Terrestrial and Mobile LiDAR mapping Systems: Understanding the Technology, Applications and Opportunities

By
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Description
Laser scanning grew into a mature technology that could replace traditional surveying tasks and significantly increase productivity and widen the services surveyors could provide to existing and new clients.

In recent years, some DoTs and some other state and federal agencies have developed standards and specifications for terrestrial and mobile LiDAR mapping systems. They included outlines for best practices in various mapping applications.

For surveyors to maintain their professional edge over other spatial data providers, have to fully understand the surveying and mapping systems they use.

Description
The objective of this seminar is:
• To review the theoretical foundation of LiDAR based mapping systems and explain the underlying system components and their technologies.
• To present the published recommended practices and applications at some DoTs and federal agencies.
• To overview business opportunities for surveyors
• To focus on terrestrial and mobile systems. Aerial LiDAR system will covered only marginally.
ALS, TLS, MLS

Lasers
- Device which generates a stream of high energy particles (photons), usually within an extremely narrow range of radiated wavelengths
- Produces a coherent light source

Incoherent light sources
Laser – coherent light form

The Electro-Magnetic Spectrum
- Gamma Rays
- X-rays
- Ultraviolet
- Visible
- Infra Red
- Microwaves
- TV/Radio
- X-Rays
- Laser

Wavelength (not to scale)
- 0.0001 µm
- 0.1 cm
- 100 µm
- 1 cm
- 100 cm
- 1 m
- 10 m
- 100 m

Grayed sections indicate significant bands of water or atmospheric absorption

Film
Electro-optical Sensors
Thermal IR
Passive Microwave
Active RADAR
Typical Terrestrial LIDAR Laser
What LIDAR Is:

- Light Detection And Ranging
- Active Sensing System
  - Uses its own energy source, not reflected natural or naturally emitted radiation.
- Day or Night operation.
- Ranging of the reflecting object based on time difference between emission and reflection.
- Direct acquisition of terrain information, whereas photogrammetry is inferential.

What LIDAR Is Not:

- NOT Light/Laser Assisted RADAR
  - RADAR uses electro-magnetic (EM) energy in the radio frequency range; LIDAR does not.
- NOT all-weather
  - The target MUST be visible. Some haze is manageable, but fog is not.
- NOT able to ‘see through’ trees
  - LIDAR sees around trees, not through them. Fully closed canopies (rain forests) cannot be penetrated.
- NOT a Substitute for Photography
  - For MOST users, LIDAR intensity images are NOT viable replacements for conventional or digital imagery.

What LIDAR Is Not:

- NOT Photography
  - We can shade the elevation and intensity data to create “imagery”
- Doesn’t capture breaklines
- Doesn’t capture planimetric features
  - Advances in software may allow automatic feature extraction soon
Traditional Photogrammetry vs. LiDAR

<table>
<thead>
<tr>
<th>LiDAR</th>
<th>Photogrammetric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day or night data acquisition</td>
<td>Day time collection only</td>
</tr>
<tr>
<td>Direct acquisition of 3D collection</td>
<td>Complicated and sometimes unreliable procedures</td>
</tr>
<tr>
<td>Vertical accuracy is better than planimetric*</td>
<td>Planimetric accuracy is better than vertical*</td>
</tr>
<tr>
<td>Point cloud difficult to derive semantic information; however, intensity values can be used to produce a visually rich image like product (example of an intensity image)</td>
<td>Rich in semantic information</td>
</tr>
</tbody>
</table>

*Complementary characteristics suggest integration

LiDAR Characteristics (ALS)

- Vertical accuracy for commercial applications at 15 cm on discrete points
- Capable of collecting millions of elevation points per hour – much faster than traditional methods
- Produces datasets with much greater density than traditional mapping
- Some systems capable of capturing multiple returns per pulse and/or intensity images
- Supported by rigorous QA/QC – similar to traditional surveying principals

Glossary

**LiDAR** - Light Detection And Ranging, a method of measuring the flight time of a beam of light to calculate range to objects at predetermined angular increments, resulting in a point cloud

**Photon LiDAR** - A LiDAR technology under development that splits the laser pulse into individual photons to improve spatial resolution. It also reduces the spot size, improving accuracy

**Flash LiDAR** - A new LiDAR technology that operates by illuminating an entire field of view simultaneously, similar to taking a picture, compared to traditional systems which fire pulses one by one through incrementing angles.
A pulse of light is emitted and the precise time is recorded.

The reflection of that pulse is detected and the precise time is recorded.

Using the constant speed of light, the delay can be converted into a “slant range” distance.

Knowing the position and orientation of the sensor, the XYZ coordinate of the reflective surface can be calculated.

Reflection strength depends on terrain and wavelength

- First reflection
- Last reflection
- Difference between first and last reflection
- Multiple reflections
Wave-form processing

Also called "echo digitalization." Scanner system that uses the pulsed time-of-flight technology and internal real-time processing capabilities of multiple returns to identify multiple targets.

Ground-Based Lidar

Conceptual Drawing
Scanning Mechanisms

Ground pattern

Most common pattern (Leica, Optech)

Figure modified from: Nikolaos 2006

Point Spacing in Lidar

Nadir

FOV Edge

Maximum Along Track Spacing

Maximum Cross Track Spacing

Glossary

Beam divergence - The increase in beam width as the distance from scan origin increases.

Beam width (Footprint) - The extent of the irradiance distribution in a cross section of a laser beam in a direction orthogonal to its propagation path at a distance away from the origin. (ASTM)

Field of view (FOV) - The angular extent within which objects are measurable by a device such as an optical instrument without user intervention. (ASTM)

Intensity - The quantity of laser energy measured at the scanner after light is reflected and returned from a surface. Typically scaled as a floating point from 0 to 1.0 or an integer from 0 to 255 or 0 to 65535.
Glossary

Reflectance - A measure of how much light is reflected off surface compared to how much initially hit the surface.

Occlusions - Areas within a point cloud that are void of measurements due to objects blocking the scanner’s line of sight.

Voids - Areas within a point cloud which were not well detailed, typically due to blocking of the scanner line of sight.

Artifacts - Erroneous points in a scan that do not accurately depict the objects intended to be measured.

Boresight - In MLS systems, this term refers to the rotation of the laser scanner frame to align with the body frame of the IMU.

Grazing angle - The angle between the laser beam and the surface (90° – incidence angle). Low grazing angles mean the laser beam is nearly parallel to the surface (oblique, poor data quality) while high grazing angles mean that the laser beam is perpendicular to the surface (orthogonal, good data quality).

Incidence angle - The angle between the incoming laser pulse and the surface normal. Low incidence angles, meaning orthogonal, direct data acquisition, are preferred. Antonym of grazing angle.

Density – The number of points per unit area; can also be expressed as the average distance between points in a point cloud.

