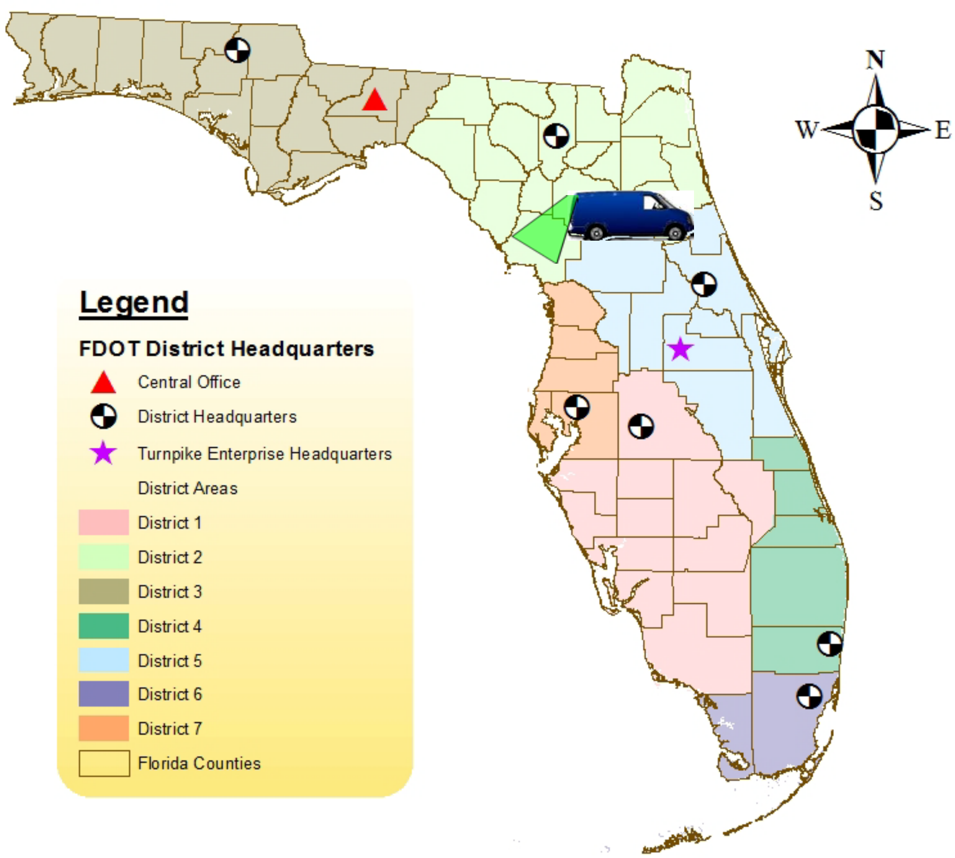
TERRESTRIAL MOBILE LiDAR SURVEYING & MAPPING GUIDELINES

Florida Department of Transportation

October 7, 2013



Contents

1.0 Introduction

The intent of this document is to provide guidelines to help insure proper and efficient use of Terrestrial Mobile LiDAR (TML) technology in support of Florida Department of Transportation Projects.

The basis for this document was adapted from *CALTRANS Surveys Manual 2011.*
http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/Manual_TOC.html

Where possible this document is intended to coincide with the National Cooperative Highway Research Program (NCHRP) : Report 748. (2013). *Guidelines for the Use of Mobile LIDAR in Transportation Applications.* Washington D.C.: Transportation Research Board of the National Academy of Sciences.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_748.pdf


NCHRP
REPORT 748
Guidelines for the Use of Mobile LIDAR in Transportation Applications

2.0 Terrestrial Mobile LiDAR

Terrestrial Mobile LiDAR (TML) uses a laser scanner(s) in combination with Global Navigation Satellite System (GNSS) receivers, Inertial Measurement Unit (IMU), and Distance Measuring Instrument (DMI) to produce accurate and precise geospatial data from a moving terrestrial platform.

