Transceiver front-end architectures in all-fiber coherent Doppler wind lidar

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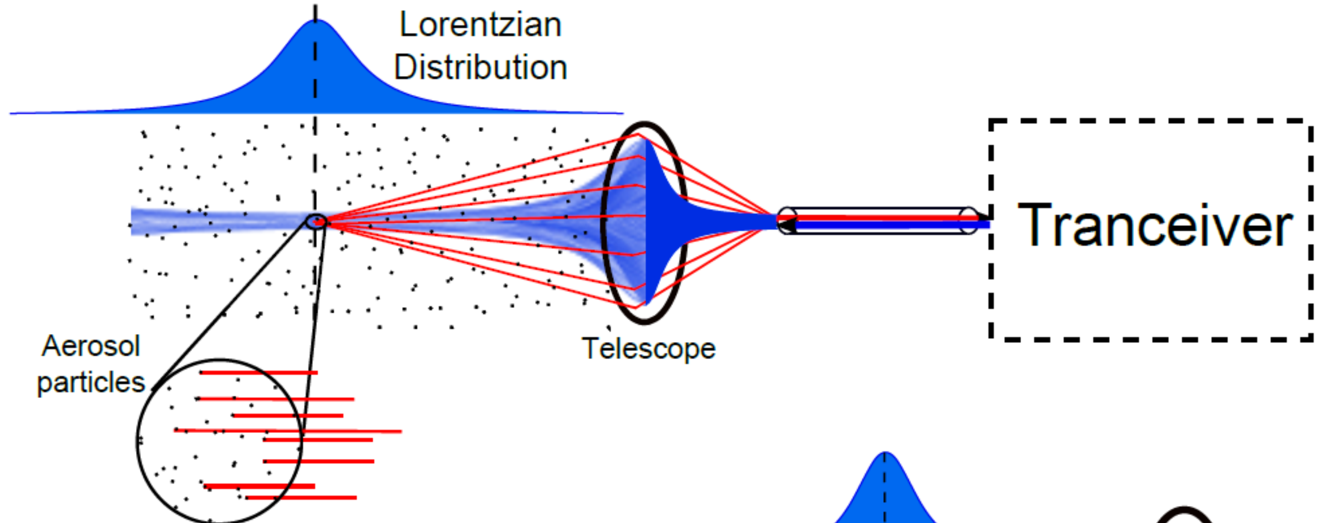
Introduction, CW lidar and ranging

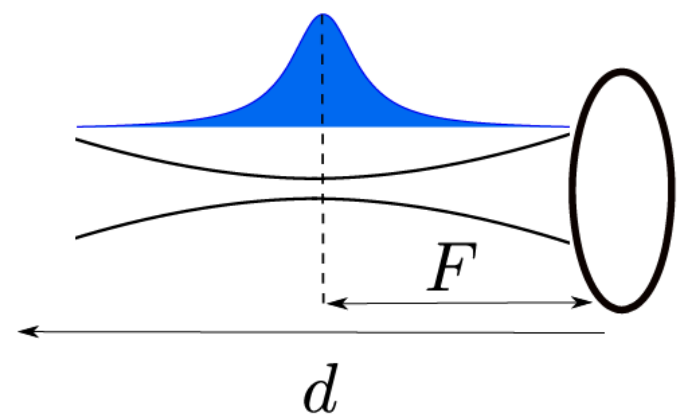
- In CW lidars ranging is achieved through focusing the laser beam which has the following properties,
  - The beam cross section has a Gaussian light intensity distribution
  - The longitudinal light intensity is Lorentzian



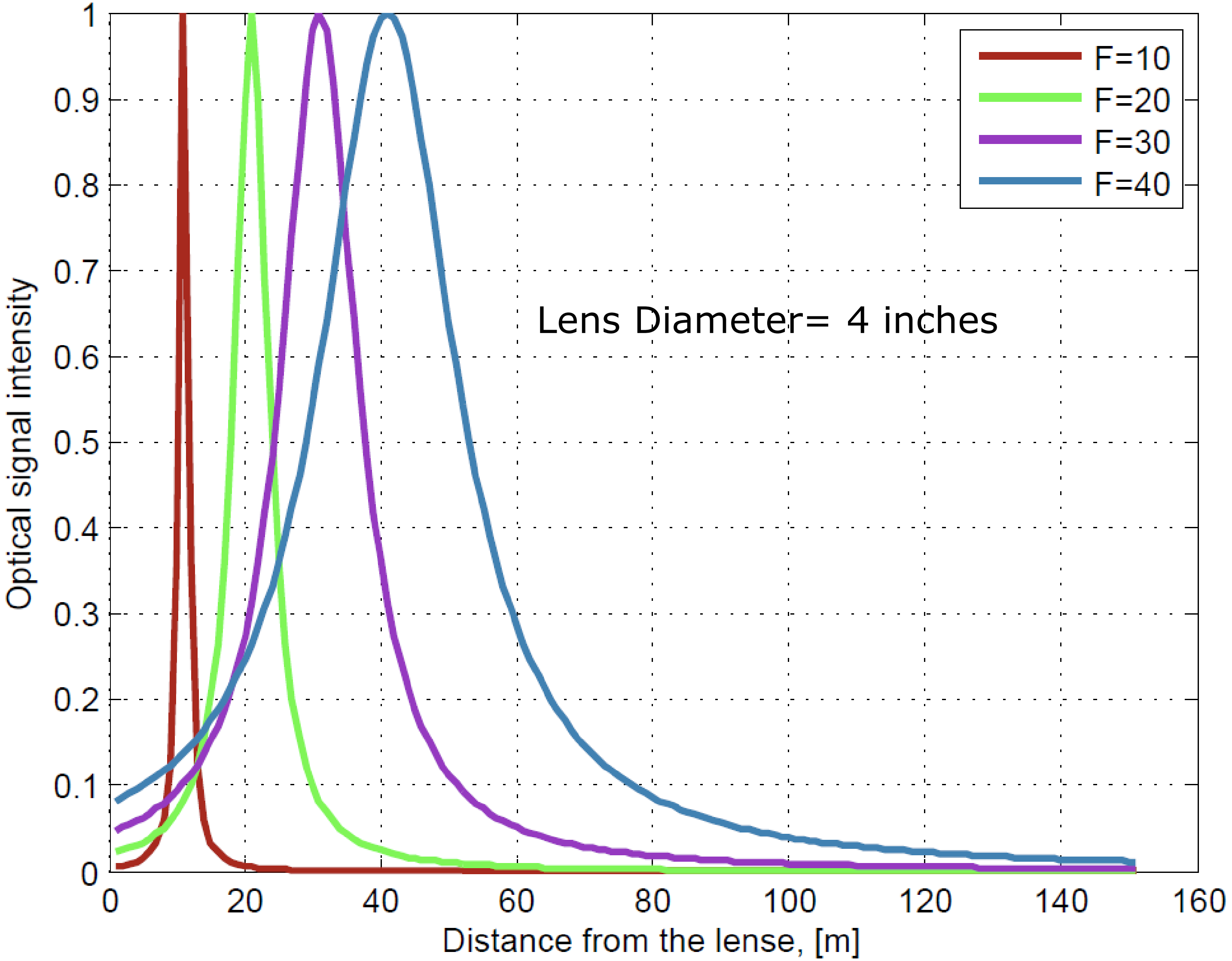
$$\Gamma = \frac{\lambda F^2}{\pi A^2}$$

$$\Delta = F - d$$

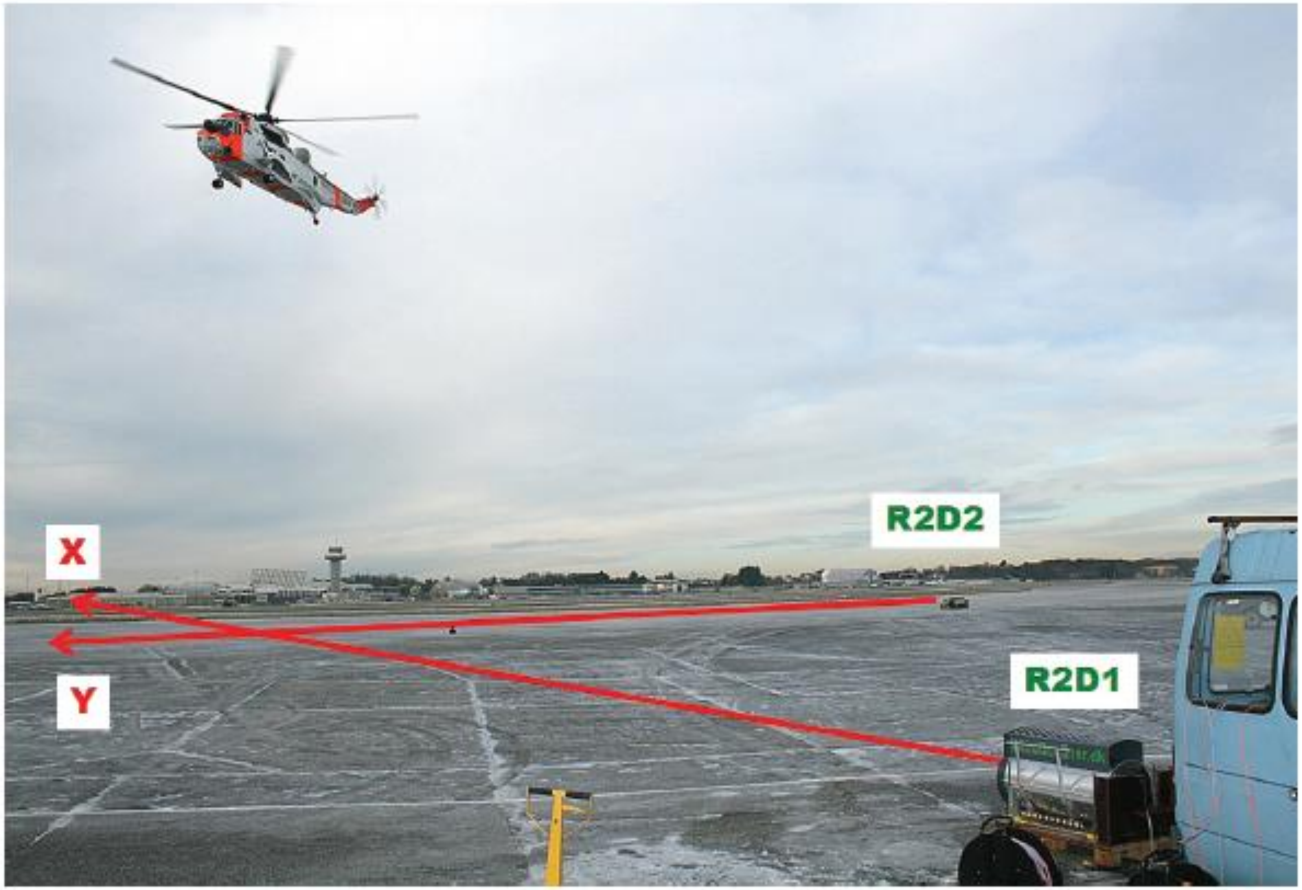
$$Intensity = \frac{\Gamma/\pi}{\Delta^2 + \Gamma^2}$$



