Chapter 9 - Mobile Terrestrial Laser Scanning

9.1 Mobile LiDAR Laser Scanning

Laser scanning or Light Detection and Ranging (LiDAR) systems use lasers to make measurements from a tripod or other stationary mount, a mobile mapping vehicle, or an aircraft. The term LiDAR is sometimes used interchangeably with laser scanning. This chapter deals with Terrestrial Laser Scanning methods.

The NJDOT Survey Manual provide specifications, describe methods and procedures needed to attain a desired survey accuracy standard. For complete accuracy standards, refer to NJDOT Survey Manual Chapter 4, NJDOT survey specifications shall be used for all NJDOT projects.

There are many uses for LiDAR in a multitude of disciplines. The following table demonstrates many of the uses and recommended accuracies and point cloud density for each use. Although most NJDOT projects will fall into Blocks 1A, 1B or 1C, there may be some that will not. The actual determination of the required accuracy and point cloud density will be based on recommendations from the mapping consultant and the concurrence of the NJDOT Survey SME and the NJDOT PM will be on a project-by-project basis.

This technology can minimize impacts to traffic and improve the safety for the surveyors in the field. Thus, reducing costs for attenuator vehicles and other safety devices and field time for the surveyors. In addition, the time it will take less time to collect and longer time to process the data will be significantly less than conventional survey methods.

Projects could employ one or more of these technologies depending on time, cost and priority of each project:

- Aerial Photogrammetry
- Airborne LiDAR
- Mobile Terrestrial Laser Scanning (MTLS)
- Stationary Terrestrial Laser Scanning (STLS)
- Conventional Survey

Matrix of application and suggested accuracy and resolution requirements. Network accuracies may be relaxed for applications identified in *red italics*. Note that these are only suggestions and may change based on project needs and specific transportation agency requirements. The accuracy and density values are to serve as a guideline.

TABLE 9-1

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**

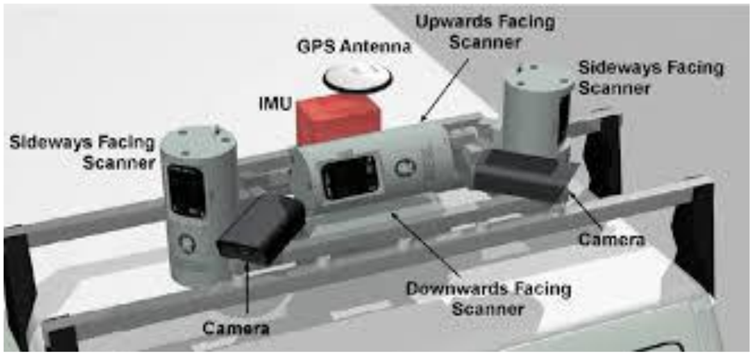
FINE **>100 pts/m^2** **(>9 pts/ft^2)**	• Engineering surveys • Digital Terrain Modeling • Construction Automation/ Machine Control • ADA compliance • *Clearances* • *Pavement analysis* • Drainage\flooding analysis • Virtual, 3D design • CAD models\baseline data • BIM\BRIM • Post-construction quality control • As-built/As-is/repair documentation • Structural inspection	• *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 Tour
	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

The above table is from the: NCHRP 15-44 Guidelines for the Use of Mobile LIDAR in Transportation Applications. The guidelines in the above table were developed for Mobile LiDAR. Actual point cloud densities and accuracies will be determined on a project-by-project basis.

Any mapping project that requires survey control to be established or utilizes a RTN network will require a Licensed Land Surveyor

9.2 Mobile Terrestrial Laser Scanning (MTLS)

Mobile terrestrial laser scanning (MTLS), also referred to as Mobile LiDAR, uses LiDAR technology in combination with Global Navigation Satellite Systems (GNSS), Distance Measuring Instrument (DMI), and Inertial Measurement Unit (IMU) to produce accurate and precise georeferenced point cloud data and digital imagery from a moving vehicle. MTLS platforms may include Sport Utility Vehicles, Pick-up trucks, Vans, Hi-rail vehicles, Boats, and other types of vehicles. MTLS improves the safety and efficiency of data collection.