LIDAR Instrumentation (ALS)

- Laser Source
- Laser Detector
- Scanning mechanism & controller
- Electronics for timing emissions & reflections
- Airborne GPS (position, speed, direction)
- Inertial Measurement Unit (orientation angles)
- High Performance Computing Support
- High Capacity Data Recorders
Several recent, enabling technological advances have made LIDAR possible:

- Airborne GPS
- Inertial Measurement
- Availability of affordable lasers and other specialized materials and sensors
- Declassified military technology
- Advances in computer technology (speed, performance, size, and of course, price)

**Glossary – IMU**

**IMU (inertial measurement unit)** - A device which utilizes a combination of gyroscopes and accelerometers to provide velocity and orientation information.

**INS (inertial navigation system)** - Not applicable to mobile mapping.

**Instrument origin** - Point from which all instrument measurements are referenced; that is, origin of the instrument coordinate reference frame (0, 0, 0). (ASTM)

**Lever arm** - In MLS systems this term refers to the difference in origin of the laser scanner frame and the body frame of the IMU.

**Inertial Measurement Unit**

- Combination of gyro and accelerometers
- Typically integrated with GPS system for Positional Updating
- Accuracies of 18 - 25 arc-seconds (0.005-deg for pitch and roll, 0.01-deg for yaw)
Inertial Measurement Unit

- 3 Accelerometers, 3 Gyros and Signal Processing Electronics
- Outputs high-accuracy acceleration and angular rate measurements digitally
- Computes the position and orientation solution - updated at 200 Hz
- Hard Mounted to the Sensor

Inertial Measurement Unit

- Importance of IMU in MLS study

<table>
<thead>
<tr>
<th>Position Accuracy during the drive test.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution type</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>GPS-only</td>
</tr>
<tr>
<td>GPS-IMU</td>
</tr>
</tbody>
</table>

Availability of the positioning solution during the drive test.

<table>
<thead>
<tr>
<th>Solution type</th>
<th>Number of epochs</th>
<th>Percentage of solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS-only</td>
<td>925</td>
<td>82.6 %</td>
</tr>
<tr>
<td>RTK-fixed (GPS-only)</td>
<td>677</td>
<td>60.4 %</td>
</tr>
<tr>
<td>GPS-IMU</td>
<td>1120</td>
<td>100 %</td>
</tr>
</tbody>
</table>

LIDAR Data Characteristics

- Raw return data are XYZ points
- High spatial resolution
  - Laser footprint on ground ≤ 0.50 meters
  - Typical density is 0.5 to 20+ pulses/m²
  - 2 to 3 returns/pulse in forest areas
  - Surface/canopy models typically 1 to 5m grid
- Large volume of data
  - 5,000 to 60,000+ pulses/hectare
  - 10 to 100+ thousands of returns/hectare
  - 0.4 to 5.4+ MB/hectare
Glossary - Scans

**Overview scan** - A low resolution scan, may be used to select specific areas within a scan which need to be scanned at higher resolution.

**Detail scan** – A scan, or portion of scan, that is performed at higher resolution. Often a detail scan of targets will be used for better alignment.

**Line scan** - Constraining the Z rotation of a laser scanner so that vehicular or platform motion results in linear scan swaths through a corridor.

**Panoramic scan** - Allowing the scanner head to rotate in the Z axis up to 360°.

Glossary – Data files

**Raw scan data** - Unprocessed data as it is initially captured from the scanner.

**XYZRGBI** - Any combination of these letters may be used to define a scanner file format, represented by X, Y, and Z point coordinates, (R)ed, (G)reen, (B)lue color values assigned to the point, and (I)ntensity value assigned to the point.

**LAS** - A binary file format that has been specifically developed by the American Society for Photogrammetry and Remote Sensing (ASPRS) to improve efficiency and compatibility of working with LIDAR data between software packages. Current version: 1.4. This is the most common format used for mobile LIDAR data.

File Types

- **LAS** – specification for a point cloud file format with x,y,z and other attributes (e.g. Intensity, RGB).
- **ASCII** – original format for LIDAR data.
- **E57** – A general purpose, open standard, file format for storing point clouds and associated meta-data (maintained by ASTM)
- **FLS** – FARO proprietary file format.
**File Types**

Example file sizes for various formats

![Comparison of file sizes for various formats.](image)

**Workflow – Raw Data to LAS Files**

- Raw Data (20 GB)
- Initial Process to some Coordinate (Source File)
- Phase II
  - Ground Scan to Scan Corrections
- Phase I
  - Known Tie Line Corrections
- Final LAS Files
- # Local System
- In Local Project Datum

**Glossary – Registration**

**Registration** - The process of determining and applying to two or more datasets the transformations that locate each dataset in a common coordinate system so that the datasets are aligned relative to each other. (ASTM)

**Reference frame** - The coordinate system or location that is used to refer to an object or point location

**On the fly** - 1) A mode of mobile mapping that utilizes continuous movement of the mapping platform while collecting data. 2) Processing of scan data in real time

**Local** - A coordinate system that is referenced using the laser scanner location as the origin of the point cloud

**Polar coordinates** - A coordinate system that locates points in space by defining an angle and a distance from a fixed reference pole
Point cloud registration (TLS)

- The most common method is based on three or more targets of known position (3D similarity transformation)
- In some applications, only the orientation registration is required. In this case the scanner's position is defined by the bearing or direction of its line of sight, its inclination in the direction of the line of sight and its inclination perpendicular to the line of sight.
- This provides enough information to correctly georeference the orientation of the scanner (but not the position).

\[
[x \ y \ z]^T = \rho \begin{bmatrix}
\cos \varphi \cos \theta & \cos \varphi \sin \theta & \sin \varphi
\end{bmatrix}^T
\]

Accuracy of TLS from field tests

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Color</th>
<th>25 m</th>
<th>50 m</th>
<th>75 m</th>
<th>100 m</th>
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<tr>
<td>Leica ScanStation</td>
<td>White</td>
<td>4.65</td>
<td>3.23</td>
<td>3.23</td>
<td>4.78</td>
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<tr>
<td></td>
<td>Grey</td>
<td>4.72</td>
<td>4.31</td>
<td>4.68</td>
<td>5.49</td>
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<tr>
<td></td>
<td>Black</td>
<td>4.72</td>
<td>3.45</td>
<td>3.65</td>
<td>7.08</td>
</tr>
<tr>
<td>Trimble GX</td>
<td>White</td>
<td>2.10</td>
<td>1.65</td>
<td>2.20</td>
<td>1.84</td>
</tr>
<tr>
<td></td>
<td>Grey</td>
<td>2.98</td>
<td>4.82</td>
<td>4.92</td>
<td>7.74</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>3.00</td>
<td>4.82</td>
<td>7.80</td>
<td>11.70</td>
</tr>
<tr>
<td>Optech ILRIS-3D</td>
<td>White</td>
<td>13.70</td>
<td>14.25</td>
<td>18.40</td>
<td>21.95</td>
</tr>
<tr>
<td></td>
<td>Grey</td>
<td>13.30</td>
<td>14.31</td>
<td>16.48</td>
<td>21.76</td>
</tr>
<tr>
<td></td>
<td>Black</td>
<td>13.67</td>
<td>14.07</td>
<td>18.93</td>
<td>18.37</td>
</tr>
</tbody>
</table>
Accuracy of TLS from field tests

