

Globally Contiguous, High Resolution Topographic Mapping of Planets and Moons via Photon-Counting

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Abstract

High resolution topographic mapping of planets and moons from orbit can best be accomplished using mJ-class, multi-kHz laser transmitters and photon-counting detector arrays followed by multichannel timing receivers. An airborne 100-channel, scanning 3D imaging lidar has been successfully flight-tested, and the scaling of the technology to spacecraft altitudes is discussed. The specific requirements for two spaceborne lidars are briefly described: 1) A 16-beam pushbroom lidar for NASA's ICESat-II mission; and 2) a 100-beam scanning lidar for NASA's Jupiter Icy Moons Orbiter (JIMO) mission.

Advantages of Photon-Counting

Photon-counting lidar altimeters and imagers are the most efficient possible since each range measurement requires only one detected photon as opposed to hundreds or thousands in conventional laser pulse time of flight (TOF) altimeters [Degnan, 2001]. The GLAS altimeter on ICESat-I, for example, has a minimum detectable signal corresponding to roughly 100 photoelectrons but can produce in excess of 10,000 detected photoelectrons per pulse from high reflectance surfaces under extremely clear atmospheric conditions. Thus, single photon sensitivity translates to up to four orders of magnitude more imaging capability. Furthermore, single photon sensitivity combined with multistop timing capability enables the lidar to penetrate semi-porous obscurations such as vegetation, ground fog or haze, thin clouds, water columns, etc. and makes contiguous, high resolution topographic mapping on a single overflight possible with modest laser powers and telescope apertures – even from orbital altitudes.

Globally Mapping Planets and Moons

The feasibility of using photon-counting lidars in daylight was first demonstrated experimentally by NASA's "Microaltimeter" system. [Degnan et al, 2001]. The feasibility of spaceborne laser altimetry using mJ-class, multi-kHz lasers and photon-counting receivers was established theoretically through link analyses and modeling of the solar noise background [Degnan, 2002a]. The specific case of a Mars orbiter at a typical altitude of 300 km was analyzed. Correlation Range Receivers (CRR's) with carefully chosen "range bins" and "frame intervals" were proposed as the "optimum" approach for extracting the surface signal from the solar background under low "contrast" (SNR) conditions. Although wide swath multi-beam "pushbroom lidars" are one approach to large scale mapping, truly contiguous topographic mapping on a global scale with several meter horizontal resolution is best accomplished using a large array detector and an optical scanner [Degnan, 2000b].

Flight Testing of Second Generation 3D Imaging Lidar

Sigma has developed and flight-tested a highly successful airborne 3D Imaging and Polarimetric Lidar prototype, which demonstrates the latter approach [Degnan et al, 2007]. In this system, shown mounted on a camera tripod in Figure 1, a microchip laser transmitter produces 380 mW of infrared power at 1064 nm and a KTP Type II doubling crystal generates about 140 mW of green power (6 μ J @ 22 kHz). The green power at 532 nm is used for 3D imaging of the terrain while the residual 240 mW of 1064 nm power is dedicated to measuring the depolarization produced by the surface.

