Argo Lidar calibration and test overview

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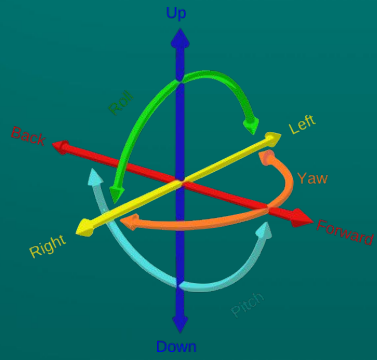
Intrinsic calibration overview



- We need to make sure that each sensor is producing a faithful representation of the world in its own coordinate system.
  - Lidar: Pointing knowledge, range, and reflectivity
- Intrinsic calibrations deal with geometries and phenomena which are intrinsic to the sensor.
- Some things that one might think of as important intrinsic parameters in fact are not critical, since the vehicle will undergo an extrinsic calibration process as well. For example:
  - Tilt in axis of rotation relative to normal of mounting surface.
  - Exact orientation of the zero azimuth position relative to locating features
  - Common feature: the point cloud can be made ‘correct’ with the choice of a suitable sensor 6-dof pose correction.
  - Counter example: Error in elevation pointing angle, resulting in horizon appearing above or below its nominal location. This cannot be corrected with a sensor 6-dof pose transformation

What is calibrated?

- Intrinsic calibration is really about making sure the point cloud is accurate.
  - We know where we're looking at all times
  - We know how far away the target is, to within bias and precision requirements, across the full operational design domain
- This leads to 4 key areas which we must consider:
  - **Azimuth estimation**
    - particularly encoder integrated nonlinearity
  - **Geometric intrinsics**
    - Extent of vertical field of view
    - Laser skew angle
  - **Range measurements**
    - Global range offset, range correction vs. elevation.
      - Future possibility: range correction vs. observed intensity
  - **Intensity / reflectivity estimation**
    - We are really looking at link loss vs. range, elevation, etc. This primarily derives from alignment, laser uniformity, and PDA performance gradients, and we may be able to accomplish this without system-level test data
- Post-calibration requirement: 0.1° static pointing accuracy
  - Corresponds to 35 cm placement error at 200 m

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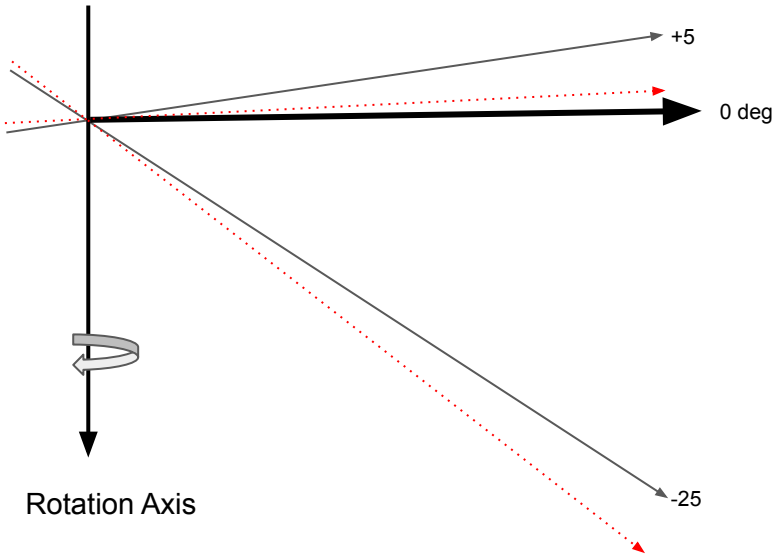
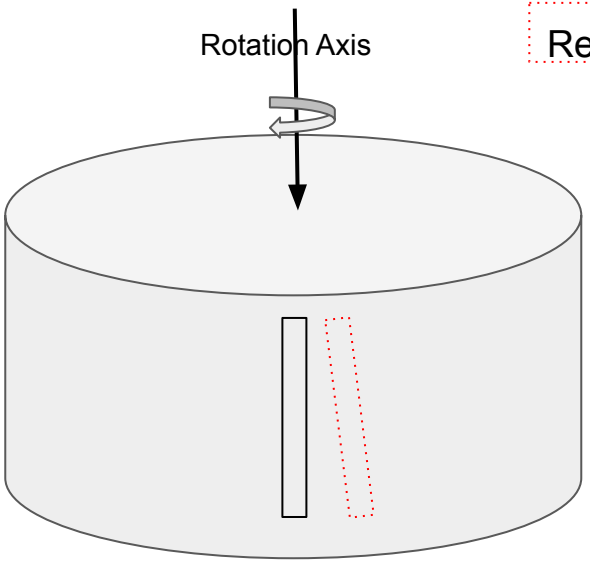
Geometric Calibration

