A review of sparse frequency linearly frequency modulated (SF-LFM) laser radar signal modeling with preliminary experimental results

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Abstract

Sparse frequency linearly frequency modulated (SF-LFM) laser radar (ladar) signals have been shown through analytical and numerical modeling to increase the effective bandwidth of a ladar signal without the need for large bandwidth modulation sources. SF-LFM waveforms increase the effective bandwidth, and hence the range resolution, of ladar signals by superimposing multiple frequency offset laser lines into the same waveguide and then coupling the superimposed lines into a single linear frequency modulator (or a quadratic phase modulator). While SF-LFM ladar signals have the distinct advantage of producing lager bandwidth signals without sacrificing linearity, the segmented bandwidth nature of the SF-LFM ladar signals can introduce additional ghosting in the matched filter output. This manuscript will review the previously developed models for SF-LFM ladar signals, and discus some preliminary experimental data which verifies some of the results of the previous models.

1. Introduction

There is a tradeoff in traditional pulsed radar as well as laser radar (ladar) when trying to successfully resolve range and velocity. In a pulsed radar/ladar system, a narrower transform limited pulse will yield better range resolution, while at the same time the velocity (Doppler) resolution will deteriorate. In the past considerable effort has been expended to develop more complex waveforms and a linear frequency modulation (LFM) waveform has become one of the most popular approaches to resolve this issue. LFM radar signals allow for an increase signal bandwidth while keeping long pulse durations, therefore allowing a radar system to resolve both a target's range and velocity.[1-3] Although LFM signals have recently been implemented in ladar systems, it remains technologically challenging to implement large linear chirps over large pulse durations.[4,5]

In previous papers we proposed a variant on traditional LFM ladar signals, called sparse frequency linear frequency modulated (SF-LFM) ladar signals.[6,7] SF-LFM ladar signals are generated by first superimposing multiple frequency offset laser lines, where each line is separated by a predefined difference frequency. Next the resultant frequency comb is coupled into an acousto-optic modulator (AOM) which applies an identical chirp to each of the laser lines. This will result in the superposition of multiple smaller chirps that coherently add to create a SF-LFM ladar signal.

It can easily be show that the complex envelope of a SF-LFM is given by,[7]

$$u(t)\,|_0^T = \tilde{A}\tilde{A}_{LO}^{*}\sum_{n=1}^{N} e^{i\left(2\pi\left(f_o+(n-1)df\right)t+\frac{1}{2}\beta t^2\right)}\,, \tag{1}$$

where $\tilde{A}$ and $\tilde{A}_{LO}^{*}$ are the complex amplitudes of the signal and LO, respectively, N is the number of optical signals, f is the optical carrier frequency, f_o is the constant frequency offset from the AOM, df is the difference frequency between each signal band, and β is the chirp coefficient defined as,

$$\beta = \frac{2\pi B}{T}\,. \tag{2}$$

Figure 2 shows the normalized power spectral density (PSD) of equation (1) where $N = 4$, $B = 50$MHz, $f_o = 750$MHz, and $df = 75$MHz.

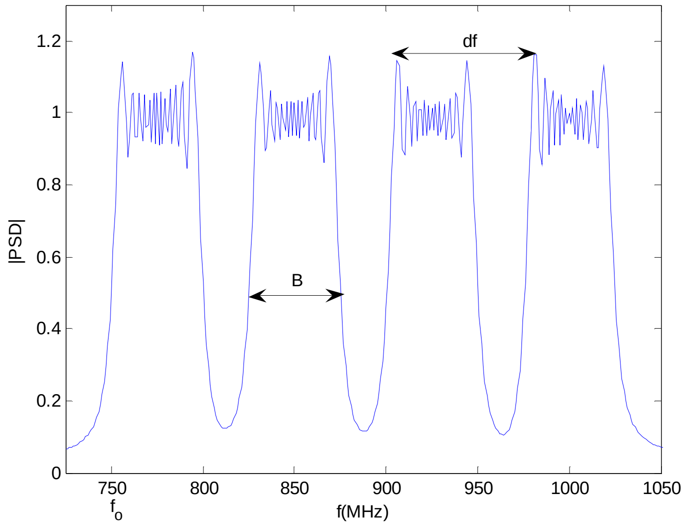

Figure 1: Normalized power spectral density (PSD) of a three chirp SF-LFM signal.

