Lidar 101

Lidar and Height Mod Workshop

August 18, 2011

Silver Spring, MD

Christopher Parrish, PhD

National Oceanic and Atmospheric Administration

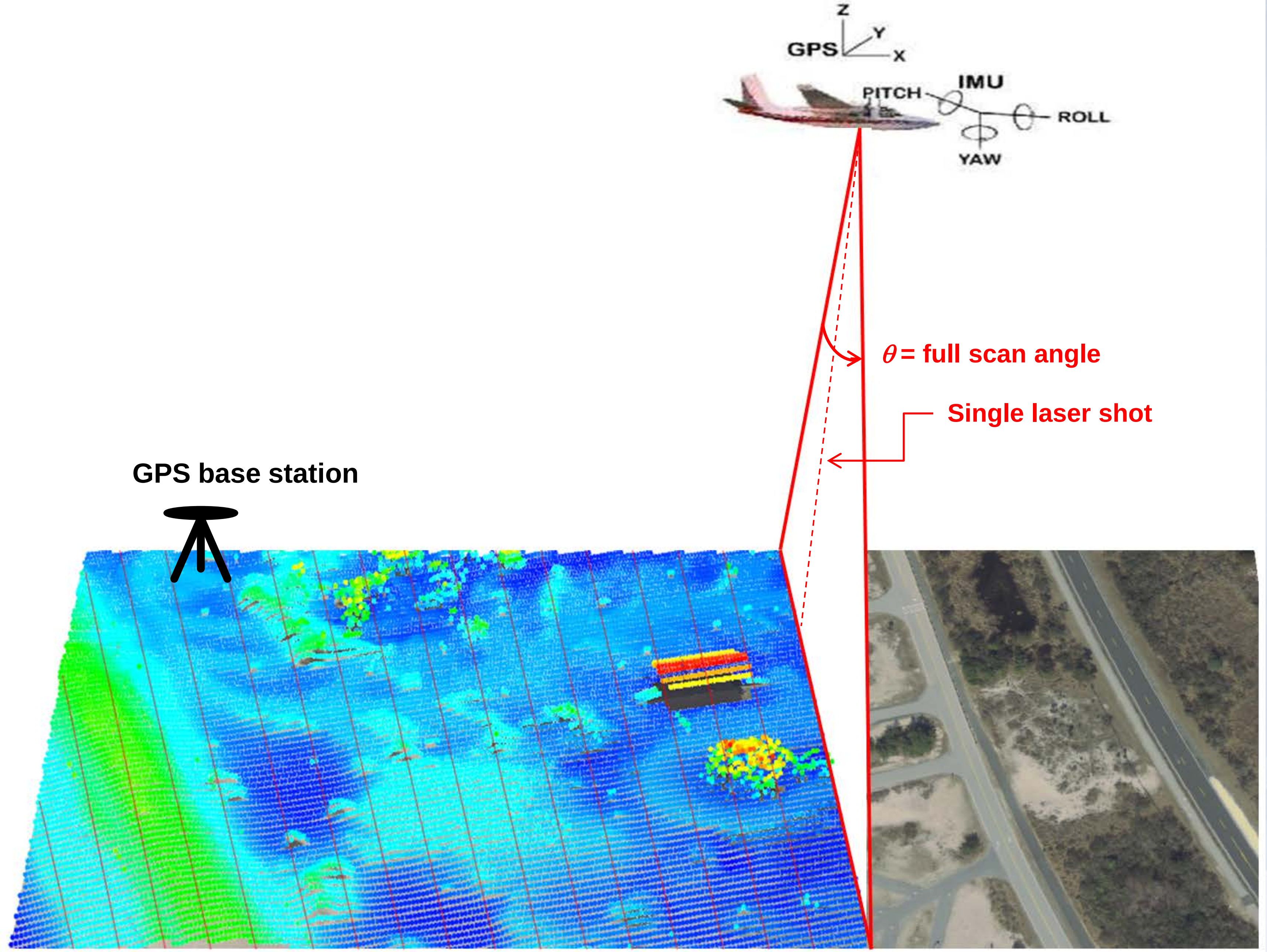
Airborne Topographic Lidar

- An active, airborne remote sensing technology that combines laser ranges, scan angles, post-processed position & orientation data from an integrated GPS/IMU system, and calibration data to generate dense, accurate, irregularly-spaced (*X*,*Y*,*Z*,*I*) point data ("point clouds"), which can be used to create DEMs, DSMs, TINs, contours, building models, canopy models, etc., etc.

Airborne Bathymetric Lidar

- Similar to topographic lidar, but with the following differences:
  - Ability to measure *depths* or *submerged topography* of coastal waters or lakes
  - Typically employs both green and near-IR beams (although there are all-green systems, e.g., EAARL)

Topo Lidar Acquisition Principles



Bathy Lidar Acquisition Principles

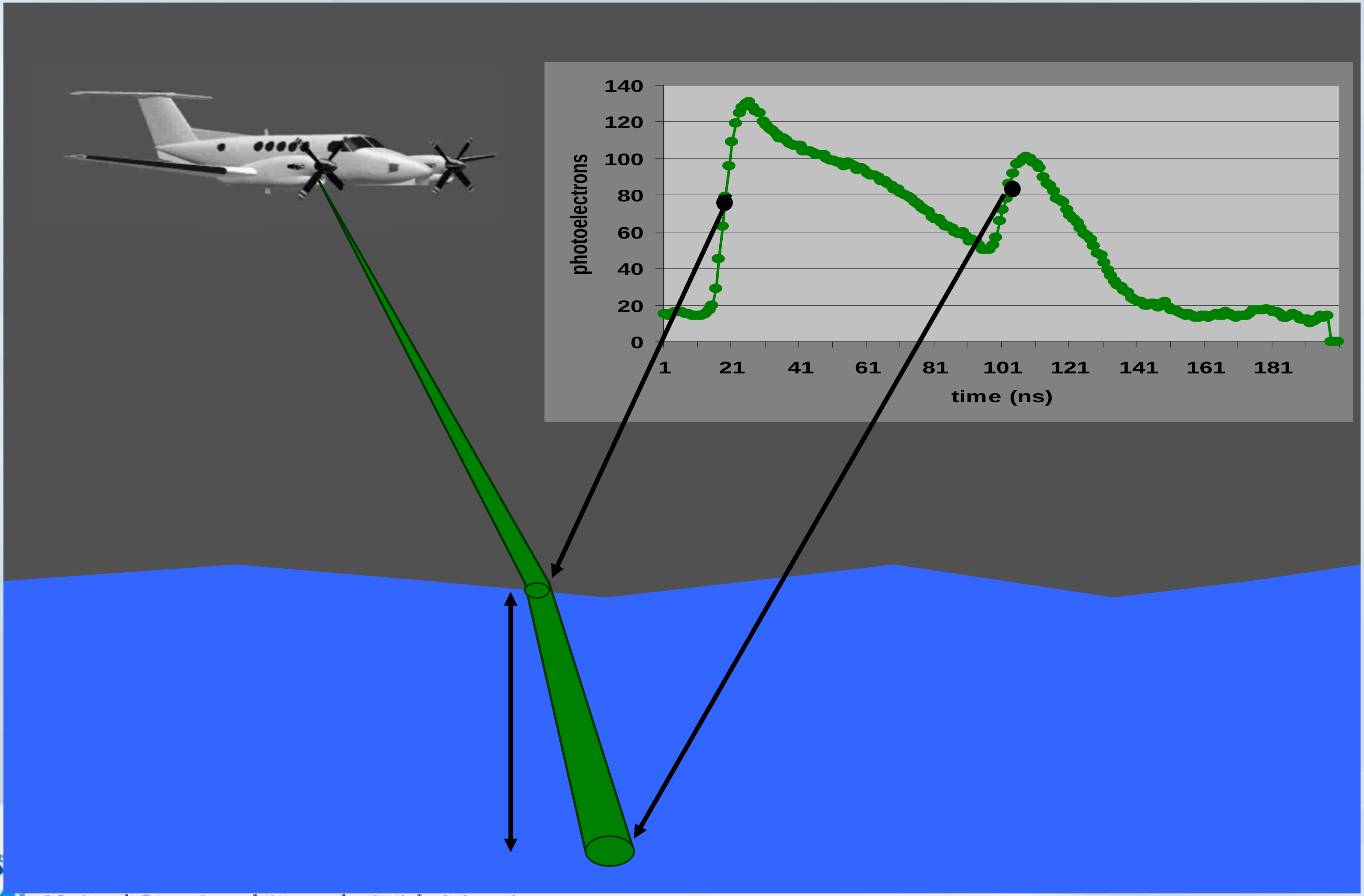


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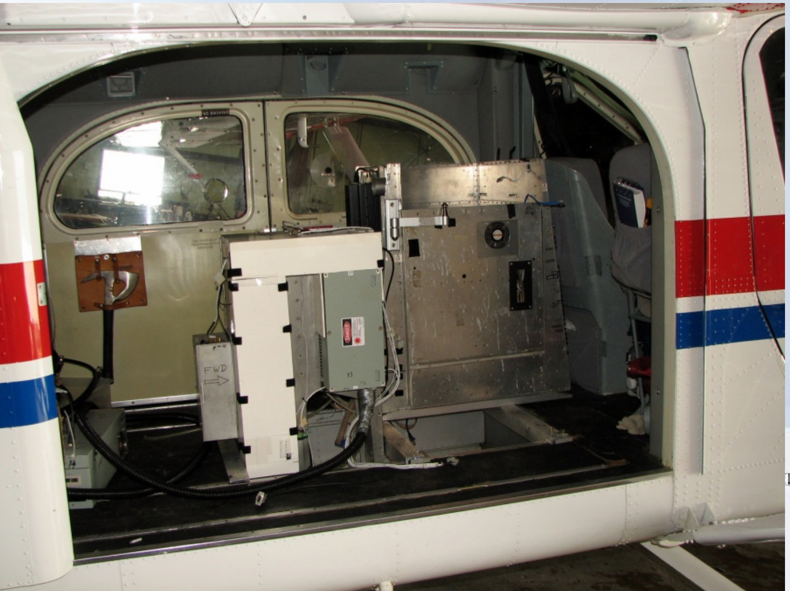
Image courtesy of Optech International

What do Lidar Sensors Look Like?

Optech Bathy Lidar (SHOALS)

Optech Topo Lidar (ALTM 2050)

Riegl Topographic Lidar (LMS-Q680)

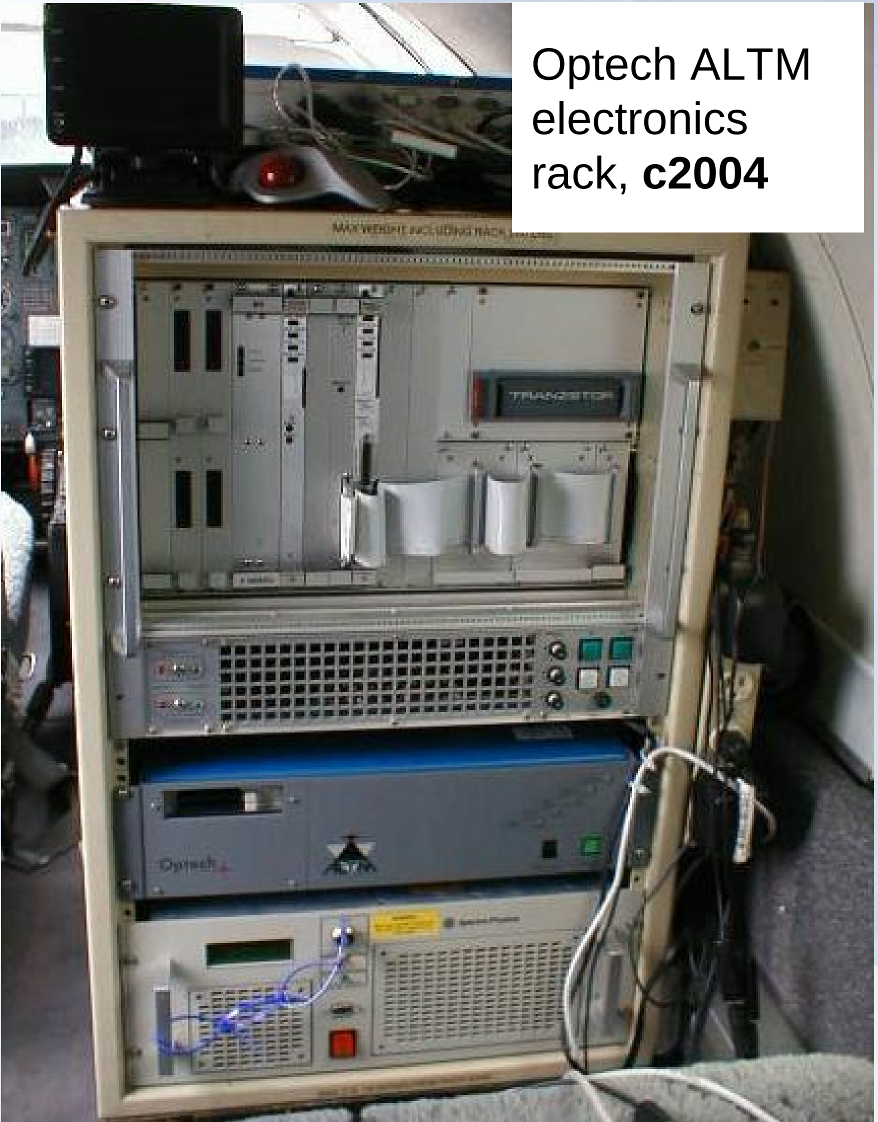


USGS Topo/Bathy Lidar (EAARL)

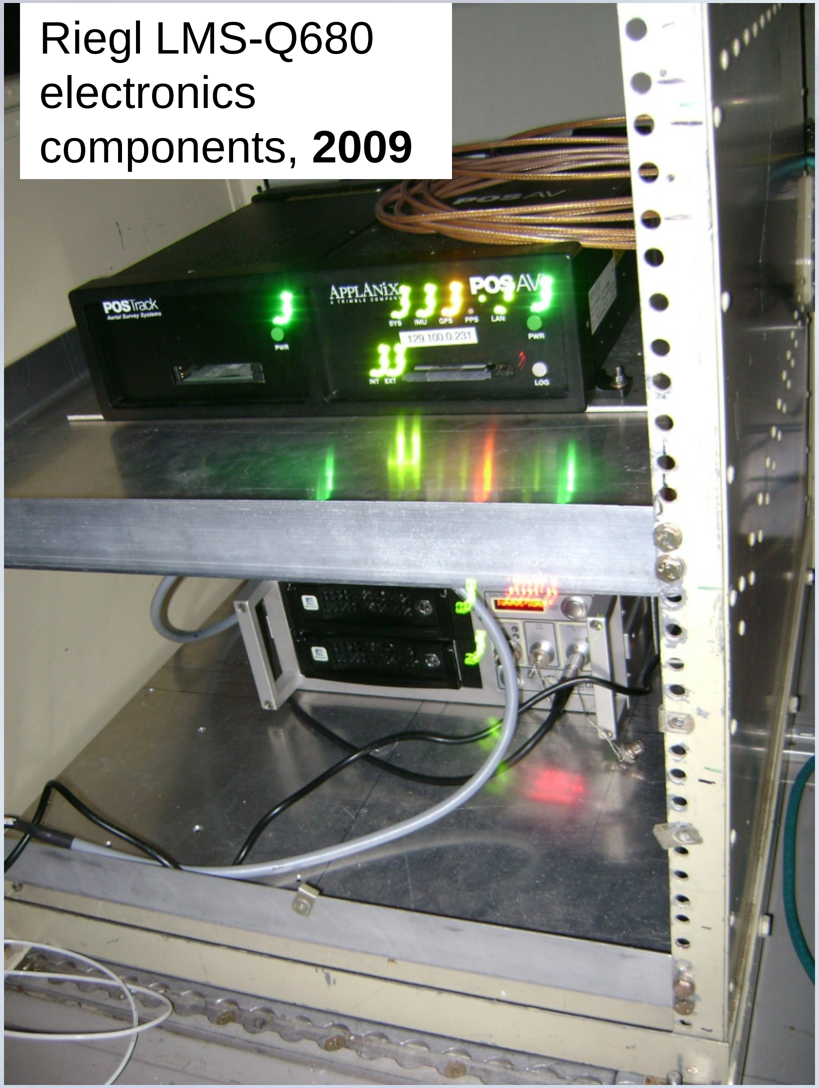
ration

Note: this is by no means a comprehensive list of manufacturers or systems– just a few photos that I happened to have on my computer…

What do Lidar Electronics Rack Components Look Like?



