A Comparison of Laser Scanners for Mobile Mapping Applications

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Presentation Outline

- Motivation
- Summary of Scanners Analyzed
- Test Description
- Analysis of Data
- Conclusions

Motivation for Study

- Majority of Systems Using Same/Similar GPS/INS Units
- Manufacturer LiDAR Specifications Based on Range and Angular Accuracy, Not Resultant 3D Point Cloud Accuracy/Precision
- Examination of Contribution of Scanner to Overall Error Budget of Mobile LiDAR System

Riegl VZ-400

Range Performance[1]

	Long Range Mode	*High Speed Mode*
Laser PRR (Peak) [2]	100 kHz	300 kHz
Effective Measurement Rate [2]	42 000 meas./sec	122 000 meas./sec
Max. Measurement Range [3] for natural targets $\rho \geq 90\%$ for natural targets $\rho \geq 20\%$	 600 m 280 m	 350 m 160 m
Max. Number of Targets per Pulse	practically unlimited [4]	practically unlimited [4]
Accuracy [5] [7]	5 mm	5 mm
Precision [6] [7]	3 mm	3 mm

Minimum Range 1.5 m
Laser Wavelength near infrared
Beam Divergence [8] 0.3 mrad

1) with online waveform processing
2) rounded values
3) Typical values for average conditions. Maximum range is specified for flat targets with size in excess of the laser beam diameter, perpendicular angle of incidence, and for atmospheric visibility of 23 km. In bright sunlight, the max. range is shorter than under an overcast sky.
4) details on request
5) Accuracy is the degree of conformity of a measured quantity to its actual (true) value.
6) Precision, also called reproducibility or repeatability, is the degree to which further measurements show the same result.
7) One sigma @ 100 m range under *RIEGL* test conditions.
8) 0.3 mrad correspond to 30 mm increase of beamwidth per 100 m of range.

Scan Performance

	Vertical (Line) Scan	Horizontal (Frame) Scan
Scan Angle Range	total 100° (+60° / -40°)	max. 360°
Scanning Mechanism	rotating multi-facet mirror	rotating head
Scan Speed	3 lines/sec to 120 lines/sec	0°/sec to 60°/sec [10]
Angular Stepwidth $\Delta\vartheta$ (vertical), $\Delta\varphi$ (horizontal)	$0.0024° \leq \Delta\vartheta \leq 0.288°$ [9] between consecutive laser shots	$0.0024° \leq \Delta\varphi \leq 0.5°$ [9] between consecutive scan lines
Angle Measurement Resolution	better 0.0005° (1.8 arcsec)	better 0.0005° (1.8 arcsec)

Riegl Q-120i

Maximum measurement range	
for wire targets, diameter ≥ 6 mm 2)	up to 45 m
for natural targets, reflectivity ρ ≥ 10 % 3)	up to 150 m
Minimum range	2 m
Accuracy 4) 6)	20 mm
Precision 5) 6)	15 mm
Laser Pulse Repetition Rate	30 000 Hz
Effective measurement rate	10 000 measurements/sec.
Laser wavelength	near infrared
Laser beam divergence 7)	2.7 mrad

1) First or last target mode selectable. Maximum measurement range and accuracy is defined below for a visibility >1km, overcast sky or night.
2) Diameter of wire in excess of 6 mm. Diffuse reflectivity of wire surface in excess of 15%. Beam incidence perpendicular to wire. The maximum measurement range to the specified target drops to 30 m in case of an angle of incidence of 45 deg, provided that the surface of the wire is reflecting strictly diffusely.
3) Diffuse reflectivity in excess of 10%. Beam incidence perpendicular to target. Size in excess of laser beam diameter. Maximum measurement range for an extended flat target of 10 % reflectivity will drop to 100 m for an angle of incidence of 45 deg.
4) Accuracy is the degree of conformity of a measured quantity to its actual (true) value.
5) Precision, also called reproducibility or repeatability, is the degree to which further measurements show the same result.
6) One sigma @ 50 m range under *RIEGL* test conditions.
7) 2.7 mrad correspond to 27 cm increase of beam width per 100 m of range.

