

Recent Advances in Photon-Counting, 3D Imaging Lidars

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Abstract. *Over the last several years, Sigma Space Corporation has been extending single photon sensitive (photon-counting) 3D imaging lidar to higher and higher altitudes. Scanning systems to date have operated at aircraft AGLs up to 8.6 km. With laser repetition rates between 20 and 32 kHz and a Diffractive Optical Element (DOE) to split the laser beam into 100 low power beamlets and a precision timing channel assigned to each beamlet, we have achieved measurement rates up to 3.2 million 3D pixels per second. Laser pulsewidths between 100 and 700 picoseconds have typically been employed, yielding high range resolution. The result has been large area coverage with decimeter horizontal and few centimeter vertical resolution contiguous 3D imagery. Our systems are presently being deployed on a variety of aircraft to demonstrate their utility in multiple applications including large scale surveying and surveillance, bathymetry, forestry, etc. Our smallest unit, the Mini-ATM (Miniature Airborne Topographic Mapper), designed for NASA to fit in a mini-UAV for wide swath cryospheric measurements, features a 90° full conical scan, measures approximately 0.03 m³ (1 ft³) in volume, weighs 12.7 kg (28 lbs), and consumes ~168 W of 28 VDC prime power.*

Introduction

Single photon sensitive 3D imaging lidars have multiple advantages:

- They are the most efficient 3D imagers possible since each range measurement requires only one detected photon as opposed to hundreds or thousands in conventional laser pulse time of flight (TOF) or waveform altimeters
- Their high efficiency enables orders of magnitude more imaging capability (e.g. higher spatial resolution, larger swaths and greater areal coverage).
- Single photon sensitivity combined with fast recovery multistop timing capability enables the lidar to penetrate semiporous obscurations such as vegetation, ground fog, thin clouds, etc. Furthermore, the 532 nm operating wavelength is highly transmissive in water thereby permitting shallow water bathymetry and 3D underwater imaging.
- Contiguous, high resolution topographic mapping and surveying on a single overflight becomes possible with very modest laser powers and telescope apertures – even from orbital altitudes.

Sigma SPL Heritage and Overview

NASA's Microlaser Altimeter or "Microaltimeter" provided the first airborne demonstration of a scanning Single Photon Lidar (SPL) in early 2001 [Degnan et al, 2001]. With less than 2 microjoules per pulse at a laser repetition rate of 3.8 kHz (7.6 mW average power), the system produced high resolution 2D profiles and crude 3D images while operating in daylight at altitudes up to 6.7 km (23 kft). From 2004 to 2007, Sigma developed its first 100 beamlet SPL, "Leafcutter", under a US Air

Force (USAF) Small Business Innovative Research (SBIR) program [Degnan et al, 2007]. “Leafcutter” was designed to fit in the nose cone of an Aerostar Mini-UAV and provide contiguous decimeter resolution images on a single overflight from altitudes between 1 and 2.5 km, depending on surface reflectance. The beamlets, which were arranged in a 10x10 square array, each contained approximately 1 mW of laser power in a 22 kHz stream of 700 psec FWHM pulses (~50 nJ per pulse). With USAF permission, NASA funded several test flights to assess SPL capabilities in the areas of biomass, cryospheric, and bathymetric measurements. A collage of sample results from “Leafcutter” is presented in Figure 1.