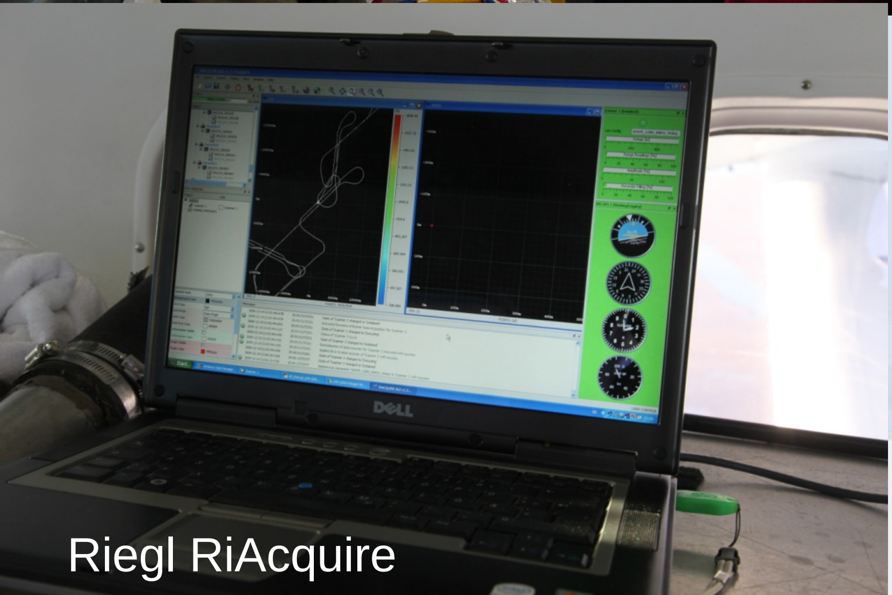
Optech ALTM electronics rack, **c2004**



Riegl LMS-Q680 electronics components, **2009**

Note: same caveat as before: this is not a comprehensive list…just some photos I happened to have on my computer…

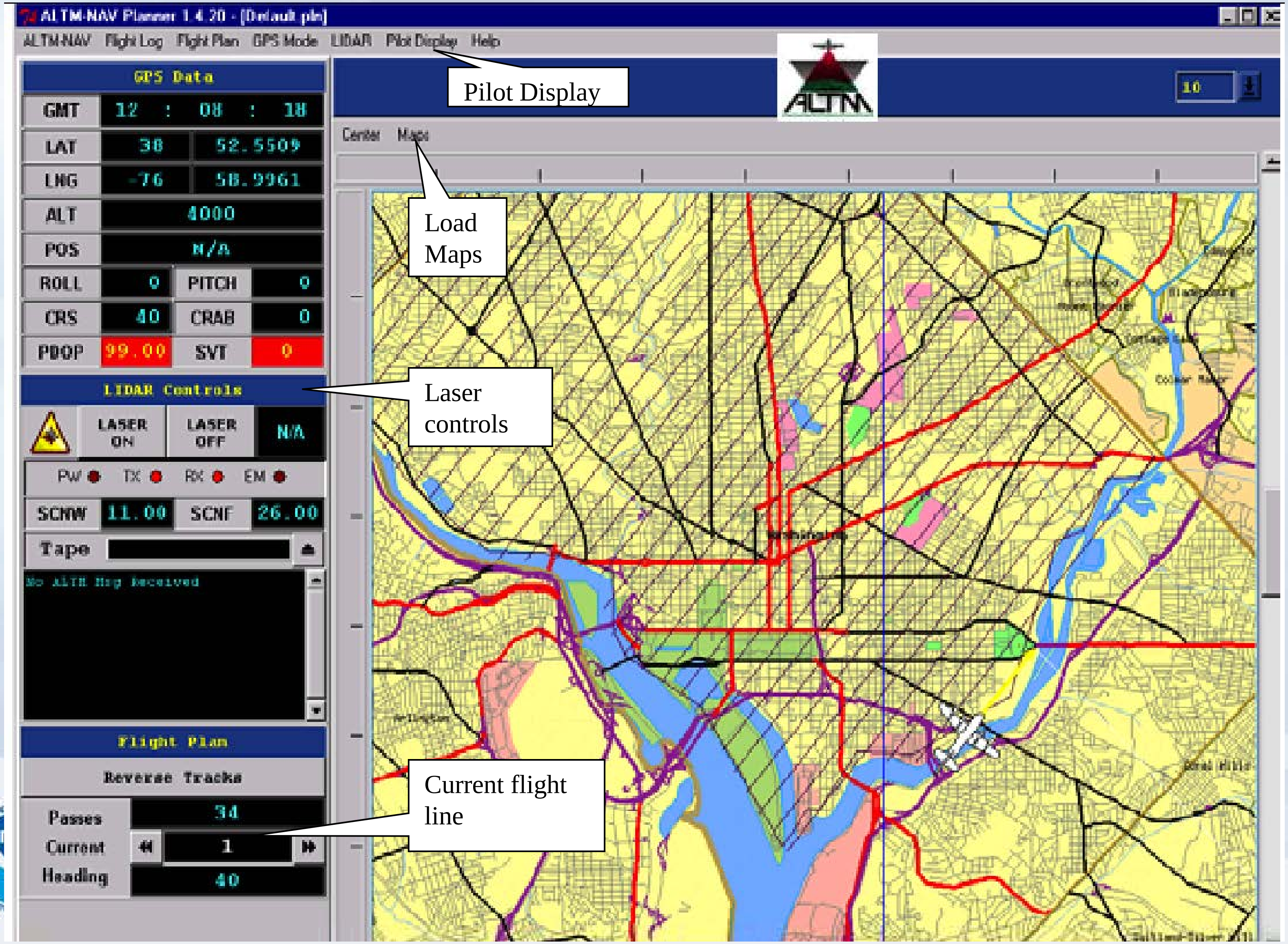
What does Lidar Data Acquisition Look Like?



Riegl RiAcquire

Optech ALTM NAV

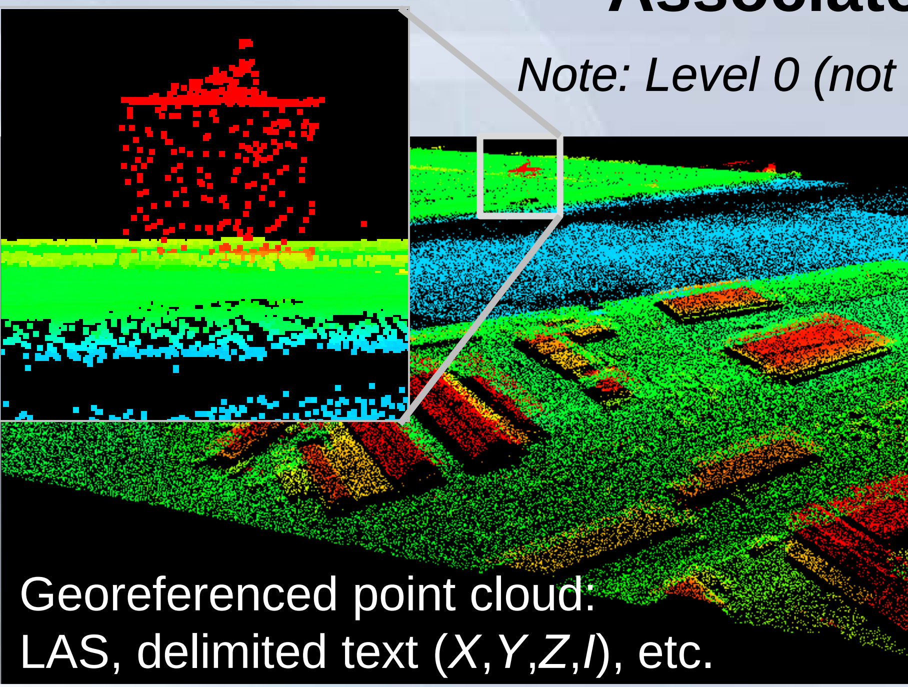
Flight Management System (FMS) Software



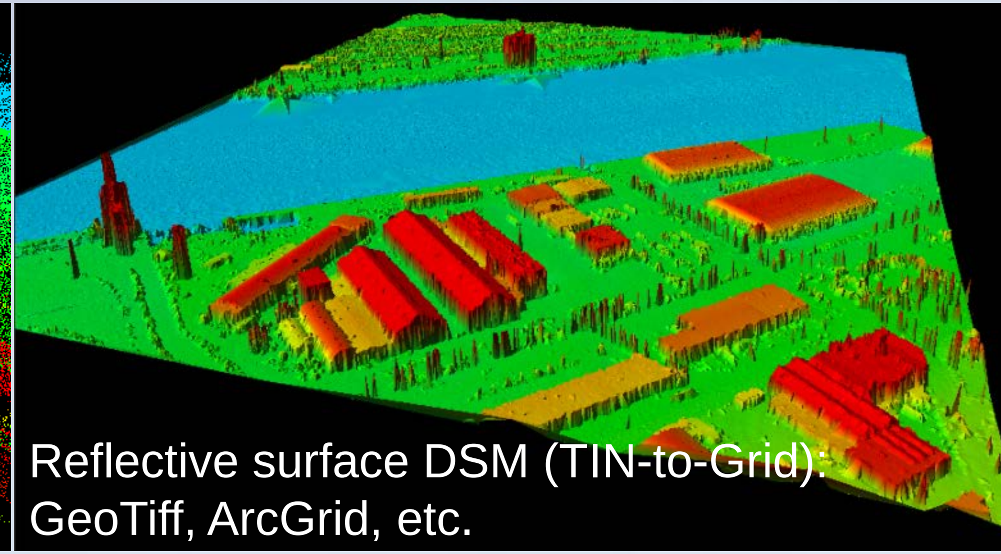
Active system => day/night operations

Examples of Some Lidar Processing Levels & Associated File Formats

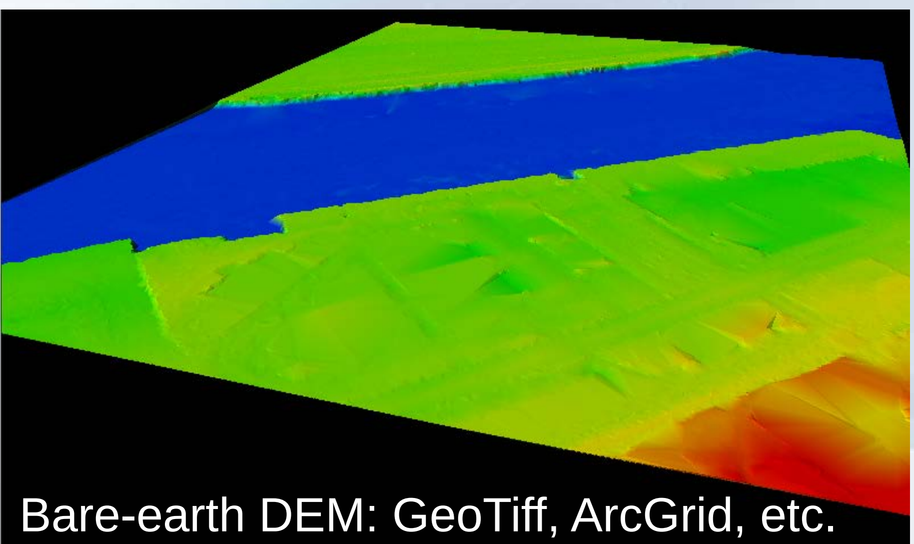
Note: Level 0 (not shown) = raw sensor data recorded on aircraft



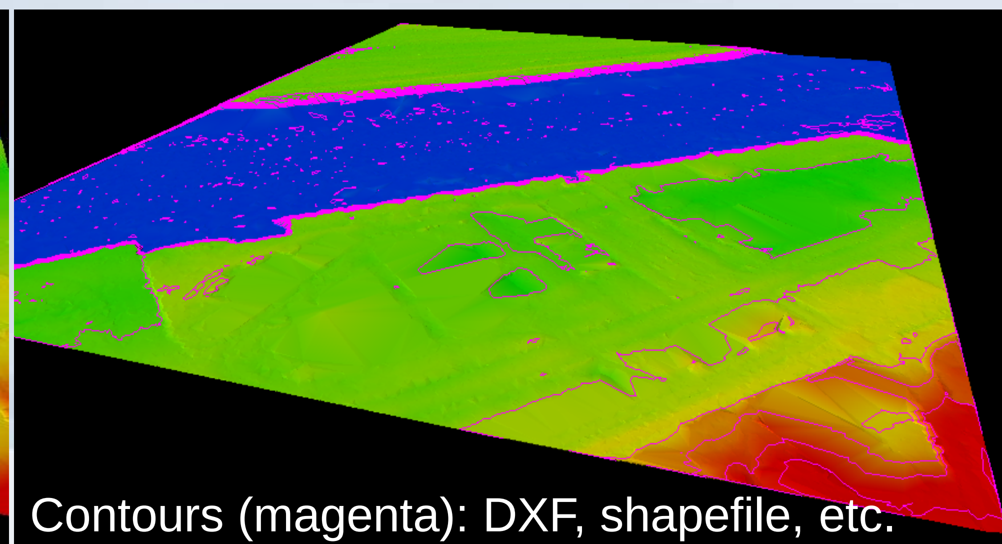
Georeferenced point cloud:
LAS, delimited text (*X*,*Y*,*Z*,*I*), etc.



Reflective surface DSM (TIN-to-Grid):
GeoTiff, ArcGrid, etc.

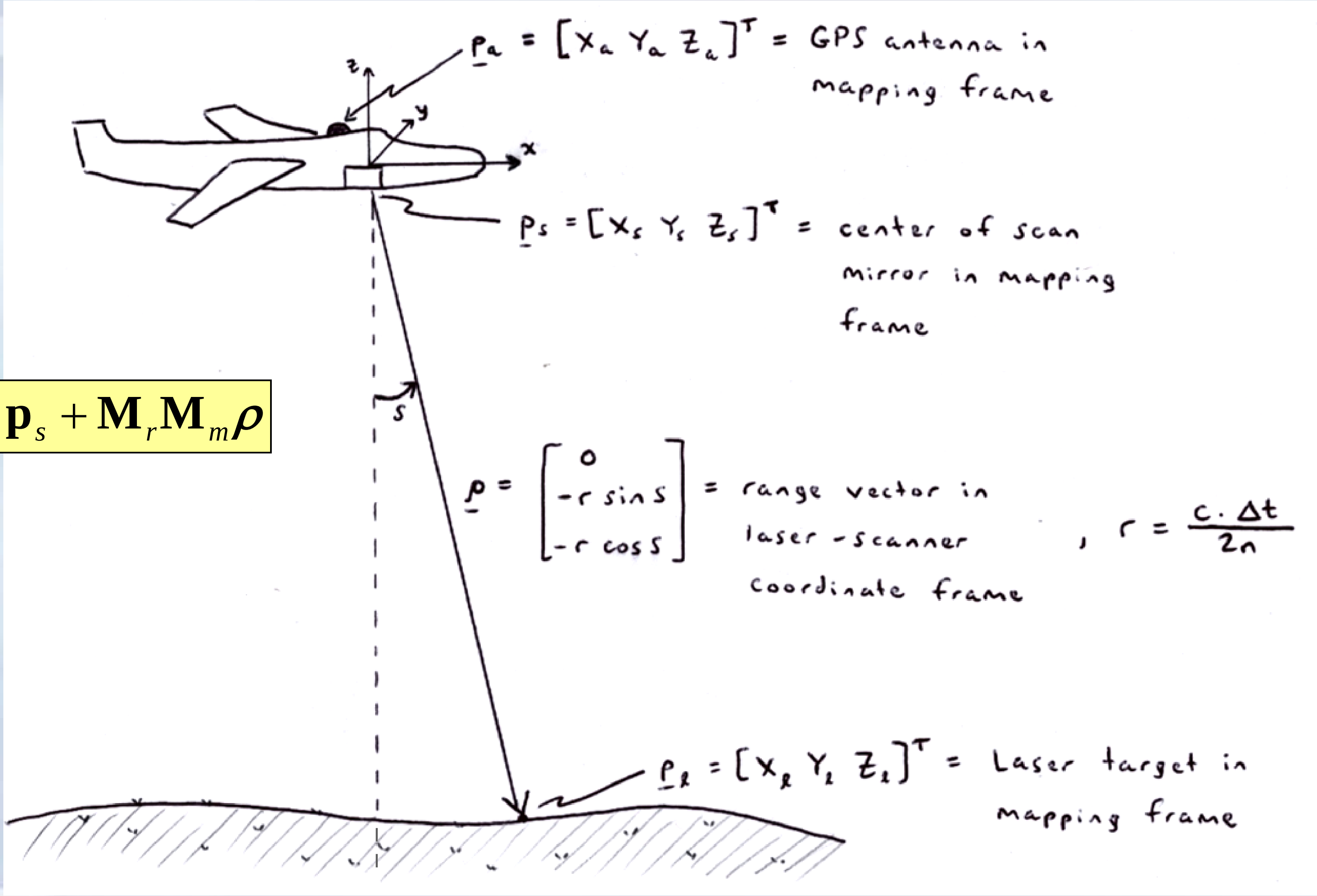


Bare-earth DEM: GeoTiff, ArcGrid, etc.