LiDAR sensors use an active (projected) light signal to measure the relative x, y, z, position and reflective properties of a point on an object. In practice this results in a point cloud with image qualities similar to other remote sensing technologies. This allows the value of a point cloud to be extended when it is mined for topographic features and information beyond what was required of the intended survey. However, the origin and accuracy of the point cloud data must be supported by a survey report for it to be used with confidence and to ensure the survey information with any byproducts are not misused.

The focus in this document is on three major survey categories of TML. The examples given here are not intended to be exhaustive. Refer to **APPENDIX – A** for other catorgories published by the Transportation Research Board.

Type A – High Accuracy Surveys

- Design Engineering topographic
- As-built
- Structures and bridge clearance
- Deformation surveys

Type B – Medium Accuracy Surveys

- Design Engineering topographic Corridor Study / Planning
- Detailed Asset inventory and management surveys
- Environmental
- Earthwork
- Urban mapping and modeling Coastal zone erosion analysis

Type C – Lower Accuracy Mapping

- Preliminary Planning
- Transportation Statistics
- General Asset inventory surveys

3.0 TML Project Selection

The following are some of the key factors to consider when determining if TML is appropriate for a particular survey project:

- Safety
- Project deliverables desired
- Budget
- Project time constraints
- GNSS data collection environment
- Terrain and length/size of project
- Traffic volumes and available observation times

4.0 TML Equipment

All of the equipment in the TML system used to collect, process, and adjust data must be of sufficient precision to meet the accuracy requirements of the project and applicable accuracy standards described in this document. This determination can be made from the stated specifications of the equipment by the manufacturers, analysis of the systems performance on projects with similar requirements, and the expert opinion of the Professional Surveyor and Mapper in responsible charge of the project survey data and supporting Survey Report.

4.1 Minimum TML system sensor components

- LiDAR sensor
    a) Follow OSHA Regulation 1926.54 and manufacturers' recommendations when using any laser equipment. Never stare into the laser beam or view laser beams through magnifying optics, such as telescopes or binoculars. Additionally, the eye safety of the traveling public and other people should be considered at all times and the equipment operated in a way to ensure the eye safety of all.

- GNSS receivers
    a) One or more onboard (roving) Global Navigation Satellite System (GNSS) dual frequency receiver(s) capable of real-time kinematic (RTK) data, and kinematic data that can be post processed.

b) One or more Static GNSS dual frequency receiver(s) at Base Station(s) capable of simultaneous collection and storage of real-time kinematic (RTK) data, and kinematic data that can be post processed.

- An Inertial Measurement Unit (IMU).
- A Distance Measuring Instrument (DMI).

The collection rate (epoch) of the all TML system sensors must be sufficient to meet project accuracy and point density requirements.

5.0 TML Project Specifications and Procedures

5.1 TML Mission

To maximize the quality and production of measurements, mission planning should be conducted before the collection of TML project data commences.

During a TML data collection mission, simultaneous GNSS signals from a minimum constellation of 5 satellites should be maintained between at least one GNSS Base Station receiver, and the GNSS roving receiver(s). The GNSS constellation PDOP should be 5 or less at the base and roving units during data acquisition. The occasional momentary loss of GNSS signals, also known as cycle slips, may occur. In these cases, the position of the LiDAR sensor is dependent on the IMU, and degrades quickly over time from the last corrected GNSS position. To avoid poor and erroneous measurements the period of lost GNSS corrections should never exceed the IMU's ability to accurately position the sensor over this time interval. The inadvertent scanning of moving targets such as traffic and pedestrians will adversely affect measurements, as well as the texture, shape, and color of the surface being scanned.

The accuracy of a project point cloud is affected by many error factors. Some of these factors can be mitigated while others can be eliminated through proper procedures. Two important factors impacting accuracy related to sensor specifications that can be controlled are; the effective range of sensor and the resulting point density.

LiDAR sensor measurement precision diminishes as the distance from the sensor increases. The effective range of the LiDAR sensor, for purposes of this document, is determined by the sensor manufacturer specifications of precision as they relate to the accuracy requirements of the project or specific areas of the project.

Point Density is primarily determined by the measurement distance to object, measurement rate of the sensor and speed of the sensor platform during measurement. The point density must be sufficient to identify and extract physical detail to the accuracy specified for the project while meeting the TML Application Requirements in ***Table 5.6b***.