Depiction of Various Mobile LiDAR Equipment Mounted on Vehicle

The scanner(s) position is determined by post-processed kinematic GNSS procedures using data collected by GNSS antenna(s) mounted on the vehicle and GNSS base stations occupying project control (or CORS stations) throughout the project area. The GNSS solutions are combined with the IMU data to produce precise geospatial locations and orientations of the scanner(s) throughout the scanning process. The point cloud generated by the laser scanner(s) is registered to these scanner positions and orientations. In addition, the use of cameras georeferenced to the point cloud can provide a very detailed data set.

In order to meet the vertical accuracy requirements for the project additional control points (local transformation points) within the scanned area are required to register the point cloud data. The point cloud is adjusted by a local transformation to well defined control points throughout the project area to produce the final geospatial values. The final scan values are then compared to independently measured validation points for quality control.

9.3 Selecting a Project

Not every project will be suited for this technology. The following are factors to consider when determining if MTLS is appropriate for a particular NJDOT project:

- Safety (see NJDOT Safety Manual and MUTCD for guidelines)
- Project deliverables desired
- Project time constraints
- Site or structure complexity or detail required
- Length/size of project
- Will Traffic slowdowns be required, are state or local police required to assist in slowdowns
- Traffic volumes and best available observation times
- Forecast weather and atmospheric conditions at planned observation time
- MTLS system
- Availability of equipment and staff
- Accuracy required
- Technology best suited to the project and desired final products (as determined by the NJDOT Survey SME and NJDOT PM)

9.4 MTLS Applications

In general, there are different types of scans, Type A, B & C. Below are some examples of each type of scans. The NJDOT PM should consult with the Survey SME to determine what type of scan is required for each project.

9.4.1 Type A – High Accuracy/Hard Surface – Topographic Surveys

- Design engineering topographic surveys
- As-built surveys
- Structures and bridge clearance surveys
- Pavement analysis
- Deformation surveys

9.4.2 Type B – Medium Accuracy – Topographic Surveys

- Corridor Study and Planning Surveys
- Asset Management and Inventory Surveys
- Environmental Surveys
- Sight Distance Analysis Surveys
- Earthwork Surveys such as rock slopes, borrow pits, stock piles
- Soil and Coastal Erosion Analysis
- Street Scape Design and Analysis

9.4.3 Type C – Low Accuracy Mapping

- Preliminary Planning
- Transportation Statistics
- General Asset Inventory

9.5 MTLS Equipment and Use

All of the equipment used to collect MTLS data, to control the data, and to collect the quality control validation points should be able to collect the data at the accuracy standards described below. This determination will be from the stated specifications for the equipment by the manufacturers.

9.5.1 Eye Safety

One major concern is that of eye safety for both the operators and the general public. The operators should follow all appropriate OSHA, State 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. MTLS equipment operators should never direct the laser toward personnel operating instruments with magnifying optics such as total stations or levels. The eye safety of the traveling public and other people should be considered at all times and the equipment operated in a manner to ensure the eye safety of all.

9.5.2 Useful Range of MTLS System

A laser scanner is capable of scanning features over long distances, and the accuracy of the scan data decreases as scan range increases. Since the scan data accuracy diminishes with range and would not meet the accuracy requirements beyond a certain distance, care should be taken to ensure that the final dataset does not include any portion of point cloud data whose accuracy is compromised by measurements outside the useful range of the MTLS system. The useful range will be determined by factors such as the range and accuracy specifications of the individual MTLS system, GNSS signal reception during data collection, and the accuracy requirements of the individual project.

9.5.3 Local Registration and Validation Points

Local registration points serve as control for adjustment of the point clouds. Validation points allow for QC checks of the adjusted scan data. Local registration and validation points may be targeted control points, recognizable features, or coordinate positions within the scans. When used, highly reflective targets, marked by reflective tape, white paint with glass beads, or reflective thermoplastic, should be located as close to the MTLS vehicle travel path as possible without compromising safety of the survey crew surveying the painted target locations. The MTLS vehicle operator(s) should adjust the vehicle speed so that the target(s) will be scanned at sufficient density to ensure good target recognition.

9.6 MTLS Specifications and Procedures

MTLS GNSS equipment must correspond with the requirements stated in NJDOT Survey Manual Chapter 4, "GPS Surveys". MTLS kinematic post-processing must comply with these specifications. MTLS kinematic GNSS/IMU data must be post-processed in forward and reverse directions (from beginning-to-end and end-to-beginning). Table XX lists the specifications required to achieve general order MTLS accuracy.

