Stretch Processing Of Simultaneous, Segmented Bandwidth Linear Frequency Modulation in Coherent Ladar

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1. Introduction

Pulse compression was conceived during World War II and has been implemented at radio frequencies for over sixty years to enhance radar signals. There are different forms of pulse compression techniques to improve range resolution over non-frequency-modulated signal radar and for better resolution long-pulse radar [1]. The first pulse compression method and likely the most abundant is linear frequency modulation (LFM) chirp [2]. Stretch processing (SP) is a ranging and detection technique in which both the local oscillator (LO) and the transmitting signal are LFM chirped. Once the transmitted signal is scattered off the target the echo signal is received and heterodyned with the LO. The heterodyne detection process is done by interfering two signals onto a photo-diode detector. The result is the time average of the combined signals is detected.

The achievable range resolution (ΔR) of an SP system is inversely proportional to the bandwidth (B). Assuming that time length of the signals is T the angular frequency (β) is

$$\beta = \frac{2\pi B}{T}. \quad (1)$$

The time average of the two combined signals has a frequency (df) which is relative to the time delay (t_1) between the LO and echo signals by

$$df = \frac{\beta t_1}{2\pi}, \quad (2)$$

where β is the angular frequency. Figure 1 pictorially demonstrates the coherently combined signals before heterodyne detection in the optical frequency domain and the time average of the signals after heterodyne detection in the radio frequency domain.

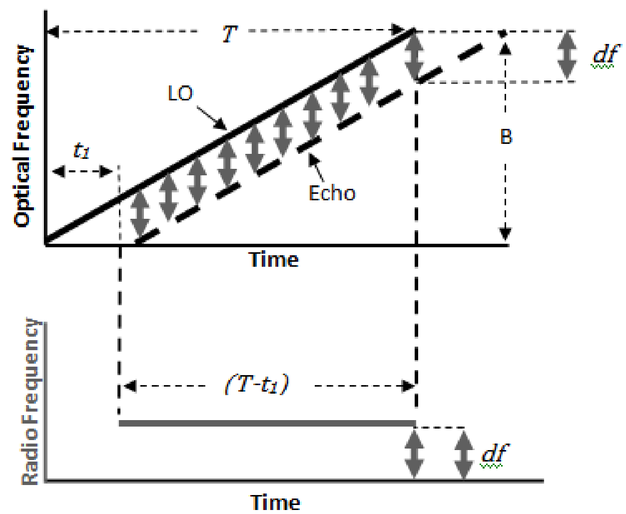

Figure 1: At optical frequency an LFM chirped LO represented by a solid line and LFM chirped echo signal represented by the dashed line interfere when mixed by detector creating a beat frequency represented by the gray line at df in radio frequency. T is the length of the signal, B is the bandwidth of the chirp, df is the difference frequency detected, and t_1 is equal to the time delay between to LO and echo signals.

Obtaining truly linear LFM chirps in the optical domain becomes increasingly difficult the larger the modulation B. Chimenti et al. discusses creating high bandwidth linear chirps by using different frequency continuous wave (CW) laser lines to simultaneously generate spectrally separate LFM chirps and combining the bandwidth. This process is known as sparse frequency linear frequency modulation, SF-LFM [3]. Using a similar technique to SF-LFM, a transmitting signal containing multiple non-frequency-overlapping chirps can be introduced into SP. When the single laser line LFM chirped LO and the now multiple laser line LFM chirped echo signal are heterodyned the result is a detected signal containing multiple frequencies ($df_1, df_2, df_3 \ldots df_n$; where n equals the number of laser lines in the transmitted/echo signal). The multiple beat frequencies of the detected signal can be processed to take advantage of the bandwidth created by the multiple laser lines of the echo signal. This technique will be referred to as multi-frequency stretch processing (MFSP).

Section two examines the idea of MFSP in-depth including what post-processing is done to achieve the gain in ΔR. Section three describes the setup used for the MFSP experiment. Section four reviews and discusses the results of the experiment. Section five concludes the paper.

2. MFSP Theory

We introduced a concept of MFSP to achieve improved ΔR by combining two or more, smaller bandwidth frequency chirped signals to emulate one larger bandwidth frequency chirped signal. Many of the same parameters such as T, B, β and t_1 apply to both SP and MFSP.