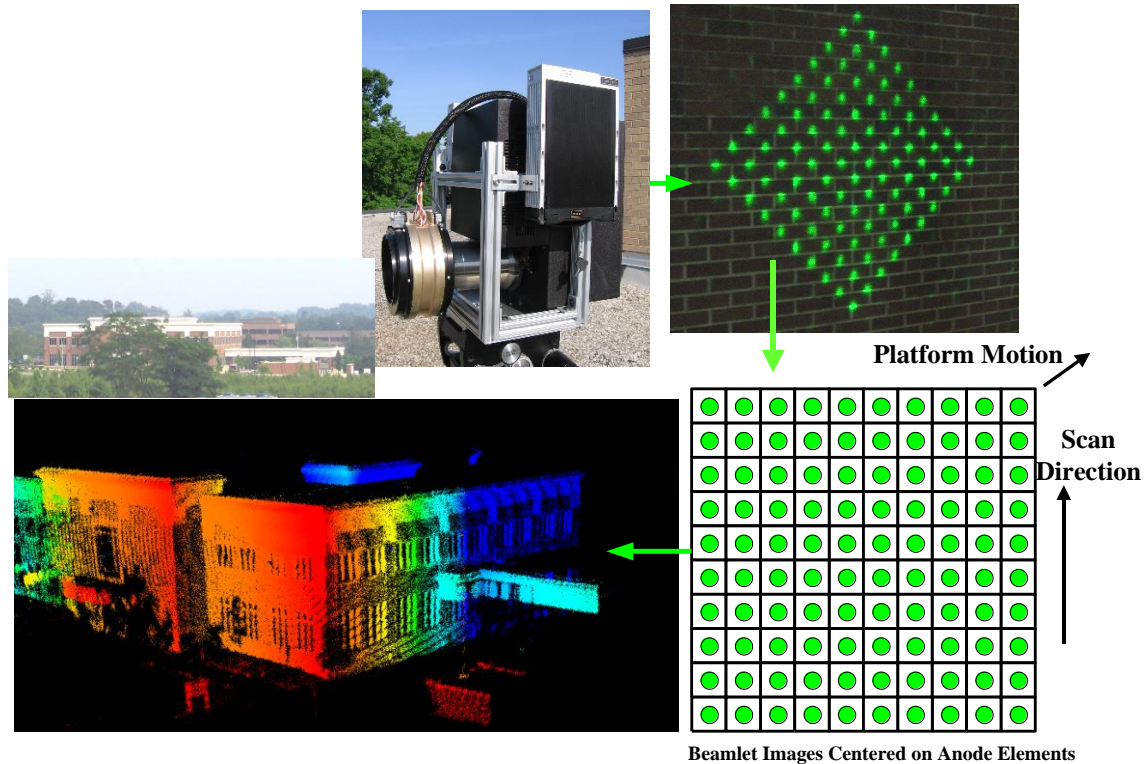


Figure 1. Clockwise from top left: Sigma 3D Imaging and Polarimetric Lidar during rooftop testing to local bank (photo inset); 10x10 beamlet array on bank wall; imaging of beamlets onto individual anodes of MCP/PMT; scanned 3D lidar image of bank.

After the two wavelengths are split by a dichroic beamsplitter, a Diffractive Optical Element (DOE) splits the 532nm beam into a 10x10 array of beamlets which are then recombined with the NIR polarimeter beam via a second dichroic. Both wavelengths are then transmitted through the central portion of a 3 inch diameter transmit/receive telescope and steered by an external dual rotating optical wedge scanner synchronized to the laser pulse. The telescope and scanner are aperture-shared by the two transmit wavelengths and their corresponding receivers .

Since the DOE is about 80% efficient, each 532 nm beamlet contains a little over 1 mW of green power (~50 nJ @ 22 kHz). The 100 individual ground beamlets are imaged onto the Microchannel Plate Photomultiplier (MCP/PMT) photocathode, and the microchannels guide the photons received from one beamlet to one anode of a matching 10x10 anode array. Each anode is then input to one channel of a 100 channel timing receiver, which has a ± 93 psec timing resolution and a 1.6 nsec deadtime. Thus, each laser pulse produces a 10x10

pixel 3D image of a 1.5 m x 1.5 m square surface from the nominal design altitude of 1 km. A wide swath contiguous image of the terrain is generated by mosaicing these individual pulse images via the aircraft motion and the optical scanner. Sample flight images are shown in Figure 2.