Scanner performance

Scan angle range 8)	± 40° = 80° total
Scanning mechanism	rotating polygon mirror
Scan speed	5 to 100 scans / sec
Angular step width $\Delta\vartheta$ 8) between consecutive laser shots	$\Delta\vartheta \geq 0.04°$
Angle measurement resolution	0.01°

Velodyne HDL-64E S2

Specifications	
Sensor:	• 64 lasers/detectors • 360 degree field of view (azimuth) • 0.09 degree angular resolution (azimuth) • 26.8 degree vertical field of view (elevation) - +2° up to -24.8° down with 64 equally spaced angular subdivisions (approximately 0.4°) • <2 cm distance accuracy (one sigma) • 5-15 Hz field of view update (user selectable) • 50 meter range for pavement (~0.10 reflectivity) • 120 meter range for cars and foliage (~0.80 reflectivity) • >1.333 M points per second • Operating temperature - 10° to 50° C • Storage temperature - 10° to 80° C
Laser:	• Class 1 - eye safe • 4 x 16 laser block assemblies • 905 nm wavelength • 5 nanosecond pulse • Adaptive power system for minimizing saturations and blinding

~ 2 mrad Beam Divergence

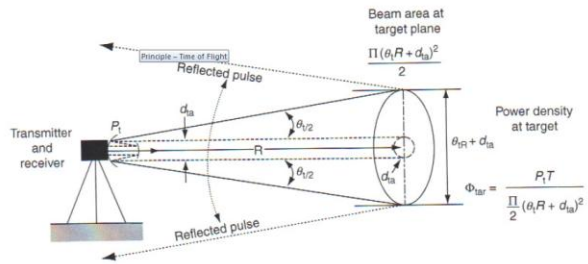
Personal Observations Regarding Scanners Studied

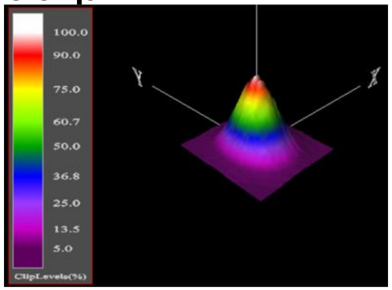
- Q-120i and VZ-400 accuracy specifications on range likely pessimistic (closer15 mm and 3 mm respectively)
- HDL-64E range accuracy specs optimistic (2.5 cm RMSE)[1,2] without additional calibration
- HDL-64E angular resolution closer to quantization level (0.025°)[1,2]

[1] Glennie, C.; Lichti, D.D. "Temporal Stability of the Velodyne HDL-64E S2 Scanner for High Accuracy Scanning Applications." Remote Sens. 2011, 3, 539-553.
[2] Glennie, C.; Lichti, D.D. "Static Calibration and Analysis of the Velodyne HDL-64E S2 for High Accuracy Mobile Scanning." Remote Sens. 2010, 2, 1610-1624.

Discussion of Angular Uncertainty

- Beam Divergence causes inherent uncertainty in angular location of laser return:[1,2]
  - Apparent location is along centerline of emitted beam
  - Actual location is anywhere within projected beam footprint
  - σ/4 for uniform beam





- Angular Uncertainty a Combination of Beam Divergence and Encoder Resolution/Accuracy

