Development of a 1310-nm, Coherent Laser Radar with RF Pulse Compression

Christopher Allen, Yanki Cobanoglu, Sekken Kenny Chong, Sivaprasad Gogineni
The University of Kansas, Radar Systems and Remote Sensing Laboratory
2291 Irving Hill Road, Lawrence, Kansas 66045 USA
Telephone: 785 / 864-3017 Facsimile: 785 / 864-7789 email: callen@eecs.ukans.edu

Abstract – NASA, ESA, and NASDA are planning to launch several satellites with LIDARs on board to measure ice sheet surface elevation, vegetation characteristics, and aerosol characteristics. LIDARs on these satellites will transmit short, high-peak power pulses to obtain adequate detection sensitivity and resolution. The disadvantages of high-eak power transmitters are that they require high-current power supplies and have low PRFs and limited lifetime. At The University of Kansas we are developing a pulse compression LIDAR featuring reduced peak power requirements and increased PRF to obtain more dense sampling.

We have developed and have reported (IGARSS'99) [1] 1550-nm fiber-optic based, coherent laser radar (lidar) that uses traditional RF pulse compression and digital signal processing techniques to enhance its range measurement capability. We have since migrated the wavelength to 1310 nm to improve the sensitivity to snow and ice while continuing to exploit the commercially available fiber-optic components such as distributed-feedback (DFB) lasers, modulators, and praseodymium-doped flouride fiber amplifiers (PDFFAs). To improve the radiometric sensitivity beyond that of the direct detection receiver, we have also developed a polarization-diverse, superheterodyne receiver.

We will present system design details, results of theoretical performance analyses, and performance test results.

INTRODUCTION

Compared to microwave radars, laser radars have several advantages. As a rule, laser radars require smaller apertures than comparable microwave radars. Further, the potential bandwidth of laser radars can translate to very precise range measurements. In nadir-looking altimeter configurations, the instantaneous-field-of-view of a laser radar is typically much smaller than that of a microwave radar, resulting in better estimates of the local terrain elevation.

Consequently, more and more laser radar satellite systems will be in orbit to study a variety of planetary characteristics including ice sheet surface elevation, vegetation characteristics, and aerosol characteristics. Typical laser radars on these satellites will transmit short, high-peak power pulses to obtain adequate detection sensitivity and resolution. The disadvantages of high-peak power transmitters are that they require high-current power supplies, have low pulse-repetition frequencies (PRFs), and limited lifetimes.

We have developed a pulse compression laser radar featuring reduced peak power requirements and increased PRF to obtain more dense sampling [1]. Over the last year we have significantly modified this system to improve its anticipated ranging capabilities over ice sheets. We report on the current state of this system in this paper.

SYSTEM OVERVIEW

Our hybrid RF/laser radar system marries fiber-optic technologies with RF and digital signal processing techniques to produce a very sensitive laser radar with fine range accuracy. To achieve this goal, an RF signal is impressed on an optical carrier for transmission and reception through a telescope. Upon reception, the signal is boosted with a fiber amplifier, optically filtered (to reject out-of-band noise), and then detected to recover the RF signal. The RF receiver acts as a matched filter to extract the weak RF signal from the background noise. Once digitized, the received signal is averaged to further improve the signal-to-noise ratio (SNR).

SYSTEM IMPROVEMENTS

The original laser radar breadboard [1] had an operating wavelength of 1550 nm and relied on direct detection of the optical signal. We recognized that these characteristics would significantly degrade the overall system performance for airborne (or spaceborne) applications over ice sheets. Consequently, we have modified the original breadboard to address these shortcomings.

Wavelength Migration

To take advantage of the available fiber-optic technology, our original design had an operating wavelength at 1550 nm. However, within the near-infrared spectrum, the reflectance of snow is weak at 1.5 μm and 2.0 μm [2]. For this reason we sought to change the operating wavelength to a region where the reflectance is more substantial.

We chose the 1310-nm region for two reasons. First, the reflectance is about an order of magnitude greater at this wavelength than at 1550 nm. Second, driven by the cable TV market, fiber-optic technology supporting operation in the 1310-nm band has recently reached a maturity level such that these components are economical and reliable.

To realize the migration, we replaced several wavelength-sensitive components. The 1550-nm DFB laser was replaced with a 1310-nm DFB laser with comparable power and spectral characteristics. The erbium-doped fiber amplifier (EDFA) was replaced with a praseodymium-doped flouride fiber amplifier (PDFFA) with a comparable gain and noise figure. The optical circulator and optical bandpass filter were also replaced. The remaining components (connectors, single-mode fiber, telescope optics) were left intact as they work equally well at both wavelengths.

Laboratory tests using a specular target confirmed that the 1310-nm system performs comparably to the 1550-nm system, as expected.