All points with compromised accuracies, especially those collected outside the effective range of the scanner, shall be classified as ***Erroneous***.

Projects with difficult TML survey conditions should be reconnoitered first to identify as many of these variables as possible and develop a plan to mitigate their effect on the data. Usually this will require additional control to ensure the TML measurements in these areas meet the project accuracy requirements.

5.2 Project Base Station Control Establishment

The project base station control that will be used to post-process the TML GNSS data shall be placed at intervals to ensure that no processed baseline exceeds the survey type requirements listed in ***Table 5.6b***. Short baselines contribute to the best possible positional accuracy outcome. During TML collection two or more GNSS base station occupations are highly recommended to guard against the possibility of wasted effort and useless data from base station failure due to equipment, accident or human error in station setup, and also allow redundant post-processing. One base station location should be near the beginning of the project and another one near the end of the project with appropriate base station(s) along the corridor to meet the baseline length limitations listed in ***Table 5.6b*** for project area to be mapped. This limitation does not apply to data collected outside of the project as often happens during vehicle staging at the beginning and ending of each pass. The project base station control used shall conform to the Department's **Surveying *Procedure, No. 550-030-101*** as it relates to *Primary GPS Control.*

5.3 Equipment Maintenance and Bore Sight Calibration

All of the sensor equipment in the TML system shall have records documenting maintenance to the manufacturer's recommendation, including all repairs and adjustments to the sensors.

Sensor alignment (bore sighting) procedures sufficient to meet project accuracy requirements shall be performed and documented immediately before and after collecting the TML data for a project. This must be performed on site if the system has been disassembled for transport.

5.4 Redundancy

TML data collection shall be conducted in such a manner as to ensure redundancy of the data. This means that more than one scan pass is necessary. The data shall be collected so that there is overlap between scan passes. The minimum amount of overlap along the sides of the scan passes should be 20%. More overlap is often necessary to cover critical areas where high accuracy surfaces are needed. The redundant passes can be made in the same direction or in opposite directions. A minimum of 15 minutes between the end of one pass and the beginning of the next overlapping pass is required. The objective is to ensure sufficient satellite constellation changes have occurred between passes, reducing the opportunity for bias in the GPS measurements.

5.5 Monitoring Data Collection

Monitoring various component operations during the scan session is an important step in the QA/QC process. The following is a list of minimum items that should be monitored and documented during TML data collection.

- Loss of GNSS reception
- Uncorrected IMU drift both in distance and time
- Proper functioning of the laser scanner
- Vehicle Speed

The system operator should be aware and note when the system encountered the most difficulty and be prepared to take appropriate action in adverse circumstances.

5.6 Local Control and Validation Points

In order to improve the local accuracy of the collected TML point cloud data, a local geometric correction must be applied. The two leading methods currently employed for this process both require local targeted control points visually identifiable in the TML point cloud (see ***Figure 5.6a***), measured independently, and having greater local accuracies than the TML data.

1. The ***preferred*** method incorporates simultaneous adjustment (least squares) of the raw navigation trajectory with weighted (constrained) control stations. This establishes the best trajectory and exterior orientation parameters for the LiDAR sensor (and any other sensors such as a camera). The best trajectory method produces improved results over the second method, and allows for sound relationships between multiple sensor data collected from the moving vehicle.
2. The other method is a least squares adjustment of the horizontal and vertical residuals between established local control points of equal or preferably better accuracy, and the corresponding values from the point clouds to produce the transformation parameters of translation, rotation, and scale for the horizontal values and an inclined plane for the vertical values. These parameters are then applied to the point cloud to produce more accurate final geospatial data within the localized area of control. This method should be used with caution especially in longer projects that may require segmented adjustments.

