Airborne and Spaceborne Single Photon 3D Imaging Lidars

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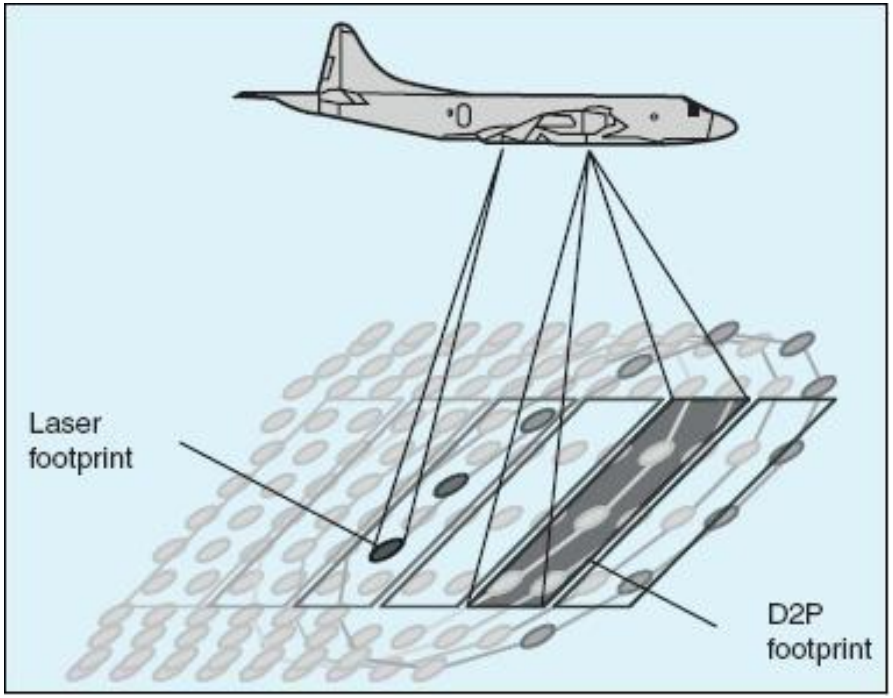
Airborne Laser Altimeter



- Maps out a surface in 3 dimensions from a host aircraft
- The laser generates a short pulse which is reflected off the ground and some of the scattered photons are captured by the receive telescope and imaged onto a detector.
- The range receiver measures the pulse roundtrip time of flight, and multiplies it by the light velocity to obtain the range to the surface.
- An optical scanner points the laser beam at the ground to form a contiguous 3D image of the surface.
- Aircraft navigation and attitude data (GPS, IMUs) are combined with the range and scanner pointing data to geolocate the source of the surface returns in a Terrestrial Reference Frame forming a “point cloud”.

Sigma Single Photon LiDARs (SPLs)

Operating altitudes ranging from 2 to 65 kft (0.6 to 20 km)

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Multiple Altimeter Beam Experimental LiDAR (MABEL) -Pushbroom

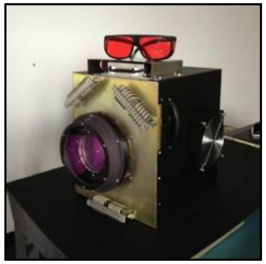
Nominal Flight AGL: 65,000 ft (20 km)
Platform : NASA ER-2
Customer: NASA GSFC (Matt McGill)
16 beams @ 10 kHz = 0.16 Million pixels/sec

High Altitude LiDAR (HAL) -Scanning

Nominal Flight AGL:: 25 to 36 kft (7.6 to 11 km)
Platform : Various
Customer: Government Agencies
100 beams@ 32 kHz = 3.2 Million pixels/sec

High Resolution Quantum LiDAR System (HRQLS1 and 2) - Scanning

Nominal Flight AGL: 6.5 to 15 kft (2 to 4.6 km)
Platform : King Air B200
Sigma Self-funded
100 beams @ 25 to 60 kHz = 2.5 to 6 Million pixels/sec



Miniature Airborne Topographic Mapper (Mini-ATM) - Scanning

Nominal Flight AGL: 2 to 6 ft (0.6 to 1.8 km)
Platform : Viking 300 UAV
Customer: NASA Wallops

Challenges to High Altitude, High Velocity Operations

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High altitude and high velocity operation permits more rapid areal coverage and lower operational costs but presents new technical challenges for a scanning lidar :

1. More laser power and/or telescope aperture is necessary to maintain the required signal levels per pixel per pulse. In our designs, we target 3 pe per pixel for 95% detection probability over 10% reflectance Lambertian terrain.

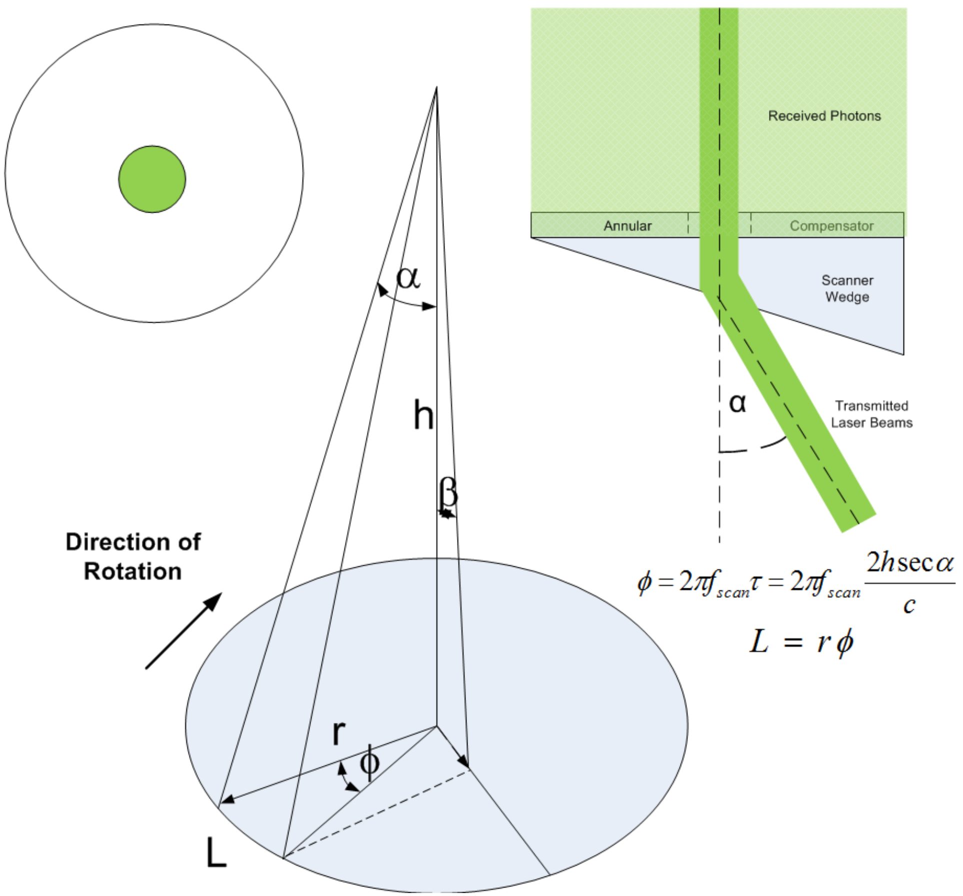
2. Small angular biases in the lidar instrumentation (e.g., A/C attitude and scanner pointing biases) result in larger and more noticeable geolocation errors if left uncorrected.

