Development of a 1319 nm Laser Radar using Fiber-Optics and RF Pulse Compression: Receiver Characterization

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Introduction

Satellites carrying lidars for measuring ice sheet surface elevation and vegetation canopy heights are scheduled to be launched in the next few years. To achieve the necessary resolution and sensitivity, lidars on these satellites use short duration, high peak power transmit pulses. These systems typically operate with a low pulse repetition frequencies (PRFs). The high peak power operation results in limited lidar lifetime and the low PRF provides sparse spatial samples along the satellite track.

To overcome these limitations, at The University of Kansas we are developing a low peak power laser radar incorporating modern radar techniques and commercially available fiber-optic technologies. We use radio frequency (RF) pulse compression and digital signal processing to achieve the receiver sensitivity needed for spaceborne applicatons when transmit powers of less than 10 W are used. Compared to high peak power lidars, our system also has a higher PRF and can provide more dense sampling. This paper summarizes the characteristics of our system's receiver.

Range accuracy and pulse compression

For altimeter systems, the key performance parameter is range accuracy, σ_R. Range accuracy is determined by the received signal bandwidth, B, and the signal-to-noise ratio, SNR [1,2].

$$\sigma_R = \frac{K\,c}{B\sqrt{SNR}} \tag{1}$$

This relationship is only valid when SNR » 1. The value of the constant K depends on the type of algorithm applied. High peak power systems typically use short-duration pulses (τ) where $B \approx 1/\tau$ with sufficient transmit power to provide the SNR needed to achieve the required range accuracy.

In our system, a long-duration ($\tau = 40\ \mu s$), low peak power (< 1 W) pulse is used to achieve a fine range accuracy ($\sigma_R = 10$ cm). The transmitted pulse is modulated by a signal with a bandwidth commensurate with the desired range accuracy. With today's off-the-shelf fiber-optic components, multi-gigahertz bandwidth modulation is possible. While the signal parameter to be modulated could be frequency, phase, amplitude, or polarization, we selected amplitude modulation so that we could readily separate the modulation signal from the optical carrier in the receiver.

A chirp (or linear FM) waveform is used as the modulation signal [3]. This waveform consists of a sinusoid whose frequency varies linearly from f_1 to f_2, where $|f_1-f_2|$ is the signal bandwidth, B. In our system, radio frequency signals are used, f_1 is 100 MHz, f_2 is 360 MHz, and B is 260 MHz. This chirp waveform is produced digitally using direct digital synthesis (DDS). As in conventional RF and microwave radar systems, once the chirp signal has been recovered in the receiver (in a process described below), the signal is dechirped (i.e., beat against the original RF chirp waveform), and low-pass filtered. The signal output from this process is a sinusoid of duration τ and frequency f_R where

$$f_R = \frac{2\,B\,R}{c\,\tau} \tag{2}$$

and R is the range to the target. This signal is digitized and analyzed to determine R. An advantage of this approach is that while the signal bandwidth is 100's of MHz, the signal to be digitized may be only a few MHz, thus, relaxing the requirements on the digitizing hardware.

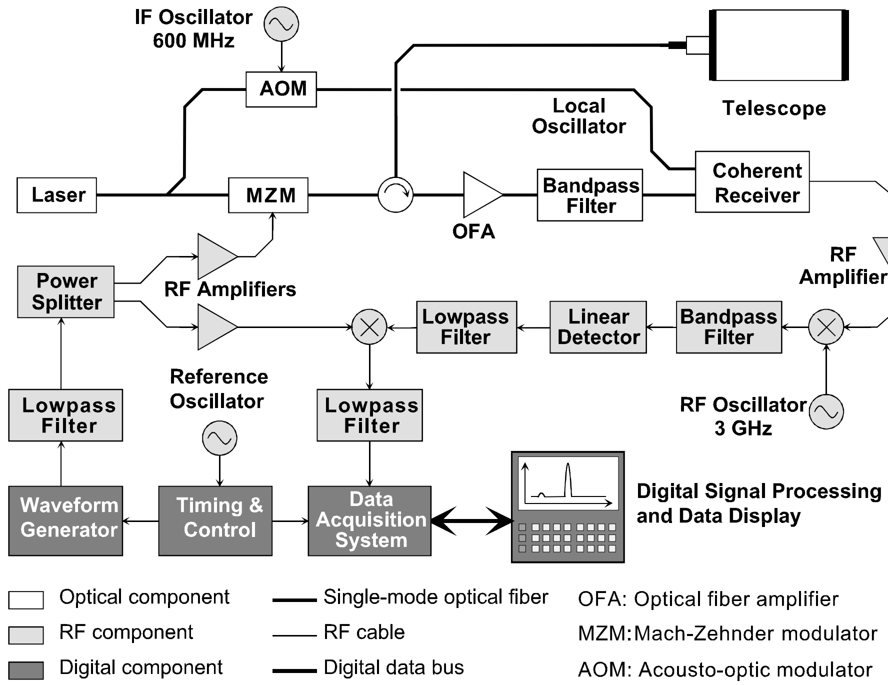


Figure 1. Block diagram of the hybrid RF/laser radar.