Introduction, CW vs. pulsed CDLs



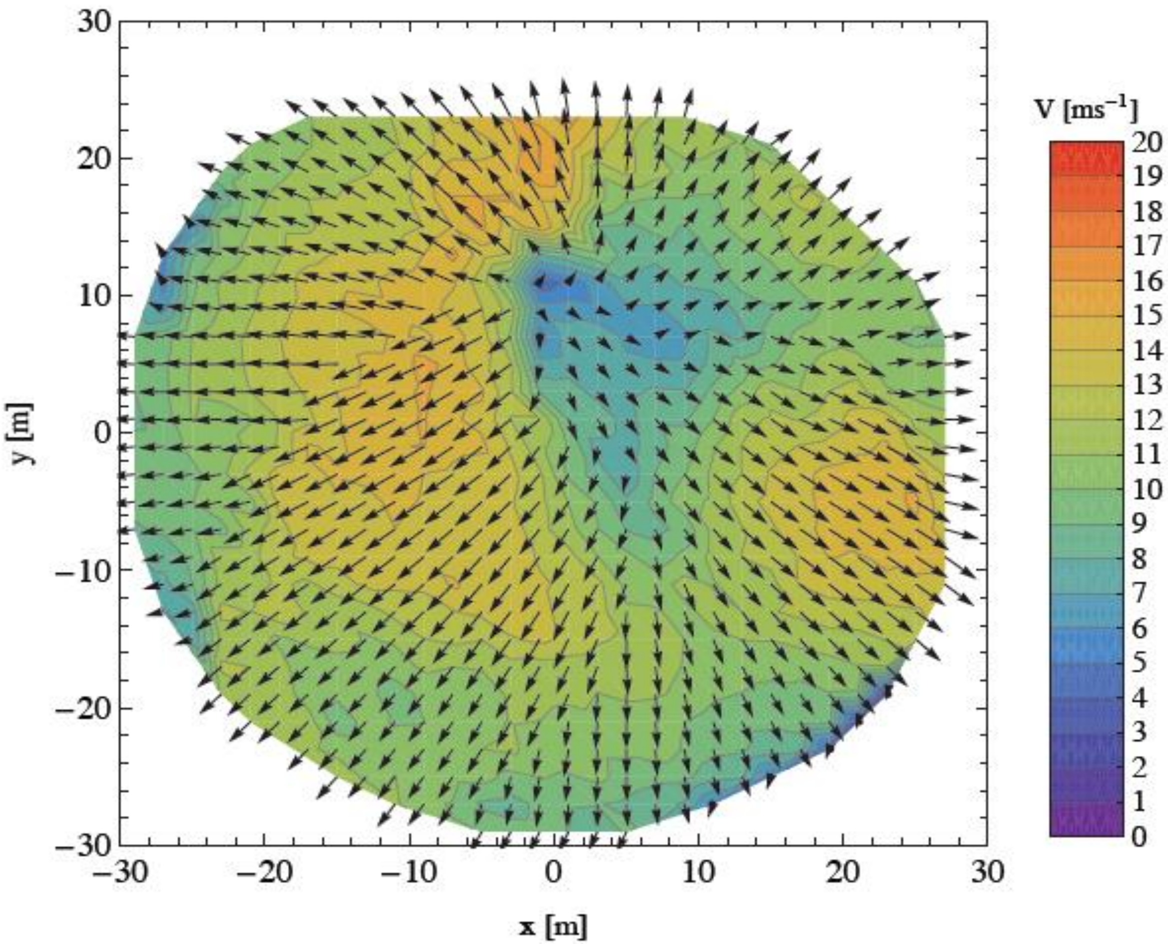
Introduction, CW application example



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

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

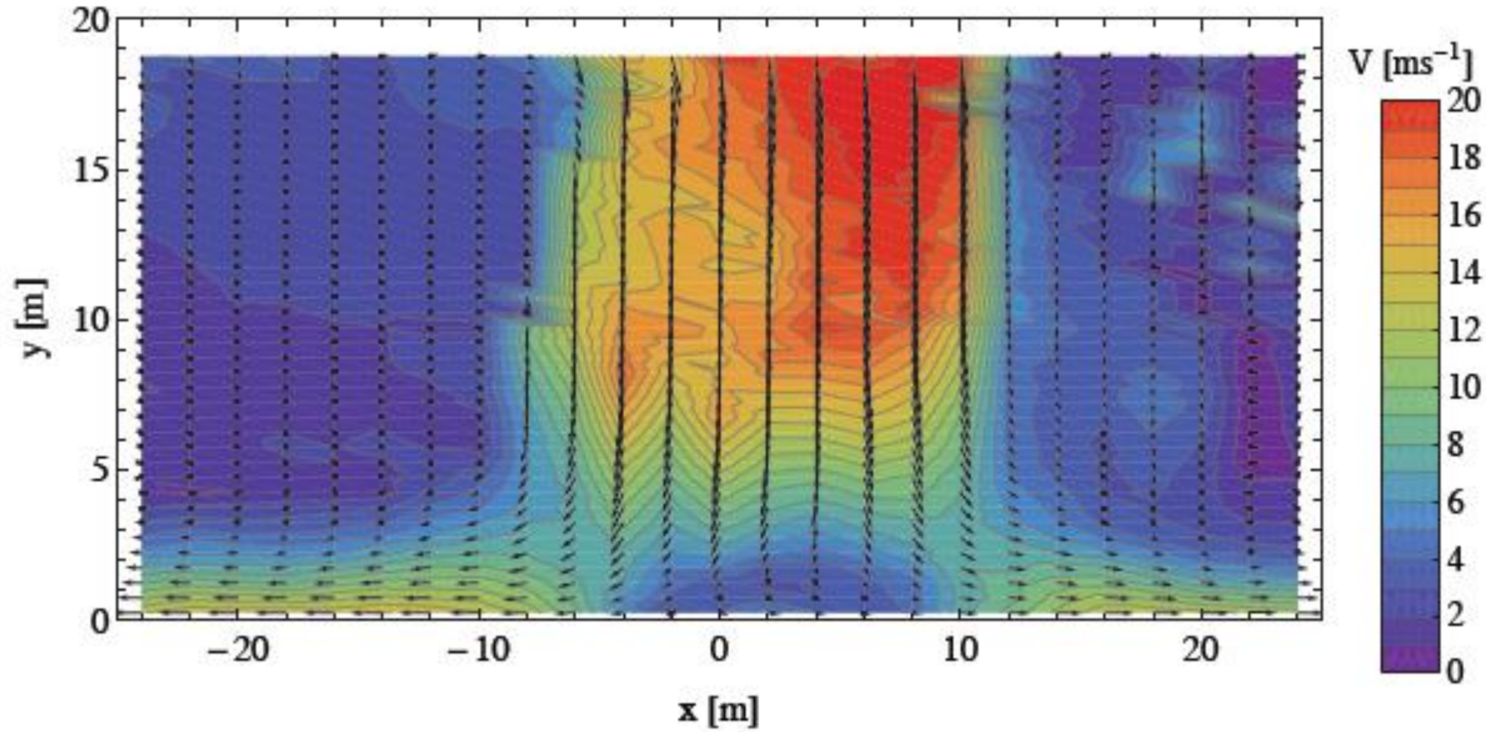
Introduction, CW application example



Figur(·trieved 2D wind field in a horizontal plane close to ground.

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

Introduction, CW application example



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

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

Introduction, signal modeling (CW)

- The transmit and receive signal may be modeled as,

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

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

- k is the portion of the transmited laser signal
- 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 net optical attenuations from aerosol particles (independant and circularly symmetric Gaussian rvs)
- Δf_l is the Doppler shift associated with the movement of the lth particle (Δf_ls are ICSG rvs)
- ϕ_l is the phase factor associated with the lth particle, modeled as a uniformly distributed rv
- all rvs are independant

Introduction, signal modeling

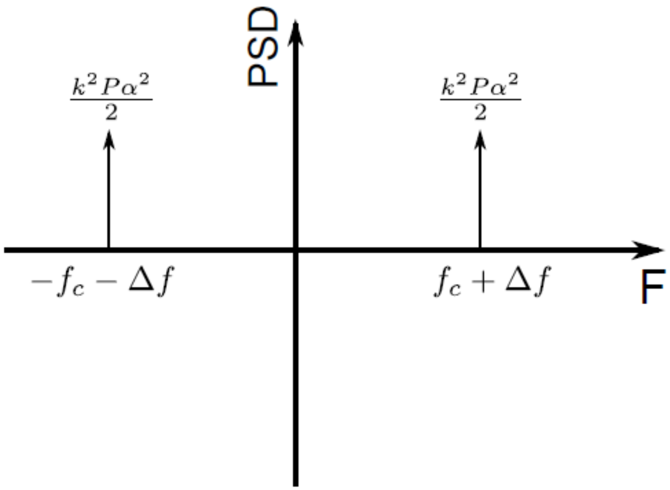
- For simplicity and without lack of generality lets adopt a receive signal model associated with the reflection from a single moving hard target where the effect of phase noise has been neglected.
-

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

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

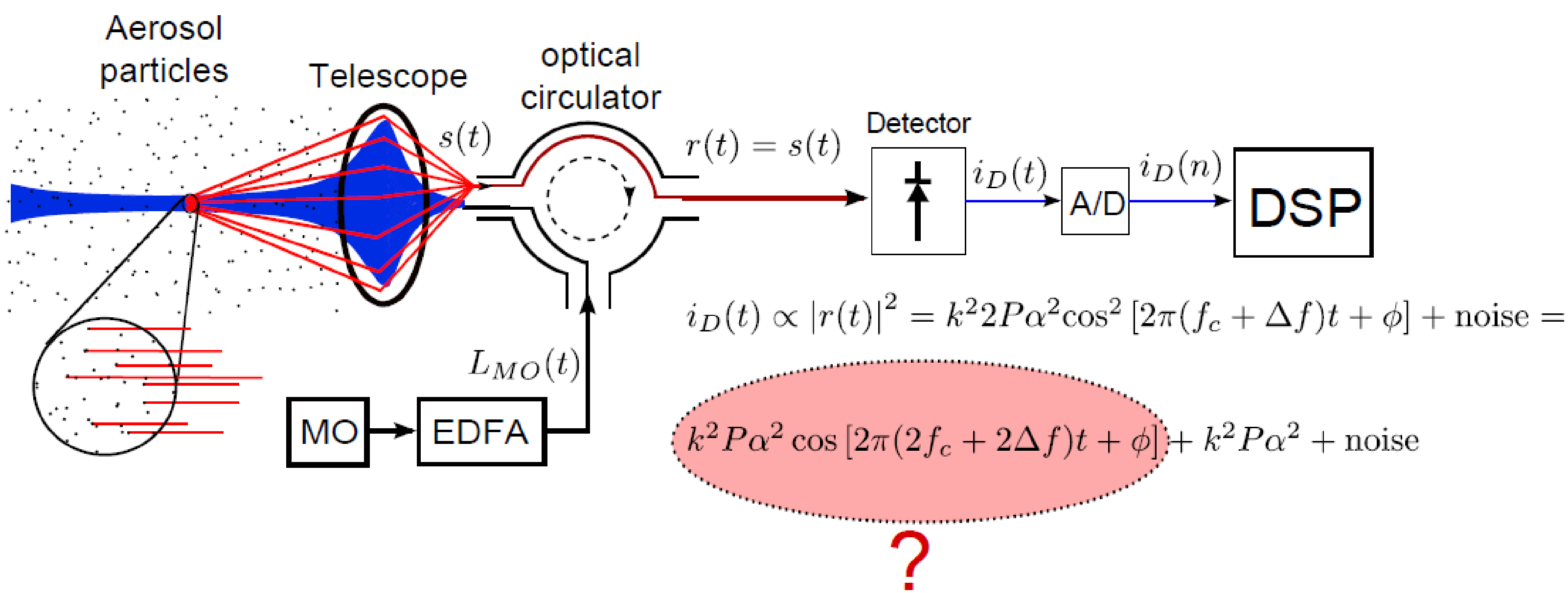
$$R(F) = \frac{k\sqrt{2P}\alpha}{2}e^{j\varphi}\delta(F + f_c + \Delta f) + \frac{k\sqrt{2P}\alpha}{2}e^{-j\varphi}\delta(F - f_c - \Delta f) \Rightarrow$$

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



Introduction, direct detection

- The optical signal needs to be converted into an electrical current for further processing -> a photo diode (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.



Introduction

- Theoretically, the detector output can be directly digitized for further processing. However,
  - The detector has a limited BW and can't follow the high freq. variations
  - The A/D has a limited BW
- As a result, the optical signal needs to be down-converted (translated) into a lower frequency region where digital processing of the signal is feasible.
- This is a familiar concept in Radio communications (heterodyning!)
- The down-conversion process is called beating, heterodyning, coherent detection, etc.
- Depending on the down-conversion procedure various front-end architectures in lidars may be realized.