3. For a nominal 20 Hz scan, the HRQLS and HAL scanners move at ground speeds of 105 and 160 km/sec respectively (as compared to ~7 km/sec ground speed in low Earth orbit) . Our dual wedge scanner compensates for finite speed of light effects to maintain optical alignment between the transmit and receive arrays over a changing topography in order to minimize data losses and geolocation errors.

4. As in SLR, refraction and group velocity effects within the atmosphere must be modeled for maximum geolocation accuracy.

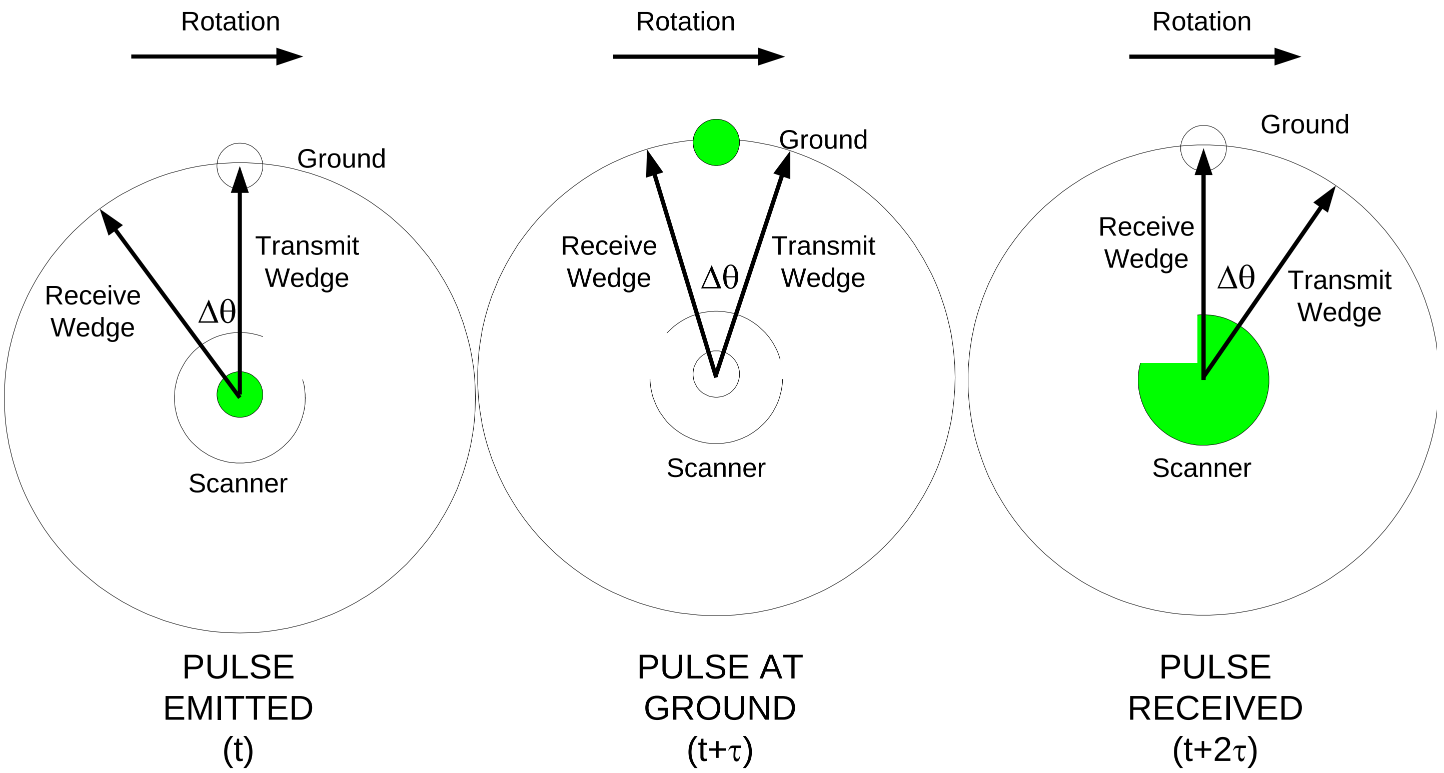
Range Impact on the Scanner

A rotating single wedge traces a circle on the surface. Over longer slant ranges, the receiver array FOV can become displaced along the circumference of the circle from the array of laser spots on the surface. To restore the overlap, we must add a “compensator wedge” which deflects the receiver FOV (or transmitter FOV but not both) at approximate right angles to the scanner wedge deflection. We use an annular compensator wedge in which the laser beams pass unaffected through the small central hole while the receiver array FOV is angularly displaced opposite to the direction of rotation so that the receiver and transmitter FOVs overlap.



For maximum overlap of transmit and receiver FOVs , the lateral displacement after correction is usually targeted to be less than one quarter pixel or ~50cm/4 =12.5 cm

Pulse Time-of-Flight Compensation



This approach also works for dual wedge scanners if a compensator wedge is bonded to each scanner wedge. Dual wedge scanners permit a wide variety of scans including linear, rotating line, variable angle conical, and spiral scans. At aircraft altitudes, the compensator wedge is oriented at 90º to the scanning wedge but at satellite altitudes the optimum orientation can differ substantially from 90º.

