Optical quadrature detection for a coherent pulsed wind lidar

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Abstract: Coherent pulsed wind lidar usually determine value and sign of wind speed thanks to a frequency shift provided by an acousto-optic modulator. The maximum measurable speed is then limited by half of the bandwidth. Noise whitening is performed for each range gate by subtracting noise spectrum to the signal spectrum. This last step is time consuming, is adding noise and could suffer from residual signal. In this paper we present the use in a pulsed lidar of an all optical hybrid detector module, formerly developed for coherent telecommunications. The main advantages of quadrature detection are to determine the sign of wind speed without frequency shift, and to flatten the noise floor without additional noise acquisition, for a better frequency estimation. We present a simple statistical estimation on performance gain using heterodyne quadrature detection. Experimental procedure in pulsed mode and comparison results of performance with classical detection are also presented.

Keywords: Coherent Wind Doppler Lidars, quadrature detection, IQ detection

1. Introduction

Study of noise detection to improve performances has been the subject of many works in lidars. Recently, Abari et al. have published studies on the impact of the use of hybrid coherent detection on correlated noise in continuous wave fiber lidars. Hybrid coherent detection modules, also called quadrature detection modules, have been developed for fiber telecommunications over the last years, which make them more efficient and affordable components for fiber lidars.

Quadrature detection consists in recording the real part (I) and the imaginary part (Q) of the beating Doppler signal. They both contain the amplitude and the Doppler information. Moreover, their phase difference gives the velocity sign, and cross-correlation of their respective spectra allow to get rid of correlated noises [1-3]. The issues about hybrid coherent detection for pulsed lidars are however slightly different compared to continuous wave lidar: a noise acquisition without significant signal can be achieved for each transmitted single pulse. Then, the noise can be subtracted to the signal acquisition at each range gate containing Doppler signal. In pulsed lidars, the pulse modulation is usually performed by an acousto-optic modulator (AOM), which shifts the frequency in the same time. With a quadrature detection, it is not necessary to introduce a frequency shifter to determine the Doppler shift sign Consequently, a simple amplitude modulator, for example an electro-optical modulator with no frequency shift can be used. The acquisition bandwidth is reduced by 2 but two acquisition channels are however necessary.

To evaluate the interest of quadrature detection for pulsed lidars, this paper presents a comparison of performances with classical simple detection.

2. Theoretical study

The considered parameter for performance evaluation in this study is the spectrum SNR, ratio of the Doppler peak height $Sig$ to a detection threshold taken as the standard deviation of the noise in the statistical ensemble of detection, as presented in figure 1. It is important to mention that $Sig$ is the height between Doppler peak and mean value of noise.
In the classical case of simple heterodyne detection, the considered statistical ensemble of detection is the random variable $X_c(\omega)$ defined in Eqn. 1 as the ratio of a power spectrum containing the signal to a power spectrum with same statistics except it doesn’t contain Doppler signal. This normalization subtracts noise within the considered range and, provided shot noise is dominating detection noise, the normalization makes the variable $X_c(\omega)$ independent of local oscillator optical power.

$$X_c(\omega) = \frac{S_c(\omega)}{S_{\text{noise}}c(\omega)}$$  \hspace{1cm} (1)

Where $S_c(\omega)$ is the sum of power spectral densities (PSD) as of a series of $n$ acquisitions at the considered range (Eqn. 2), and $S_{\text{noise}}c(\omega)$ defined as $S_c(\omega)$ but at a range where the Doppler peak is largely negligible and not considered.

$$S_c(\omega) = \sum_{k=1}^{n}|s_{c,k}(\omega)|^2$$  \hspace{1cm} (2)

Where $s_{c,k}(\omega)$ is the Fourier transform of one temporal acquisition $k$, $s_{c,k}(t)$, at the considered range.

To calculate the detection threshold $S_{d,c}$, a case where there is no Doppler peak at the considered range is used. $S_{d,c}$ depends only on $n$, the number of acquisitions (Eqn. 3).

$$S_{d,c} = \sqrt{\text{Var}[X_{\text{noise}}c(\omega)]} = \sqrt{\frac{2}{n}}$$  \hspace{1cm} (3)

Without impacting the validity of results in the case of atmospheric backscatter, we consider that the Doppler shifted light optical power received by the lidar to be constant over acquisitions during integration time. The mean value of $X_{\text{noise}}c(\omega)$ is equal to 1 and the Doppler peak height $\text{Sig}_c$ is given by Eqn. 4, where $X_{\text{doppler}}c(\omega_{\text{doppler}})$ is the value of $X_c$ in the presence of Doppler signal at $\omega_{\text{doppler}}$.

$$\text{Sig}_c = X_{\text{doppler}}c(\omega_{\text{doppler}}) - X_{\text{noise}}c(\omega_{\text{doppler}}) = \frac{K P_r}{\mu_\omega}$$  \hspace{1cm} (4)

$K$ is a parameter proportional to detecting photodiode responsivity and local oscillator optical power on the photodiode ($P_{LO}$). $P_r$ is the Doppler shifted light optical power reaching the photodiode, and $\mu_\omega$ is the mean value of PSD of a unitary noise temporal acquisition. $\mu_\omega$ is proportional to $P_{LO}$, resulting in...
independence of $Si g_C$ versus $P_{LO}$. The performance parameter of classical simple detection is then given by Eqn. 5.