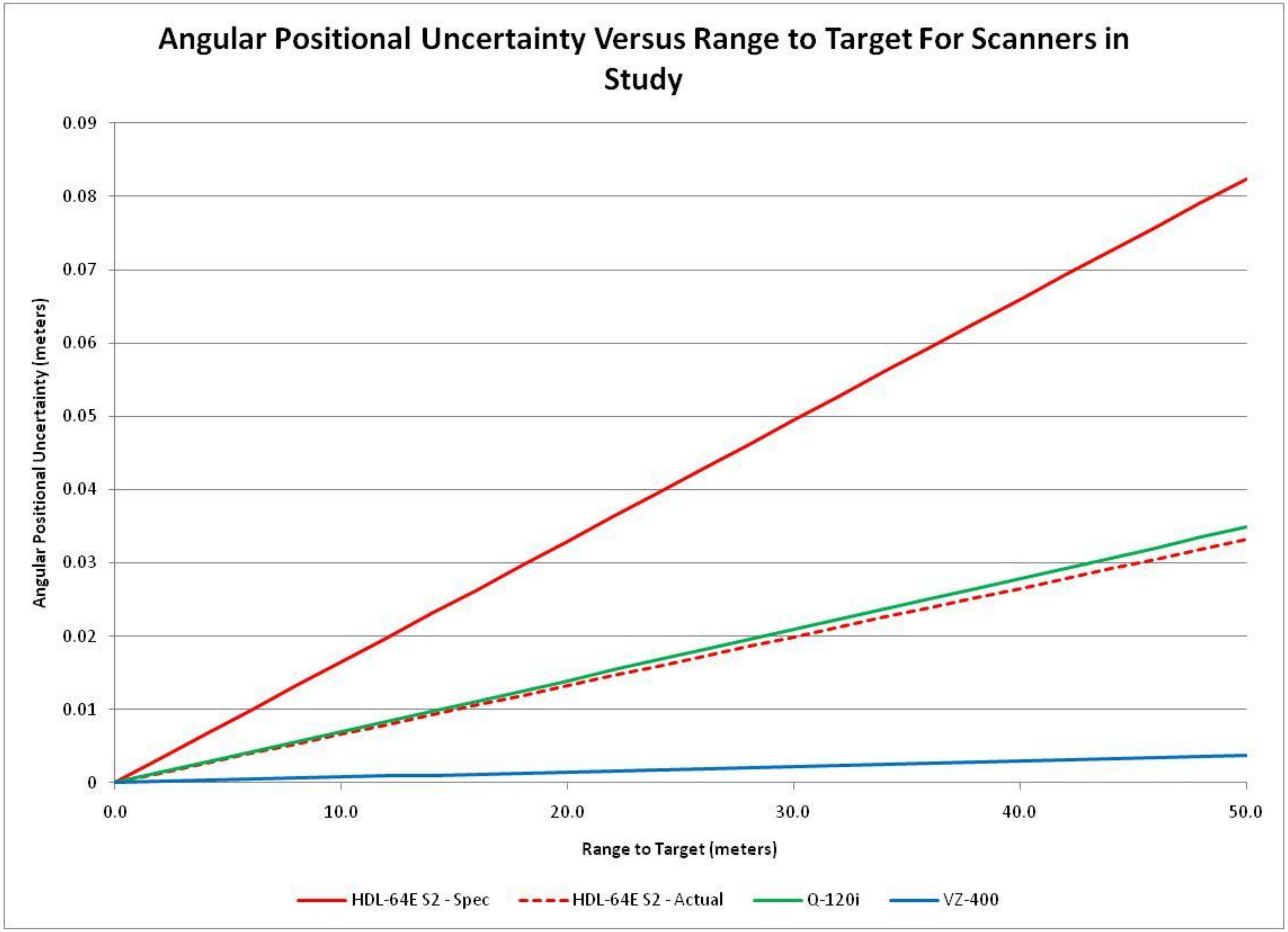
Laser	Divergence (mrad)	Angle Resolution (°)	Angular Uncertainty (°)
HDL-64E S2	2	0.0900	0.0944
HDL-64E S2*	2	0.0250	0.0380
Q-120i	2.7	0.0100	0.0399
VZ-400	0.3	0.0005	0.0043

*considering observed angular error

[1] Glennie, C., (2007). Rigorous 3D error analysis of kinematic scanning LIDAR systems. Journal of Applied Geodesy 1, 147-157.

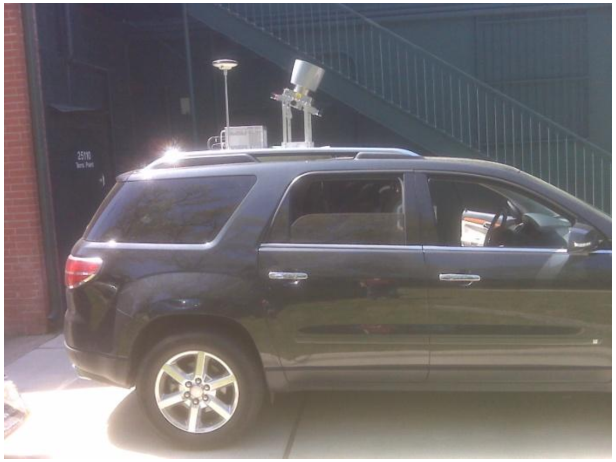
[2] Lichti, D.D., and S.J. Gordon (2004). Error Propagation in Directly Georeferenced Terrestrial Laser Scanner Point Clouds for Cultural Heritage Recording. Proceedings of FIG Working Week, Athens, Greece, May 22-27.