OTHER SPEED AND ALTITUDE IMPACTS

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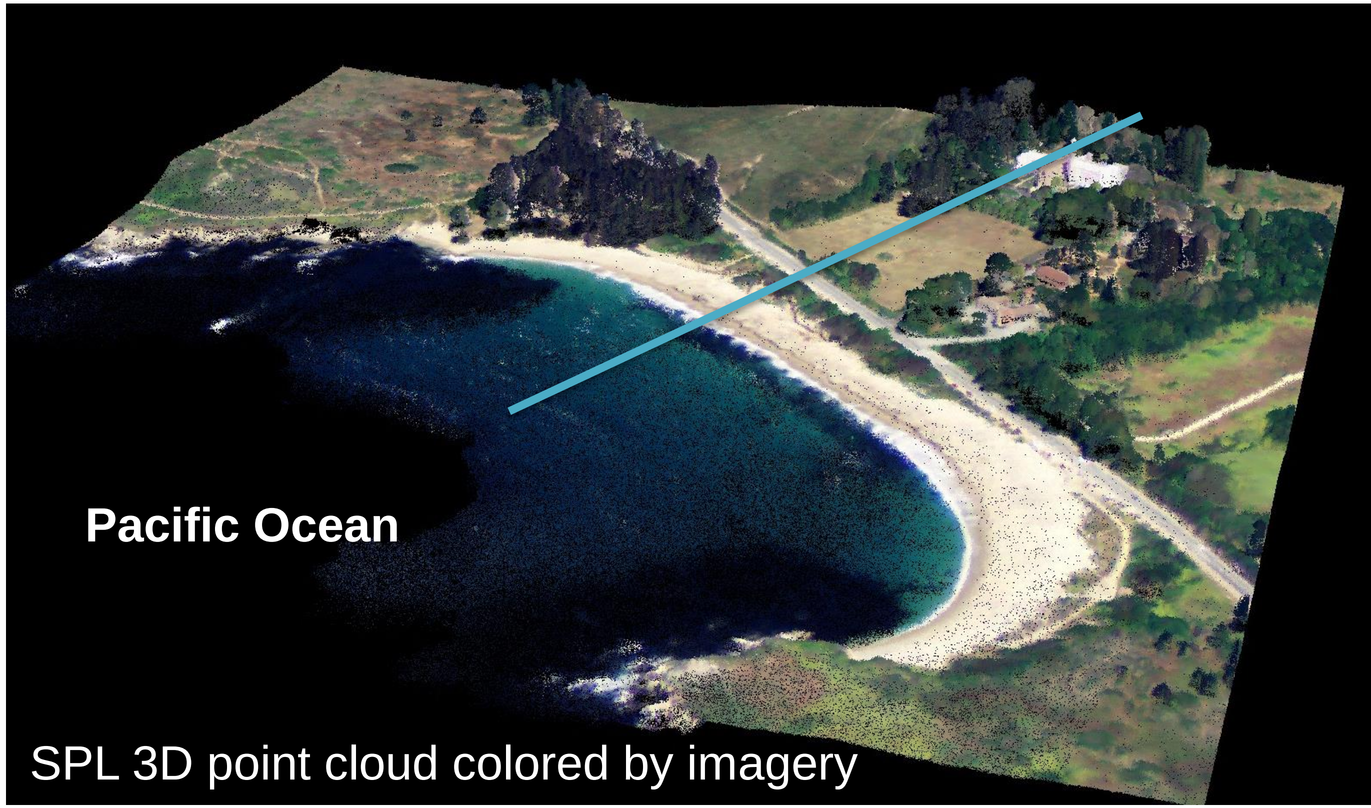
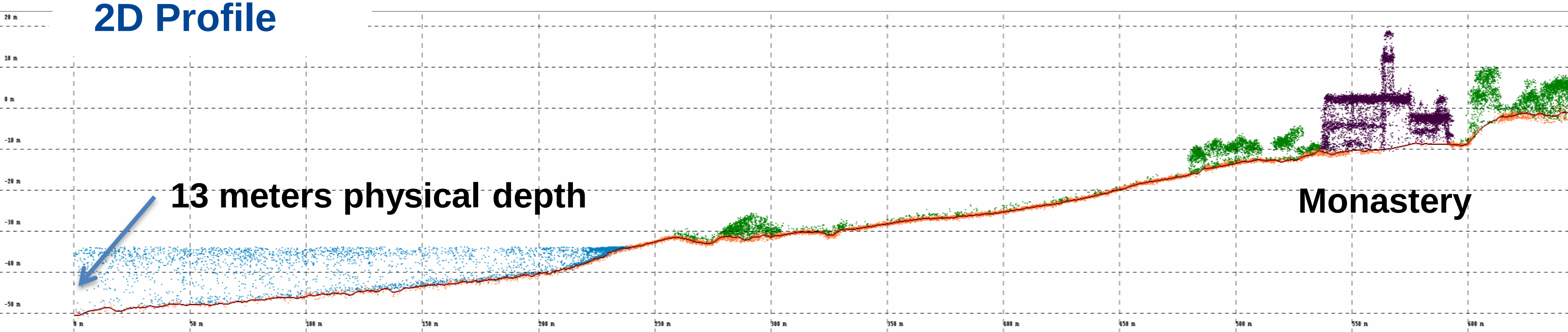
- At longer ranges, geolocation errors due to angular biases (e.g., scanner pointing errors, aircraft attitude biases, etc.) become more severe.
- Geolocation errors due to the atmosphere must be better accounted for using atmospheric models such as the Marini-Murray spherical shell model. As in SLR, these errors occur due to two effects:
    - The bending of the light rays as they pass through different atmospheric densities with altitude; and
    - The slowing down of the laser pulse velocity as it encounters denser layers in the atmosphere
- Other angular errors occurring at interfaces between dielectric media having different indices of refraction such as the interior and exterior faces of aircraft windows.
- These biases can be determined and corrected using “conjugate points” , defined as easily recognized and well-defined points (e.g. corners of rooftops) observed multiple times during the mapping process.

