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SNR Analysis of a Novel Wideband Doppler Lidar Detection Technique.

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1. Introduction.

The problem of the wideband detection technique is essential for creation of airborne and satelite Doppler lidars [1,2] as well as in ground based systems operating at high frequency instability [3,4]. A new method for Doppler detection by not strictly tracking the reference frequency was developed, using discrete sets of frequencies and offering an essential simplification of the electronics blocks in the reference channel. In this work a signal-to-noise ratio (SNR) analysis of the detection part of such a system is presented and compared with the wellknown quadrature Doppler detection method. It is shown that the accuracy of Doppler frequency estimates remain the same as in the case of quadrature detection technique.

2. Theoretical analysis.

The backscattered signal, carrying information about the Doppler shift f_D induced by the wind motion, $U(t)=A_D(t).cos[2\pi(f_{Ds}+f_D)t+\varphi_D]$ after the preamplifier is mixed with a reference signal $U_o(t)=A_o cos(2\pi f_o t+\varphi_C)$ in the presence of a wideband noise $n(t)=N(t).cos[2\pi f_{off}t+\theta(t)]$. Here f_{off} is the beating frequency of the local oscilator and the transmitted radiation; f_{Ds} is an additional Doppler shift due to the motion and scanning of the laser beam or to the frequency instability; the full bandwidth of the pre-amplifier is $\Delta=\Delta f_{Ds}+2f_{Dm}$ where f_{Dm} is the maximum expected useful Doppler frequency and $\Delta f_{Ds}=f_h-f_l$ where f_h and f_l are the higher and lower frequency f_{Ds} extrema. In airborne systems variations of f_{Ds} can reach 80-100 MHz. We consider two cases of mixing according to [3]:

- with a discrete set of reference frequencies f_o not strictly tracking f_{Ds} - the Doppler spectrum appearing at the one side of $|f_o-f_{Ds}|$;
- with two discrete sets of frequencies f^+ and f^- not strictly tracking f_{Ds} from both sides - the Doppler spectrum appearing to the left of $|f^+, f^- - f_{Ds}|$ in one of the channels. The exact value of f_{Ds} is determined within the laser shot.For comparison we consider the case of quadrature detection of Doppler signals with a reference frequency f_o tuned to be equal to f_{Ds}. This approach reqiures an exact knowledge of the frequency f_{Ds} before the laser shot as well as a wideband tuning of the coherent oscillators providing 90° phaseshift between reference signals.

To analyse different changes caused in the SNR by a low-pass filtering of the mixed signals we consider the case of a narrowband Doppler signal with a bandwidth $\sigma_D << f_o$ and A_D ~const within the gating cell. The noise is white with a variance $N_0\Delta$, where for simplicity rectangular transfer function for the pre-amplifier is assumed, Thus, the wideband input SNR at the pre-amplifier output is given by $SNR_{inp}=A_D^2/2N_o\Delta$. To find the SNR at the mixer output we take the fluctuating component of the signal at this point, its spectrum given by the autoconvolution of

$$F_\Sigma(f) = F_s(f) + N_o rect(f/\Delta).rect(f/\Delta) = \begin{cases} 1 & at \quad |f| \leq \Delta/2 \\ 0 & at \quad |f| > \Delta/2 \end{cases}$$

with

$$F_S(f) = \frac{A_o^2}{2}\delta(f - f_o + f_{off}) + \frac{A_D^2}{2}\delta(f - f_{Ds} - f_D + f_{off})$$

After the mixing the resultant spectrum becomes

$$F_o(f) = \frac{A_o^2 A_D^2}{4} * \delta'(f - f_D') + \frac{N_o}{2} rect(f/\Delta) * [A_o^2 \delta'(f - f_n') + A_D^2 \delta'(f - f_{Dn}')] + N_o^2(\Delta - |f|)$$

where

$$\delta'(f - \xi) = \delta(f - \xi) + \delta(f + \xi); f_D' = |f_{Ds} + f_D - f_o|, f_n' = |f_{off} - f_o|, f_{Dn} = |f_{Ds} + f_D - f_{off}|$$

As $\alpha = A_o/A_D >> 1$, the mixing of the reference signal with the noise gives the main contribution to the noise at the mixer output; the other two components can be neglected. After a LPF with a cut-off frequency $f_c = \beta\Delta/2$, the noise variance becomes

$$\sigma_o^2 \approx N_o\{0.5\beta N_o \Delta^2(2 - 0.5\beta) + A_o^2[0.5(\beta + 1)\Delta - f_n' + [0.5(\beta - 1)\Delta + f_n'] * rect[4f_n'/(1 - \beta)\Delta]]\}$$

Thus, the SNR after the mixing and filtering will be as follows:

- for the quadrature detection when $f_o = f_{Ds}$ and $f_c = f_{Dm}$ we obtain

$$SNR_{out} = \frac{4\alpha^2 SNR_{inp}^2}{\beta[\beta + 4SNR_{inp}(1 + \alpha^2)]}$$

At $\alpha >> 1$ the ratio SNR_{out}/SNR_{inp} at the mixer output is $1/\beta > 1$. The reference frequency changes within $\Delta f_{Ds} = f_h - f_l$ which means equal SNR for all its values. The required sampling frequency is twice the maximum Doppler shift and is minimal in this case. When a fixed reference frequency $f_o = f_{off}$ is used, $f_c = \Delta/2$, $SNR_{inp} \sim SNR_{out}$ and no improvement of the SNR is obtained. The sampling frequency is $\Delta/2f_{Dm}$ times higher than in the former case.