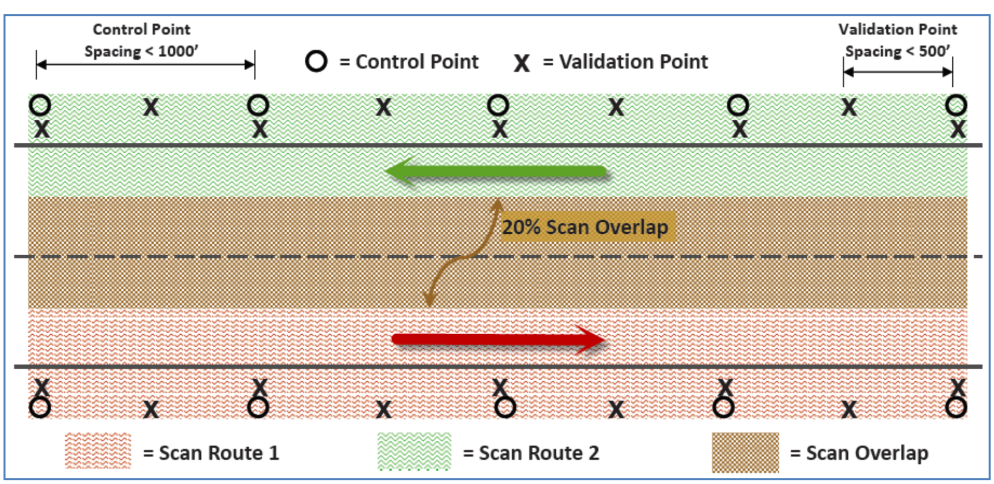
Validation (a.k.a. check) points must be established with the same local accuracies as the control. Validation points by definition are **not** constrained in the adjustment of the TML data to local control points. Validation points are to be used for statistical accuracy computations validating the adjusted TML point cloud.

Control and validation point targets for Type A and Type B TML surveys must be of sufficient size and reflectivity to ensure identification and correct measurement within the point cloud.

The Local Control Points shall be located at the beginning, end, and evenly spaced throughout the project to ensure that the project MLS collection area is bracketed. The maximum distance with respect to route centerline stationing spacing between these points shall be based on the type of survey see ***Table 5.6b***.

Validation Points are used to check the geospatial data adjustment. Validation Points shall be located at the beginning, end, and evenly spaced throughout the project. The maximum distance with respect to route centerline stationing spacing between these points shall be based on the type of survey see ***Table 5.6b***.

Figure 5.6a ** Typical TML Type "A" Local Control and Validation Point Layout*



**Adapted from CALTRANS Surveys Manual 2011*

Table 5.6b - TML Survey Requirements

Operation/Specification	TML Survey		
	TML Type A	**TML Type B**	**TML Type C**
Bore sight calibration of TML system per manufacturers' specifications before and after project data collection.	Required		
Dual-frequency GNSS	Required; See Note 6		
Inertial Measurement Unit	Required; See Note 6		
Distance Measurement Instrument	Required; See Note 6		
GPS Azimuth Measurement Subsystem (GAMS)	Recommended; See Note 8		
GNSS positioning should be constrained to local project control.	Yes		
Minimum horizontal (H) and vertical (V) accuracy for GNSS control base stations.	Must meet or surpass TML local accuracy requirement of the project.		
Minimum accuracy of Local Transformation Points and Validation Points	See Note 5		
TML project positional accuracy requirements relative to Local Transformation Points and Validation Points	H < 0.06' V > 0.06'	H ≤ 0.10' V ≤ 0.10'	H and V See Note 5
Maximum post-processed baseline length	5 miles		10 miles
GNSS base stations located at each end of project	Recommended		
Minimum number of common healthy satellites in view for GNSS base stations and mobile scanner	See Notes 1 thru 5		
Maximum PDOP during TML data acquisition	5		
Allow sufficient time between runs to ensure that the satellite constellation has at least 3 different satellites in view	Each Overlapping Pass		
Minimum overlapping coverage between adjacent runs	20%		
Minimum orbit ephemeris for kinematic post-processing	Broadcast		
Observations – sufficient point density to model objects	Each pass		
Vehicle speed – limit to maintain required point density	Each pass		
Minimum number of local transformation points required	4		
LiDAR point density requirements (see note 9)	FINE (≥ 10 pts/ft^2)		See note 10
Local control point maximum station spacing throughout the project on each side of scanned roadway	1000 foot intervals	1500 foot intervals	See note 5
Validation point maximum station spacing throughout the project on each side of scanned roadway for QA purposes as safety conditions permit. (See Note 3)	500 foot intervals	800 foot intervals	N/A
Minimum NSSDA Horizontal and Vertical Check Points	20 points (see note 7)		

Table 5.6b - Notes:

1. Areas in the project that have poor satellite visibility should be identified and a plan to minimize the effect on the data developed.