HRQLS-1 Combined Topography and Bathymetry @532 nm, Pt. Lobos, CA

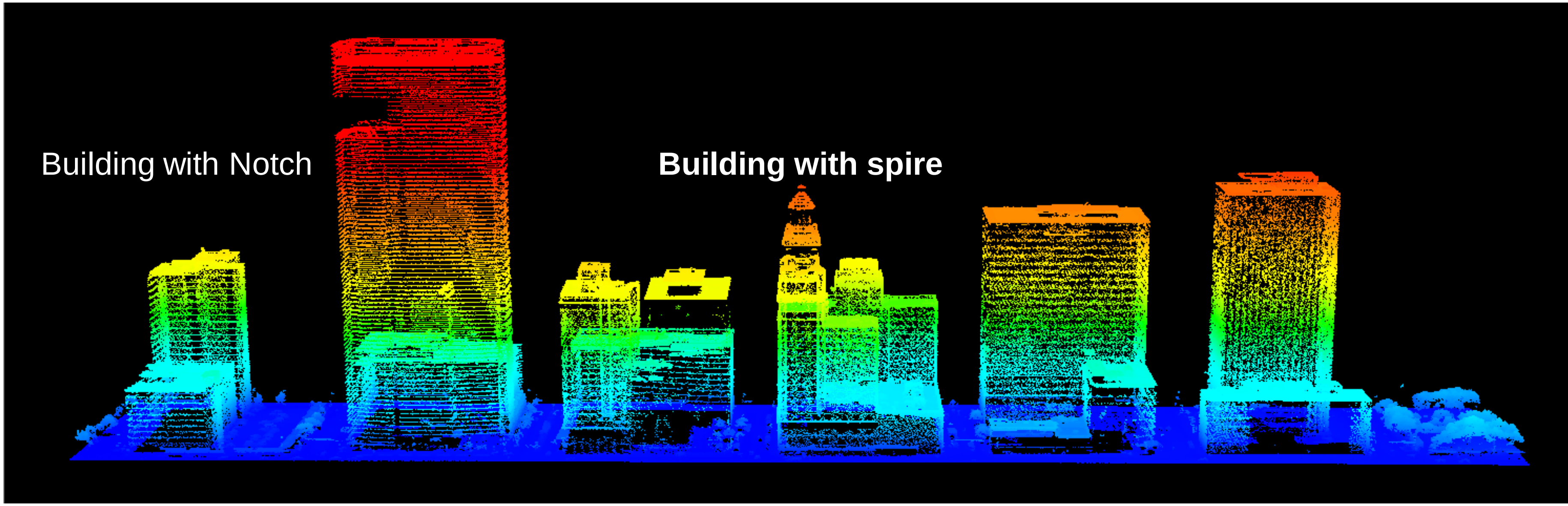
Sample:
Double Pass
AGL: 7500 ft
Velocity: 180 knots





HRQLS-2* DOWNTOWN HOUSTON

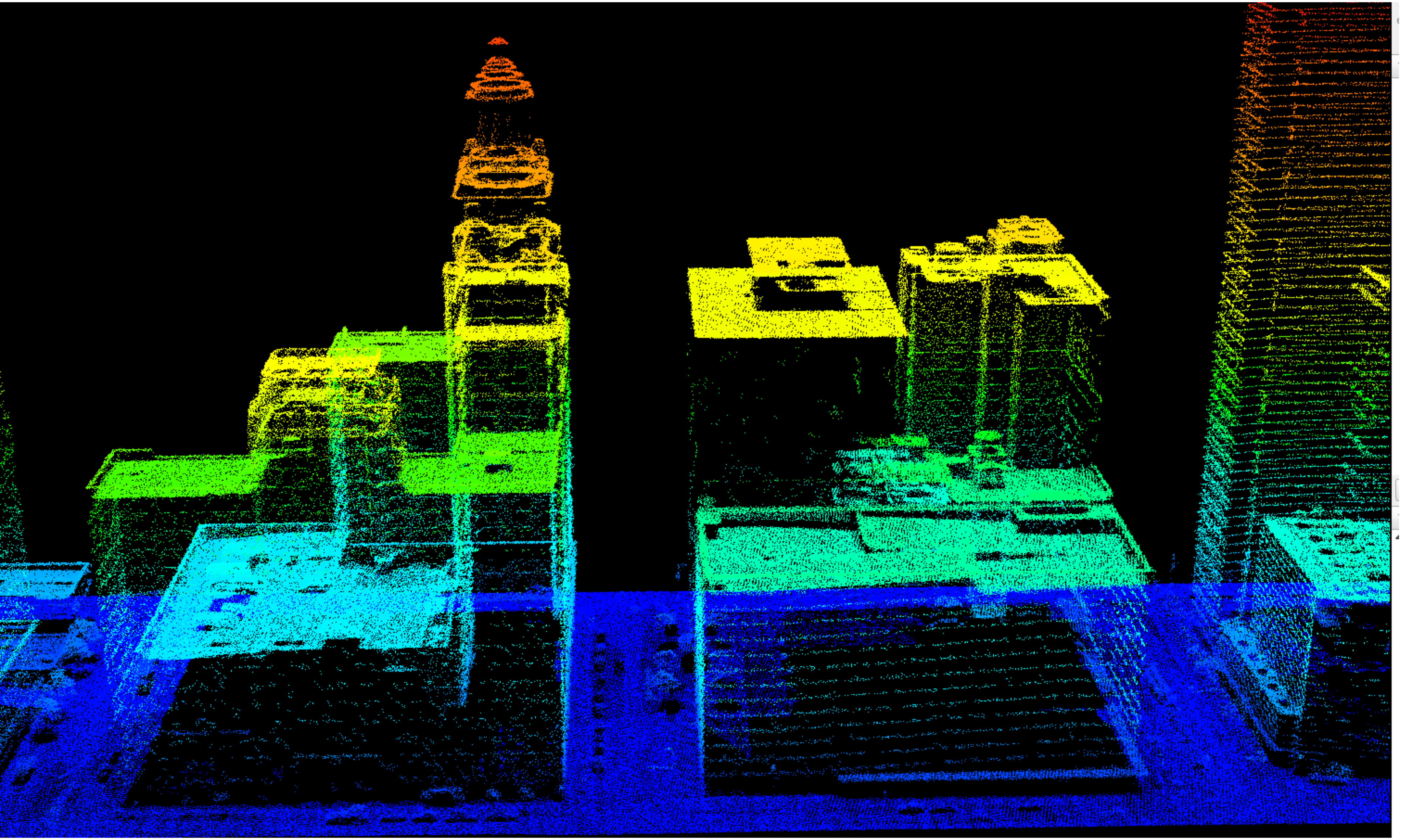
Aircraft Speed: 140 knots (260 km/hr)
AGL: 4 lines at 12 kft (3.7 km), 3 lines at 14 kft (4.3 km)
Conical Scan Half Angle: 15 degrees
Swath: 1.96 km @ 3.7 km AGL, 2.29 km@ 4.3 km AGL
Coverage per Line: 508 km^2/hr @ 3.7 km km AGL, 593 km^2/hr @4.3 km AGL
Laser Repetition Rate: 50 kHz
Number of Laser Beamlets/Detector Pixels: 100
Maximum Surface Measurement Rate: 5 Million pixels per second



