INTERNATIONAL SCHOOL ON LIDAR TECHNOLOGY

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Indian Institute of Technology Kanpur, INDIA

Lecture 9: LiDAR System overview and instrument calibration

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Leica Geosystems AG

- when it has to be right

Leica Geosystems

Presentation outline

1. Hardware Components
2. System Calibration

Objectives of this workshop

Provide the participant with an overview of the various LIDAR technologies available *for purchase in the market today*

- **primarily intended as an overview of currently-marketed systems**
- **limited technical discussion of proprietary systems currently in use**

Provide the participant with insights into the LIDAR design process

Provide appreciation for how currently-available systems evolved

Highlight principles of operation and technical differences between systems currently in use

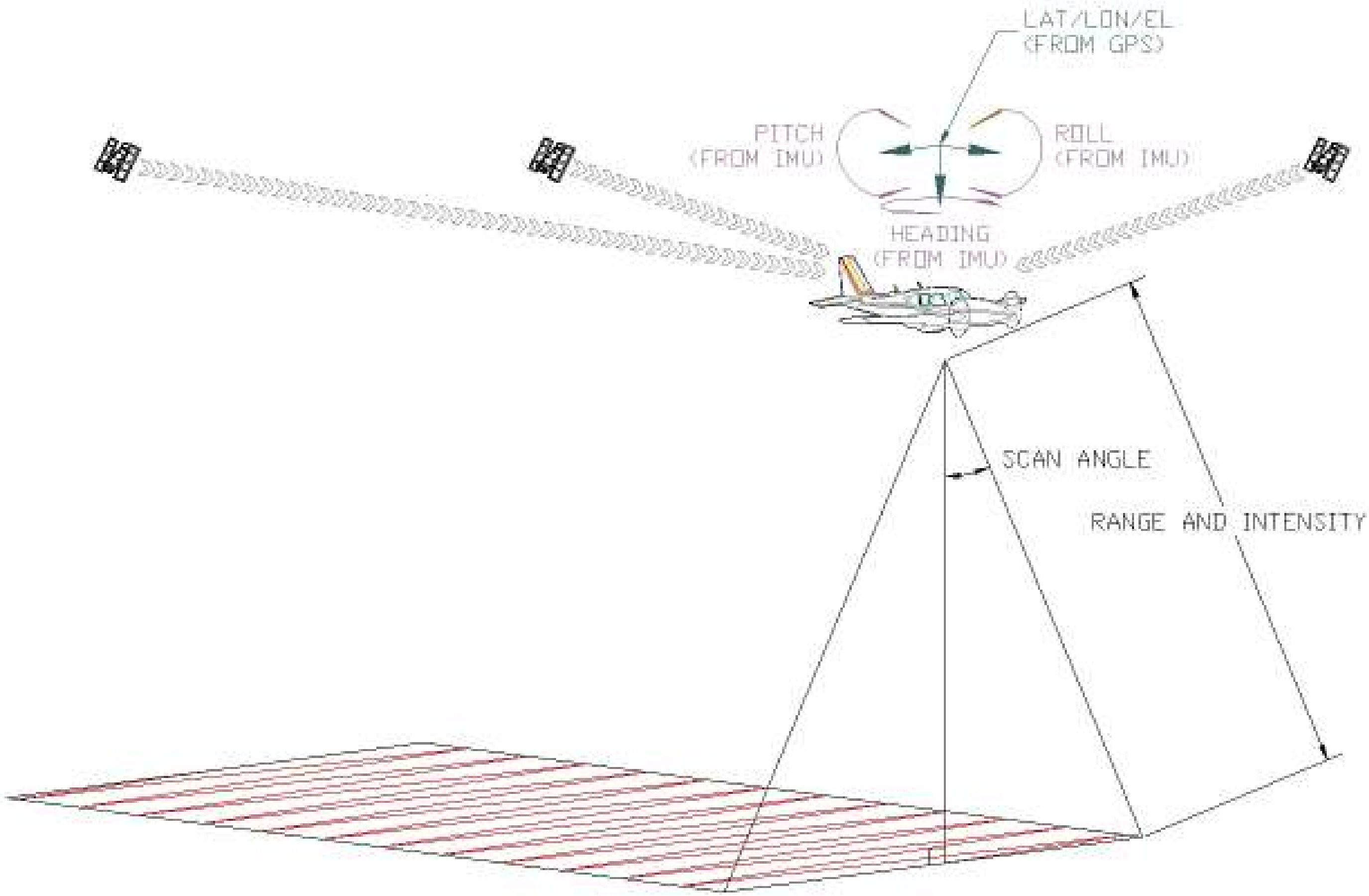
Focus on the technical approaches used and the resulting performance characteristics

Discuss major subsystems within a typical LIDAR device

Technical trade-offs

- **various subsystem technology options**
- **within individual subsystem technologies**

Typical LIDAR technology implementation
scanning, ranging, aircraft position and attitude



Major subsystems

Position measurement

Orientation measurement

Range measurement

Scan actuation

Scan angle measurement

External interfaces

Position measurement subsystem
available options

Vendors

- **Leica (part of IPAS)**
- **Trimble/Applanix (part of POS)**
- **NovAtel (part of SPAN)**
- **IGI (connected to AeroControl)**

Receiver technologies

- **GPS**
- **GLONAS**

Correction technologies

- **Post processed**
  - Using one or more base stations
  - PPP
- **Real-time correction**
  - Via satellite broadcast
  - Via uplink from ground station

Orientation measurement subsystem

available options

Vendors

- Leica (part of IPAS)
- Trimble/Applanix (part of POS)
- NovAtel (part of SPAN)
- IGI (connected to AeroControl)

IMU technologies

- MEMS (e.g., ISI ISIS, Systron Donner) – generally very small, less expensive, but low accuracy and rapid drift
- Fiber optic gyro (e.g., Northrop Grumman LN-200) – compact, rugged, high accuracy, low drift
- Dry-tuned gyro (e.g., ISI AIMU, Sagem) – medium size, somewhat sensitive mechanics, high accuracy, low drift
- Ring laser gyro (e.g., Honywell uIRS) – largest size and cost, highest accuracy, lowest drift

Related technologies – “tightly coupled” GNSS/IMU processing

- Allows faster re-acquisition after temporary loss of satellite
- Most applicable to mobile ground based systems where frequent GPS outtages can occur
- Can benefit airborne systems by allowing steeper banked turns

Range measurement technologies
key components

Pulsed laser transmitter

Optical receiver

Range measurement electronics

Range measurement subsystem
laser technology dependencies

Pulse width

- **Shorter is generally better (unless it is so short that the detector cannot see it)**
  - Pulse energy / pulse width = peak power
  - Peak power is what detectors respond to → detectivity is measured in Amperes out / Watt input
  - Short pulses yield higher peak power with lower average power → good for eye safety
- **Shorter pulse width *generally* means faster rise time (see below)**
- **Also helps to reduce minimum vertical discrimination distance**

Pulse rise time

- **Faster is generally better**
- **Crisp leading edge benefits constant fraction discrimination**

Consistency of pulse shape over a range of pulse rates

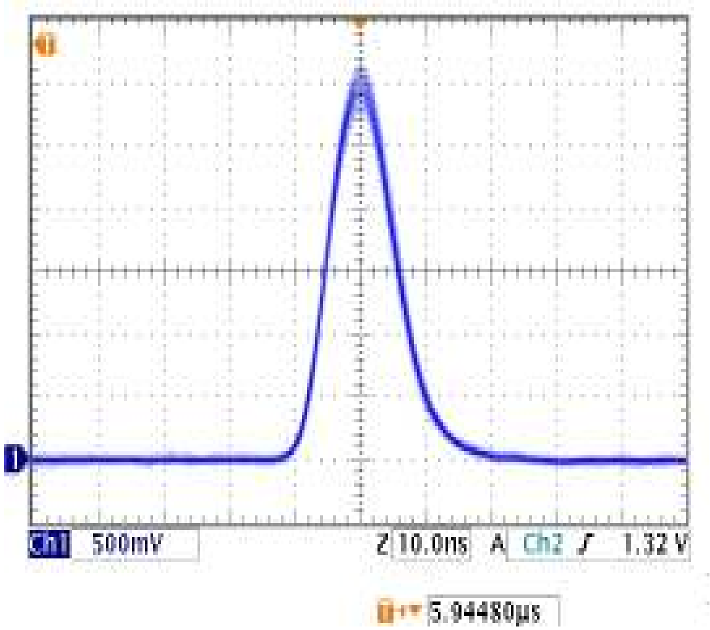
- **Can cause range bias as pulse width changes with increasing pulse rate**
- **Can cause reduced accuracy as pulse jitter increases with pulse rate**
- **Systematic issue with conventional diode-pumped solid-state lasers**

Beam divergence

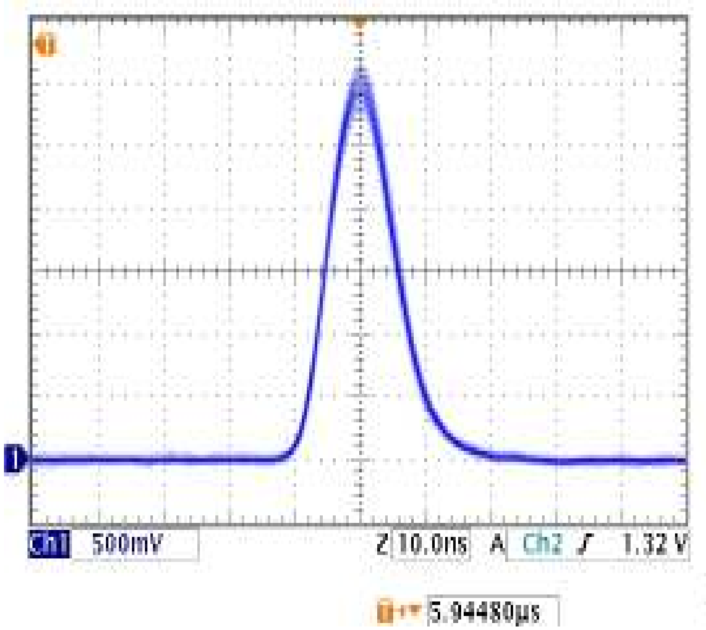
- **Minimize to improve XY accuracy via small footprint**

Single ALS50-II laser
clean pulses even at high pulse rates

Typical laser pulse



ALS50-II laser pulse



33 kHz

- when it has to be right

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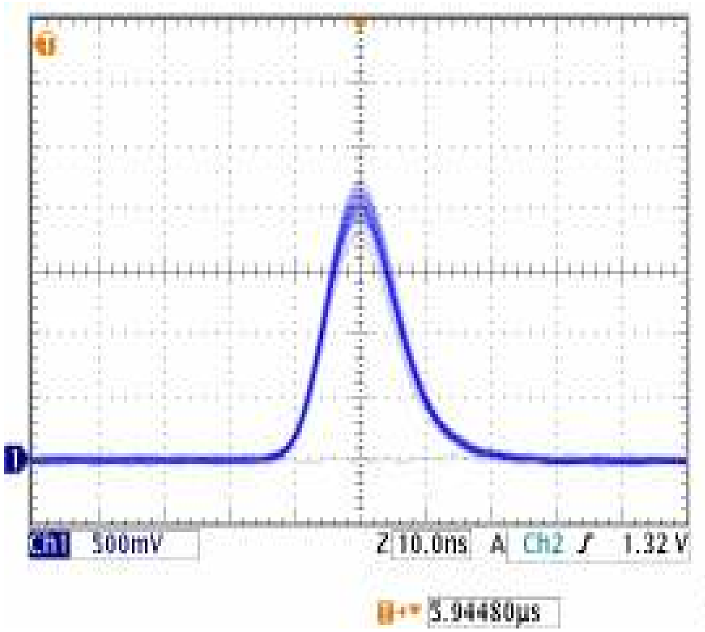
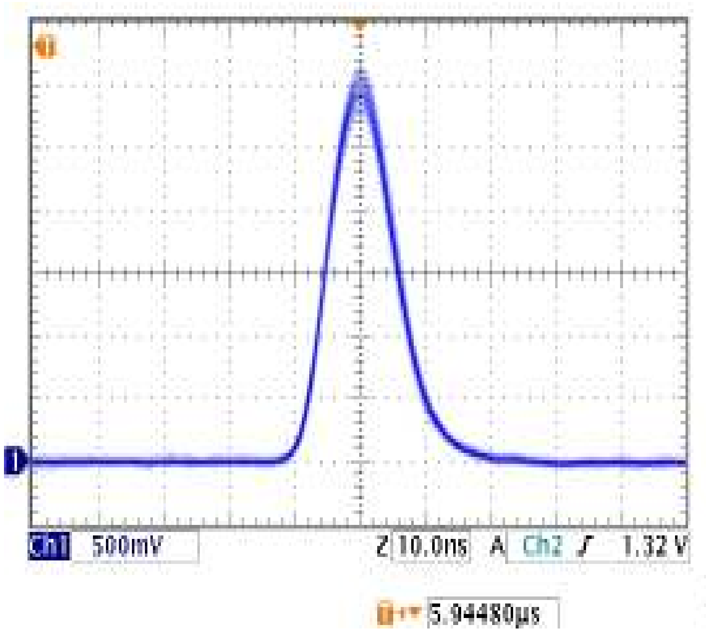
Single ALS50-II laser
clean pulses even at high pulse rates

Typical laser pulse



ALS50-II laser pulse



50 kHz

- when it has to be right

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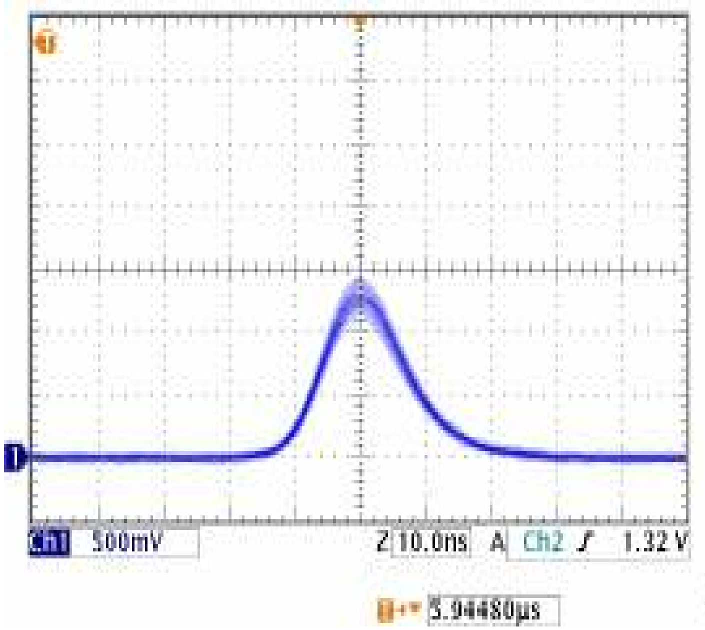
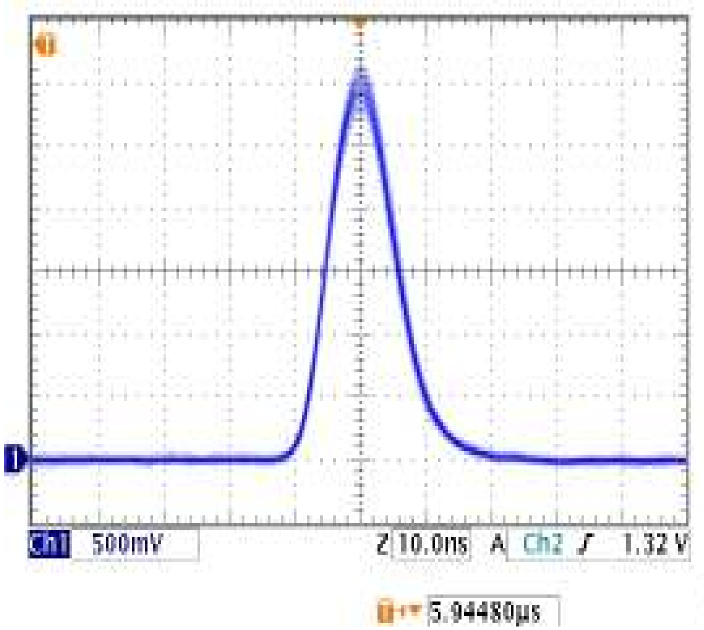
Single ALS50-II laser
clean pulses even at high pulse rates