Elevation FOV offset



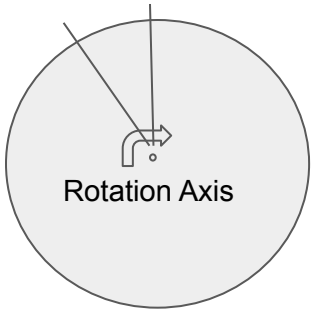
Laser Skew



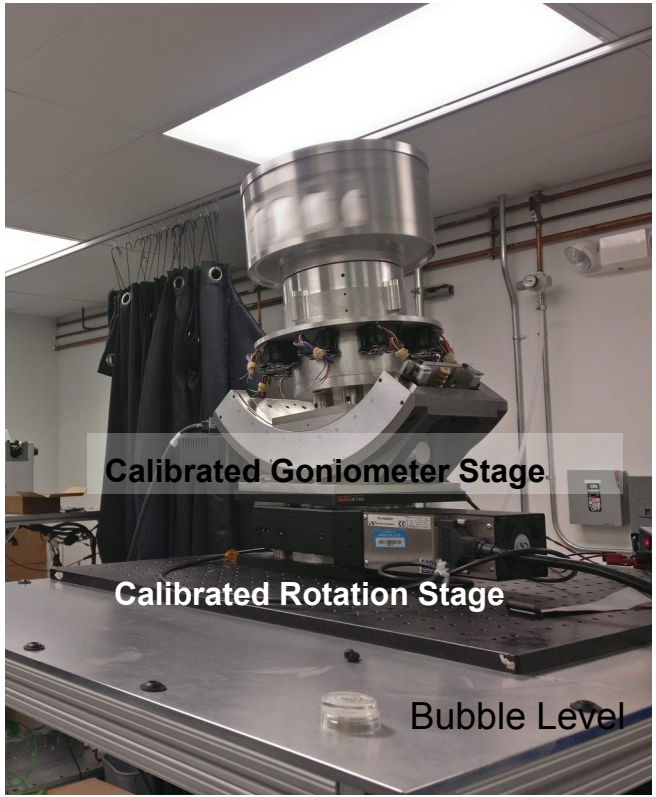
Azimuth Estimation

Reported Δθ = 14.5 deg

True Δθ = 15 deg



Geometric Calibration Setup



1. Mount lidar on intrinsic test cart setup
2. Adjust intrinsic test cart until level to ground
3. Set goniometer tilt to 0

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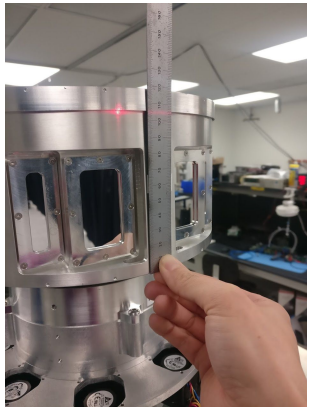
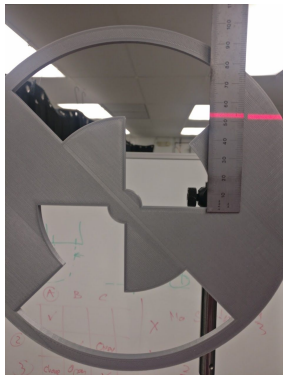
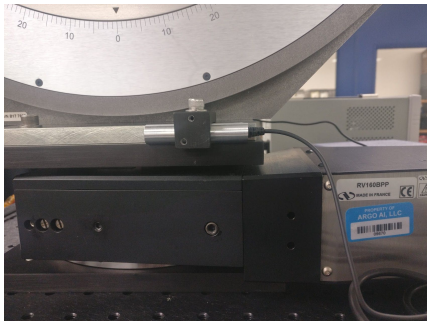
Geometric Calibration Setup