2. Theoretical Setup

In our previous work we assumed the transmit and receive setup shown in figure 2. In figure 2 the signal is produced by making use of N frequency offset laser sources. The N laser lines are combined into one optical fiber which is then fed into the acousto-optic modulator (AOM), making sure all signals receive the same chirp and modulator noise. The SF-LFM signal is then sent to a target and the reflected radiation is mixed with a local oscillator (LO) in an I/Q detection setup. I/Q detection allows for the signal to be separated into its in-phase and quadrature components allowing the complex envelope to be match filtered (auto-correlated). [6,7]

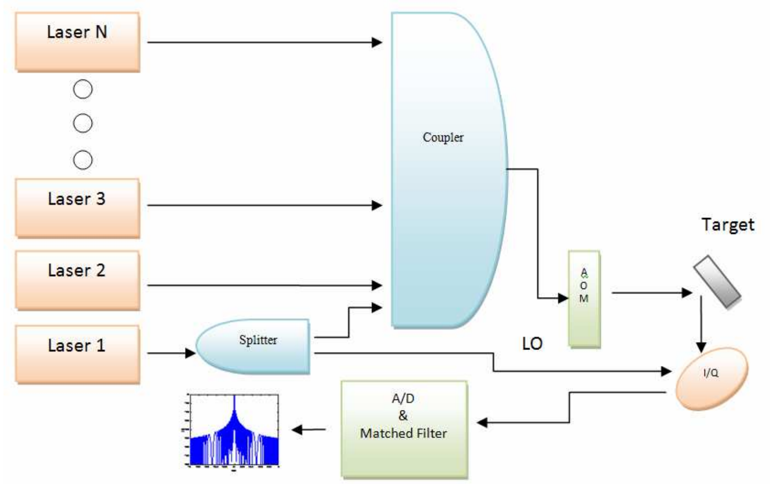

Figure 2: Schematic setup for a SF-LFM N chirp signal and the detection process.

3. Dual Chirp Ambiguity

The auto-correlation of a signal is equal to the signal's ambiguity function, in the limit that the Doppler shift of the signal is equal to zero (e.g. a stationary target).[1,6] Making use of this relationship we were able to derive an approximated analytic solution for the range ambiguity of a dual chirp SF-LFM signal, N=2, assuming a stationary target.

$$|\chi(\tau,0)| = I \times I_{LO} \left|\mathrm{sinc}(B\tau) e^{-i2\pi\left(f_o+\frac{B}{2}\right)\tau}\left(1+e^{-i2\pi df\tau}\right) + \frac{B-df}{B}\left[\delta\left(\tau+\frac{Tdf}{B}\right)+\delta\left(\tau-\frac{Tdf}{B}\right)\right] e^{-i\frac{2\pi^2 df}{B}(df+2f_o)\tau} \otimes \begin{cases} \mathrm{sinc}((B-df)\tau)e^{-i2\pi\left(f_o+\frac{B+df}{2}\right)\tau}, & if\ df \le B \\ 0, & if\ df > B \end{cases}\right|, \quad (3)$$

where τ is the time delay due to signal propagation (range), T is the period of the pulse, and I and I_{LO} are the intensities of the signal and LO, respectively.[6,7] From this analytic model we can see a central peak at $\tau = 0$ and two symmetric side peaks at $\tau = \pm\frac{T \times df}{B}$. As the chirps are pulled apart by increasing df, the symmetric side peaks become less pronounced until they disappear at approximately $df = B$. The symmetric side lobes in the ambiguity function are due to interference in the frequency domain between the two overlapped chirped signals, which is why they disappear when $df \geq B$. While the presence of large symmetric side lobes can cause significant ghosting, the phase associated with the central lobe $\left(1+e^{-i2\pi df\tau}\right)$ decreases the full width half max (FWHM) of the central lobe as the difference frequency is increased, while pushing the energy into the side lobes. The narrowing of the FWHM of the central lobe ($\delta\tau$) will yield a better range resolution due the relationship,

$$\delta R = \frac{\delta\tau \times c}{2}, \quad (4)$$

where c is the speed of light, and δR is the range resolution of the signal.

