(All-Fiber) Coherent Detection Lidars 2

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Table of contents:

- **Reminder**
  - Signal modeling, CW CDLs
  - Direct detection vs. coherent detection
  - image-reject coherent homodyne detection
  - Spectral processing and lab prototype
- **CW CDL, continued**
  - Measurement field campaign
  - Dual polarization (polarization diversity) CW CDL
- **Pulsed (long-range) CDLs**
  - Signal modeling
  - Pulsed CDL vs. radar
  - Signal processing in pulsed CDL
  - Practical considerations
  - Dual polarization pulsed CDL
- **Conclusion**

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  - Practical considerations
  - Dual polarization pulsed CDL
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Signal modeling, CW CDL

The transmit and receive signal may be modeled as,

Reminder

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

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

- 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
- α_ls are backscatter coefficients associated with aerosol particles (independant Gaussian rvs)
- Δf_l is the Doppler shift associated with the movement of the lth particle (Δf_ls are independant Gaussian rvs)
- ϕ_l is the phase factor associated with the lth particle, modeled as a uniformly distributed rv
- all rvs are independant

Signal modeling

Reminder

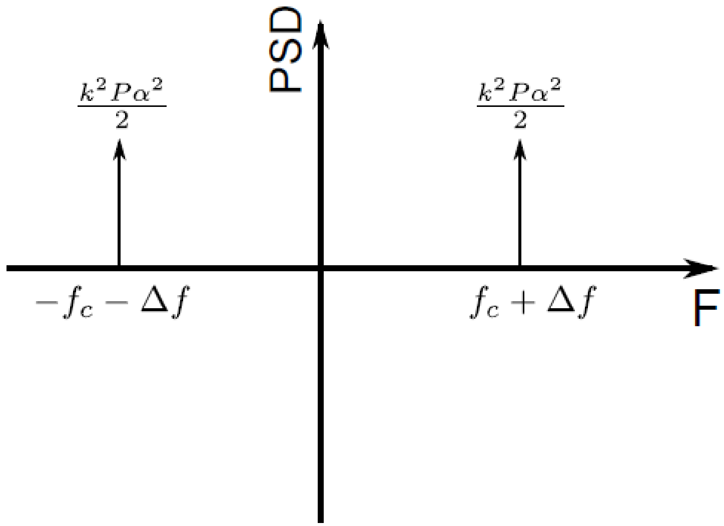
- For simplicity and without lack of generality lets adopt a receive signal model associated with the reflection from a single moving hard target where the effect of phase noise has been neglected.

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

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

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

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

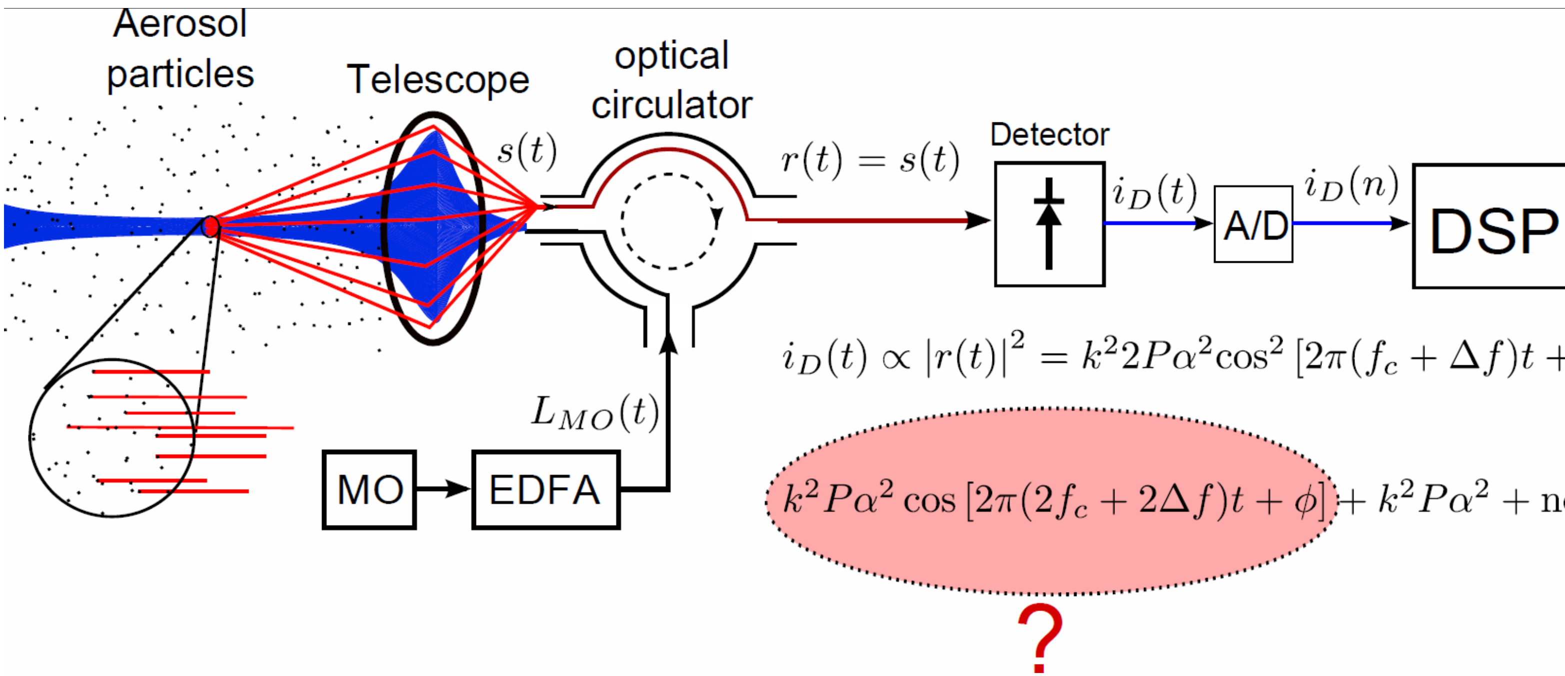


Why coherent detection (heterodyning)?

Reminder

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

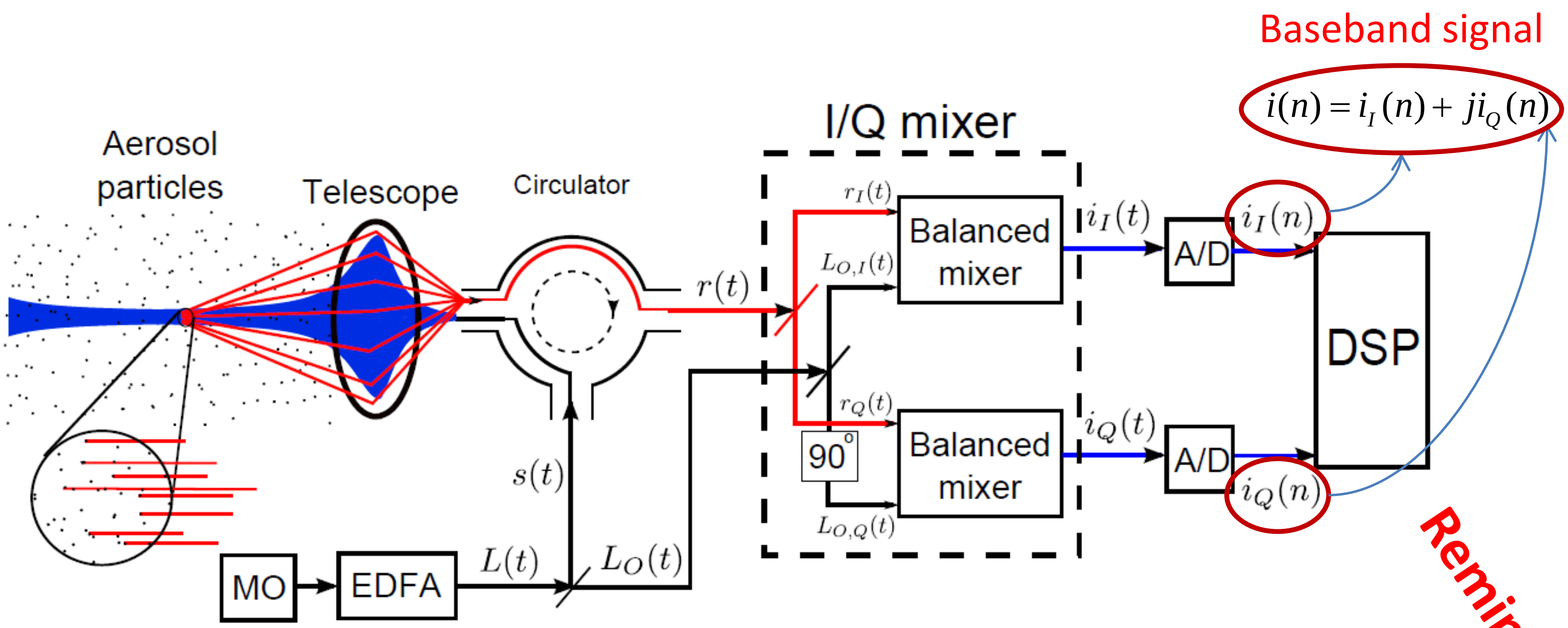
- Due to numerous advantages digital signal processing (DSP) algorithms provide, the received signal needs to be digitized for estimating the Doppler shift.



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

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

CW CDL, Image-Reject Homodyne



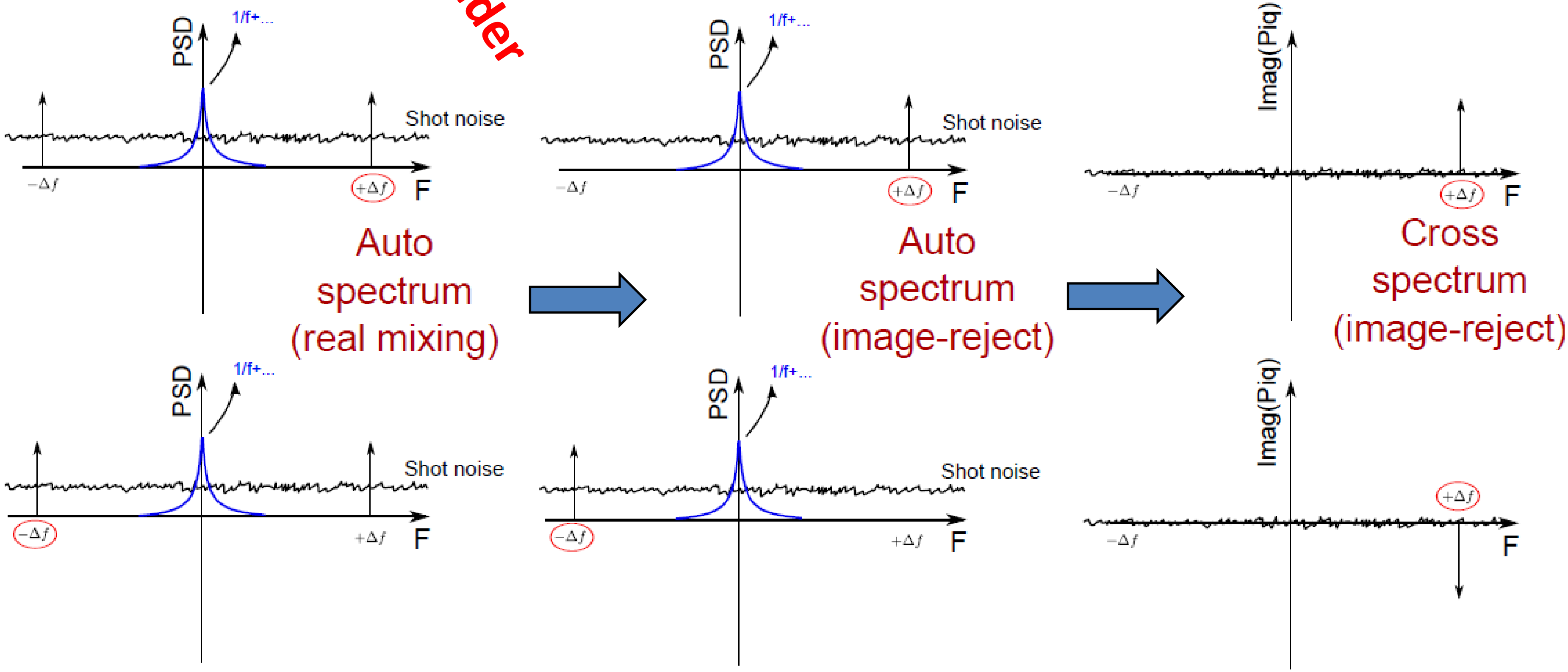
➢To resolve the sign ambiguity one may use a concept popular in wireless communications called homodyne image-reject receivers, also known as homodyne with complex mixing, I/Q or quadrature detection.