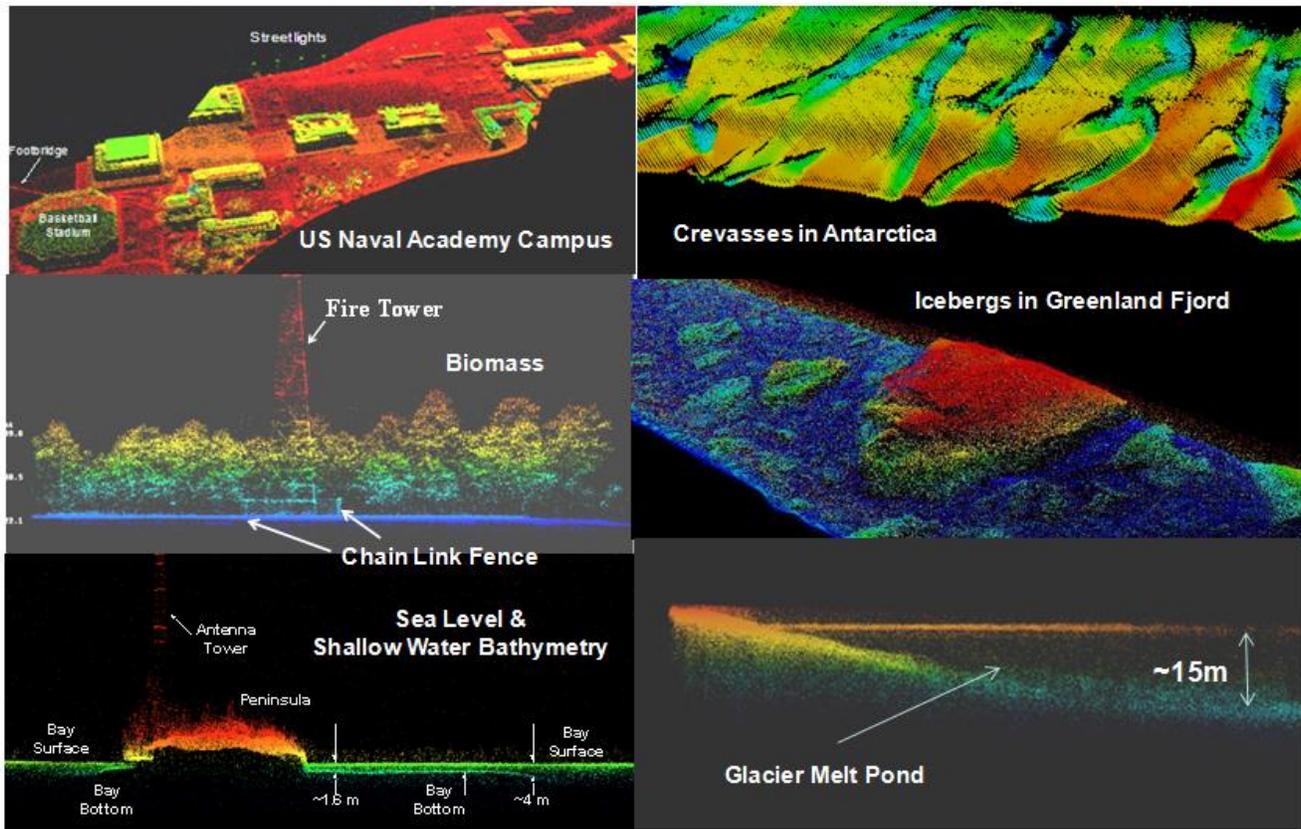


Figure 1: A collage of images created on a single overflight by the 2nd generation “Leafcutter” SPL. The images in the left half were over low reflectance surfaces at AGLs of 1 km (3.3 kft) or less while those in the right half were high reflectance cryospheric measurements in Greenland and Antarctica from AGLs up to 2.5 km (8.2 kft). The images are color-coded according to the lidar-derived surface elevation (blue = low, red = high).

Given the successful cryospheric results obtained by “Leafcutter”, NASA funded development of an even smaller 100 beamlet system to potentially replace the venerable, but much larger and heavier, Airborne Topographic Mapper (ATM), which had mapped the Greenland ice sheets for many years. The resulting “Mini-ATM” reused most “Leafcutter” components and subsystems but was light-weighted and designed to fit into the payload bay of a Viking 300 micro-UAV. Mini-ATM, including the IMU, features a 90° full conical scan, measures approximately 0.03 m³ (1 ft³) in volume, weighs 12.7 kg (28 lbs), and consumes ~168 W of 28 VDC prime power. For the nominal Viking 300 velocity of 56 knots and altitude ceiling of 10 kft, the system can contiguously map up to 600 km²/hr with a

mean measurement point density in excess of $1.5/\text{m}^2$ – about 10 times denser than that achieved by the original ATM.