9.6.1 Mission Planning

Before the MTLS project data collection commences, a mission planning session should be conducted to assure adequate GNSS satellites availability during the data collection especially for GNSS-challenged locations. During the data collection there shall be a minimum of six (6) satellites in view for the GNSS Base Stations at all time during data collection. The project area shall be reconnoitered to determine the best time to collect the data to minimize traffic impact and reduce excessive "artifacts" from surrounding traffic as well as to identify obstructions that may cause GNSS signal loss.

MTLS systems require a safe location for a "static session" in an area with relatively open sky before and after collecting data. This may be as simple as parking for several minutes to collect static GNSS/IMU data for sensor alignment. Some MTLS systems may require a larger area such as a parking lot to perform a series of "figure-8" maneuvers.

Project areas that have poor satellite visibility due to terrain and local obstruction should be identified, and a mitigation plan should be developed for GNSS-challenged areas. A mitigation plan could include a densified network of transformation points and validation points. In addition, an area with open sky view suitable for static session nearby should be identified. The MTLS operator should stop in an open sky area for a short static session (3 to 5 minutes) after driving and collecting data through a GNSS-challenged area so that the GNSS/IMU system can reacquire GNSS signals before the next data recording session.

- Mission Planning should include:
- Control targets placement plan
- Quality Management plan
- MTLS data collection drive route plan

- Safety plan
- Traffic control plan (if traffic control is required)

9.6.2 GNSS Project Control

The GNSS Base Station data at the time of MTLS data collection is required in the post processing of GNSS/IMU data. The GNSS base station location shall be placed near the middle of the project in order to keep the GNSS baseline as short as possible/practical.

The GNSS baseline shall not exceed 12.5 miles in length. Shorter baseline (9 miles or less) would contribute to the best possible positional accuracy outcome. Dual redundant GNSS base stations are highly recommended to guard against the possibility of wasted effort and useless data from GNSS base station failure due to equipment failure, accident, loss of battery power, or human error in station setup. In a dual redundant GNSS base station setup, both GNSS base stations should be located near the middle of the project to minimize baseline length. The horizontal accuracy standard of the GNSS base stations shall meet the 0.07' local network accuracy.

9.6.3 Equipment Calibration

Before collecting the MTLS data, all of the equipment in the MTLS system shall be calibrated to the manufacturer's specifications and serviced according to the manufacturer's recommendations. Sensor alignment (bore sighting) procedures shall be performed prior to scanning if the sensor(s) has been disassembled for transport or service. User should follow the manufacturer's recommended sensor alignment procedures.

9.6.4 Redundancy

MTLS data collection shall be conducted in such a manner as to ensure redundancy of the data. The data should be collected so that there is an overlap, which means more than one pass in the same direction along the roadway, overlapping passes in opposite directions, or both shall be collected. Overlap dimensions: minimum of 25% sidelap (see Figure X-1). The redundant overlap data provides data for quality control.

9.6.5 Monitoring Equipment during the Data Collection

Monitoring various component operations during the scan session is an important step in the QA/QC process. 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. The MTLS equipment shall be monitored throughout the data collection to track the following as well as any other factors that need monitoring:

- Distance traveled during, or time duration, and location of degraded or lost GNSS reception. The operator must not exceed the uncorrected position time or distance travelled capabilities of the MTLS system's IMU as recommended by the manufacturer.
- Data storage availability
- Proper functioning of the MTLS system including but not limited to: power supply, vehicle power voltage, laser scanner(s), and digital camera(s).
- Vehicle speed appropriate for desired point density.

9.6.6 Local Registration and Validation Requirements

In order to increase the accuracy of the collected and adjusted geospatial data, a local registration of the MTLS point clouds shall be conducted. Different types of local registration may be employed. For example, one common method is single elevation adjustment of vertical values between established local registration points and the corresponding values from the point clouds. This method works well only for small projects. A long corridor scan would require adjustment to the vehicle trajectory using registration targets and/or points along the roadway. The painted local registration points may also be used to adjust the positional values (X, Y, and Z) of the point cloud. Points on horizontal flat planes (vertical registration points) may be used for vertical (Z)-only adjustment. The MTLS manufacture’s painted target recommendations and specifications (size and shape) should be followed. The painted targets are often white with embedded high reflectivity material (glass beads) and borders painted in flat black. Reflective tape may be used for the painted targets. Flat black target borders enable easier target point classification. Painted local registration point targets shall be located at the beginning, end, and evenly spaced throughout the project and each MTLS data recording or pass. Vertical registration points shall be located evenly spaced in between the painted local registration point targets (see Figure 9-1).