➢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.

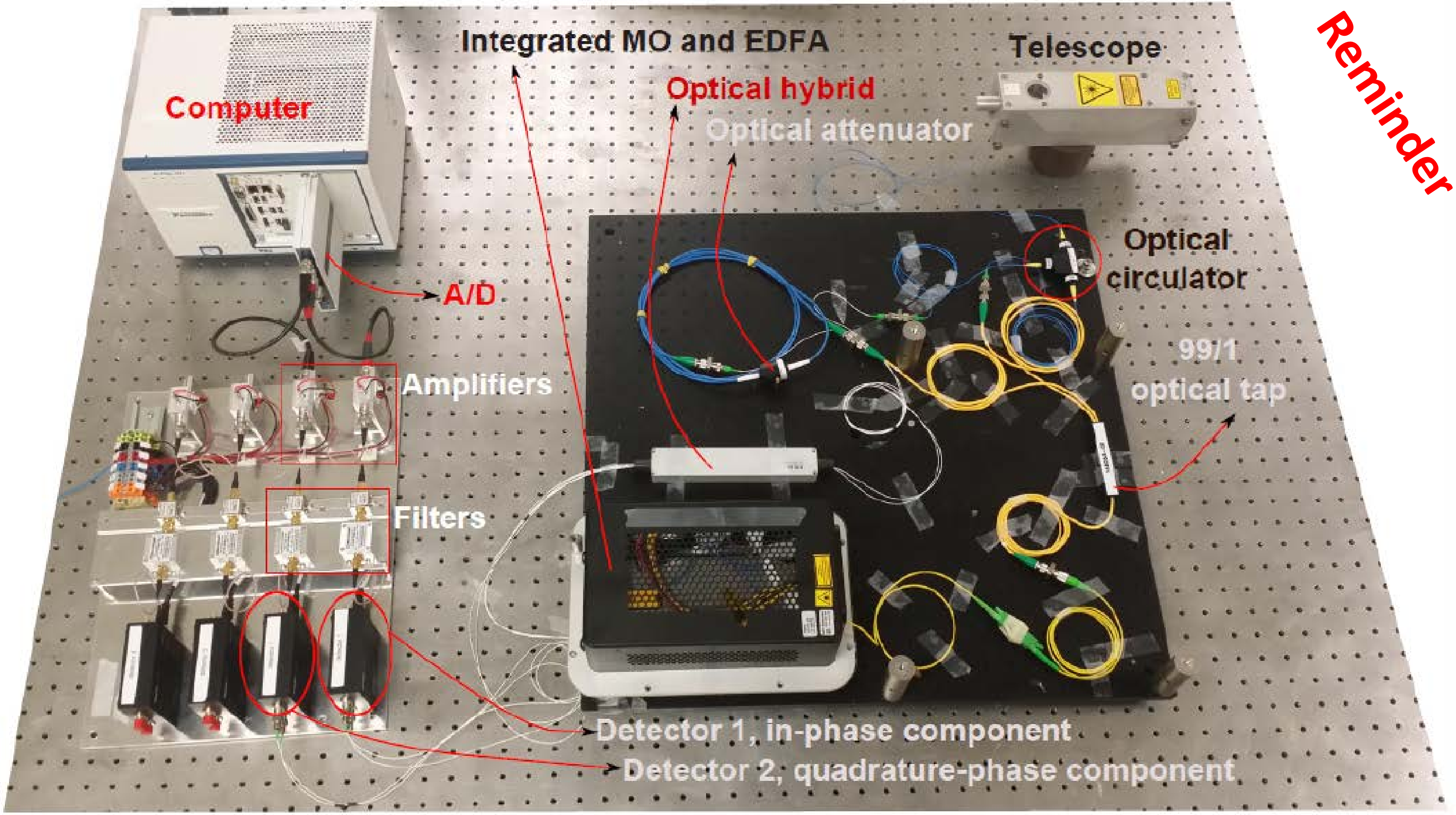
- To eliminate/suppress the noise sources present in the signal, a cross-correlation approach can be employed.
- The cross-correlation benefits from the fact that the noise sources in in-phase and quadrature-phase paths are independent.
- The information is ideally contained in the imaginary part of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

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

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

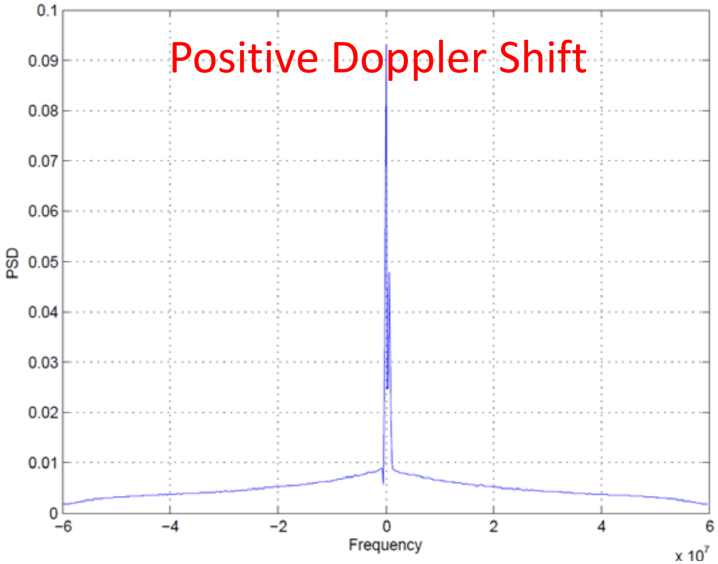


CW CDL, Image-Reject Homodyne Prototype

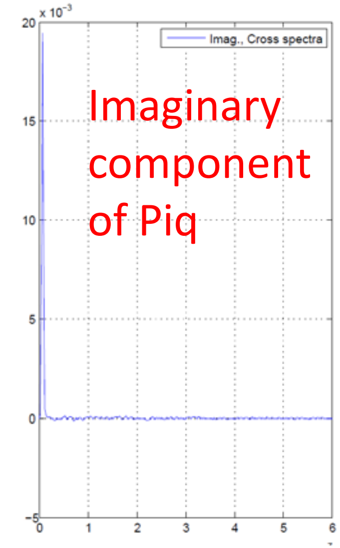


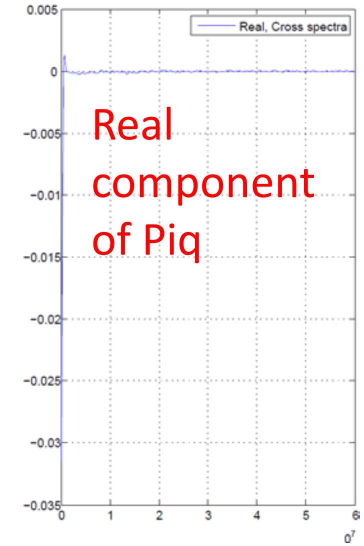
C. F. Abari, A. T. Pedersson, and J. Mann, " An all-fiber image-reject homodyne coherent Doppler wind lidar", Optics Express, vol. 22, no. 21, pp. 25 880-25 894, 2014.