Superheterodyne Detection

While our laser radar uses low-power, long-duration transmit pulses to achieve a system sensitivity comparable to conventional laser radars (that use high-power, short-duration pulses), we rely on post-detection signal processing to improve the SNR. The signal-processing techniques we use to enhance receiver sensitivity include RF pulse compression and coherent integration. These signal-processing techniques promise SNR improvements between about 50 and 60 dB [1]. An additional 20-30 dB receiver sensitivity gain is expected from the fiber amplifier and coherent down conversion.

Our original breadboard laser radar used a direct detection optical receiver to convert the received optical signal to an RF signal. However, due to the square-law nature of direct detection, the resulting SNR of the recovered RF signal is unacceptably low. For this system concept to be feasible, linear optical detection is required. To illustrate this requirement, we compare a direct detection receiver with a coherent (linear) detection receiver. In a direct detection receiver with a fixed noise level, an increase of 1 dB in optical path loss results in a 2-dB reduction in both the detected signal power and the SNR. However, for a coherent receiver with the same noise power, that same 1-dB increase in optical path loss results in only a 1-dB decrease in both the signal level and the SNR. So if the optical path loss were 80 dB, the resulting SNR reduction for the direct detection case would be 160 dB, while for the coherent detection case the SNR reduction would be only 80 dB. Therefore the amount of signal-processing gain required is much less when coherent detection is used. Also the required SNR improvement is commensurate with the projected gain using the proposed techniques.

The receiver architecture (Fig. 1) follows that of a superheterodyne receiver used in amplitude modulation (AM) radio receivers. The similarity arises due to the fact that for both our system and the AM detection case, the information is contained in the envelope and not in the frequency or phase of the carrier signal. Amplitude (or intensity) modulation is preferred for this application because current laser technology lacks the stability required for coherent frequency or phase demodulation.

Challenges Associated with Superheterodyne Receivers

The improved sensitivity offered by a superheterodyne receiver comes at a price. Not only does the receiver architecture become more complicated, but the nature of the detected signal is also more complex.

The first stage involves coherent optical signal detection where a local oscillator signal is beat with the received signal. The detected RF signal is sensitive, not only to the received signal's amplitude variations, but to its frequency, phase, and polarization as well. To reduce the effect of polarization

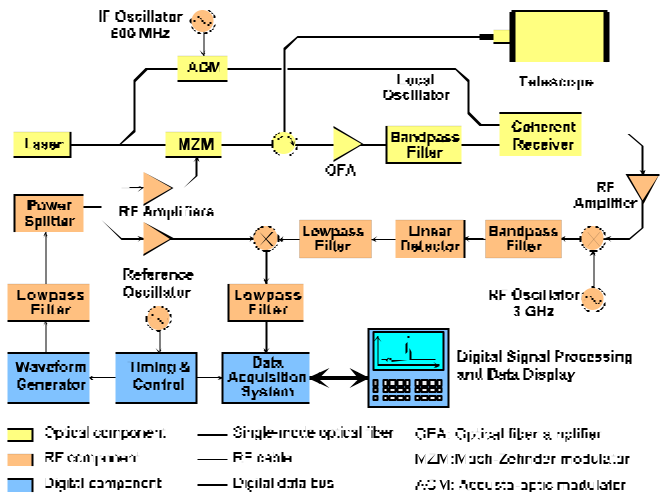

Figure 1. Block diagram of the hybrid RF/laser radar with linear detection.

fluctuations on the output signal, we chose a standard polarization-diversity receiver configuration with balanced 800-MHz photoreceivers.

Coherent receivers are inherently sensitive to changes in the frequency and phase of the received signal relative to the local oscillator. This is a particular concern for laser radars with significant round-trip travel times. To avoid phase and large-scale frequency drift problems, we use a stable laser oscillator to provide the signals for both the local oscillator and the transmitted signal. To realize a superheterodyne receiver, the local oscillator signal is frequency shifted (by 600 MHz) so that the output from the coherent optical receiver has a 600-MHz intermediate frequency (IF) (see Fig. 1). Therefore the output signal (envelope) rides on this 600-MHz carrier (as illustrated in Fig. 2).

To address the frequency and phase variations in the received signal due to propagation and scattering phenomena, our design recovers the information content of the received signal while discarding these variations. As the information we seek is contained in the waveform's envelope, we accomplish this through envelope detection. Specifically, the signal is then frequency up-converted to about 3 GHz (to improve detection efficiency), and the linear detector recovers the envelope signal. A Schottky-barrier diode driven with an appropriate input RF power level serves as the linear envelope detector. At this point in the receiver, most

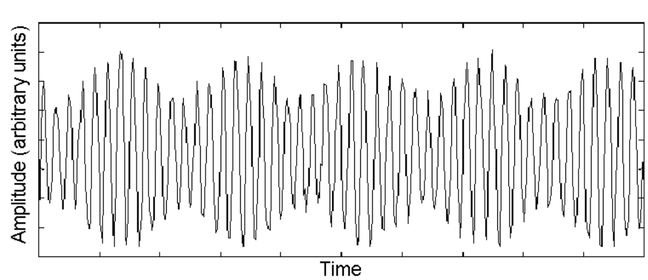

Figure 2. Sample RF signal heterodyne receiver output.

of the signal processing gain has not yet been applied; therefore, under normal operating conditions the incident power level will be dominated by noise. Thus it is possible to maintain a relatively constant incident RF power level.