For Type A MTLS surveys, bracket the scanned area on both sides of the roadway with painted local registration point targets at a maximum of 1500-foot spacing. Vertical local registration points should be on both sides of the scanned roadway at a maximum of 500-foot spacing in between the painted local registration point targets (see Figure X - 1). Type A MTLS surveys require local transformation points and validation points to have surveyed local positional accuracies of Hz ≤ 0.03 foot & Z ≤ 0.02 foot or better. The preferred method of establishing Type A MTLS local transformation point elevations is differential leveling to NJDOT third order or better specifications.

For Type B MTLS surveys, bracket the scanned area on both sides of the roadway with painted local registration point targets at a maximum of 3000-foot spacing. Vertical local registration points should be placed in between the painted local registration point targets (1500 foot from the painted local registration point target). Type B MTLS surveys require local transformation and validation points to have surveyed local positional accuracies of Hz & Z ≤ 0.10 foot or better (see Table 9-2).

In GNSS-challenged areas, where GNSS signal is severely limited due to terrain and/or obstruction from structures and trees, painted local registration point targets should be densified to 500 foot spacing. Example GNSS-challenged environments are tunnels, tree canyons, and urban canyons.

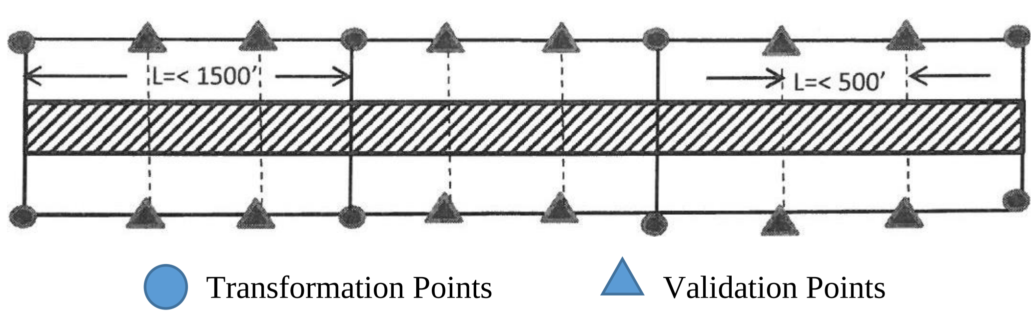


Figure 9-1 Typical MTLS Type A Local Transformation Layout

Image Courtesy of California Department of Transportation

Table 9-2 Terrestrial Mobile LiDAR (TML) Applications Requirements

Operations/Specifications	TML Applications		
	TML Type A	TML Type B	TML Type C
Bore sight calibration of TML system per manufacturer's specifications before and after project data collection Adds cost and is not practical	Required		
Dual frequency GNSS	Required: See note 6		
Inertial Measurement Unit	Required: See note 6		
Distance Measuring Instrument	Required: See note 6		
GNSS positioning should be constrained to local project control	Yes, not for C		
Minimum horizontal (H) and vertical (V) accuracies for GNSS control base stations	Must meet or surpass TML accuracy requirements of the project		
Minimum accuracy of Local transformation Points and Validation Points	H ≤ 0.07' V ≤ 0.05'	H ≤ 0.12' V ≤ 0.10'	Hand V See Note 5
Maximum post-processed baseline length	(5 miles)	10 miles	20 miles
GNSS base stations located to minimize baseline lengths.	Required A & B Recommended C		
Minimum number of common healthy satellites in view for GNSS base stations and mobile scanner	See Notes 1 thru 5		
Sustained Maximum POOP during TML data acquisition	5		
Overlapping coverage between adjacent runs	Required		
Minimum orbit ephemeris for kinetic 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	8	8	As Scoped
Local transformation point maximum spacing throughout project on either side of scanned roadway	750' interval	1500' interval	See Note 5
Validation point maximum spacing throughout project on either side of scanned roadway for QA purposes as safety conditions permit (see Note 3)	750' interval	1500' interval	**N/A**
Minimum NSSDA Horizontal and Vertical Check Points	20 (See Note 7) As needed for Type C		

Table 9-2 is courtesy of North Carolina Department of Transportation

Table 9-2 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 near structures, and overhead obstructions where GPS visibility is poor.
4. GNSS coverage of less than 5 satellites in view must not exceed the uncorrected position time or distance traveled capabilities of the TML system IMU.
5. Sufficient for data collected by TML system 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 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, the additional check points will be needed in those areas to meet this requirement.