System description

A block diagram of our system is shown in Figure 1. The RF chirp signal produced in the waveform generator is used to drive the Mach-Zehnder modulator (MZM) which amplitude modulates the CW optical carrier (1319 nm) being guided by single-mode optical fiber. The modulated optical signal is launched into free space using a Schmidt-Cassegrain telescope with the open end of the optical fiber in the telescope's focal plane. A fiber-optic circulator allows the same telescope to be used during transmit and receive. The received optical signal is coupled from free space into the single-mode fiber in the telescope and may be amplified in an optical fiber amplifier. An optical bandpass filter (bandwidth = 1 nm) follows the optical fiber amplifier to reject out-of-band noise produced by the optical amplifier.

A sample of the CW laser light is frequency-shifted by 600 MHz in an acousto-optic modulator which serves as the local oscillator in our heterodyne coherent receiver. The detected signal is a 600 MHz carrier that is amplitude modulated by the chirp waveform. The carrier signal is then upconverted to 3.6 GHz prior to envelope detection, where the chirp waveform is recovered. The remainder of the pulse compression process, previously described, follows. Prior to frequency analysis (typically done using a fast Fourier transform), digitized samples of previous echos may be averaged together to suppress the noise while preserving the signal. By averaging N echoes, this coherent integration process provides an improvement in the SNR by a factor of N.

As the coherent receiver is sensitive to polarization state, polarization-maintaining, single-mode fiber is used throughout the local oscillator path and between the laser and the MZM. Also, since the state of polarization of the received signal may be unknown, a polarization diversity receiver is used (see Figure 2). The power of the local oscillator signal is sufficient to cause the shot noise to dominate the thermal noise in the photodetector.

In envelope detection, which is accomplished through Schottky-barrier diode rectification, the envelope signal is recovered and the carrier signal is rejected. To efficiently perform envelope detection, the carrier frequency must be at least ten times greater than the maximum frequency of the envelope waveform, which is why we upconverted the signal to 3.6 GHz. Through envelope detection, we effectively discard the optical phase information and avoid many temporal correlation issues commonly associated with coherent laser remote sensing such as laser phase noise, atmospheric turbulence, and frequency shifting due to Doppler effects.

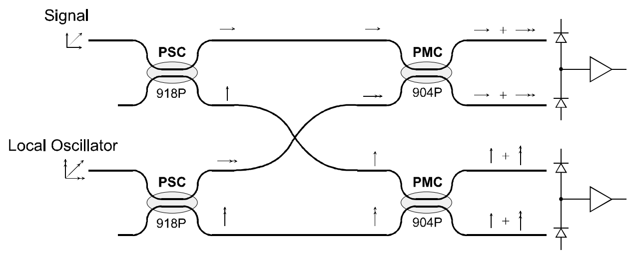


Figure 2. Block diagram of the coherent receiver applying polarization diversity.
PSC: polarization-splitting coupler, PMC: polarization-maintaining coupler

Under normal operating conditions (large optical path loss), the signal power at the photodetector output is much smaller than the noise power (SNR « 1). Signal processing gains (pulse compression and coherent integration) are required to achieve the SNR required for accurate range measurement (SNR » 1).

Envelope detection

For cases where the SNR « 1, the receiver system was designed to have a linear transfer characteristic, i.e., a 1 dB change in received optical signal power is translated into about a 1 dB of change in the detected signal power and SNR. Experimental tests have validated the linearity of the receiver up to the envelope detector input. To determine the tranfer characteristic of the envelope detector for the SNR « 1 case we used simulations, experiments, and analysis.

The envelope can be thought of as sidebands about the RF carrier. The square law characteristic of the detector generates a term which is a product of the carrier and the sideband which is the baseband version of the envelope signal. In our noise dominated condition, noise is also mixed with the carrier and sidebands, effectively increasing the noise power. Consequently during envelope detection, the SNR is degraded by about 10 dB. In addition, since both the carrier and the sidebands are both attenuated by the optical losses, the product of these two terms is affected doubly by the optical path loss. Consequently the envelope detector has a nonlinear transfer characteristic.