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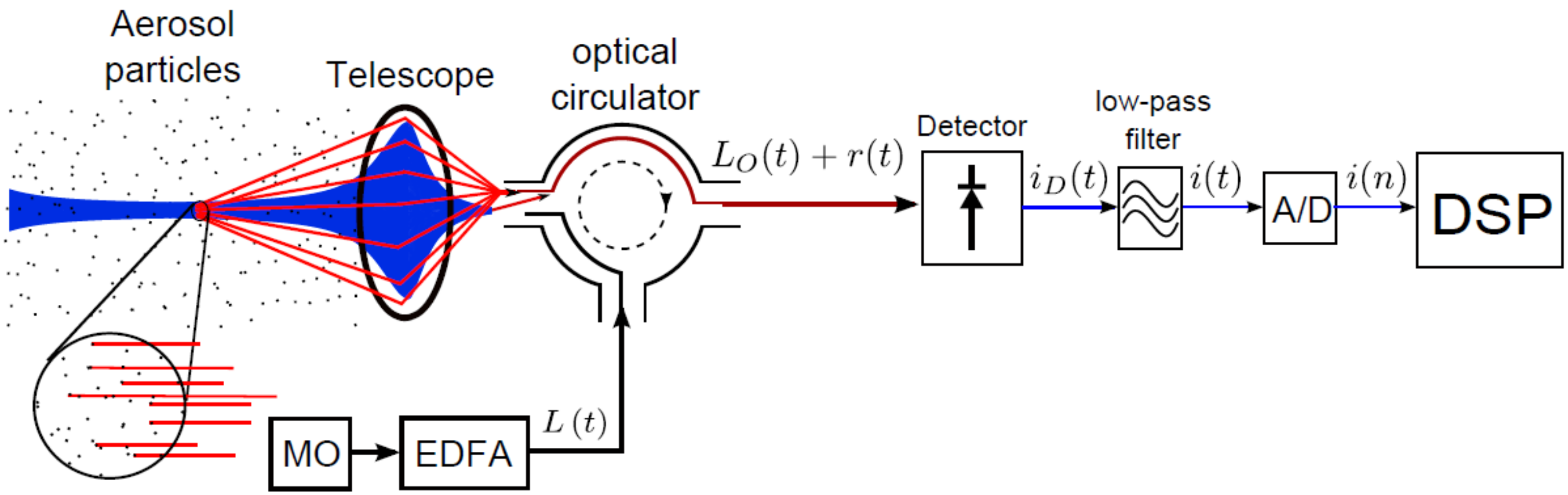
Homodyne receivers, real-mixing



- The simplest homodyne receiver is a direct down-conversion configuration with real mixing (what does real mixing mean?)
- In such systems, the received signal is mixed with a portion of the LO signal reflected (through polishing the fiber end at a certain angle) from the end facet of the delivery fiber right before the telescope.
- Commercial examples are ZePHiR and Windar

Homodyne receivers, real-mixing

- The beating process is carried out by the photo-detector.

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

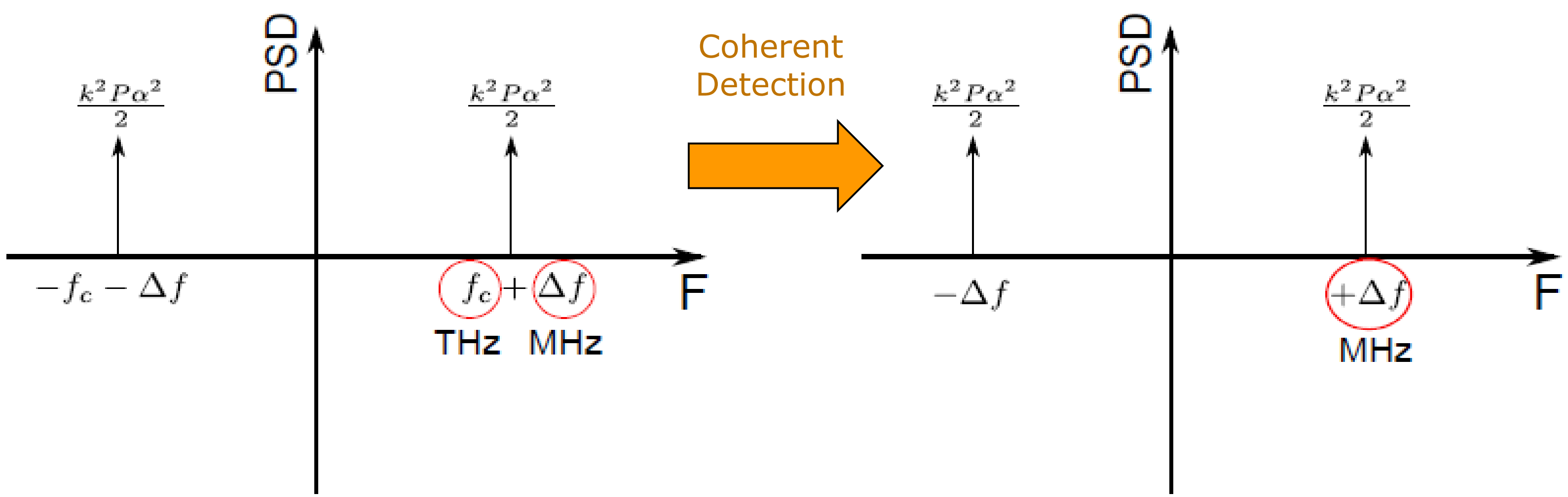
$$i_D(t) = \alpha\left[r(t)^2 + L(t)^2 + 2L(t)r(t)\right] + \eta_{sn}(t) + \eta_{th}(t) + \eta_{1/f}(t).$$

- After proper filtrering and signal conditioning,

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

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

-

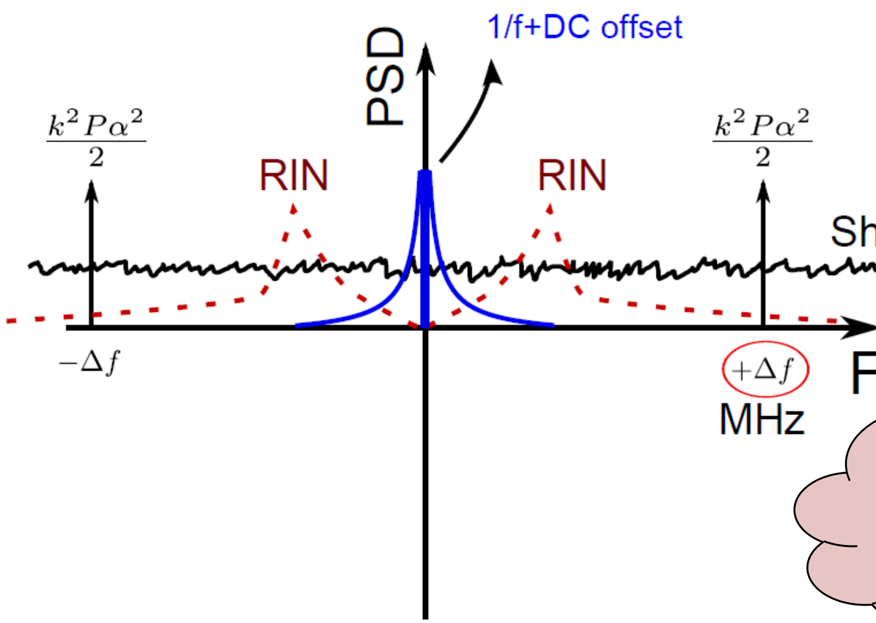


Homodyne receivers, real-mixing

- The dominant noise is the detector's shot noise which appears as a white Gaussian noise, i.e., it has a flat PSD and masks most of the other noise terms. The DC offset, 1/f and RIN's peak are exceptions.

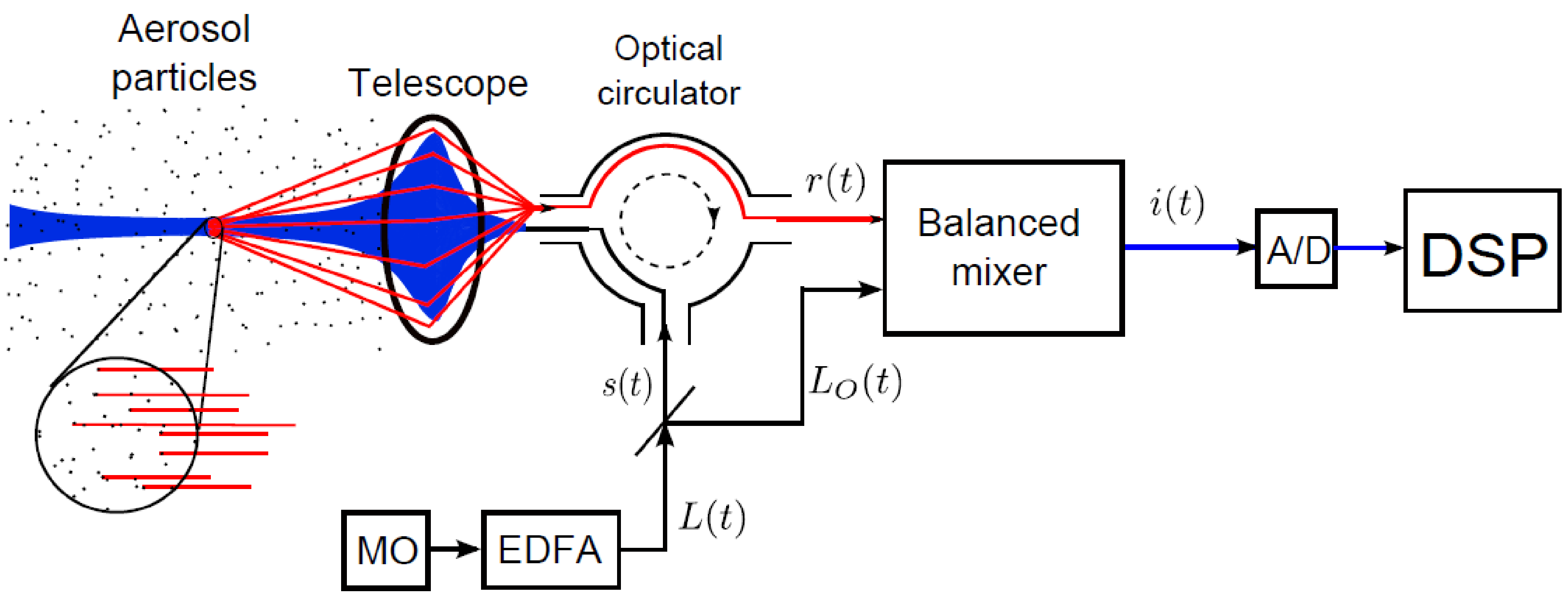
- The noise terms are the nuisance which may be reduced by proper signal processing or employing high-quality components.

- There is only so much one may do to improve the noise behavior so one has to live with it.