Figure 24: Range Precision, 95% RMSE for different surface reflectivity

Accuracy of TLS from field tests

Figure 25: Incidence Angle test fixture, and illustration of Incidence and Coverage Angle

Accuracy of TLS from field tests

Table 3: RMSE values of Noise for different surface reflectivity levels

<table>
<thead>
<tr>
<th>Scanner Model</th>
<th>RMSE (mm)</th>
<th>95% Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leica Leica</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Leica Trimble</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Optech Optech</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Leica Leica</td>
<td>2.0</td>
<td>2.1</td>
</tr>
<tr>
<td>Leica Leica</td>
<td>3.0</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Target recognition test

Figure 26: Surface Precision - Noise test fixture

Figure 27: Target recognition test - model
Coordinate Transformation for MLS

- Coordinates on the ground are calculated by combining the information from the laser scanner, integrated GPS/INS navigation system and calibration parameters:

\[ P_l^u = P_{l,\text{GPS}} + R_b^l \cdot r' - R_s^l \cdot l_b \]

Where:

- \( P_l^u \) = Coordinates of Target point in local level (l) frame
- \( P_{l,\text{GPS}} \) = Coordinates of navigation sensor center in (l) frame
- \( R_b^l \) = Rotation matrix from body (navigation) frame (b) to (l) frame (roll, pitch, yaw)
- \( R_s^l \) = Rotation from scanner frame (s) into body frame (a.k.a. boresight matrix)
- \( r' \) = Coordinates of Target point in scanner frame
- \( l_b \) = Lever arm from scanner origin to navigation center origin in body frame

Coordinate Transformation for MLS

An alternative form of the last equation is:

\[
\begin{bmatrix}
X_l \\
Y_l \\
Z_l
\end{bmatrix} = \begin{bmatrix}
X_s \\
Y_s \\
Z_s
\end{bmatrix} + R_b^l \left( d\varphi \; d\kappa \right) \left( R_s^l \cdot d\phi \; d\kappa \cdot r' \left( \alpha \; d \right) - l_b \right)
\]

The equation above shows that the ground coordinate calculated for the laser return depends on 14 observed parameters.

- \( X_s, Y_s, Z_s \) = location of the navigation sensor (GNSS+IMU).
- \( d\alpha, d\phi, d\kappa \) = roll, pitch and yaw of the sensor with respect to the local level frame. (IMU)
- \( d\alpha_s, d\phi_s, d\kappa_s \) = the boresight angles which align the scanner frame with the IMU body frame. (boresight calibration)
Coordinate Transformation for MLS

\[ \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} + R_x(\alpha_0, \beta_0, \gamma_0) \begin{bmatrix} \phi \\ \theta \end{bmatrix} R_y(\alpha, \beta, \gamma) \begin{bmatrix} \psi \\ \theta \end{bmatrix} \]

\( \alpha_0 \) and \( \beta_0 \) – the scan angle and range measured and returned by the laser scanner assembly.

\( \gamma_0 \) – the lever arm offsets from the navigation origin (IMU origin) to the measurement origin of the laser scan assembly. These values must be determined by measurement or system calibration.

Factors Affecting Accuracy

Laser Data Quality - Resolution

Two primary factors affect data resolution:

- Measurement Spacing
- Range Precision
Assessing quality of the point cloud data

Point to plane (dt) analysis - used for assessing quality of the point cloud data.

Empirically
\[
\begin{align*}
    \Delta t_{ij} &= n_x x_i + n_y y_i + n_z z_i + \Delta t_j \\
    \max \Delta t_j &= \Delta t_{ij} \\
    \min \Delta t_j &= \Delta t_{ij} \\
    \text{rms} \Delta t_j &= \sigma_{\Delta t_j}
\end{align*}
\]

Theoretically
\[
\sigma_{\Delta t_j} = f(n_x, n_y, n_z, p, \sigma_x, \sigma_y, \sigma_z)
\]

Tie Plane Determination & Selection

• Determines correspondence between lines & selects appropriate tie planes for self calibration
• Based upon the point to plane analysis
• Selection criteria includes size, shape, no. points, shape, orientation fitting error
• Redundancy!

A Methodology for Self Calibration

Requirement: Redundant information

Least squares observation equation
\[
\mathbf{e}_{ij} = n_x x_i + n_y y_i + n_z z_i = 0
\]
where
\[
\mathbf{x}_i = f(\text{obs}, \text{cal}, \text{par}, \text{corrections})
\]
\[
\text{obs} = l, \theta, x, y, z, r, p, h
\]

Least squares solution

Determine a set of corrections by minimizing the weighted square sum of the observation residuals

Applying the correction while reprocessing laser points
Self Calibration with Control Points

How should GCP’s be collected?

On flat (planar) surfaces in multiple dimensions

Boresight Errors

- Misalignments between the laser scanner and IMU measurement axes.
- It is the physical mounting angles between an IMU and a digital camera that theoretically describe the misalignment angles between the IMU and the digital camera frames of reference.

Figure 1 Camera/IMU Boresight
Boresight Errors

Various approaches exist for determining boresight angle.

- In general, we take advantage of overlapping LIDAR strips, usually acquired by collecting data for the same area in both directions.
- Tie point and/or control point observations between overlapping LIDAR strips are collected, then run through a least squares adjustment to determine the boresight angles that have the best fit.

Calibration and corrections

System Calibration
To recover the parameters of the two error sources in MLS point clouds:

1. The boresight angles that define the angular offsets between the laser(s) and the navigation system (IMU).
2. The physical 3D offset between the navigation system center and the laser(s) center.

TRB team recommends that the data procurement requires submission of a complete calibration report documenting the following items:

- The equipment used for data collection,
- The calibration procedure used, along with the calibration parameters and their estimated accuracies,
- The equipment installation schematics, and
- Verification of temporal or long-term stability of calibration parameters.
Calibration and corrections

Geometric Correction

- This correction employs DGNSS or total station surveyed targets along the project corridor.
- These targets (control points) are identified in the laser data and the MLS point cloud is “adjusted” to the control point locations.
- This process improves the overall accuracy of the point cloud and mitigates any problems with the computed navigation trajectory of the vehicle (loss of lock).
- The observed control points must be directly input as observations into the raw navigation trajectory estimation (i.e., the GNSS/INS post-processing software).
- Other ad-hoc geometric corrections could include 3D Rigid Body transformation of each MLS pass to fit the point cloud data to control per project.
- Any applied geometric corrections, full documentation (including the methodology, type, and magnitudes) needs to be provided.