Typical laser pulse



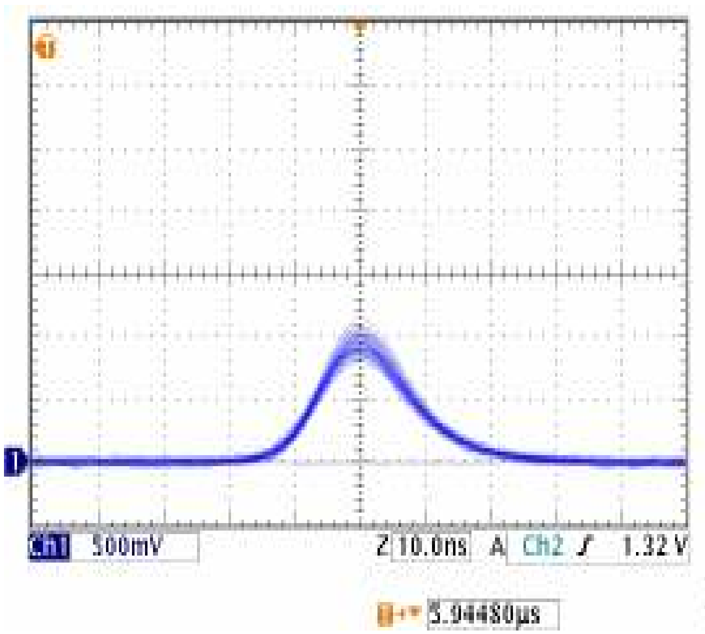
ALS50-II laser pulse



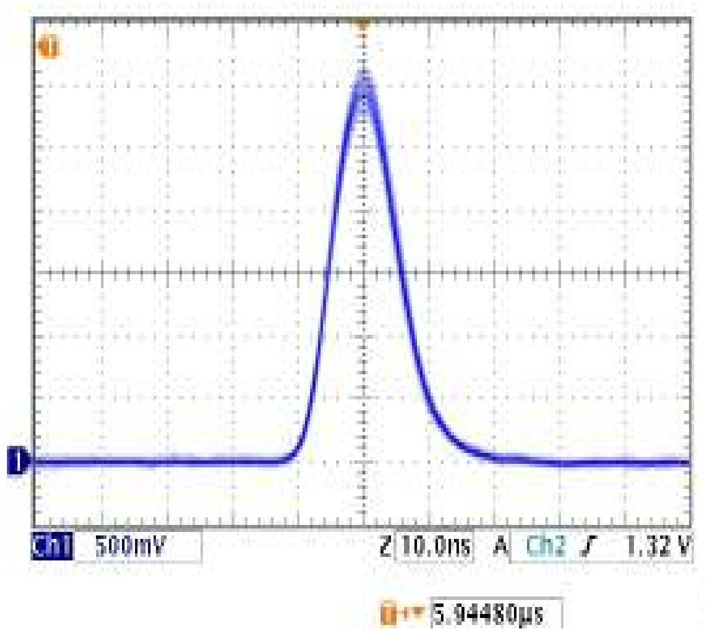
70 kHz

Single ALS50-II laser
clean pulses even at high pulse rates

Typical laser pulse



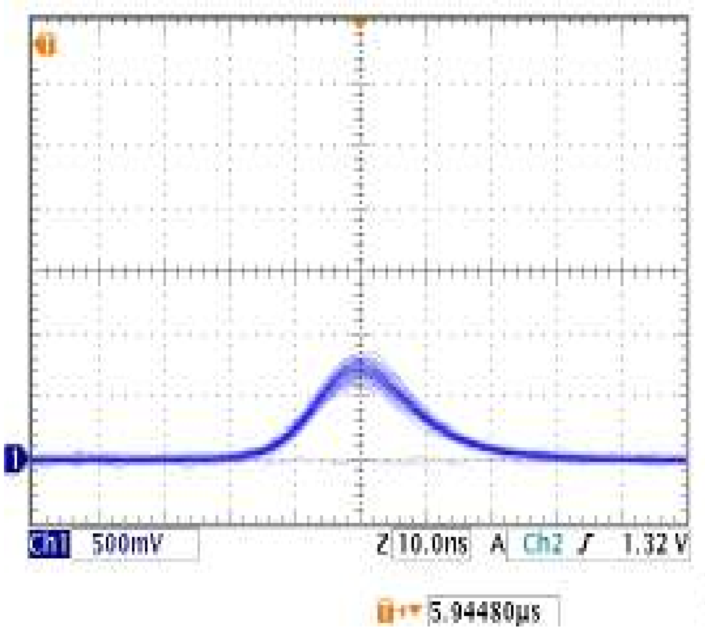
ALS50-II laser pulse



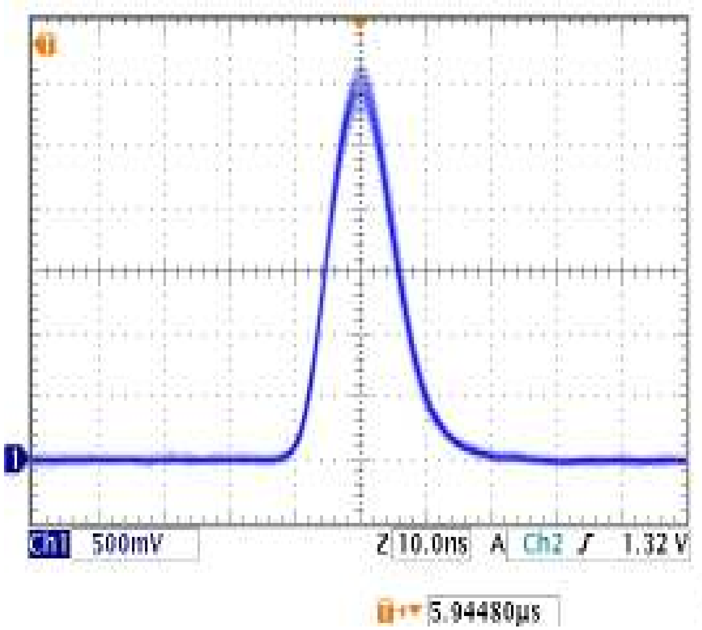
85 kHz

Single ALS50-II laser
clean pulses even at high pulse rates

Typical laser pulse



ALS50-II laser pulse



100 kHz

- when it has to be right

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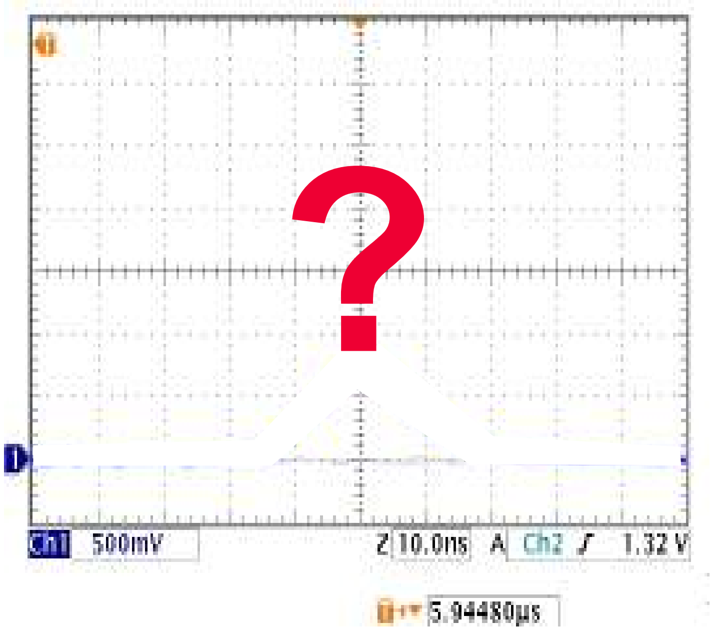
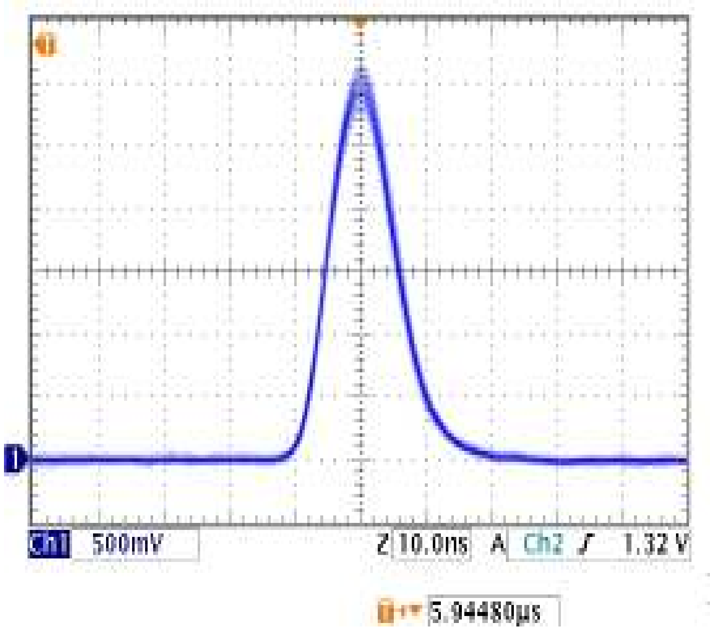
Single ALS50-II laser
clean pulses even at high pulse rates

Typical laser pulse



ALS50-II laser pulse



150 kHz

- when it has to be **right**

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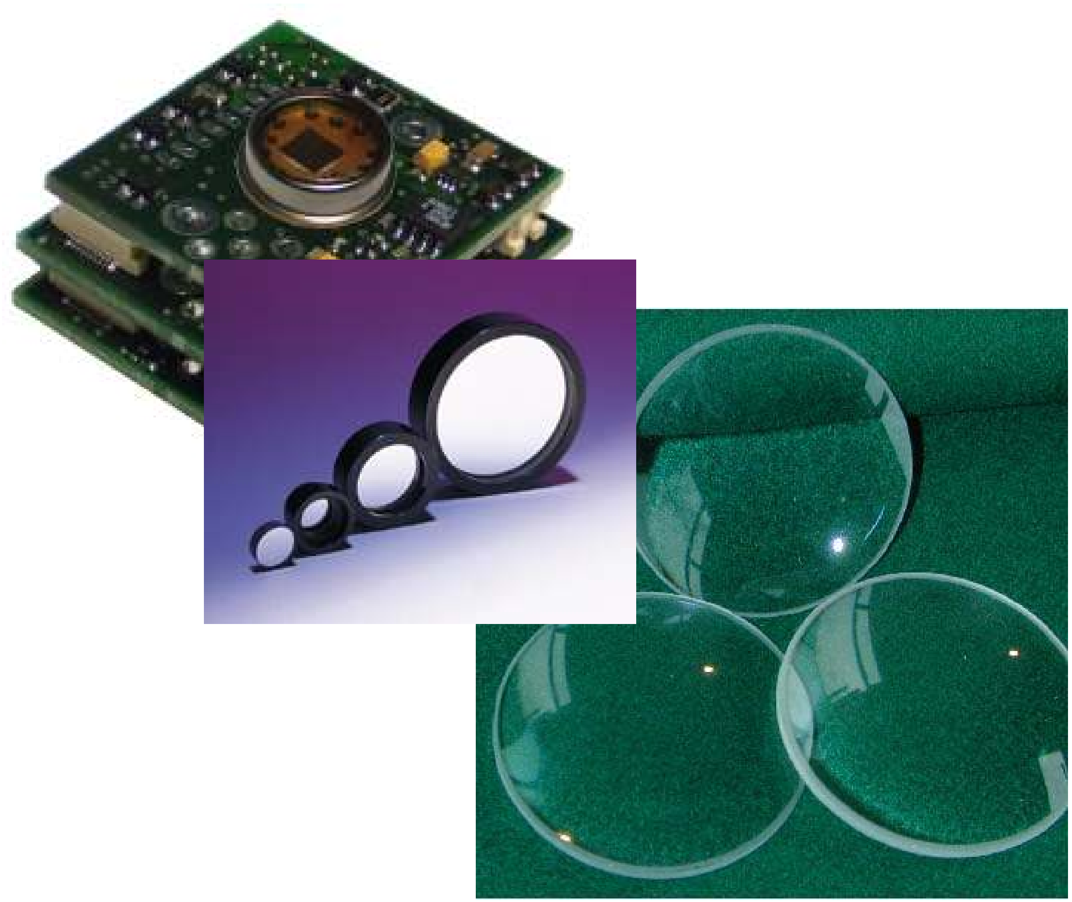
Range measurement subsystem
receiver technology dependencies

Key elements

- Detector
- Receiver electronics
- Optical filtering
- Receiving optics



Range measurement subsystem
receiver technology dependencies

Detectors

- Generally avalanche photodiodes
- Must be responsive at laser wavelength (Note: detectors at "eye-safe" wavelengths ~1550 nm are less sensitive than detectors at more common 1064 nm wavelength
- Smaller area yields lower noise and faster response time
- Larger area increases tolerance to time-of-flight-induced focal spot wander

Receiver electronics

- Fast enough to see laser pulse
- Wide dynamic range (low noise and high overhead)

Receiving optics

- Larger optics allow greater sensitivity (small targets, high altitudes, low reflectivity targets ,lower laser power)
- Smaller optics generally facilitate high scan rates

Optical filtering should be employed

- Reduces solar background collected by detector
- Narrow pass band gives better solar rejection, but more sensitive to thermal variations and generally less throughput
- Wider pass band gives better tolerance to thermal changes, better throughput, but more solar throughput

Range measurement subsystem
measurement electronics used

Time-of flight

- Direct counting
- Direct counting + fine interpolation
- Waveform digitization and analysis

Establishment of critical timing marks

- Threshold detection
- Constant fraction discrimination
- Waveform analysis

Range measurement subsystems
Multiple Pulses in Air (MPiA)

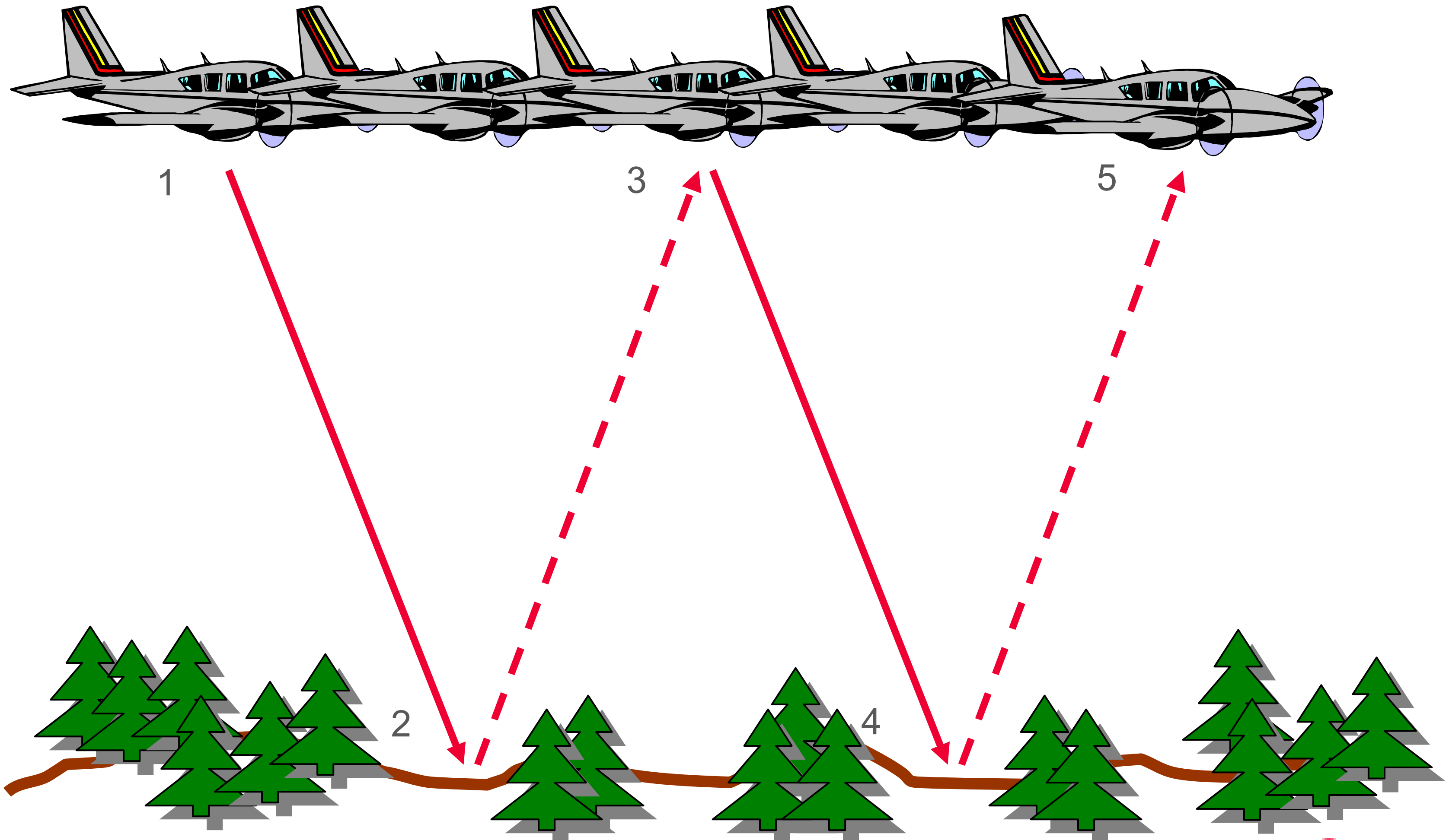
Significant benefits

- Double the data density at current swath
- Double the swath at current density
- Data acquisition cost savings approaching 50%

Important system engineering factors

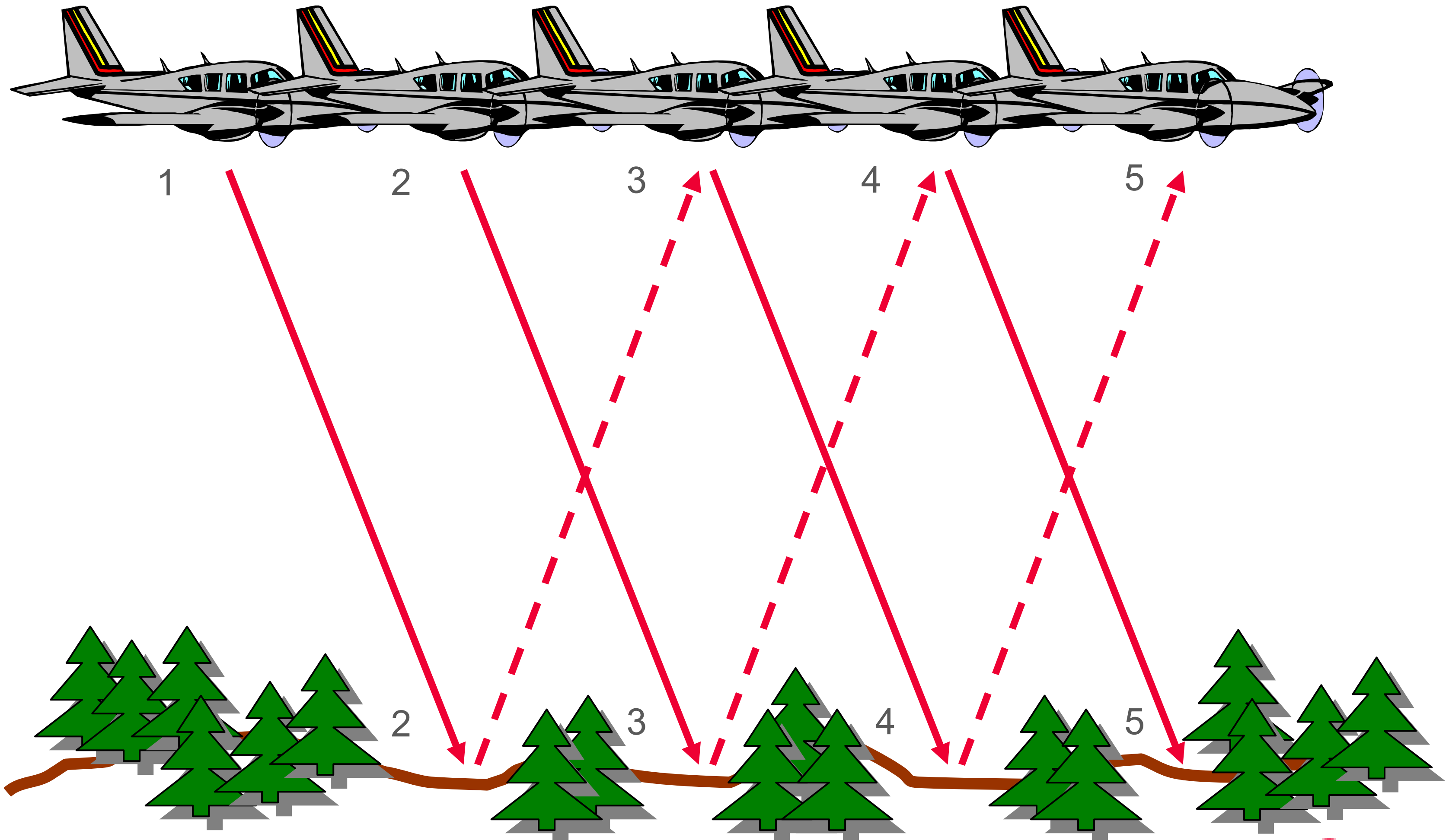
- Ensuring that laser is powerful enough to allow MPiA at all altitudes
- Getting as close as possible to the theoretical 2:1 benefit
- Simplifying system set-up for MPiA operation

