
Second-Generation, Scanning, 3D Imaging Lidars Based on Photon-Counting

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Abstract

Sigma Space is building a new generation of 3D imaging/polarimetric lidars based on photon-counting for use in small aircraft or mini-UAV's. The most recent system is designed to provide contiguous, high resolution (15 cm horizontal, 3 cm vertical) 3D volumetric images of the underlying terrain on a single overflight from an altitude of 1 km. Based on prior experiments with a first generation NASA prototype system and significant technological improvements, the second generation instruments are expected to have greatly enhanced spatial resolution, areal coverage, and ability to penetrate atmospheric haze, tree canopies, and even water columns for underwater imaging.

Introduction

In 2001, a prototype photon-counting laser altimeter was developed by NASA Goddard Space Flight Center [Degnan et al, 2001]. This first generation NASA system flew at altitudes up to 6.7 km and, using single photon returns in broad daylight, successfully recorded high resolution images of the underlying topography including soil, low-lying vegetation, tree canopies, water surfaces, man-made structures, ocean wave structures, and moving vehicles. The lidar was able to see the underlying terrain through trees and thick atmospheric haze (even when onboard cameras and personnel could not) and performed shallow water bathymetry to depth of a few meters over the Atlantic Ocean and Assawoman Bay off the Virginia coast. An external conical scanner, combined with the aircraft motion, allowed the generation of 3D images as in Figure 1.

Second Generation Lidar

Sigma Space Corporation is presently developing a more compact and higher capability second generation 3D imaging and polarimetric lidar for high resolution

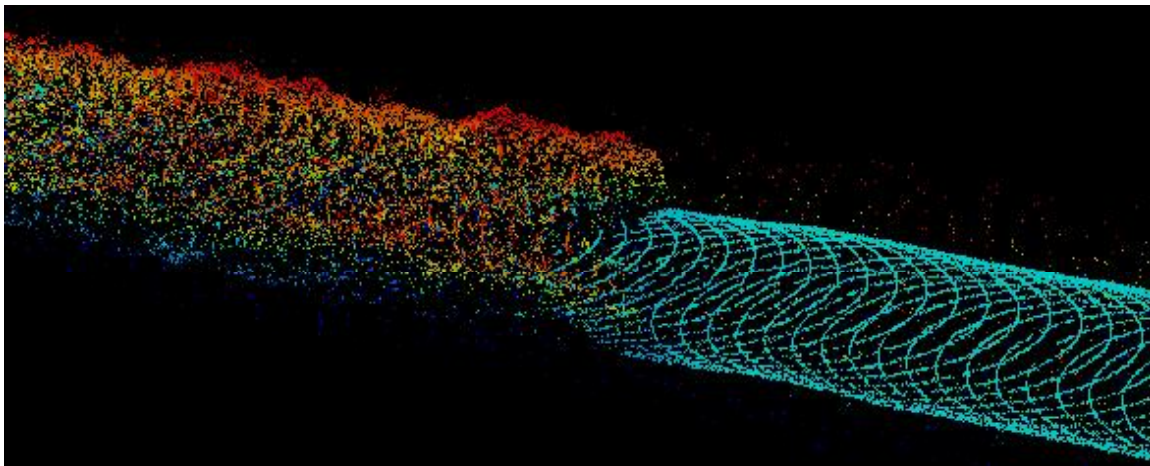


Figure 1: 3D image of a forest edge obtained in daylight by the 1st generation NASA photon-counting microlaser altimeter. (Courtesy Jan McGarrv. NASA/GSFC)

surveying and surveillance from a low altitude, mini-UAV. The shared transmitter is a passively Q-switched Nd:YAG microchip laser oscillator operating at a nominal fire rate of 20 kHz and producing 380 mW of output power at 1064 nm. The photon-counting imager operates at pulse rates up to 22 kHz with approximately 142 mW of frequency-doubled output power at 532 nm; the 238 mW of residual 1064 nm power