Contours (magenta): DXF, shapefile, etc.

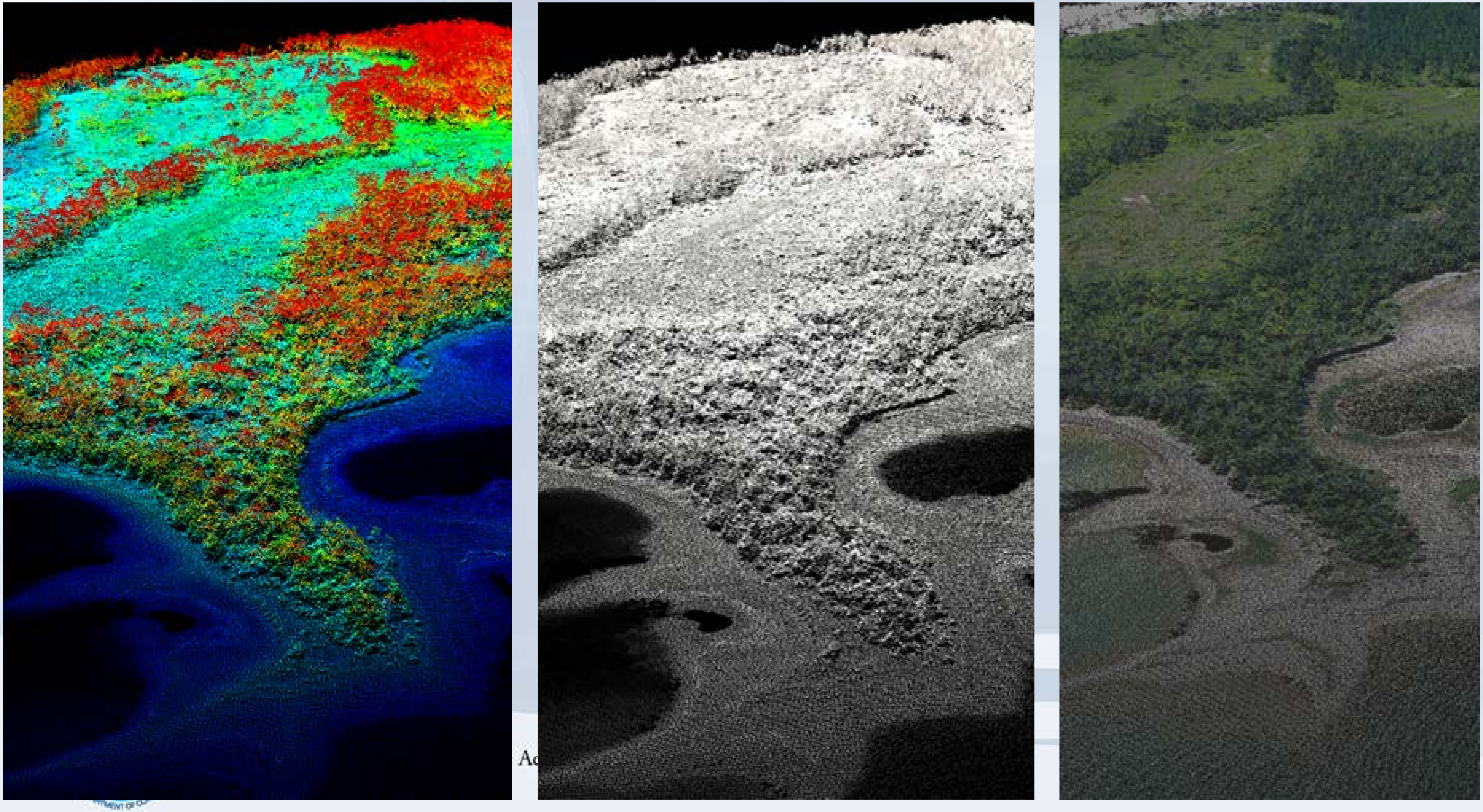
Georeferencing waveforms (laser geolocation equation):



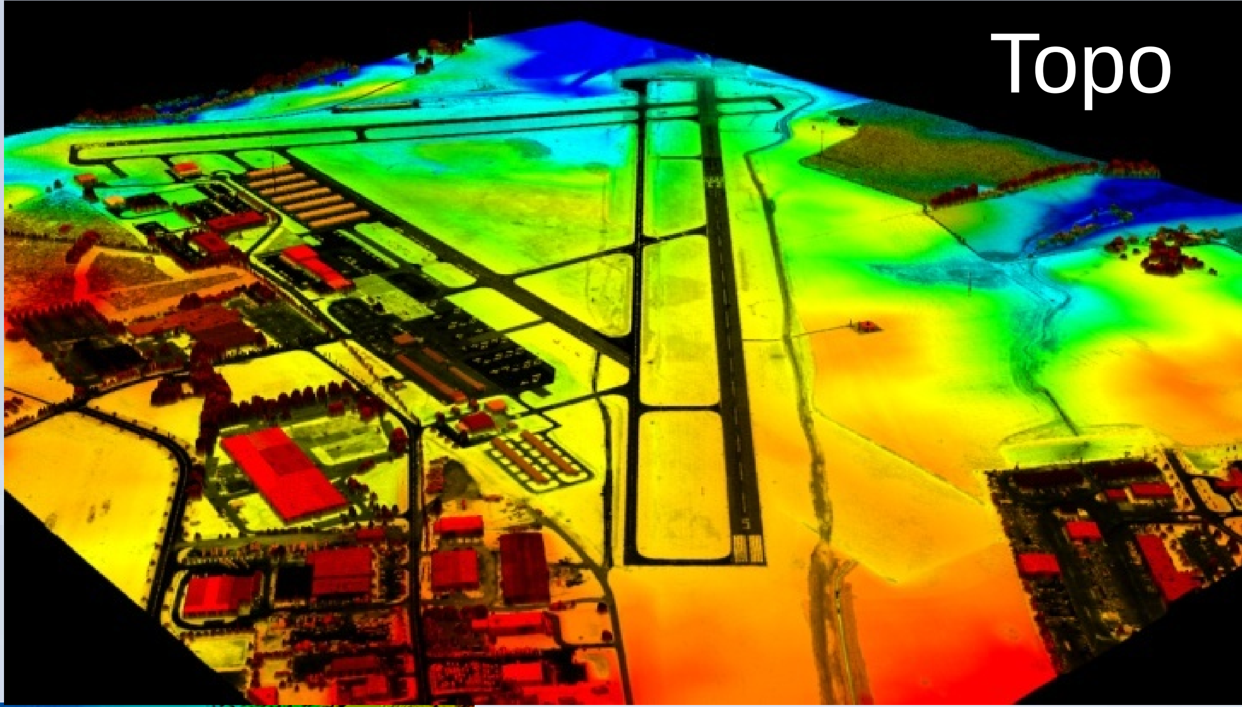
$$\mathbf{p}_l = \mathbf{p}_s + \mathbf{M}_r \mathbf{M}_m \boldsymbol{\rho}$$

$$\mathbf{M}_r = \begin{bmatrix} \cos\Theta\sin\Psi & -\cos\Psi\cos\Phi - \sin\Psi\sin\Theta\sin\Phi & \cos\Psi\sin\Phi - \sin\Psi\sin\Theta\cos\Phi \\ \cos\Theta\cos\Psi & \sin\Psi\cos\Phi - \cos\Psi\sin\Theta\sin\Phi & -\sin\Psi\sin\Phi - \cos\Psi\sin\Theta\cos\Phi \\ \sin\Theta & \cos\Theta\sin\Phi & \cos\Theta\cos\Phi \end{bmatrix}$$

Examples of NGS Lidar Point Clouds Color-Coded by Elevation (left), Intensity (middle), and RGB Image Bands (right)



Topo and Topo/Bathy Lidar Data



Terminology

- Light Detection And Ranging (lidar, LIDAR, or LiDAR)
- Other terms:
  - Airborne laser scanning (laserscanner) (ALS)
  - Airborne laser swath mapping (ALSM)
  - Airborne (scanning) laser altimetry
  - Laser Detection And Ranging (LADAR)
  - Note: These terms are often used to describe the same R/S technology, but some differ in what they imply about the system

Terminology (cont'd)

- **Point Cloud:** Irregularly-spaced points in 3D space, with each point denoting an individual laser reflection point
- **Pulse Repetition Frequency (PRF):** Number of laser pulses transmitted per second (also called pulse repetition rate, PRR) (kHz)
- **Scan rate:** Number of times per second the sensor's FOV is scanned (Hz)
- **Pulse width:** Time interval btwn leading edge and trailing edge of Tx pulse (ns)

Terminology (cont'd)

- **Point density:** number of points in the output point cloud per unit area (pts/m^2)
- **LAS:** Publicly-available, open file format for lidar point cloud data published by ASPRS
- **Full Waveform:** System that records the entire backscattered laser echo through digitization and storage of the received signal
- **Boresight:** Calibration performed to determine (and correct for) misalignment angles between IMU and sensor frames

Terminology (cont'd)

- **Scan Pattern:** pattern of laser points on the ground, created by particular method of steering the beam (e.g., zig-zag, elliptical, parallel, sinusoidal)
- **Beam Divergence:** angular measure of increase in beam diameter with distance (mrad)
- **Footprint:** size of laser beam on ground, typically specified by diameter (cm or m)
- **Multipulse (or MPiA):** ability to increase survey efficiency by enabling multiple laser pulses in the air simultaneously

Brief History of Topo Lidar

- 1960s: Lunar laser ranging
- 1977: Atmospheric Oceanographic Lidar (AOL)
  - Joint NASA, NOAA project
- 1980s: Commercial laser profilers
- 1993: First ALTM (Optech)
- 1998: First Azimuth Aeroscan System
  - Evolved into the Leica Geosystems ALS family of instruments (currently ALS60)
- 2003: ASPRS LAS format v1.0 released

Brief History of Topo Lidar (cont'd)

- 2004: Release of "ASPRS Lidar Guidelines—Vertical Accuracy Reporting for Lidar Data v1.0"
- 2004: first full-waveform, commercial, topographic lidar systems (Riegl LMS-Q560 and turnkey systems based on it, e.g. by IGI)
- 2006 – present: LAS v1.3 (2010); >6 commercial topo lidar manufacturers (Optech, Leica, Riegl, AHAB, Trimble (formerly TopoSys), IGI, others), multi-pulse, FW commercial systems, lots of COTS software, statewide collects becoming more prevalent, …

Brief History of Bathy Lidar

- 1977: Atmospheric Oceanographic Lidar (AOL)
  - Joint NASA, NOAA project
- 1984: LARSEN-500 bathymetric lidar system (Optech, Terra Surveys Ltd., Canadian Hydrographic Service)
  - First operational hydrographic system
- 1986-1989: Development of Australian WRELADS and LADS, and Swedish FLASH systems; USACE begins SHOALS program
- 1990s: LADS (now owned by Fugro), SHOALS (Optech), and HawkEye (now AHAB) operational
- 2000s – present: LADS Mk 2 and 3, SHOALS 3000, HawkEye II, EAARL all operational; CZMIL and EAARL+ development nearly complete

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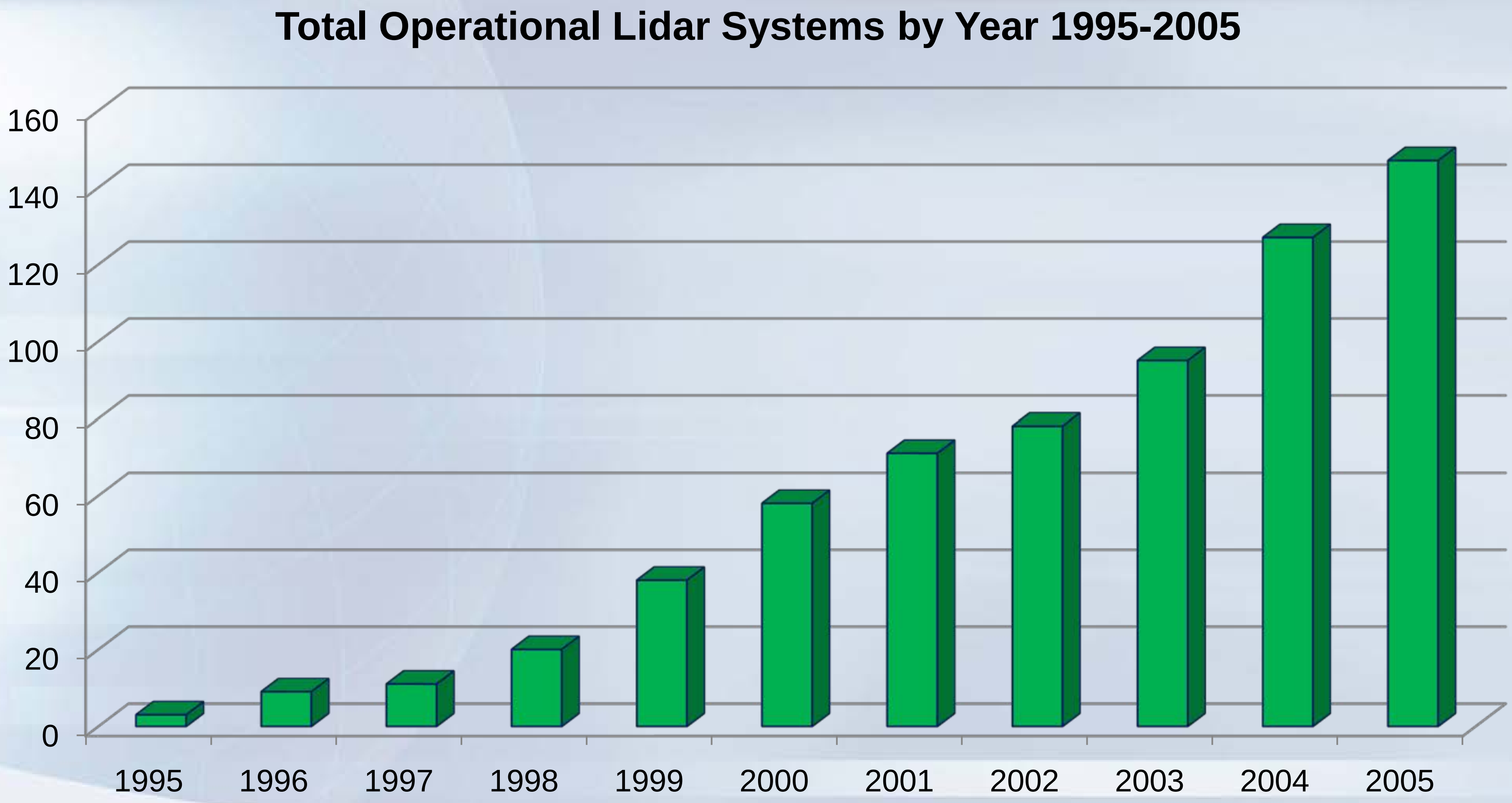
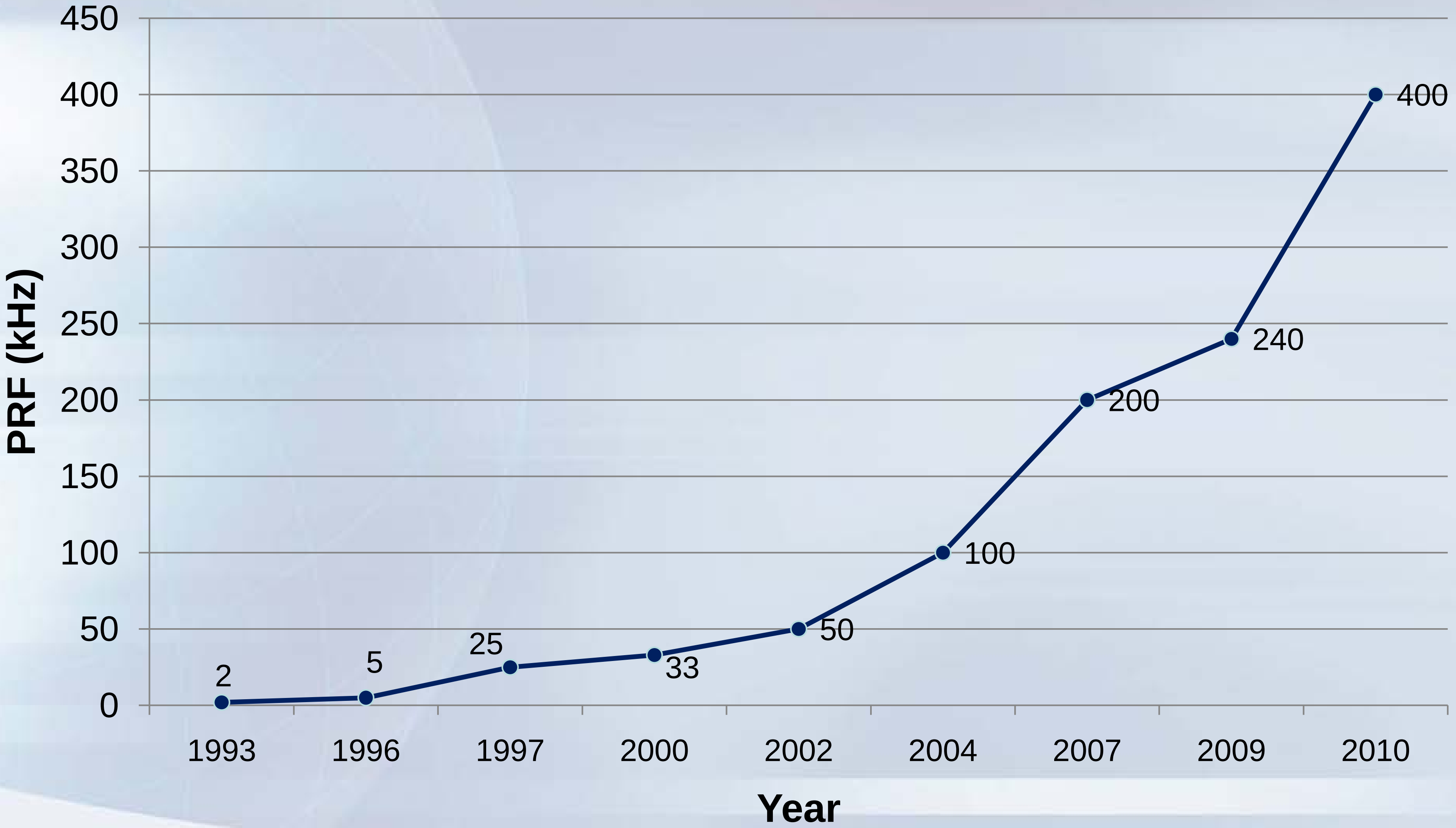
Growth in commercial use of topographic lidar systems: 1995 to 2005