- in the case when a discrete set of reference frequencies with a step δf is used with $|f_o - f_{Ds}| > f_{Dm}$ and $f_c > 2f_{Dm} + \delta f$ the sampling frequency is of the order of Δ. As the reference frequency does not follow strictly f_{Ds} its variation exceeds the interval $\Delta f_{Ds} = f_h - f_l$, which means different SNR values depending on f_o. For example, at $f_o = f_c - \Delta/2$ SNR_{out} is twice larger than at $f_o = f_{off}$. The lowest value of SNR_{out} is $\sim SNR_{inp}$.

- in the case when two discrete sets of reference frequencies with a step δf are used with $|f^+, f^- - f_{Ds}| > f_{Dm}$ and $f_c > 2f_{Dm}$ the sampling frequency is lower and the SNR higher. In this approach we must take into account the difference between SNR's values in the two channels, which arises out of the large difference between $|f^+ - f_{off}|$ and $|f^- - f_{off}|$. In Fig.1 noise spectra in both channels are schematically shown for f_{off}=60MHz, f^+=65MHz, f^-=35MHz, f_{Ds}=50MHz and the cut-off frequency of LPF 21MHz.

The use of a not strictly tracking reference frequency requires additional digital filtering of the sampled data. This can be done in the frequency domain within the interval with length f_{Dm} to ensure the same SNR_{out} as in the quadrature detection case. For this purpose periodogram-based spectral estimators [5] can be used. In the case when a discrete set of reference frequencies with $|f_o - f_{Ds}| > f_{Dm}$ is used we 1)compare the surfaces under the signal spectrum within the intervals f_{Dm} on both sides of $|f_o - f_{Ds}|$ and take a decision which interval contains Doppler spectrum; 2)extract the mean spectrum level from the spectrum in the chosen interval and construct the frequency estimate. It is clear that following this procedure, when two frequencies f^+, f^- are used, cases of wrong channel selection may occur. To avoid this we propose to "correct" the data in one of the channels multiplying them by the ratio of the expected wideband SNR values in the both channels, which can be easily evaluated knowing f^+, f^-, f_{Ds} and f_c.

3. Computer simulations and results.

Computer simulation of both cases of not strictly tracking of f_{Ds} with sets of discrete frequencies has been made. The model output is the standard deviation of the first spectral moment estimate. The signal and noise realisations with Gaussian distribution are generated in the time domain as a MA process at a given wideband input SNR. The noise correlation function will be $R(\tau)=N_o.cos(2\pi f_{off}).sin(\pi\Delta\tau)/\Delta\tau$. The signal component has a Gaussian spectrum with halfwidth $\sigma_D/2$ at level e^{-1}. As mixing doubles the frequencies, the realizations at the mixer input are modelled with the sampling step $\delta\tau > 1/2(2f_{off}+\Delta)$. Also, as the condition $\sigma_D << \Delta$ is fulfilled, we generate the signal realizations at $\delta\tau' > 1/4\ \sigma_D$ and attach the same signal value to all $\delta\tau'/\delta\tau$ noise members within every step $\delta\tau'$. The LPF is a Chebyshev filter. In Fig.2 the standard deviation of the Doppler frequency estimate and the percentage of cases with error less than 1m/s are given for the following values of the parameters: useful Doppler shift f_D =4 MHz, f_{Ds} =45 MHz, , f_{Dm}=10 MHz, f_{off}=60 MHz, Δ = 60 MHz ; members of convolution for noise and signal generation are equal to 30 and 40 respectively; the realisations at the mixer input are generated at 440 MHz with duration of the gating cell ~3μs. The case of wide Doppler spectrum is modelled at $\sigma_D/2f_{Dm}$=0.1. The cut-off frequencies of the LPF are 11, 22 and 44 MHz, respectively for the cases of quadrature detection (QD) $f_o=f_{Ds}$; tracking of f_{Ds} with f^+=61 MHz, f^-=29 MHz and tracking of f_{Ds} with f_o=60 MHz. The number of processed realisations for every SNR varies from 1500 to 3000. As seen, there is a very good coincidence between standard deviation values of Doppler frequency estimates for the proposed processing approach with a discrete number of reference frequencies and the traditional quadrature detection case. It may be concluded that the new method [3] can be effectively applied in any wideband Doppler system offering simplification of the entire electronics in the reference and detection hardware.