Limitations of Mobile Scanning

- Line-of-Sight
- Weather Considerations
  - Rain
  - Fog
  - Standing Water
- Sky-line Visibility
- Urban Canyons
- Steep Terrain

Figure 9. Minimum expected horizontal and vertical errors under ideal conditions (site independent, optimal incidence) for typical mapping and survey grade MLS.
Advantages of Mobile Scanning

- Safety
- Schedule
- Survey Grade Accuracy
- Data extracted with calibrated photos
- Cost Effective because more efficient data collection equates to cost saving
- "Scan in the Can" lends to future data extraction without further field visits
- Video & Imagery
- Deliverables in standard formats

Challenges Present in mobile LiDAR Survey operations

- Systematic errors
- How 'good' is 'good'? How good is accuracy verification? Data misalignment
- Internally To control
- Correcting misalignments need effort to fix
- DASHMap, Terramatch
- Rescan

Comparison of ALS and MLS

**Airborne LiDAR**

- Direct view of pavement & building tops
- Poor (oblique) view of vertical faces
- Faster coverage
- Larger footprint
- Laser travels much farther
- Not limited to area visible from roadway
- Lower point density (1–32 points/m²)
Comparison of ALS and MLS

**Mobile LIDAR**
- Good view of pavement
- Direct view of vertical faces
- Cannot capture building tops
- Slower coverage
- Smaller footprint
- Closer to ground/objects
- Limited to objects close and visible from the roadway
- Higher point density (100s points/m²) but more variable

Overall Comparison of ALS, MLS and TLS

- **Applicability** – MLS can provide survey/engineering-quality data faster than TLS. ALS (with the exception of low-flying helicopter) generally do not provide survey/engineering-quality data.
- **Cost-effectiveness** – Despite a higher initial cost than TLS, MLS received a higher cost-effective rating due to long-term benefits of reduced acquisition time.
- **Data collection productivity** – MLS and ALS were both more productive than TLS.
- **Data collection productivity** – MLS and ALS were both more productive than static scanning.

Overall Comparison of ALS, MLS and TLS

- **Ease-of use** – Because of the integration of multiple sensors and calibration of these sensors, MLS requires more training than static scanning. However, it requires less training than ALS because a pilot is not needed.
- **Level of detail** – TLS provided the highest level of detail.
- **Post-processing efficiency** – ALS had the best rating for post-processing efficiency and both TLS and MLS were given low ratings.
- **Safety** – All platforms provided safety benefits; however, ALS received the highest rating due to limited traffic exposure.
Comparison of ALS and MLS 

Similarities

• Both acquire data kinematically using similar hardware components (GNSS, IMU, and LIDAR).
• Both capture a point cloud.
• Both systems typically provide laser return intensity (return signal strength) information for each laser return.
• Each point is individually geo-referenced with both systems.
• While MLS can offer significantly improved horizontal accuracy due to look angle, both systems can provide data with high vertical accuracy.
• Both systems can simultaneously acquire imagery and scan data.

“Baker's Dozen: 13 Laws of Mobile LIDAR”

1. Too much is better than not enough.
2. Sometimes more is just more, not better.
3. Hard drives are cheap, time isn’t.
4. Consistency counts; stop guessing.
5. When someone wants “full planimetrics,” they really don’t.
6. The stated laser range is X’, but the lasers are only capturing data to Y’; and Y’ is definitely less than X’, yet nobody can tell you what Y’ is...
7. The data you capture is only as good as the applied control.

from Michael Baker Jr. Inc. blog

“Baker's Dozen: 13 Laws of Mobile LIDAR”

8. Today’s best practices will be tomorrow’s old habits.
9. Field vs. office time ratios are pipe dreams.
10. Mobile LIDAR systems are not created equal, and neither are the operations behind them.
11. Off-the-shelf processing software will only do 50% of what you need it to do.
12. When the system encounters issues, take a breath and reboot.
13. Mobile LIDAR is not all fun and games, but it does feel like it some days.”
### Laser scanning sensors employed in commercial MLS (October 2013)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Range (m)</th>
<th>Scan freq. Hz</th>
<th>Point rate kHz</th>
<th>Angle resolution deg</th>
<th>Range resolution mm</th>
<th>Range accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datascan 3D</td>
<td>120/30/90</td>
<td>10</td>
<td>5</td>
<td>0.03</td>
<td>10</td>
<td>90%</td>
</tr>
<tr>
<td>Datascan 5250</td>
<td>250</td>
<td>20</td>
<td>36</td>
<td>0.03</td>
<td>10</td>
<td>10%</td>
</tr>
<tr>
<td>Sprick 3200 (price)</td>
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<td>20-200</td>
<td>75-200</td>
<td>0.144</td>
<td>N/A</td>
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<td>Sprick 1100 (price)</td>
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<td>Reid VQ-250</td>
<td>500</td>
<td>100</td>
<td>300</td>
<td>0.001±0.72</td>
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</tr>
<tr>
<td>Reid VQ-450</td>
<td>800</td>
<td>-200</td>
<td>550</td>
<td>0.001±0.88</td>
<td>N/A</td>
<td>8 mm</td>
</tr>
<tr>
<td>Mlidle (milex)</td>
<td>250</td>
<td>20</td>
<td>35</td>
<td>0.05</td>
<td>N/A</td>
<td>24 mm</td>
</tr>
<tr>
<td>Mlidle (milex)</td>
<td>10</td>
<td>10</td>
<td>700</td>
<td>0.16±1.35</td>
<td>N/A</td>
<td>20 mm</td>
</tr>
<tr>
<td>FARO Point 120</td>
<td>PS</td>
<td>53</td>
<td>61</td>
<td>905</td>
<td>0.099</td>
<td>2 mm</td>
</tr>
<tr>
<td>FARO Focus 300</td>
<td>PS</td>
<td>150</td>
<td>97</td>
<td>976</td>
<td>0.099</td>
<td>2 mm</td>
</tr>
<tr>
<td>FARO Focus 5010C</td>
<td>PS</td>
<td>57</td>
<td>50</td>
<td>1016</td>
<td>0.0034</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Z+F Profine 9012</td>
<td>PS</td>
<td>19</td>
<td>50-200</td>
<td>1016</td>
<td>0.099</td>
<td>0.1 mm</td>
</tr>
</tbody>
</table>

### Laser scanning sensors employed in commercial MLS (October 2013)

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Range repeatability (mm)</th>
<th>Beam divergence (mm @ mrad)</th>
<th>Spot size @ 50 m</th>
<th>Field of view (°)</th>
<th>Wavelength (nm)</th>
<th>Specific</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datascan 3D</td>
<td>50 mm</td>
<td>5.5±0.5</td>
<td>10 mm</td>
<td>8.0±1.5</td>
<td>965</td>
<td>IRF6</td>
</tr>
<tr>
<td>Datascan 5250</td>
<td>50 mm</td>
<td>2.5±0.2</td>
<td>10 mm</td>
<td>8.0±1.5</td>
<td>965</td>
<td>IRF5-160° cone</td>
</tr>
<tr>
<td>Sprick 3200 (price)</td>
<td>8</td>
<td>0.5</td>
<td>N/A</td>
<td>1064</td>
<td>4 Micron</td>
<td>4 Micron</td>
</tr>
<tr>
<td>Sprick 1100 (price)</td>
<td>8</td>
<td>0.5</td>
<td>N/A</td>
<td>1064</td>
<td>4 Micron</td>
<td>4 Micron</td>
</tr>
<tr>
<td>Reid VQ-250</td>
<td>5 mm</td>
<td>9.0±0.35</td>
<td>18 mm</td>
<td>1550</td>
<td>1 Micron</td>
<td>Pall wavefront</td>
</tr>
<tr>
<td>Reid VQ-450</td>
<td>8 mm</td>
<td>7.0±0.35</td>
<td>15 mm</td>
<td>1550</td>
<td>1 Micron</td>
<td>Pall wavefront</td>
</tr>
<tr>
<td>Mlidle (milex)</td>
<td>N/A</td>
<td>2.0</td>
<td>10 mm</td>
<td>905</td>
<td>1 Micron</td>
<td>Multi-line</td>
</tr>
<tr>
<td>Mlidle (milex)</td>
<td>N/A</td>
<td>2.79</td>
<td>14 mm</td>
<td>905</td>
<td>1 Micron</td>
<td>Multi-line</td>
</tr>
<tr>
<td>FARO Point 120</td>
<td>2.2 mm @ 25 m</td>
<td>3.0±0.16</td>
<td>8 mm</td>
<td>905</td>
<td>TLS</td>
<td>TLS</td>
</tr>
<tr>
<td>FARO Focus 300</td>
<td>3.5 mm @ 25 m</td>
<td>2.25±0.17</td>
<td>10 mm</td>
<td>905</td>
<td>TLS</td>
<td>TLS</td>
</tr>
<tr>
<td>Z+F Profine 9012</td>
<td>1.9 mm @ 50 m</td>
<td>1.9±0.5</td>
<td>25 mm</td>
<td>1500</td>
<td>Only 360° PS scanner</td>
<td>TLS</td>
</tr>
</tbody>
</table>