4. Effective Bandwidth

A numeric model was developed in order to calculate the range resolution and the peak to side lobe ratio (PSLR) of the zero Doppler ambiguity function (auto-correlation) for SF-LFM ladar signals as a function of difference frequency.[6,7] As a point of comparison the normalized analytic and numeric models where compared and shown to match to within one percent at the central peak and relatively close throughout the rest of the function.[6] It should be noted that while the numeric model is more accurate since the analytic model includes simplifying assumptions, the analytic model was created in order to understand the underlying mechanisms for understanding the properties of the signal.

When the range resolution of a SF-LFM ladar signal was compared to the range resolution of a standard LFM ladar signal, it was shown that the effective bandwidth (B_{eff}) followed the relationship,[6,7]

$$B_{eff} \approx B + (N-1)df, \quad (5)$$

where B is the bandwidth of the modulator, and N is the number of superimposed laser lines.

5. Preliminary Experimental Results

We developed an experiment to validate the results of the numerical model discussed in the previous section. For our experiment we use two lasers (N=2), a modulation bandwidth, B, of 37 MHz and took 29 data points at varying difference frequencies. As a specific example of one point we will look at a difference frequency of 40.3775 MHz (±0.125 MHz). For this signal we measured a range resolution of 1.80 m and a PSLR ration of -11.76 dB with standard deviations of 0.0375 m and 0.0679 dB respectively. These values closely match the theoretical model which predicted a range resolution of 1.68 m and a PSLR of -11.93 dB.[8] Figure 3 shows the matched filter output (autocorrelation) of the experimentally measured signal. For more details of the experiment see Ref 8.

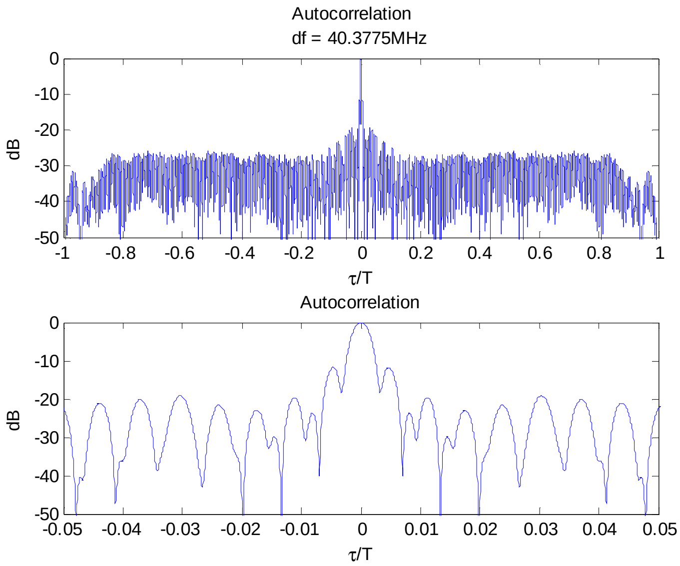

Figure 3: Matched filter output for $df = 40.3775$MHz and a bandwidth of $B = 37$MHz.

6. Conclusion

In conclusion we have shown that the effective bandwidth of a LFM ladar signal can be increased by the use of SF-LFM ladar signals. This increase in bandwidth does not come without a price; when the chirps are overlapped in frequency space there are large symmetric side lobes, and as the difference frequency increases past the modulation bandwidth the PSLR worsens as the energy from the central lobe is pushed into the side lobes. Finally we showed preliminary experimental results which verify the previously developed models.

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