$$SNR_C = \frac{K \cdot P_r}{\mu \omega} \sqrt{\frac{n}{2}}$$

(5)

In the case of quadrature detection, the statistical ensemble of detection that is considered is $X_{IM}(\omega)$ as defined in [1] (Eqn. 6). The correlated noises between the two quadrature signals $i$ and $q$ are cancelling.

$$X_{IM}(\omega) = \sum_{k=1}^{n} T F (\int_{-\infty}^{\infty} i_k(t)q_k(t-\tau)dt) = \sum_{k=1}^{n} 1m(i_k(\omega).\overline{q_k}(\omega)^*)$$

(6)

Considering the case where $i_k$ and $q_k$ series of acquisition don’t show any Doppler signal, the detection threshold is then given by Eqn. 7.

$$S_{d,IM} = \sqrt{Var_{\omega}[X bruit IM(\omega)]} = \mu \omega \sqrt{\frac{n}{2}}$$

(7)

Where $\mu_\omega$ has the same value as in the classical simple detection scheme, provided the local oscillator optical power on each photodiode is the same as in the classical detection scheme.

The Doppler shifted optical power received by the lidar is divided in two parts, and assuming they are equal, the Doppler peak height $Si g_{IM}$ is given by Eqn. 8.

$$Si g_{IM} = \frac{K \cdot n \cdot P_r}{2}$$

(8)

The performance parameter is then defined by Eqn. 9 and equal to the performance parameter of the classical simple detection scheme.

$$SNR_{IM} = \frac{K \cdot P_r}{\mu \omega} \sqrt{\frac{n}{2}}$$

(9)

Thus, if the sum of optical power on both photodiodes in quadrature is equal to the optical power received on photodiode in simple detection, the performance parameters are the same in both schemes.

3. Experimental comparison

The aim of the experiment is to compare performances of classical simple detection and quadrature detection with same parameters. Using same In-phase and Quadrature signals acquisitions, both IQ detection performance and an equivalent performance of classical detection are calculated. Using Eqn. 3 and 4, the equivalent performance of classical detection is simply calculated by the sum in Eqn. 10.

$$SNR_{C, equivalent} = \frac{Si g_{C,I}}{s_{d,c,I}} + \frac{Si g_{C,Q}}{s_{d,c,Q}} = SNR_{C,I} + SNR_{C,Q}$$

(10)

The experimental setup consists in a classical pulsed lidar chain, equipped with an IQ module and a two channel acquisition system. The IQ demodulator for this specific experiment has been assembled at Leosphere labs. It had no optimal transmission since it was a simplified unbalanced scheme, but this has no impact on the purpose of the experiment. Temporal signals corresponding to about 1,000 successive pulses were recorded and post-processed.

Experimentally, statistical ensembles of detection $X_{C,I}$, $X_{C,Q}$ and $X_{IM}$ are calculated as defined by Eqn. 1 and 6 (figures 2 and 3). Performances $SNR_C$ and $SNR_{IM}$ are then given measuring the Doppler peak height and standard deviation in a frequency range where no Doppler signal is present.
To get rid of the sampling effects, a Gaussian fit is performed on spectra and a CNR is calculated, corresponding to the area under the fitted Gaussian peak. The obtained CNR values are used as the corresponding $\text{Sig}$ parameters. The CNR are normalized to the noise standard deviation of noise (Table 1). Using Eqn. 10 the comparison is done on spectra, with parameter $\text{SNR}_{c,\text{equivalent}}$. The relative difference between theoretical unitary value of ratio $\text{SNR}_{IM}/\text{SNR}_{c,\text{equivalent}}$ and the measurement is 5%. 

Figure 2. Measured sum of PSD of signal on I detector (a) and corresponding normalized sum $X_{c,I}$ (b)

Figure 3. Measured statistical ensemble of detection $X_{IM}$
Table 1. Detection performances on channels I and Q individually ($SNR_{CI}$ and $SNR_{CQ}$), and on cross-correlation ($SNR_{IM}$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$SNR_{CI}$</td>
<td>39.5</td>
</tr>
<tr>
<td>$SNR_{CQ}$</td>
<td>56</td>
</tr>
<tr>
<td>$SNR_{C\text{equivalent}}$</td>
<td>95.5</td>
</tr>
<tr>
<td>$SNR_{IM}$</td>
<td>100</td>
</tr>
<tr>
<td>$SNR_{IM}/SNR_{C\text{equivalent}}$</td>
<td>1.05</td>
</tr>
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Whereas the IQ scheme was not optimized in terms of transmission, the lidar demonstrated a measurement range of about 250 m (figure 4), similar to the conventional scheme.

![Figure 4](image)

(a) CNR [dB] vs Range [m]
(b) Estimated radial wind speed [m/s] vs Range [m]

Figure 4. Measurements of CNR (a) and radial wind speed (b) computed on cross-correlated quadrature signals

4. Conclusion

Theoretical and practical evaluation of cross-correlation quadrature detection in a pulsed lidar scheme has been performed. They conform well to show that, in terms of SNR, the performances of quadrature detection and classical simple detection are very close to each other. Then, the challenge is now to set up a quadrature detection module with low insertion loss. If this challenge is overcome, full advantage in terms of acquisition bandwidth reduction and frequency shifter suppression will be achievable.

5. References

