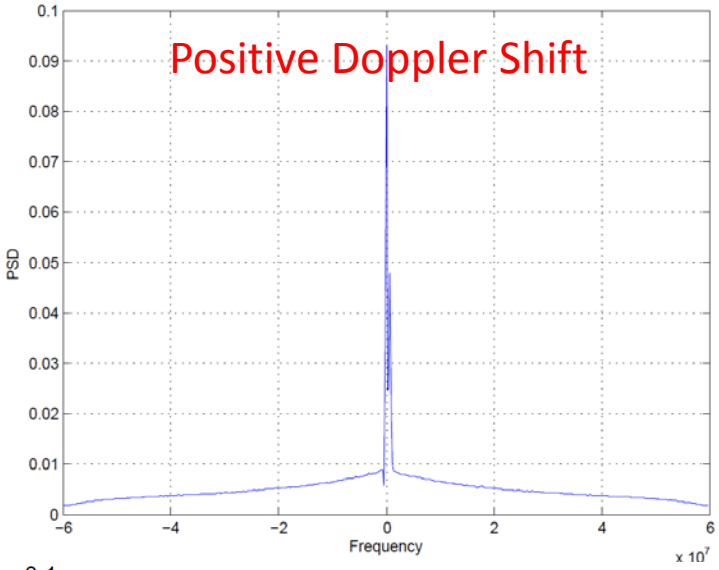


# CW CDL, Image-Reject Homodyne Prototype

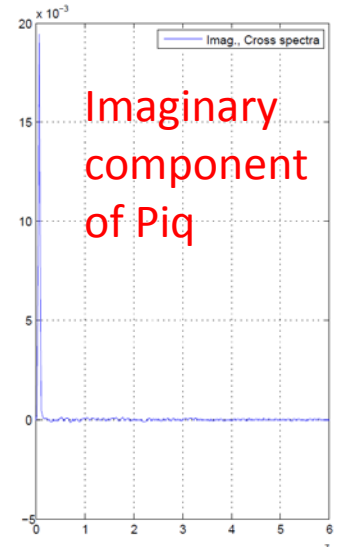



C. F. Abari, A. T. Pedersson, and J. Mann, " An all-fiber image-reject homodyne coherent Doppler wind lidar", Optics Express, vol. 22, no. 21, pp. 25 880-25 894, 2014.