---

**Applications of MLS**

- **Remote sensing and mapping**
- **Environmental monitoring**
- **Urban planning and design**
- **Architectural and engineering surveys**
- **Archeology and heritage preservation**
- **Geology and mining exploration**
- **Agriculture and forestry assessment**
- **Traffic and transportation studies**
- **Forestry and vegetation mapping**
- **Wildlife and habitat conservation**

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**31-Dec-14**
Types of Terrestrial Laser Scanners (TLS) Surveys - CALTRANS

"Type A" TLS surveys are hard surface topographic surveys with data collected at engineering level accuracy:
- Pavement Analysis Scans
- Roadway/pavement topographic surveys
- Structures and bridge clearance surveys
- Engineering topographic surveys
- Detailed Archaeological Surveys
- Architectural and Historical Preservation Surveys
- Deformation and Monitoring Surveys
- As-built surveys
- Forensic surveys

"Type B" TLS surveys are topographic surveys with data collected at lower level accuracy:
- Corridor study and planning surveys
- Asset inventory and management surveys
- Environmental Surveys
- Sight distance analysis surveys
- Earthwork Surveys such as stockpiles, borrow pits, and landslides
- Urban mapping and modeling
- Coastal zone erosion analysis

Types of Mobile Laser Scanners (MLS) Surveys - CALTRANS

"Type A" MLS surveys are hard surface topographic surveys:
- Engineering topographic surveys
- As-built surveys
- Structures and bridge clearance surveys
- Deformation Surveys
- Forensic surveys
Types of Mobile Laser Scanners (MLS) Surveys - CALTRANS

“Type B” MLS surveys are Earthwork and low-accuracy topographic surveys:

- Corridor study and planning surveys
- Asset inventory and management surveys
- Environmental Surveys
- Sight distance analysis surveys
- Earthwork Surveys such as stockpiles, borrow pits, and landslides
- Urban mapping and modeling
- Coastal zone erosion analysis

Accuracy Specification for MLS

Two types of accuracy are defined for MLS: network accuracy and local accuracy. (FGDC)

- **Local accuracy** - The local accuracy of a control point is a value that represents the uncertainty in the coordinates of the control point relative to the coordinates of other directly connected, adjacent control points at the 95-percent confidence level. The reported local accuracy is an approximate average of the individual local accuracy values between this control point and other observed control points used to establish the coordinates of the control point.

- **Network accuracy** - The network accuracy of a control point is a value that represents the uncertainty in the coordinates of the control point with respect to the geodetic datum at the 95-percent confidence level. For NSRS [National Spatial Reference System] network accuracy classification, the datum is considered to be best expressed by the geodetic values at the CORS supported by NGS. By this definition, the local and network accuracy values at CORS sites are considered to be infinitesimal, i.e., to approach zero.
Matrix of Application and Suggested Accuracy and Resolution Requirement

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>HIGH &lt; 0.05 m (&lt; 0.16 ft)</th>
<th>MEDIUM 0.05 to 0.20 m (0.16 to 0.66 ft)</th>
<th>LOW &gt; 0.20 m (&gt; 0.66 ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>A</td>
<td>2A</td>
<td>3A</td>
</tr>
</tbody>
</table>

- Engineering surveys
- Digital terrain modeling
- Construction automation/Machine control
- ADA compliance
- Clearances
- Placement analysis
- Drainage/roadway analysis
- Virtual, 3D design
- CAD models/Baseline data
- BIM/IMB
- Post-construction quality control
- As built/As is/Repair documentation
- Structural inspections
- Pedestrian/accident investigation
- Historical preservation
- Power line clearance
- Roadway condition assessment (general)

Matrix of Application and Suggested Accuracy and Resolution Requirement

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>HIGH &lt; 0.05 m (&lt; 0.16 ft)</th>
<th>MEDIUM 0.05 to 0.20 m (0.16 to 0.66 ft)</th>
<th>LOW &gt; 0.20 m (&gt; 0.66 ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOD</td>
<td>1A</td>
<td>2A</td>
<td>3A</td>
</tr>
</tbody>
</table>

- Unstable slopes
- Landslide assessment
- General mapping
- Drainage assessment
- Autonomous navigation
- Automated这是我加的
- Automatic extraction of signs and other features
- Coastal change
- Infrastructures
- Environmental studies
- Asset management
- Inventory mapping
- Sports
- Virtual cloud

Point density to sample spacing conversion table

<table>
<thead>
<tr>
<th>LOD</th>
<th>Point Density pts/m²</th>
<th>Sample Spacing m</th>
<th>Sample Spacing ft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>1000</td>
<td>0.082</td>
<td>0.104</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>0.145</td>
<td>0.147</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.071</td>
<td>0.232</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.100</td>
<td>0.328</td>
</tr>
<tr>
<td>B</td>
<td>90</td>
<td>0.105</td>
<td>0.346</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>0.112</td>
<td>0.367</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>0.120</td>
<td>0.392</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.129</td>
<td>0.424</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.141</td>
<td>0.464</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>0.158</td>
<td>0.519</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>0.183</td>
<td>0.599</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.221</td>
<td>0.728</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.316</td>
<td>1.037</td>
</tr>
</tbody>
</table>
### Stationary Terrestrial Laser Scanning Specifications