Fundamentals of MPiA technology
single-pulse technology limits pulse rate



Fundamentals of MPiA technology

MPiA allows doubling of pulse rate



Maximum pulse rates using MPiA
doubling pulse rate means flight cost savings

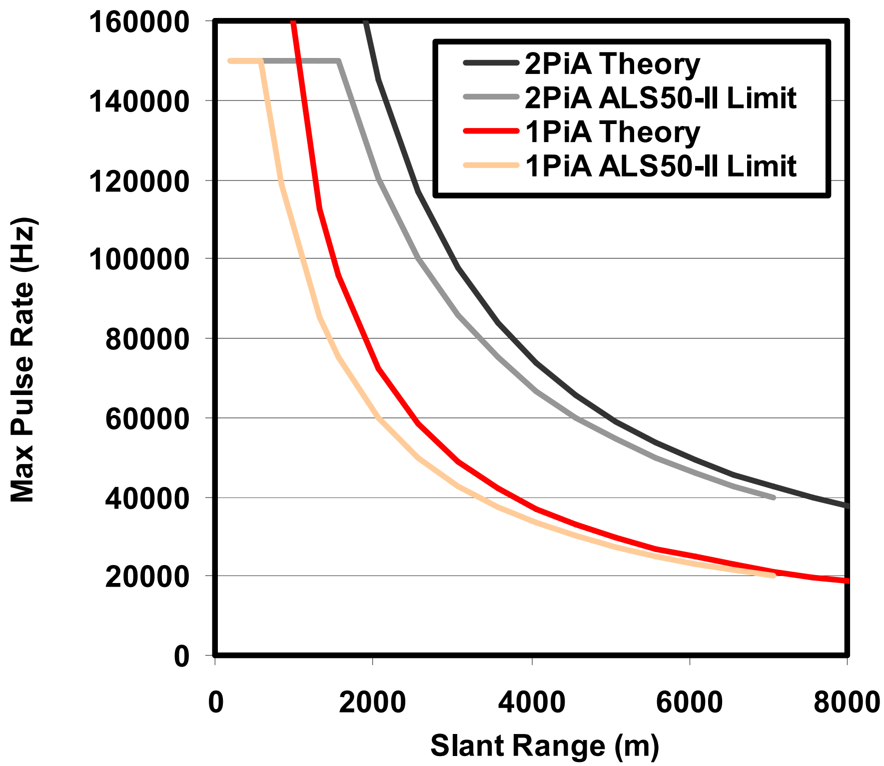
2PiA limit is twice 1PiA limit at any given altitude

Laser imposes practical limit at 150 kHz

ALS50-II 150kHz pulse rate attainable at up to 570 m AGL for 1PiA and 1569 m AGL for 2PiA

Important design goals

- Get as close as possible to theoretical limits
- Have enough laser power at any given pulse rate to allow MPiA operation



Scanning subsystems
general options

Unidirectional scanning

- **Polygon mirror**
- **Nutating mirror with fiber array**

Cyclic (back and forth) scanning

Scanning subsystems
polygon mirror scanners

Principle

- Laser transceiver is aimed at the facets of a continuously rotating polygon mirror
- As each facet passes by, a scan line is created across the ground below

Manufacturers: Riegl (including IGI and Toposys turn-key offerings)

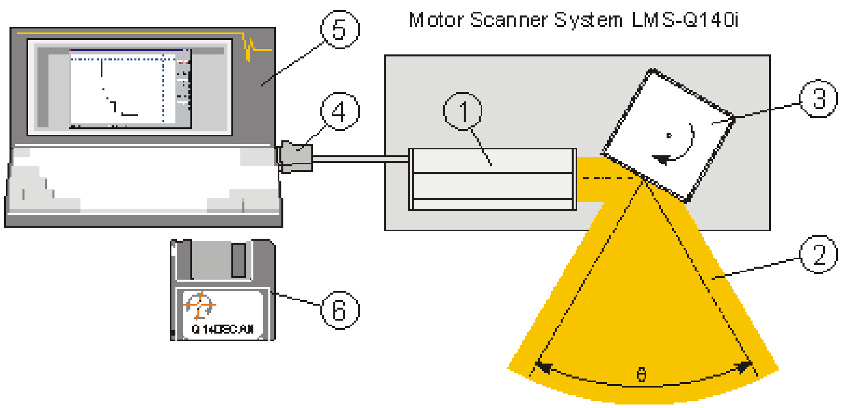
Proprietary systems: Fugro/Chance FliMap

Advantages

- Low power consumption
- Constant point spacing in along-track direction

Disadvantages

- Low scan efficiency – transceiver can not collect data “in between facets” → measurement rate is generally much smaller than laser pulse rate
- Constant angular velocity causes wider cross-track point spacing as off-nadir angle increases
- Typically small collecting aperture (~50 mm diameter)



Scanning subsystems
nutating mirror/fiber scanners

Principle

- Laser transmitter and receiver are each coupled to a fiber optic. These 2 fibers are then aimed at a nutating mirror that scans the out put of these two fibers across a circular array of "scan fibers". The output ends of the scan fibers are arranged in a linear array that is then aimed at an output (collimating) optic.
- For each rotation of the nutating mirror, a scan line is created across the ground below

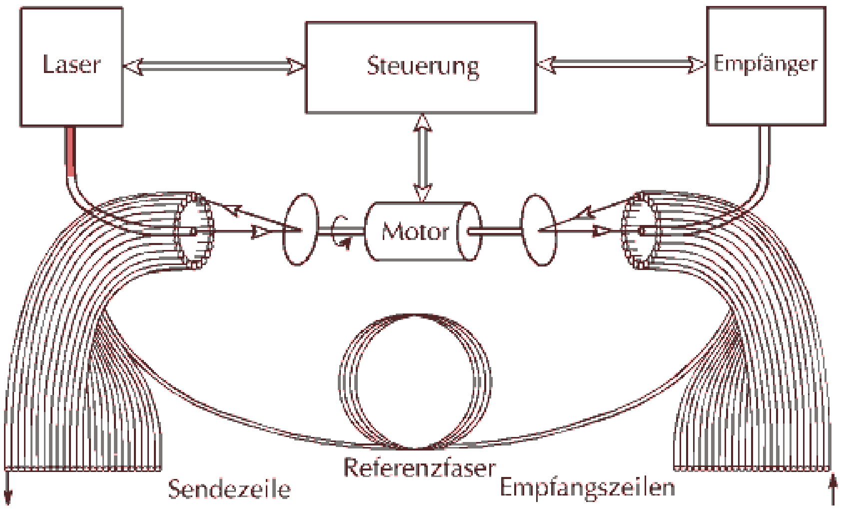
Manufacturers: Toposys (Falcon series scanners)

Advantages

- Low power consumption
- Constant point spacing in along-track direction
- 100% scan efficiency – no "dead time" between scans

Disadvantages

- Low coupling efficiency – difficult to get optical energy in/out of fiber, thus limiting max altitude capability
- Typically small collecting aperture (~50 mm diameter)
- FOV, number of data points per scan are fixed by design
- Cross-track point spacing increases with off-nadir angle, unless specifically designed out via non-constant fiber spacing at linear end of bundle



Scanning subsystems
cyclic scanners

Principle

- Laser transceiver is aimed at an oscillating mirror
- For each oscillation, a cyclic scan pattern is created across the ground below

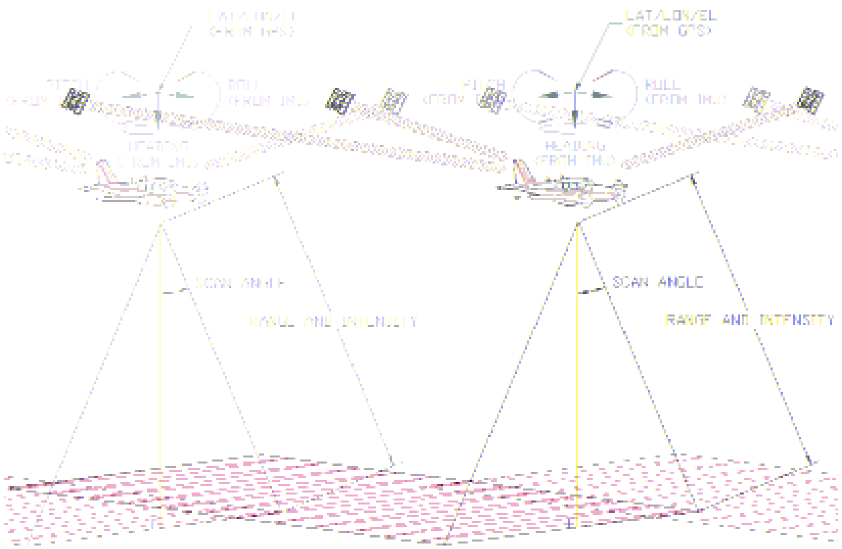
Manufacturers: Leica Geosystems, Optech

Advantages

- Programmable scan pattern, FOV and scan rate allow tremendous flexibility in setting swath and point density
- Large apertures possible
- 100% scan efficiency

Disadvantages

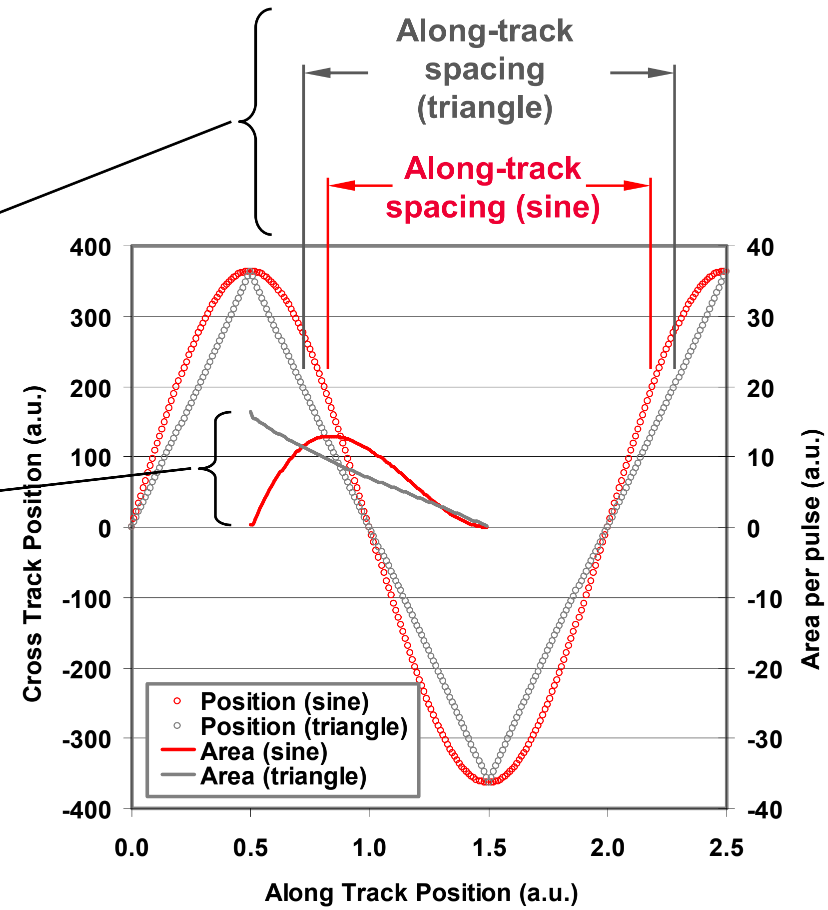
- Higher power consumption



Scanning subsystems
sinusoid and triangle scan patterns

Triangle wave scanners provide slightly more consistent cross-track spacing across FOV, but…

- Sinusoid scans offer closer approximation to raster; more consistent along-track spacing
- At FOV edge, 27% greater area is covered per laser shot when using triangle scan (cross-track spacing x along-track spacing), lowering definition at FOV edge



Scan angle measurement subsystems
available options

Idealized optical encoder

- High angular rate
- High query rate
- High resolution
- High accuracy
- Low inertia

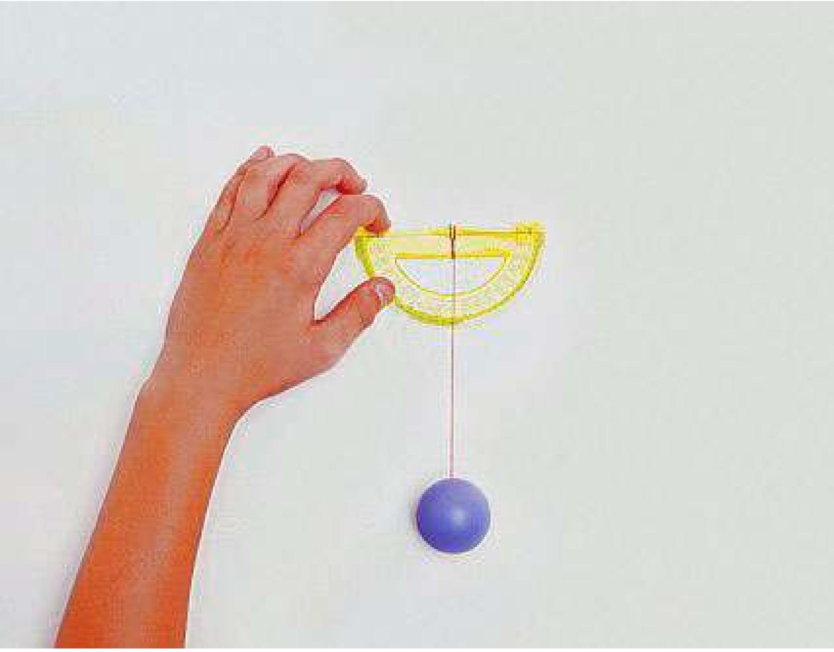
Trade-offs

- Accuracy and resolution versus max angular rate
- Accuracy and resolution versus encoder size and inertia → affects scanning speeds due to greater load

Additional enhancement techniques

- Sub-sample to overcome query rate limitations
- Post processing software that assumes a uniform motion profile to affect smoothing of the data → most applicable to scanners with constant angular rates

Note: Given constant angular rate (i.e., well regulated), a "start-of-scan" pulse could substitute for a scan angle encoder



Accessory subsystems
integrated imaging

Real-time imagery to check for clouds / haze in line of sight

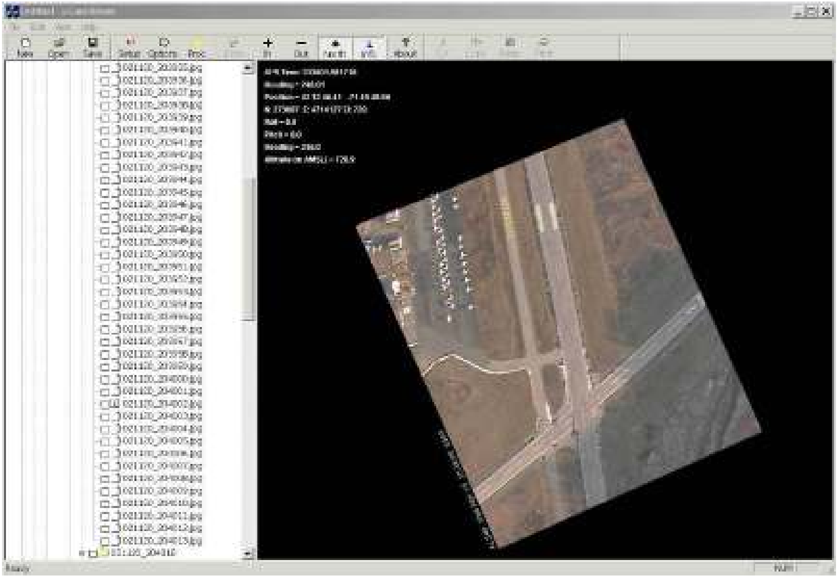
“What was that” editing support

Technology choices:

- Video
- Frame camera with frame grabber
- Webcam

Important features

- Compact data (e.g., JPEG)
- Images time-indexed and contain all georeferencing data
- Adequate resolution (e.g., 1280 x 1024)
- Software for easy post-flight image look-up



External system integration
desirable characteristics

Multiple ports for external sensors (~45% of LIDAR systems now have external imaging capabilities)

Flexibility to interface with

- Cameras
- Thermal sensors
- Hyperspectral sensors
- Other external sensors / systems

Accesses common GPS/IMU data

Sample system design
power line mapping system

Objectives

- High point density
- High accuracy
- Low flying height
- Maximize hits on power line

Subsystem design response

Positioning: high accuracy → field-placed DGPS base stations

Orientation: medium accuracy due to low flying height “lever arm” → mid-range IMU such as FSAS

Ranging: very high pulse rate laser with high pulse-to-pulse consistency, but small optics OK

Scanning: slow scanning speeds OK, but wide field and large roll compensation range needed

Scan angle measurement: medium accuracy due to low flying height “lever arm”

External interfaces: 2 medium-format cameras (ortho and forward oblique)

Sample system design
wide area mapping system

Objectives

- Low point density
- Medium accuracy
- High flying height
- Maximize coverage subject to meeting point density requirements

Subsystem design response

Positioning: medium → real-time DGPS corrections or PPP a possibility

Orientation: highest accuracy due to high flying height "lever arm" → high-end IMU such as uIRS

Ranging: high peak power laser, low pulse rate. Low beam divergence (for low XY ambiguity), MPiA data handling, large optics required

Scanning: slow scanning speeds OK, but wide field needed, roll compensation range not critical due to smoother flight

Scan angle measurement: highest accuracy due to high flying height "lever arm"

External interfaces: 1 medium-format cameras (ortho)

Overview of ALS50-II
a state-of-the-art LIDAR system

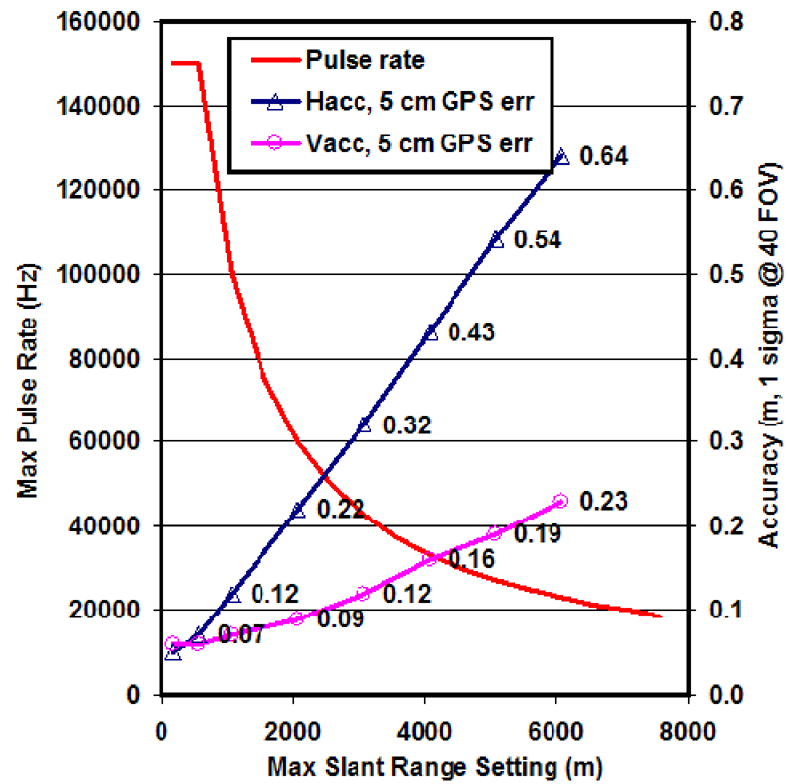
Maximum pulse rate of 150 kHz

No degradation of accuracy with increasing pulse rate (accuracy to 3.1 cm demonstrated) owing to improved laser technology

Expanded maximum operating altitude (6000 m AGL)

Large optics for high performance in poor visibility or with small / low-reflectivity targets

High XY accuracy due to small beam divergence and highly accurate scan angle encoder