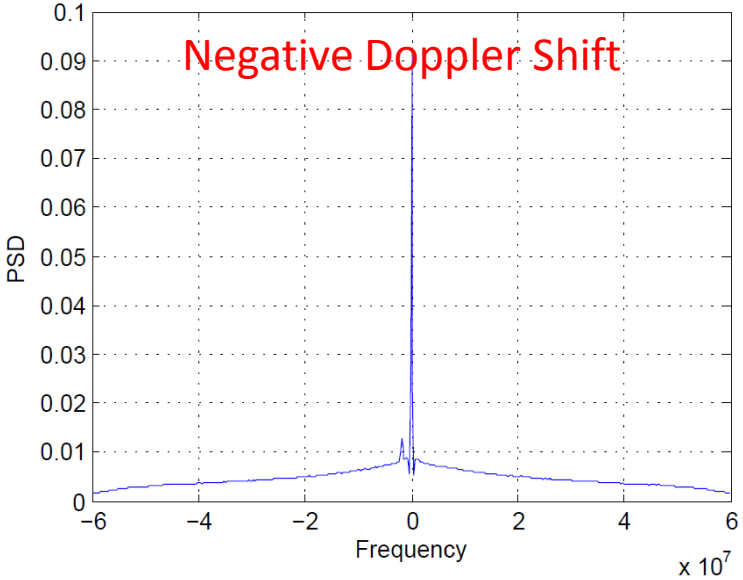
# Homodyne receivers, complex-mixing



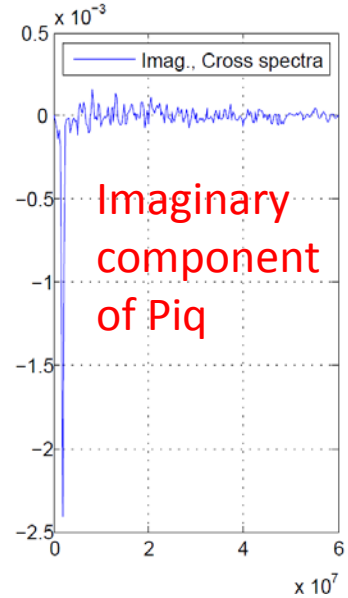

Cross-spectrum
Between I/Q



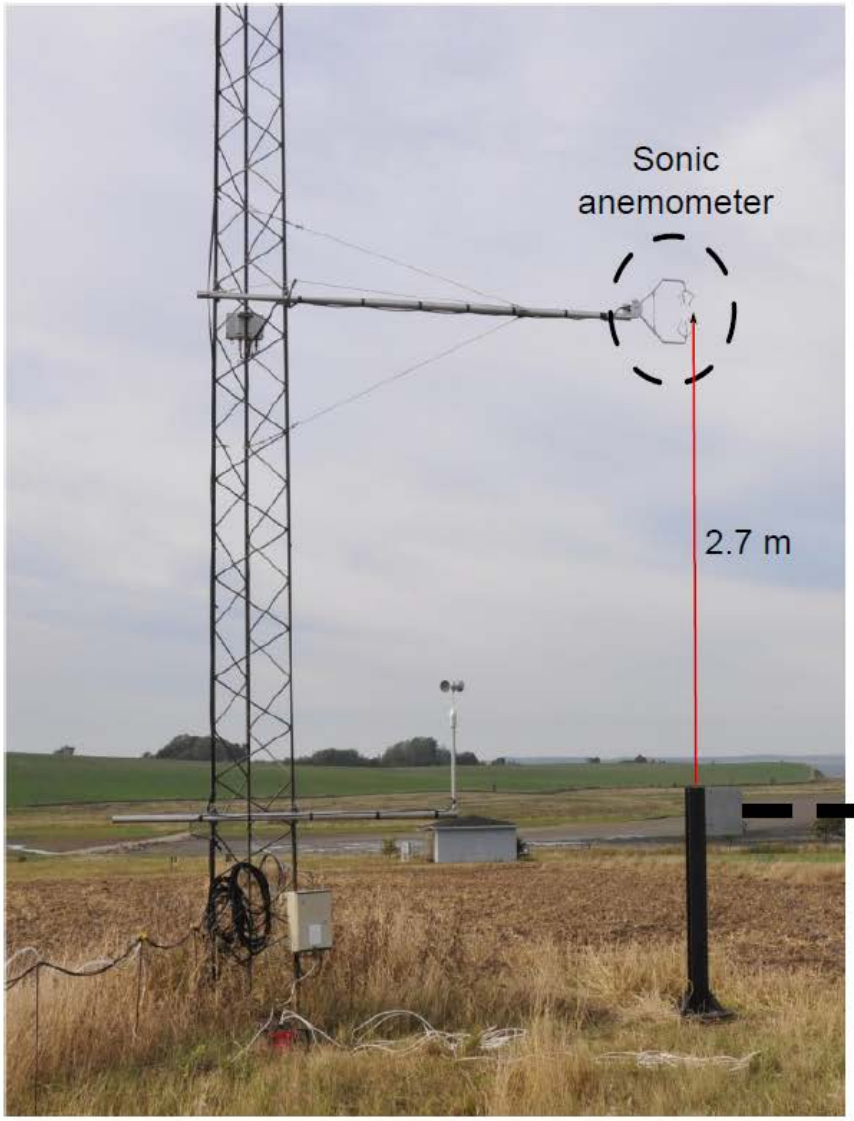




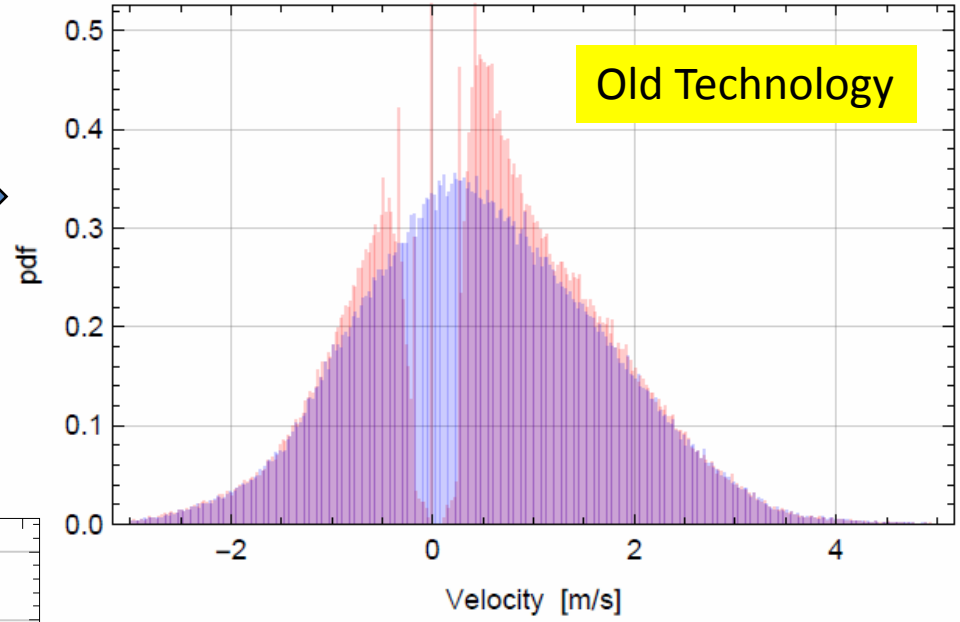