2. If necessary project area shall be reconnoitered to determine the best time to collect the data to minimize GNSS outages and excessive artifacts in the data collection from surrounding traffic or other factors.

3. If safety conditions permit, additional validation points should be added in challenging GNSS environments such as mid sections of tunnels and urban canyons.

4. GNSS coverage of less than 5 satellites in view must not exceed the uncorrected position time or distance travelled capabilities of the TML system IMU.

5. Sufficient for TML survey data and products to meet or surpass accuracy requirement of the project.

6. Manufacturer's specifications for precision must be sufficient for TML system to meet or surpass accuracy requirements of the project.

7. Validation points may also serve as NSSDA check points to meet the requirements of this section. However, if critical areas of the point cloud are to be used outside of the locations of the Validation points, then additional check points will be needed in those areas to meet this requirement.

8. A second onboard GNSS dual frequency receiver is recommended. This allows for establishing a GPS Azimuth Measurement Subsystem (GAMS). The GAMS solution is more robust than a single receiver system as it assists in vehicle heading determination and helps to further compensate during brief periods of GNSS signal loss.

9. Point desnisty should be verified through sample point spacing analisys using the formula:

$$Sample\ spacing = \sqrt{1/point\ density}$$

National Cooperative Highway Research Program (NCHRP) : Report 748. (2013). *Guidelines for the Use of Mobile LIDAR in Transportation Applications.* Washington D.C.: Transportation Research Board of the National Academy of Sciences.

10. Unlike TML Type A and B surveys which both reside in the NCHRP Data Collection Category (DCC) "1A", TML Type C surveys may fall in any one of several DCCs (see **APPENDIX – A**). Therefore the scope of work and resulting TML Survey Report must specifiy which DCC accuracy is desired and achieved based on point cloud accuracy and density.

5.7 National Standard for Spatial Data Accuracy (NSSDA)

The accuracy analysis of TML point cloud data shall conform to the NSSDA requirements for geospatial data classification as published by the FGDC in document FGDC-STD-007.3-1998 titled *Geospatial Positioning Accuracy Standards Part 3: National Standard for Spatial Data Accuracy,* http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3). A minimum of 20 independent horizontal and vertical check points shall be measured and distributed to reflect the geographic area of interest and expected distribution of error in the data sets. The resulting comparisons shall meet or surpass the positional accuracy requirements for the survey at the 95% confidence level based on the NSSDA and shall be included in the Survey Report.

5.8 Quality Management Plan (QMP)

Engineering design survey data points collected using TML are checked by various means including comparing scan points to validation points, reviewing the digital terrain model, reviewing independent cross section data to scan surfaces, and redundant measurements. Redundant measurements with TML can only be accomplished by multiple scan runs or passes that offer overlapping coverage.

The TML data provider shall provide a Quality Management Plan (QMP) that includes descriptions of the proposed quality control and quality assurance plan. The QMP shall address the requirements set forth in this document as well as other project specific QA/QC measures.

6.0 TML Deliverables and Documentation

As stated earlier the origin and accuracy of the point cloud data must be supported by a survey report for it to be used with confidence, and to ensure the survey information and any byproducts are not misused.

Documentation of project MLS survey(s) is an essential part of surveying work. The documentation of a scanning project must show a clear data lineage from the published primary control to the final deliverables. All project deliverables and documentation shall be included or clearly identified by reference in the survey report.