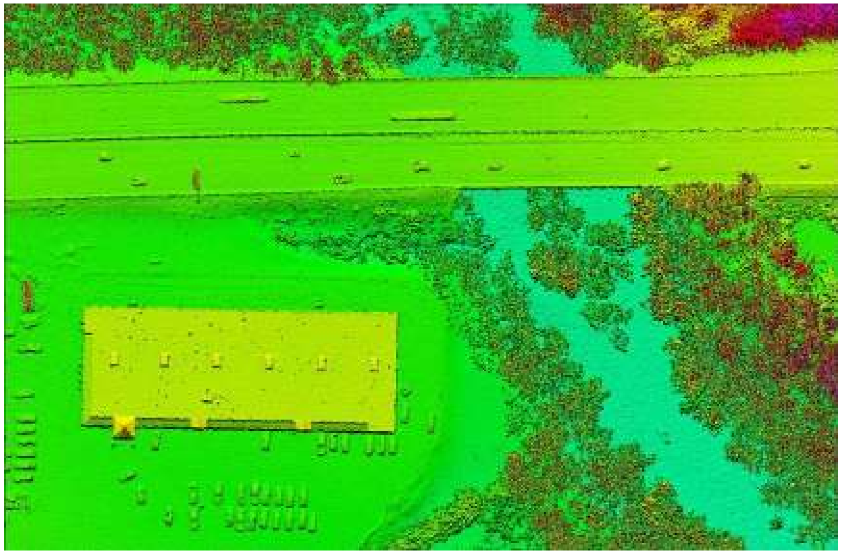
Ground resolution and surface accuracy

12 points/m^2 (~0.30 m posting) generated on a regular basis from 780 m AGL

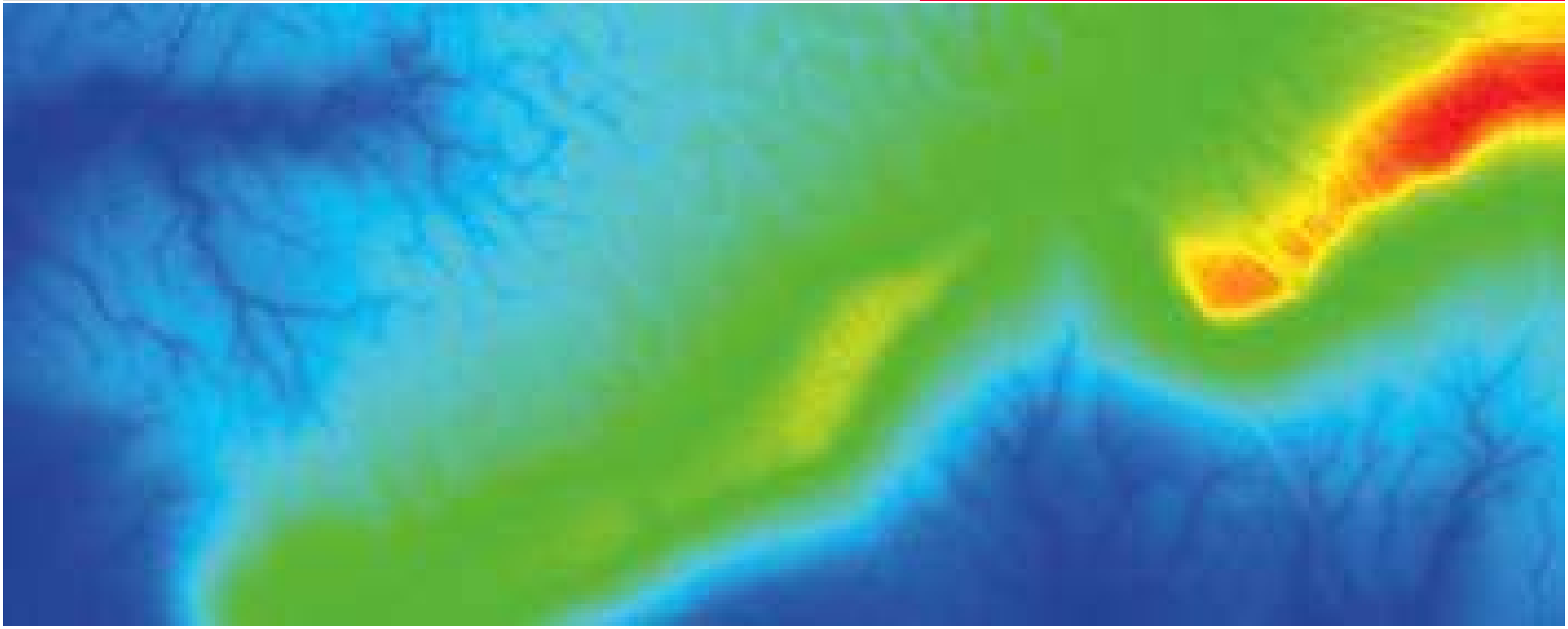
Accuracy to 3.1 cm from ~3000 m AGL

~6-meter postings with 6246 m swath at 6000 m AGL, 31 cm vertical, 72 cm horizontal accuracy

All above with fixed wing aircraft



Leica Geosystems ALS50-II Configuration



ALS Calibration

the difference between good results and bad results

- when it has to be **right**

Leica Geosystems

Lidar system calibration

- **Factory determined values**
  - IBRC
  - Encoder Offset / Scan Angle Correct
- **Factory tuning**
  - Electronic Components
- **AB based calibration**
  - Misalignment calibration
  - Range offset

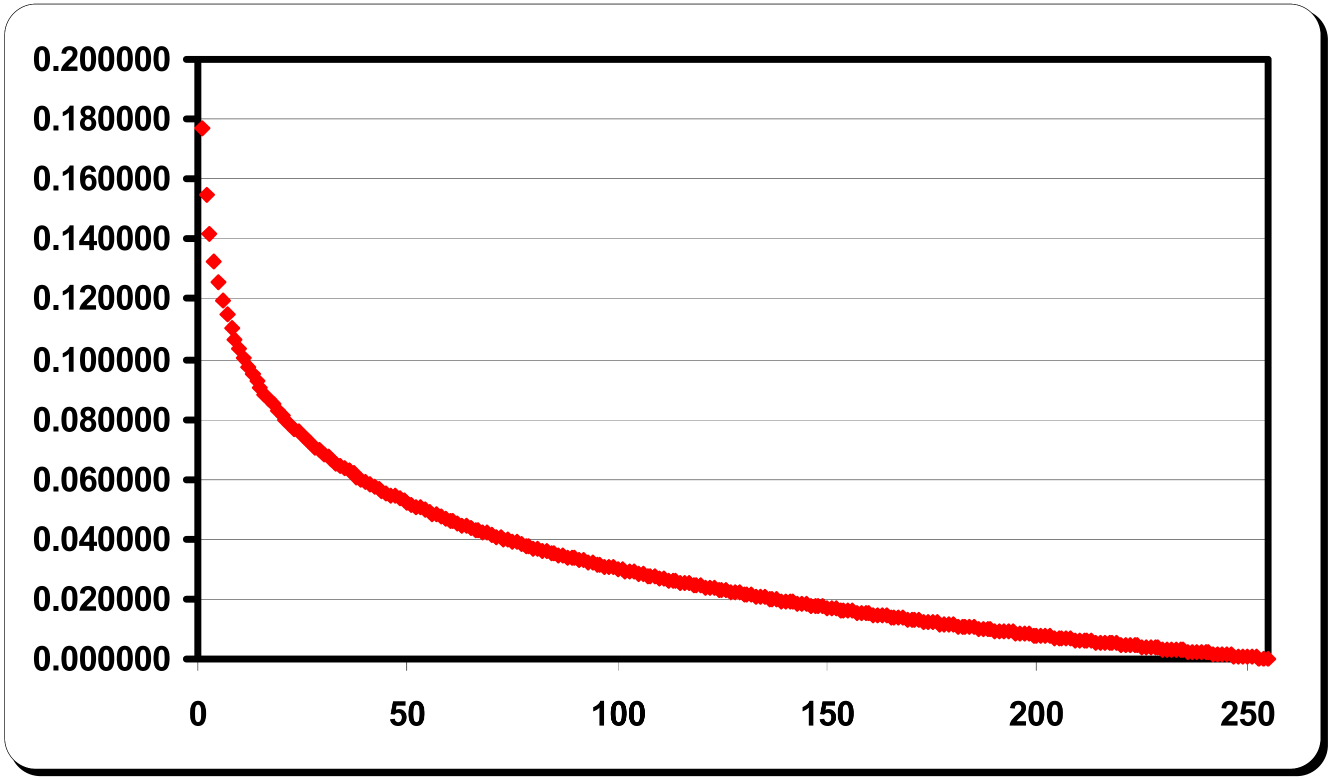
Calibration Parameters from Factory
Intensity based range correction – What is it?

Laser returns from bright surfaces will reflect quicker and appear to have a higher elevation.

Laser returns from darker surfaces will reflect slower and appear to have a lower elevation.

The IBRC-table contains an amount to be subtracted from the range correction for each intensity value 0 to 255.

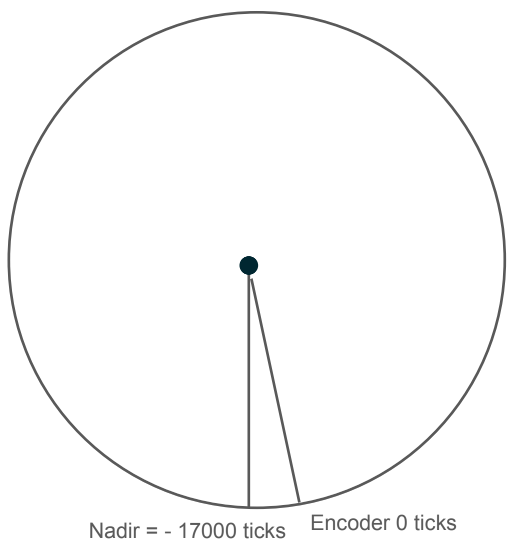
Calibration Parameters from Factory
IBRC Table - Example



Calibration Parameters from Factory
Encoder Offset or Scan Angle Correct

Where the encoder "thinks" nadir is and where nadir actually is are different

Encoder offset is the encoder reading at the exact center of the scan pattern



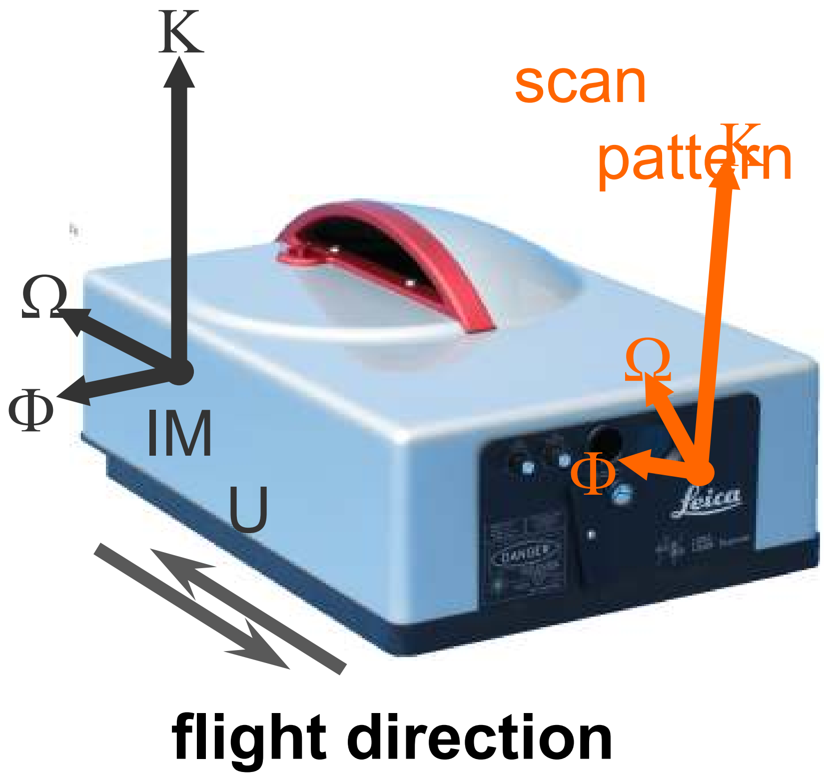
Calibration Parameters from Factory Electronic Tuning

1. AGC Board
2. Receiver Tuning
3. Mainboard Discriminator
4. Range Boards
5. Data Control Board
6. Encoder Interface
7. Laser Trigger
8. Galvo Tuning
9. Laser Boresite
10. Intensity Board

-> These values fixed during manufacture

Objective of boresight calibration

- **Determine the angular misalignment between the IMU and the scan pattern frame (ω, ϕ, κ)**
- **Determin Range offset against GCP. Any constant electronic time delay to lead constant offset in the range measurement.**
- **Approach**
  - Traditional Profile approach
  - Leica's Attune approach to utilize intensity information



Roll Misalignment
what is roll misalignment?

Roll misalignment defines the misalignment, in radians, around the X axis between the IMU and the laser. Any alignment of the scan encoder is also incorporated in roll error.

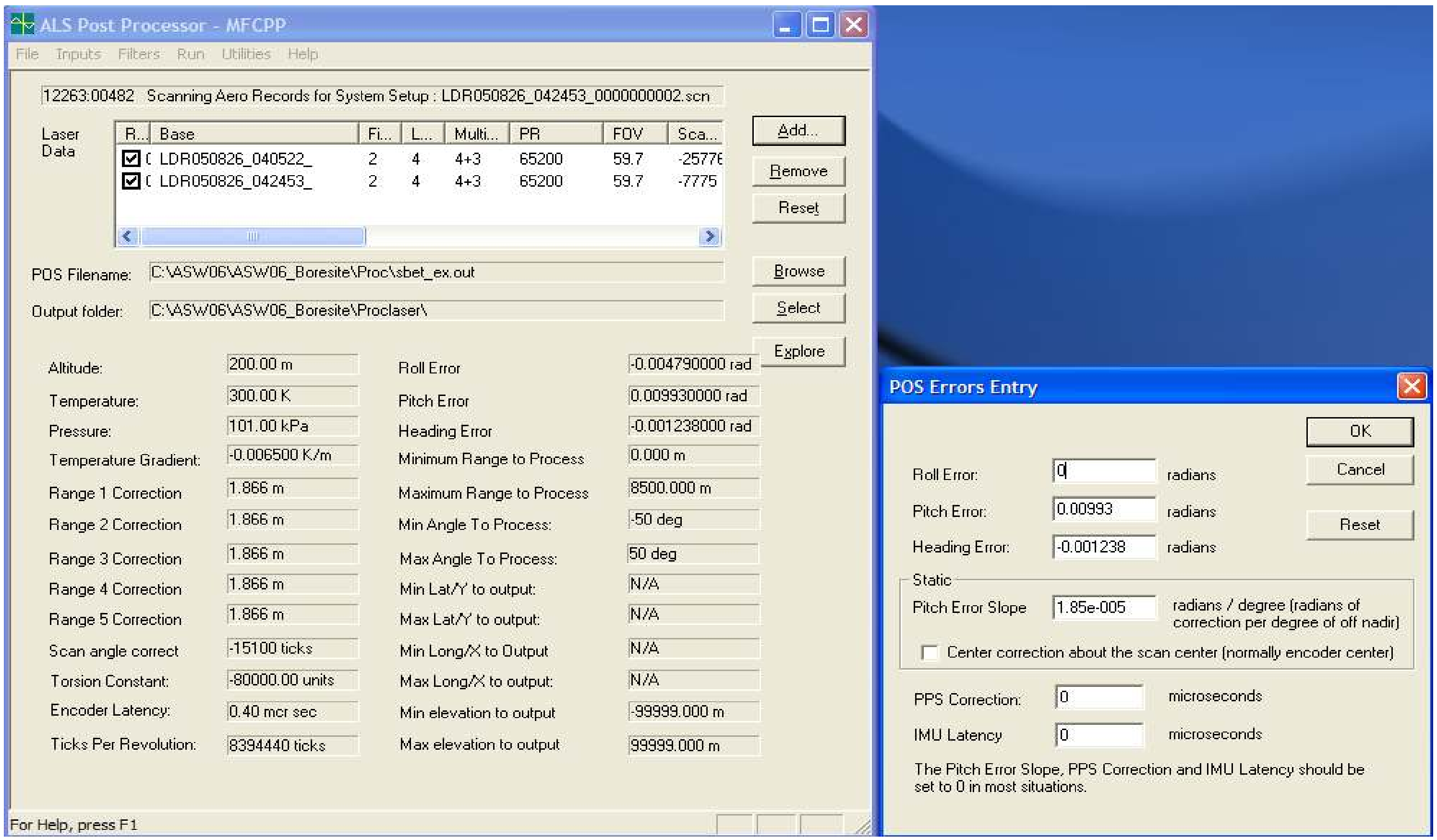
With the Scanner Assembly mounted with the cables to the front the X axis is positive to the nose of the aircraft. In this case a positive rotation will move the data clockwise.

With the Scanner Assembly mounted with the cables to the rear the X axis is negative to the nose of the aircraft. In this case a positive rotation will move the data counter-clockwise.

Roll error moves the data up on one side of the swath and down on the other side of the swath

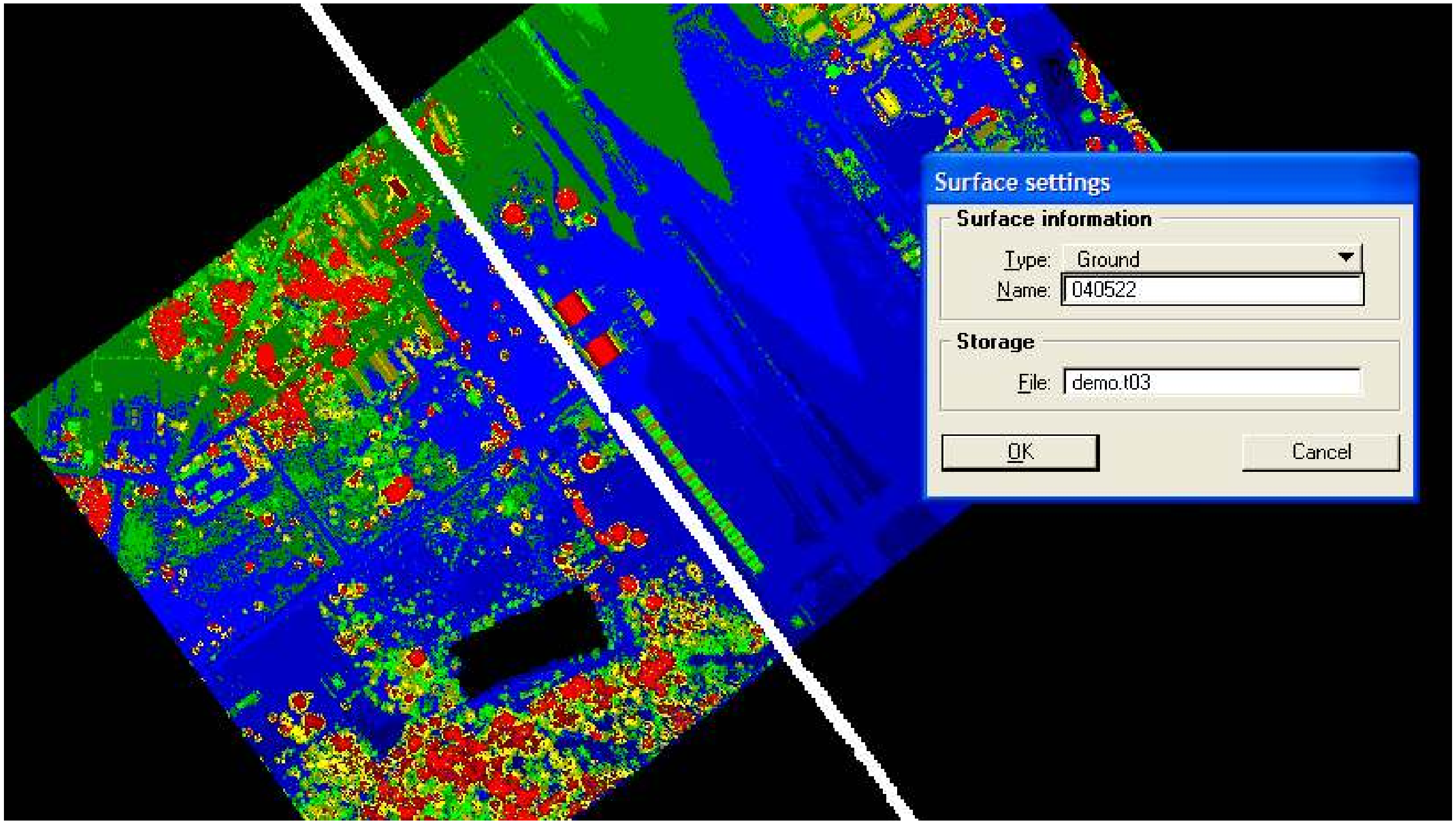
How do I check for roll error?