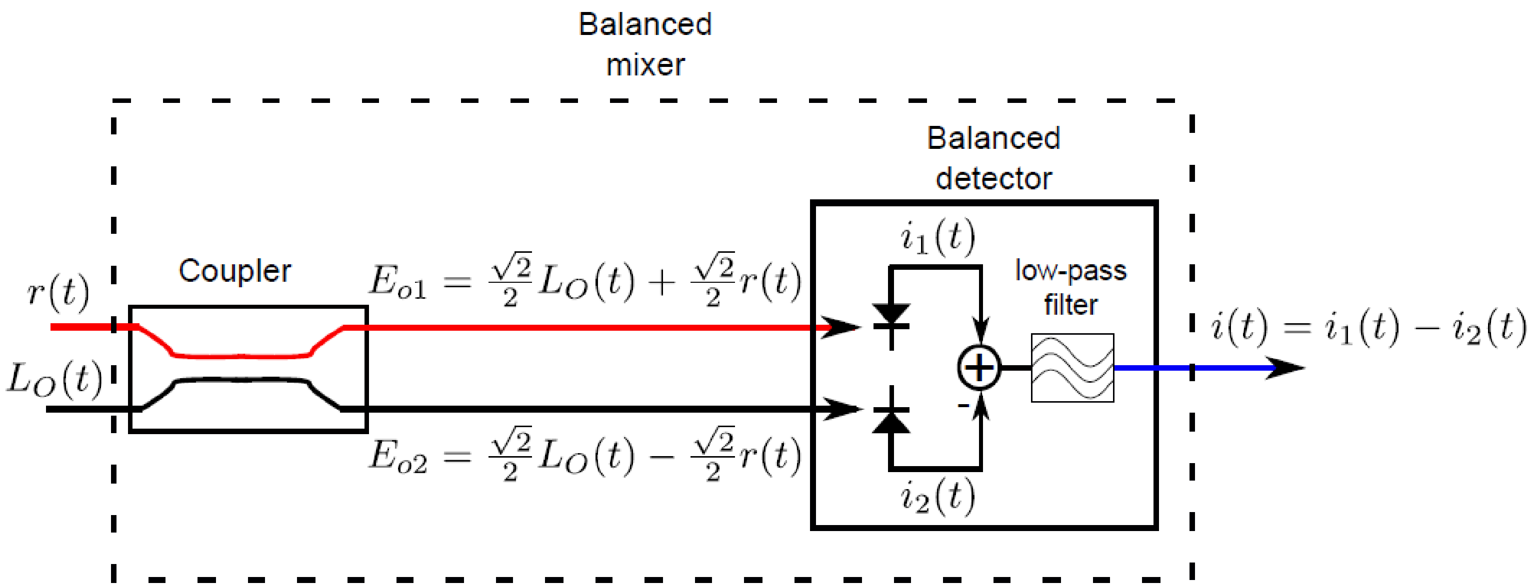
Thermal noise is buried under the detector's shot noise!

Homodyne receivers, real-mixing



- Another possible configuration is to use optical couplers to mix the signal before the detector.
- The LO signal is derived from the local oscillator through a beam splitter.

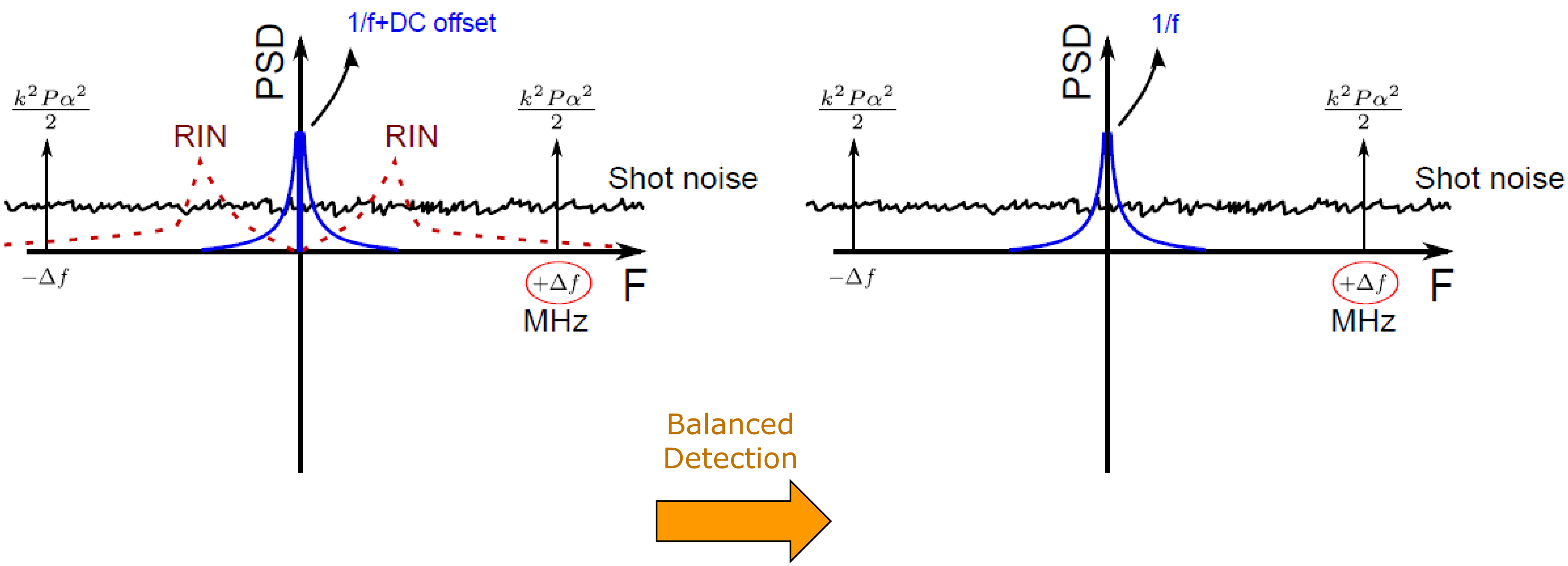
Homodyne receivers, balanced detector



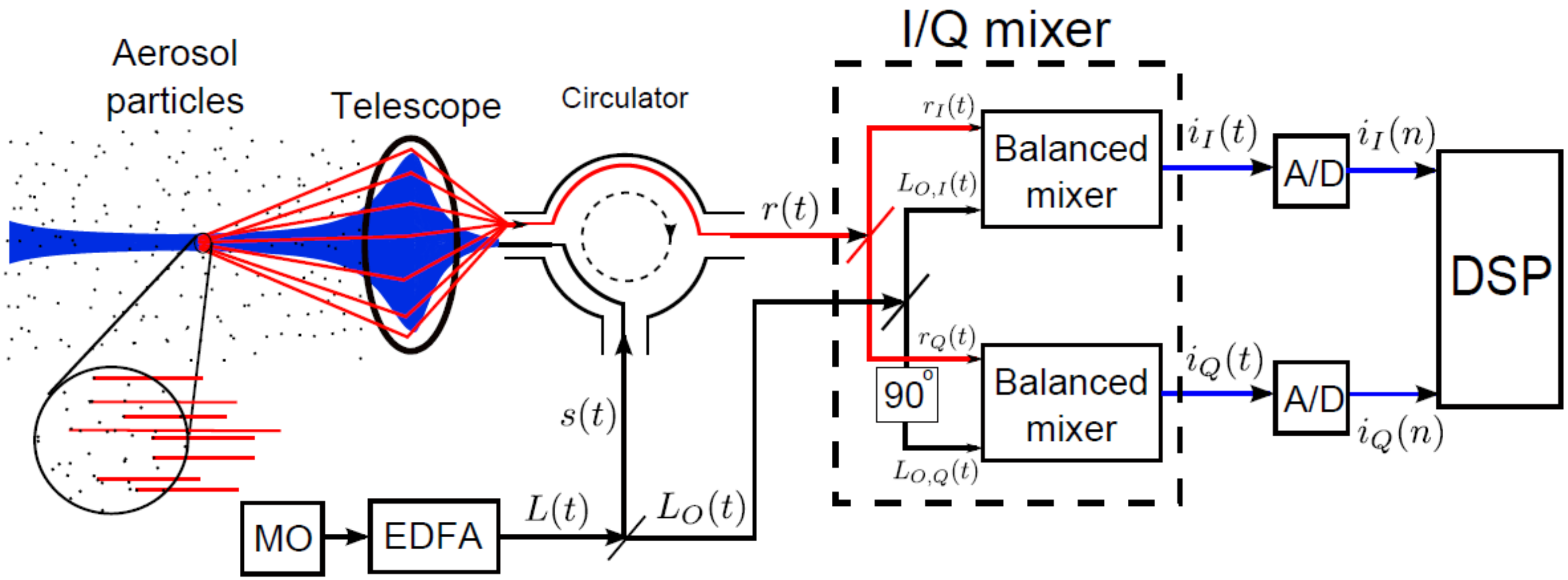
- If only one detector is used half the signal power, i.e., 3 dB is lost.
- A balanced detector needs to be used so not only all signal power is used but also the effect of DC noise as well as laser's RIN noise can be ideally removed. This in effect can improve the SNR significantly.
- Its performance is characterized through common mode rejection ratio (CMRR), i.e., the common mode signals from the LO path are removed.

Homodyne receivers, real-mixing

- The main short-coming with homodyne receivers as such is the inability to discriminate the sign of the radial wind velocity. In other words, it is not possible to distinguish between negative and positive radial velocities.



Homodyne receivers, complex mixing



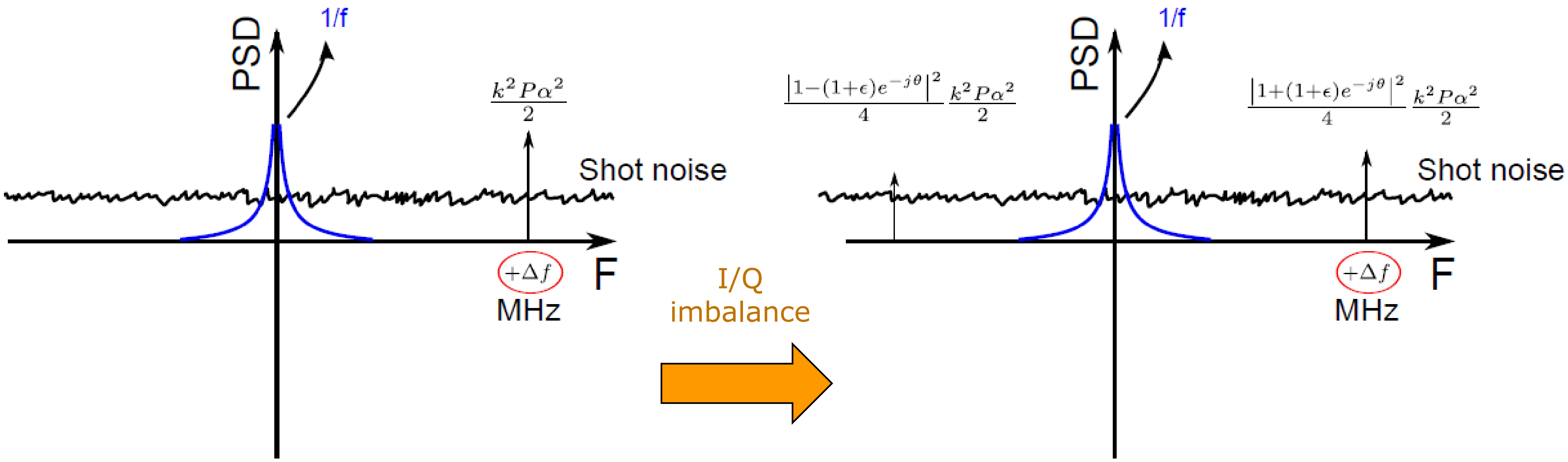
- To resolve the sign ambiguity one may use a concept popular in wireless communications called homodyne image-reject receivers, also known as homodyne with complex mixing, I/Q or quadrature detection.

- 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.

Homodyne receivers, complex-mixing

- A homodyne receiver as such may suffer from imbalances in the real and quadrature arms of the receiver. For instance, any gain imbalance (ε) or phase imbalance (θ) between the real and quadrature LO signals may increase the sign ambiguity. The ambiguity can be (partially) compensated through DSP algorithms in the base band.

- Such architectures are also more sensitive to depolarized signals which is not a major problem in lidars.