Adapted from data in Fowler et al., 2007. *Topographic and Terrestrial Lidar, in Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Ed., Maune (Ed), American Society for Photogrammetry and Remote Sensing, Bethesda, MD.

Increase in PRF for Commercial Airborne Topographic Lidar Systems: 1993-2010



Compiled from a variety of sources, including Fowler et al., 2007; Lemmens, 2007; and Lemmens, 2009 (*GIM International* Product Survey).

GIM International Market Studies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Product Survey

Product Survey > Airborne Lidar Sensors, February 2009

Airborne Lidar Sensors, February 2009

By dr ir Mathias Lemmens, contributing editor

This is our third product review on airborne Lidar sensors. The second was published in February 2007 and the first under the title 'Airborne Laser-scanners' in May 2004.

Airborne Lidar has matured to an accurate technology for the highly automated capturing of terrain data through xyz point clouds. "Mature" means that improvements are no longer founded on major technological breakthroughs, but are incremental. Lately the steps comprise full waveform digitisation, multiple pulses in air, and increased accuracy resulting from enhanced GNSS positioning and INS attitude determination.

Manufacturers are coming from two opposite directions: system building versus service provision. System builders include Leica Geosystems and Optech Inc., but most conspicuous is Riegl. Until late 2006, the latter was a manufacturer for manufacturers only, offering 'laser sensors for airborne applications but not complete airborne Lidar systems,' as our 2004 survey notes to explain the many N/As in the columns. But in the 2007 survey, Riegl presented its full-fledged systems LMS-S560 and LMS-Q560. On the service provision side is Fugro, listed in the 2007 survey. Like TopEye and Terrapoint, Fugro developed its own in-house system, Flimap. The system has been regular and is

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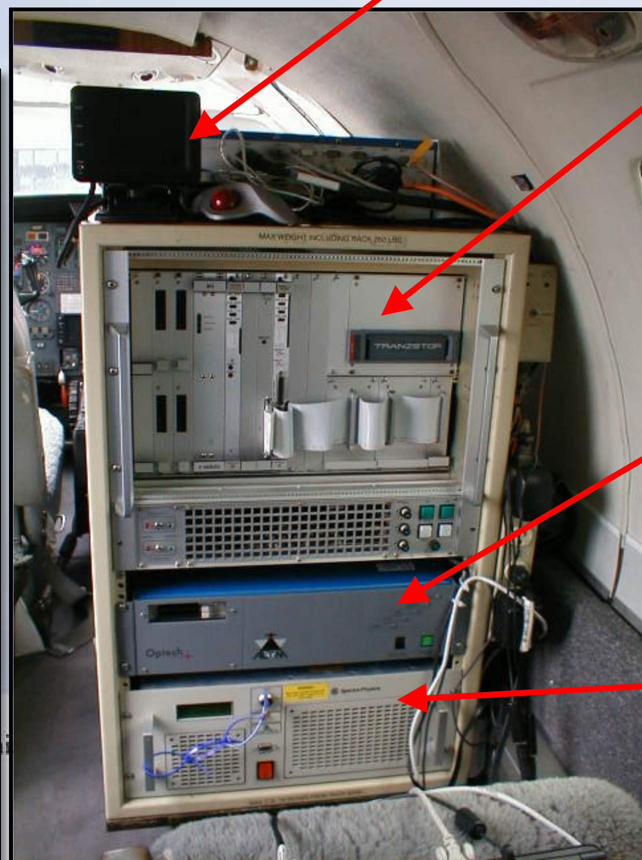
Lidar System Subcomponents

- IMU
- Laser
- Scan Mechanism
- Optics
- Receiver



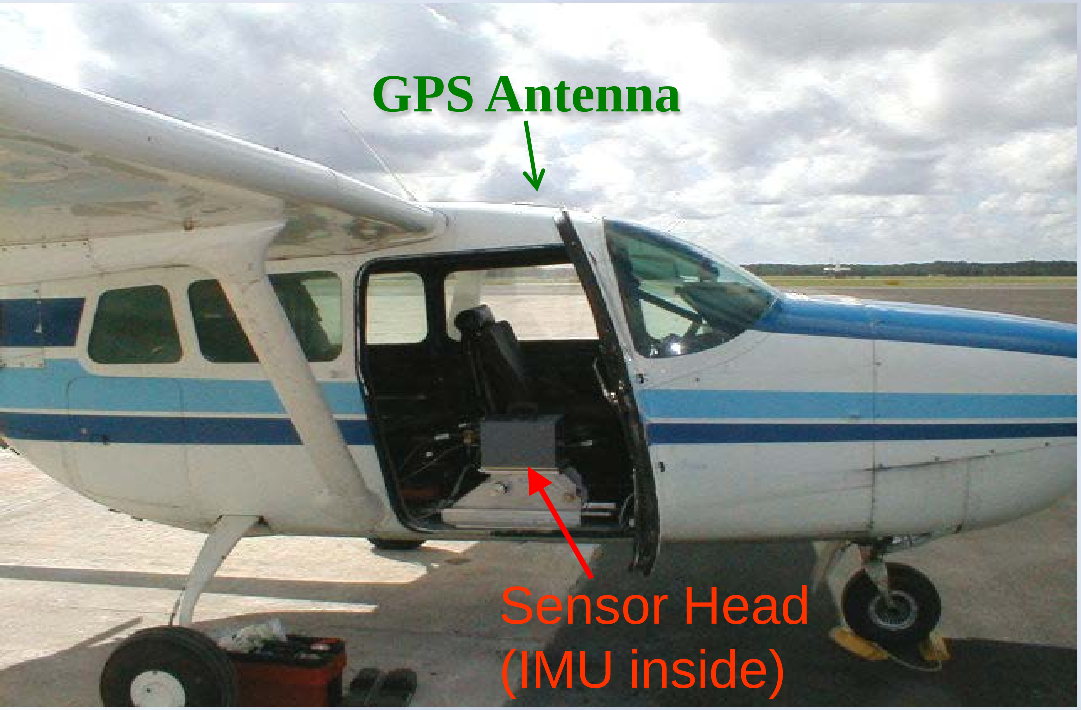
Down-look monitor
- Fish-eye lens
- Video camera

VME
- Removable hard drive
- Computer
- Electronics
- Power supplies

Position and Orientation System (POS)

Laser power supply

GPS

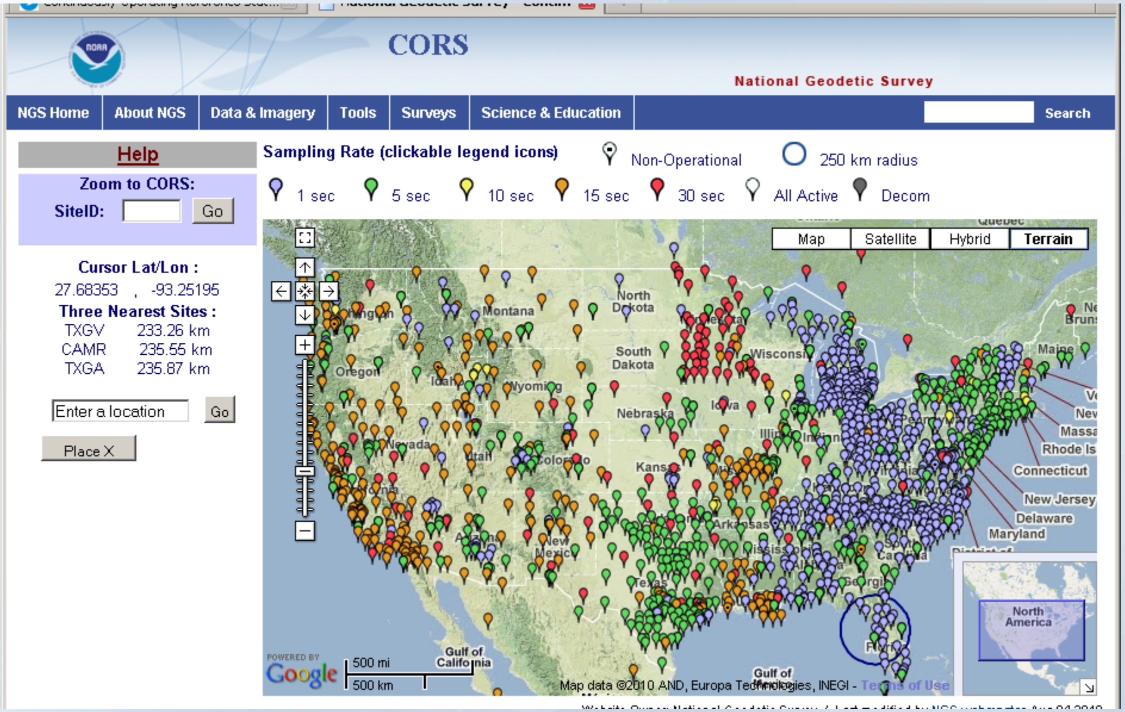


GPS Receiver is in here

Dedicated
Base Station

GPS Base Stations – Methods of tying to NSRS

Use of CORS in lieu of dedicated base stations for post processing airborne GPS



Operating distances affect data quality

Dedicated GPS Base Station with OPUS coordinates

Base station set up over mark with known (published)—*caution advised!*

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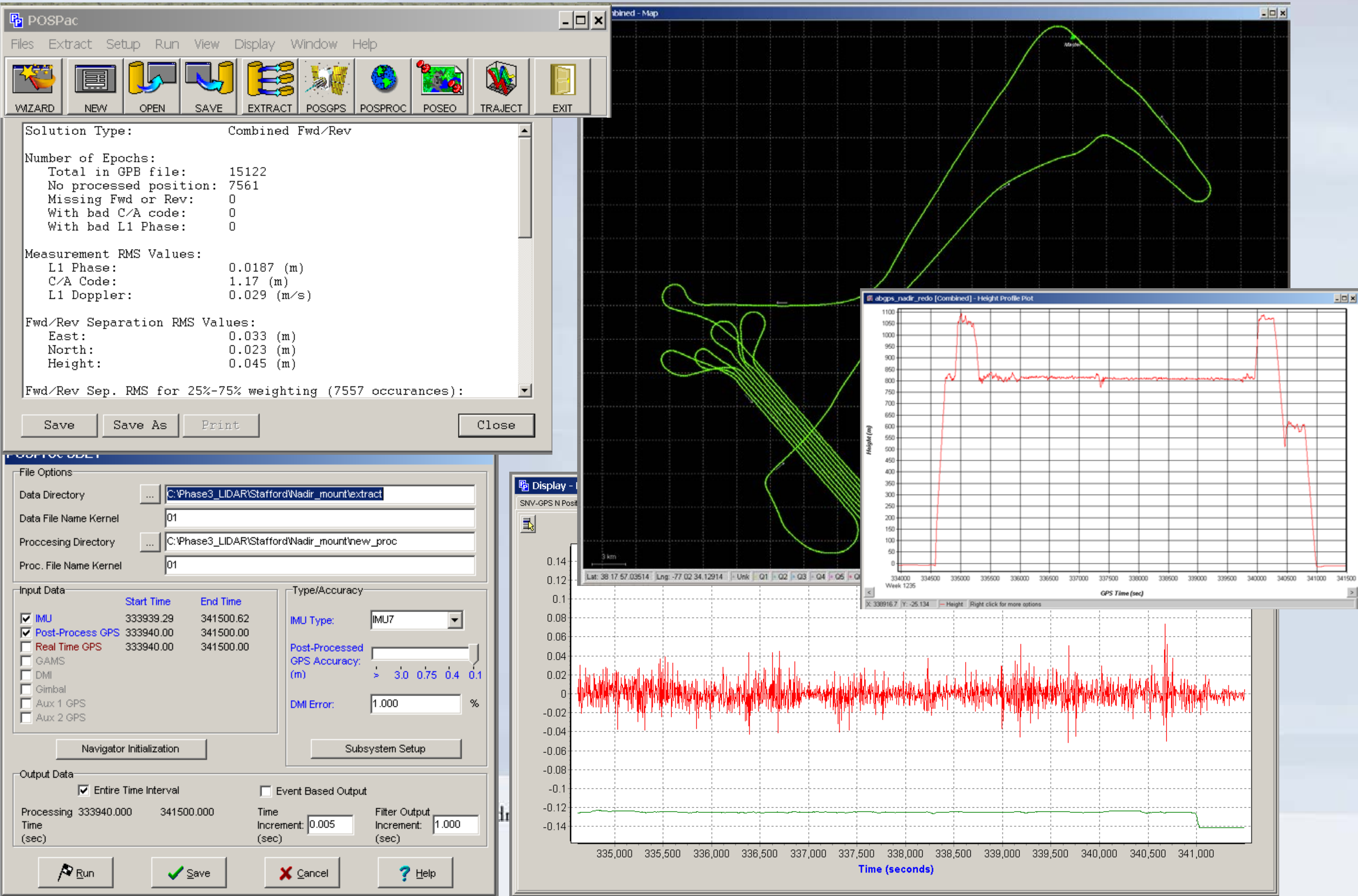
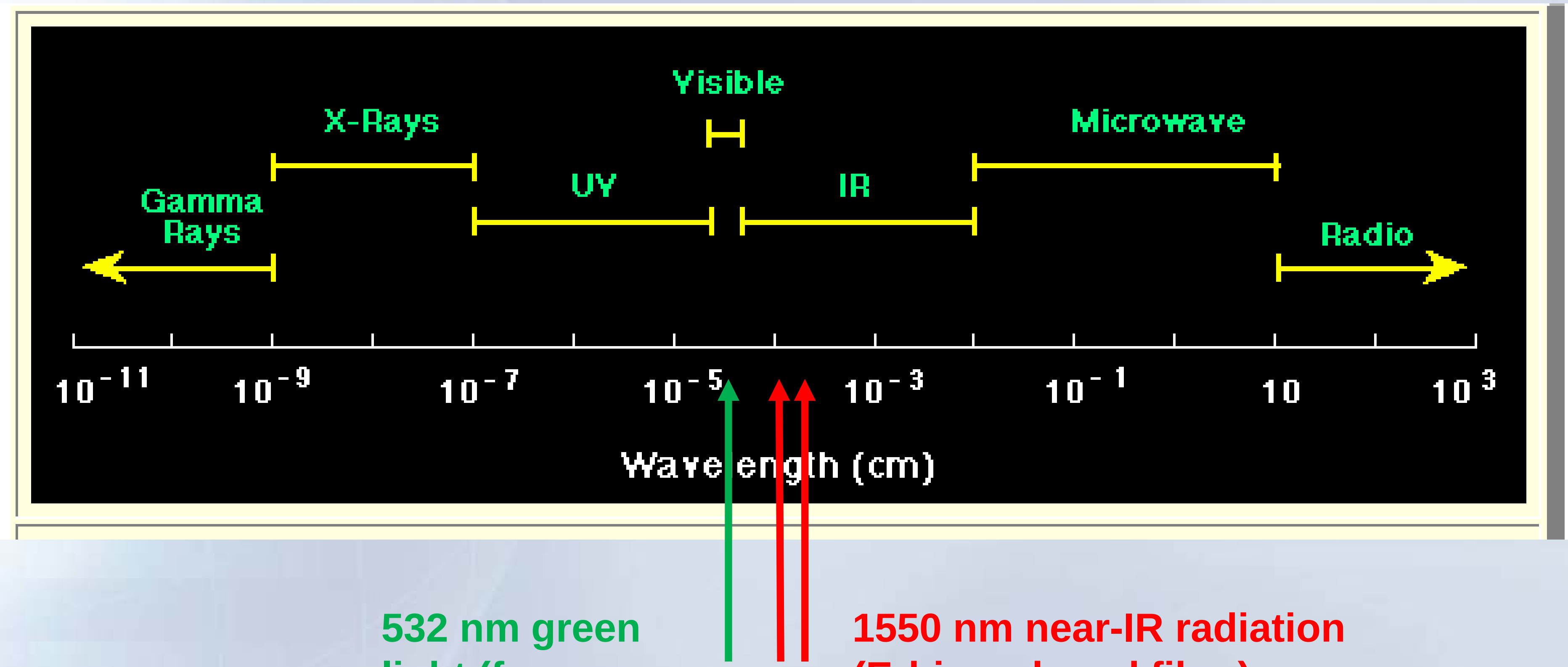
GPS/IMU Post-Processing