Step 1. Collect data for a single flight line flown in opposite directions over a flat surface. Process with roll error set to zero.



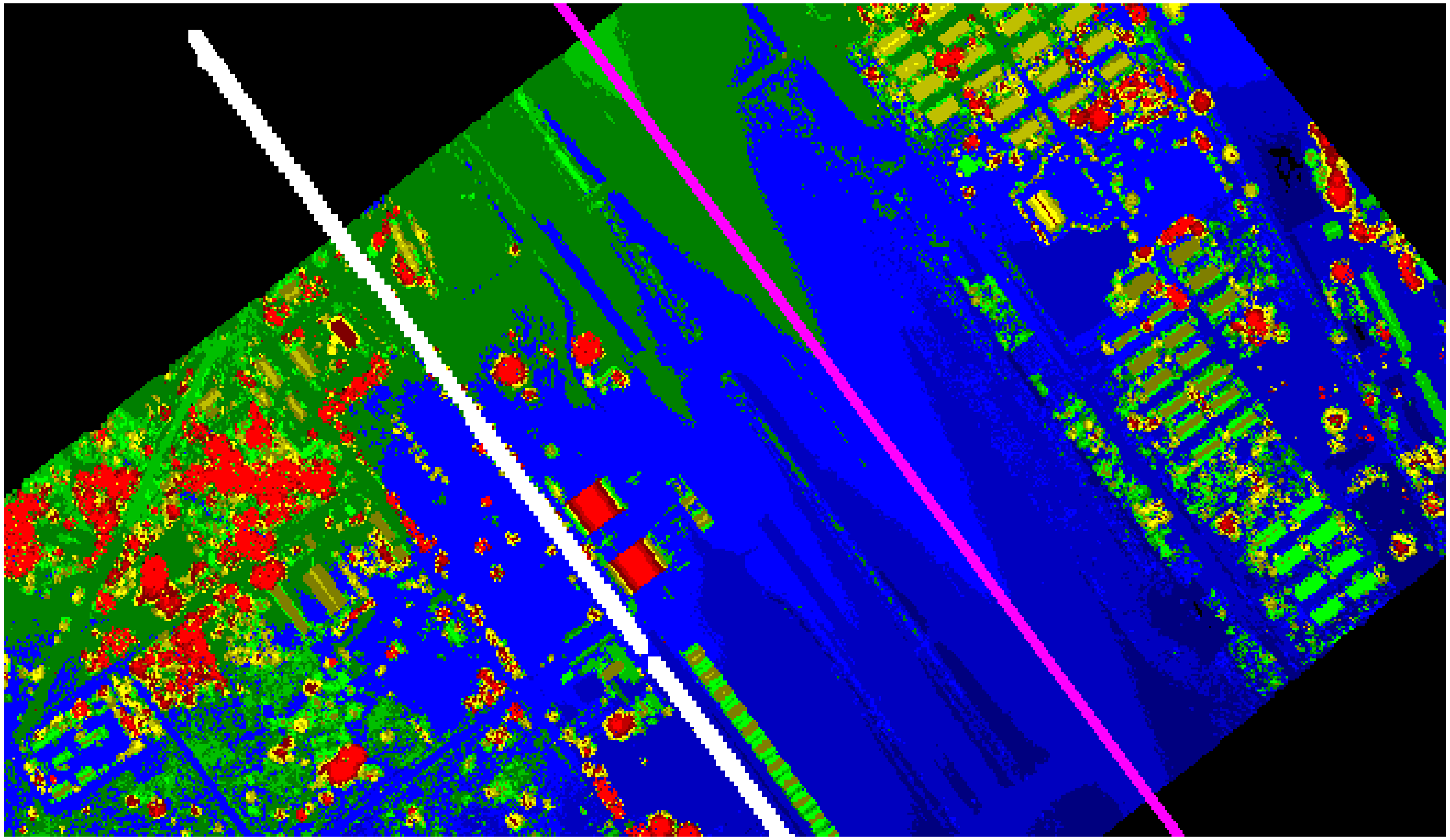
How do I check for roll error?

Step 2. Load points in TerraScan and output surface models for the opposing flight lines.



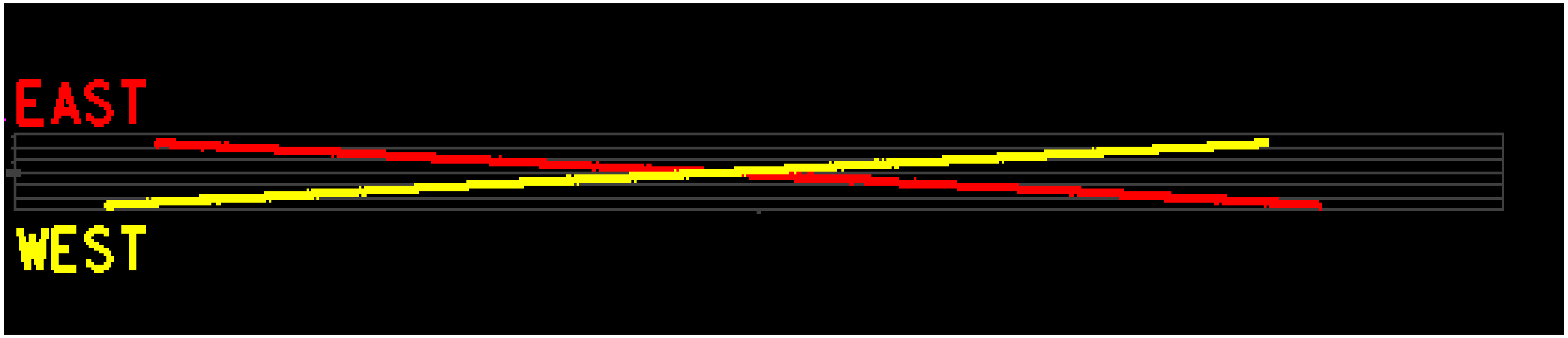
How do I check for roll error?

Step 3. Select a flat area free of trees and buildings covering the width of the swath.



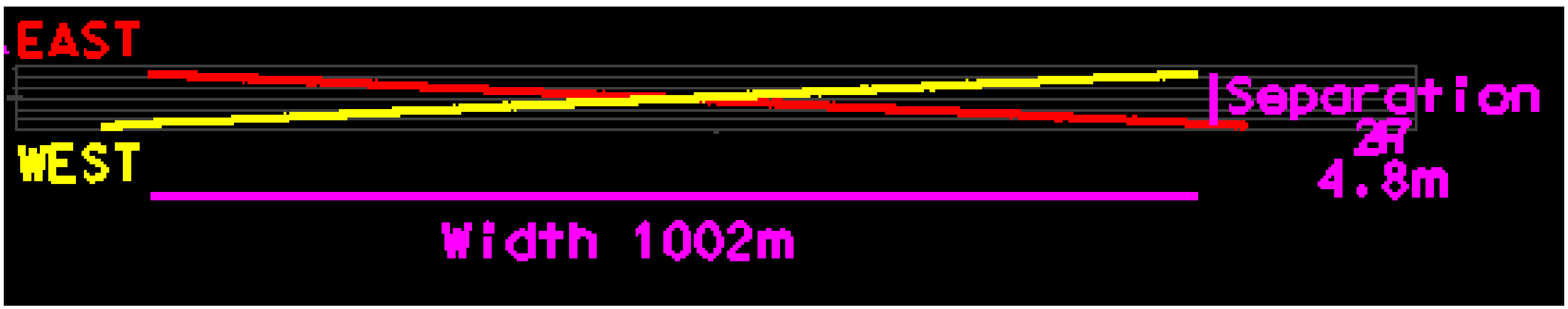
How do I check for roll error?

Step 4. In TerraModeler draw a profile across track through both surfaces. If the roll value is correct the surfaces should coincide.



How do I check for roll error?

Step 5. If the surfaces do not coincide measure the separation and width. Adjust the initial roll error value by separation divided by width.

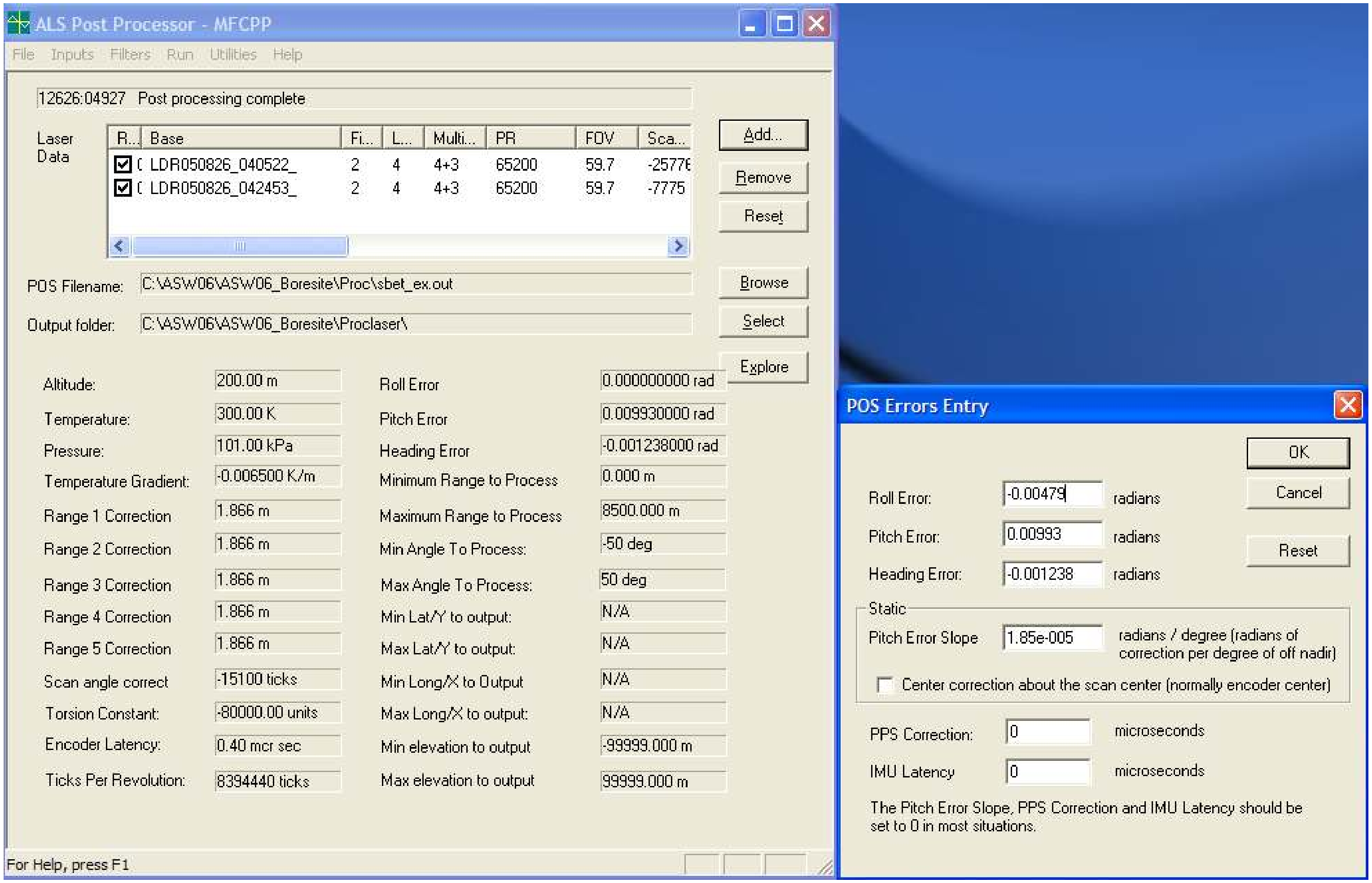


How do I check for roll error?

Step 6. Initial roll error 0.000000. Adjustment required is 4.8/1002 = 0.00479. Adjustment required is counter clockwise. Adjusted roll value is -0.00479

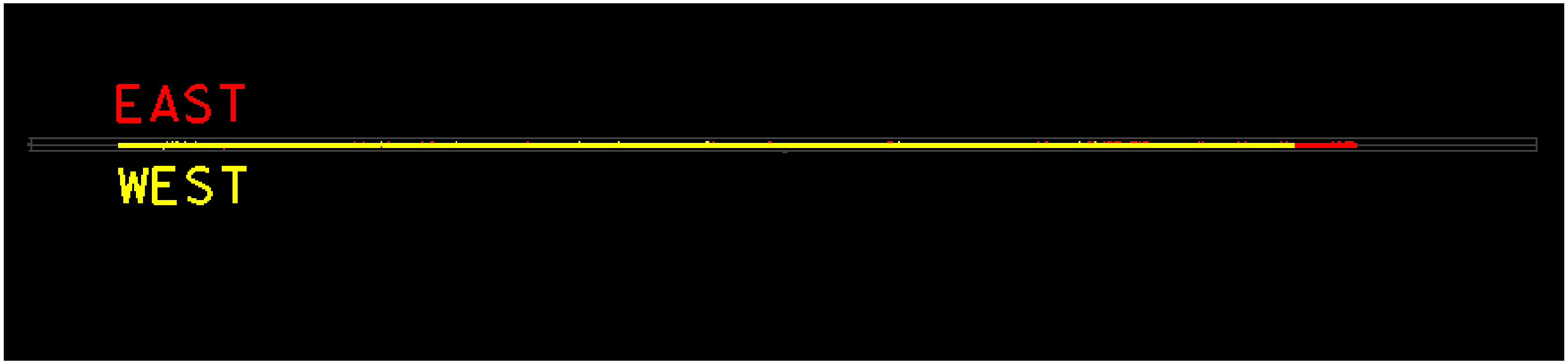
How do I check for roll error?

Step 7. Reprocess data with adjusted roll error of -0.00479



How do I check for roll error?

Step 8. Check that profiles coincide using adjusted roll error value.



Pitch Error
what is pitch error?

Pitch error defines the misalignment, in radians, around the Y axis between the IMU and the laser.

With the Scanner Assembly mounted with the cables to the front the Y axis is positive to the right wing of the aircraft. In this case a positive rotation will move the data forward.

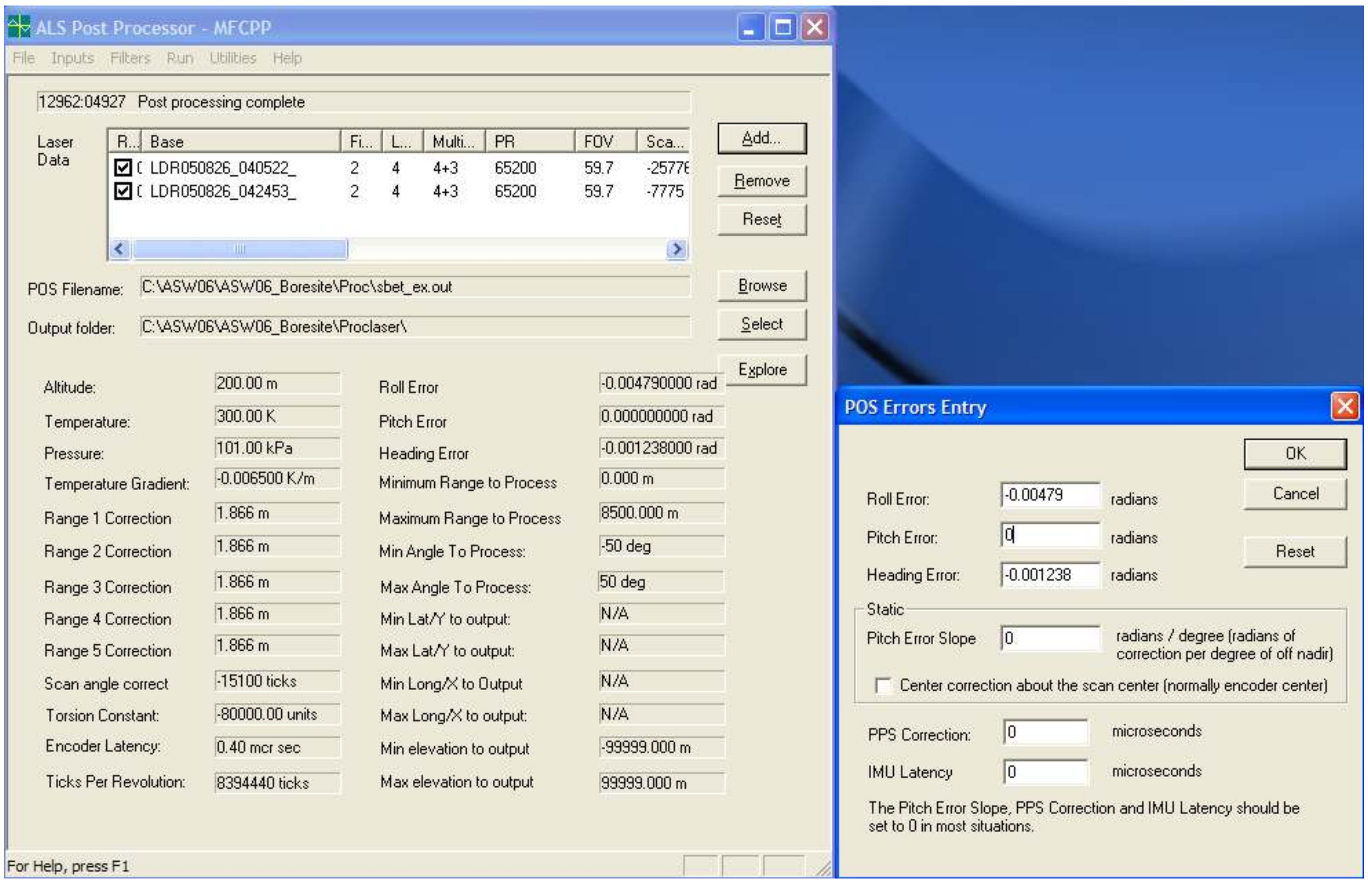
With the Scanner Assembly mounted with the cables to the rear the Y axis is positive to the left wing of the aircraft. In this case a negative rotation will move the data forward.

Pitch error moves all the data forward or back.

Pitch error is not apparent over a flat surface.

How do I check for pitch error?

Step 1. Collect data for a single flight line flown in opposite directions over an evenly sloped surface. Process with pitch error set to zero.