Homodyne receivers, complex-mixing

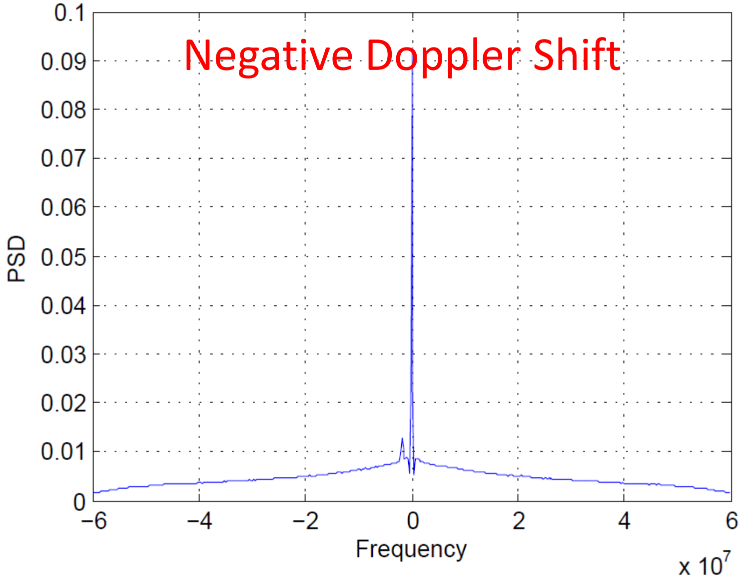


Cross-spectrum
Between I/Q

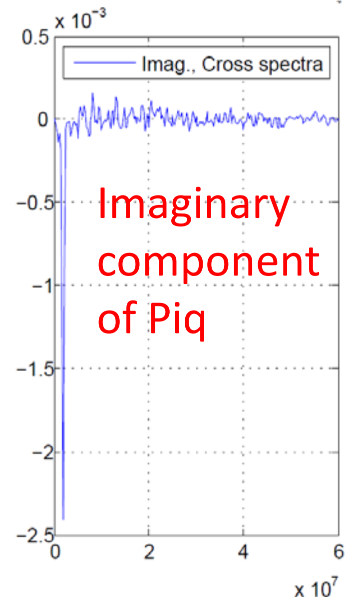


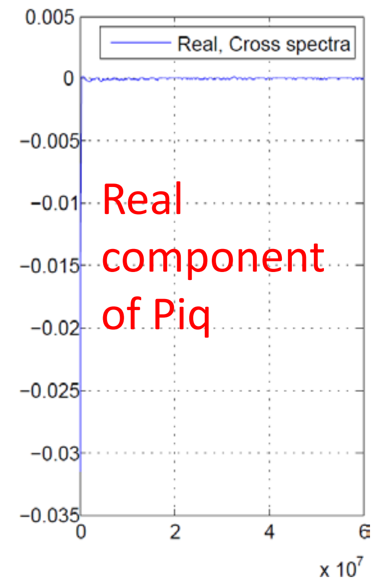


Reminder



Cross-spectrum
Between I/Q





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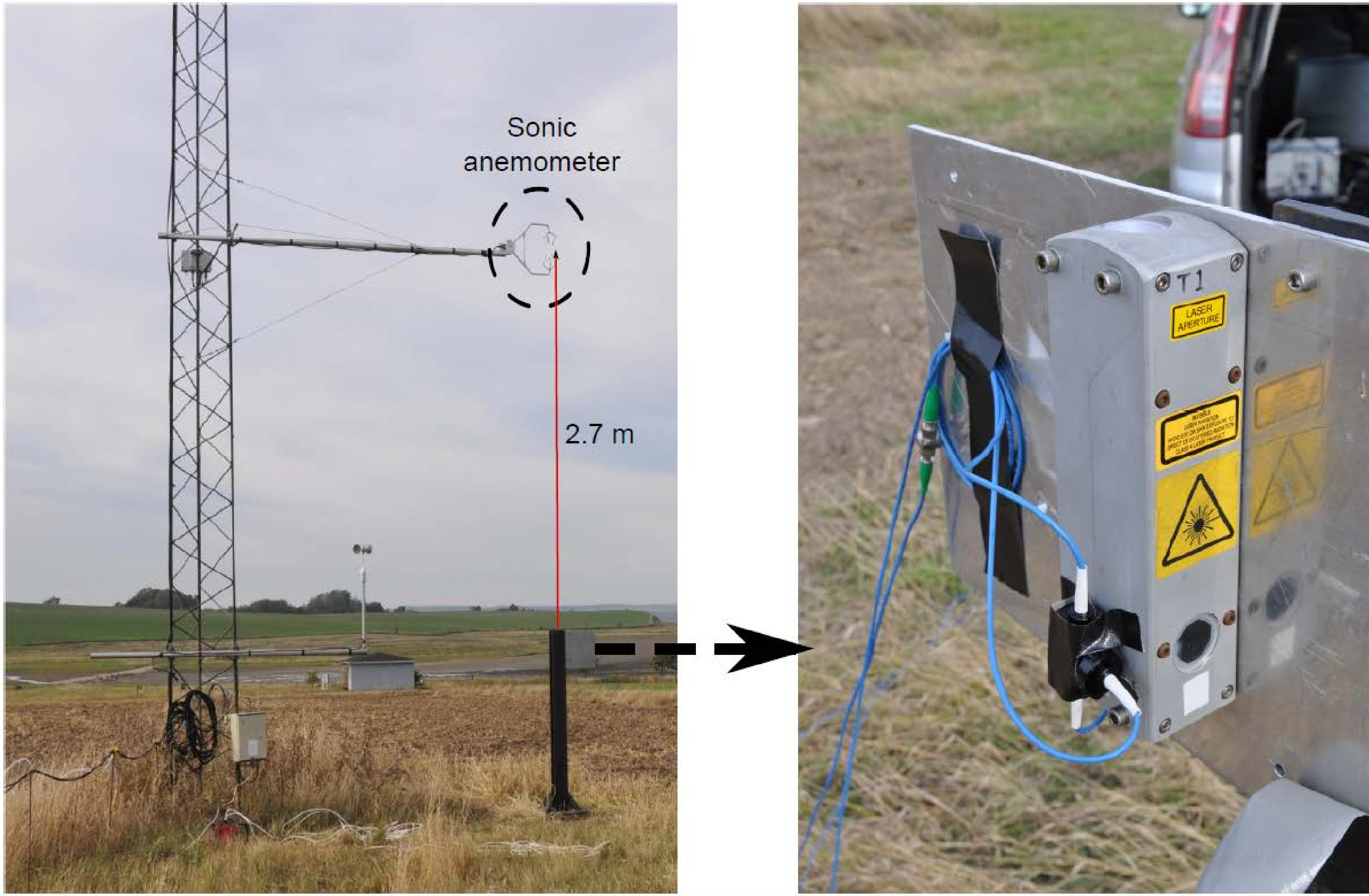
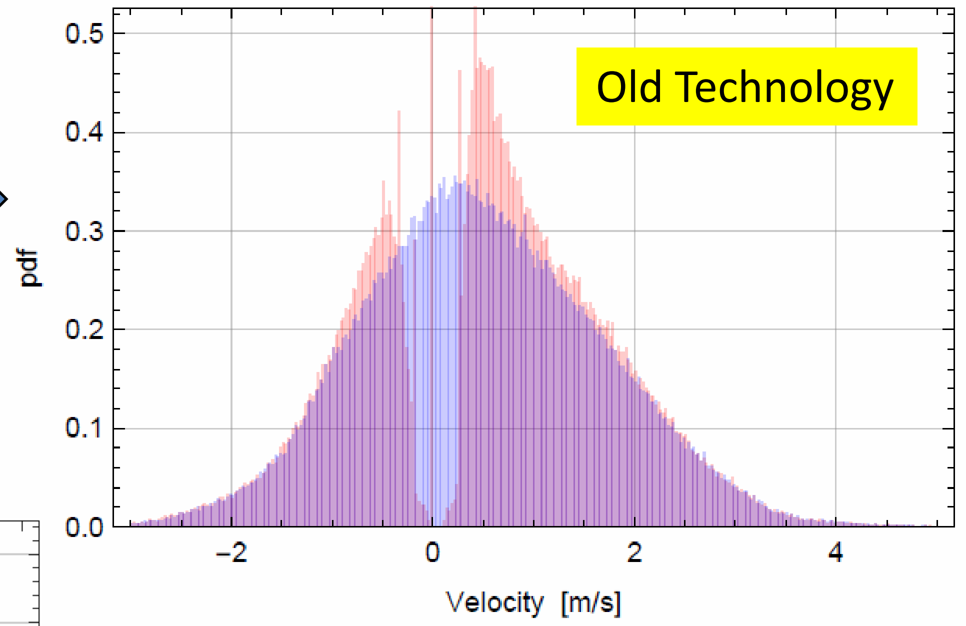
  - Practical considerations, optical circulator
  - Dual polarization pulsed CDL

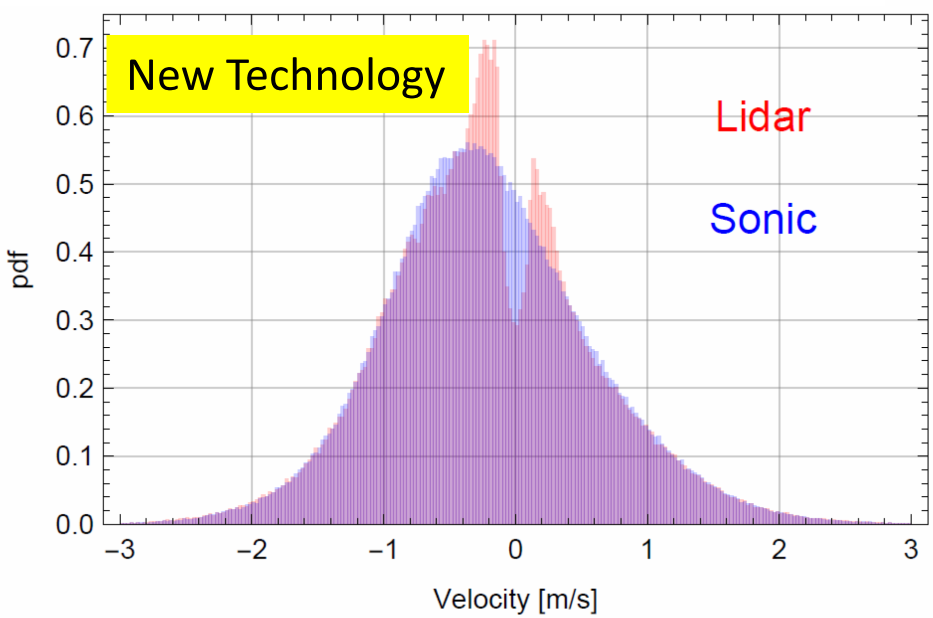
- **Conclusion**

CW CDL, Image-Reject Homodyne, Field Campaign



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



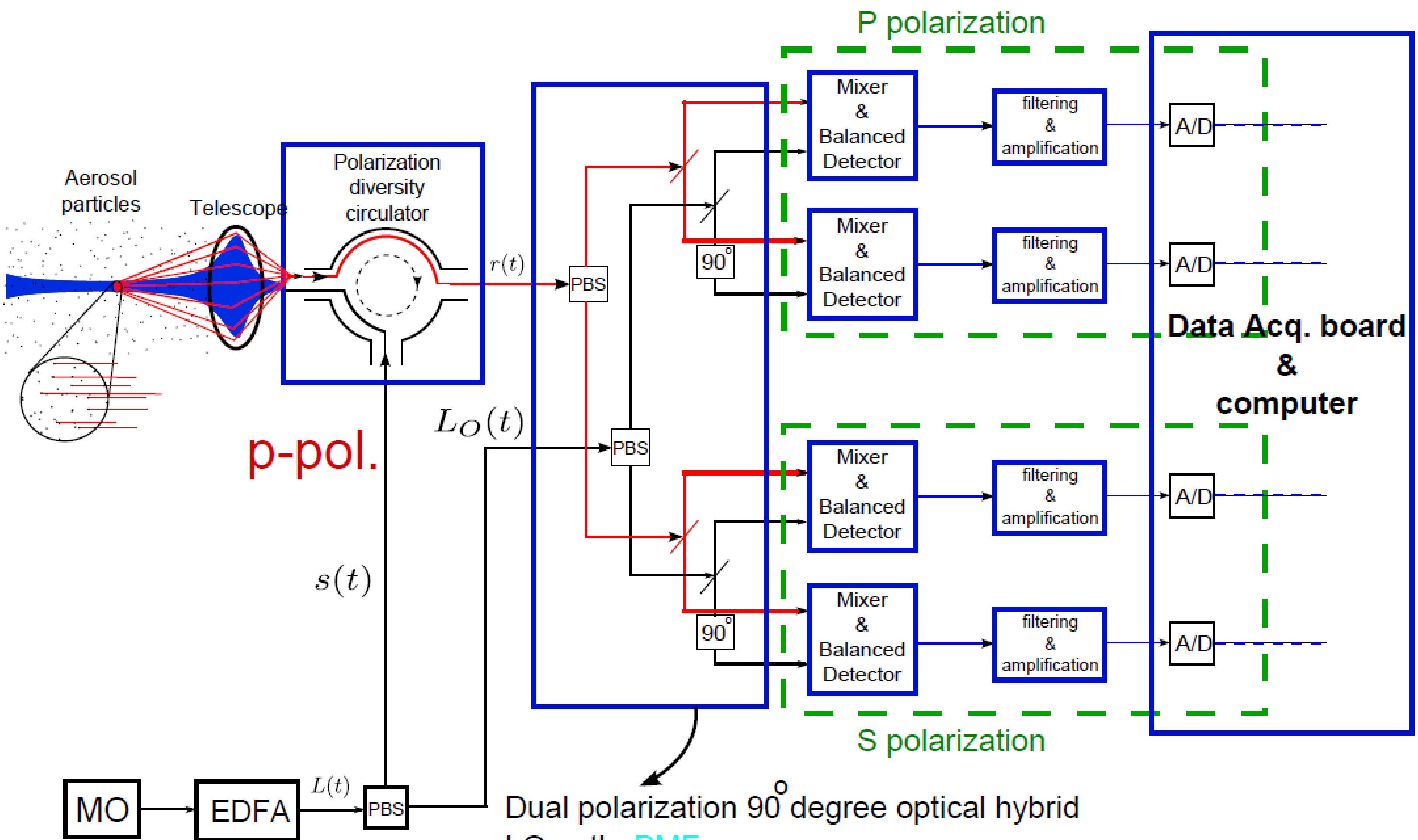


Measurements carried out by a CW CDL benefiting from an image-reject homodyne receiver