Common Airborne Topographic & Bathymetric Lidar Wavelengths: Where they fall in the EM spectrum



532 nm green light (frequency-doubled Nd:YAG)

1550 nm near-IR radiation (Erbium-doped fiber)

1064 nm near-IR radiation (Nd:YAG)

<u>Scanner</u>: used to produce a swath on the ground

Scanning animation from Wikipedia Lidar article:

http://en.wikipedia.org/wiki/Lidar

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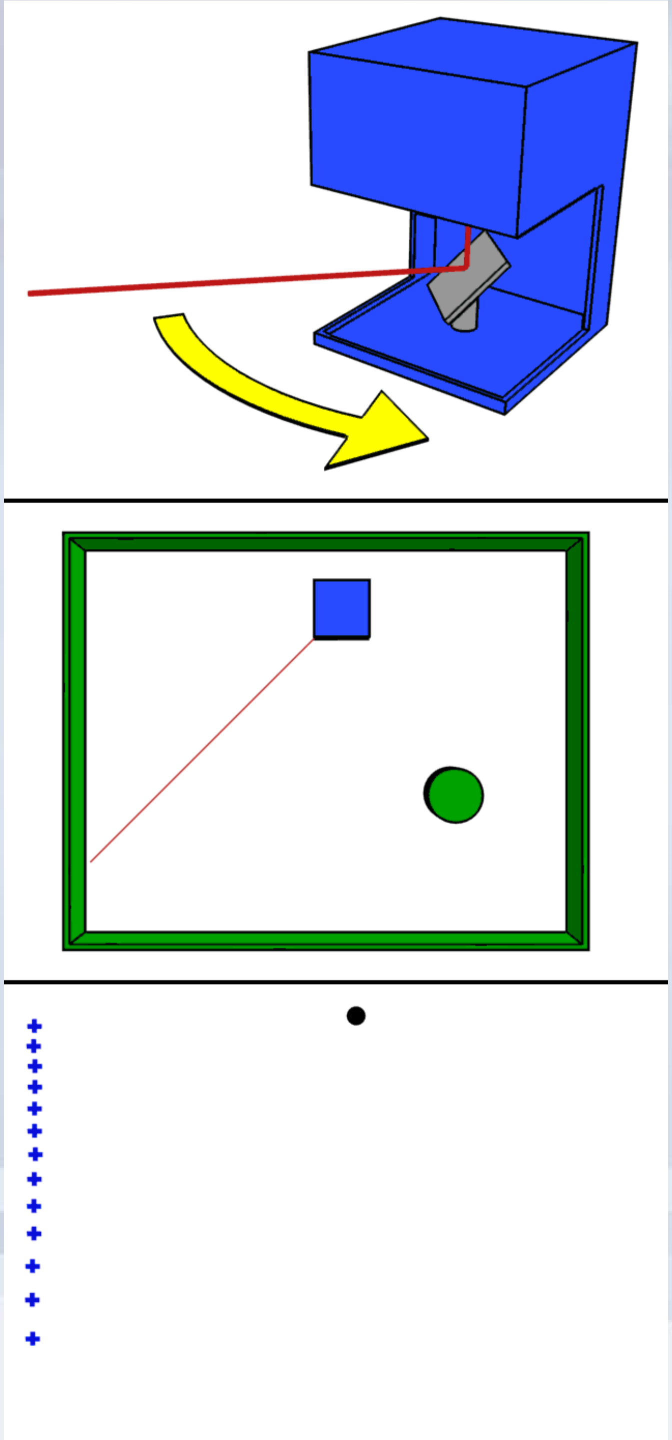
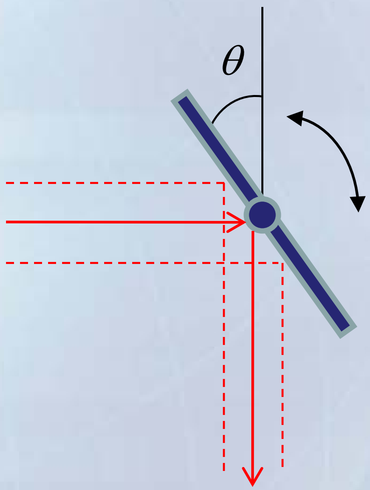
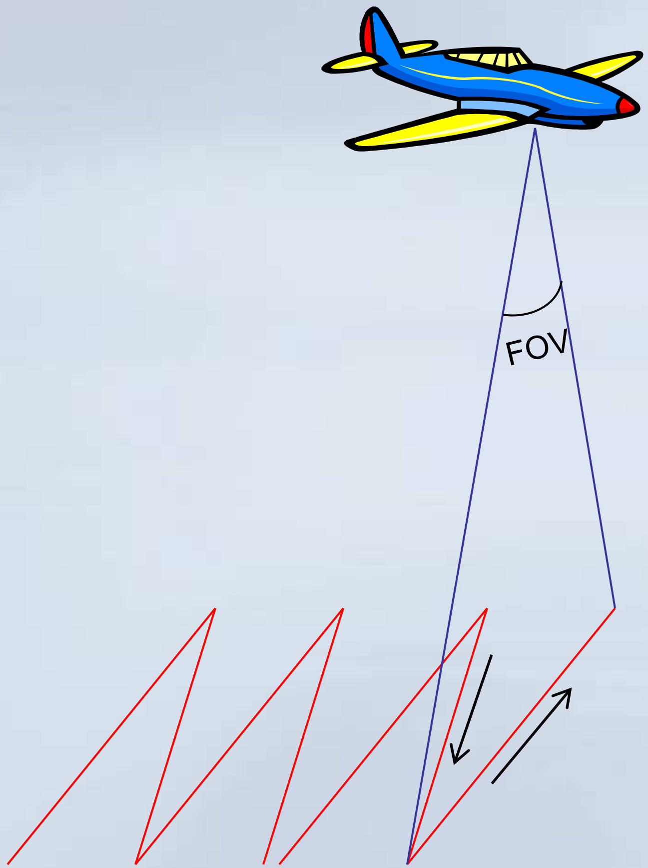


Different scan mechanisms => different scan patterns on ground

Oscillating scan mirror



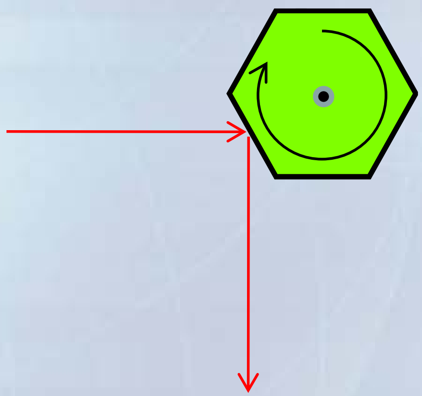


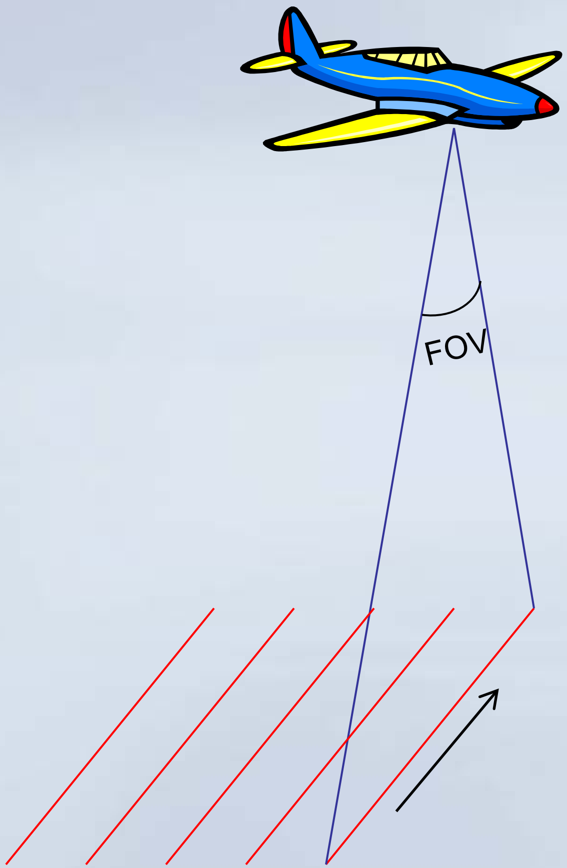
Zig-zag (or "sawtooth") scan pattern

Adapted from: Wehr, A. and U. Lohr, 1999. Airborne laser scanning—an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing,* 54 69, 8-82; and Manue, D., 2007. *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Ed., American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland.

Different scan mechanisms => different scan patterns on ground

Rotating polygon





Line scan pattern (parallel lines)

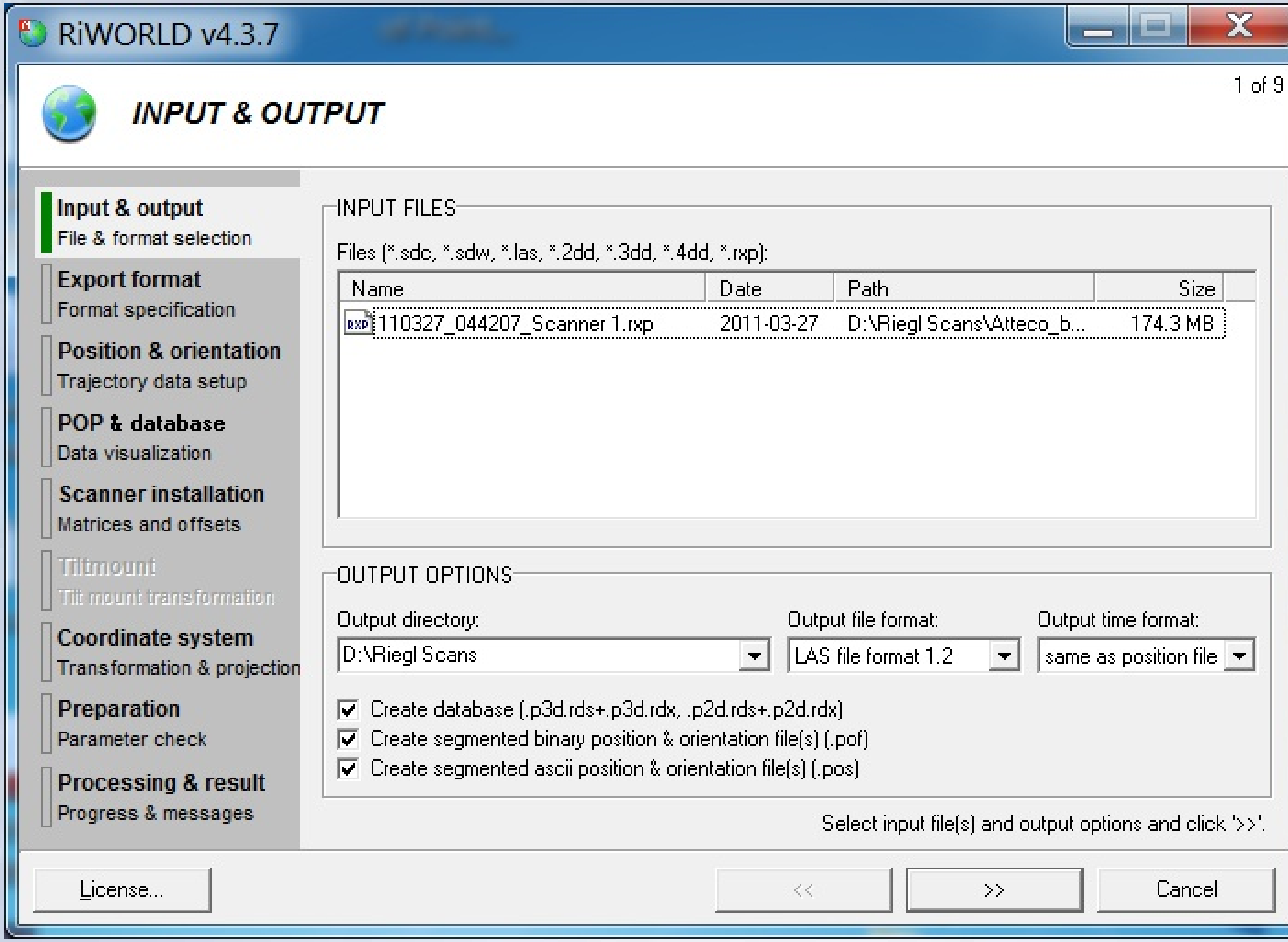
Adapted from: Wehr, A. and U. Lohr, 1999. Airborne laser scanning—an introduction and overview. *ISPRS Journal of Photogrammetry and Remote Sensing,* 54 69, 8-82; and Manue, D., 2007. *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Ed., American Society for Photogrammetry and Remote Sensing, Bethesda, Maryland.