References

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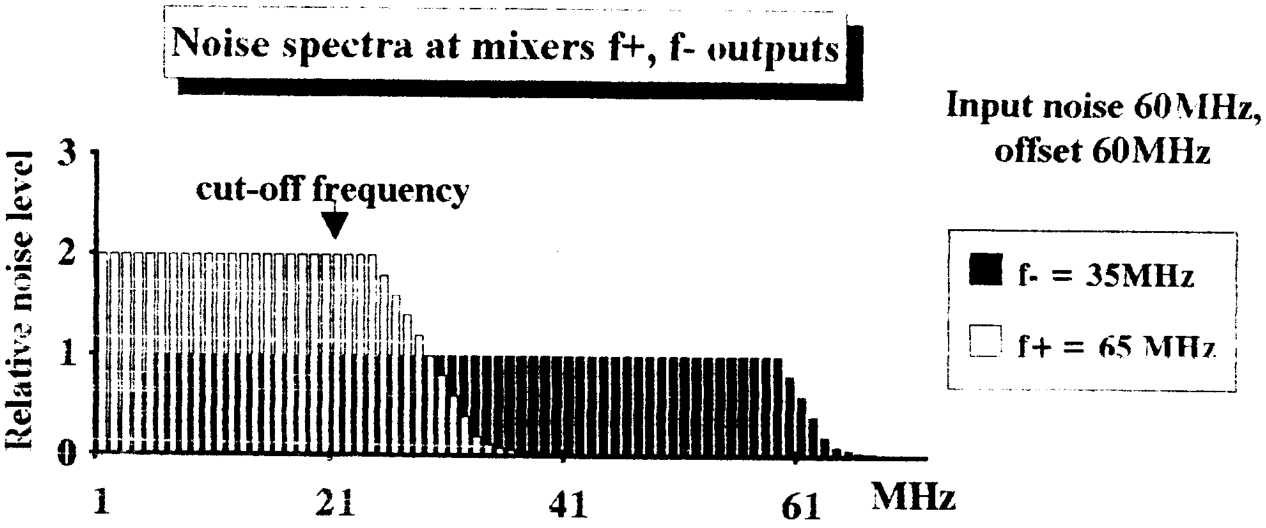
Noise spectra at mixers f+, f- outputs
Input noise 60MHz,
offset 60MHz
Relative noise level
cut-off frequency
f- = 35MHz
f+ = 65 MHz
0
1
2
3
1
21
41
61
MHz

Fig.1.

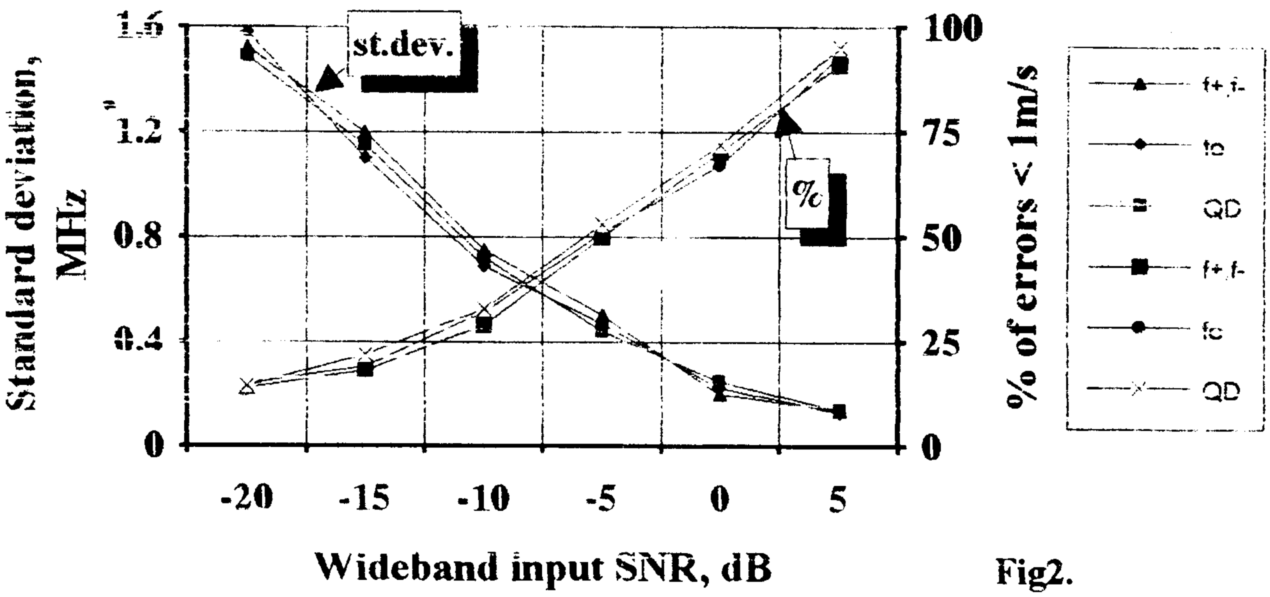
Standard deviation, MHz
% of errors < 1m/s
st.dev.
%
f+,f-
fc
QD
f+,f-
fc
QD
0
0.4
0.8
1.2
1.6
0
25
50
75
100
-20
-15
-10
-5
0
5
Wideband input SNR, dB

Fig2.