Angular Uncertainty Versus Range



Test Description

- All Three Lasers Tested With Identical GPS/INS System
  - IMAR iNAV-RQH-003 Navigation Grade IMU
    - 0.005° Roll/Pitch, 0.01° Heading Accuracy
    - 0.8 nm/hr or 0.003 °/h drift rate
    - Comparable to Applanix 510
  - Novatel OEM IV GPS
    - Dual Frequency GPS Only
  - Control Interface and Data Logging for GPS/INS and Laser Developed by Terrapoint



Test Description

- Data Collection in Unobstructed Parking Lot
  - Each Test Had a Minimum of 8 GPS Satellites Continosly Visible
  - Results Meant to Show Overall Noise Level of Combined System (Laser and GPS/INS)
  - VZ-400 – 10/15/2009, HDL-64E S2 – 3/23/2010, Q-120i – 5/01/2010

Data Processing Description

- Trajectory For Each Test Determined Using Terrapoint CAPTIN Tightly Coupled GPS/INS Software With Optimal Smoothing
  - In all Three Tests, Fwd/Rev Seperation < 2 cm All the Time
- Trajectory and Raw Laser Data Combined Using Terrapoint LPP (Laser Post Processing) Software to Create Georeferenced Point Clouds
- Boresights and Lever Arms Estimated in a Least Squares Adjustment Using Planar Surfaces As Observables.
- Majority of Range Observations < 20 meters

Velodyne Scanner Calibration

- [1, 2] noted that factory calibration of Velodyne scanner showed systematic trends in static point clouds
- Papers proposed and implemented an enhanced mathematical model for the scanner.
- 3D RMSE of resultant static point cloud improved from 3.6 cm to 1.3 cm.
- Therefore, proceedings results for Velodyne quoted with both factory calibration, and with enhanced calibration values.

[1] Glennie, C.; Lichti, D.D. "Temporal Stability of the Velodyne HDL-64E S2 Scanner for High Accuracy Scanning Applications." Remote Sens. 2011, 3, 539-553.
[2] Glennie, C.; Lichti, D.D. "Static Calibration and Analysis of the Velodyne HDL-64E S2 for High Accuracy Mobile Scanning." Remote Sens. 2010, 2, 1610-1624.

Planar Adjustment Analysis

- Georeferenced LiDAR Points Given By:

$$\vec{r} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}^m = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{GPS} + R_b^m \left[R_s^b \begin{pmatrix} lx \\ ly \\ lz \end{pmatrix} + \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}^b \right]$$

IMU-Laser Offsets

Rotation – Body to Mapping Frame (IMU)

Boresight Rotation Matrix

Local Scanner Coordinates

- Georeferenced LiDAR Points Are Conditioned to Lie On Planar Surfaces[1], i.e.

$$\left\langle \vec{g}_j, \begin{bmatrix} \vec{r} \\ 1 \end{bmatrix} \right\rangle = 0 \qquad \vec{g}_j = \begin{bmatrix} g_1 & g_2 & g_3 & g_4 \end{bmatrix}^T$$

Plane Constants

- Solution by Combined, or Gauss-Helmert Least Squares Adjustment Model[1]