More recent Sigma scanning 3D imaging SPLs include the moderate altitude (6.5 k to 18 kft) High Resolution Quantum Lidar System (HRQLS) and the High Altitude Lidar (HAL). HAL, to date, has successfully produced decimeter resolution maps at AGLs up to 28 kft. Both lidars were designed to provide contiguous few decimeter resolution topographic coverage on a single overflight at aircraft speeds up to about 220 knots (407 km/hr).

Sigma also provided key engineering (mechanical, thermal, and electronics), integration, testing and flight operations support to NASA's MABEL (Multiple Altimeter Beam Experimental Lidar) instrument, which was developed as a precursor and testbed for the ATLAS SPL, scheduled to be launched in 2016 into a 500 km orbit on ICESat-2. MABEL is a non-scanning, 24 beam (8 @ 1064 nm, 16 @ 532 nm) pushbroom lidar hosted on NASA's ER-2 Research aircraft and has successfully demonstrated single photon surface profiling at AGLs of 65 kft (20 km) in both California and Greenland.

Recent Sample Data from HRQLS

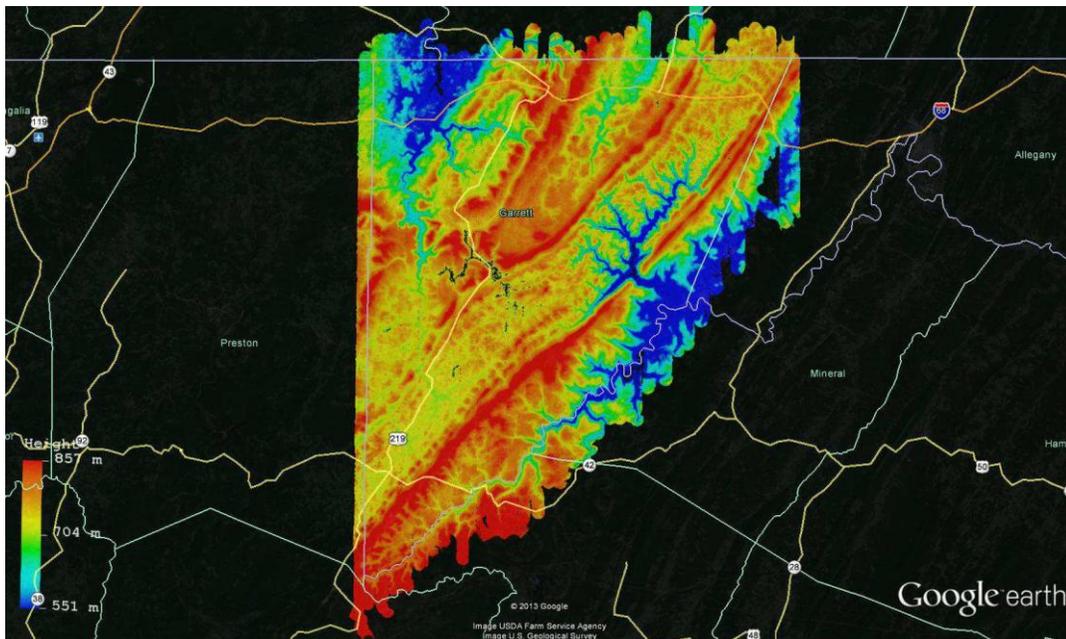
Development of the moderate altitude HRQLS lidar was self-funded by Sigma. HRQLS features a dual wedge scanner which allows a range of full cone angles between 0 and 40 degrees. This allows measurement point density (or spatial resolution) to be traded off against swath and areal coverage. As with the predecessor "Leafcutter" system, test flights of HRQLS have been funded by several customers to assess its capabilities for general surveying, tree height and biomass estimation, and bathymetry. In particular, the University of Maryland recently funded the airborne survey of Garrett County in Northwestern Maryland. The county - which is mountainous, heavily wooded, and has a total area of about 1700 km^2 - was surveyed in approximately 12 hours. With a nominal altitude of 7.5 kft, the half-maximum cone angle of 20 degrees resulted in a swath of 0.81 km. At an aircraft velocity of 150 knots (278 km/hr), the resulting areal coverage was $224 \text{ km}^2/\text{hr}$. The full lidar data set for the county, color-coded from blue to red with increasing surface elevation, is shown superimposed on a Google Earth map in Figure 2.