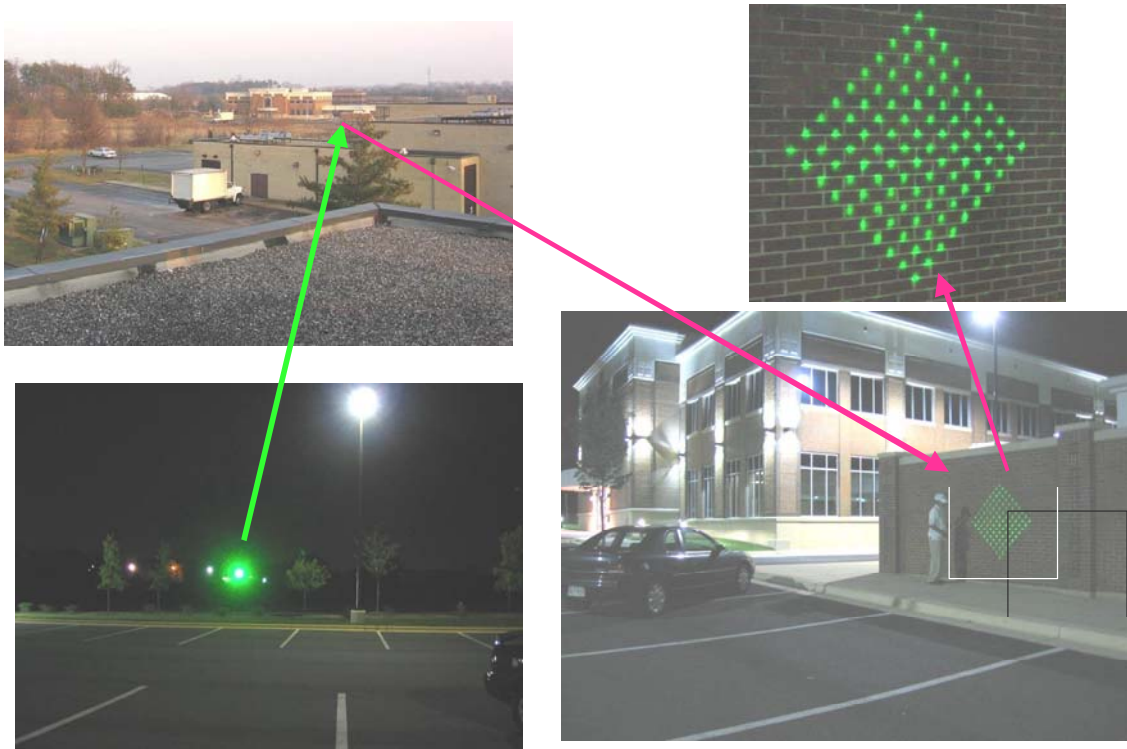


Figure 2: Counter clockwise from top left: View of target area (most distant building) from the Sigma rooftop; lidar beam as viewed from the target area; projection of holographically altered Gaussian beam on a brick wall at a distance of 250 m; closeup of 10x10 array of beamlets on the brick wall.

is allocated to polarimetry. Since the green wavelength is near the peak transmission of water, it is suitable for undersea imaging applications. The imager is designed to provide a contiguous, high resolution 3D topographic/volumetric map during a single overflight of the ground scene. From 1 km altitude, the scanner has a swath width of 150 m, a horizontal resolution of 15 cm, and an expected vertical (range) resolution of less than 3 cm. A Holographic Optical Element (HOE) breaks the spatially Gaussian laser beam into a 10x10 array of quasi-uniform eyesafe spots at the target (see Figure 2). The 100 individual far field spots from the HOE are then imaged by the receive optics onto individual anodes of a 10x10 GaAsP segmented anode microchannel plate photomultiplier. The output of each anode is input to one channel of a 100 channel, multistop amplifier/discriminator/timer. Presently, 50 multiple-stop timing channels can be accommodated by one amplifier/discriminator and one Time-of-Flight (TOF) Printed Circuit Board (PCB). The prototype timer has a demonstrated ± 100 picosecond timing (± 1.5 cm range) resolution, a multistop capability with a 2 nsec recovery time per channel (corresponding to a capability to resolve objects separated by 30 cm or more in a single pixel for a single laser fire), and an ability to transfer up to 2.2 million ranges per second to onboard memory for long term storage and post-flight processing. Thus, each laser pulse produces a 100 pixel 3D volumetric image of

a 1.5 m x 1.5 m ground area. The individual images are then mosaiced together via the platform velocity and the action of a highly flexible dual wedge optical scanner synchronized to the laser pulse train.