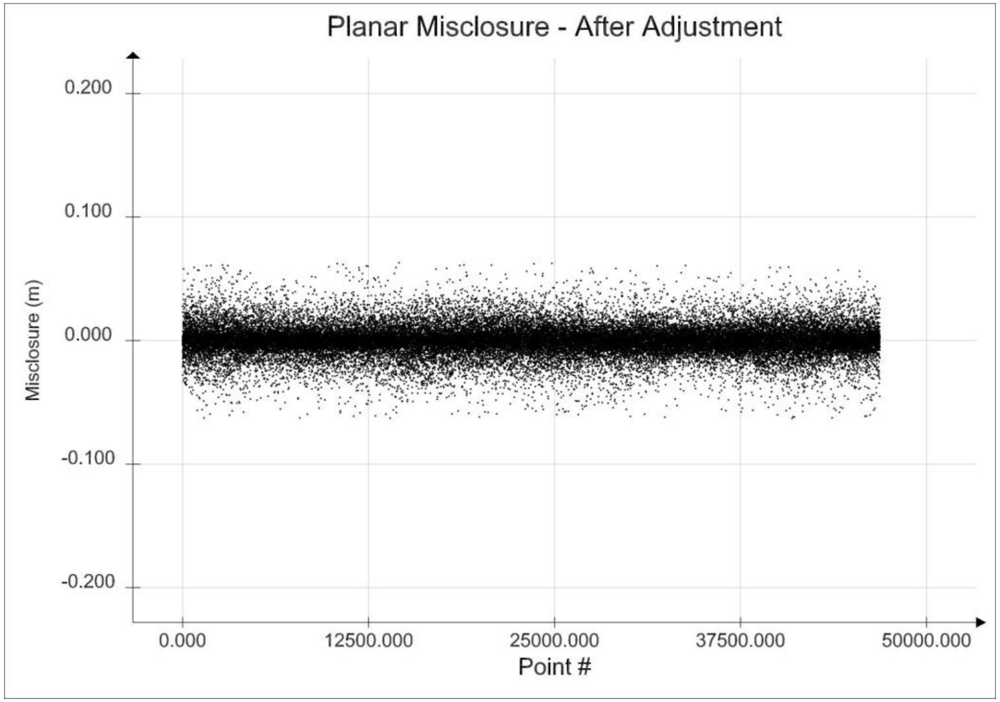
[1] Skaloud, J., Lichti, D., 2006. Rigorous approach to bore-sight self-calibration in airborne laser scanning. ISPRS Journal of Photogrammetry & Remote Sensing 61, 47-59.

Planar Adjustment Analysis

- Adjustment is used to solve for Lever arm offset and boresight angles between IMU and Laser
- Solution is highly redundant, and therefore Least Squares Adjustment allows examination of residuals w.r.t. planar surfaces
- Residuals on planar surfaces should represent combined noise level of GPS/INS solution and laser scanner
  - Assuming all systemic errors have been accounted for
- All Planar Surfaces Observed More Than Once Temporally, and At Different Ranges/Orientation Angles

Planar Parameter Analysis

- Residuals of Adjustment for Velodyne Scanner
- Similar (although different magnitude) for VZ-400 and Q-120i.
- No Systematic trends apparent in residuals



LiDAR Scanner Comparison

- Residuals Are W.R.T. Planar Surfaces

	LMS-Q120i	VZ-400	Velodyne HDL -64E S2*	Velodyne HDL-64E S2
RMSE (m)	0.021	0.013	0.027	0.036
Mean (m)	0.000	0.000	0.000	0.000
Minimum (m)	-0.116	-0.052	-0.143	-0.171
Maximum (m)	0.124	0.052	0.149	0.173

* With additional laboratory calibration

Examination of Trajectory Noise

- Final 3D RMSE Should be Combination of Trajectory Noise (σ_{nav}), Range Noise(σ_R), and Angular Uncertainty(σ_θ)

$$RMSE_{3D} = \sqrt{\sigma_{nav}^2 + \sigma_R^2 + \sigma_\theta^2}$$

- Given This Relationship, The Following Table Is Populated

	3D RMSE (m)	σ_{nav} (m)	σ_R (m)	σ_θ (m)
VZ-400	0.013	0.0125	0.003	0.002
Q-120i	0.021	0.0085	0.015	0.012
HDL-64E S2*	0.027	0.0136	0.020	0.012
HDL-64E S2	0.036	0.0229	0.025	0.012

Specifications

Extrapolation to Other Scanners

- Riegl VQ-250 – 10 mm, 0.3 mrad, 0.001°
  - Angular Uncertainty of 2 mm at 20 m.

- Expected 3D RMSE Is Then:

$$RMSE_{3D} = \sqrt{(0.0115)^2 + (0.01)^2 + (0.002)^2} = 0.0154 \text{ m}$$

Average from Previous Slide

- Can Be Used To Examine Any Scanner to Determine Noise Floor Under Good GPS/INS Conditions

Conclusions

- Trajectory noise under ideal GPS conditions appears to be at approximately the 1 cm level.
- 3D Precision ranges from 1 to 3 cm, for short ranges (< 20 meters) for all varieties of laser scanners tested.
- Even the most demanding applications may be possible with the Velodyne HDL-64E S2 – with careful calibration

Thank You!

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