Multi-frequency stretch processing begins with a non-modulated single frequency LO and non-modulated transmitting signal containing multiple laser lines at different frequencies. All laser lines possess the same temporal time span, T. The multiple laser lines of the transmitting signal are separated enough spectrally that when the signal is modulated they will not overlap. An LFM chirp is simultaneously imposed on the multiple-frequency transmitting signal and single frequency LO signal which results in the bandwidth, B, of all the LFM chirps to be equal.

Figure 2 pictorially demonstrates the received signal using a two laser line transmitting signal MFSP system. Heterodyne detection in MFSP results in multiple frequencies $(df_1, df_2, df_3, \dots df_n)$ laser lines from the mixing of the LFM chirped LO (solid black line Figure 2) and multiple frequency LFM chirped laser lines of the echo (two black dashed lines Figure 2).

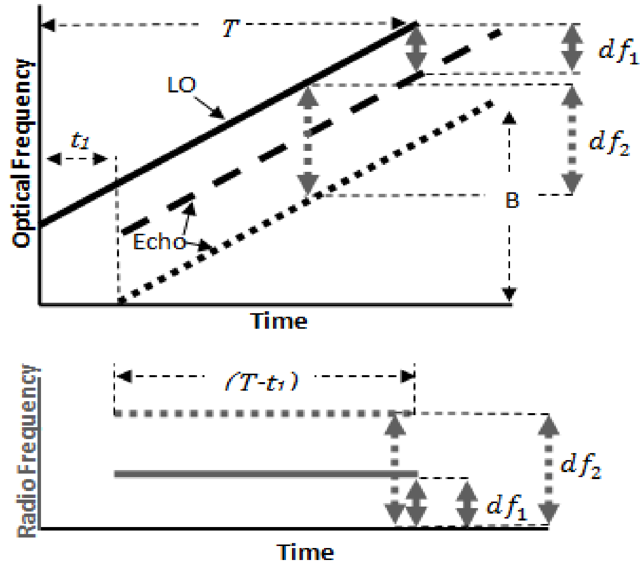

Figure 2: In the optical frequency regime an LFM chirped LO represented by a solid line and a dual laser line LFM chirped echo signal represented by the two dashed lines interfere when mixed by a photodiode detector creating beat frequencies represented by the gray lines at df_1 and df_2 in radio frequency. T is the length of the signals, B is the bandwidth of the chirps, $df_1$and df_2 are the difference frequencies detected, and t_1 is equal to the time delay between to LO and echo signals.

The frequencies of the detected laser lines $(df_1, df_2, df_3 \dots df_n)$ can be shown mathematically to be

$$df_1 = \frac{\beta}{2\pi} t_1, \tag{3}$$

$$df_2 = DF_{1,2} + \frac{\beta}{2\pi} t_1, \tag{4}$$

and

$$df_n = DF_{1,n} + \frac{\beta}{2\pi} t_1, \tag{5}$$

where β is the angular frequency of the LFM chirp, t_1 is the delay accumulated by the echo signal while travelling to and from the target at range and $DF_{1,n}$ is the spectral difference between the un-modulated LO and one of the un-modulated laser lines of the transmitting signal [4]. The frequency offset accrued while travelling to and from the target, $\frac{\beta}{2\pi} t_1$, is the same for every laser line in the detected signal. The increase in B comes from extracting this frequency offset.

The MFSP detected signal must be post processed to take advantage of the increased bandwidth to achieve the gain in ΔR. This section will explain how the post processing is preformed on the MFSP detected signal. Post processing can be sufficiently described as if the echo signal contained two different frequency laser lines, $n = 2$.

Post processing begins by Fourier transforming the heterodyned signal. The complete Fourier transform of the heterodyned signal is shown in Figure 3. The two peaks in the signal represent the detected laser lines at the frequencies df_1 and df_2 that is created during heterodyning.