Cross-spectrum
Between I/Q

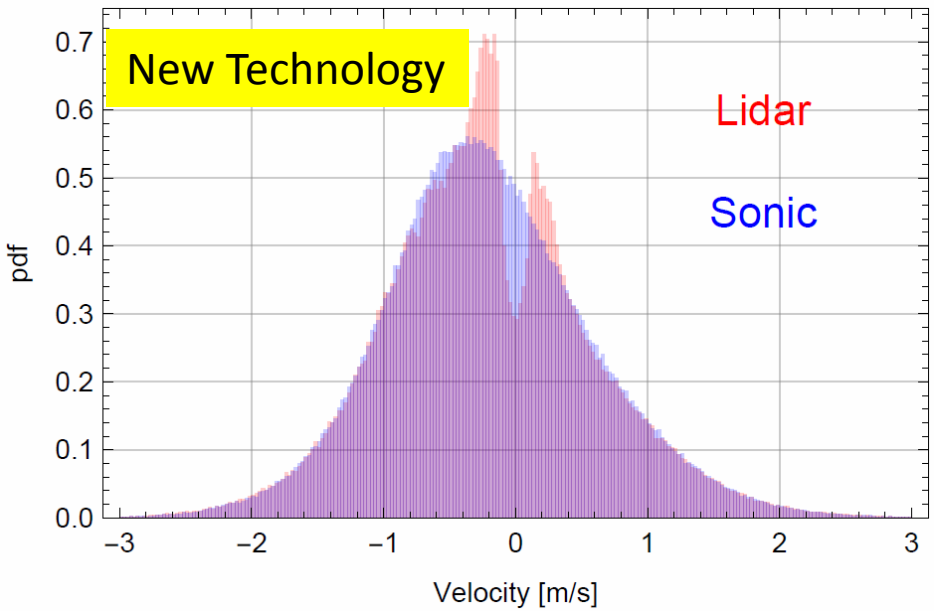



# CW CDL, Image-Reject Homodyne, Field Campaign




Measurements carried out by a CW CDL benefiting from an AOM-based heterodyne receiver with IF sampling

