Test results from a 1319-nm laser radar with RF pulse compression

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***Abstract*—We report in this paper the results of a three-year, NASA-funded project at The University of Kansas Radar Systems and Remote Sensing Laboratory on the development of a laser radar that uses RF pulse compression to significantly improve system performance. Receiver sensitivities of less than –90 dBm have been demonstrated by applying heterodyne optical downconversion and RF pulse compression. With the improved sensitivity, the required transmit power is significantly reduced. This system approach also permits multi-kilohertz pulse-repetition frequencies that enable spatially dense range measurements. Compared to lidars like GLAS and MOLA, this sensor requires a lower peak transmit power while providing orders of magnitude more measurements per second.**

In the receiver design, we have evaluated two detection schemes: envelope detection and direct downconversion. Envelope detection provides the benefit of discarding the effects of optical phase variations on the detected signal consequently avoiding many temporal correlation issues, however it is less efficient in terms of the resulting signal-to-noise ratio (SNR). Direct downconversion to baseband is more SNR efficient, however the baseband signal contains the effects optical phase variations, which include laser phase noise, effects of atmospheric turbulence, and frequency shifting due to Doppler effects.

We have demonstrated the feasibility of using a linear array of optical fibers in the telescope's focal plane to launch and receive the optical signals. Using separate fibers for transmit and receive while sharing telescope optics, we have achieved the required transmitter-receiver isolation of a bistatic system without the accompanying alignment difficulties.

With our breadboard system ranging measurements from both manmade and natural extended targets have been made and the results are presented.

These results support the feasibility of a satellite-based altimeter (600 km altitude), capable of making more than 4000 range measurements per second with 10 cm accuracy using less than 10 W peak transmit power. While the present breadboard operates at 1319 nm, the overall concept is wavelength independent. Benefits of this development may include increased system reliability, reduced power requirements, smaller sensor mass and volume, improved eye-safety, and lower probability of signal detection.

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 measurement accuracy, these lidars use short-duration, high-peak-power transmit pulses. Also, these systems typically operate with low pulse repetition frequencies (PRFs). The high-peak power operation results in limited laser lifetime and the low PRF provides sparse spatial samples along the satellite track.

To overcome these limitations, at The University of Kansas we have developed a low peak-power laser radar that incorporates modern radar techniques and commercially available fiber optic technologies to enhance receiver sensitivity. Building on concepts reported previously by Mullen et al. [1], we use optical heterodyne downconversion, 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 much higher PRF and can therefore provide more dense sampling. This paper summarizes the test results of our system. Previously published papers also describe the system [2,3,4,5,6].

System Description

System block diagram

A block diagram of the system is shown in Figure 1. Both the transmitted signal and the local oscillator are derived from a single laser. A chirp waveform (260-MHz bandwidth, 100-MHz start frequency, 200-μs duration) is used to intensity modulate the optical carrier in the MZM. The optical signal is then frequency shifted by 600 MHz in the AOM. An optical fiber amplifier is used to boost the signal power before the signal is launched into free space via the 127-mm diameter, f/10, Schmidt-Cassegrain telescope. Single-mode fiber is used between these components.

A portion of the transmitted signal backscattered from the target is captured by the same telescope and coupled to a

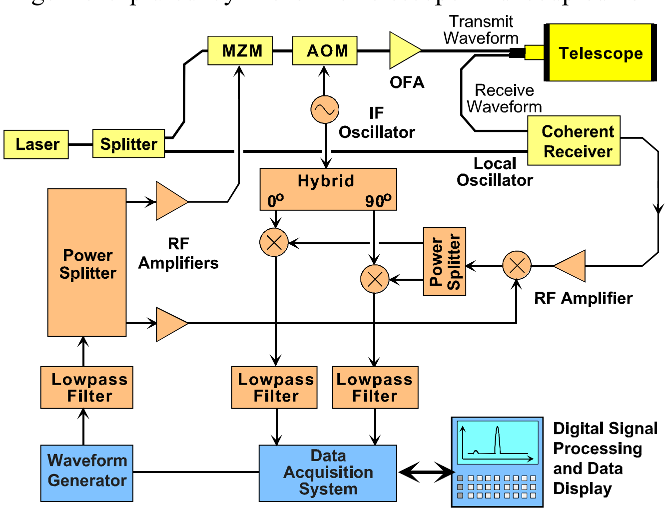

Figure 1. Block diagram of the hybrid RF/laser radar with I and Q direct downconversion. MZM: Mach-Zehnder modulator, AOM: acousto-optic modulator, OFA: optical fiber amplifier.