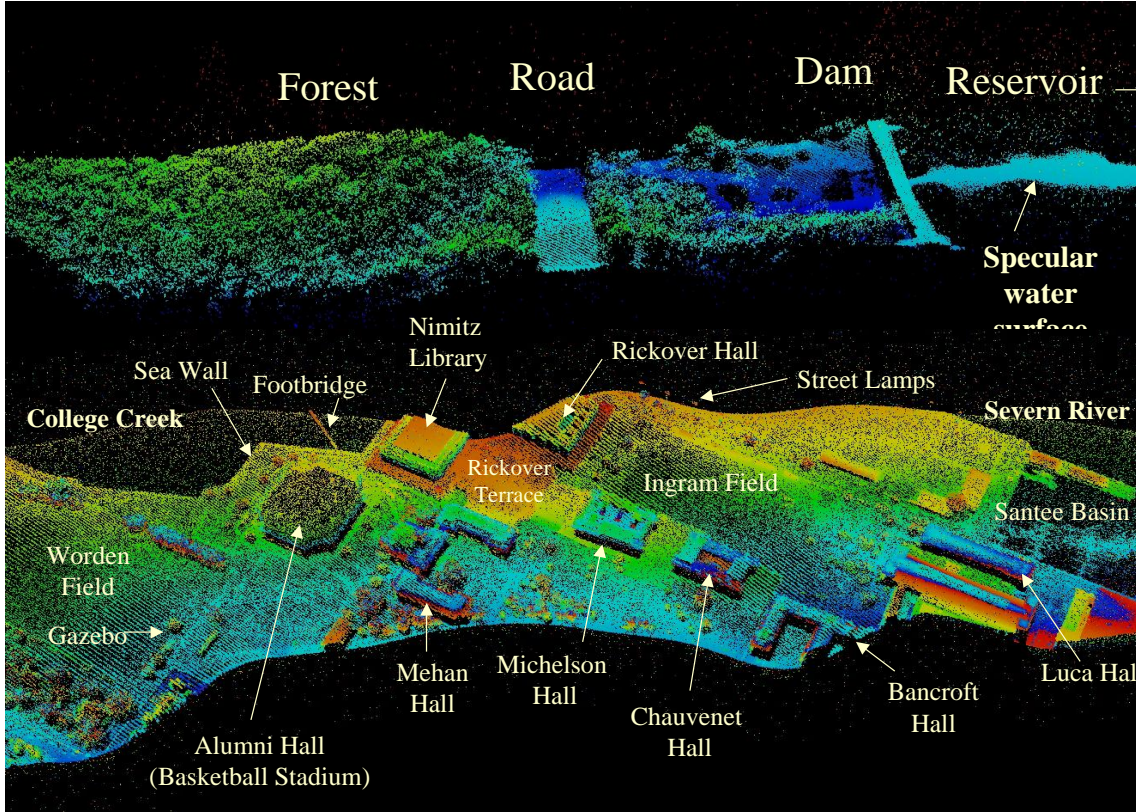


Figure 2. Sample inflight images taken with the 2nd Generation 3D Imaging Lidar: (a) Triadelphia Reservoir; (b) US Naval Academy Campus in Annapolis, MD.

Requirements for Contiguous Mapping

The Sigma 2nd generation 3D Imaging Lidar design is essentially an airborne prototype of a prior spaceborne 3D imaging lidar concept [Degnan, 2002b]. In order to map contiguously from an aircraft or spacecraft, the lidar instrument must satisfy three conditions on scan speed, laser repetition rate, and power-aperture product. For contiguous along-track imaging the scan frequency must satisfy the condition

$$f_{scan} \geq \frac{v_g}{\sqrt{2}(N\delta)} \quad (1)$$

where v_g is the ground velocity of the aircraft/spacecraft, N^2 is the number of pixels in the $N \times N$ detector array, and δ is the desired horizontal ground resolution. For contiguous crosstrack imaging across a swath width S , the laser repetition rate must satisfy the condition

$$f_{qs} \geq \frac{2v_g S}{(N\delta)^2} \quad (2)$$

Finally, we need a certain Transmitted Energy-Receive Aperture ($E_t A_r$) product to satisfy the altimeter link equation for all channels, and this requirement can be expressed as [Degnan, 2002a]

$$E_t A_r > \frac{n_p \pi h \nu N^2 R^2}{\eta_c \eta_r \rho \cos \sigma T_0^2} \quad (3)$$

where, from Poisson statistics, $n_p = 3$ is the received photoelectrons per ranging channel per pulse required to achieve a per channel detection probability per pulse of 95% in photon-counting mode, R is the range to the surface, η_c is detector counting efficiency, η_r is the optical throughput efficiency of the receiver optics, $h \nu$ is the laser photon energy, ρ is the surface reflectance, σ is the surface slope, and T_0 is the one-way atmospheric transmission at zenith. Combining (2) and (3) gives a minimum Power-Aperture product, i.e.

$$P_t A_r = f_{qs} E_t A_r > \frac{n_p \pi h \nu}{\eta_c \eta_r \rho T_0^2} \frac{2v_g S R^2}{\delta^2} = \frac{2v_g S R^2}{C_a \delta^2} \quad (4)$$

where we have defined the ‘‘altimeter constant’’ C_a and used the fact that, for the vast majority of surfaces, $\cos \sigma \sim 1$.

NASA’s Jupiter Icy Moons Orbiter (JIMO) Mission

In late 2006, Sigma completed a preliminary study for NASA Headquarters on a scanning lidar for the JIMO mission. The science goal was to globally map the surfaces of three primary moons of Jupiter – Ganymede, Callisto, and Europa - from a 100 km orbit about each moon. The resolution goals were 10 m horizontal and sub-meter vertical. A major technical challenge was to map Europa in one month before Jupiter’s intense radiation field damaged onboard electronics. However, later studies published by researchers JPL suggested that the Europa portion of the mission might be extended up to 3 or 4 months with proper shielding. Nevertheless, our study considered a 30 day requirement at Europa which led to a minimum swath width of 14.4 km which applied to all three Jovian moons because of the fixed orbital altitude. The results of our JIMO study are summarized in Table 1 assuming $N^2 = 100$ and a nominal surface reflectance for soil ($\rho = 0.15$ @ 532 nm).