***HRQLS-2 is now sold as SPL100 by Leica Geosystems**

Photo of Building with Notch on Previous Slide

Closeup of Building with Spire



LIDAR IMAGE OF HOUSTON, TEXAS

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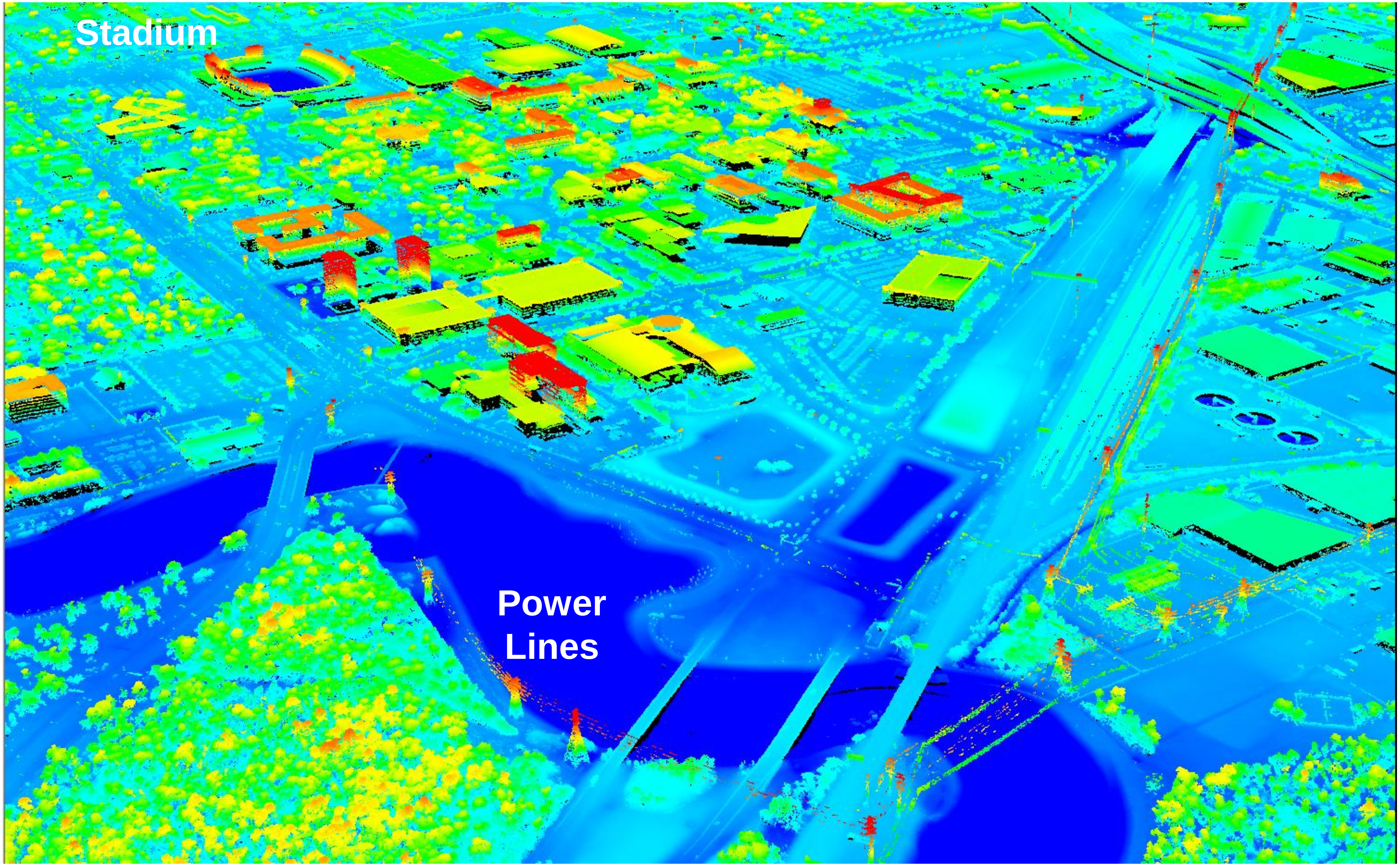
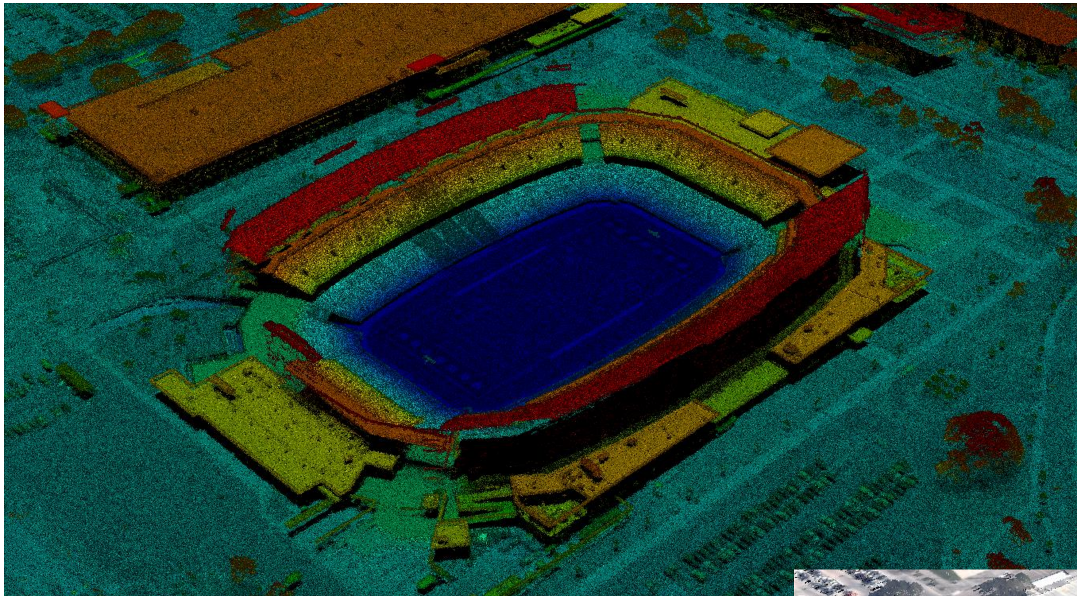