Homodyne receivers, complex-mixing

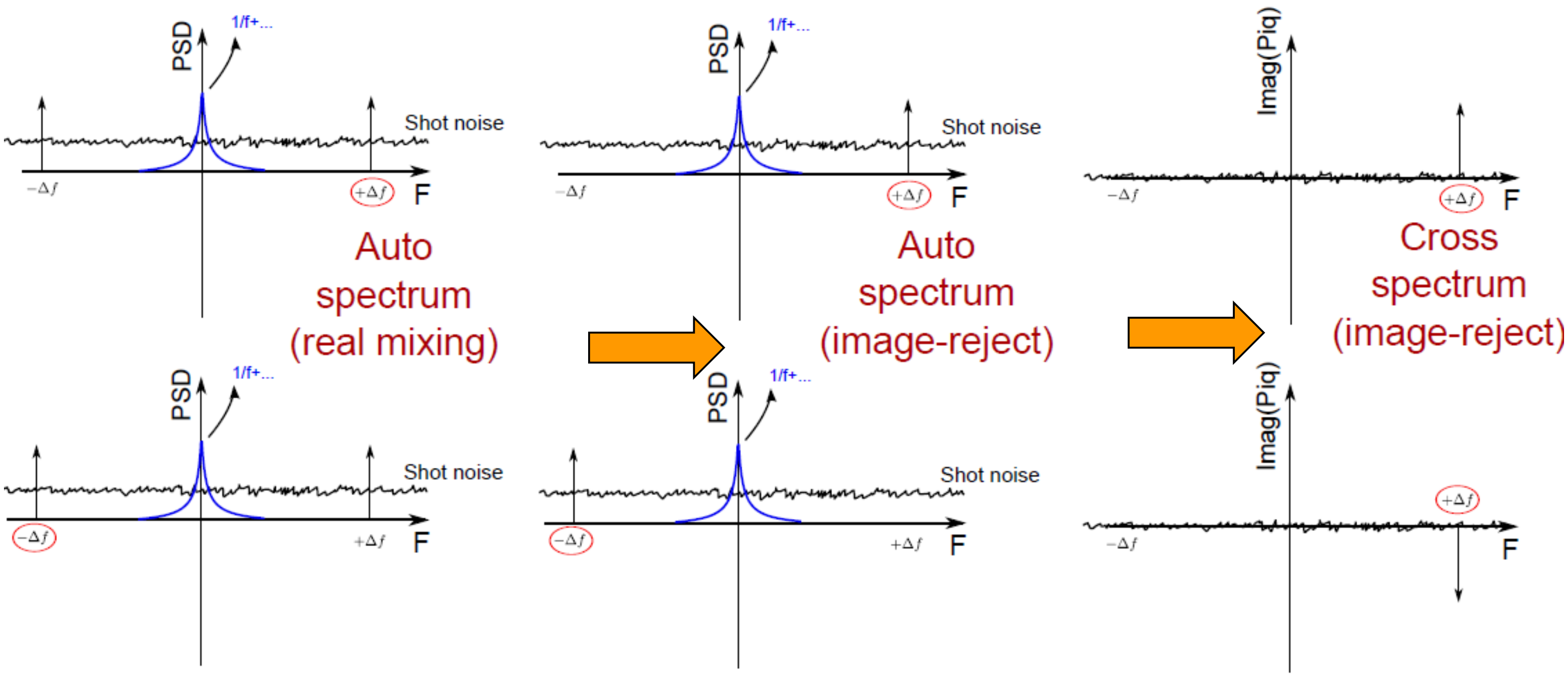
- For instance, if in an exemplary receiver the gain and phase imbalances are 5 degree and 15% respectively,

$$\mathrm{IRR} = 10\log_{10}\frac{P_{\mathrm{desired}}}{P_{\mathrm{image}}} = 21\ \mathrm{dB}$$

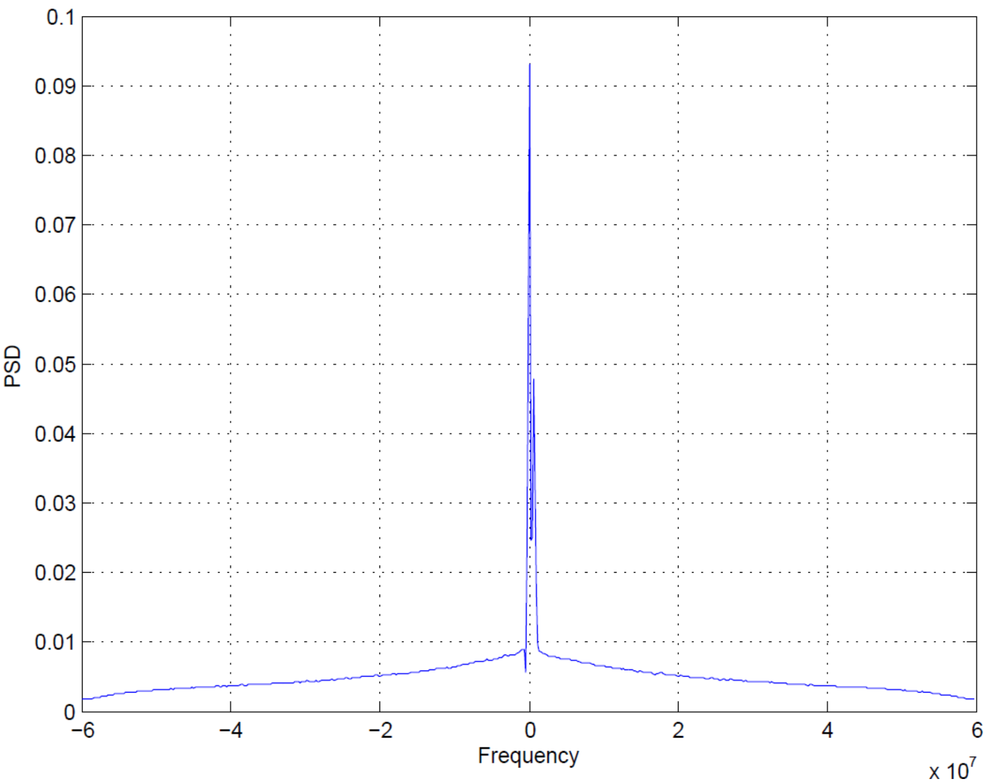
where IRR is the image-reject ratio.

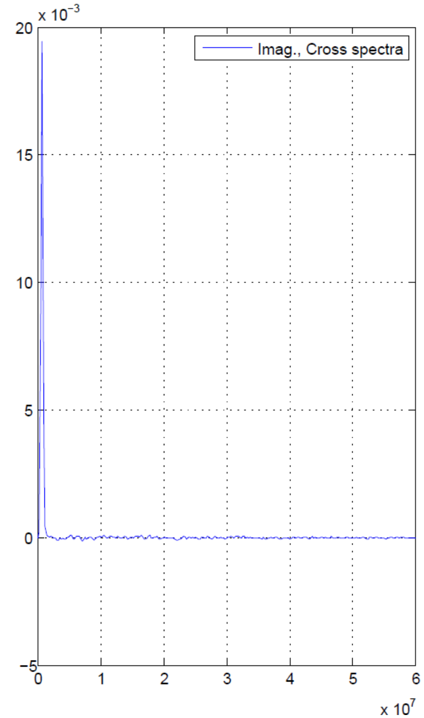
Homodyne receivers, complex-mixing

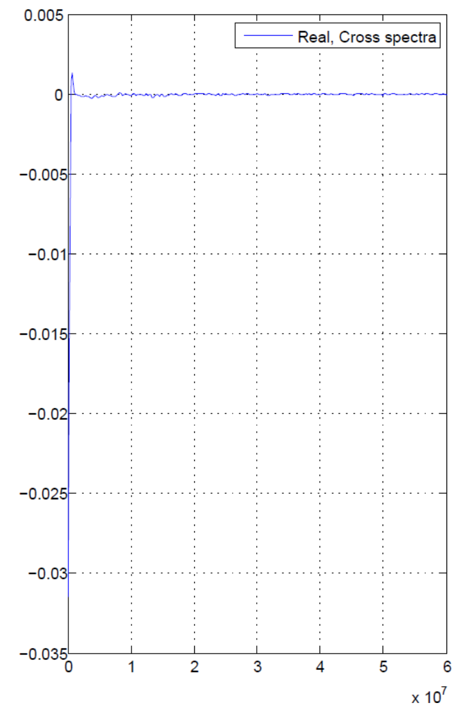
- To eliminate/suppress the noise sources present in the signal, a cross-correlation approach can be employed.
- The cross-correlation benefits from the fact that the noise sources in in-phase and quadrature-phase paths are independent.
- The information is ideally contained in the imaginary part of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