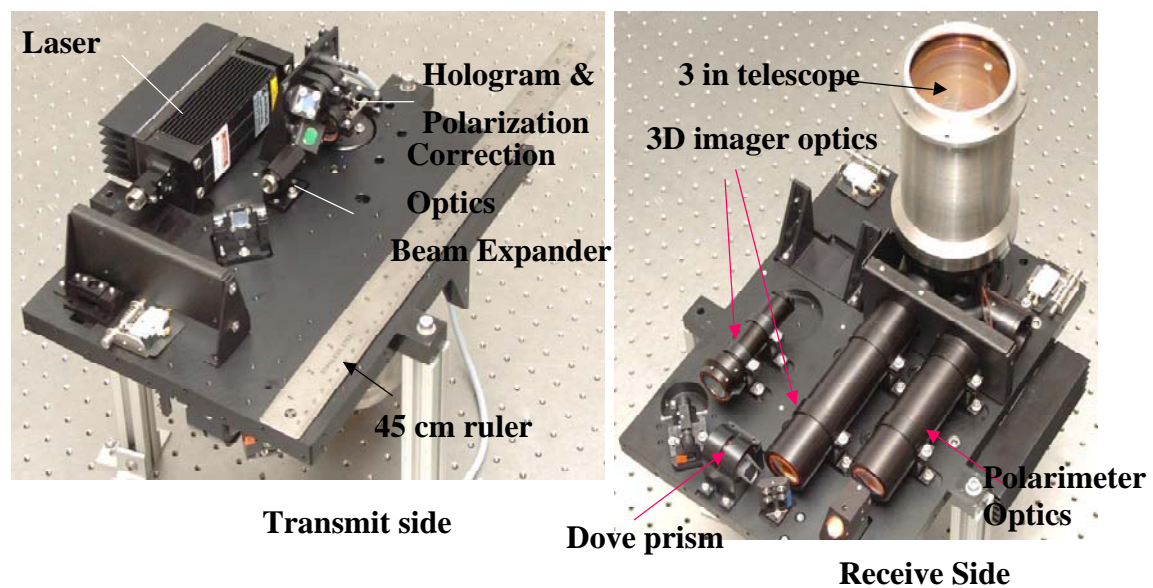


Figure 3: Optical bench and telescope for second generation 3D imaging and polarimetric lidar. An 18 inch (45cm) ruler is shown for reference

The transmitter and two receivers (imaging and polarimetry) share a common, 3 inch diameter afocal telescope and optical scanner. This allows the transmitter and receiver to have a common, but narrow, field of view (FOV) to aid in noise rejection and ensures that the imaging and polarimetric data are geographically coregistered. The polarimeter uses the residual laser power (~ 238 mW) at 1064 nm and two single element detectors to detect two polarization components (although the optomechanical design can accommodate up to 4 NIR detectors for a full determination of the Stokes parameters). Thus, the polarimeter has a nominal horizontal spatial resolution of 1.5 meters. A photo of the lidar optical bench (excluding scanner) is shown in Figure 3. The swath and scan frequency of the dual wedge optical scanner in Figure 4 are tailored to provide contiguous coverage of a ground scene in a single overflight [Degnan and Marzouk, 2003]. The highly flexible servo controller is capable of independently locking the phase and rotation rate of each wedge to the multi-kHz laser pulse train for an infinite variety of precision patterns. These include linear raster scans at various angles to the flight path and conical scans of varying cone angle as well as 2-dimensional rotating line or spiral scans, which might be useful for slow-moving aircraft, helicopters or hovering UAV's. Examples of a 1D linear scan at 45° to the flight path and a 2D rotating line scan are shown in Figures 5a and 5b respectively. The phase locking capability causes the laser beam to be laid down in precisely the same positions with each scan, thereby eliminating the need to record, store, and transfer the scanner wedge positions on each laser fire and greatly reducing data storage and handling. The measured scan repeatability is about 0.07 pixels or about 1 cm at an altitude of 1 km.