LIDAR IMAGE OF HOUSTON STADIUM

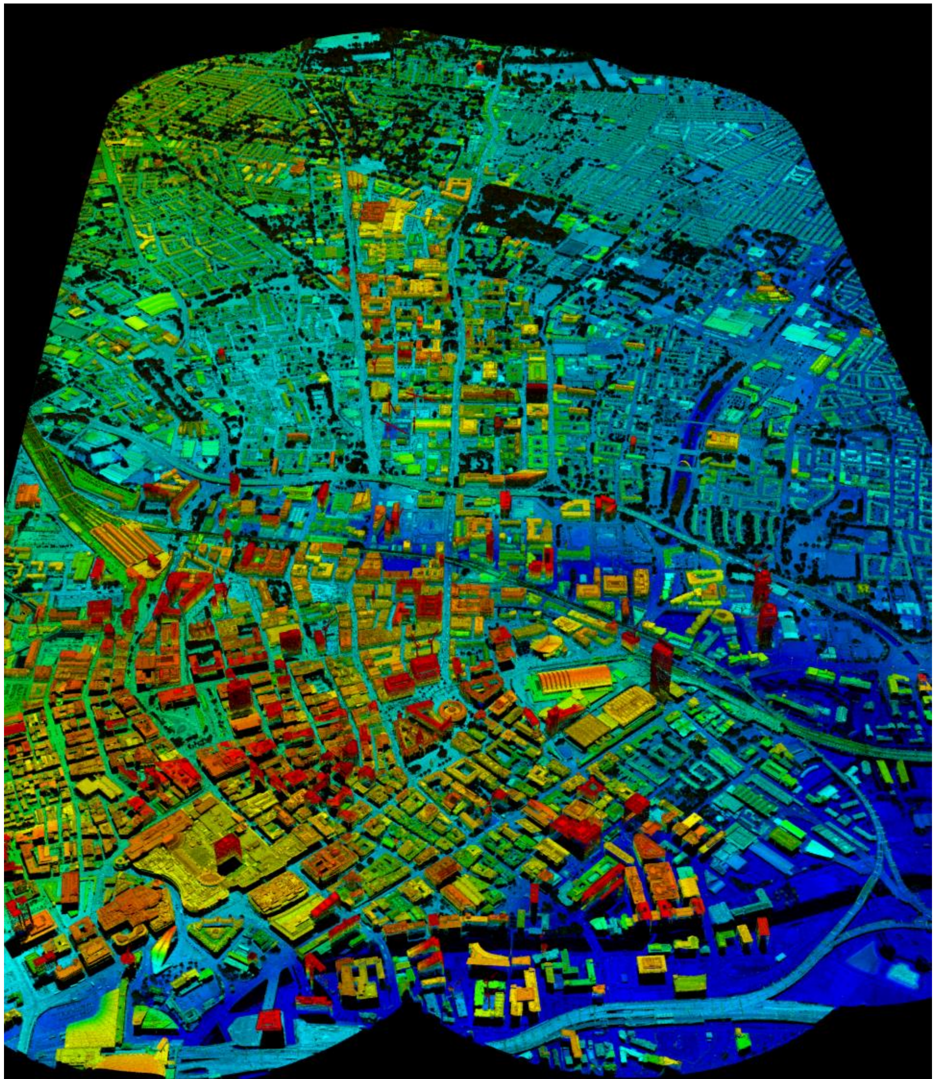


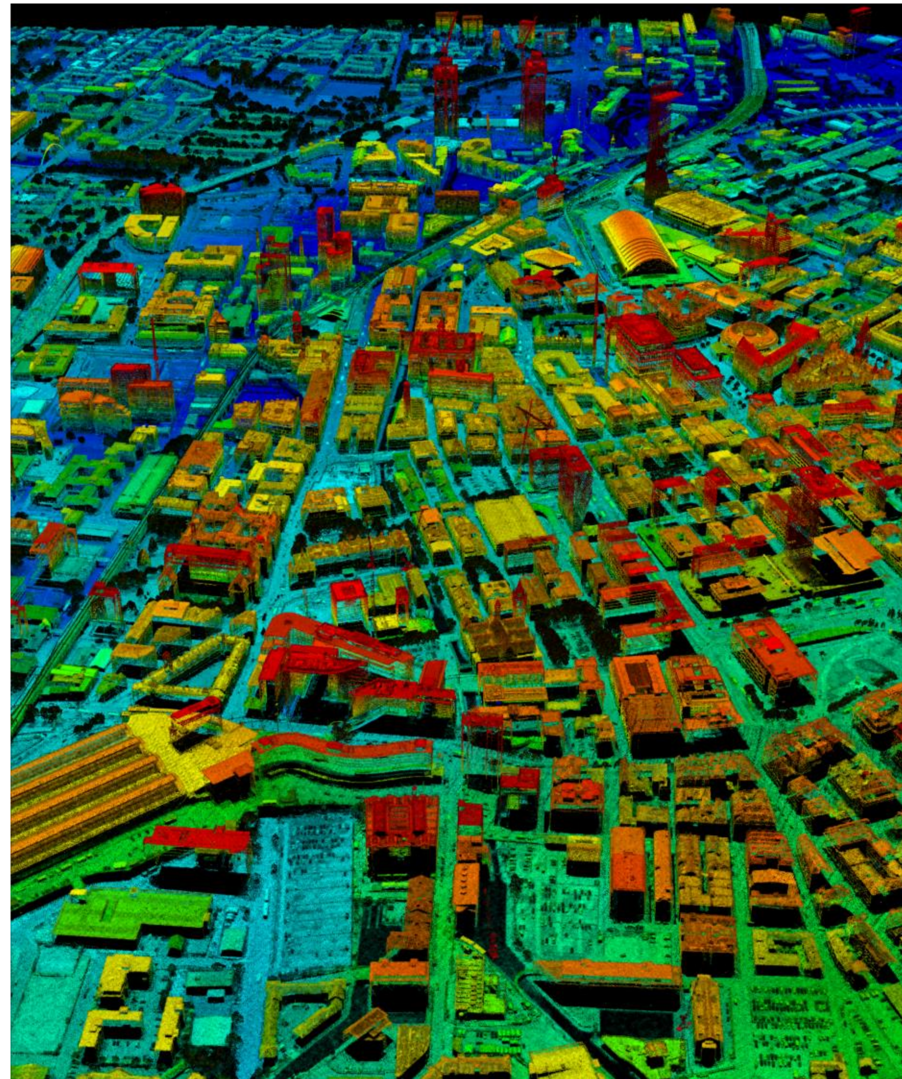
Lidar Image

Lidar Image with RGB Overlay