#### Operation/Specification

<table>
<thead>
<tr>
<th>STLS Scan Application</th>
<th>Scan Type A</th>
<th>Scan Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial calibration of instrument at startup and during operation. Excessive vibration may render the scanner inoperable.</td>
<td>Each set-up</td>
<td>Each set-up</td>
</tr>
<tr>
<td>Level compensator should be turned ON unless unusual situations (See Note 1) require that it be turned OFF.</td>
<td>Each set-up</td>
<td>Each set-up</td>
</tr>
<tr>
<td>Minimum number of targeted control points required</td>
<td>2 for each set-up</td>
<td></td>
</tr>
<tr>
<td>STLS control and validation point surveyed positional local accuracy</td>
<td>( H \leq 0.03 \text{ ft.} ) ( V \leq 0.02 \text{ ft.} )</td>
<td>( H ) and ( Y ) ( \leq 0.10\text{ foot} )</td>
</tr>
<tr>
<td>Strength of figure ( \alpha ) is the angle between each pair of adjacent control targets measured from the scanner position.</td>
<td>Recommended ( 60^\circ \leq \alpha \leq 120^\circ )</td>
<td>Recommended ( 40^\circ \leq \alpha \leq 140^\circ )</td>
</tr>
</tbody>
</table>

#### Stationary Terrestrial Laser Scanning Specifications

<table>
<thead>
<tr>
<th>Operation/Specification</th>
<th>STLS Scan Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target placed at optimal distance to produce desired results</td>
<td>Each set-up</td>
</tr>
<tr>
<td>Control targets scanned at high density</td>
<td>Required</td>
</tr>
<tr>
<td>Measure instrument height (when occupying control) and target heights</td>
<td>Yes</td>
</tr>
<tr>
<td>Check position of instrument and targets over occupied control points</td>
<td>Begin and end of each set-up</td>
</tr>
<tr>
<td>Be aware of equipment limitations when used in rain, fog, snow, smoke or blowing dust, or on wet pavement.</td>
<td>Each set-up</td>
</tr>
<tr>
<td>Distance to object scanned not to exceed best practices for laser scanner and conditions - Equipment dependent</td>
<td>Manufacturer’s specification</td>
</tr>
</tbody>
</table>
### Stationary Terrestrial Laser Scanning Specifications

<table>
<thead>
<tr>
<th>Operation/Specification</th>
<th>STLs Scan Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>STLS Scan Application</td>
<td></td>
</tr>
<tr>
<td>STLs Scan Application</td>
<td>A</td>
</tr>
<tr>
<td>STLs Scan Application</td>
<td>B</td>
</tr>
<tr>
<td>Distance to object scanned not to exceed scanner capabilities to achieve required accuracy and point density.</td>
<td>Each set-up</td>
</tr>
<tr>
<td>Observation point density</td>
<td>Sufficient density to model object</td>
</tr>
<tr>
<td>Overlapping adjacent scans (percentage of scan distance)</td>
<td>5%-15%</td>
</tr>
<tr>
<td>Maximum measurement distance to meet vertical accuracy standard for horizontal (pavement) surface measurements</td>
<td>260 feet</td>
</tr>
<tr>
<td>Minimum measurement distance</td>
<td>Manufacturer’s specification</td>
</tr>
<tr>
<td>Registration of multiple scans in post-processing</td>
<td>Required</td>
</tr>
</tbody>
</table>

### Mobile Terrestrial Laser Scanning Specifications

<table>
<thead>
<tr>
<th>Operation/Specification</th>
<th>MTLS Scan Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTLS Scan Application</td>
<td>A</td>
</tr>
<tr>
<td>MTLS Scan Application</td>
<td>B</td>
</tr>
<tr>
<td>MTLS equipment must be capable of collecting data at the intended accuracy and precision for the project.</td>
<td>Required</td>
</tr>
<tr>
<td>Initial calibration of MTLS system (per manufacturers specs)</td>
<td>As Required</td>
</tr>
<tr>
<td>Dual-frequency GNSS recording data at 1 Hz or faster</td>
<td>Required</td>
</tr>
<tr>
<td>Minimum IMU positioning data sampling rate capability</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Maximum IMU Gyro Rate Bias</td>
<td>1 degree per hour</td>
</tr>
<tr>
<td>Maximum IMU Angular Random Walk (ARW)</td>
<td>0.125 degree per 1 hour</td>
</tr>
<tr>
<td>Maximum IMU Gyro Rate Scale Factor</td>
<td>150 ppm</td>
</tr>
<tr>
<td>Minimum IMU uncorrected positioning capability due to lost or degraded GNSS signal</td>
<td>GNSS outage of 60 seconds or 0.6 miles distance travelled</td>
</tr>
</tbody>
</table>
### Mobile Terrestrial Laser Scanning Specifications

<table>
<thead>
<tr>
<th>Operation/Specification</th>
<th>MTLS Scan Application</th>
<th>Scan Type A</th>
<th>Scan Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum duration or distance travelled with degraded or lost GNSS signal resulting in uncorrected IMU positioning</td>
<td>GNSS outage of 60 seconds or 0.6 miles distance travelled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum uncorrected IMU X-Y positioning drift error for 60 second duration or 0.6 mile distance of GNSS outage</td>
<td>0.33 foot (0.100m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum uncorrected IMU Z positioning drift error for 60 second duration or 0.6 mile distance of GNSS outage</td>
<td>0.23 foot (0.070m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum uncorrected IMU roll and pitch error/variation for 60 second duration or 0.6 mile distance of GNSS outage</td>
<td>0.020 degrees RMS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum uncorrected IMU true heading error/variation for 60 second duration or 0.6 mile distance of GNSS outage</td>
<td>0.020 degrees RMS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Project Control

- Project control should be the constraint for GNSS positioning.
- Minimum order of accuracy for GNSS base station horizontal (H) and vertical (V) project control:
  - H: 2nd
  - V: 3rd
- MTLS Local Transformation Point and Validation Point survey positional accuracy requirements:
  - \( H \leq 0.03 \) foot
  - \( V \leq 0.02 \) foot
  - \( H \) and \( V \) \leq 0.10 foot
- GNSS base stations located at each end of project: Recommended
- Maximum post-processed baseline length: Five (5) miles
- Maximum PDOP during MTLS data acquisition: Five (5)

### Minimum Number of Common Healthy Satellites

- Minimum number of common healthy satellites in view for GNSS base stations and mobile scanner (See Notes 1 and 4): Five (5)

### Overlapping Coverage

- Minimum overlapping coverage between adjacent runs: 20% sidelap

### Monitor MTLS System

- Monitor MTLS system operation for GNSS reception: Throughout each pass
- Monitor MTLS system operation for IMU operation and distance and duration of any uncorrected drift: Throughout each pass
- Monitor MTLS laser scanner operation for proper function: Throughout each pass
- Monitor MTLS system vehicle speed: Throughout each pass
- Minimum orbit ephemeris for kinematic post-processing: Broadcast
Mobile Terrestrial Laser Scanning Specifications

<table>
<thead>
<tr>
<th>Operation/Specification</th>
<th>MLS Scan Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observations</td>
<td>Scan Type A</td>
</tr>
<tr>
<td>- sufficient point density to model objects</td>
<td>Each pass</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>limit to maintain required point density</td>
</tr>
<tr>
<td>Filter data to exclude measurements exceeding scanner range</td>
<td>Each pass</td>
</tr>
<tr>
<td>Local transformation point maximum stationing spacing throughout the project on each side of scanned roadway</td>
<td>1500 foot intervals</td>
</tr>
<tr>
<td>Validation point maximum stationing spacing throughout the project on each side of scanned roadway for QC purposes as safety conditions permit</td>
<td>500 foot intervals</td>
</tr>
</tbody>
</table>