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

Main motivation: the detection of depolarized backscatter

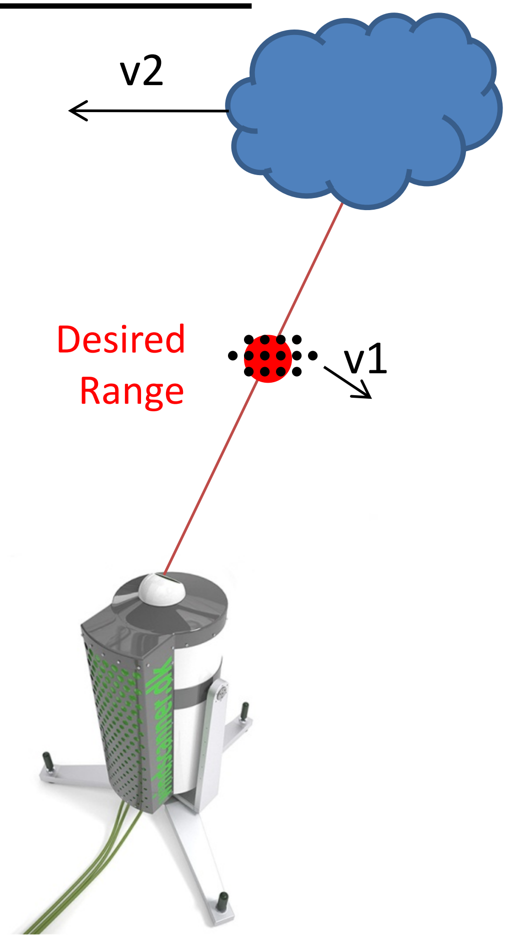


Dual polarization 90° degree optical hybrid
LO path: PMF
signal path: PMF

Dual pol. image-reject homodyne, CW CDL

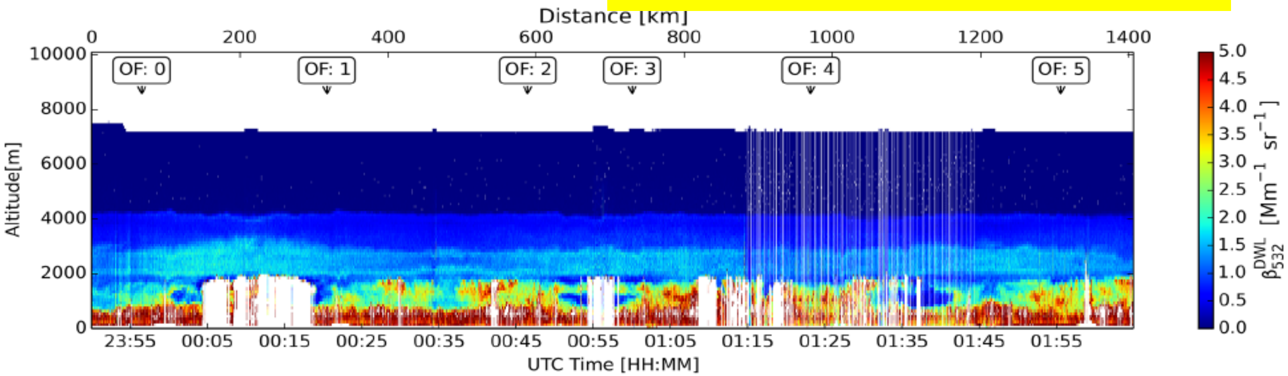
Applications/Advantages:

- 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



<u>Backscatter Coef. Estimation, Single-Polarization Coherent Doppler Lidar</u>

<u>**How accurate?**</u>



(Courtesy of German DLR, pulsed CDL)

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Pulsed CDL signal modeling

The transmit/receive signal associated with backscatter from one single particle may be modeled as,

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

$$r(t) = \alpha\sqrt{2P_s}\, s(t - t_0)\cos\left[2\pi\left(f_c \pm \Delta f\right)t + \theta(t) + \phi\right]$$

$$s(t) = u(t) - u(t - T)$$

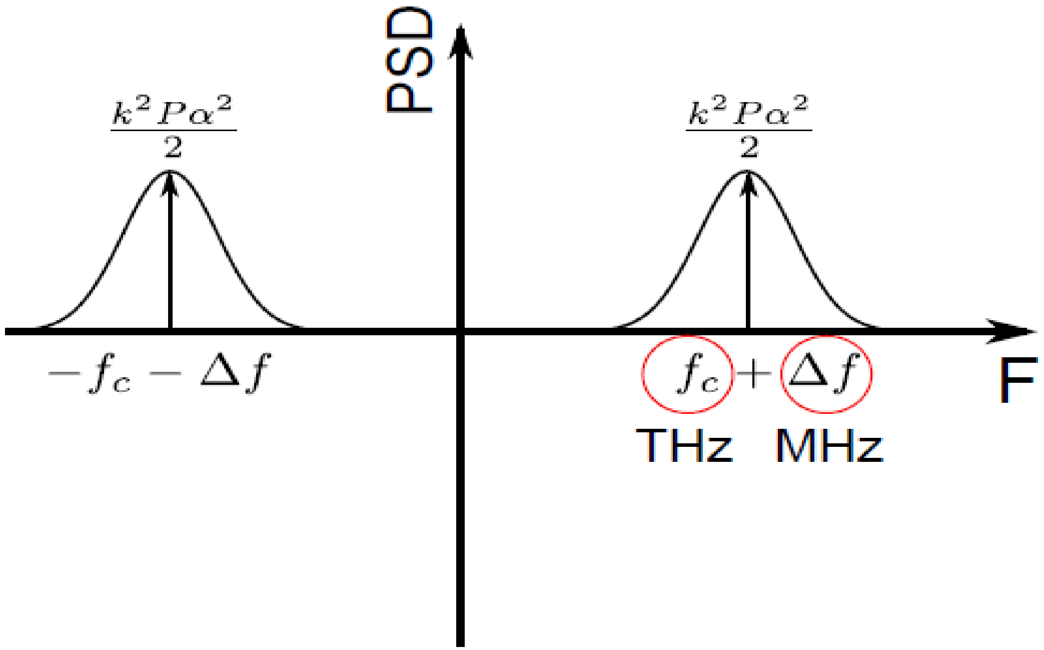
- f_c is the laser frequnecy (carrier frequency)
- $\theta(t)$ is the laser phase noise described by a Weiner process (Lorentzian spectral shape)
- L_R(t) is the laser relative intensity noise (RIN) having a peak at the relaxation oscillation frequency
- α is the net optical attenuation for one single particle
- Δf is the Doppler shift associated with the movement of the particle
- ϕ is the phase factor
- P_s is the transmit signal power
- $s(t)$ is the normalized pulse shape, ie, p_s=1
- t_0 is the time shift associated with the particle distance from the lidar

Pulsed CDL signal modeling

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

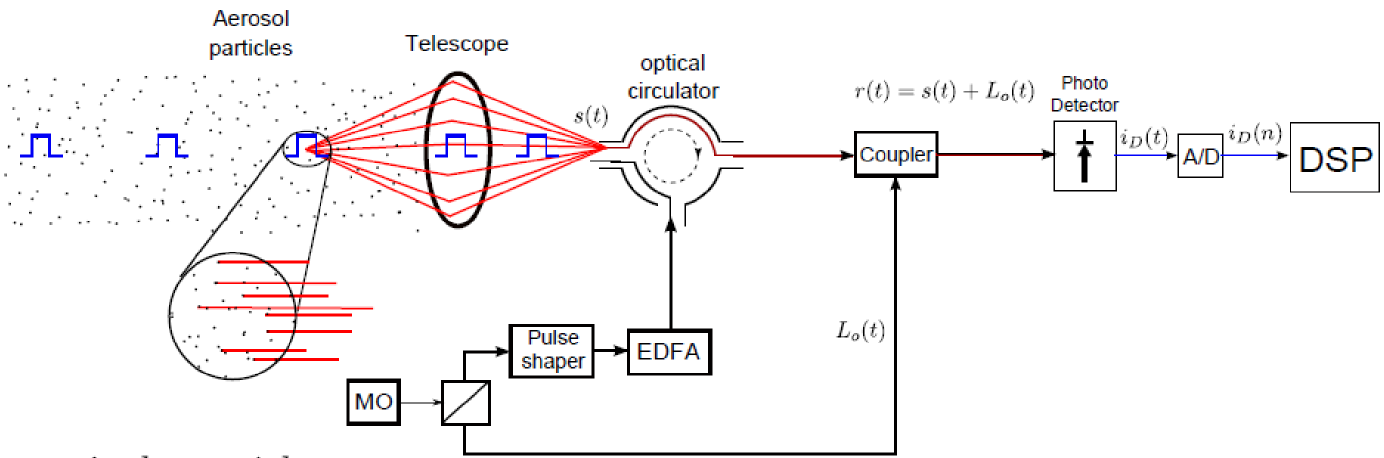
$$R(F) = S(F) \otimes \left[\frac{\sqrt{2P_s}\alpha}{2} e^{j\varphi} \delta(F + f_c + \Delta f) + \frac{\sqrt{2P_s}\alpha}{2} e^{-j\varphi} \delta(F - f_c - \Delta f) \right] \Rightarrow$$

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



Pulsed CDL signal modeling

The transmit and receive signal (for a detector responsivity of 1) may be modeled as,



For a single particle:

$$i_D(t) \propto | r(t) |^2 = L_o(t)^2 + s(t)^2 + 2L_o(t)s(t) + \text{noise and}$$

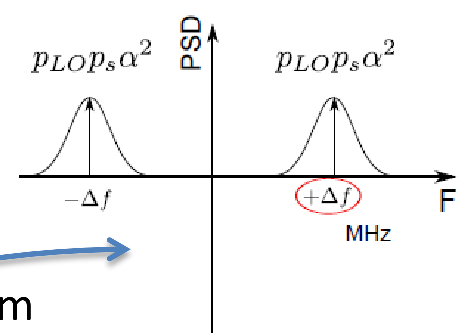
$$2L_o(t)s(t) = 4p_{LO}p_s\alpha s(t)\cos\left[2\pi(f_c+\Delta f)t+\phi\right]\cos\left(2\pi f_c t\right) =$$

$$2p_{LO}p_s\alpha s(t)\left(\cos\left(2\pi\Delta f t+\phi\right)+\cos\left[2\pi(2f_c)t+2\pi\Delta f t+\phi\right]\right)$$

Thus,

$$i_D(t) = \boxed{2p_{LO}p_s\alpha s(t)\cos\left(2\pi\Delta f t+\phi\right)} + \text{noise}$$