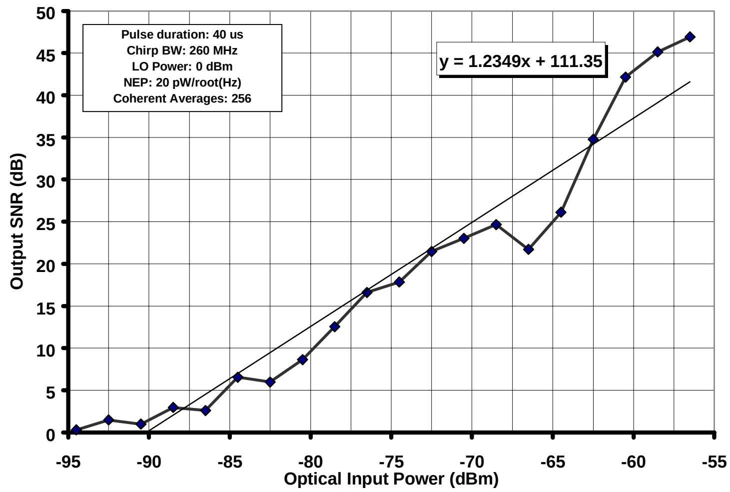
Detected SNR versus optical signal power was measured in the laboratory replacing the circulator, telescope, optical amplifier, and bandpass filter with a variable optical attenuator. Figure 3a shows measured data. In system parameters used in this experiment are shown within the figure. A linear least squares fit of the data has a slope of 1.23 which we attribute to the nonlinearities of envelope detection. The LO power (0 dBm) represents the power level input to the polarization diversity receiver.

Direct downconversion

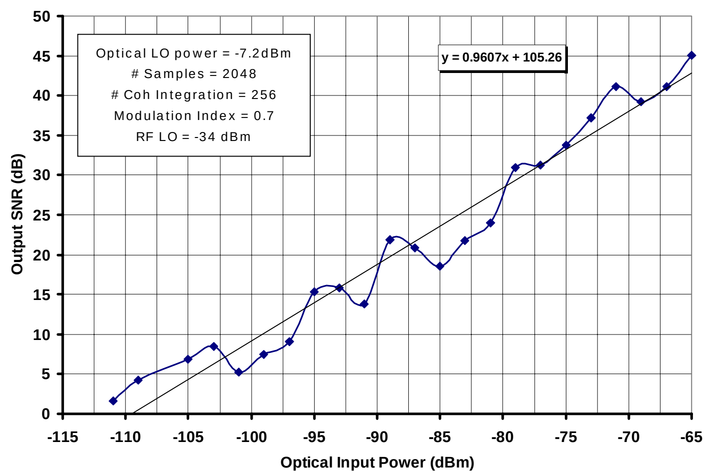
As an alternative to evelope detection, we have also applied direct downconversion of the RF signal to baseband. In this approach, rather than mix the photodetected RF signal up to 3.6 GHz, we instead mix it down to DC so that the chirp signal is at baseband. The signal is then dechirped and processed as previously described. By avoiding envelope detection, this approach should provide a more linear transfer characteristic than the envelope detection.

Laboratory measurements of this system implementation were made using the same test setup described for the previous case. The results are shown in Figure 3b. The linear least squares fit has a slope of 0.96 indicating a more linear transfer characteristic. In addition, although the optical local oscillator power is lower than in the previous case, the sensitivity of the receiver is greater than before by about 10 dB. The increased sensitivity is attributable to the fact that the 10 dB SNR degradation of the envelope detection is avoided, and the fact that a releatively strong (-34 dBm) RF local oscillator is present to down convert the chirp sidebands.

A drawback to direct downconversion exists, however. In direct downconversion the effects of the optical frequency and phase remain in the detected signal. The phase stability of the detected signal both intrapulse and pulse to pulse is now impacted by laser phase noise, atmospheric turbulance, Doppler effects, etc. This fact may preclude the use of coherent integration to further boost the SNR.



(a)



(b)

Figure 3. Measured SNR output from the receiver signal processor versus optical signal power input to the polarization diversity reciever.
a. Envelope detection using a Schottky-barrier diode.
b. Direct downconversion used.

Summary

The feasibility of using RF pulse compression and coherent averaging to enhance receiver sensitivity has been demonstrated. Doubling the transmitted pulse duration doubles the detected SNR. Doubling the number of coherent integrations also doubles the SNR of the detected signal. Envelope detection degrades the SNR by 10 dB when the signal is dominated by noise, and has a nonlinear transfer characteristic. However it has the advantage of discarding the effects of optical frequency and phase variations on the detected signal. Direct downconversion has a more linear transfer characteristic yet effects of the optical signal's frequency and phase remain in the detected signal.

References

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