One can get a sense of the surface resolution by looking more closely at subsets of data within the map. Figure 3 provides different lidar views of a coal mine while Figure 4 shows a heavily treed mountainous area. Details of the coal mining operation such as buildings, conveyor belts and coal piles can be seen in Figure 3 as can the surface underlying the dense tree canopies in Figure 4. The surface resolution obtained by HAL at 28 kft is comparable in quality to that of HRQLS, but release of the data has not been approved by the customer. In preparation for 3D imaging that can be viewed by the aircraft crew or transmitted to a ground station in near real time, we are currently implementing inflight algorithms that edit out solar and/or electronic noise and correct for atmospheric effects.

Future Spaceborne Applications

The high efficiency of SPL and its modest data storage requirements (<32 bits per surface measurement) makes the technique highly attractive for use in future spaceborne altimeters [Degnan, 2002a,b]. NASA has adopted the SPL technique for its followon ICESat-2 mission to be launched in

2016 [Abdalati et al, 2010]. As it currently stands, the ATLAS lidar is a 6-beam “pushbroom” (non-scanning) lidar. There are three “weak” beams and three “strong” beams. The latter have four times the energy/power as the weak beams in order to better monitor sea ice and penetrate tree canopies.



Google earth

miles 30
km 60



Figure 2. HRQLS lidar map of Garrett County in the state of Maryland USA superimposed on a Google Earth map.

In 2006, Sigma completed a one year NASA study on the feasibility of an SPL mapping of three Jovian moons (Ganymede, Callisto, and Europa) as part of the cancelled Jupiter Icy Moons Orbiter (JIMO) mission. The goals were to obtain global maps with at least 10 m horizontal resolution and 1 m vertical resolution from a nominal orbital altitude of 100 km. A major constraint was an expected one month mission duration at the innermost moon, Europa, due to the deleterious effects of Jupiter’s high radiation field on orbiting electronics. In one month, the satellite would complete only 348 orbits with a mean spacing between ground tracks of 14.5 km. Nevertheless, it was demonstrated analytically that a scanning, 100 beamlet lidar with a 532 nm laser producing 4 to 5 W at 10 kHz (comparable in power to that of the ATLAS laser), combined with a nominal half-meter telescope (similar to the Mars Orbiter Laser Altimeter), could map all 31 million square kilometers of Europa’s surface in one month with roughly twice the desired horizontal spatial resolution and an order of magnitude better vertical accuracy. The larger moons, Ganymede and Callisto (with surface areas of 87 and 72 million square kilometers respectively) would each require approximately two months to complete a global map with the same resolution [Degnan, 2012].