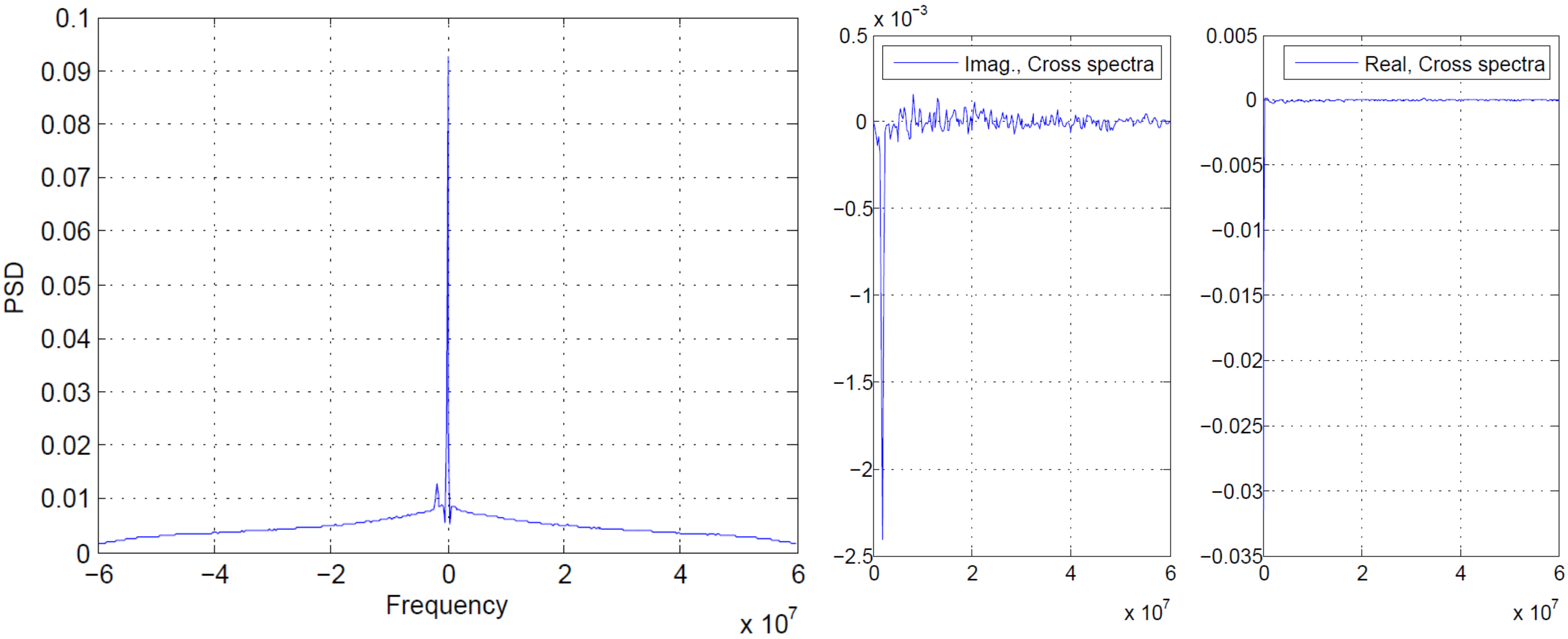
Homodyne receivers, complex-mixing







Homodyne receivers, complex-mixing



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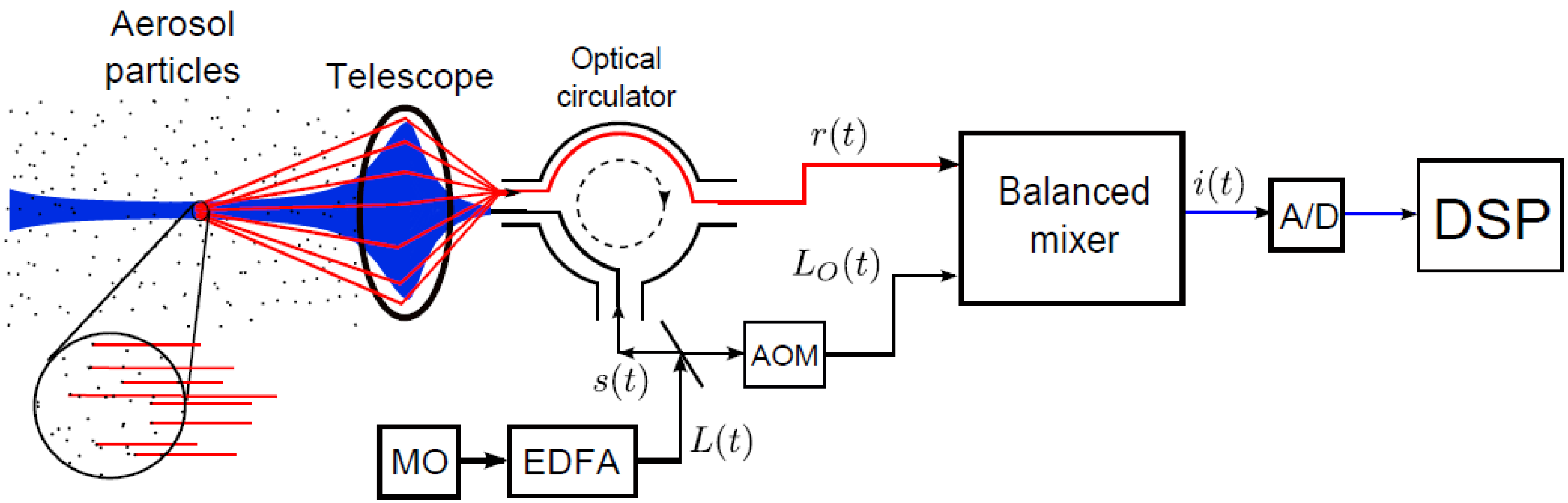
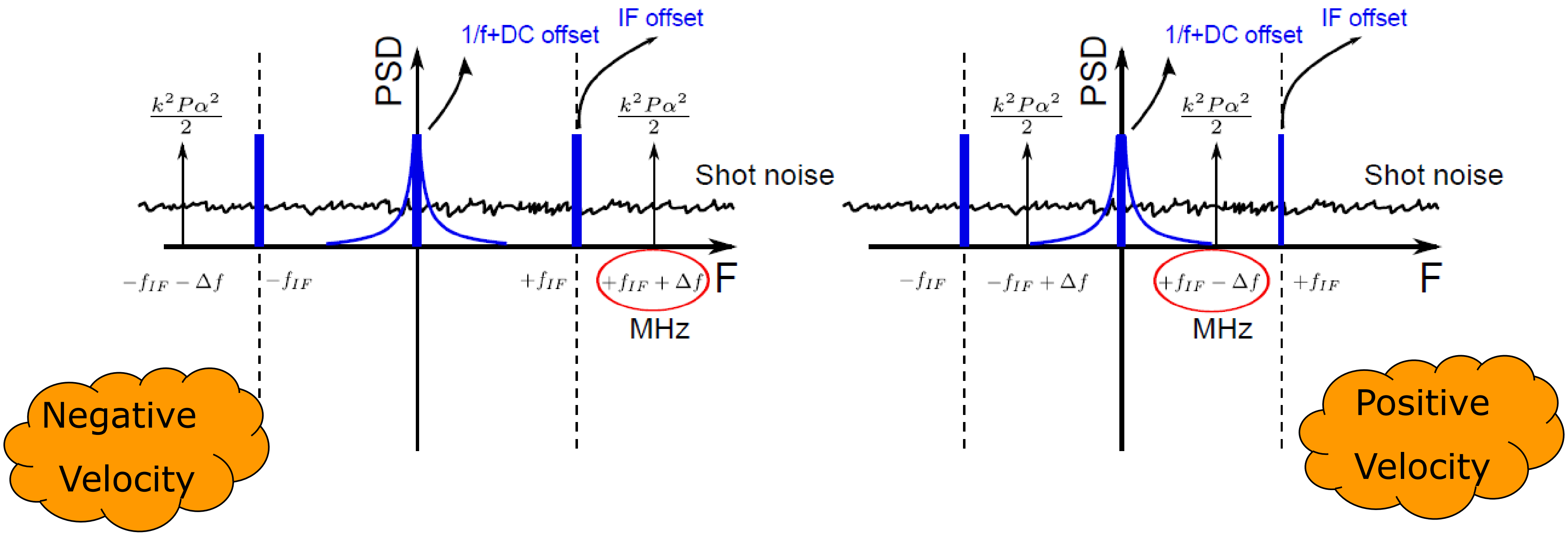
Heterodyne receivers, IF sampling



- In heterodyne receivers, the Doppler shift is down-converted to the intermediate band. As a result, depending on the location of the resultant spectra with respect to the intermediate frequency (IF), the sign of the Doppler shift can be deduced.

- 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.

Heterodyne receivers, IF sampling



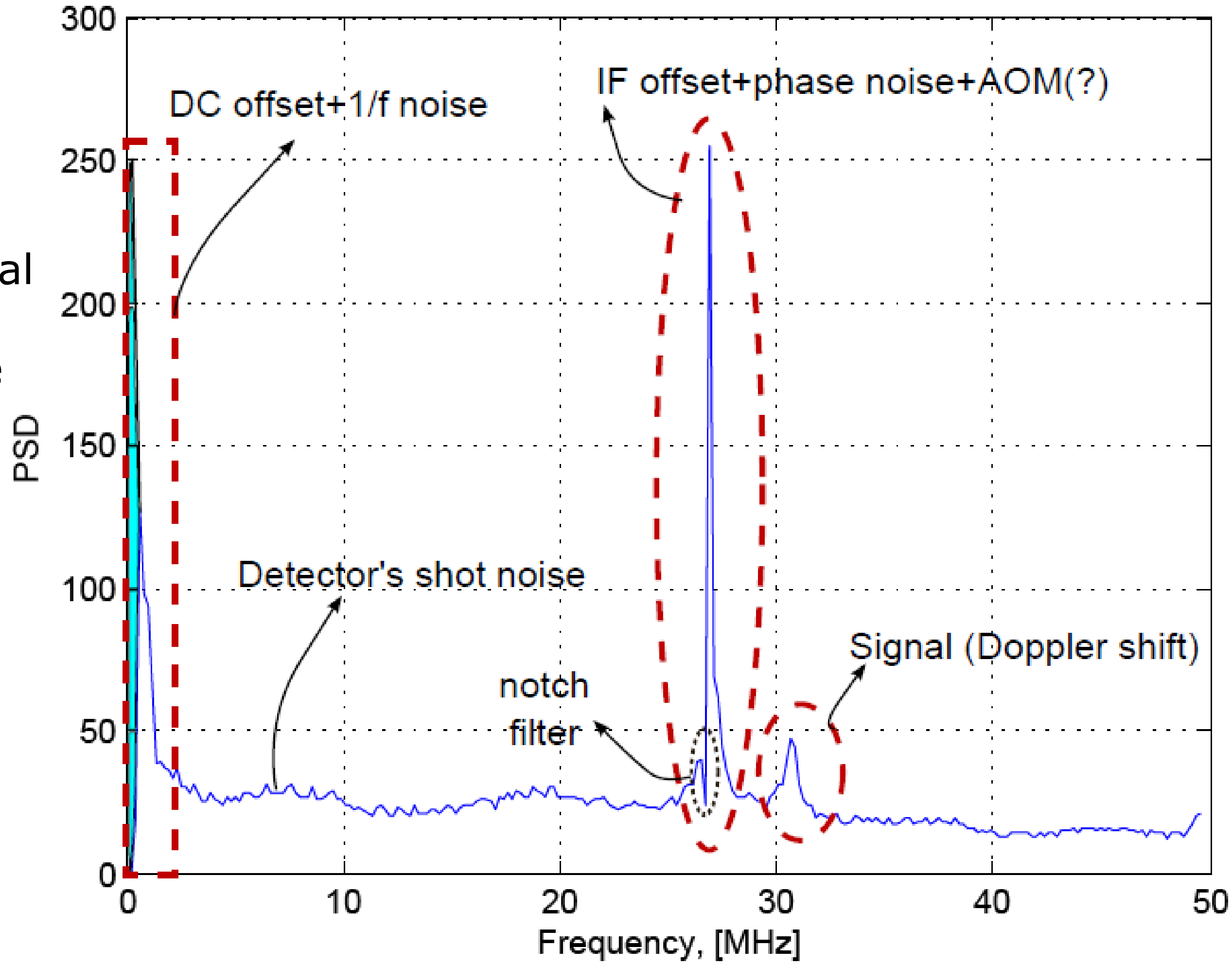
- Due to the presence of IF, one needs to employ an A/D with much wider BW if the same radial velocity range is sustained.
- The price of A/D doesn't increase linearly with respect to the BW.
- Due to the reflections from the optical surfaces as well as the optical circulator cross-talk, a strong signal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

Heterodyne receivers, IF sampling

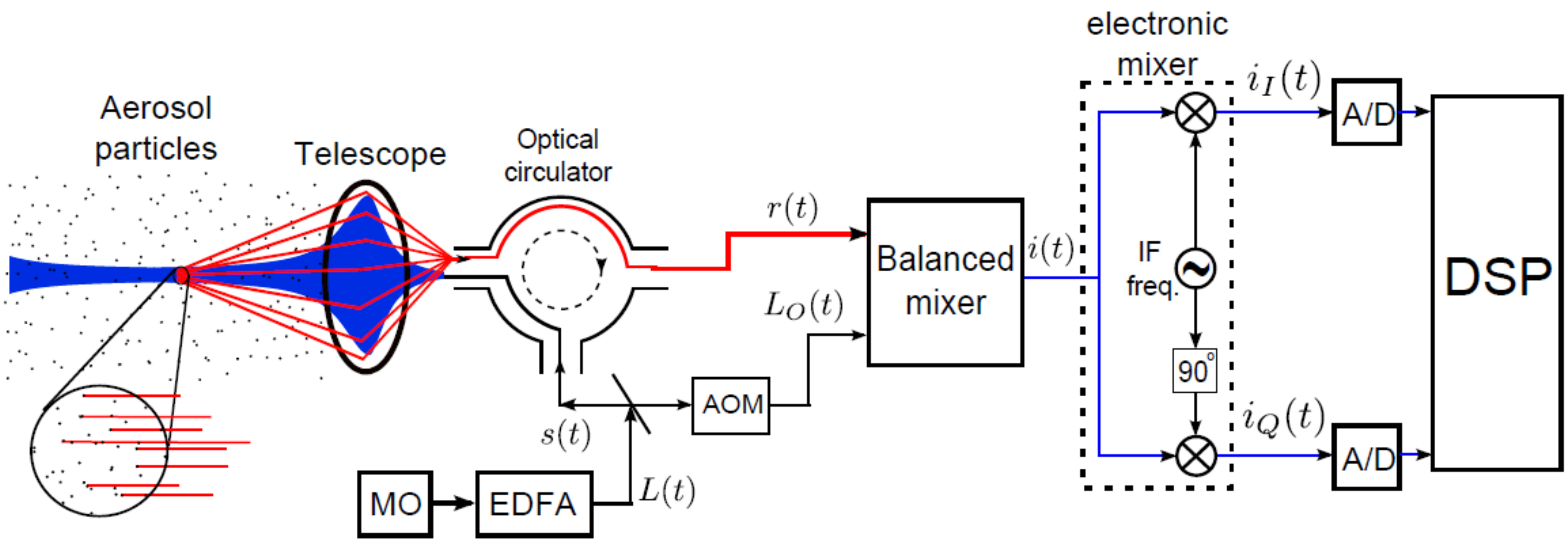
-The measured spectra is quite consistent with the predicted models

-Phase noise and addtional AOM drifts seem to have more contributions to the noise around IF than expected

-Temperature dependent drift on laser as well as the notch filter makes it difficult to tune the filter