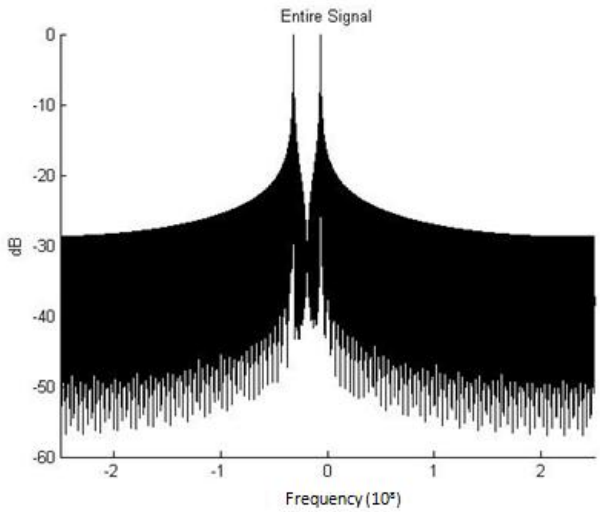

Figure 3: Entire signal Fourier transformed detected MFSP signal when the number of difference frequency laser lines equals 2 ($n = 2$).

The signal is segmented into multiple frequency spans. Figure 4 demonstrates which portion of the data points are windowed to encompass each peak created by the multiple laser lines. The portion which is separated is chosen as the minimum between two adjoining peaks. The more different frequency laser lines the detected signal contains, the smaller the allotted window for each frequency peak can be.

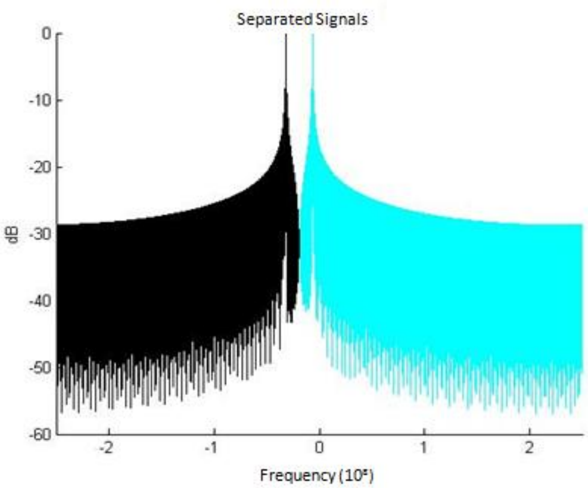

Figure 4: Entire signal Fourier transformed detected MFSP signal when separated by major frequencies. The separation of the two is denoted by different colors in the graph.

The frequency of each peak is shifted by $DF_{1,n}$ overlapping all frequency peaks at βt_1 or $2\pi df_1$ (Equations 3, 4, 5). The phases are matched in the time domain to create a continuous time signal n times longer than what can be achieved by an SP system containing the same modulator.

The MFSP signal contains n-times the bandwidth as the SP signal, so an improvment of n-times is expected in the ΔR. Figure 5 compares a stretch processed signal to a MFSP signal when the echo signal contains two different frequency laser lines, $n = 2$. The widths of the peaks at -3dB reveal improved range resolution.

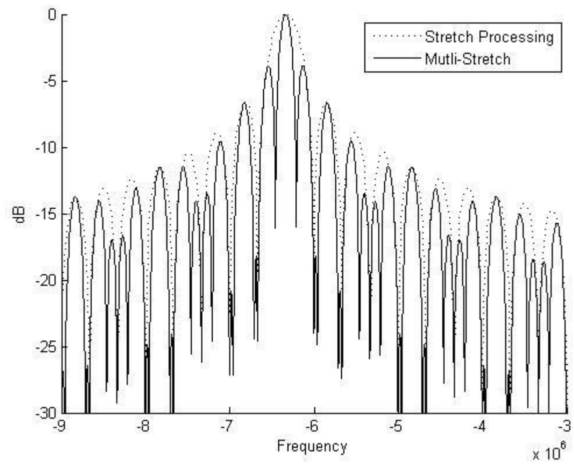

Figure 5: Spectra comparison of a SP and MFSP $n = 2$ after post processing.

3. Experimental Setup

The experiment uses two laser sources with a frequency offset of $DF_{1,2}$ between them. A schematic of the system is illustrated in Figure 6. The figure shows a block diagram of the experimental setup, along with polarization orientation of the signals denoted by the circles containing arrows. The small boxes attached to the polarization circles denote frequency versus time of each laser line in the signal. The laser 1 signal passes through a splitter to create two laser lines. One of the lines of the split signals is designated as the LO. For the experiment to work as described, the LO must be a single laser line therefore it must be separated from the transmitting signal. In order to separate it from the transmitted signal, its polarization is rotated by 90^o (denoted as P in Figure 4). It is important to note that by orthogonally polarizing the two signals they can propagate down a single fiber independently and simultaneously. The other branch of the split signal is mixed with the output of Laser 2 and together they become the transmitted signal. The two signals are combined with the LO, but do not interfere with it due to the orthogonal polarizations. The resulting signals pass through an acousto-optic modulator, AOM, where the frequencies of the signals are chirped, each receiving identical modulation and noise.