The 3D imaging and polarimetric lidar consists of two parts – an optical head and a supporting electronics box. The optical head measures approximately 33 cm x 30 cm x 43 cm and houses the optical bench in Figure 3 (transmitter, imaging and polarimetric optics and detectors, telescope, laser gyros and inclinometer for attitude

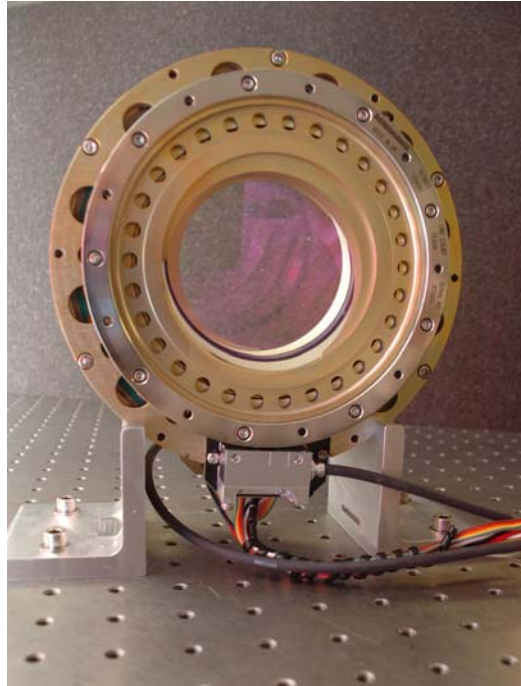


Figure 4: Photo of the direct drive dual wedge annular ring scanner developed under the NASA JIMO program. The annular ring motors have cryogenic and vacuum compatible counterparts suitable for space use.

determination, etc) plus the external dual wedge scanner in Figure 4, the MCP/PMT gating PCB, and the Amplifier/Discriminator/Timer PCB boards. The electronics box has a volume of 0.027 m^3 and houses the scanner electronics, GPS receiver, Reference Oscillator and Timing Distribution Circuits, Navigation and Imaging/Polarimeter Data Acquisition Modules, the laser power supply, and various DC/DC converters and voltage regulators. The manner in which the entire lidar system fits within the forward electronics bay of an Aerostar mini-UAV is illustrated in Figure 6.

Summary

Photon-counting altimeters are extremely sensitive and highly efficient, requiring only one photon per range measurement, and, with multistop capability, can be operated day or night with large temporal gate widths for monitoring large elevation changes or simultaneously detecting the tops of tall buildings and city streets or tall treetops and the underlying terrain. Post-detection Poisson filters easily extract the signal from the solar background [Degnan, 2002]. The ability to penetrate obscurants (ground fog, vegetation, water) on a single shot (i.e. without “staring” at a scene while multiple pulses are fired) was demonstrated in the NASA prototype [Degnan et al, 2001]. This penetration capability was the result of the single photon sensitivity and the rapid multiple stop capabilities of the range receiver and will be substantially enhanced in our second generation instruments due to a factor of 12 increase in the effective signal photoelectrons received per ground pixel ($\sim 3 \text{ pe}$ vs 0.25 pe in the NASA prototype).

Since the laser fires at a rate higher than necessary for contiguous coverage, the 3 pe/pixel is accumulated during multiple interrogations of the pixel during the scan, i.e. typically 3 interrogations at 1 pe which results in a higher probability of detection ($\sim 99\%$) than 3 pe for one interrogation (95%). The integration of a dual wedge scanner in the 2nd generation systems will eliminate the gaps in coverage previously observed with a single wedge conical scanner (see Figure 1) and provide contiguous coverage on a single overflight.