6.1 All TML Type Deliverables

The first product deliverable for all TML Type surveys is an original post-processed geo-referenced point cloud in the latest (unless otherwise directed) ASPRS published LAS binary format file. Supporting documentation required but not limited to:

- Statistical system reports
- PDOP values during the survey
- Separation of forward and reverse solution (difference between forward and reverse post-process roll, pitch, yaw and XYZ positions solution).
- Areas of the project that the data collected exceeded the maximum elapsed time or distance traveled of uncorrected IMU drift due to GNSS signal loss or obstruction.
- Comparison of elevation data from overlapping (side lap) runs
- Comparison of points at the area of overlap (end lap) if more than one GNSS base is used.
- NSSDA report comparison

6.2 TML Type A and B Deliverables

The LAS file deliverable for TML Types A and B is the result transformed/adjusted point cloud. The next form of the TML point cloud data is the transformed/adjusted point cloud image also saved in an LAS specific binary format.

Supporting documentation required but not limited to:

- Statistical comparison of point cloud data and finished products to validation points

- Statistical comparison of at least 5 cross sections showing differences between the surfaces created from adjusted point cloud data to cross sections collected from independent measurements of equal or higher accuracy.

The most developed TML point cloud data has been adjusted, verified, and classified by subject type. A Classified point cloud has the added value of having the individual points within it identified by class. All required classes should be specified in the contract scope as this task can be very time consuming.

Table 6.2a

ASPRS Standard LIDAR Point Classes	
Classification Value	*Meaning*
0	Created, never classified
1	Unclassified3
2	Ground
3	Low Vegetation
4	Medium Vegetation
5	High Vegetation
6	Building
7	Low Point (noise)
8	Reserved
9	Water
10	Rail
11	Road Surface
12	Reserved
13	Wire – Guard (Shield)
14	Wire – Conductor (Phase)
15	Transmission Tower
16	Wire-structure Connector (e.g. Insulator)
17	Bridge Deck
18	High Noise
19-63	Reserved
64-255	User definable

Note: The Department continues to review classifications for TML surveys on transportation projects. District Survey Managers should be consulted before point classification begins.

The only required class at this time is "Erroneous" used for points with compromised accuracies. The ASPRS Classification Value of 64 should be used for this class

64	Erroneous

Whenever possible the current ASPRS classifications should be followed at this time.

The point cloud data is now ready to be imported into various software packages for further data analysis and feature extraction as well as fusing with other types of data and analytical tools creating a variety of value-added products.

The following digital products related to TML surveys that are applicable to the project shall be included:

- Binary LAS files of point cloud data from original scans
- Binary LAS files of adjusted and Classified point cloud data
- Digital video or photo mosaic files
- FGDC compliant metadata files

Additional digital CADD products (these products are covered in the current FDOT CADD Manual: *http://www.dot.state.fl.us/ecso/downloads/publications/Manual/default.shtm*

- Topographic Design Files
- Surface / TIN files

The project digital products shall be submitted to the Department on a portable external USB or fire wire computer drive accompanied by an itemized transmittal letter. All digital products submitted, along with any digital and hardcopy media shall become the property of the FDOT. The digital media drive shall be labeled on the outside with the following information:

- Project Title
- Survey Report Title
- Date of Survey
- FM Number
- Consultant Name
- Name of Consultant Surveyor in Charge
- Central Office Image Tracking Number

6.3 TML Survey Report

The documentation of a mobile scanning project must show a clear data lineage from the published primary control to the final deliverables. The data path of the entire process must be defined, documented, assessable, and allow for identifying adjustment or modification. 3D data without a documented lineage is susceptible to imbedded mistakes, difficult to validate, and offers little or no reliability.

General Survey Report Content:

- Project name & identification: County, Route, Section, etc.
- Survey date, limits, and purpose
- Datum, epoch, and units
- Control found, held, and set for the survey
- Personnel, equipment, and surveying methods used
- Problems encountered
- Declare what TML Type A, B, or C accuracy was achieved
- Project base stations occupied
- Identification of control target points (transformation and validation)

- Results of constrained adjustment of TML data to local transformation control points
- QA/QC reports as described in subsection 5.8
- NSSDA analysis of Validation Points from subsection 5.7

All TML Surveying and Mapping products submitted shall be supported by a ***Survey Report*** containing at a minimum all information necessary to support the precision and accuracy of TML measurements and products, and meets the ***Minimum Technical Standards*, *Rule* 5J-17, *F.A.C.,*** pursuant to ***Chapter 472, F.S.*** To this end the Survey Report shall include but is not limited to the documentation and references to digital reports, products and media, identified in this document.