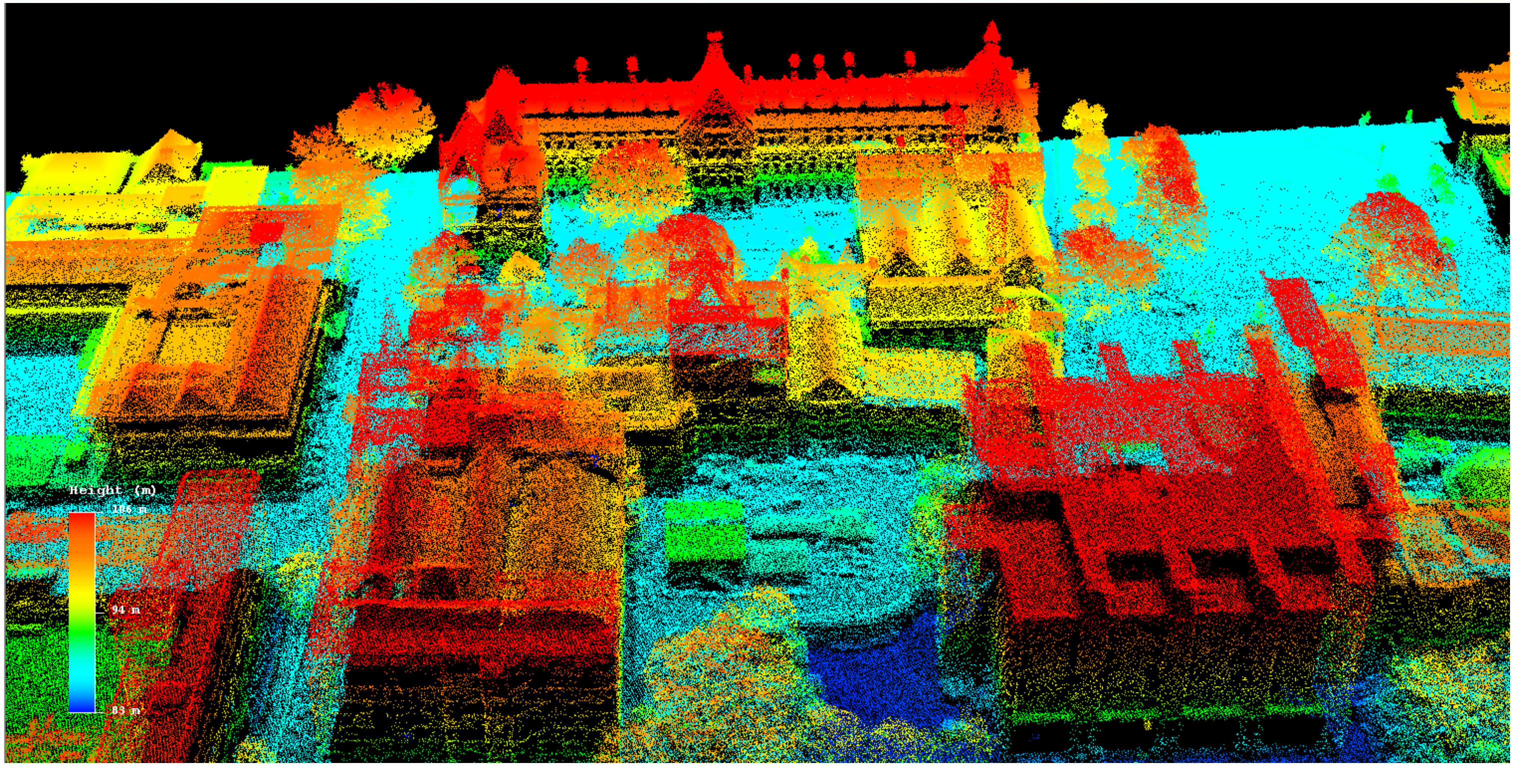
Manchester, England

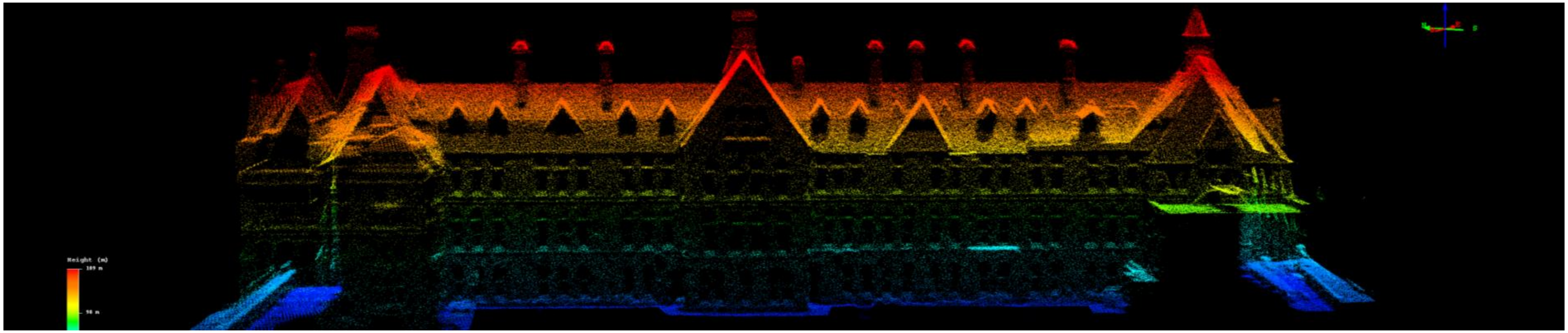
AGL =7300 kft, flight speed = 140 knots, point density = $33/m^2$ (4 lines w 50% overlap)