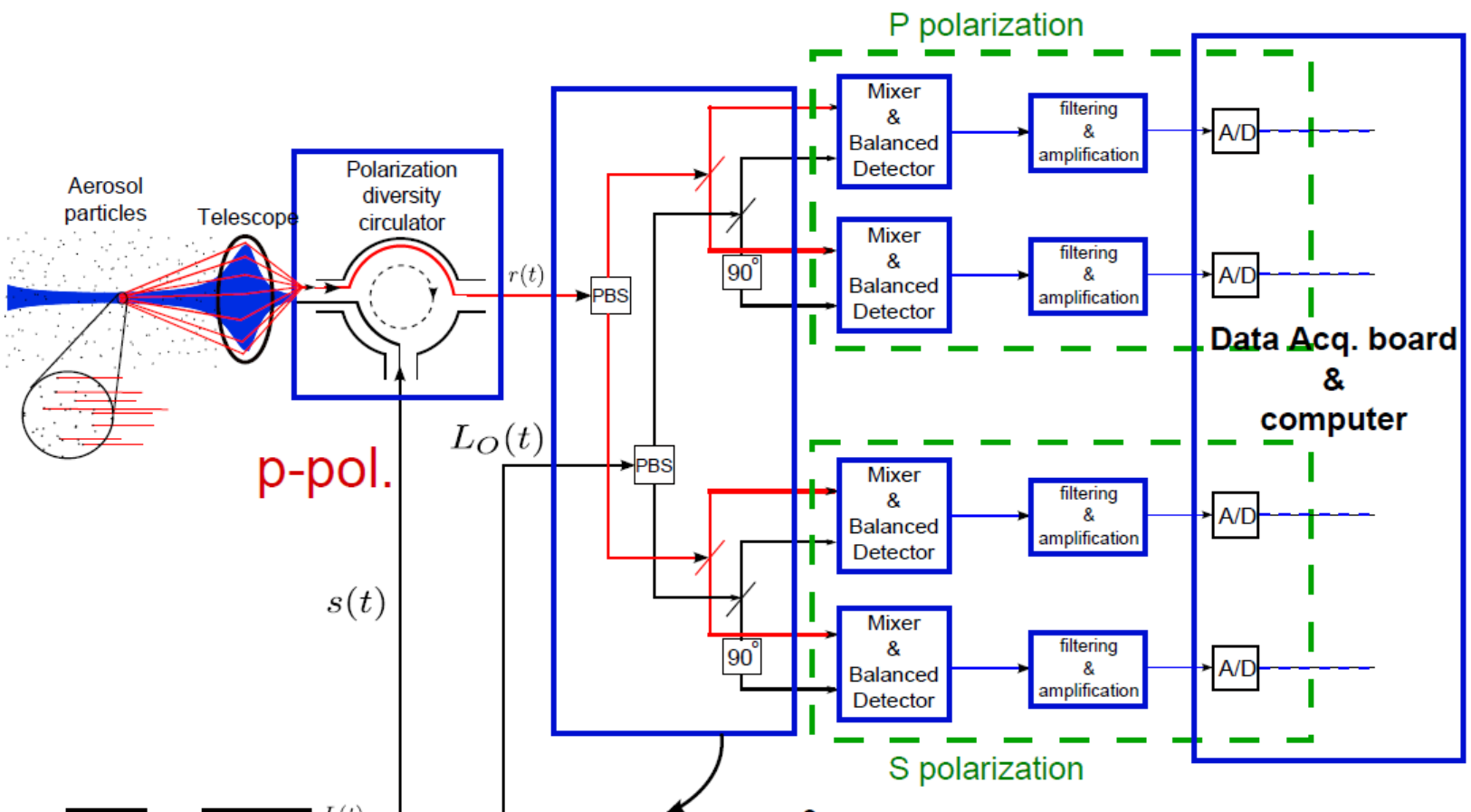



Measurements carried out by a CW CDL benefiting from an image-reject homodyne receiver

C. F. Abari, A. T. Pedersson, E. Dellwik, and J. Mann, “Performance evaluation of an all-fiber image-reject homodyne coherent Doppler wind lidar,” in Atmos. Meas. Tech., vol. 8, pp. 3729-3752, 2015.