7.0 Abbreviations / Definitions

- **Albedo** - The fraction of light energy reflected by a surface or body, usually expressed as a percentage; also called the reflection coefficient.
- **Artifacts** - Erroneous data points that do not correctly depict the scanned area. Objects moving through the scanner's field of view, temporary obstructions, highly reflective surfaces, and erroneous measurements at edges of objects (also known as "Edge Effects") can cause artifacts. Erroneous depiction of features can be due to inadequate or uneven scan point density.
- **ASPRS** – American Association for Photogrammetry and Remote Sensing
- **CADD** – Computer Aided Design and Drafting.
- **Data Voids** - Gaps in scan data caused by temporary obstructions or inadequate scanner occupation positions. Overlapping scans and awareness of factors causing data shadows can help mitigate data voids. Some data voids are caused by temporary obstructions such as pedestrians and vehicles.
- **Decimation** - Reduction in density of the point cloud.
- **DMI** – Distance Measuring Instrument.
- **F.A.C. –** Florida Administrative Code.
- **FDOT –** Florida Department of Transportation.
- **FGDC –** Federal Geographic Data Committee.
- **F.S.** – Florida Statute.
- **GAMS -** GPS Azimuth Measurement Subsystem. The GAMS solution is more robust than a single receiver system as it assists in vehicle heading determination and helps to further compensate during brief periods of GNSS signal loss.
- **GNSS -** Global Navigation Satellite System.
- **Inertial Measurement Unit** (**IMU**) - A device that senses and quantifies motion by measuring the forces of acceleration and changes in attitude in the pitch, roll, and yaw axes using accelerometers and gyroscopes.
- **Image** - A pattern formed by electromagnetic radiation that approximately duplicates the pattern formed by a real object or a physical field detectable by the radiation.
  This definition is more general than the usual definition because many instruments used for detection operate at other than light frequencies but in ways similar or analogous to those used for forming optical images. The kind of radiation forming an image is usually specified by adding a word that identifies the part of the spectrum involved, e.g., radio image, infrared image, optical image, and X-ray image. However, the terms "radar image" and "X-ray image" are used to refer to optical images of the images formed by radar or X-ray. *Source: National Geodetic Survey: Geodetic Glossary. Library of Congress Catalogue Card Number 86-61105. 1986.* http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml
- **Intensity** - A value indicating the amount of laser light energy reflected back to the scanner.
- **LAS** - A binary file standard supported by American Society of Photogrammetry & Remote Sensing (ASPRS) for storing point location and attribute information primarily used for LiDAR data.
- **LIDAR** - Light Detection and Ranging is an active optical remote sensing technology which measures the return properties of scattered light to determine range, direction and other information of a distant line-of-site object.
- **Noise** - Erroneous measurement data resulting from random errors.
- **NSSDA** – National Standard for Spatial Data Accuracy
- **Orthophotograph** - A photographic copy, prepared from a perspective photograph, in which the displacements of images due to tilt and relief have been removed. *(Source: American Congress on Surveying and Mapping and the American Society of Civil Engineers. Definitions of*

Surveying and Associated Terms. Library of Congress Catalogue Card Number 72-76807. Washington 1972, 1978.)