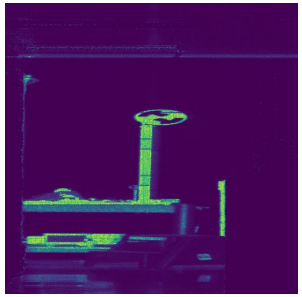


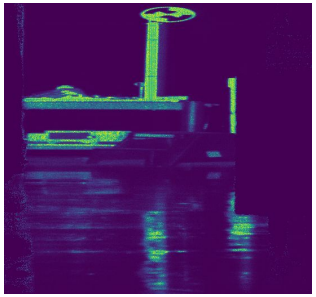


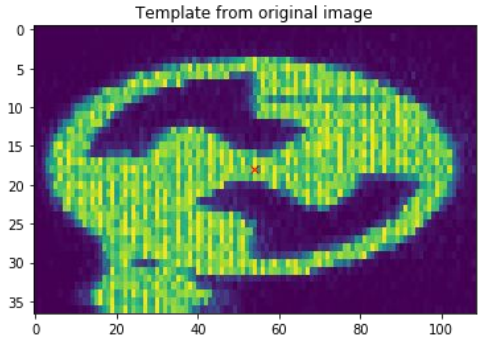


1. Mount lidar on intrinsic test cart setup
2. Adjust intrinsic test cart until level to ground
3. Set goniometer tilt to 0
4. Adjust laser level so that level line is at the height of the lidar origin
5. Position fiducial target with center at same height as lidar origin at minimum of 10 m away for SR, 20 m for LR
6. Adjust rotation stage so that goniometer tilts directly at target

Geometric Calibration Setup







Log collection time: ~ 8 min*
Analysis time: ~30 min

1. Mount lidar on intrinsic test cart setup
2. Adjust intrinsic test cart until level to ground
3. Set goniometer tilt to 0
4. Adjust laser level so that level line is at the height of the lidar origin
5. Position fiducial target with center at same height as lidar origin at minimum of 10 m away for SR, 20 m for LR
6. Adjust rotation stage so that goniometer tilt axis is perpendicular to target normal
7. Acquire raw gmapd data at different goniometer tilt, rotation stage positions
8. Process data to locate apparent center of fiducial at each position

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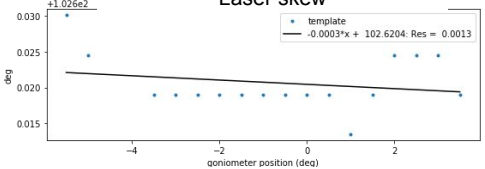
*Assumptions: 50 swaths at 10 Hz swath rate, 5 s reposition, 48 stage positions