- when it has to be right

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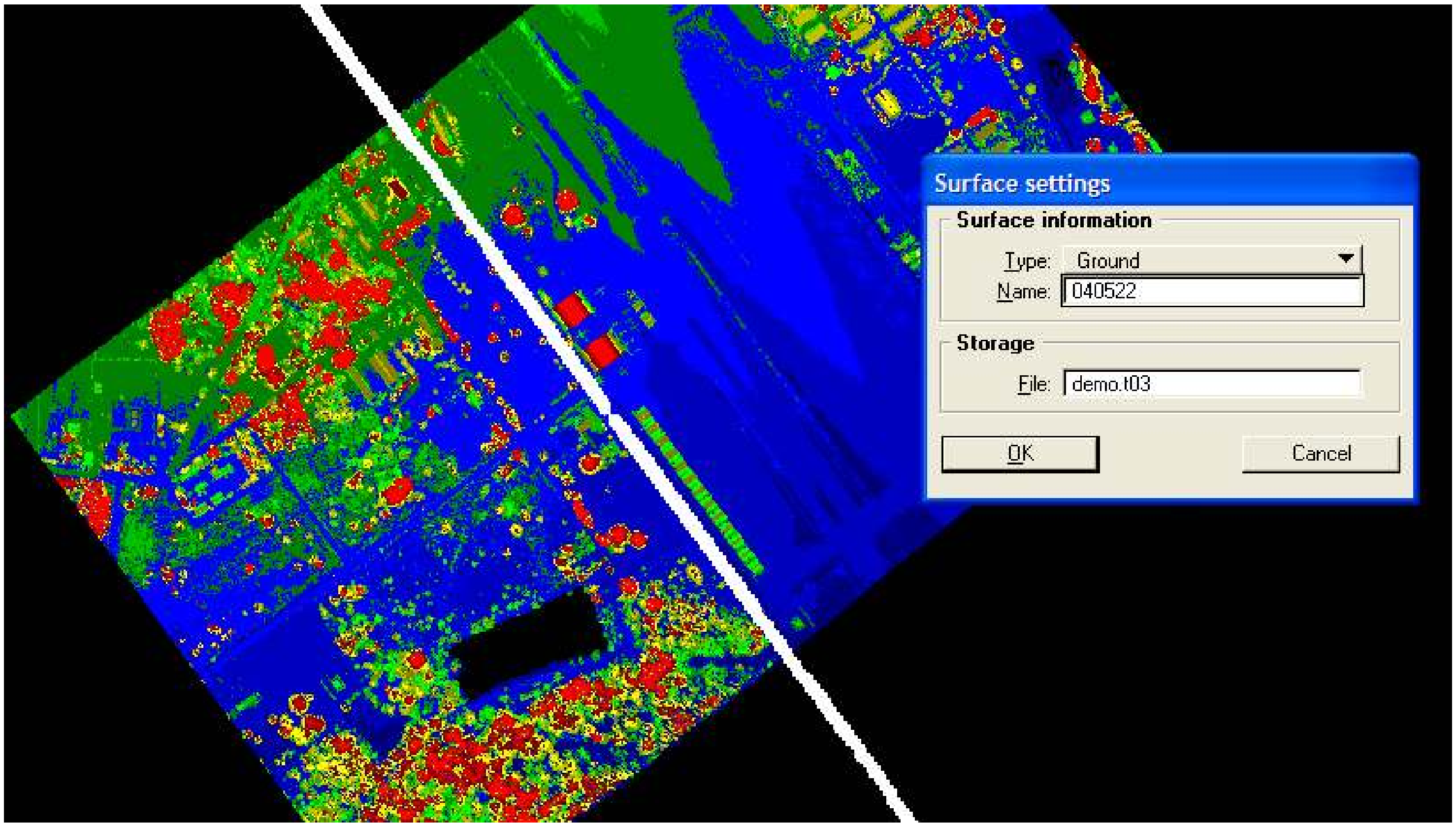
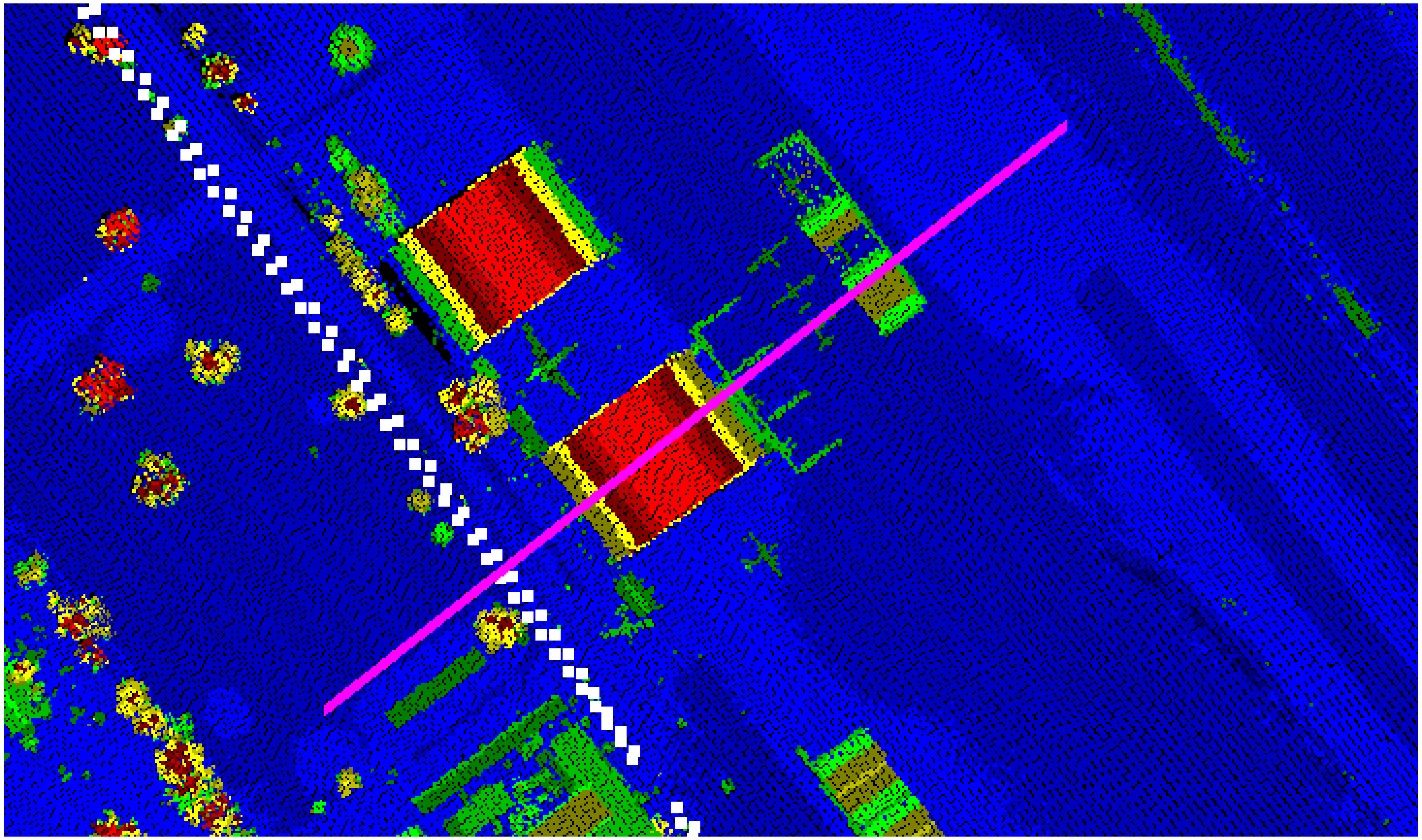
How do I check for pitch error?

Step 2. Load points in TerraScan and output surface models for the opposing flight lines



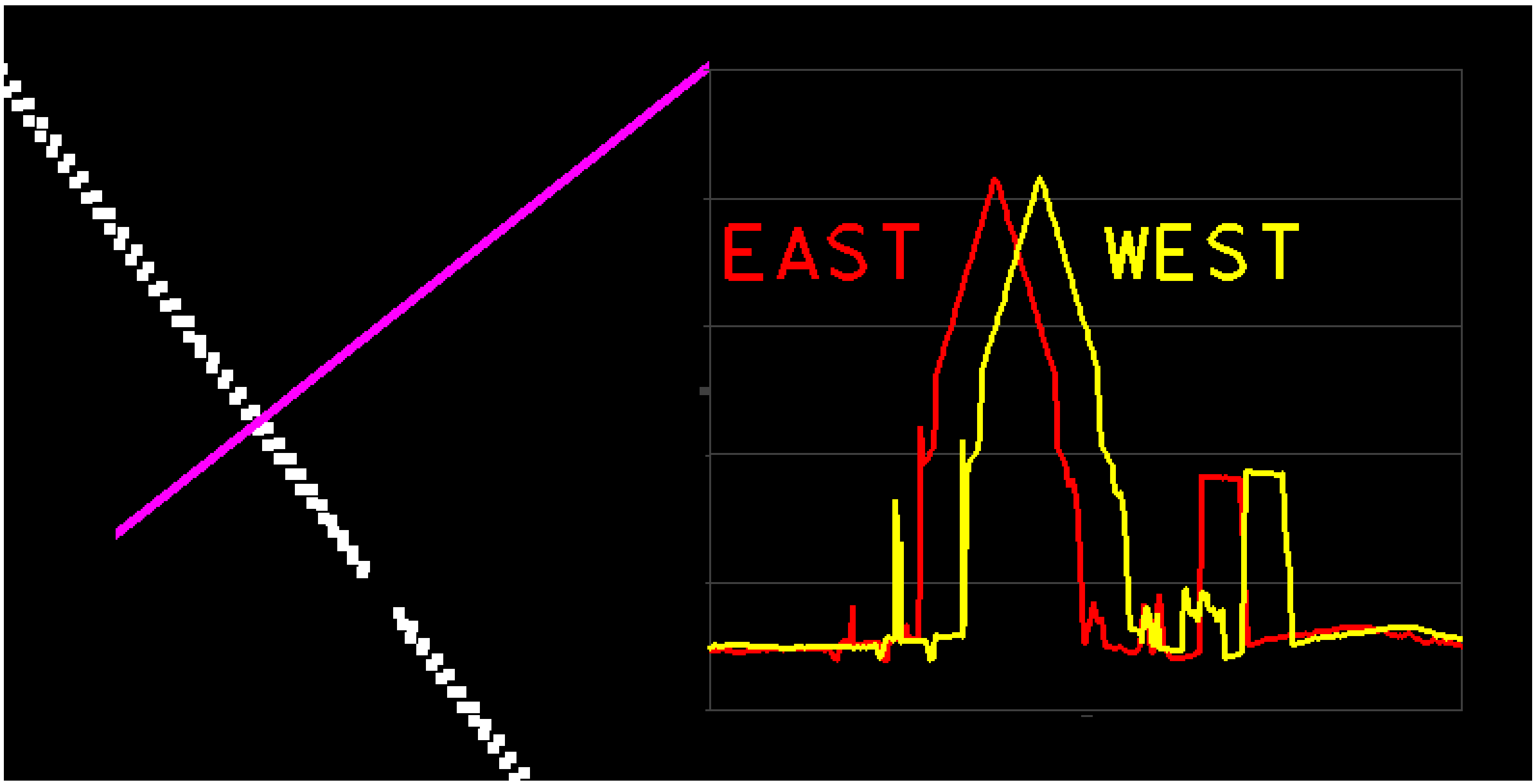
How do I check for pitch error?

Step 3. Select an evenly sloped area in the along track direction in the middle of the swath



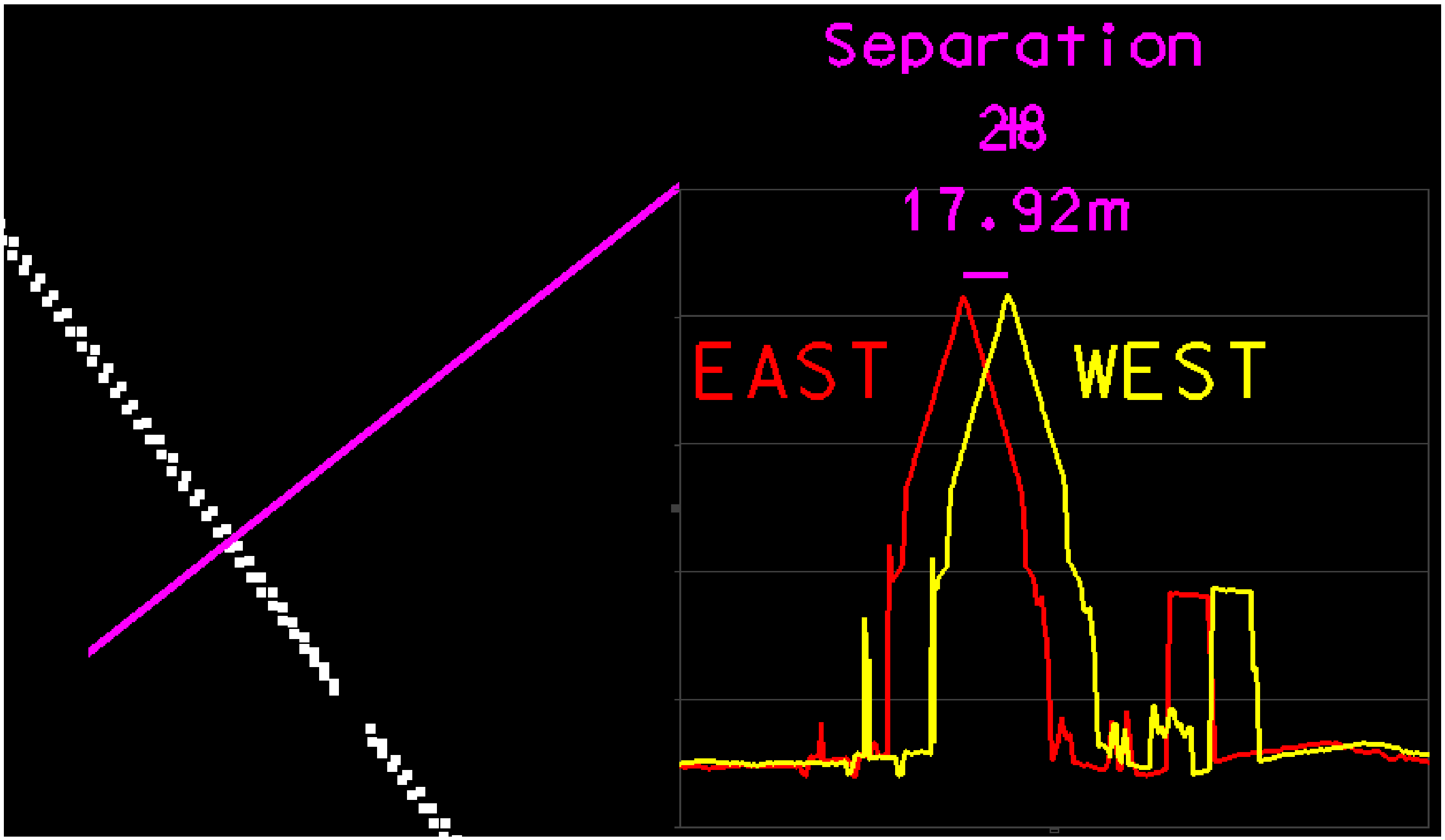
How do I check for pitch error?

Step 4. In TerraModeler draw a profile along track through both surfaces. If the pitch value is correct the surfaces should coincide.



How do I check for pitch error?

Step 5. If the surfaces do not coincide measure the separation and flying height. Adjust the initial pitch error value by separation divided by 2 divided by flying height.

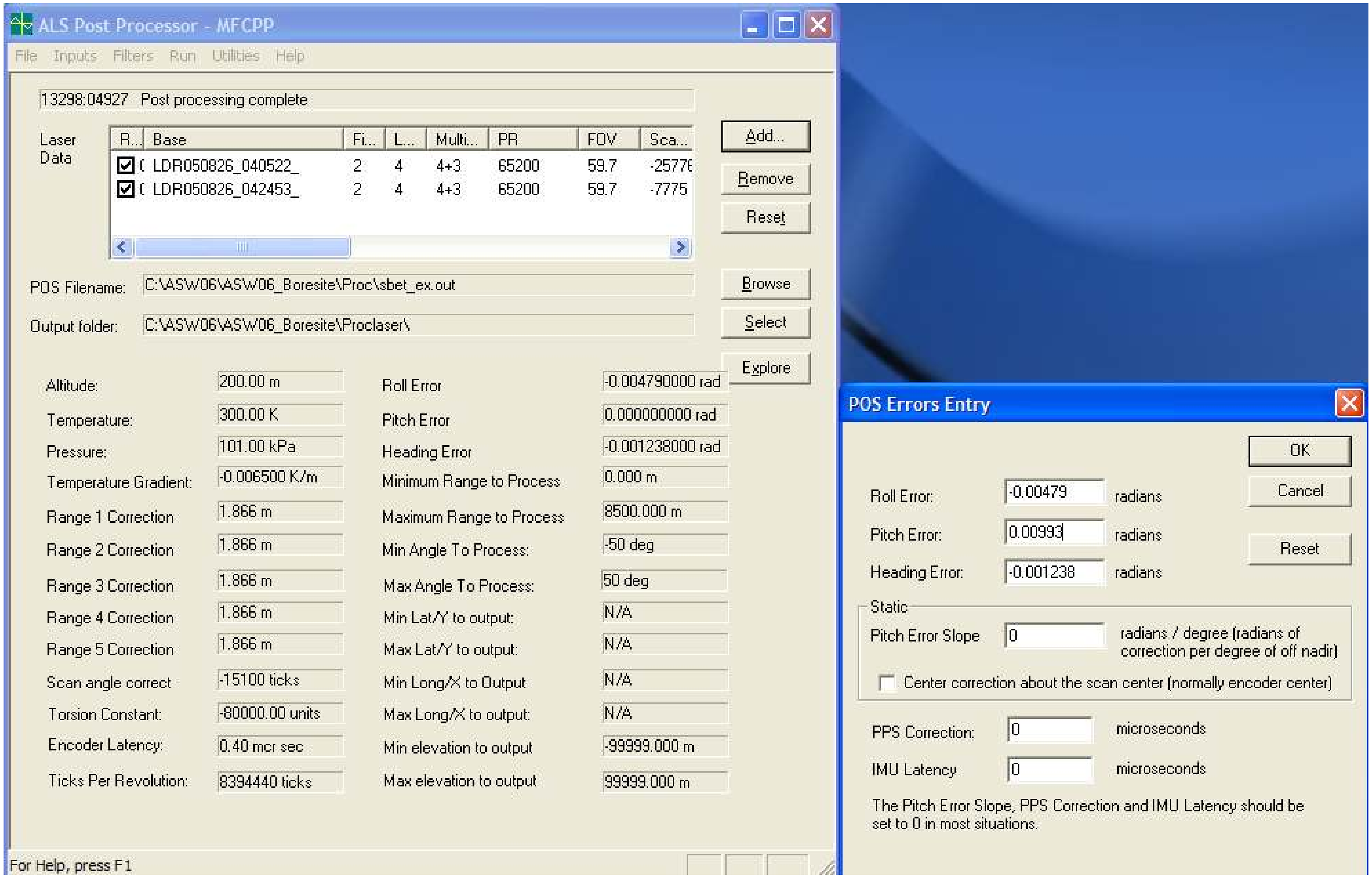


How do I check for pitch error?