Decision flowchart to determine when MLS use is appropriate for a project

Decision flowchart to determine when MLS use is appropriate for a project

Legend:
- Decision
- Considerations
- Y
- N

Decision flowchart to determine when MLS use is appropriate for a project

Legend:
- Decision
- Considerations
- Y
- N

Mobile Lidar

Safety

Schedule

- Traffic: Volume and speed
- Impact to public safety
- Site accessibility
- Weather
- Day vs. night collection
- Site distance

- Emergency project
- Large area (5 miles or greater)
- Short schedule (1-2 weeks)
- Product user: who needs access to data and when
- Point cloud only or secondary mapping
- Weather

Consider ML

- Alternate methods of collection
- Mobilization
- Risk of return to field visits
- Other supplemental data collection needed

Alt. methods of collection

HLD - High Level Detail
LLD - Low Level Detail
H_Ac - High Accuracy
L_Ac - Low Accuracy
L_Ar - Large Area
S_Ar - Small Area
### Generalized MLS Workflow

![Generalized MLS Workflow Diagram]

### Example of costs for a project using MLS

<table>
<thead>
<tr>
<th>Category</th>
<th>Typical Expenses</th>
<th>Variance Between Projects Based on Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Equipment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scanner, IMU, GNSS, Cameras, etc.</td>
<td></td>
<td>Systems vary substantially in cost based on accuracy and resolution requirements</td>
</tr>
<tr>
<td>GNSS Base Station Maintenance</td>
<td></td>
<td>Minimal variance in cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some variation in costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Advanced calibration procedures needed for higher grade systems</td>
</tr>
<tr>
<td><strong>Vehicle</strong></td>
<td>Ownership/Rent Insurance and Maintenance</td>
<td>Vehicle needs vary substantially in cost based on accuracy and resolution requirements</td>
</tr>
<tr>
<td></td>
<td>Fuel Charges Storage Fees Transport/Mobilize</td>
<td>Minimal variance in cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased passes to improve accuracy, resolution and coverage will increase fuel costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimal variance in cost Location dependent</td>
</tr>
<tr>
<td><strong>Personnel</strong></td>
<td>Driver LIDAR System Operator Ground Control Personnel</td>
<td>Minimal variance in cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Minimal variance in cost Location dependent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Substantial variation in cost depending on quality control needs.</td>
</tr>
<tr>
<td><strong>Travel</strong></td>
<td>Transport Costs for Personnel Lodging and Meals at Survey Location</td>
<td>Location dependent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Location dependent</td>
</tr>
</tbody>
</table>

---
### Example of costs for an MLS project

<table>
<thead>
<tr>
<th>Category</th>
<th>Typical Expenses</th>
<th>Variance Between Projects Based on Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acquisition</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning site</td>
<td></td>
<td>Some variance depending on project needs</td>
</tr>
<tr>
<td>Visits</td>
<td></td>
<td>Substantial variation in cost depending on</td>
</tr>
<tr>
<td>Ground Truth Surveys</td>
<td></td>
<td>quality control needs</td>
</tr>
<tr>
<td>Network</td>
<td></td>
<td>Minimal variance in cost</td>
</tr>
<tr>
<td>Subscription Fees</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibrations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Data Processing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delivery</td>
<td></td>
<td>Large variance depending on deliverables</td>
</tr>
<tr>
<td>Licensing</td>
<td></td>
<td>Large variance depending on deliverables</td>
</tr>
<tr>
<td>Personnel Training</td>
<td></td>
<td>Minimal variance in cost</td>
</tr>
<tr>
<td>Data Storage &amp; Handling</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td>Other Expenses</td>
<td>Large variance depending on deliverables</td>
</tr>
<tr>
<td>(vary by project)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Relative costs of MLS primary deliverable workflow stages

<table>
<thead>
<tr>
<th>Workflow/Deliverable Stage</th>
<th>Cost Increment</th>
<th>Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning and acquisition</td>
<td>$5–$555</td>
<td>Acquisition could be a small part of the project (e.g., for a limited area) or a large part (e.g., for a statewide collection). Planning, in most cases, will be a small part of the cost of this task.</td>
</tr>
<tr>
<td>Georeference point cloud</td>
<td>$5–$555</td>
<td>Generally, this step is completed using proprietary, system specific software. However, it may also include geometric corrections and local transformations. Higher accuracy requirements (particularly network) will result in significantly more expense due to additional field constraints and advanced processing procedures and adjustments, requiring substantial expertise and skill.</td>
</tr>
<tr>
<td>Quality control/quality assurance (QA/QC) evaluation</td>
<td>$</td>
<td>Depends on the desired DCC. High accuracy work requires significantly more QA/QC evaluation. On large, critical projects, possibly consider a third party entity (different from the data provider) to do this work.</td>
</tr>
<tr>
<td>Tile/organize data</td>
<td>$</td>
<td>A variety of software exists to complete this task.</td>
</tr>
<tr>
<td>Sanitize point cloud</td>
<td>$5</td>
<td>Removal of unwanted features and outliers. Can depend heavily on traffic conditions at acquisition time.</td>
</tr>
</tbody>
</table>
### Relative costs of MLS primary deliverable workflow stages

<table>
<thead>
<tr>
<th>Workflow/Deliverable Stage</th>
<th>Cost Increment</th>
<th>Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classify point cloud</td>
<td>$$</td>
<td>Depends on the type of features to classify. Ground vs. non-ground would be relatively inexpensive. Other features, however, require more sophisticated algorithms and manual techniques. Ground filtering software works better for airborne LiDAR data.</td>
</tr>
<tr>
<td>Data extraction attribution</td>
<td>$$-$$$$</td>
<td>Extraction of points and linework to develop maps and or digital terrain models (virtual surveying). Addition of attributes to features may also be done during this process or later in data mining.</td>
</tr>
</tbody>
</table>

### Relative costs of MLS primary deliverable workflow stages

<table>
<thead>
<tr>
<th>Workflow/Deliverable Stage</th>
<th>Cost Increment</th>
<th>Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 3D solid objects</td>
<td>$$$-$$$$</td>
<td>Depends heavily on type of objects to be modeled. Some (geometric primitives) can be obtained through semi-automatic processes; others require manual processes.</td>
</tr>
<tr>
<td>Analyze</td>
<td>$$-$$$</td>
<td>Depends heavily on the type of analysis needed.</td>
</tr>
</tbody>
</table>

### Existing geospatial guidelines relevant to mobile LiDAR

<table>
<thead>
<tr>
<th>Geospatial</th>
<th>Key Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federal Geographic Data</td>
<td>95% confidence evaluation, 20 control points, methodology on how to compute accuracy statistics.</td>
</tr>
<tr>
<td>Committee (FGDC) 1996</td>
<td>National Standard for Spatial Accuracy (NSBA)</td>
</tr>
<tr>
<td>National Digital Elevation</td>
<td>DTM certification, reporting of accuracy across many different remote sensing platforms. Discusses Fundamental, Supplemental, and Consolidated Vertical Accuracies (FVA, SVA, CVA).</td>
</tr>
<tr>
<td>Plan (NDEP) 2004</td>
<td></td>
</tr>
</tbody>
</table>
### Existing geospatial guidelines relevant to mobile LIDAR