Note that through this process we are essentially recovering the envelope signal from the optical signal through an incoherent process; i.e., despite the use of a coherent optical receiver, we are discarding the optical phase information. Hence, we avoid many temporal correlation issues commonly associated with coherent laser remote sensing. Factors that contribute to temporal decorrelation include laser phase noise, effects of atmospheric turbulence, and frequency shifting due to Doppler effects.

Conventional microwave radar signal processing (dechirping, digitization, averaging, and frequency analysis) follow envelope detection to complete the detection and ranging process. It is through these processes that we realize the SNR improvements. The anticipated output SNR following these processing steps will be comparable to that of a short-pulse, high-power laser radar system.

A complication to the signal processing described above arises from the fact that while envelope detection permits us to recover the desired portion of the signal, this step also changes the statistical characteristics of the noise [3]. Prior to envelope detection, the noise has Gaussian probability distribution with a zero mean. Following envelope detection, the signal has a Rayleigh distribution and a non-zero mean. After accumulating several (four or more) independent samples, the probability distribution function again is approximately Gaussian, with a non-zero mean. We anticipate this detail to have a minimal impact on the overall signal-processing effectiveness.

RESULTS

Simulations and laboratory experiments of the essential elements of the laser radar's signal processor system have been performed to evaluate its performance. Here are some of the findings from these efforts.

As the information is contained in the waveform's envelope, experiments and simulations were conducted to determine the effects of a very large modulation index. We had concerns about how signal harmonics resulting from the nonlinear transfer characteristics of the Mach-Zehnder modulator (MZM) might degrade system performance. Observations have shown that while the signal-to-harmonic ratio might be only 20-25 dB, the **presence of signal harmonics has no measurable impact on system performance**. Consequently, we drive the MZM with sufficient RF power to achieve a modulation index of 100%.

Experiments and simulations confirm that for a fixed pulse bandwidth, the signal processing gain (SNR improvement) is directly proportional to pulse duration. Therefore **doubling the pulse duration** doubles the received signal power, has no effect on the received noise power, and **results in a 3-dB SNR improvement**. Further, for a fixed pulse duration and receiver bandwidth, **changing the transmitted pulse bandwidth**, while impacting range resolution and accuracy estimates, **has negligible effect on SNR**.

We conducted experiments to address the question of whether the inclusion of the optical amplifier and bandpass filter in the receiver increases the receiver's noise floor. By varying the gain of the optical amplifier together with the insertion loss of an optical attenuator to maintain a constant output signal power, we monitored the background noise power in the presence of a weak received signal. The results show **no detectable increase in the receiver noise level due to the presence of the optical amplifier**.

We have experimentally verified a one-to-one trade of optical attenuation and SNR when using the superheterodyne optical receiver. A **1-dB increase in optical path loss results in a 1-dB reduction in SNR,** whereas with the direct detection receiver a 2-dB decrease in SNR results.

The signal-processing gain (SNR improvement) provided by coherent integration (echo averaging or stacking) has been validated both experimentally and through simulation. For the case of **direct detection**, we have found that **doubling the number of coherent integrations improves the SNR by 3 dB**. We have also demonstrated that coherent integration is effective even when noise is greater than the input level. For the superheterodyne receiver, simulations and experimental investigations of this relationship will be done this summer.

CONCLUSIONS

Several improvements to our original laser radar system have been implemented. We have successfully migrated the operating wavelength of our laser radar to 1310 nm to improve its sensitivity to ice and snow surfaces. To improve the radar's sensitivity, a superheterodyne receiver has been developed, which linearly recovers the envelope through an incoherent process, avoiding temporal decorrelation effects.

Key operating features of our laser radar have been validated. These include RF pulse compression, coherent integration, and the benefits of using an optical amplifier.

ACKNOWLDEGMENTS

This work is funded by the NASA Earth Science Enterprise's Instrument Incubator Program contract number NAS1-99052.

REFERENCES

[1] C. Allen and S. Gogineni, "A fiber-optic-based 1550-nm laser radar altimeter with RF pulse compression," *Proceedings of the 1999 International Geoscience and Remote Sensing Symposium* (IGARSS '99), Hamburg, Germany, pp. 1740-1742, June 1999.

[2] H. W. O'Brien and R. H. Munis, "Red and near-infrared spectral reflectance of snow," U.S. Army Cold Region Research and Engineering Laboratory, Hanover, NH, CREEL (AD-A007732), 1975.

[3] F. T. Ulaby, R. K. Moore and A. K. Fung, *Microwave Remote Sensing*, Vol. II, Ch. 7, Artech House, Norwood, MA, 1986.