Manchester, England





ICESat-2: FIRST SPL IN SPACE

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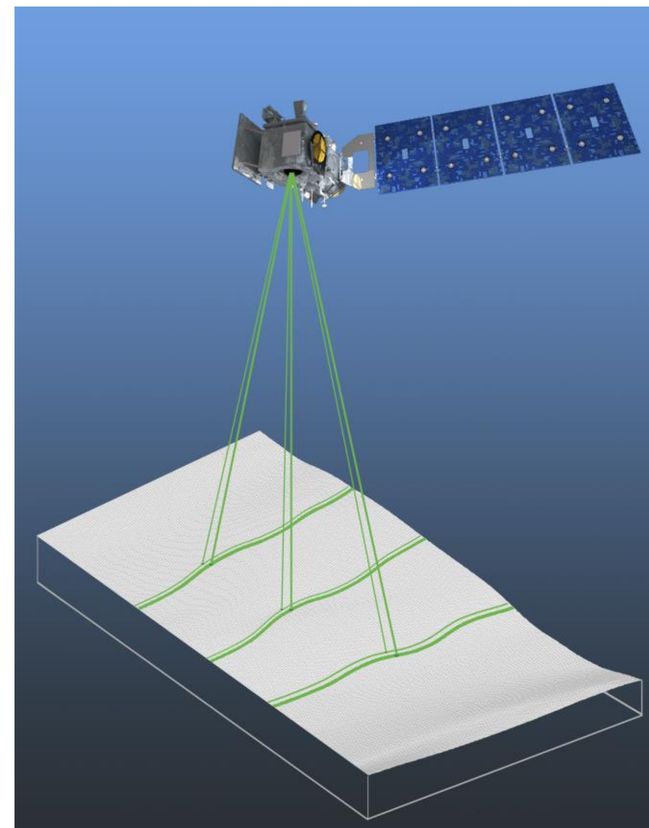
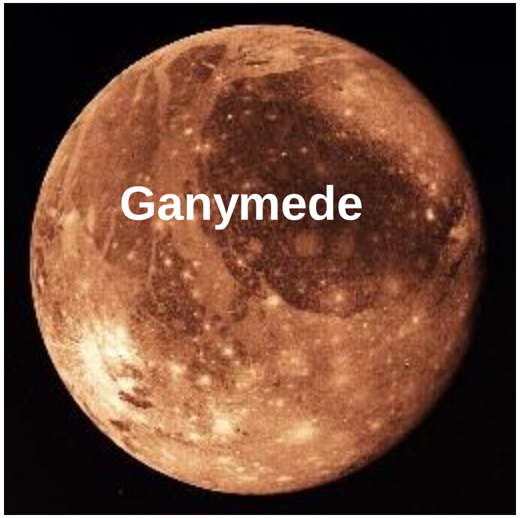
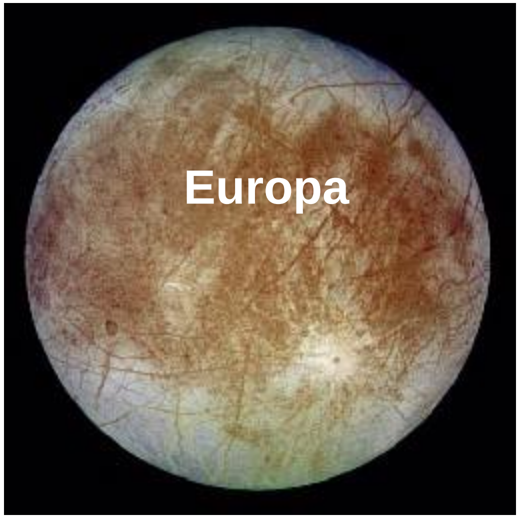
- ATLAS = Advanced Topographic Laser Altimeter System
- Launched on Sept. 15, 2018 from Vandenberg Air Force Base in California
- 500 km high near-polar orbit
- Actively Q-switched Nd:YAG Laser: 5W at 532 nm at 10 kHz (500 μJ per pulse)
- Pushbroom Lidar: 6 beams, 3 “strong” (~132 μJ each) and 3 “weak” (~33 μJ each)
- Telescope Diameter: 80 cm



Jupiter Icy Moons Orbiter (JIMO)





JIMO 3D Imaging Goals

•Globally map three Jovian moons with

•Horizontal Resolution: <10 m

•Vertical Resolution: < 1 m

Analysis: HR<5m; VR<0.1m with 5 W ATLAS laser & 50 cm receiver

Worst Case Constraints

•Europa (last stop) map must be completed within 30 days due to strong radiation field*

- •348 orbits at 100 km altitude
- •14.5 km mean spacing between JIMO ground tracks

•Surface Area: 31 million km^2

* More recent JPL studies have indicated that, with proper shielding, Europa operations could possibly be extended to 3 or 4 months, allowing proportionally higher resolution maps.

Summary

•Our 100 beam scanning SPLs have provided decimeter level (horizontal) and few cm RMS (vertical) resolution topographic maps from aircraft AGLs up to 28 kft (8.6 km). Data rates to date vary between 2.2 and 6 million 3D pixels per second., up to 60 times faster than conventional multiphoton lidars.

•The multibeam NASA MABEL pushbroom SPL has operated successfully at AGLs up to 65 kft (20 km).

•Our smallest lidar, Mini-ATM, designed for large scale cryospheric measurements, weighs only 28 pounds (12.7 kg) , occupies 1 ft^3 (0.028 m^3), has a $\pm$ 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.

•Our low deadtime (1.6 nsec) detectors and range receivers permit daylight operation and multiple range measurements per pixel per pulse, allowing penetration of volumetric scatterers such as tree canopies, water columns, ground fog, etc. The green wavelength allows combined topographic and bathymetric surveys with a single instrument.

•Our moderate to high altitude lidars built to date provide contiguous topographic and bathymetric maps on a single overflight at aircraft speeds up to 220 knots (407 km/hr). Surface point densities and elevation accuracies errors meet USGS QL1 standards ($>8/m^2$ and <10 cm) . Our latest commercial lidar, HRQLS-2 (Leica Geosystems SPL100), flies at altitudes between 11and 15 kft (3.4 to 4.6 km).

•Using a laser comparable to that developed for the ATLAS SPL on NASA's ICESat-2 and a MOLA-sized 50 cm diameter telescope , one could <u>contiguously and globally</u> map the three Jovian moons from a 100 km orbit at rates up to 1 Million measurements/sec (100 beams @ 10 kHz) with better than 5 m horizontal resolution in 1 month (Europa) or 2 months (Ganymede and Callisto) each. Conventional, pushbroom style, spaceborne laser altimeters have already mapped the Earth (40 Hz), Moon (5 beams@28 Hz)=140Hz, Mars (10 Hz), Mercury (8 Hz), and several asteroids but at several orders of magnitude lower point densities.