Laser Point Processing

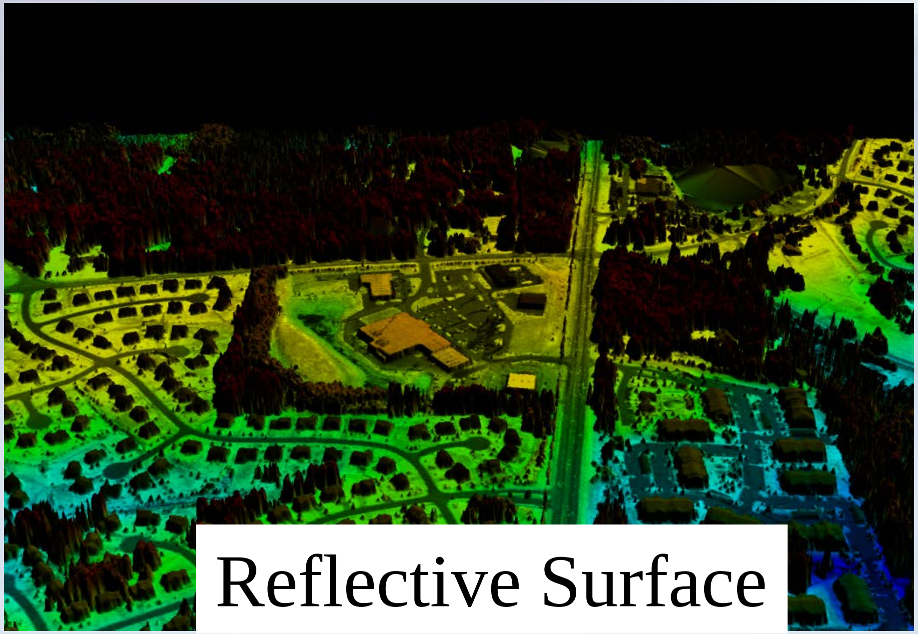
Manufacturer's software combines:

- Laser ranges
- Scan angles
- Post-processed GPS/IMU data
- Calibration parameters

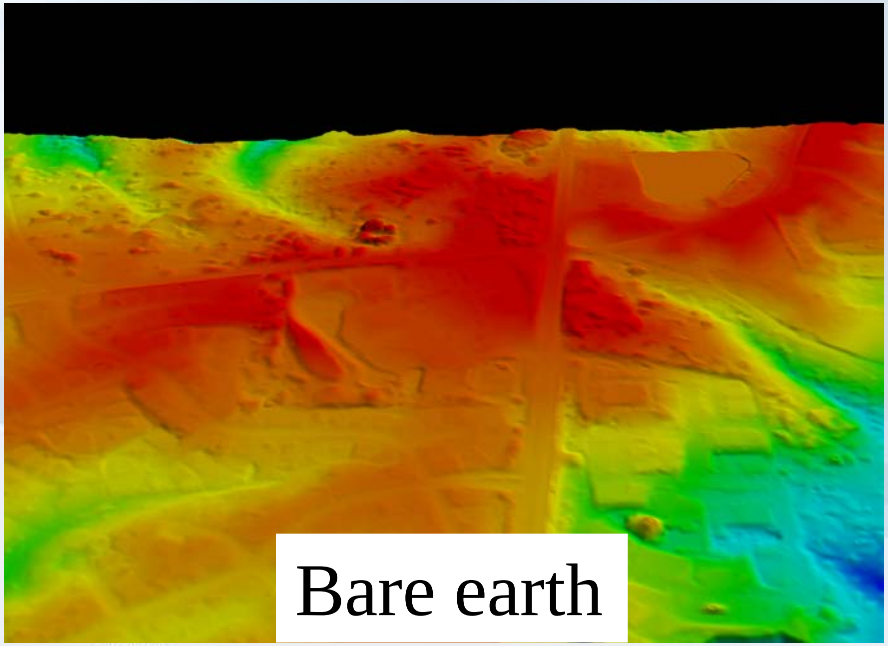
to create and output georeferenced point clouds



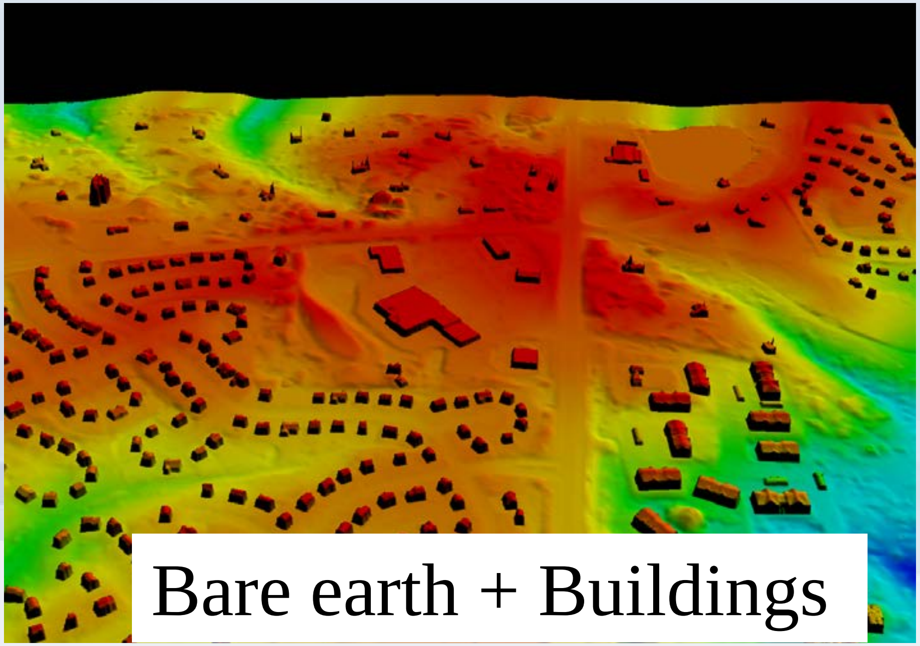
Filtering/ Classification



Reflective Surface



Bare earth



Bare earth + Buildings

Calibration of Lidar Systems

- Purpose:
  - Correct for any systematic errors
  - Enable achieved accuracy to meet theoretically-expected accuracy
  - Verify that subcomponents are working within specs
- *Note: After poor GPS, poor calibration is the #1 culprit in lidar data sets that fail to meet expected accuracies!*

Types of Calibration

- System calibration
  - Factory Calibration
    - Start with (proprietary) sensor and error models and compute geometric calibration parameters in controlled lab environment
  - In-situ calibration (boresight and lever arm determination)
- Data calibration
  - Intensity calibration (if desired)

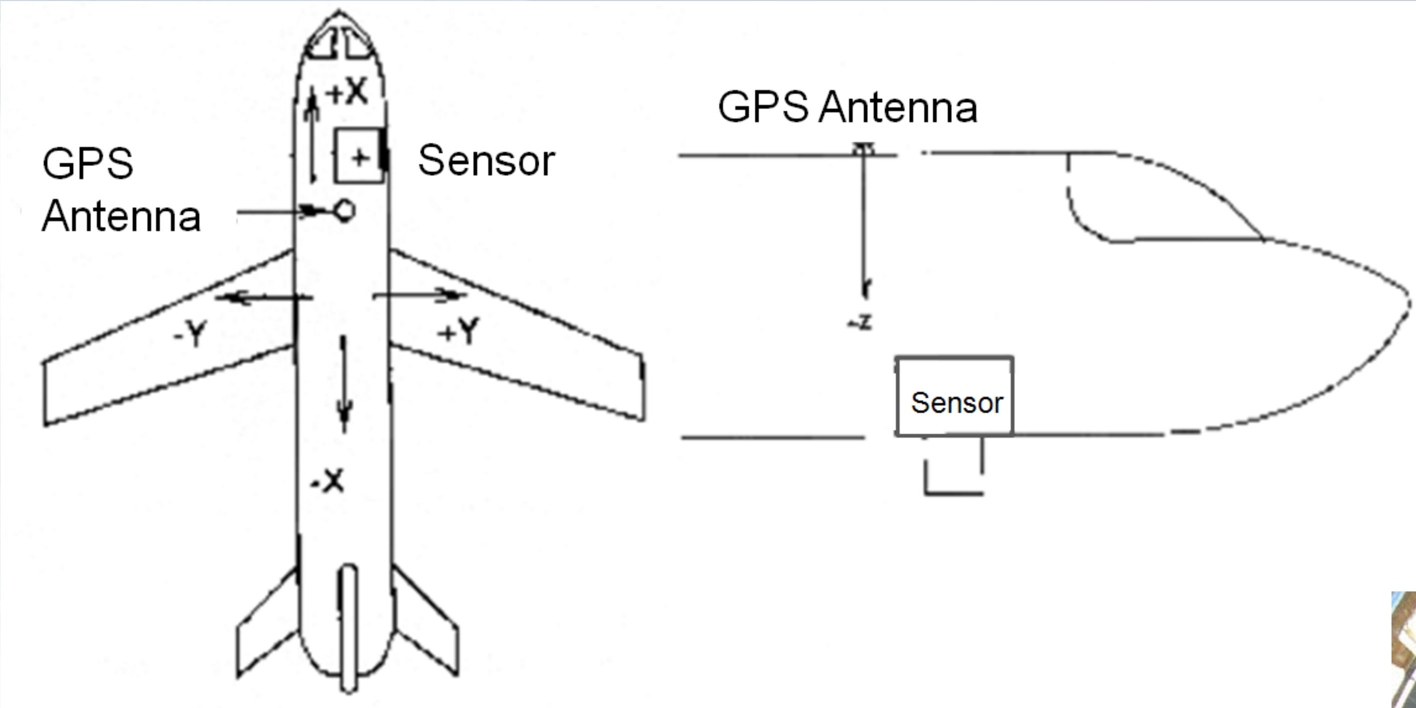
Factory Calibration

- Geometric Calibration
  - Range calibration
    - Determine range offsets (e.g., “range walk” look-up table)
  - Scanner Calibration
    - Verify that scanner passes accuracy and repeatability criteria
    - Provide scanner offset and scale calibration values
  - IMU-Laser Alignment
    - Determine misalignment angles
  - Determine other geometric calibration parameters in (typically proprietary) sensor model

Factory Calibration

- Radiometric Calibration (sensor response)
  - Ensure that the output of the laser meets specifications for pulse energy, pulse width, rise time, frequency, and beam divergence
  - Measure receiver response from a reference target to ensure that response level is within specification
  - Check alignment between transmitter and receiver
  - Measure T_x (transmit) response

In situ calibration: Lever Arm Measurements



In-Situ Calibration

- Determine corrections to pitch, roll, heading, scan angle, and (possibly) other calibration parameters
- Performed by flying over calibration site that has been accurately surveyed using GPS
  - Calibration site may contain a large, flat-roofed building and runway, taxiway or parking lot surveyed with GPS
- Should be performed every time system is re-installed <u>and</u> at regular intervals

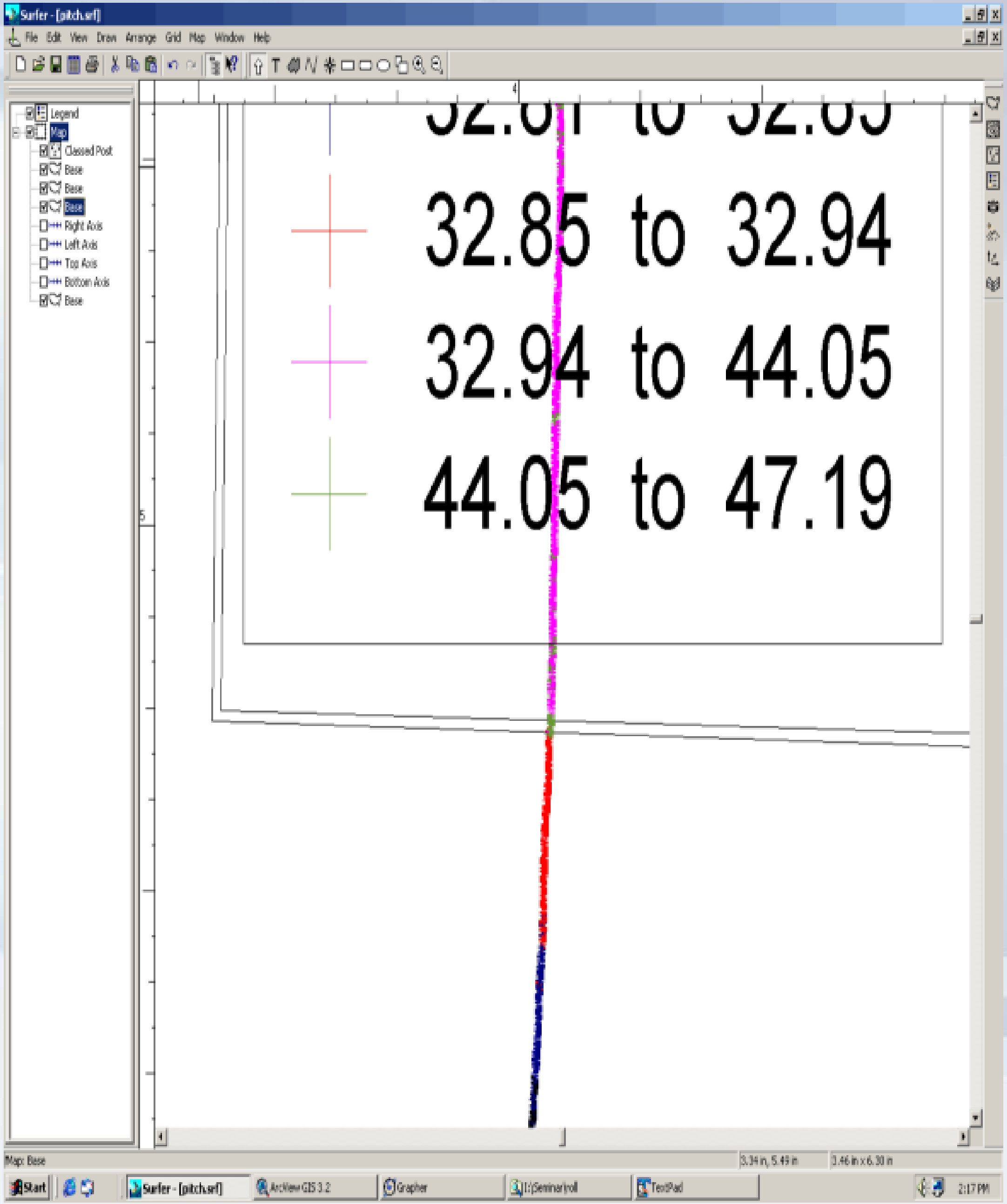
Rigorous Approach to In Situ Calibration:

- Rigorous error model: physical understanding of each source of error => parameterize each
  - Acquire data over calibration site; identify common features (surface patches, cultural features) in overlapping swaths
  - Solve optimization problem to output statistically-optimal (based on some defined optimality criterion) values of the calibration parameters (e.g., laser beam orientation point offsets, roll, pitch, heading offsets, range offset, scan angle offset and scale factor, and, possibly, higher order polynomial coefficients) that provide “best fit” of data (or extracted features) to control and data in overlapping swaths to one another
    - Note: specific set of calibration parameters is system-dependent and identified through sensor modeling process

Manual (Trial and Error) Approach to Sensor Modeling:

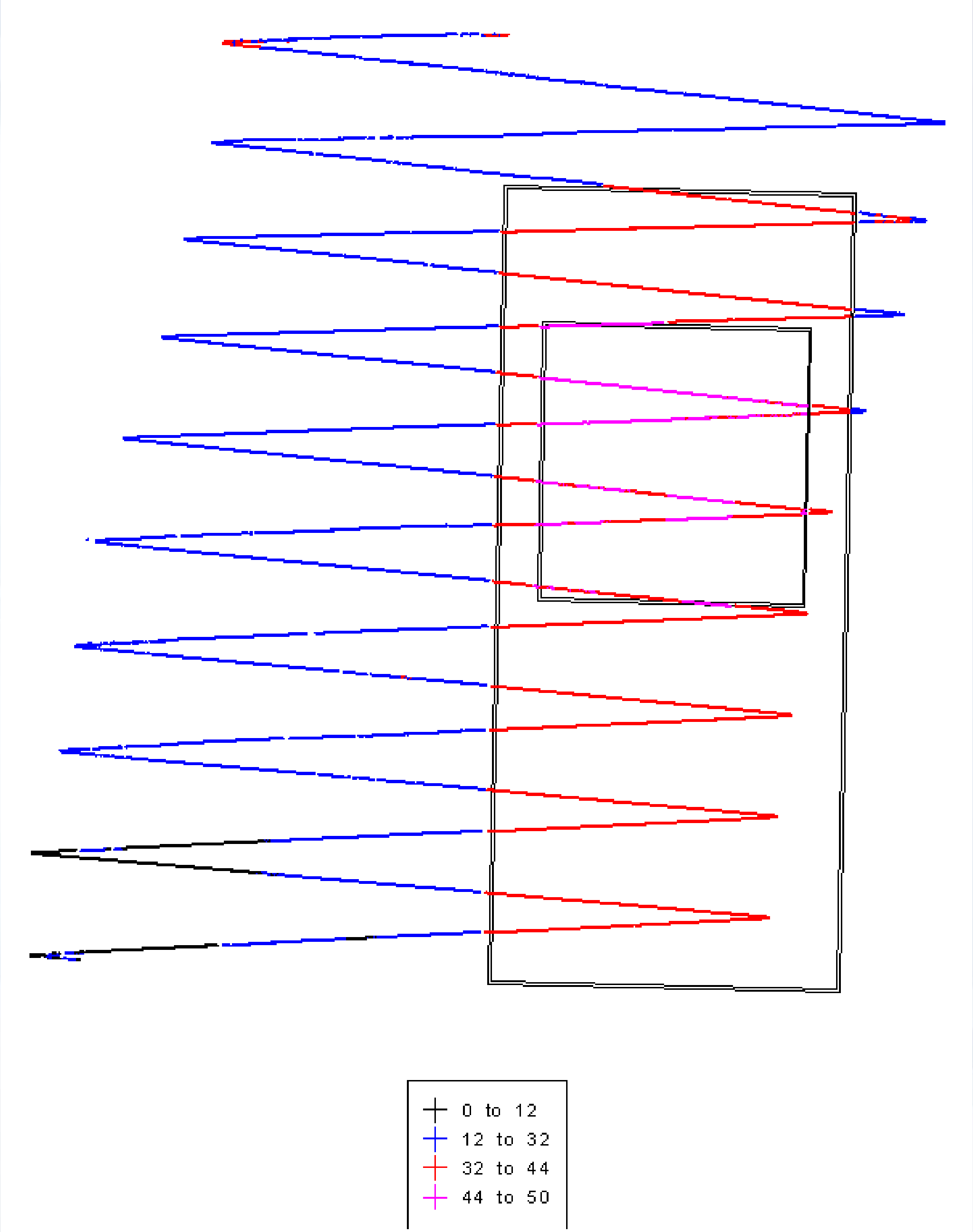
- Identify “signatures” of certain types of systematic errors in point clouds
  - E.g., scanner scale error could cause “smile” or “frown” in cross-track profile of area known to be flat
  - Pitch error could cause building edges to be displaced in along-track direction
  - Roll error could cause building edges to be displaced in across-track direction
- Look for these types of effects in your data
- Manually adjust calibration parameters, reprocess, and see if effect is reduced or eliminated
- Iterate until satisfied