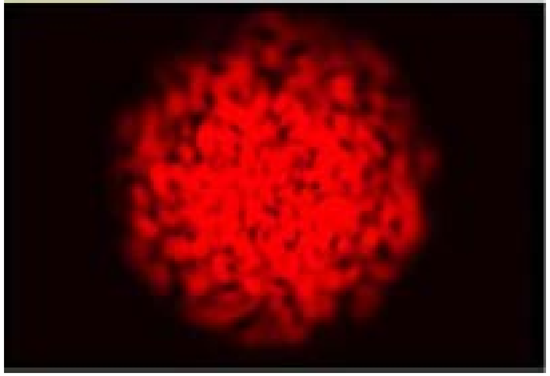
Fourier Transform



Noise in CDLs

- Noise plays an important role in signal detection in lidars. There are many noise terms in the resultant signal,
  - **DC (and IF offset) noise**
  - **Detector's shot noise**
  - **Thermal noise**
  - **Dark noise**
  - **1/f noise**
  - **RIN noise**
  - **Target speckle noise**

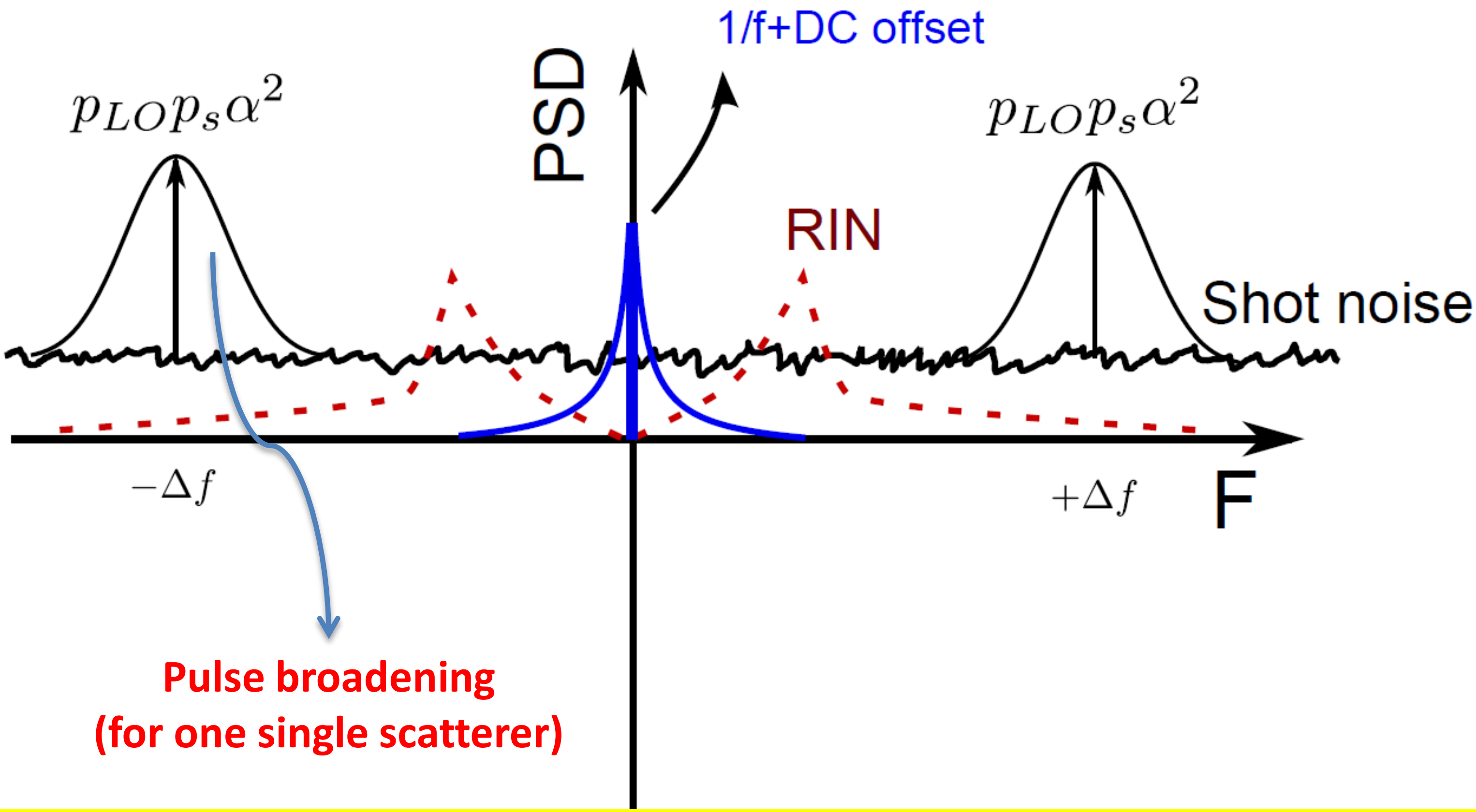
Negligible



Speckle noise

- Shot noise power is primarily a function of the LO power. It has a Gaussian distribution, why not Poisson?
- Interferometric noise is due to leakage in optical components such as circulator; it is not an issue in pulsed lidars but poses a problem in CW
- RIN noise is mainly due to output power fluctuations of the laser

Noise in CDLs



- **Noise in pulsed CDLs can be more troublesome when compared to CW CDLs. This is due to the fact that less signal data/lower spectral resolution is available in pulsed CDLs. This is especially exacerbated in the event of diffused target.**

- **As a result, smarter signal processing algorithms are required to process the data.**

Signal Modeling in Pulsed CDLs

Transmit Signal (also known as modulated pulse)

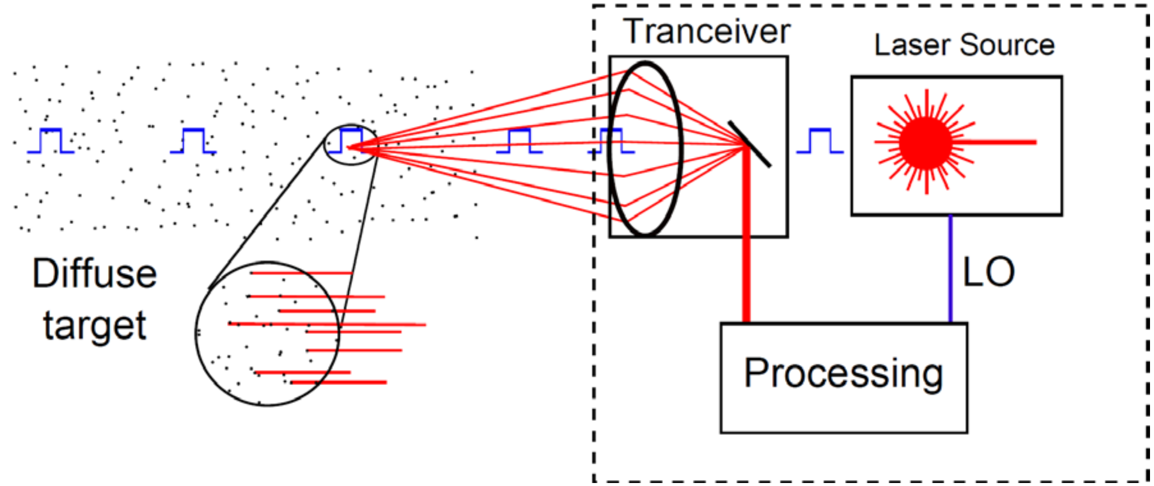
$$E(t) = \sqrt{2P_s}\, s(t)\cos\left(2\pi f_c t\right)$$

$$s(t) = u(t) - u(t-T)$$

$$i(t) = k\int_0^{+\infty} s(t-t')\boxed{\sum_{l=1}^{N}\alpha_l\delta\left(t'-t_l\right)}dt'$$

Complex Baseband Signal

No Doppler

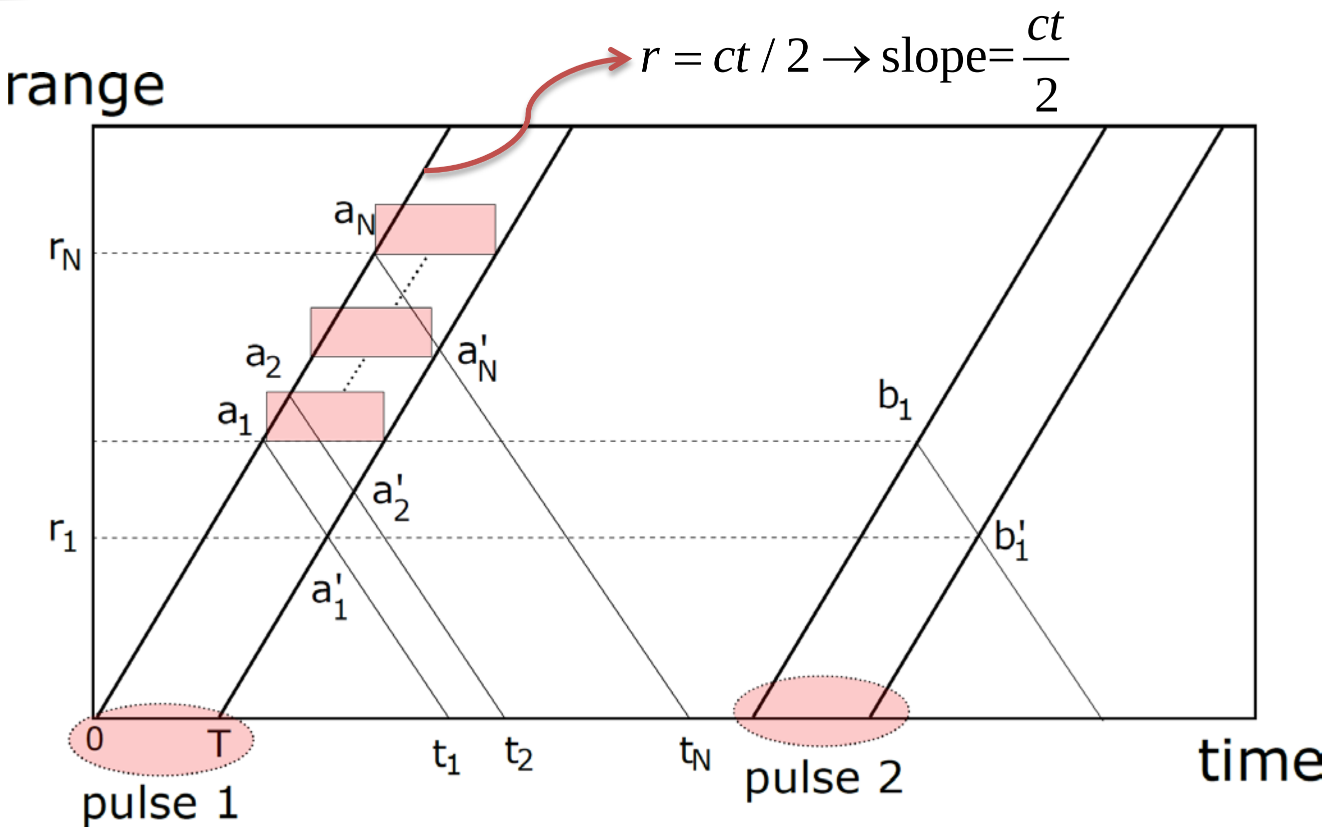


$$\begin{cases} i(t) = h(t)\otimes s(t) \\ h(t) = k\sum_{l=1}^{N}\alpha_l\delta\left(t-t_l\right) \end{cases}$$

If we include the effect of Doppler, i.e., the particles are not stationary,

$$i(t) = k\int\int_0^{+\infty} s(t-t')\exp\left[j2\pi f'(t-t')\right]\sum_{l=1}^{N}\alpha_l\delta\left(t'-t_l\right)\delta\left(f'-f_l\right)dt'df'$$

Signal Modeling/Processing in Pulsed CDLs, Radar Vs. CDL

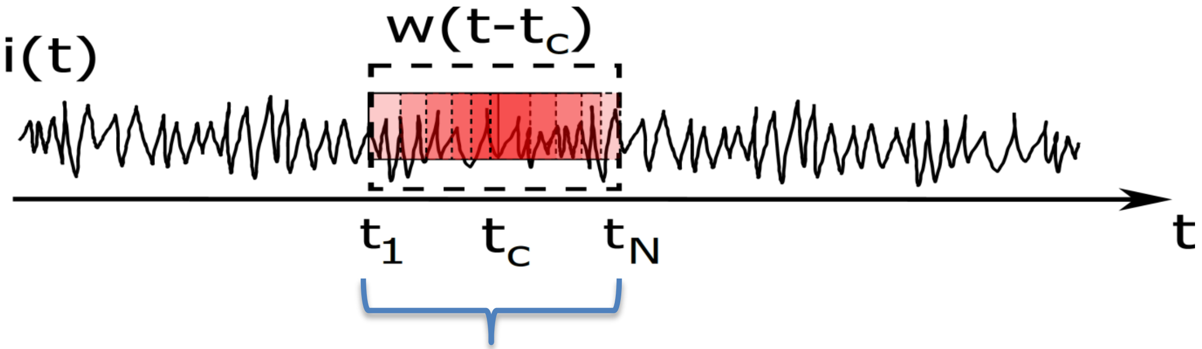


- In radars, (phase) correlation is preserved from pulse to pulse (atmospheric correlation time is on the order of 10 ms for radar frequencies).