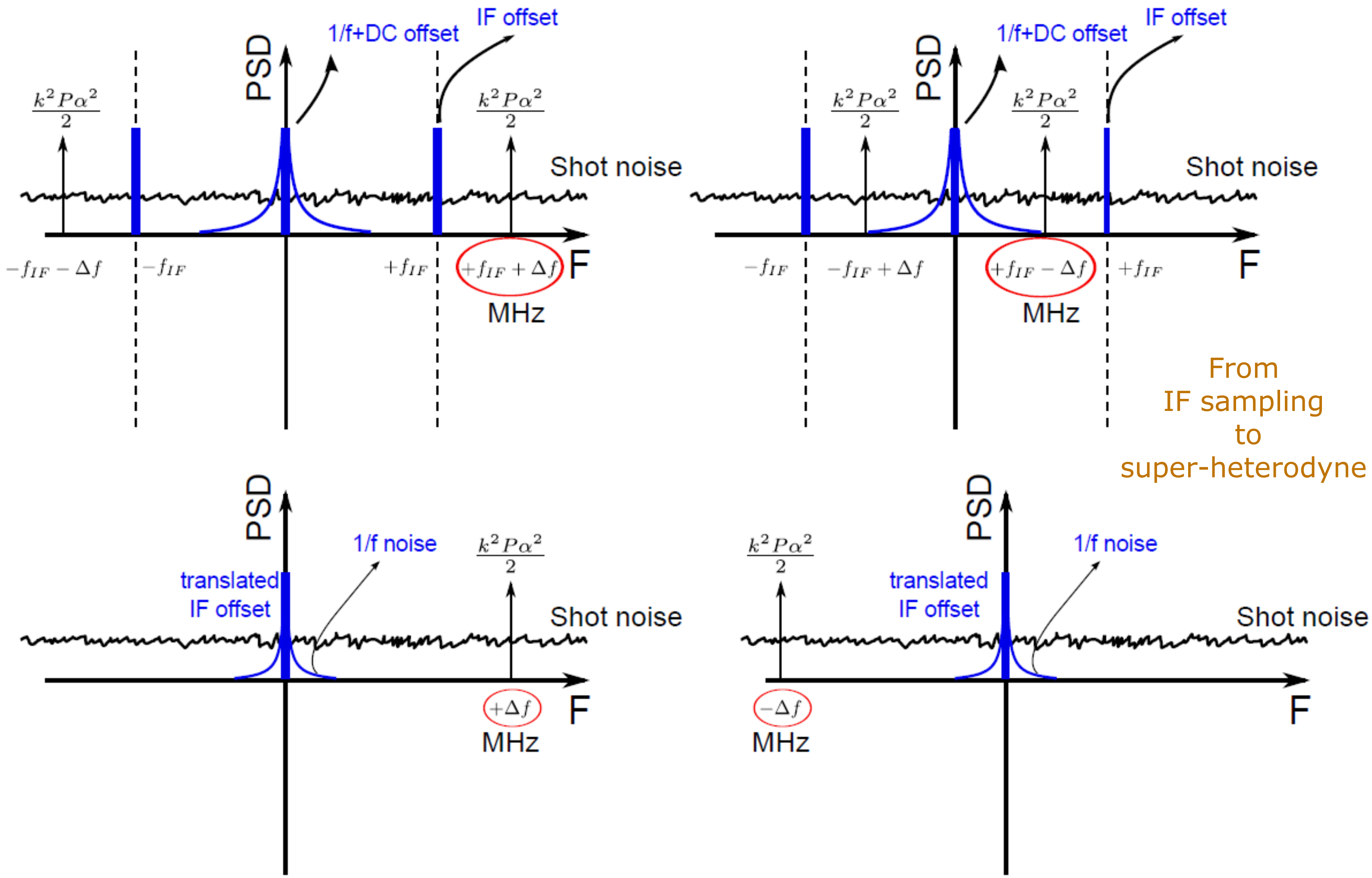


Heterodyne receivers, super-heterodyne



- To overcome some of the mentioned problems a super-heterodyne receiver, i.e., heterodyne with electronic I/Q demodulation can be employed.
- Through a 2nd down-conversion stage, the following can be achieved,
  - A/D BW reduction or velocity range increase
  - 1/f and additional DC noise removal
  - Translation of the spurious effects around IF into baseband for more effective treatment → eliminating the costly notch filters at IF
- Despite its improved noise behavior, this system may suffer from other error sources due to the presence of an additional RF mixer.

Heterodyne receivers, super-heterodyne



From
IF sampling
to
super-heterodyne

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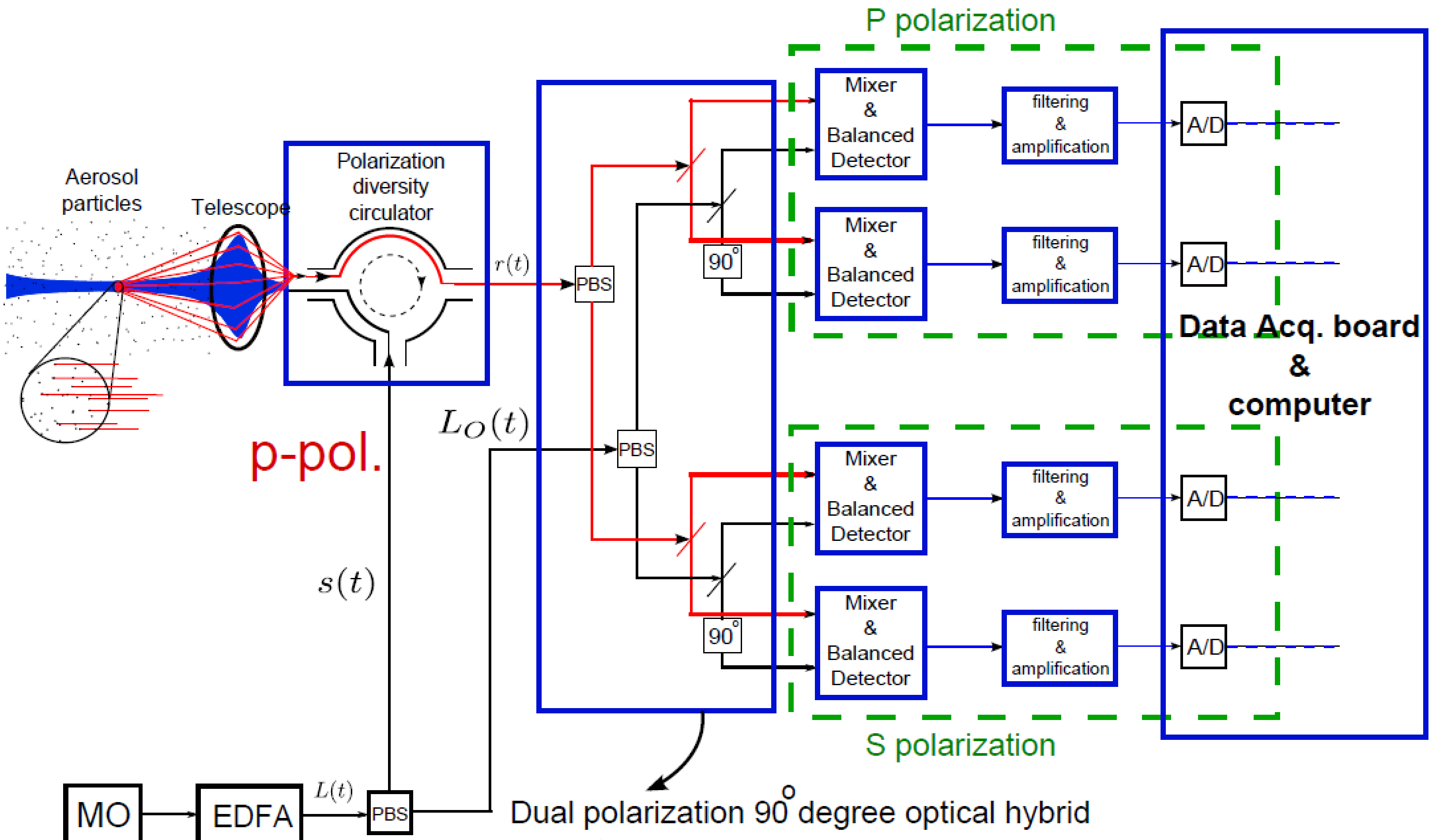
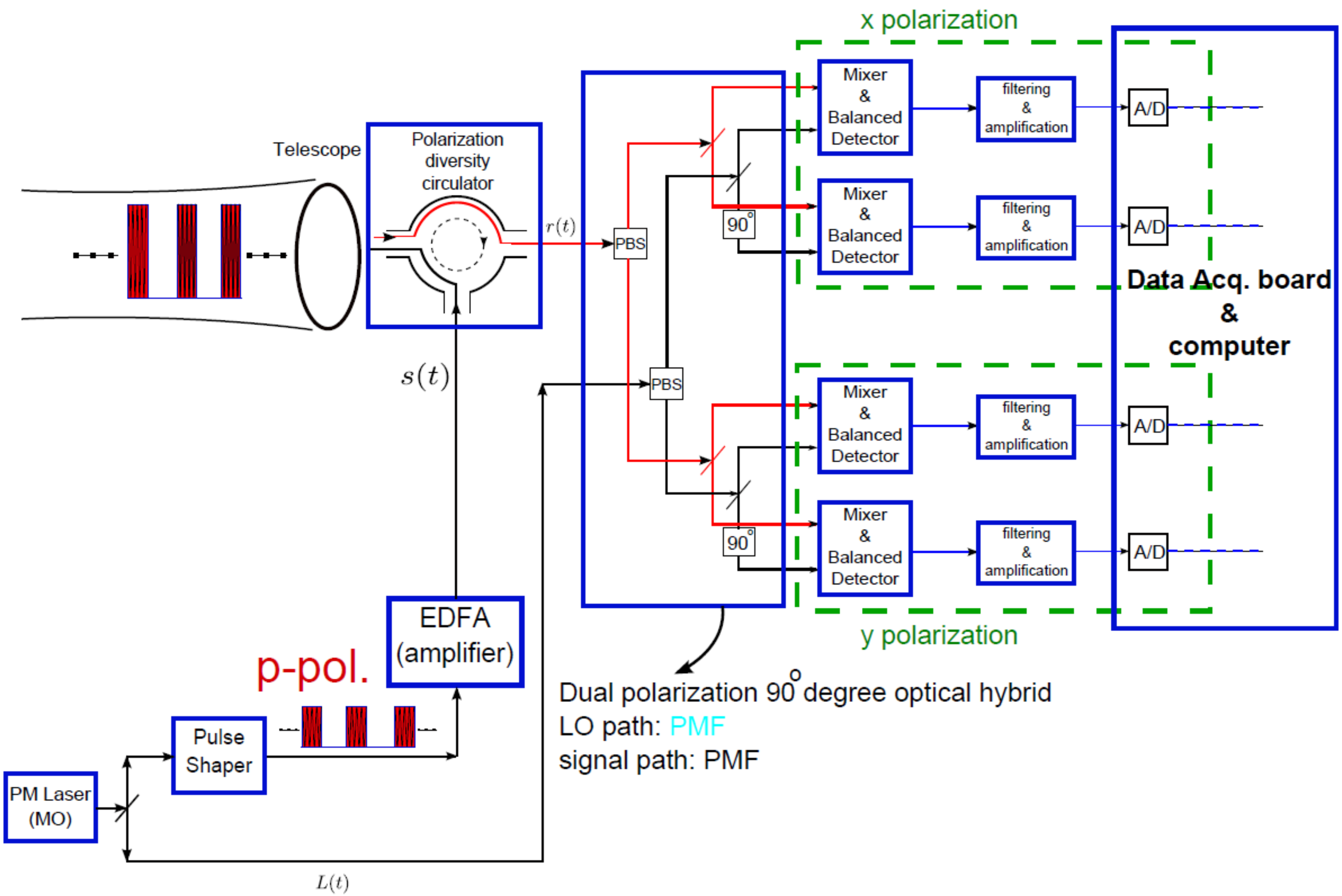
Dual pol. image-reject homodyne, CW CDL