Pitch Bias Determination



- Fly over a field-surveyed building in "profile mode" (scan angle = 0)
- Superimpose lidar points—color coded by elevation–on plot of surveyed building edges
- A pitch bias will be manifest as an offset between the field-surveyed building edges and lidar elevation transition points

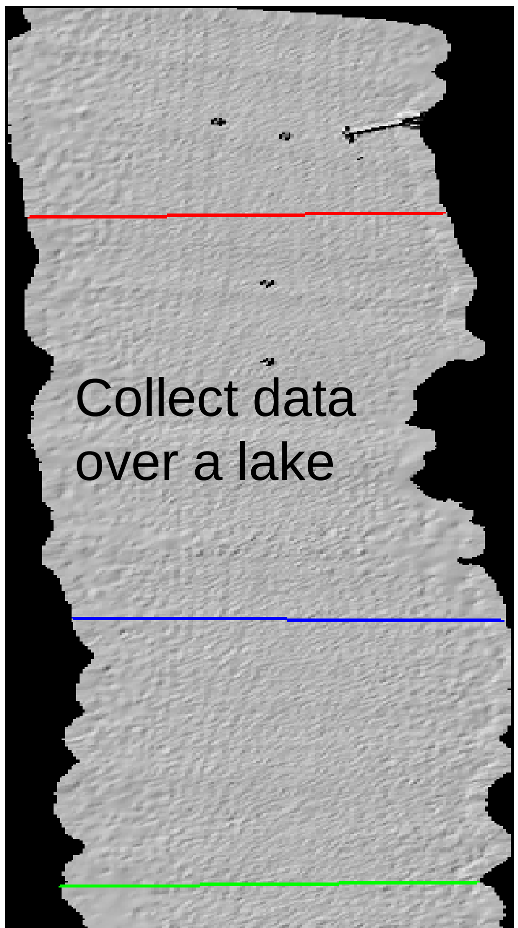
Roll Bias Determination



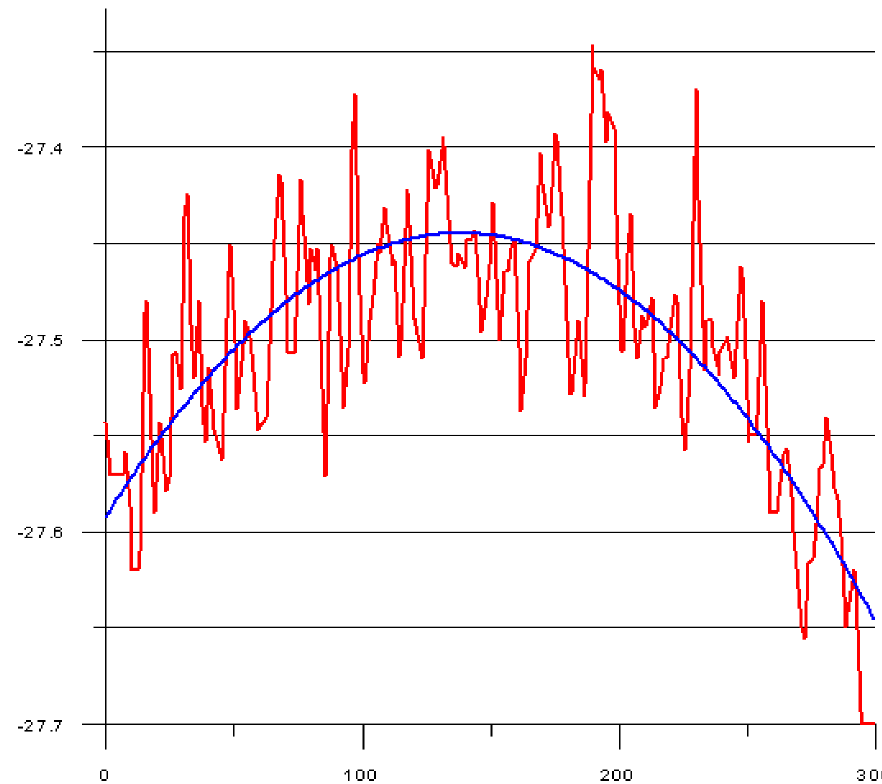
- Fly the field-surveyed building using a narrow scan angle: ~5°
- Again, superimpose lidar points—color coded by elevation–on plot of surveyed building edges
- Roll bias will be manifest by poor correspondence between field-surveyed and lidar-depicted roof/wall transition points

Scale Bias Determination

- Fly over a water body, such as a lake
- When the scanner mirror angles are under-reported, a profile will show a “frown
- When the angles are over-reported, the profile will show a “smile”



A frown in a profile from the water points indicates scanner mirror angles are being under-reported



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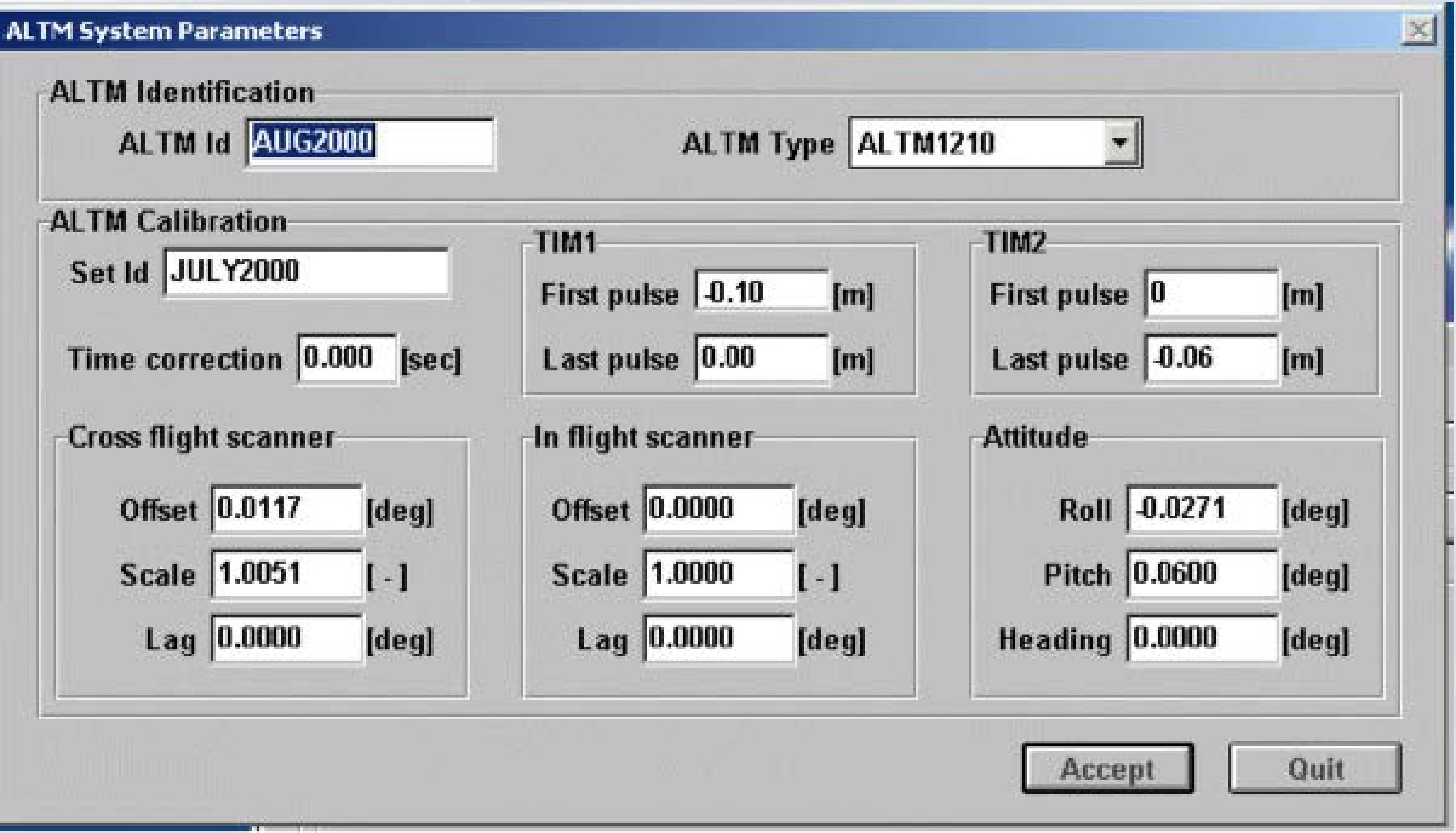
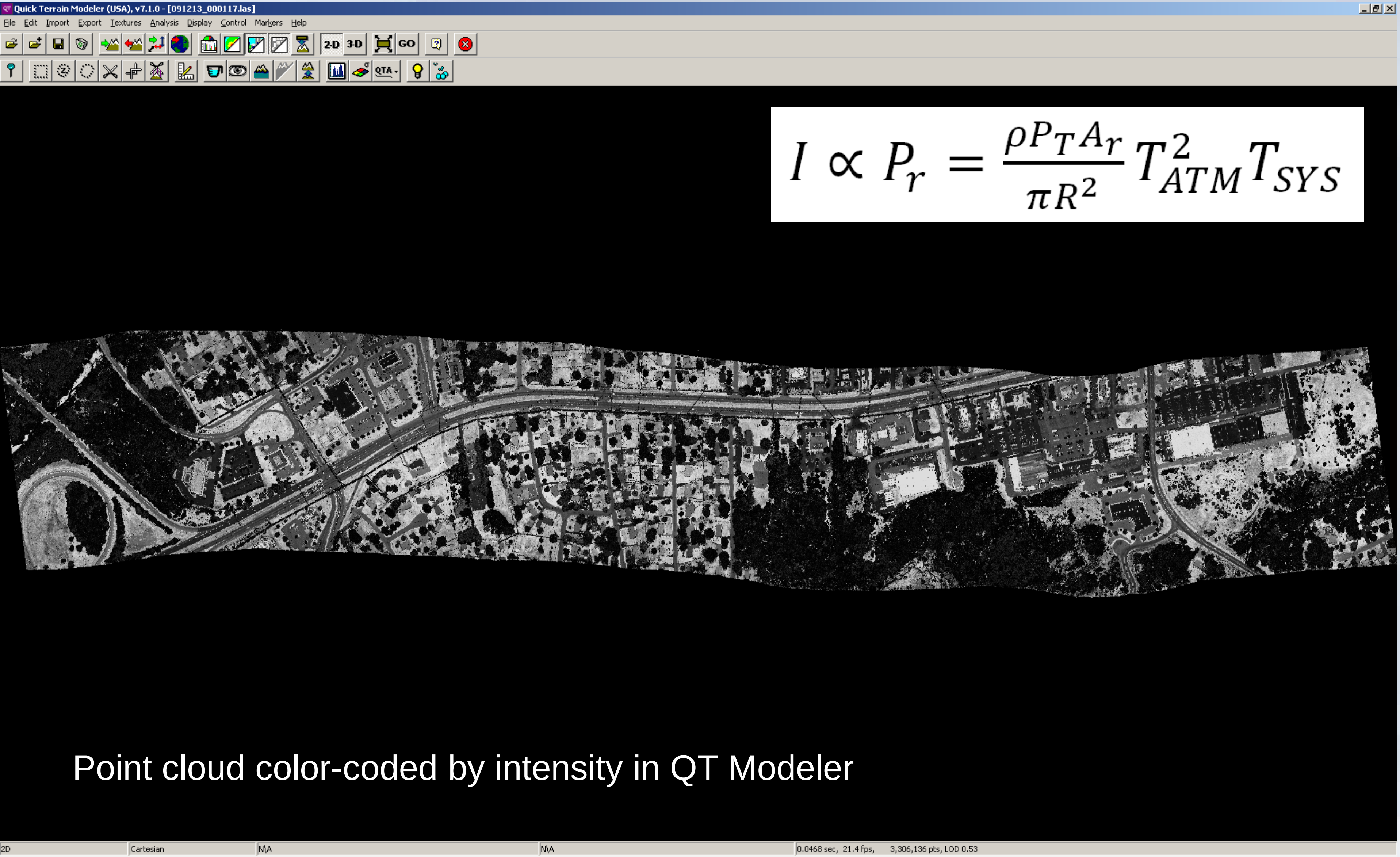
Entering Pitch, Role, Scale Calibration Parameters:



Radiometric Calibration:



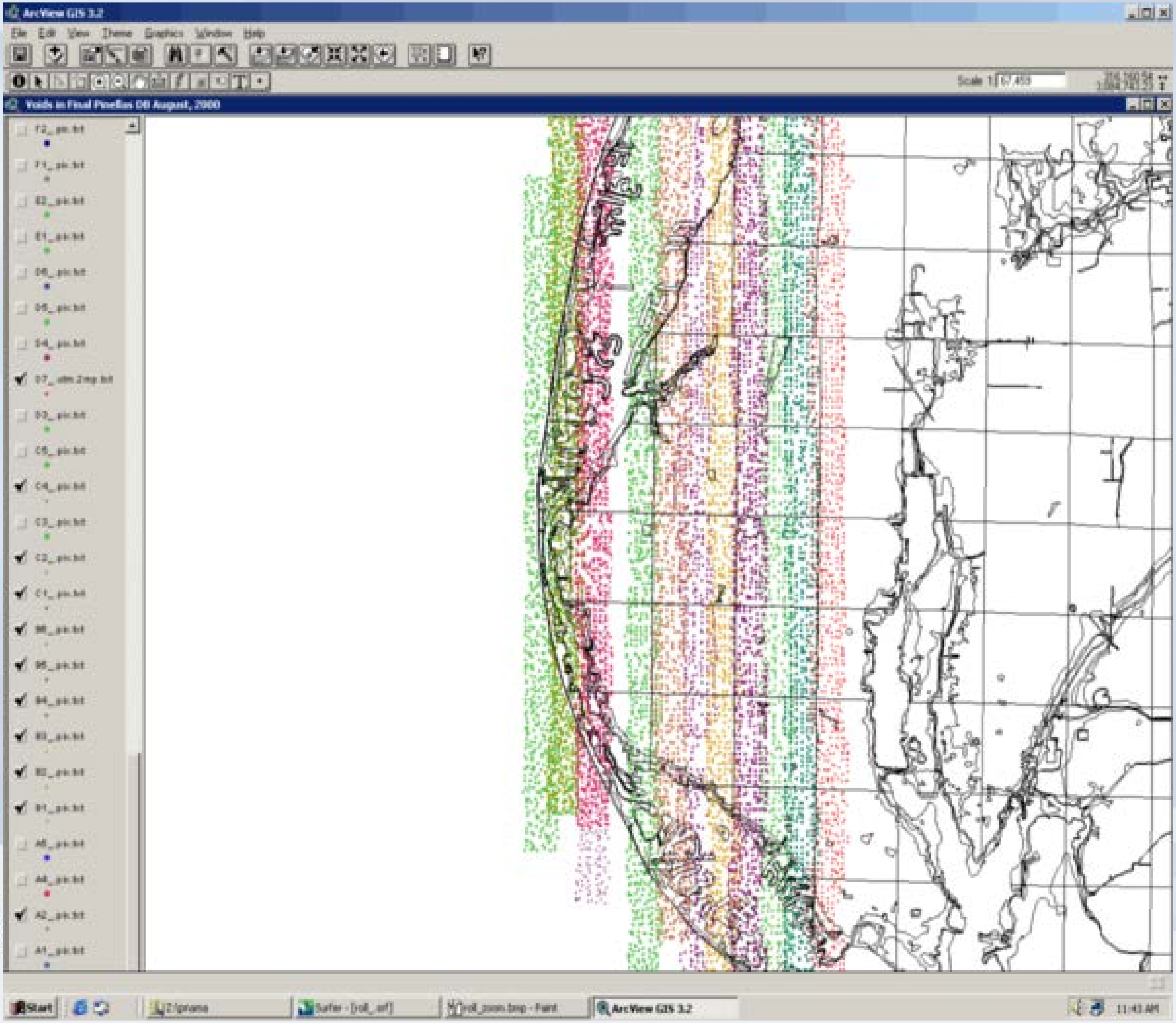
$$I \propto P_r = \frac{\rho P_T A_r}{\pi R^2} T_{ATM}^2 T_{SYS}$$