- **Orthophotomosaic –** An assembly of orthophotographs forming a uniform-scale mosaic. *(Source: American Congress on Surveying and Mapping and the American Society of Civil Engineers. Definitions of Surveying and Associated Terms. Library of Congress Catalogue Card Number 72-76807. Washington 1972, 1978.)*
- **Orthorectification** – A special case of image resampling whereby the effects of image perspective and relief displacement are removed so that the resulting orthoimage has uniformly scaled pixels, resembling a planimetric map. *(Source: American Society for Photogrammetry and Remote Sensing Manual of Photogrammetry Fifth Edition, 2004, page 963)*
- **PDOP –** Positional Dilution of Precision
- **Photogrammetry** - The science or art of obtaining reliable measurements by photography. *(Source: American Congress on Surveying and Mapping and the American Society of Civil Engineers. Definitions of Surveying and Associated Terms. Library of Congress Catalogue Card Number 72-76807. Washington 1972, 1978.)*
- **Phase based measurement** - Distance measurements based on the difference in a light's sinusoidal modulated power and it's reflected return from a surface.
- **Point Cloud** - A relatively precise group of three dimensional point data collected by a laser scanner from a single observation session. A point cloud may be merged with other point clouds to form a larger composite point cloud.
- **Point Density** - The number of points per unit area; can also be expressed as the average distance between points in a point cloud. National Cooperative Highway Research Program (NCHRP) : Report 748. (2013). *Guidelines for the Use of Mobile LIDAR in Transportation Applications.* Washington D.C.: Transportation Research Board of the National Academy of Sciences.
- **QA –** Quality Assurance
- **QC** – Quality Control
- **Registration** - The process of joining point clouds together or transforming them onto a common coordinate system. Registration can be by use of a) known coordinates and orientations b) target transformation or c) surface matching algorithms.
- **Remote Sensing** - The process of detecting and/or monitoring the chemical or physical properties of an object without physically contacting the object. *(Source: American Congress on Surveying and Mapping and the American Society of Civil Engineers. Definitions of Surveying and Associated Terms. Library of Congress Catalogue Card Number 72-76807. Washington 1972, 1978.)*
- **Resolution** – Degree of detail which can be seen. Directly related to point density.
- **Scan** - The acquiring of point cloud data by a LiDAR system.
- **Scan Speed** - The rate at which individual points are measured and recorded.
- **Time-of-flight measurement** - Distance measurements based on the time between emitting a pulse of light and the detecting the reflection of the pulse.
- **TRB** – Transportation Research Board
- **Wave-form processing** - Also called "echo digitization." Scanner system that uses the pulsed time-of-flight technology and internal real-time processing capabilities of multiple returns to identify multiple targets.

8.0 APPENDIX - A

TRB Accuracy and Resolution Matrix

Table 1. Matrix of application and suggested accuracy and resolution requirements.

Accuracy	HIGH < 0.05 m (< 0.16 ft)	MEDIUM 0.05 to 0.20 m (0.16 to 0.66 ft)	LOW > 0.20 m (> 0.66 ft)
Density	1A	2A	3A
FINE >100 pts/m^2 (>9 pts/ft^2)	• Engineering surveys • Digital terrain modeling • Construction automation/ Machine control • ADA compliance • *Clearances** • *Pavement analysis* • Drainage/Flooding analysis • Virtual, 3D design • CAD models/Baseline data • BIM/BRIM** • Post-construction quality control • As-built/As-is/Repair documentation • Structural inspections	• *Forensics/Accident investigation** • *Historical preservation* • Power line clearance	• Roadway condition assessment (general)
	1B	2B	3B
INTERMEDIATE 30 to 100 pts/m^2 (3 to 9 pts/ft^2)	• Unstable slopes • Landslide assessment	• General mapping • *General measurements* • Driver assistance • Autonomous navigation • Automated/Semi-automatic extraction of signs and other features • Coastal change • *Safety* • Environmental studies	• Asset management • Inventory mapping (e.g., GIS) • Virtual tourism
	1C	2C	3C
COARSE <30 pts/m^2 (<3 pts/ft^2)	• *Quantities (e.g., earthwork)* • Natural terrain mapping	• *Vegetation management*	• Emergency response • Planning • Land use/Zoning • Urban modeling • Traffic congestion/ Parking utilization • Billboard management

**Network accuracies may be relaxed for applications identified in red italics.*
**BIM/BRIM: BIM = Building Information Modeling; BRIM = Bridge Information Modeling.
These are only suggestions; requirements may change based on project needs and specific transportation agency requirements.

National Cooperative Highway Research Program (NCHRP) : Report 748. (2013). *Guidelines for the Use of Mobile LIDAR in Transportation Applications.* Washington D.C.: Transportation Research Board of the National Academy of Sciences.