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

Dual Pol. Image-reject homodyne, pulsed



Dual polarization 90° degree optical hybrid
LO path: PMF
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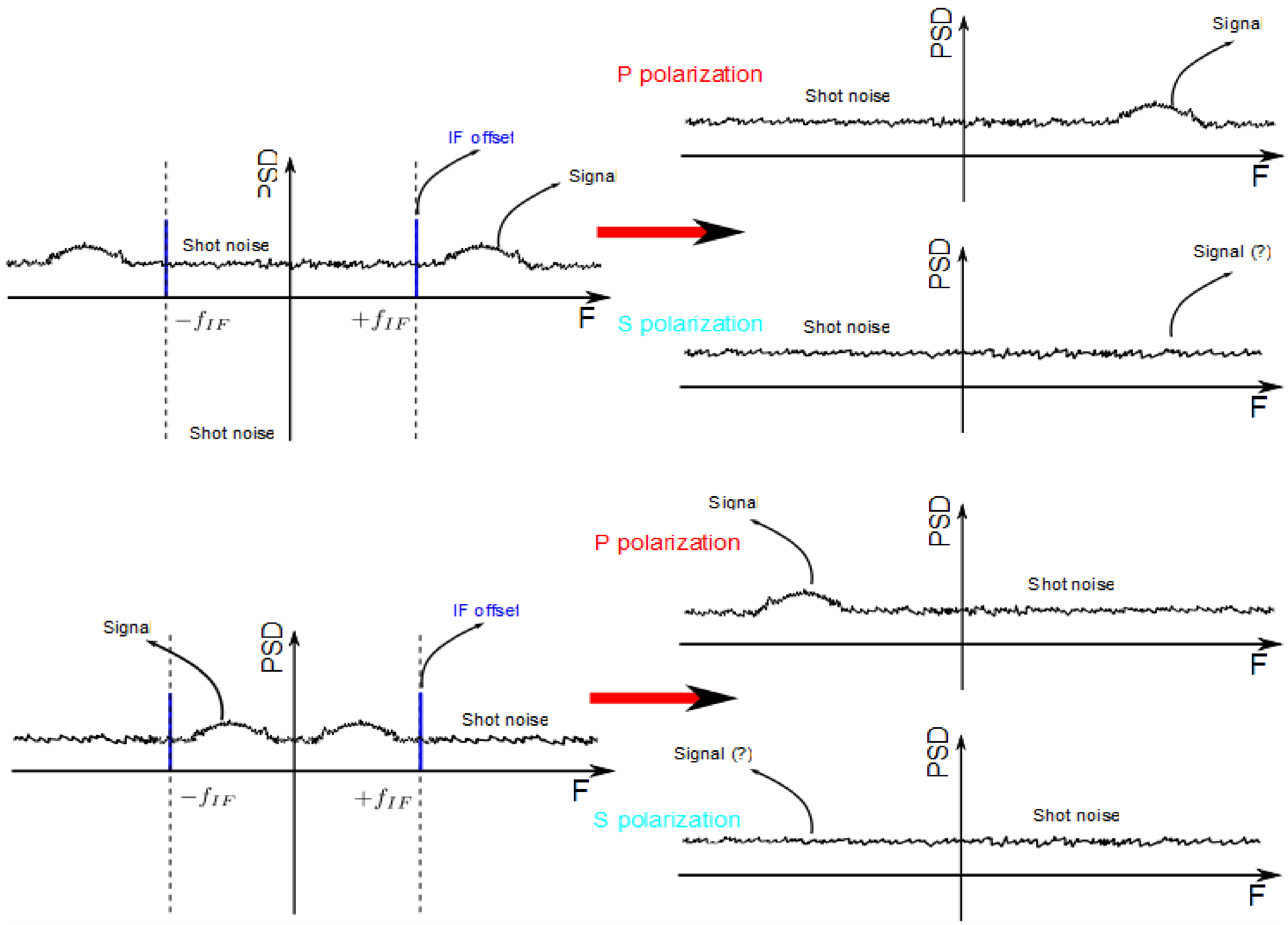
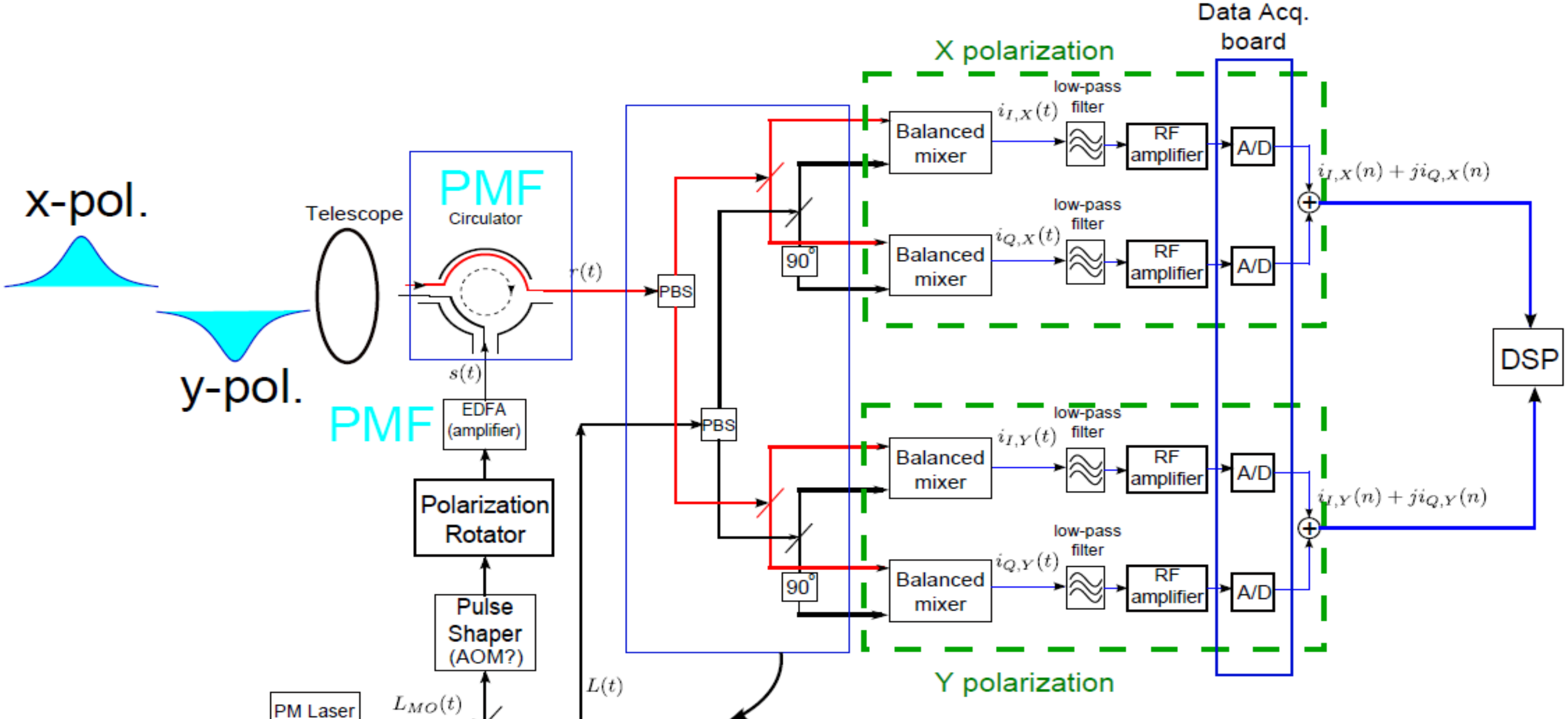
Dual Pol. Image-reject homodyne, pulsed



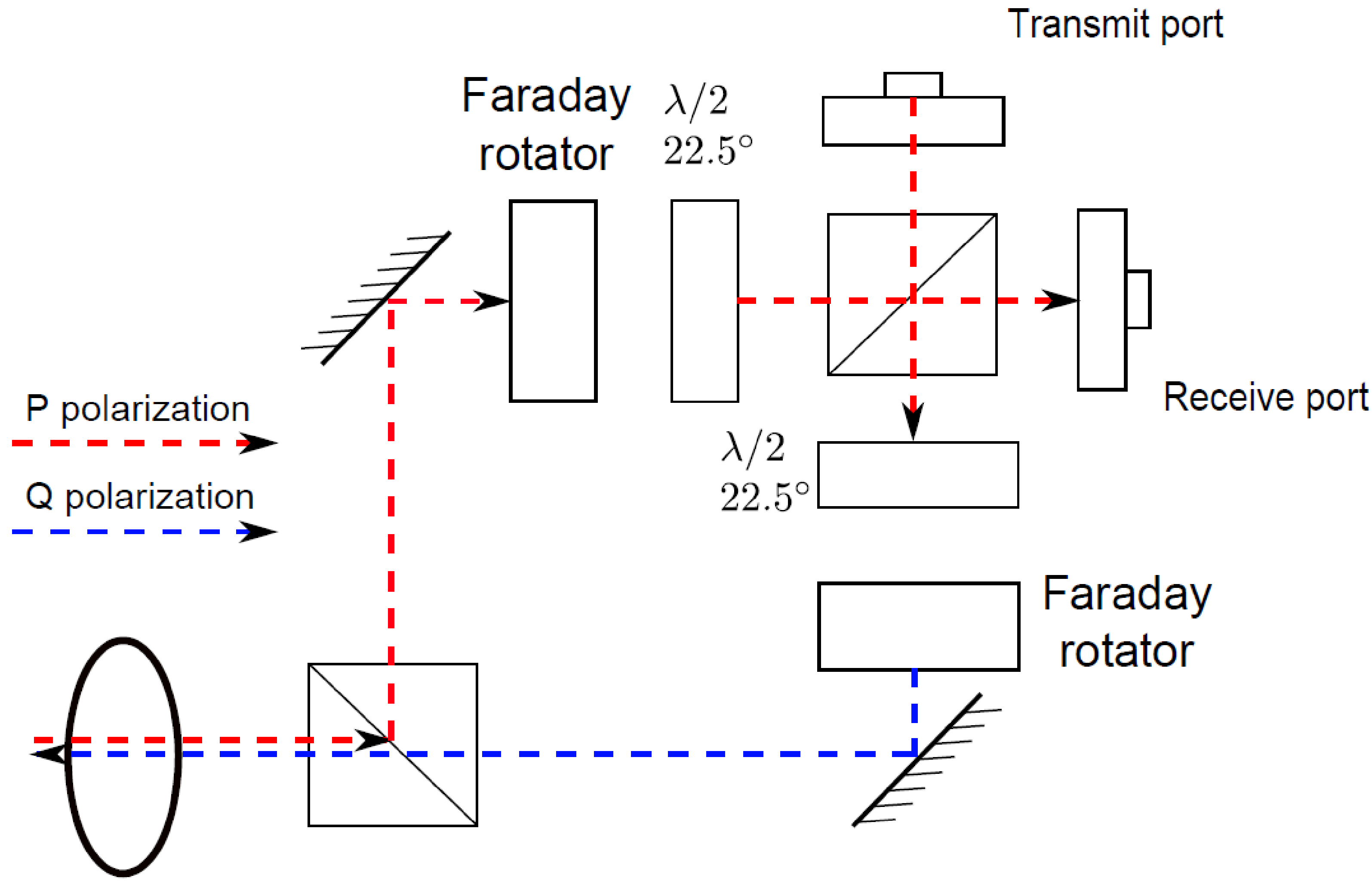
Polarization diversity pulsed CDL



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)

Polarization diversity circulator



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Conclusion

- To discriminate the sign of the radial wind velocity, either a heterodyne or homodyne receiver with image-reject structure is needed.
- The heterodyne receiver with IF sampling has been developed and is currently used at DTU Wind Energy.
- Due to various spurious effects inherent to such systems, they suffer from noisy observations. This is more pronounced for low radial wind velocity measurements where the Doppler shift appears close to the IF.
- Heterodyne receivers may also suffer from imperfections of the AOM not to mention its cost.
- It seems implementing a homodyne receiver with image-reject architecture may alleviate some of the problems in heterodyne receivers while providing cost saving possibilities.Homodyne receivers impose lower DSP requirements specially when carrying out PSD calculations.
- Homodyne receivers also require less BW expensive components such as photo detectors.

Conclusion

- Dual polarization CW CDLs allow capturing the depolarized signals. By measuring the amount of depolarization more information can be deduced about the nature of the target.

- The polarization discrimination by the dual polarization CW makes it possible to remove unwanted return signals with a different polarization signature.

- Employing a polarization diversity pulsed CDL allows doubling the pulse repetition rate (PRR) in pulsed lidars without sacrificing power or range.

Thanks for listening!

Questions?