Point cloud color-coded by intensity in QT Modeler

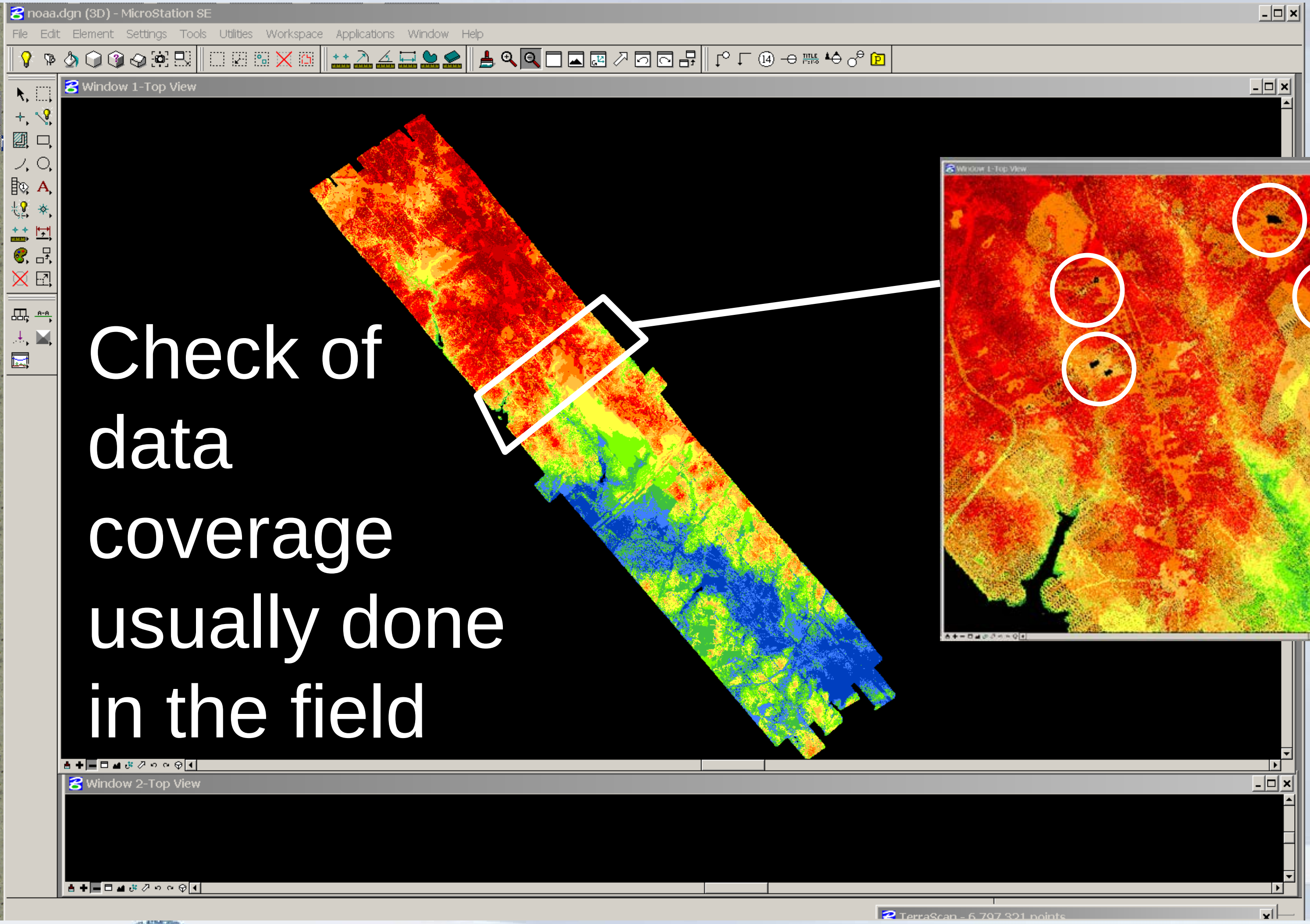
QA/QC & Accuracy Assessment

- Verify coverage
- Compare elevations in strip overlap areas
- Use check points (an independent data set of higher accuracy) to test the accuracy of the lidar data
  - Follow ASPRS Guidelines: Vertical Accuracy Reporting for Lidar Data

Check Coverage



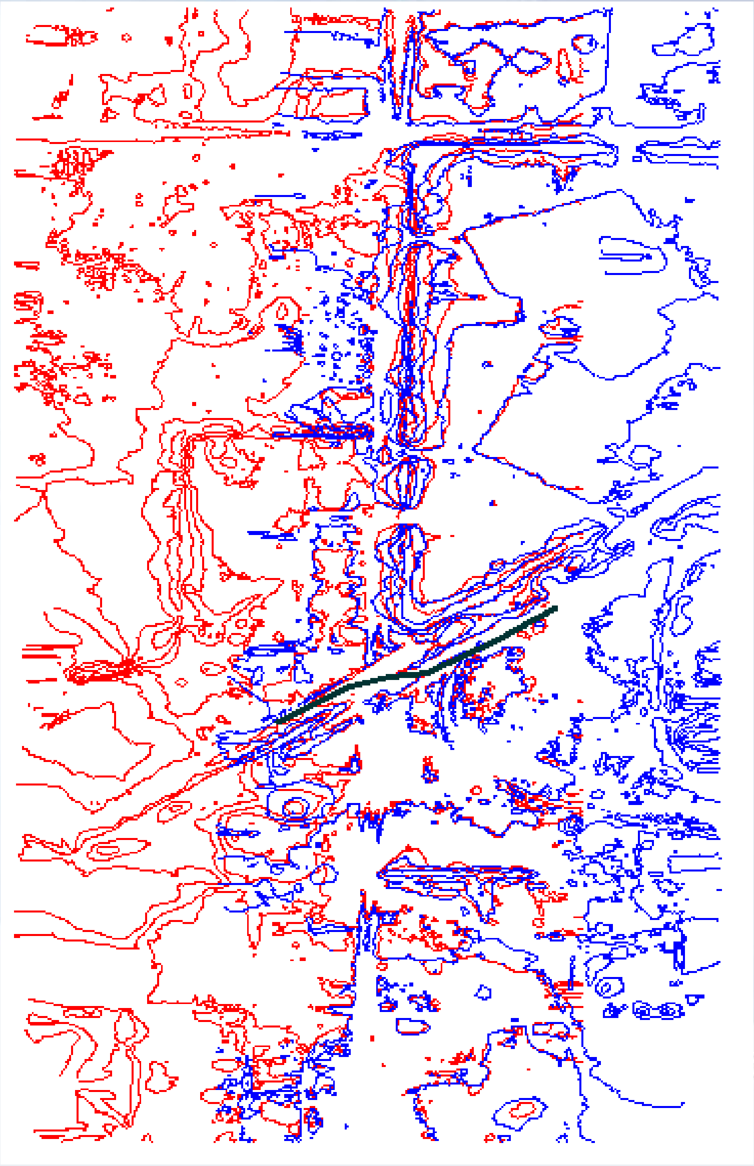
Data QC

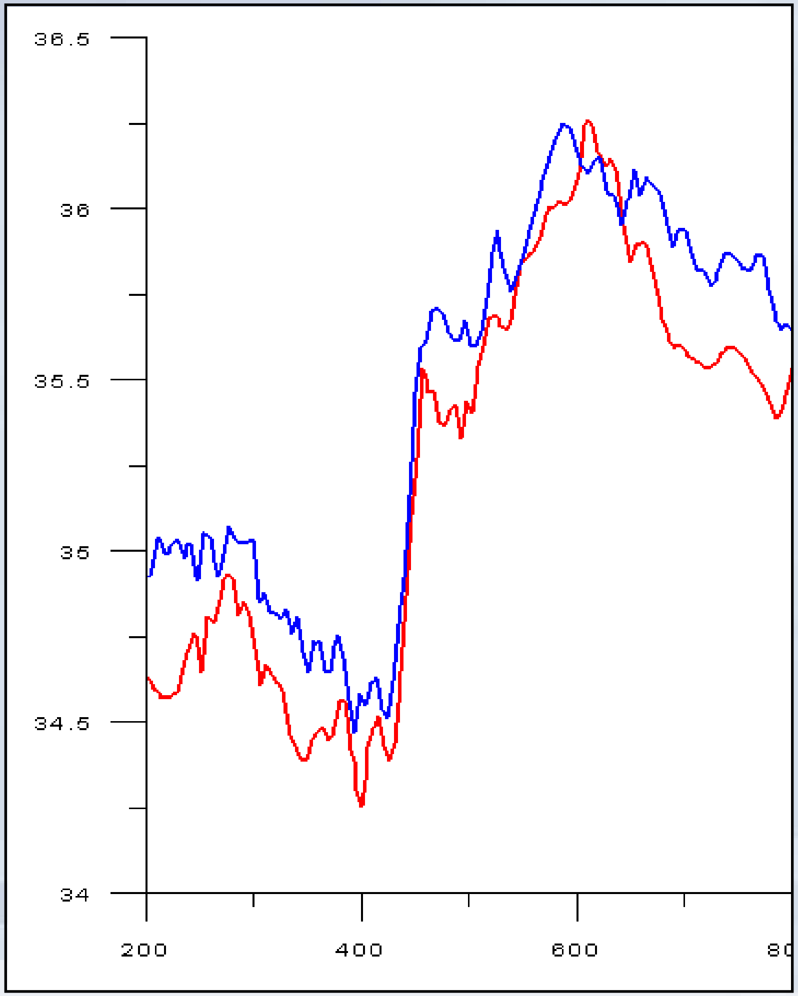


Check of data coverage usually done in the field

Examine data voids

Analyze Strip Overlap Area





Accuracy Assessment

- ASPRS Guidelines - Vertical Accuracy Reporting for Lidar Data
  - The lidar dataset's required fundamental vertical accuracy, which is the vertical accuracy in open terrain tested to 95% confidence, shall be specified, tested and reported
  - If information is required on the vertical accuracy achieved within other ground cover categories outside open terrain, then supplemental vertical accuracies shall be specified, tested and reported for each land cover class of interest

ASPRS Guidelines (cont'd)

- *Following NSSDA*: vertical accuracy should be reported at the 95% confidence level for data tested by an independent source of higher accuracy
- Checkpoints should be well distributed throughout the dataset
  - Checkpoints may be distributed more densely in the vicinity of important features
  - For rectangular area, checkpoints may be distributed so that points are spaced at intervals of at least 10%of the diagonal distance across the dataset and at least 20% of the points are located in each quadrant of the dataset

ASPRS Guidelines (cont’d)

- *The NSSDA states: A minimum of 20 checkpoints shall be tested, distributed to reflect the geographic area of interest*
- However, ASPRS recommends collecting a minimum of 20 checkpoints (30 preferred) in each of the major land cover categories representative of the area
- Common land cover categories are as follows:
  - Open terrain (sand, rock, dirt, plowed fields, lawns, golf courses)
  - Tall weeds and crops
  - Brush lands and low trees
  - Forested areas fully covered by trees
  - Urban areas with dense man-made structures

Example of GPS Check Point Locations for Coastal Project

$$RMSE_z = \sqrt{\frac{\sum \left(z_{datai} - z_{checki} \right)^2}{n}}$$

$$Accuracy_z = 1.96\left(RMSE_z \right)$$

Note that for error that is not normally distributed, ASPRS recommends Accuracy(z) be determined by 95th percentile testing, not by the use of above equations

Example of results of just one lidar empirical accuracy assessment study

Hodgson, M.E., and P. Bresnahan, 2004. Accuracy of Airborne Lidar-Derived Elevation: Empirical Assessment and Error Budget. *Photogrammetric Engineering and Remote Sensing*, Vol. 70, No. 3.

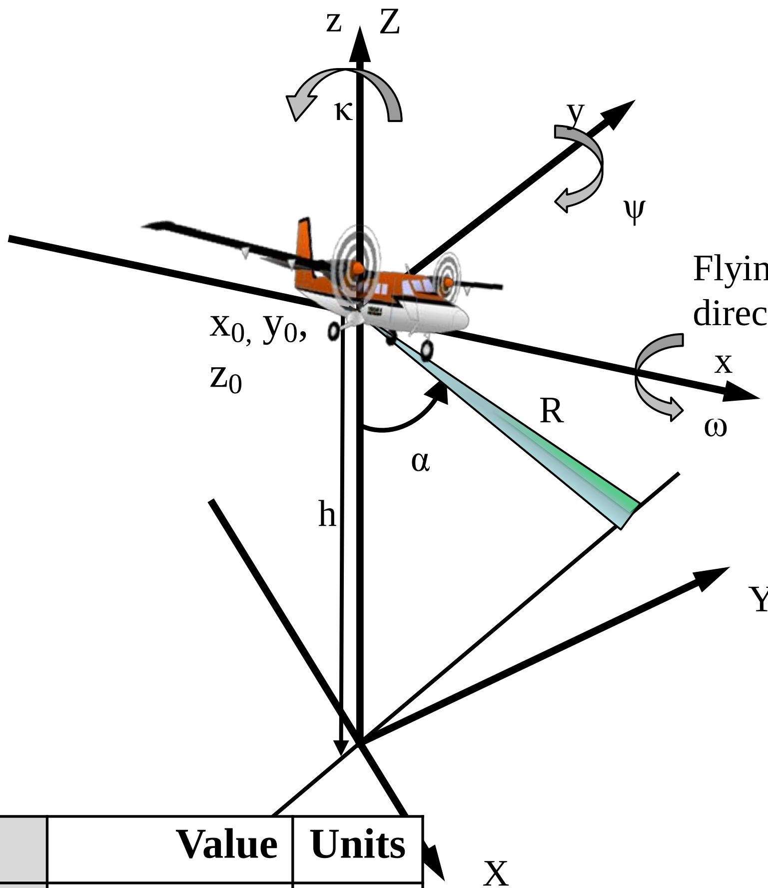
TABLE 4. OBSERVED LIDAR ELEVATION ERROR AT POINTS AND INTERPOLATION ERROR AT POINTS (ELEVATIONS IN CM)

	Cover Type					
	Pavement	Low Grass	High Grass	Brush/Low Trees	Evergreen	Deciduous
$RMSE_{Observed\ Lidar\ Pts}$	18.9	22.5	18.9	23.3	17.2	25.9
$RMSE_{Observed\ in\ TIN}$	**22.1**	**25.8**	**22.2**	**26.6**	**17.6**	**23.5**

- Informative in looking at RMSE as a function of cover type.
- “Pavement” class is probably most indicative of ASPRS “fundamental accuracy”
- Other classes (low grass, high grass, brush/low trees, etc.) => “supplemental vertical accuracies”
- To comply fully with ASPRS guidelines, would need to convert from RMSE to 95% CL values

National Oceanic and Atmospheric Administration

Another Approach: TPU modeling



Variable	Value	Units	Variable	Value	Units
(XYZ) Offsets	50	mm	Roll Measurement	0.003	deg.
Roll Offset	0.0006	deg.	Pitch Measurement	0.003	deg.
Pitch Offset	0.0006	deg.	Heading Measurement	0.004	deg.
Heading Offset	0.0012	deg.	Range Measurement	50	mm
GPS Absolute	80	mm	Angle Measurement	0.001	deg.
GPS Relative	10	mm	Refraction Angle	0.0011	deg.
			Latency Angle	0.005	deg.
			Torsion Coefficient	7.3614×10^{-5}	N/A

(All values are reported at one standard deviation)

Topics in week-long "Lidar 101" Short Course that were omitted here

- Project/flight planning
- Overview of lidar application areas:
  - Floodplain mapping, building modeling, forestry, VO detection, power line mapping, coastal geomorphology, etc.
- Full-waveform lidar principles and applications
- Bathymetric lidar
- Case study: lidar shoreline mapping with VDatum
- In-depth look at lidar system subcomponents
- Standards, specs, and best practices