Step 6. Initial pitch error 0.000000. Adjustment required is 17.92/2/902.5 = 0.00993. Adjustment required is forward. Adjusted pitch value is 0.00993

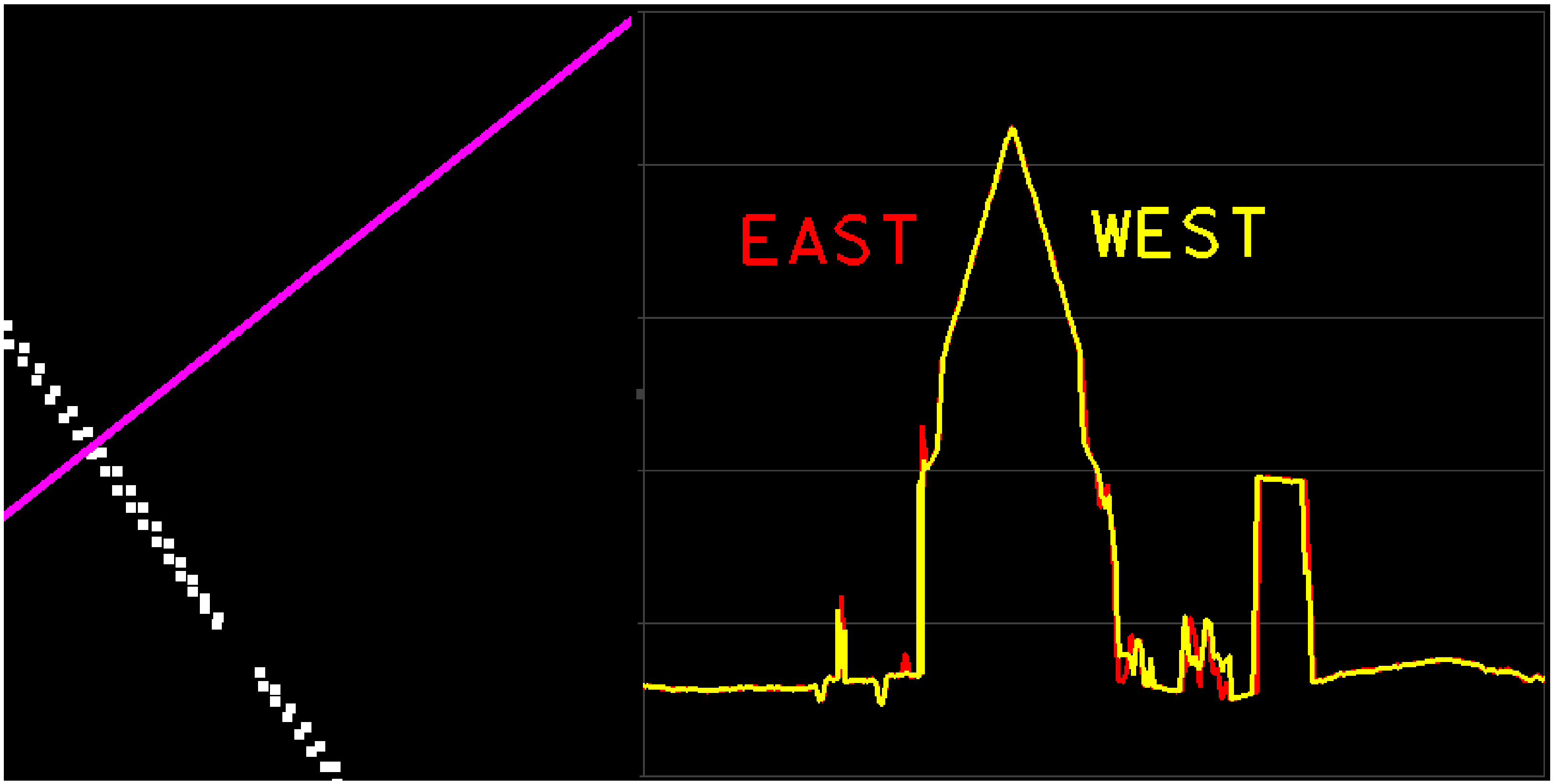
How do I check for pitch error?

Step 7. Reprocess data with adjusted pitch error of 0.00993



How do I check for pitch error?

Step 8. Check that profiles coincide using adjusted pitch error value.



- when it has to be **right**

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Heading Error
what is heading error?

Heading error defines the misalignment, in radians, around the Z axis between the IMU and the laser.

With the Scanner Assembly mounted with the cables to the front or to the rear the Z axis is positive to the ground.

A positive rotation will move the data forward on the left and to the rear on the right.

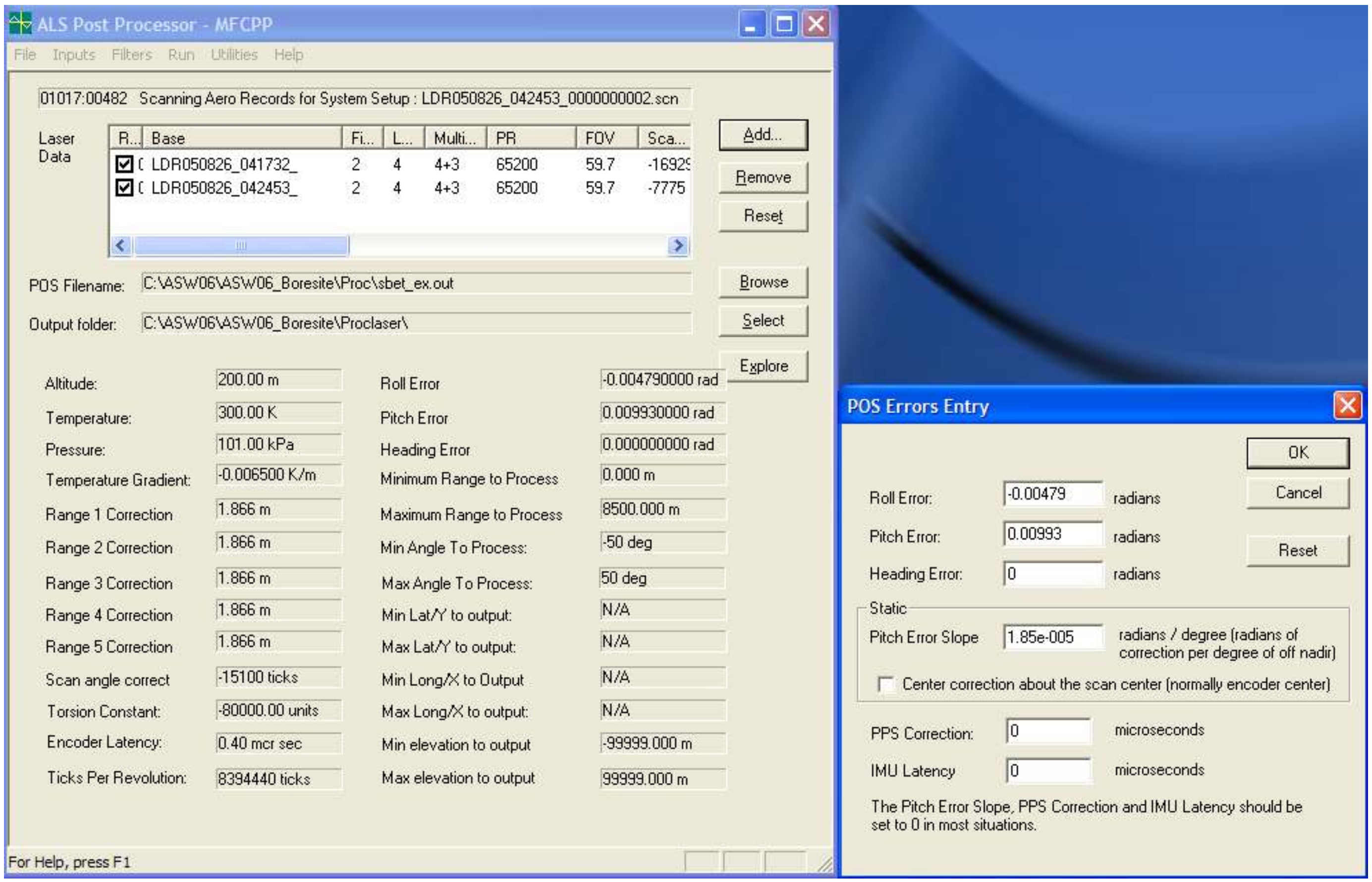
A negative rotation will move the data forward on the right and to the rear on the left.

There is no effect from heading error in the middle of the swath.

Heading error is not apparent over a flat surface.

How do I check for heading error?

Step 1. Collect data for two overlapping flight lines flown over an evenly sloped surface. Process with heading error set to zero.



- when it has to be right

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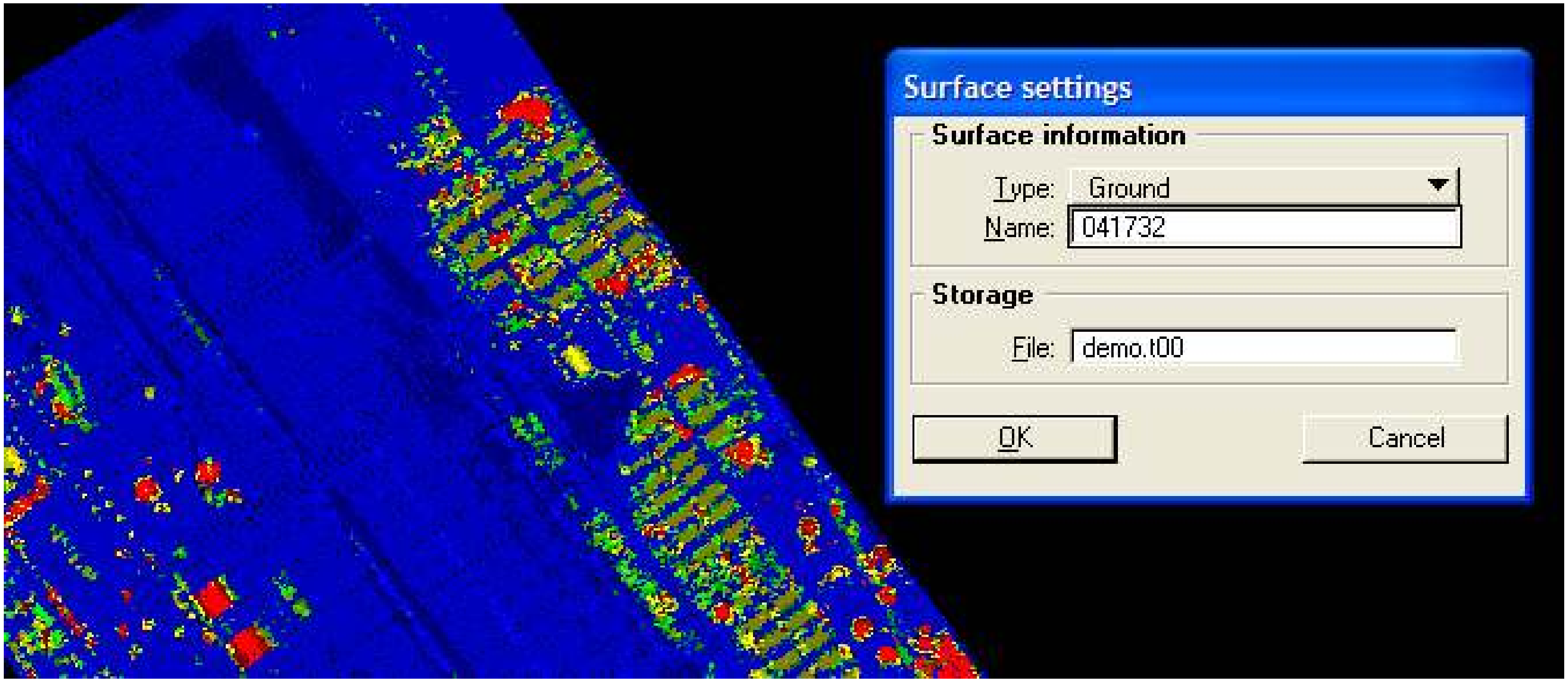
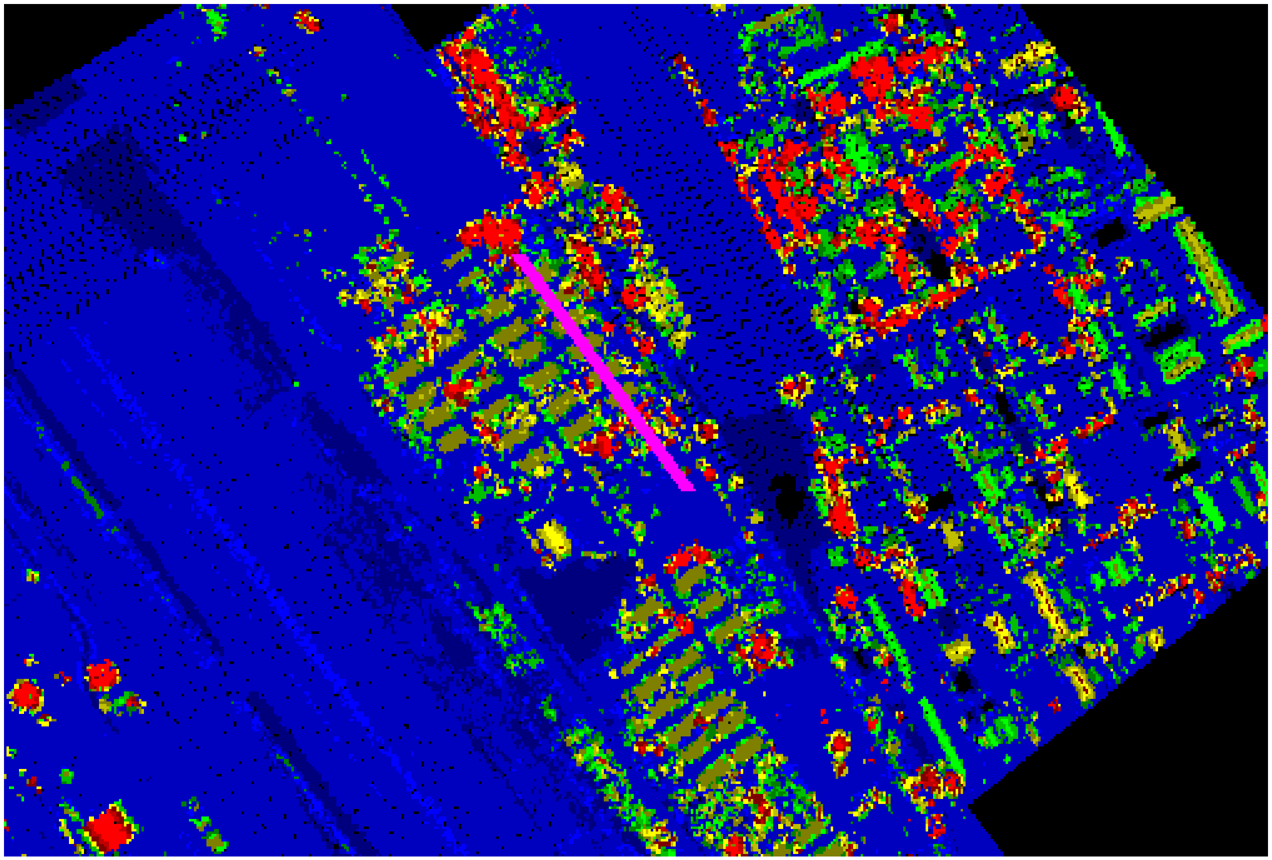
How do I check for heading error?
Step 2. Load points in TerraScan and output surface models for each flight line.



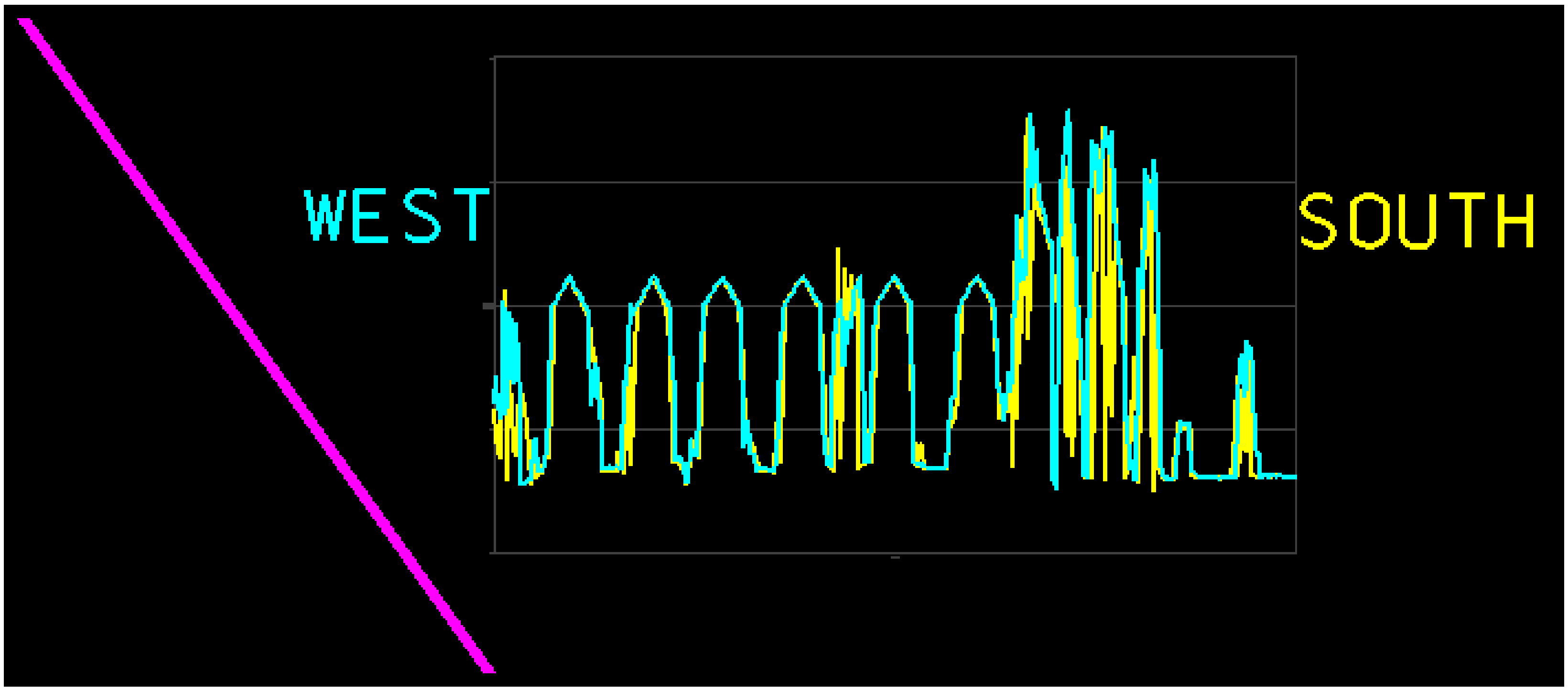
How do I check for heading error?

Step 3. Select an evenly sloped area in the along track direction on the edge of one swath and in the middle of the other swath.