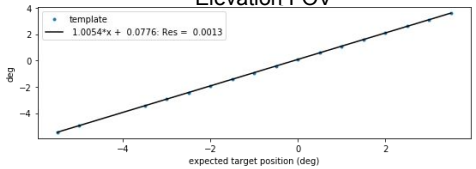
Output of Geometric Calibration

Goniometer Scan

Laser skew

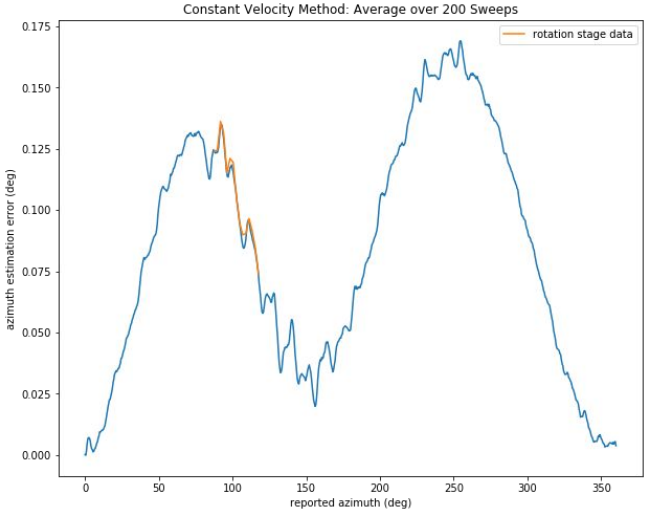


Elevation FOV



Rotation Stage Scan:

Match to alternative method - still needs to be verified with magnetic encoder



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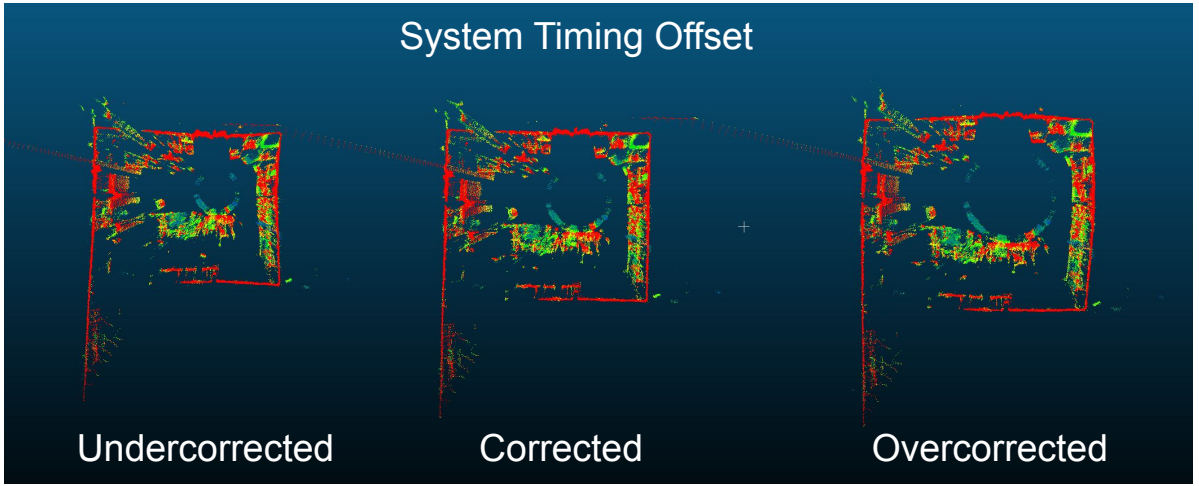
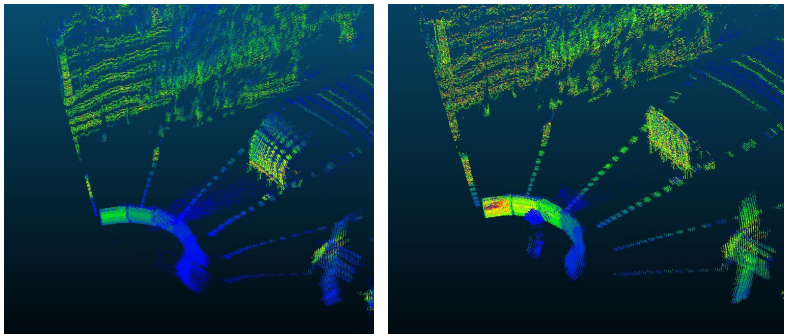
Range Calibration and Performance Testing

Factors to Calibrate:

1. System Timing Offset - adds constant range offset to all pixels
2. Pixel-to-pixel variation - breakdown voltage gradients, inhomogeneities



Underbiased: makes timing offset by pixel worse



Proper overbias: reduces effect of pixel variation

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Range Calibration and Performance Testing

Test Setup - Current setup

1. Test scene with calibrated diffuse reflectance targets (**5**, 10, 20, **53**, 74, **88%**) and retro targets at different ranges (**5**, 10, 15, 20, **25**, 30, 40, 60, **75** m for SR, out to 200 m for LR)
    a. As more lidars are built and modeling is validated, fewer targets and distances will be needed
    b. Solar simulator to be used indoors
2. Lidar on test cart - uses goniometer stage to adjust tilt so different pixels view target

Distance	Log Length (s)
5	1
10	2
15	4
20	7
25	13
30	16
40	28
50	63
60	63
75	112

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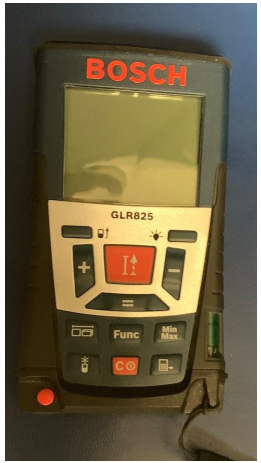
Additional equipment

Halogen lamps 2x 500W with variac for controlled background

Ground Truth Devices



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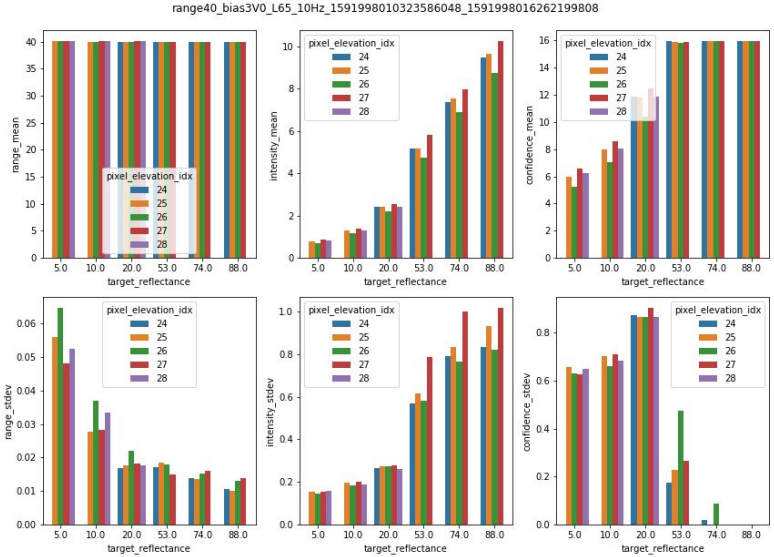
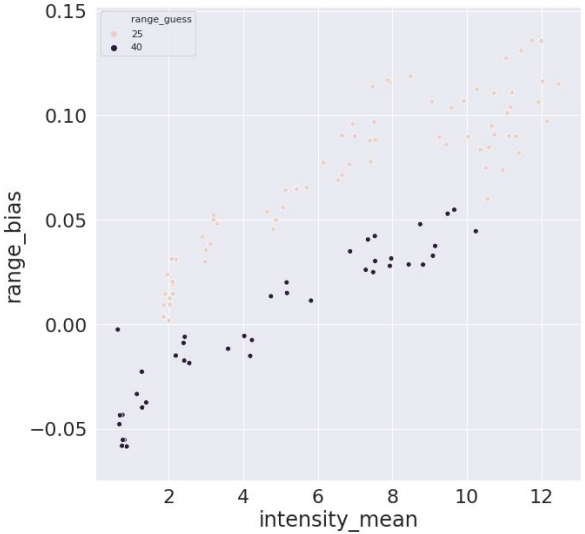
Performance Evaluation

Overlay with ground truth measurements

Extract statistics after segmenting targets



Evaluate uncorrected errors



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