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separate single-mode fiber that guides this signal to the heterodyne optical receiver. The received signal and the local oscillator together impinge on a balanced photodetector to produce a 600-MHz RF signal containing the received chirp waveform. This signal is then amplified and dechirped (i.e., mixed with the chirp waveform) before be the in-phase (I) and quadrature (Q), direct downconversion to baseband. After low-pass filtering, the signal is digitized.

In the digital-signal processor a fast-Fourier transform (FFT) is performed on both the I and Q signals. These signal vectors are then squared and summed to complete the detection process.

Since this implementation uses direct downconversion (and not envelope detection described in [4]), coherent integration (averaging consecutive echo waveforms) will not be effective as the phase of the detected waveform may vary randomly pulse to pulse. Post detection averaging (incoherent integration) may be used to reduce the noise variability.

Table 1 lists the relevant parameters for this proof-of-concept system.

A comparison with an incoherent (direct-detection) laser radar will present the benefits of this approach. For the case when the received signal power is about 100 fW, the signal-to-noise ratio (SNR) following coherent detection is about -38 dB, whereas the SNR of the incoherent receiver will be about –132 dB, a difference of 94 dB. When the transmitted pulse duration is increased from 4 ns (hence the 260 MHz bandwidth) to 200 μs, a further SNR improvement of 47 dB results to yield an SNR of +11 dB.

Fiber array for signal launch and reception

A common optical aperture is used for both transmit and receive operations. Not only does this simplify the overall design; it also ensures alignment field of view (FOV) of the transmitter and the receiver. System testing on nearby targets (range < 30 km) means that transmit and receive operations will overlap in time. Therefore significant isolation between transmitter and receiver is required. An optical circulator was tried [3] and found to have inadequate isolation (about 45 dB)

TABLE I
LASER RADAR SYSTEM PARAMETERS

Parameter	Value
Laser wavelength	1319 nm
Laser linewidth	< 5 kHz
Transmit power	30 mW
Optical LO power	1 mW
Telescope diameter	127 mm
Telescope f-number	f/10
Chirp duration	200 μs
Chirp start frequency	100 MHz
Chirp bandwidth	260 MHz
Photodetector NEP	24 pW/√Hz
Responsivity	0.7 A/W
IF oscillator frequency	600 MHz
A/D resolution	8 bits
A/D sample frequency	8 MHz

In addition, the 4% backreflection from the glass-air interface overwhelmed the receiver.

A solution was found using a standard MTP termination that provides a linear arrangement of 12 single-mode fibers (center-to-center spacing of 250 μm). The coupling between separate fibers (one for transmit, another for receive) was found to be -90 to -100 dB when placed in the telescope's focal plane. We attribute this coupling to internal reflections within the telescope. With this approach coincident transmit and receive illumination patterns can be realized automatically. In addition, one of the other 10 fibers can be used to transmit visible light through the same telescope system to allow the operator to see what the system is illuminating as well as the spot size. The received signal power was maximized when the projected spot size on the target was small (2-5 mm); therefore the system had to be adjusted for each range measurement.

TEST RESULTS

Using the system configuration described above, the system was characterized using a fiber-optic variable attenuator to bypass the telescope optics. From these tests we found the receiver sensitivity or minimum detectable signal (resulting in an SNR of about 10 dB) to be about 400 fW or -94 dBm. With a transmit power of 15 dBm (30 mW), the resulting loop sensitivity is about 109 dB.

Detection of scattering targets

In laboratory tests at short ranges (~ 3 m) detection of signals from scattering targets provided the first validation of the system concept. Range measurements to various targets (plain white paper, leaves, and rocks) in the laboratory were conducted prior to readying the system for longer-range testing on outdoor targets.

To investigate the scattering nature of these targets, a few special experiments were performed. In one such experiment a fiber-optic collimator was used as the transmit aperture 1 m from the target and the 127-mm telescope was used as the receive aperture 3 m from the target. Signals from both a specular target (a first-surface mirror) and a scattering target (plain paper) were measured. The signal power from the scattering target was about 60 dB below that from the specular target. Whereas theory predicts a 37 dB difference, the remaining 23 dB may be attributed to a reduced reflectance of paper and inefficient coupling of the scattered signal into the single-mode fiber.