9.6.7 Quality Control

Quality control (QC) measures must be performed to ensure the accuracy of the registered MTLS point clouds meets the required accuracy of the project. Survey data points collected using MTLS are checked by various means including comparing scan points to validation points, reviewing the digital terrain model, reviewing data terrain lines in profile, and comparing redundant measurements. Redundant measurements with MTLS can only be accomplished by multiple scan runs or passes that offer overlapping coverage.

The MTLS data provider shall provide a Quality Management Plan (QMP) that includes descriptions of the proposed plan for quality control. The QMP shall provide all methods and means in detail to ensure the point cloud data meets the required accuracy of the project.

There are three common QC methods for MTLS point clouds:

1. Using validation points (targets and/or vertical control points not used for registration) to check the errors at the validation points after the registration. These errors are XYZ for painted target or Z only for a vertical control point.
2. Compare the point cloud location differences (vertically Z only on road surface and/or horizontally with vertical surface) of overlap area from two registered point clouds collected from two different times. 6” to 1” wide cross-sections every 50 to 100 feet are often used in the comparison throughout the point cloud.
3. Using data points from conventional survey to check the (X, Y or Z only) error(s) at the conventional survey points after the registration. Five (5) or more points per mile is recommended.

The QC process must employ two or more of the above methods. Point cloud areas with larger than expected errors would require additional quality control examination or supplemental survey by conventional survey or static laser scanning.

The QC report shall list the results of the MTLS including but not limited to the following documentation:

1. The GNSS/IMU post-processing accuracy report should contain the following from the GNSS/IMU post-processing software:
   a. The location coordinates, datum, vertical datum, and epoch date of the GNSS base station used for GNSS/IMU post-processing. The base station location NGS data sheet should be attached if available.
   b. Number of satellites
   c. Solution status plot
   d. GNSS baseline distance plot
   e. Best estimated post-processed position and orientation error estimates plot
   f. Forward/Reverse Separation plot. Separation of forward and reverse solutions (difference between forward and reverse post-processed XYZ positions solution). Forward and reverse refers to time: processing from beginning-to-end and end-to-beginning.
   g. Narrative on location(s) with large error and migration if applicable.
2. Registration report
   a. Adjustments (horizontal and vertical) made to the MTLS point cloud
   b. If cloud-to-cloud registration was performed, the reference cloud and the adjustments made should be provided.
   c. Average magnitude and standard deviation errors of ground controls and adjustment if available.
3. QC report on the registered point clouds

   The Control report should contain the following:
   a. Table showing the delta Z and/or delta XY differences between validation target points and MTLS registered point cloud.
   b. Comparison of elevation data from overlapping (sidelap) runs.
   c. Comparison of points at the area of overlap (endlap) if more than one GNSS base station is used for the project.
   d. Statistical comparison of registered point cloud data and validation points from conventional survey. The ground truth survey shall be independent of the target control survey and utilize the same horizontal and vertical constraints.
   e. Average, minimum and maximum dZ for each run (optional).
   f. Narrative of QC methods employed and their results.

9.7 MTLS Deliverables and Documentation

Different projects and customers require different types of deliverables. One of the inherent features and fundamental advantages of laser scan data is that it is acquired, processed and delivered in digital format allowing the user to generate laser scan-derived end products for a very wide range of applications and customers beyond the original intent.

The deliverables from a MTLS project should be specified in the NJDOT Survey Request or contract task order.

Deliverables specific to MTLS surveys may include, but are not limited to:

- Registered point clouds in other specified format. ASCII CSV (XYZI or XYZIRGB files), LAS, LAZ.
- MTLS raw data files
- Current NJDOT CADD Standards for Roadway, Bridge, Electrical
- Digital video or photo files with data files supported by TopoDOT
- Survey narrative report including project metadata and GNSS base station data sheet
- Project Control report (see NJDOT Survey Manual Chapter 11)
- MTLS QC report