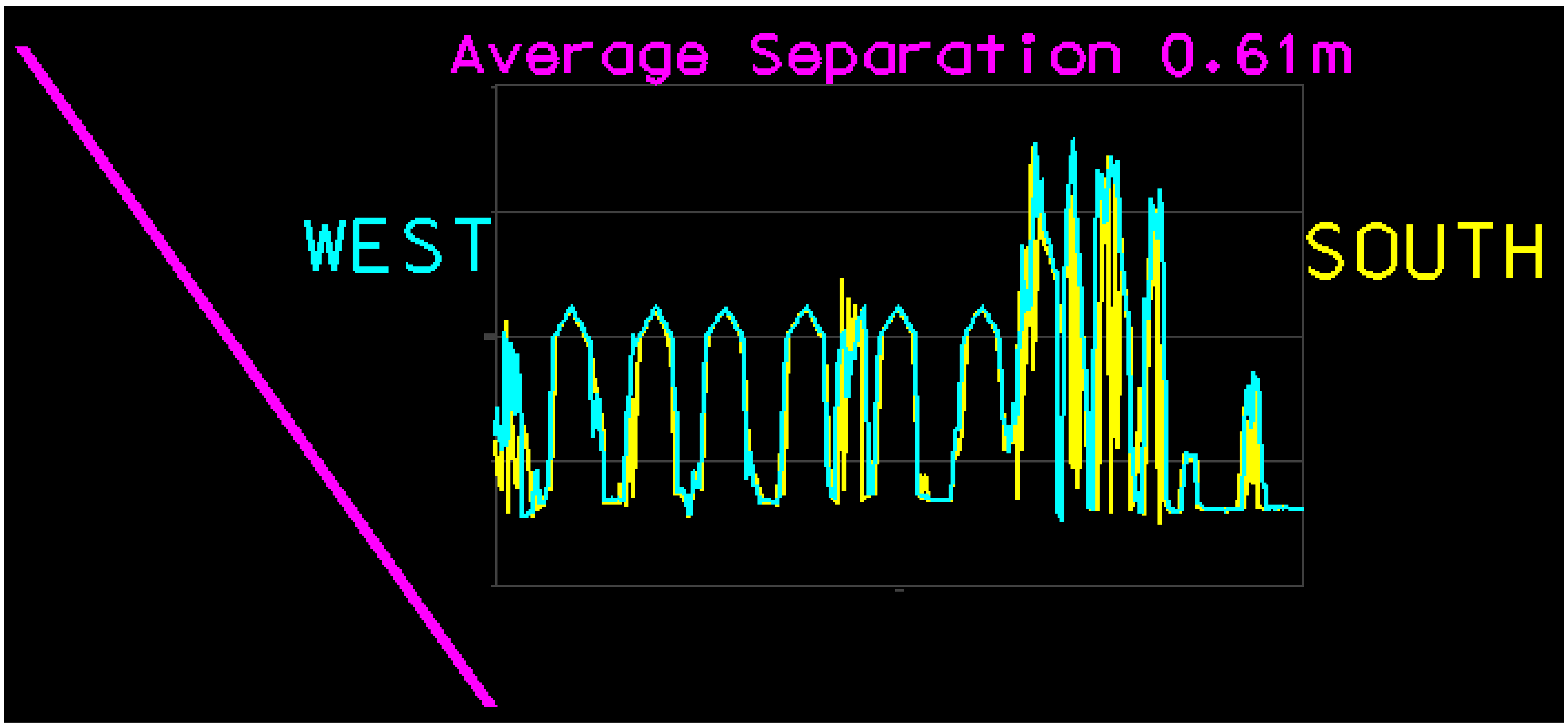
How do I check for heading error?

Step 4. In TerraModeler draw a profile along track through both surfaces. If the heading value is correct the surfaces should coincide.



How do I check for heading error?

Step 5. If the surfaces do not coincide measure the separation and distance from nadir. Adjust the initial heading error value by separation divided by distance from nadir.



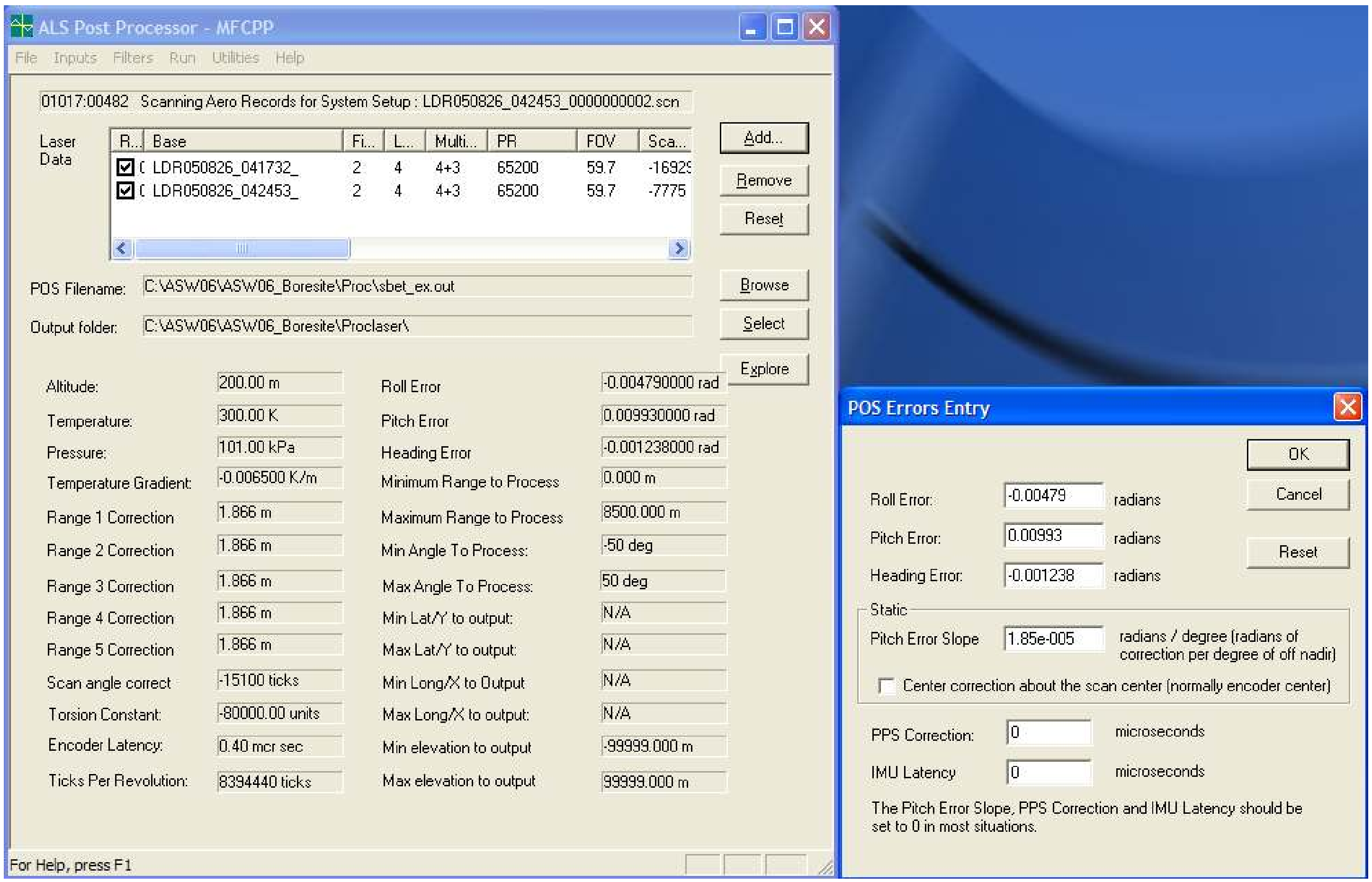
How do I check for heading error?

Step 6. Initial heading error 0.000000. Adjustment required is 0.61/493 = 0.001238. Adjustment required is to the rear on the left. Adjusted heading value is -0.001238

Note. In this example there is no heading effect on the west bound flight line as the profile location is in the nadir position.

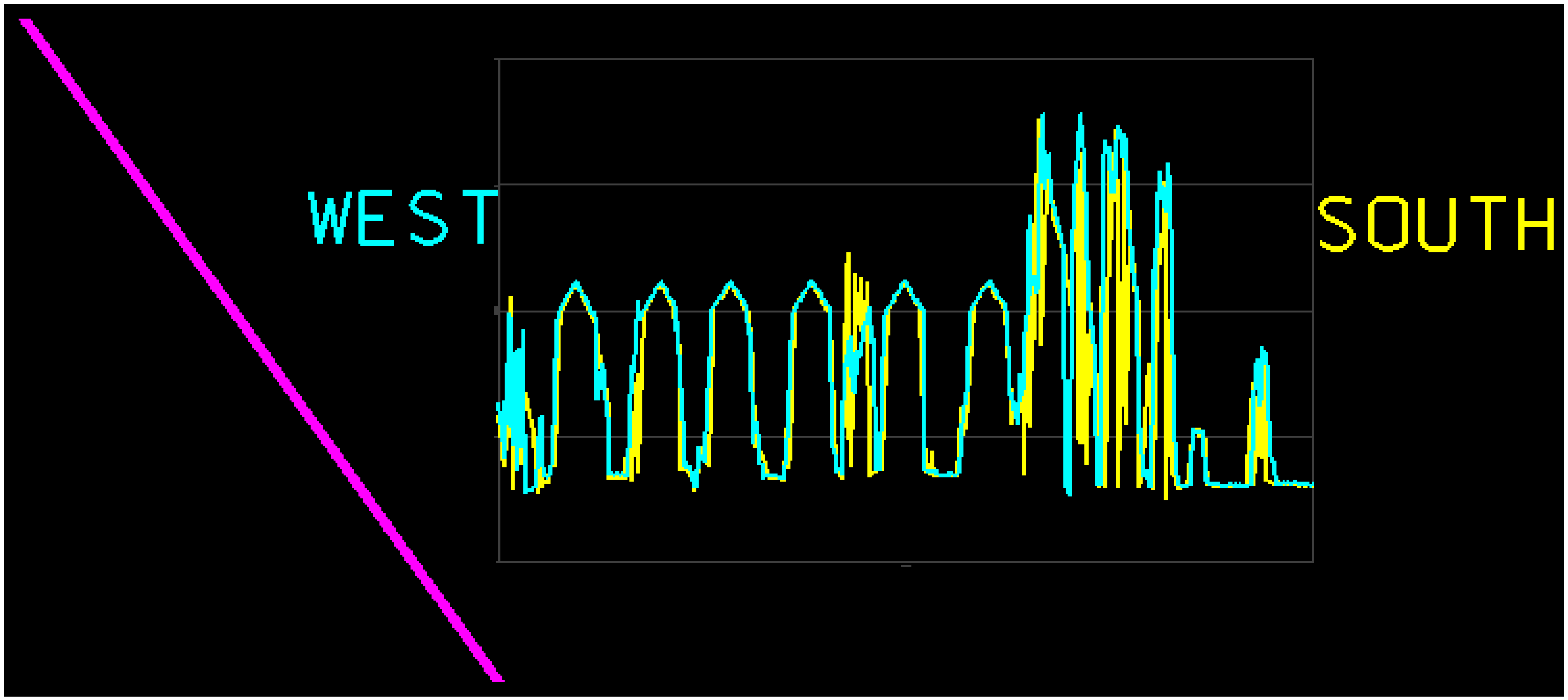
How do I check for heading error?

Step 7. Reprocess data with adjusted heading error of -0.001238



How do I check for heading error?

Step 8. Check that profiles coincide using adjusted heading error value.



- when it has to be **right**

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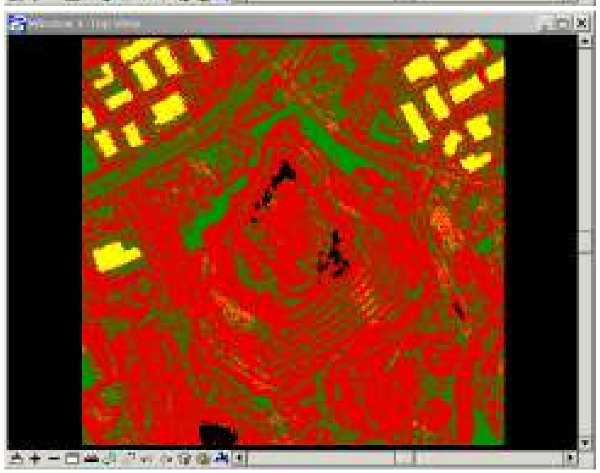
Leica Geosystems ‘Attune’

compute misalignment angle based on points and intensity image

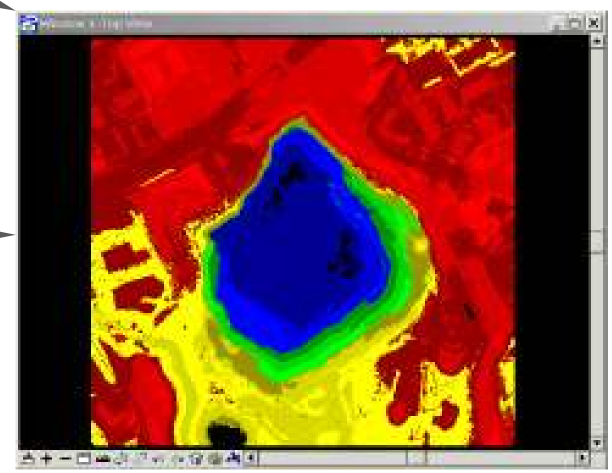


Classified elevation data (x, y, z, “ground points” class)

Intensity images (x, y, intensity) in which tie points will be picked

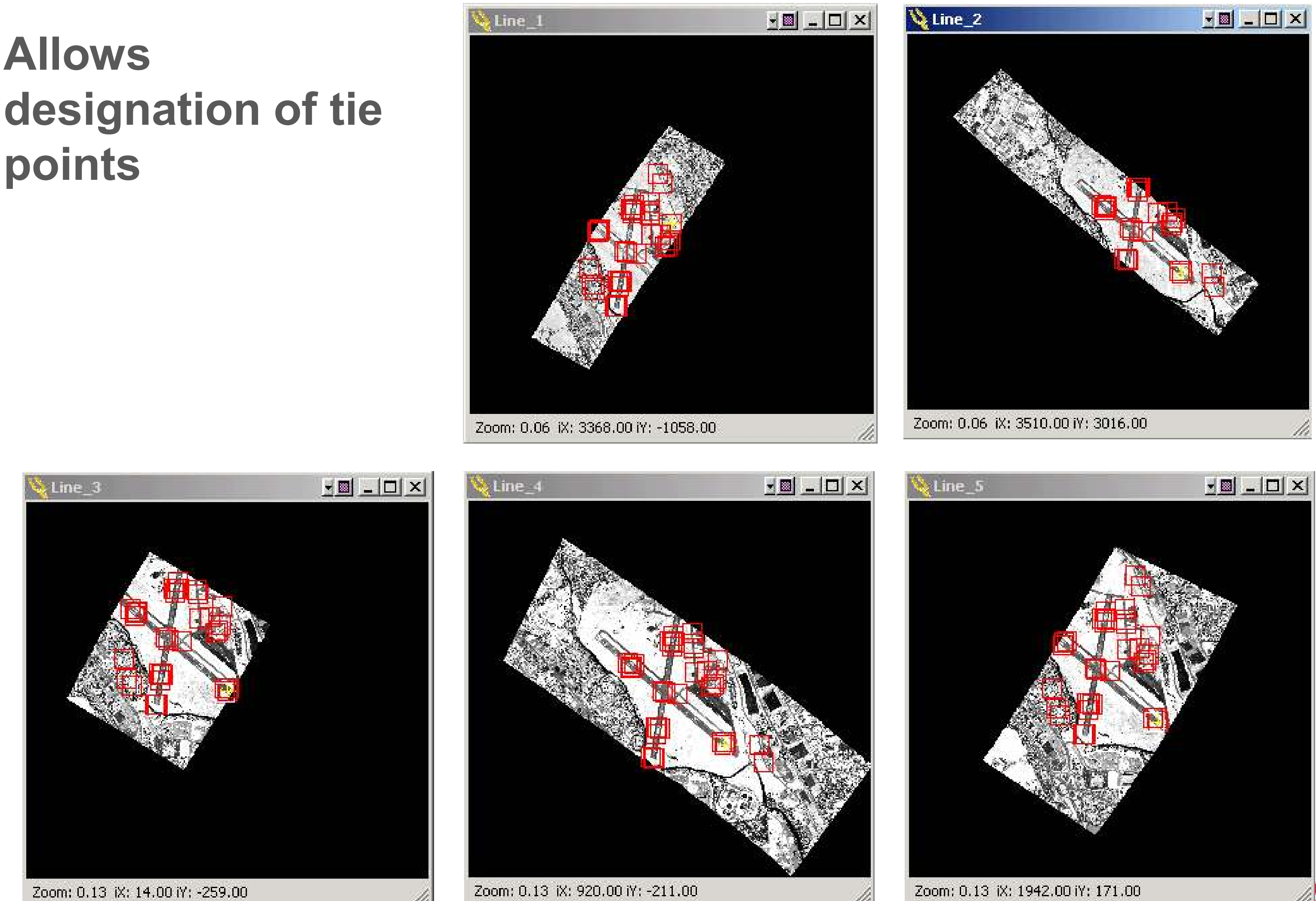
tie points

“ground class” only



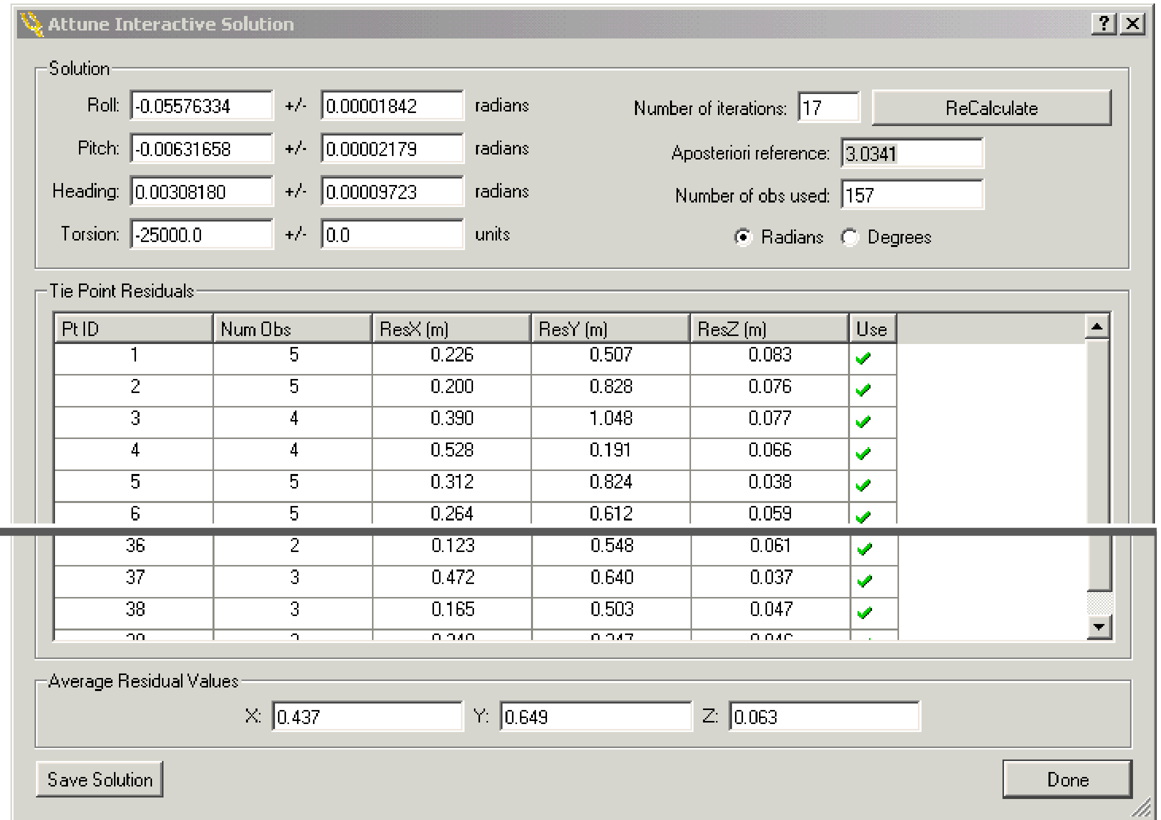
Attune tie point collection window

Allows designation of tie points



Attune tie point report window

- Provides feedback on residuals for individual selected points
- Provides calculations of system calibration parameters
- Provides error estimators for calibration coefficients provided



Conclusions

Good data accuracy is dependent on accurate determination of system calibration inputs.

Calibration requires a good trajectory solution, because all lidar measurements are based on the trajectory. Good Mission planning is essential for a calibration flight!

Thank you
questions?

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- when it has to be right

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