#### Mobile LIDAR (Current)

<table>
<thead>
<tr>
<th>Key Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caltrans Chapter 15 Survey Manual 2011</td>
</tr>
<tr>
<td>Florida DOT 2011</td>
</tr>
<tr>
<td>FLDOT TLS and MLS specifications, various classes of data (Type A-high accuracy, Type B-lower accuracy), requirements for: mission planning, control placement, system calibration, overlap requirements, QA/QC.</td>
</tr>
</tbody>
</table>

#### Mobile LIDAR (Development)

<table>
<thead>
<tr>
<th>Key Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORS DOT</td>
</tr>
<tr>
<td>ASPRS Mobile Mapping Comm. At outline stage</td>
</tr>
<tr>
<td>Missouri DOT 2010</td>
</tr>
<tr>
<td>Evaluation of MLS usage for DOT activities</td>
</tr>
</tbody>
</table>

### Existing geospatial guidelines relevant to mobile LIDAR

#### Mobile LIDAR

<table>
<thead>
<tr>
<th>Key Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAA 2011</td>
</tr>
<tr>
<td>NOAA 2009</td>
</tr>
<tr>
<td>USGS 2012</td>
</tr>
<tr>
<td>ASPRS Vertical</td>
</tr>
<tr>
<td>ASPRS Horizontal</td>
</tr>
<tr>
<td>ASPRS Geospatial Procurement Guidelines</td>
</tr>
<tr>
<td>FEMA Guidelines</td>
</tr>
<tr>
<td>Includes LIDAR (airborne, static, and mobile) standards and recommended practices for airport surveys. System Calibrations, data processing.</td>
</tr>
<tr>
<td>Use of LIDAR for shoreline and flood mapping.</td>
</tr>
<tr>
<td>V1.0: Base Specification, Post spacing, overlap requirements, classification, metadata example, DEM, vertical accuracy assessment, glossary of terms.</td>
</tr>
<tr>
<td>Applying FGDC and NDEP guidelines to airborne LIDAR. Land cover types, selection of checkpoints.</td>
</tr>
<tr>
<td>Considerations (and difficulty) of horizontal accuracy verification.</td>
</tr>
<tr>
<td>Draft phase. Distinguishes between professional/technical services and commercial geospatial products.</td>
</tr>
<tr>
<td>LIDAR use in floodplain mapping.</td>
</tr>
</tbody>
</table>

### References

- CALTRANS Survey Manual
- NCHRP Report 671
- CALTRANS Survey Manual
### DOT Questionnaire on MLS

Statistics for familiarity and importance of LIDAR among respondents (1-Low, 10-High)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Median</th>
<th>Mode</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>How familiar are members of your department with 3D Laser Scanning and/or LIDAR?</td>
<td>6.4</td>
<td>7.0</td>
<td>7.0</td>
<td>2.3</td>
</tr>
<tr>
<td>How familiar are members of your department with mobile LIDAR/ Laser scanning systems?</td>
<td>5.4</td>
<td>5.5</td>
<td>5.0</td>
<td>2.2</td>
</tr>
<tr>
<td>How important are these technologies to the future operations within your organization?</td>
<td>7.8</td>
<td>8.0</td>
<td>10.0</td>
<td>2.4</td>
</tr>
</tbody>
</table>
**DOT Questionnaire on MLS**

Over the last 12 months, number of DOTs involved in:

<table>
<thead>
<tr>
<th>Method</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airborne LiDAR</td>
<td>22</td>
</tr>
<tr>
<td>Mobile LiDAR</td>
<td>27</td>
</tr>
<tr>
<td>Static laser scanning</td>
<td>34</td>
</tr>
<tr>
<td>Not Sure</td>
<td>4</td>
</tr>
</tbody>
</table>

**Statistics for percent of data acquisition and design work performed in-house vs. contracted out**

<table>
<thead>
<tr>
<th>Question</th>
<th>Mean</th>
<th>Median</th>
<th>Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Currently what percent of surveying work/data acquisition is performed in-house vs. contracted out to private firms?</td>
<td>57.9</td>
<td>70.0</td>
<td>28.4</td>
</tr>
<tr>
<td>What percent of the design work in your organization is performed in-house vs. contracted out to private firms?</td>
<td>53.3</td>
<td>60.0</td>
<td>24.0</td>
</tr>
</tbody>
</table>

Figure B-10: The State DOTs transition from 2D to 3D
Figure B-11: Factors holding back the adoption of 3D workflows.

Figure B-12: Mobile LIDAR applications that organizations will pursue in the next 5 years.

Figure B-13: Types of services the organizations provide.
DOT Questionnaire on MLS

DOTs strategies to streamline adoption of scanning technology, including:

• Convince “non-design users to accept this tool as viable”.
• Work with asset management and GIS professionals, who have been hesitant to accept this technology. (However, one DOT mentioned that their organization uses the technology for asset management but not for engineering/design work.)
• Create a professional network, through which information and procedures could be shared.
• Produce flexible guidelines to address the varying needs of end users for their many applications.

Figure B-14: Importance of mobile LIDAR over the next 5 years

Figure B-15: Mobile LIDAR surveying challenges experienced by DOTs
### DOT Questionnaire on MLS

#### Figure B-16: Areas where guidelines would be most helpful

- Survey accuracy: 78%
- QA/QC procedures: 80%
- Data interoperability: 79%
- Data management: 76%
- Software integration: 72%
- Other: 16%

#### Figure B-17: Level of accuracy and resolution required to support daily workflows

- **Accuracy:**
  - mm level: 37%
  - cm level: 27%
  - dm level: 16%
  - m level: 11%

- **Resolution:**
  - mm level: 57%
  - cm level: 13%
  - dm level: 21%
  - m level: 11%

### Vendors Questionnaire on MLS

#### Figure B-19: Mobile LIDAR-related business involving DOTs

- Currently what percent of your company's Mobile LIDAR-related business involves a DOT?
- What percent of the DOTs your company is tracking, or are currently working with, are investigating the use of Mobile LIDAR?
- What percent of the DOTs your company is tracking or are currently working with are using Mobile LIDAR?
- What percent will be working with Mobile LIDAR within the next 5 years?
Figure B-21: Top three factors delaying the adoption of mobile LiDAR by the DOTs

Figure B-22: Supported applications by service providers currently and in the future

Figure B-23: Areas in which guidelines would be most helpful regarding the procurement of mobile LiDAR/laser scanning products and/or services
### Service Providers Questionnaire on MLS Deliverables

1. Point clouds (raw, geo-referenced, or classified LAS file)
2. Viewing software
3. Calibrated imagery
4. Reports (methods, procedures, data quality achieved, control fit)
5. CAD or geodatabase files of extracted features
6. Planimetrics
7. DTM
8. Control surveys
9. Lineage documents
10. Corrected trajectory files
11. Check points
12. Ortho-photographs
13. Metadata

.... Or ....