- In pulsed CDLs, phase correlation is lost from pulse to pulse (atmospheric correlation time is on the order of a few micro seconds).

Signal Processing in Pulsed CDLs

$$i(t)=k\int\int_{0}^{+\infty}s(t-t')\exp\left[j2\pi f'(t-t')\right]\sum_{l=1}^{N}\alpha_l\delta(t'-t_l)\delta(f'-f_l)dt'df'$$



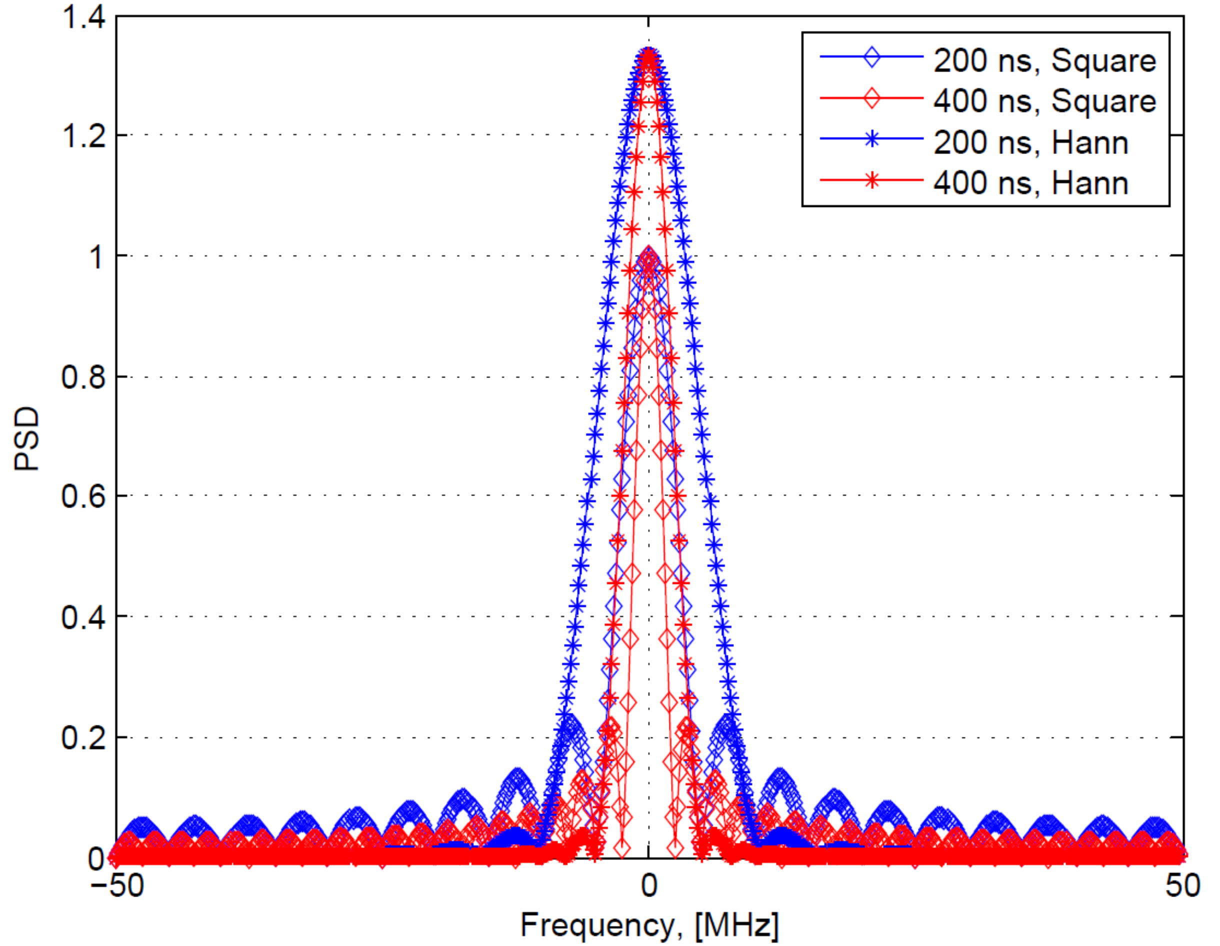
Range Gate (Range Gate in pulsed CDLs in defined by the pulse length and truncation window)

$$i_T(t)=w(t-t_c)i(t)\Rightarrow$$

$$P_{i_T}(f)=\mathrm{E}\left\{\left|I_T(f)\right|^2\right\}=k^2\sum_{l=1}^{N_0}\mathrm{E}\left\{\left|\alpha_l\right|^2\right\}\left[\left|W(f)\right|^2\otimes\left|G(f)\right|^2\otimes\mathrm{E}\left\{P_{T_0}(f)\right\}\right]$$

Thus, the spectra is a convolution of the actual Doppler spectra, window function, and pulse spectra!

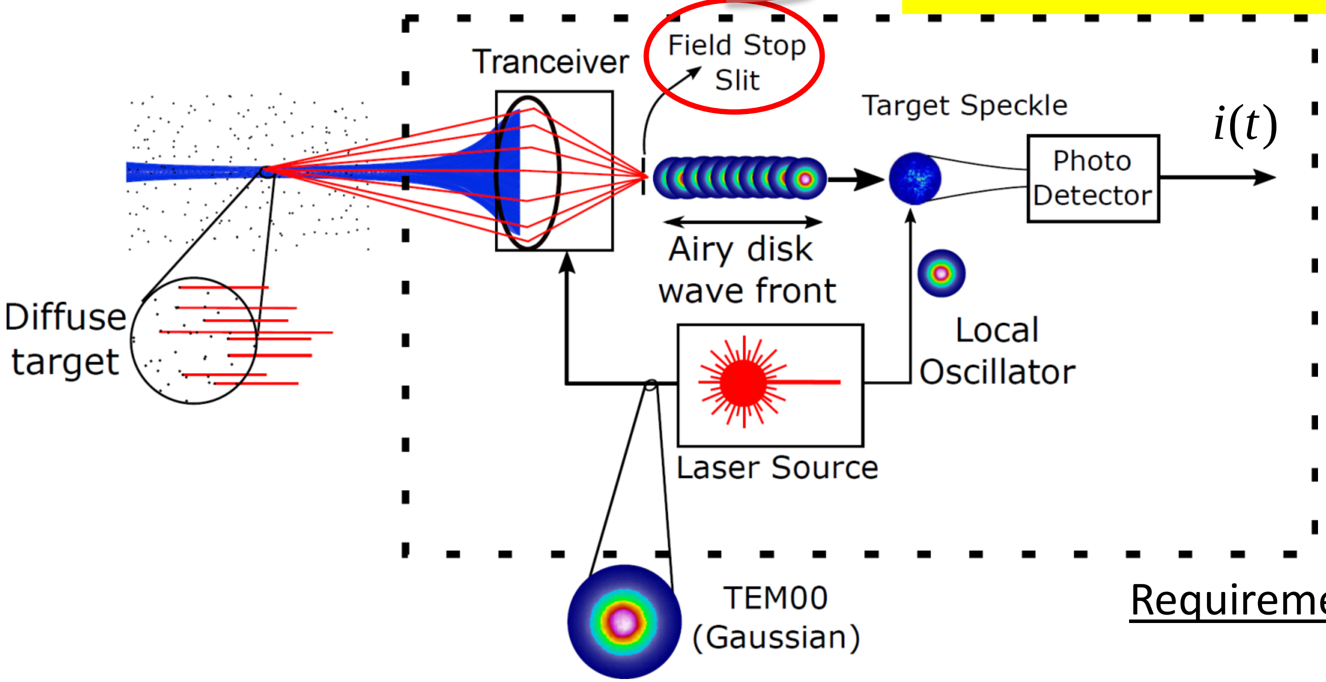
Practical considerations, pulse shape effect



The same holds for the window function. Looks like having a very long window function can be beneficial (due to less spectral broadening). **<u>What's the catch?</u>**

Practical considerations, target speckle

In all-fiber CDLs, fiber end acts as the slit!



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

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

Requirements for coherent detection:

- Wave-front matching between signal and LO; limited receiver field of view: diffraction-limited optics
- Polarization matching between signal and LO; detection efficiency scales with the cosine of the angle between signal and LO polarization states

Practical considerations, atmospheric turbulence

$$A_{eff}(z)=\frac{\pi D^2}{4}\left[1+\left(\frac{\pi D^2}{4\lambda z}\right)^2\left(1-\frac{z}{F}\right)^2+\frac{D^2}{2\rho_0^2}\right]^{-1},$$

$$r_0=\left[1.45\left(\frac{2\pi}{\lambda}\right)^2\int_0^z C_n^2(z')\left(1-\frac{z'}{z}\right)^{\frac{5}{3}}dz'\right]^{-\frac{3}{5}}$$

For a constant C_n^2,

$$r_0=\left[\frac{4.35}{8}\left(\frac{2\pi}{\lambda}\right)^2 C_n^2 z\right]^{-\frac{3}{5}}$$