Because of their larger diameter, Callisto and Ganymede require a minimum 56 and 60 days respectively to complete one global map. Since the ground velocity is highest at Ganymede, this moon drives the requirements on scan frequency, laser repetition rate, and power-aperture product as predicted by equations (1) through (4). The JIMO scan and repetition rate requirements actually fall below the capabilities of our current airborne lidar, i.e. $f_{scan} = 25$ Hz and $f_{qs} = 22$ kHz. The required Power-Aperture product of $1.12 \text{ W}\cdot\text{m}^2$ is well within the laser state of the art for modest telescope apertures, e.g., 3 W and 50 cm. To reduce instrument mass, volume, and prime power, the optical scanner would be placed internal to the telescope.

Table 1. Summary of JIMO lidar requirements, assuming a 30 day mission at Europa and an orbital altitude of 100 km at all three Jovian moons. The moon driving a particular lidar specification is indicated by **boldface** type.

Jovian Moon	Europa	Callisto	Ganymede
Lunar Mass, M_i (kg)	4.80×10^{22}	1.08×10^{23}	1.48×10^{23}
Mean Volumetric Radius, R_i , km	1569	2400	2634
Orbital period about Jupiter, Days	3.551	16.7	7.15
Surface Area, km^2	3.094×10^7	7.238×10^7	8.718×10^7
Satellite Altitude, r_i (km)	100	100	100
Ground Velocity, v_g (km/sec)	1.30	1.63	1.83
Satellite Orbital Period, min	126	154	151
Mission Duration, D_i (Days)	30	56	60
3D Imager Resolution, δ (m)	10	10	10
Polarimeter/Hyperspectral Resolution, $N\delta$ (m)	100	100	100
Swath Width, s_i (km)	14.4	14.4	14.4
Scanner FOV Half Angle, (deg)	5.72	5.72	5.72
Scan Frequency, Hz	9.2	11.5	12.9
Lidar PA-Product, $\text{W}\cdot\text{m}^2$	0.797	0.998	1.12
Min. Laser Fire Rate, f_{qs} (kHz)	3.74	4.68	5.26

Cross Track Channel (CTC) Lidar on ICESat II

Sigma has proposed a visible 16-beam “pushbroom lidar” [Degnan, 2002b] to fly alongside the conventional 1064 nm lidar on NASA’s ICESat-II mission. As presently envisioned, a DOE would generate 16 separate groundtracks from a single 4W frequency-doubled Nd-based transmitter (400 μJ @ 10 kHz @ 532 nm) or 0.25 W (25 μJ @ 10 kHz) per ranging channel. The 16 beams would be arranged such that periodic spacecraft yaw rotations of 90° designed to follow the Sun would reproduce the same groundtrack pattern. The groundtracks would be separated by roughly 140 m on the ground for a total swath of 2.1 km. Besides providing greater spatial coverage, the photon-counting CTC lidar would provide improved alongtrack and crosstrack slope information, important to ice science.

Summary

Photon-counting lidars can detect single photon surface returns and thereby increase the spatial coverage and resolution by orders of magnitude relative to conventional multi-photon lidars for a given Power-Aperture Product. Rooftop and airborne tests of 1st and 2nd generation 3D imaging lidars have demonstrated the feasibility and accuracies of photon-counting lidars operating in daylight and their scalability to space platforms. Photon-counting lidars are ideal for planetary and lunar mapping missions where instrument mass, size, and prime power are heavily constrained. They are especially attractive for mapping the outer planets and their Moons where the solar background count rates are relatively low compared to Earth (e.g. 25 times less at Jupiter). The proposed Cross Track Channel (CTC) lidar on NASA’s ICESat-II mission, if approved, will space qualify and lifetest all of the key components needed for future interplanetary pushbroom lidars, including the transmitter, detector, and timing electronics. Ruggedized lasers already meet or exceed the functional requirements of the JIMO and CTC missions. Optical scanners for globally contiguous

mappers will require further independent development and testing to demonstrate long term reliability.

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