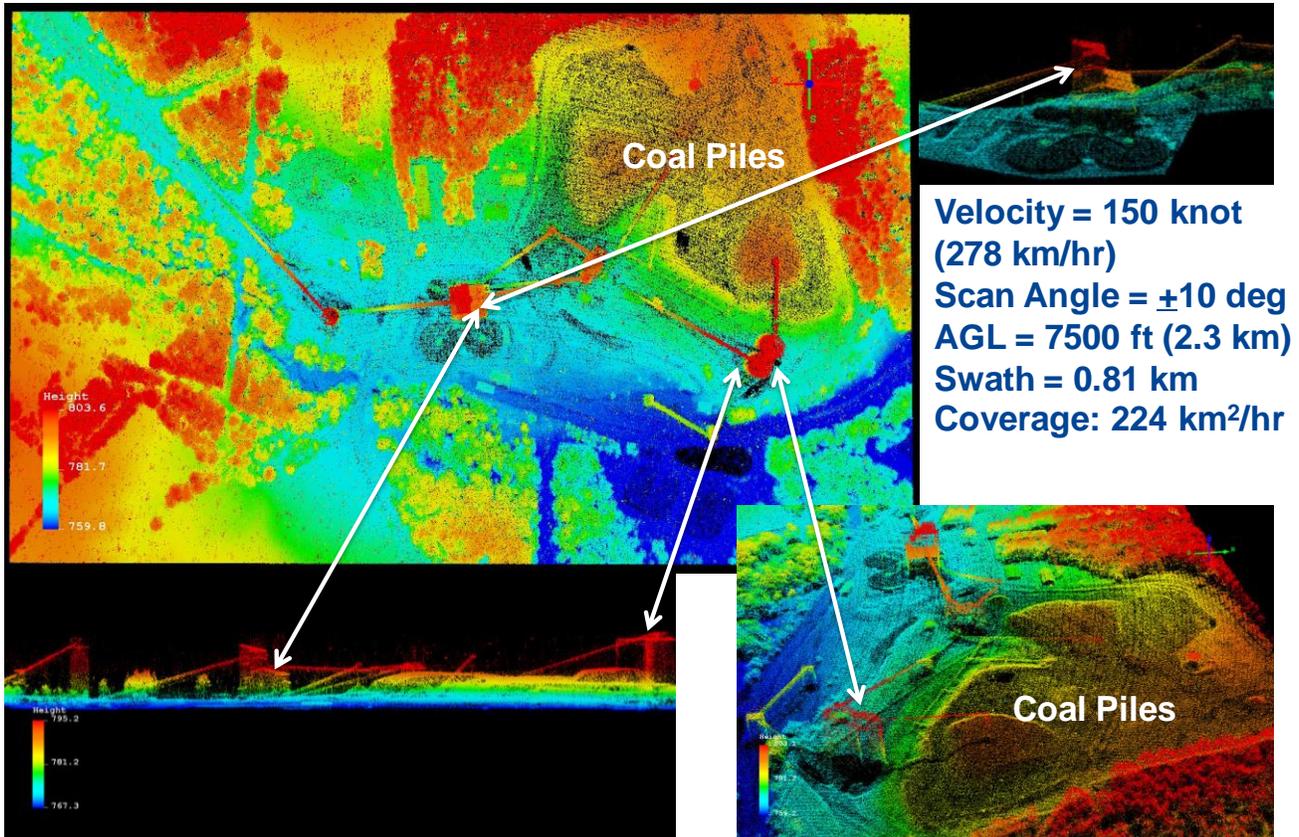


Figure 3: Lidar images of a Garrett County coal mine from different perspectives. Moving counter clockwise from upper left, we have: (1) an overhead view of a large area, (2) a side view of buildings and towers which move the coal along a conveyor belt, (3) a different perspective with the coal piles on the right, and (4) a closeup of the main building/tower.

Summary

- Our 100 beam scanning lidars have provided decimeter level (horizontal) and few cm (vertical) resolution topographic maps from aircraft AGLs up to 28 kft. Data rates vary between 2.2 and 3.2 million 3D pixels per second.
- The multibeam pushbroom NASA MABEL lidar has operated successfully at AGLs up to 65 kft (20 km)
- Our low deadtime (1.6 nsec) detectors and range receivers permit multiple range measurements per pixel on a single pulse.
- Our moderate to high altitude lidars built to date have been designed to provide contiguous topographic coverage on a single overflight at aircraft speeds up to 220 knots (407 km/hr).
- We are currently implementing inflight algorithms to edit out solar and/or electronic noise and to correct for atmospheric effects in preparation for near realtime 3D imaging.
- Our smallest lidar, Mini-ATM, designed for cryospheric measurements, weighs only 28 pounds (12.7 kg), occupies 1 ft³ (0.028 m³), has a ± 45 degree conical scan, fits in a mini-UAV, and covers more area with higher spatial resolution than the much larger and heavier predecessor NASA ATM system.

- Using a laser comparable to that developed for the ATLAS lidar on ICESat-2 and a MOLA-sized telescope (~50 cm) in a 100 km orbit , one could globally map the three Jovian moons with better than 5 m horizontal resolution in 1 month (Europa) or 2 months (Ganymede and Callisto) each.

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