Refractive Index Structure Function

Turbulence Coherence Diameter

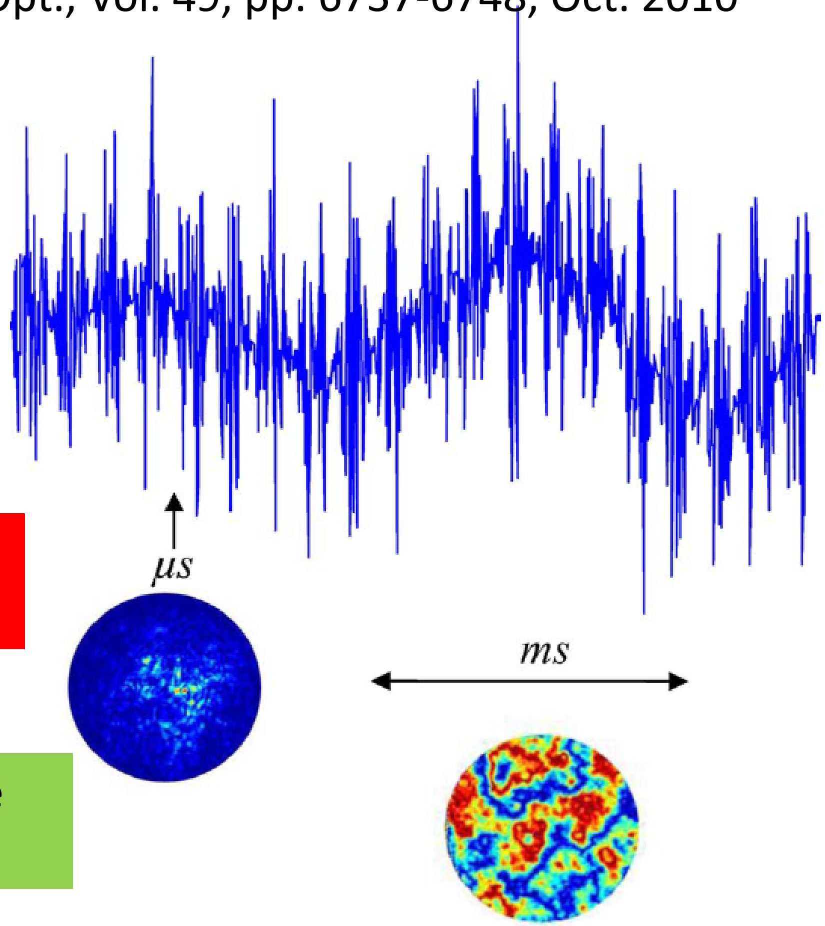
$c_n^2=10^{-12}$

Strong Turbulence

$c_n^2=10^{-14}$

Moderate Turbulence

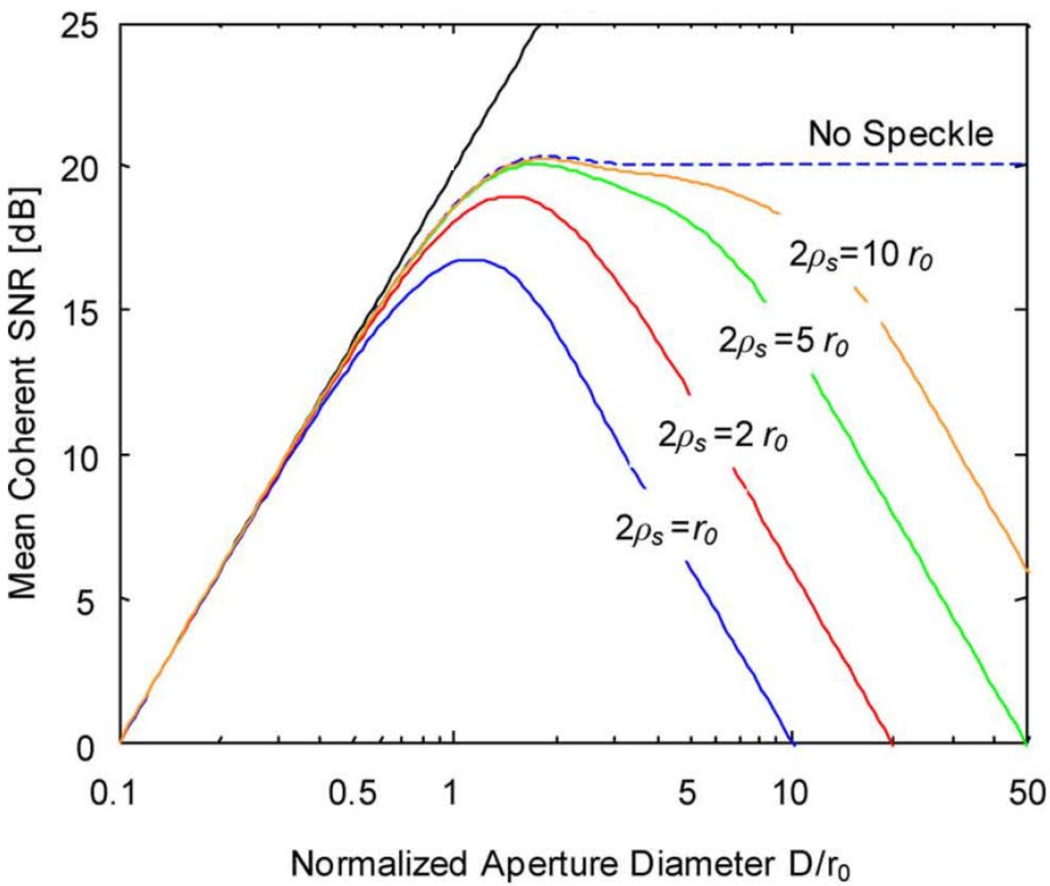
A. Belmonte, “Statistical model for fading return signals in coherent lidars”, J. Appl. Opt., Vol. 49, pp. 6737-6748, Oct. 2010



Target vs. Turbulence Induced Speckle

Practical considerations, aperture size

Imagine a target speckle coherence radius ρ_s and turbulence coherence radius r_0, then



A. Belmonte, "Statistical model for fading return signals in coherent lidars",J. Appl. Opt., Vol. 49, pp. 6737-6748, Oct. 2010

As a rule of thumb, the aperture diameter for normal (average) atmospheric conditions and measurement range is about 4 inches.

Practical considerations

o The signal after digitization is a time series which contains the information for all ranges. Thus, range gating needs to be performed.

o In other words, the signal associated with the desired signal is a windowed version of the original signal. As a result, the processed Doppler spectrum is,

$$P_{i_T}(f) \approx |W(f)|^2 \otimes |G(f)|^2 \otimes \mathrm{E}\left\{P_{T_0}(f)\right\}$$

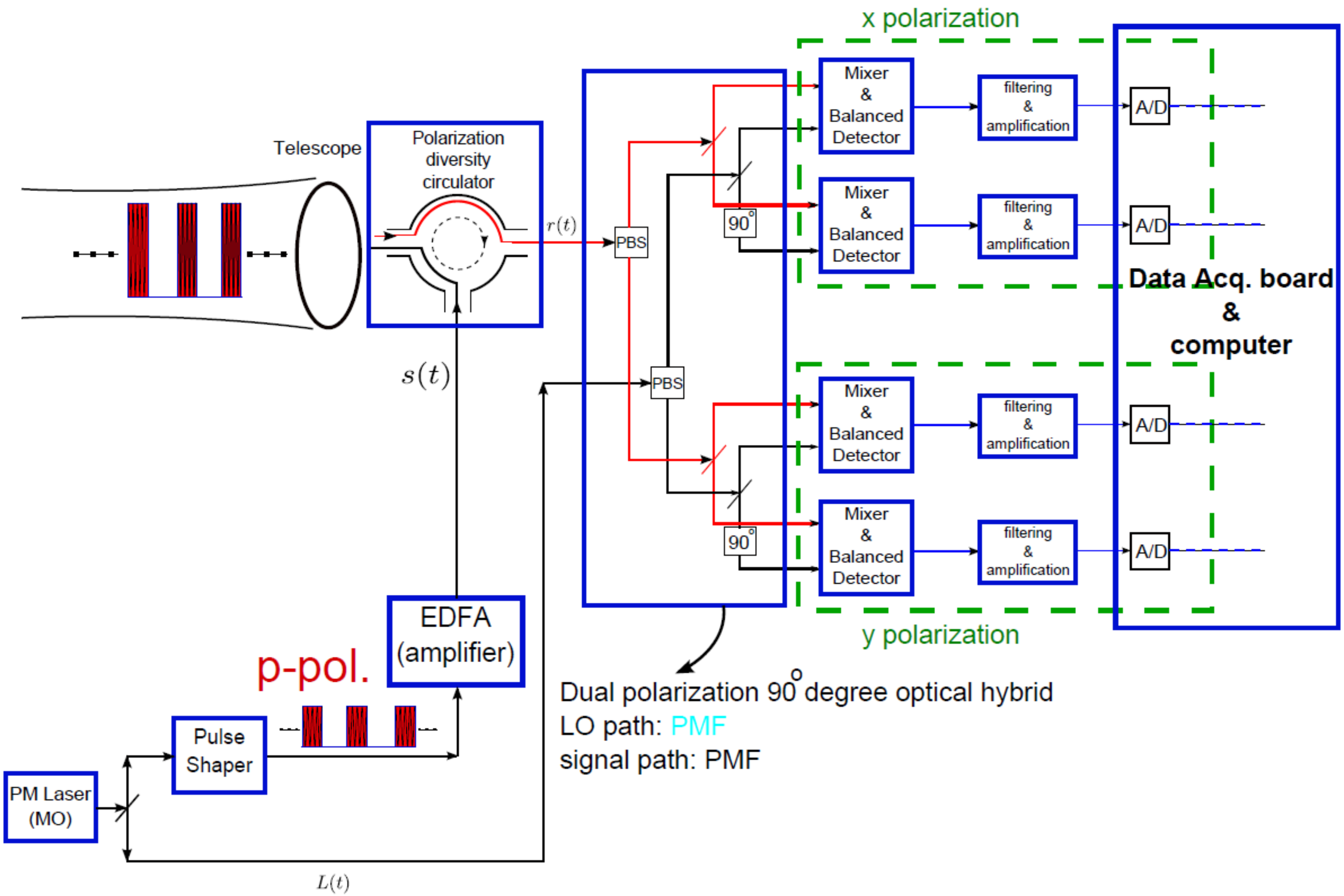
o The effect of windowing as well as pulse shape is spectral broadening and leakage.

o Pulse shape design is a trade-off between range resolution and spectral broadening.

o The longer the pulse the lower the spectral broadening but a worse range resolution.