Range measurements to natural, extended surfaces

Range measurements to natural, extended, in situ targets were conducted to complete the proof-of-concept validation. From a third-floor window near our laboratory, the fiber-fed telescope was directed to the surface about 10 m below. Range measurements were made to an asphalt surface, a grassy area, and finally a snow covered area. Using the system parameters given in Table I, and the fiber array launch system, signals were detected from these surfaces at ranges between 20 and 30 m.

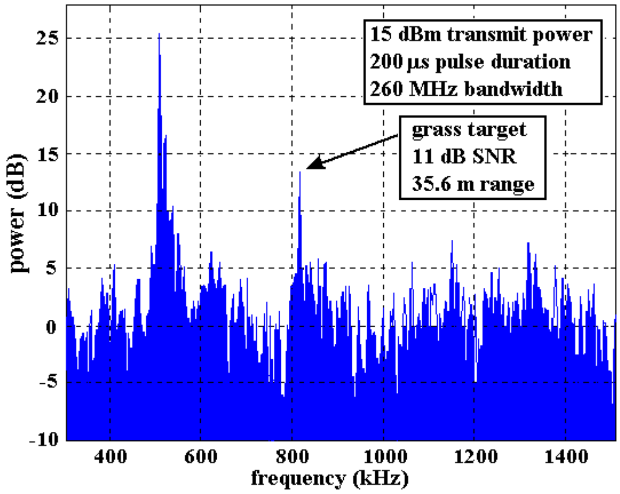

Figure 2. Measured signal from grass. No coherent integrations, no incoherent integrations.

In Figure 2 the measured data from the grass target is shown. The range to the target was 35.6 m corresponding to a frequency of about 816 kHz. The measured SNR was about 11 dB. Neither coherent averaging nor incoherent averaging was used in this measurement. The strong signal term at around 508 kHz is due to the internal telescope reflection discussed earlier.

Figure 3 shows measured data from a snow-covered area. The range to the target was 21.6 m corresponding to a frequency of about 700 kHz. The measured SNR was 8 dB. In this measurement 100 incoherent averages were performed which significantly reduced the noise variability. At around 512 kHz the internal telescope reflection is clearly visible.

This data is also significant as it validates the decision to change the operating wavelength from 1550 nm to 1319 nm [3] to support range measurements to snow surfaces.

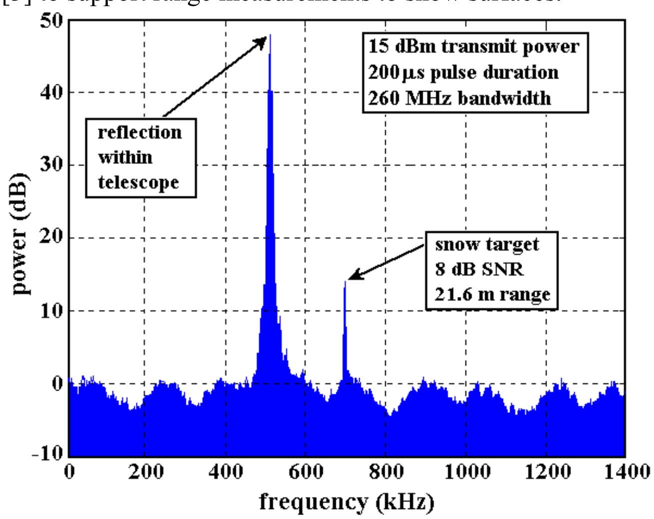

Figure 3. Measured signal from snow surface. No coherent integrations, 100 incoherent integrations.

CONCLUSIONS

Methods have been demonstrated for improving the receiver sensitivity of a laser radar system. Using off-the-shelf fiber optic components and modern radar signal processing techniques, an receiver with a heterodyne optical detector and an RF in-phase and quadrature detector were assembled. The combination of coherent optical detection and RF pulse compression have improved the receiver sensitivity by over 150 dB compared to a conventional, short-pulse, direct-detection laser radar receiver.

Range measurements from area extensive, scattering targets were made using this laser radar system which validated this concept. These findings support the feasibility of extending this concept to satellite altimetry applications.

The benefits of this development may include increased system reliability, reduced power requirements, smaller sensor mass and volume, improved eye-safety, and lower probability of signal detection.

ACKNOWLEDGMENT

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