Once the combined signals are chirped they pass through a polarization beam splitter. One output from the polarizer contains the signal that will be transmitted to the target, while the other output will be the LO. The transmitted signal is scattered off the target and the echo from the target is received. The LO signal's polarization is rotated to match the echo signal's polarization. The LO and the echo are mixed together for heterodyne detection. The detector's output is digitized and processed using a Fourier transform to analyze the range and range resolution.

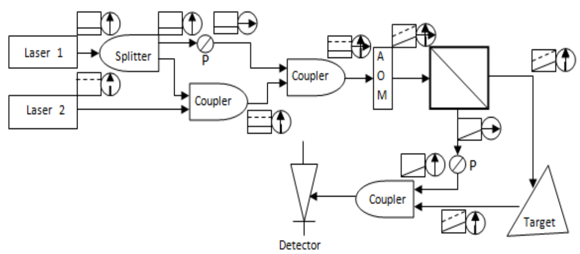

Figure 6: Block diagram of experimental setup. Splitters and couplers are shown; P is a polarization rotator and AOM denotes an acousto-optic modulator that generates the frequency chirp.

The polarization maintaining fiber is not designed to propagate two orthogonally polarized optical signals. When the orthogonally polarized LO and transmitted signals are propagating in the same fiber an unintended mixing occurs between the two signals. In the final experiment a parasitic peak appears at $2\pi DF_{1,2}$ as a result of this unintended mixing. As shown in the results the parasitic peak at $2\pi DF_{1,2}$ did not influence the proof that MFSP is a viable option for increasing ΔR.

4. Results

The purpose of this project was to develop an SP system that could take advantage of the increased bandwidth created by SF-LFM. Using multiple shorter LFM chirps to simulate a longer LFM chirp a gain in range resolution, ΔR, is achieved. Doing this exploits the fact that it is easier to maintain linearity over shorter time bandwidth constant wave LFM chirps. Another advantage is noise created by the modulator being duplicated over the length of the multiple LFM chirps; making this noise periodic in the processed signal.

The experiment succeeded in proving that a gain in resolution can be achieved by MFSP over SP. As theorized the gain in resolution is proportional to the number of laser lines in the transmitting/echo signal. The calculated gain in resolution can be observed in Figure 7 by the -3dB width difference of the two dashed lines. The dashed lines are the numerical models of the frequency response of SP and MFSP. The calculated MSFP is when there are two different frequency laser lines in the echo signal as it is in the experiment. The black line in Figure 7 is the detected and processed results of MFSP with a dual laser line echo.

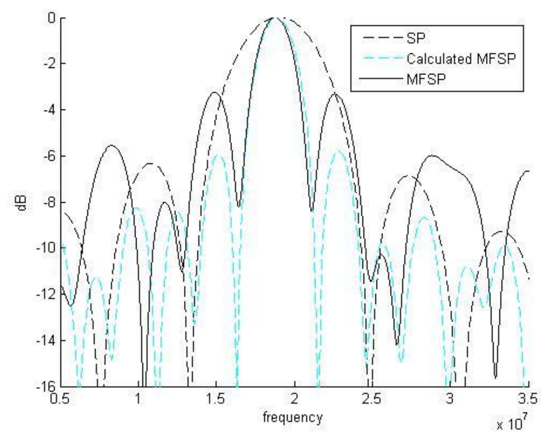

Figure 7: Final Result of MFSP experiment when the echo signal contains two frequencies.

5. Conclusion

The experiment performed verified that MFSP is a viable way to increase ΔR. Multi-frequency stretch processing significantly improves ΔR when compared to SP systems with the same modulation abilities. The cost of this improvement is the extra processing done to increase usable bandwidth. During post processing of MFSP attention has to be paid to the phasing when extending the detected signal. The limit number of chirps in the transmitting signal (n) is the modulation bandwidth multiplied by the highest detectable frequency of the diode.

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6. Refrences

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