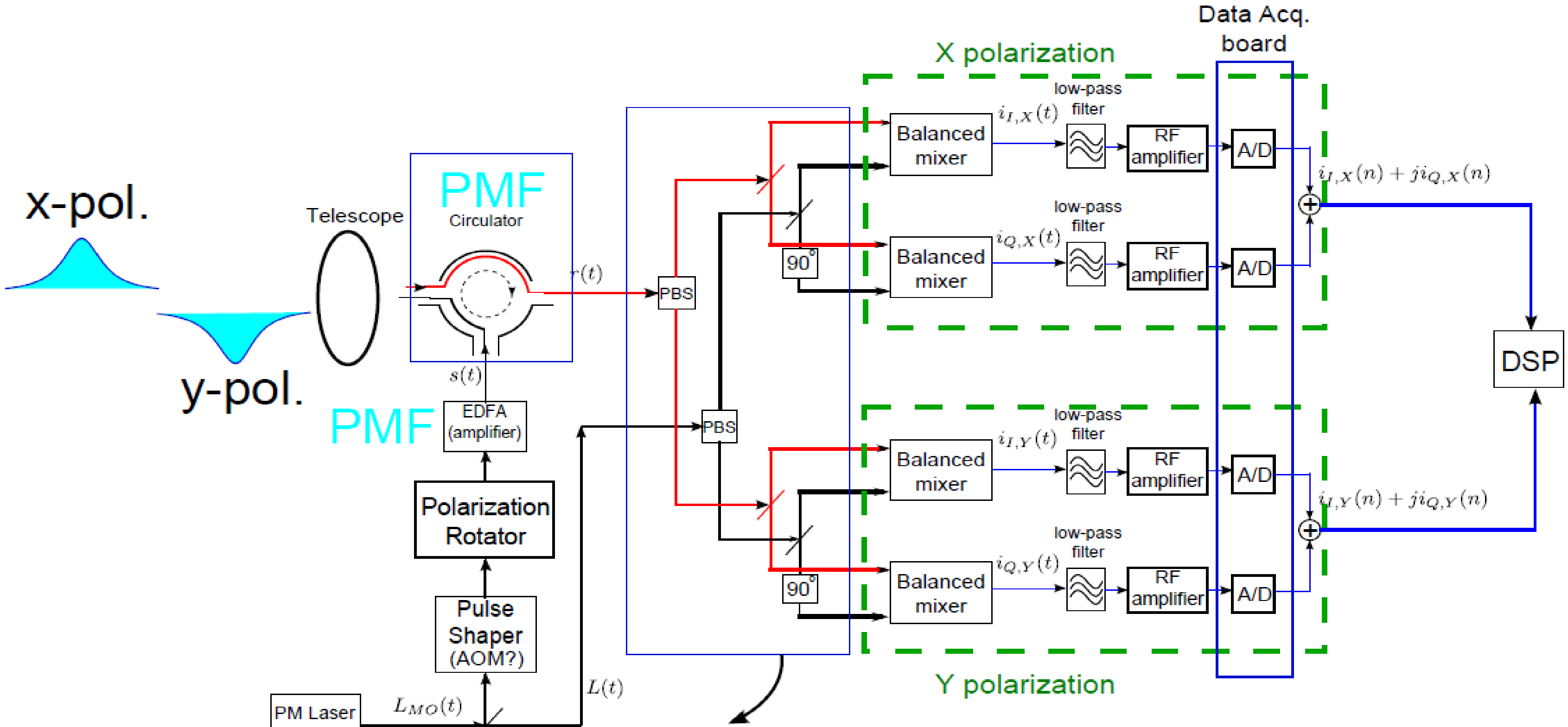
o Most pulsed CDLs have a pulse length of 200-400 ns.

Dual Pol. Image-reject homodyne, pulsed



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

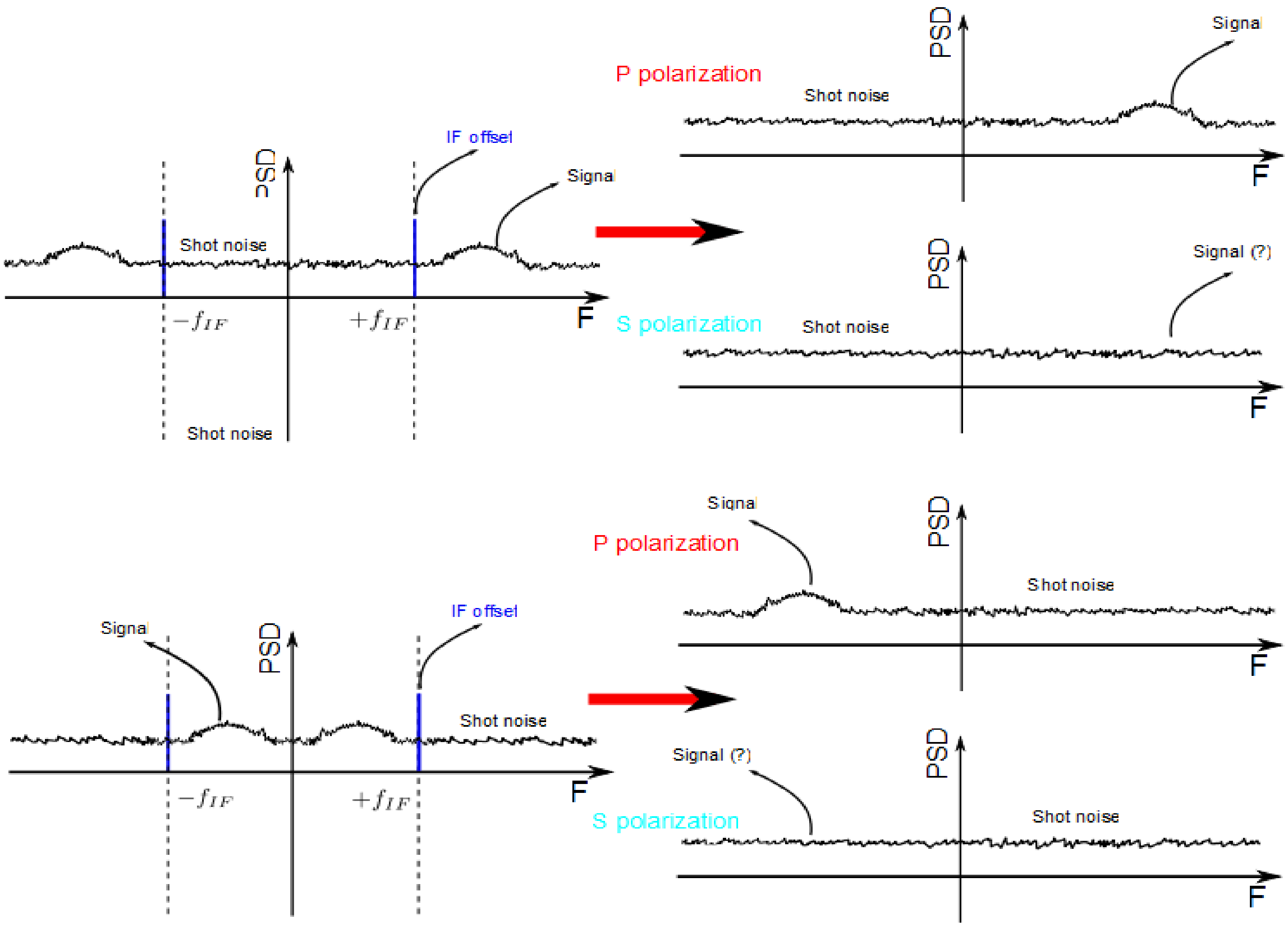
Polarization diversity pulsed CDL



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

A/D sampling freq.: 100 MHz
velocity range (m/sec): [-40,40]
(twice the range compared to the one with AOM)

Dual Pol. Image-reject homodyne, pulsed



Polarization diversity circulator

Although fiber-coupled and compact circulators are commercially available, their application in pulsed CDLs in very limited due to high pulse energies. The beam needs to be expanded before passing through optical components to prevent optical damages.

[Dual polarization and fiber coupled open-space optical circulator]()

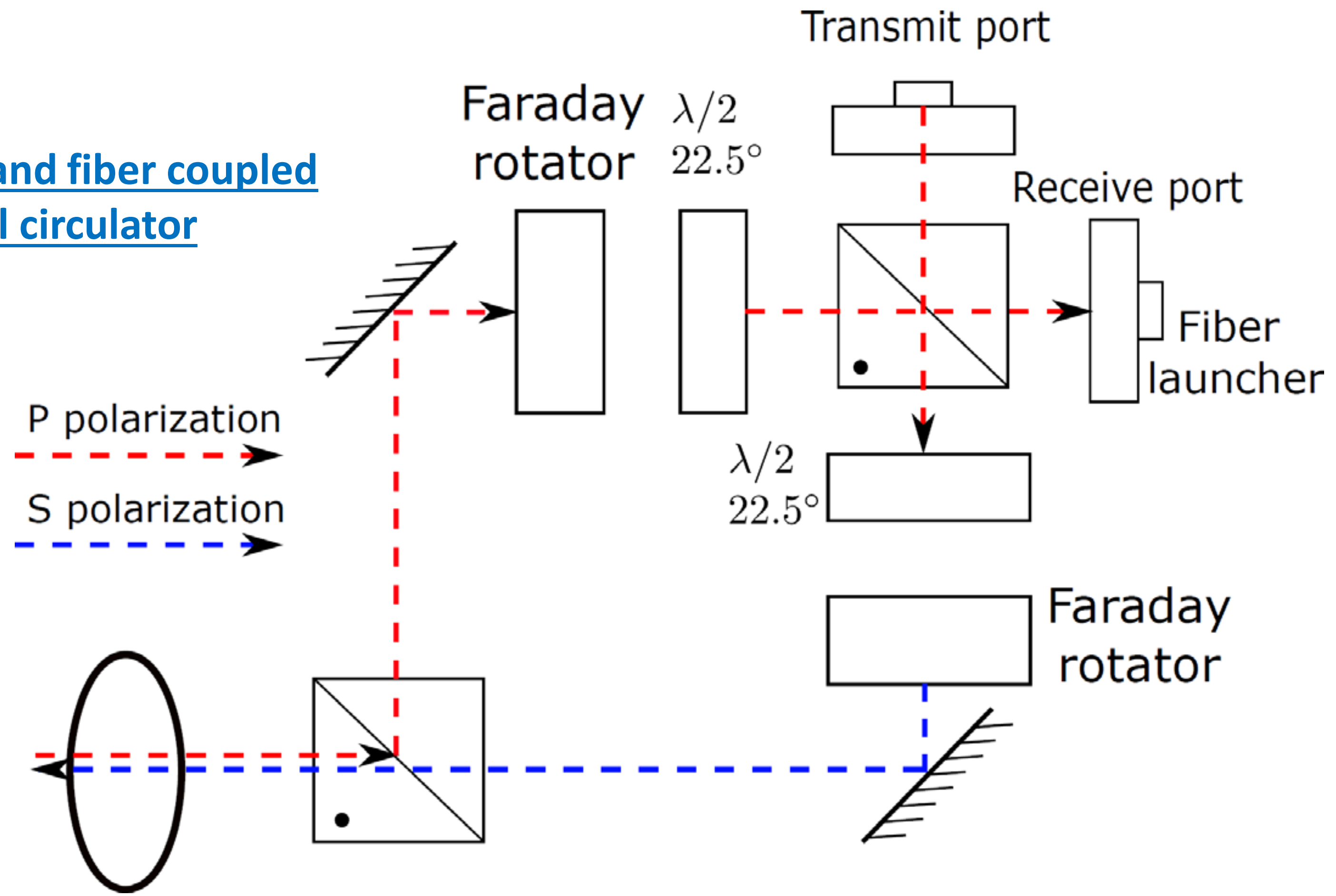


Table of contents:

- **Reminder**
  - Signal modeling, CW CDLs
  - Direct detection vs. coherent detection
  - image-reject coherent homodyne detection
  - Spectral processing and lab prototype
- **CW CDL, continued**
  - Measurement field campaign
  - Dual polarization (polarization diversity) CW CDL
- **Pulsed (long-range) CDLs**
  - Signal modeling
  - Pulsed CDL vs. radar
  - Signal processing in pulsed CDL
  - Practical considerations
  - Dual polarization pulsed CDL
- **Conclusion**

Conclusion

✓Pulsed CDLs are capable of measurements over longer ranges.

✓Due to the principle of operation, pulsed CDLs are similar to radars, however, optical frequencies pose new challenges, not seen in radars.

✓When designing the pulsed CDLs, a few practical considerations need to be taken into careful consideration (e.g., aperture size, pulse shape, length, etc.).

✓By benefiting from robust and cost effective fiber components, available through the optical communication market, traditionally-known-challenges become much easier; for instance, dual polarization pulsed CDLs.

✓Among other things, fiber-based lidars remove the need for tedious beam alignments in the traditional open-space optics lidars.

✓Until compact optical components become available, certain components, such as circulators, need to be built using open-space optics.