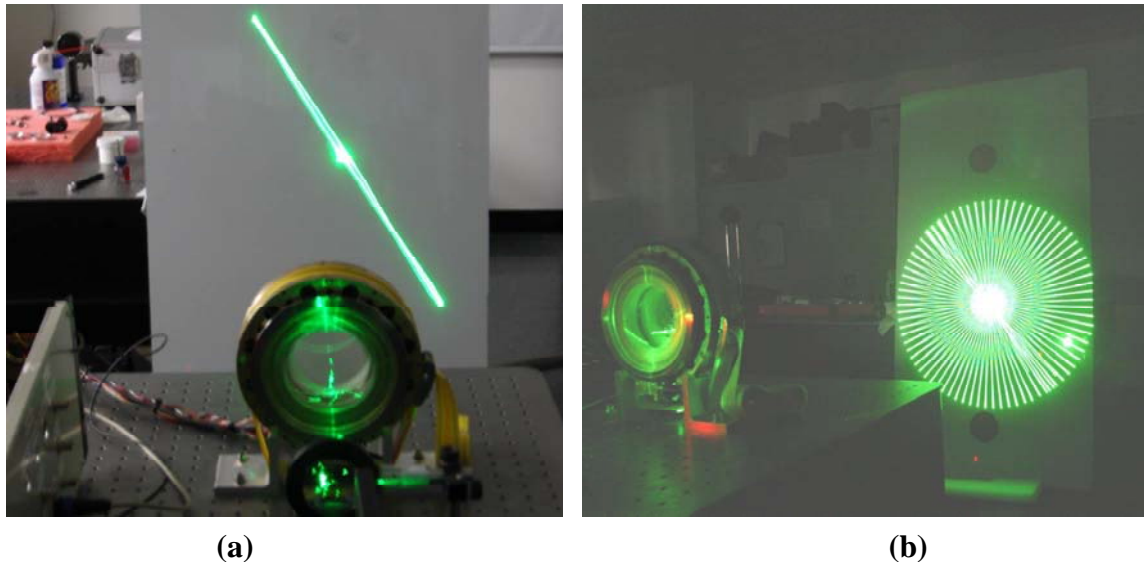


Figure 5: NASA prototype Direct Drive Internal Scanner generating (a) a linear scan and (b) a rotating line scan on a near field screen. Both scan types were run at 18 Hz and synchronized to a nominal 9 kHz Q-switched microchip laser pulse train. The slight bowing of the linear scan in (a) is due to near field displacement of the beam in the optical wedges but collapses to a true line in the far field. The non-uniformity of the rotating line scan at the 4 o'clock and 10 o'clock positions is due to a slight overlap of two consecutive rotating line scans.

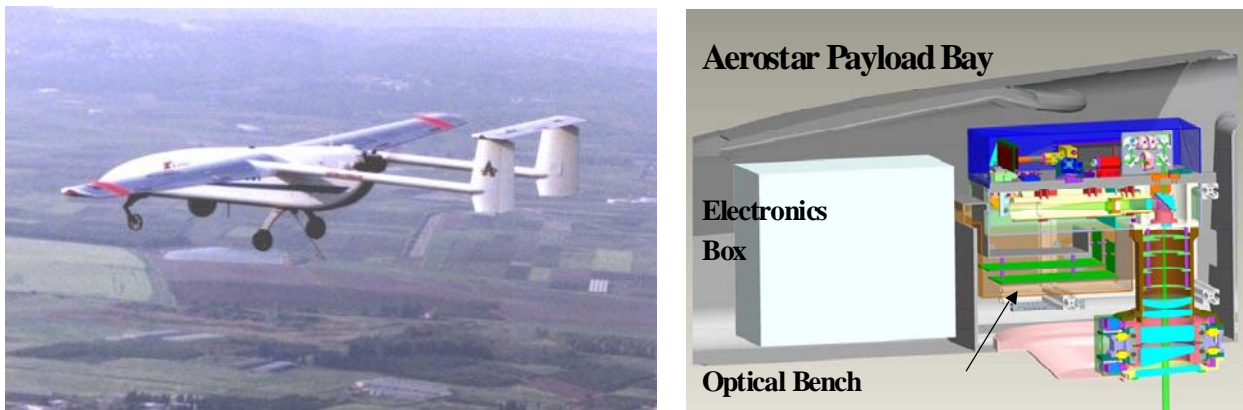


Figure 6: (a) Aerostar mini-UAV in flight; (b) Packaging of the 3D imaging/polarimetric lidar within the nose electronics bay.

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