# Dual pol. image-reject homodyne, CW CDL




Dual polarization 90° degree optical hybrid
LO path: PMF
signal path: PMF

# Dual pol. image-reject homodyne, CW CDL

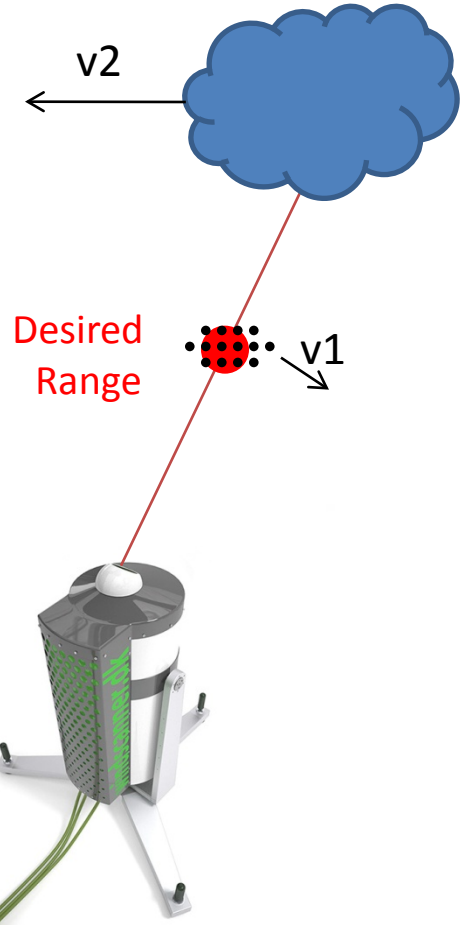
**Applications/Advantages:**

o Identification of clouds, ash and smoke plumes, etc.

o Spurious cloud removal in a processed spectra

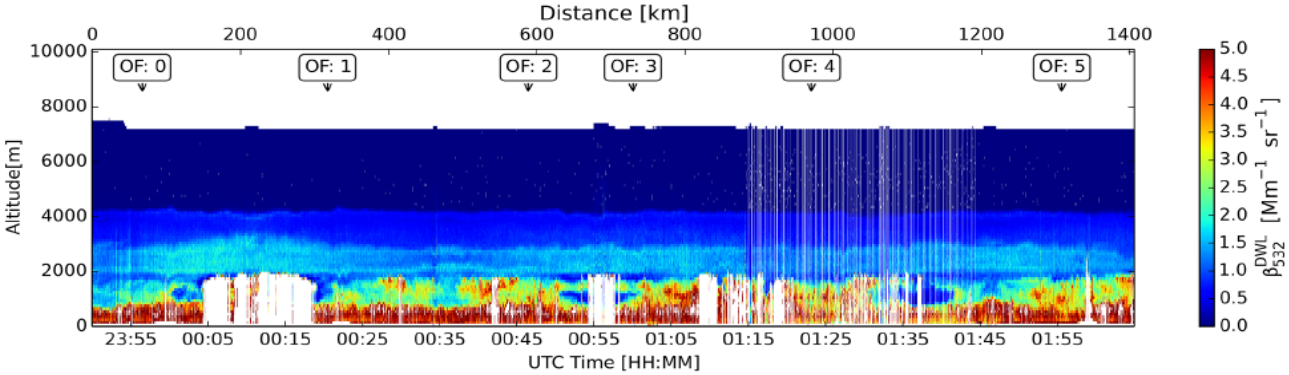
o Accurate estimation of backscatter coefficient

o SNR improvement




Backscatter Coef. Estimation,
Single-Polarization Coherent Doppler
Lidar

**How accurate?**




(Courtesy of German DLR)

# Table of contents:

# Conclusions

- ✓ Due to the employed wavelengths, lidars are capable of receiving backscatter from tiny particles such as aerosols and molecules.
- ✓ Compact (optical fiber based) lidars provide the opportunity to employ and benefit from the technology and component-base available through a more mature industry, i.e., optical communications.
- ✓ CW coherent detection lidars provide fast measurements for short distances. Areas where CW CDLs thrive are where small sampling volume is required, fast scanning and measurement needs to be done, and short measurement ranges where other types of lidars, such as pulsed lidars, may fail.
- ✓ There are different approaches to coherent detection. Depending on the principle of optical down-conversion, different receivers can be used.
- ✓ Image-reject homodyne detection has only recently been practically employed, thanks to the advances in fiber-optic technology.
- ✓ Other advanced technologies in fiber-optic communications can be adopted to provide more efficient and accurate lidar measurements.