CHAPTER 9

Laser Scanning and LiDAR Applications

Chapter Contents

Sec. 9.00 Introduction & References

The intent of this Chapter is to provide guidelines to help ensure proper and efficient use of Laser Scanning and/or Light Detection and Ranging (LiDAR) technology in support of Virginia Department of Transportation projects. The guidelines and/or specifications herein are not intended to be all encompassing or unnecessarily restrictive; nor are they intended to extend beyond the described laser scanning applications into more general survey use. The guidelines identified in this chapter are specific to laser scanning technology and allow for the proper collection, registration, validation, and quality control of resultant point cloud datasets.

This Chapter was partially adapted from CALTRANS Surveys Manual revised 2018. Please see **Surveys Manual | Caltrans** or visit

https://dot.ca.gov/programs/right-of-way/surveys-manual-and-interim-guidelines

and further adapted in part from the Florida Department of Transportation Surveying and Mapping Handbook revised 2021. Please see **Appendix A (windows.net)** or visit

https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/GeoSpatial/documentsandpubs/surveying-and-mapping-handbook.pdf?sfvrsn=593bb55c_16

Where practicable these guidelines are intended to coincide with the National Cooperative Highway Research Program (NCHRP): Report 748. (2013). *Guidelines for the Use of Mobile LiDAR in Transportation Applications.* *http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_748.pdf*

Reference is also made to the Federal Geographic Data Committee, GeoSpatial Positioning Accuracy Standards, Part 3: National Standard for Spatial Data Accuracy (NSSDA). Please see **National Standard for Spatial Data Accuracy (fgdc.gov)** or visit

https://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

Sec. 9.01 General

Laser Scanning or Light Detection and Ranging (LiDAR) systems are popular land surveying methods that can precisely measure and collect 3D coordinates from a variety of surfaces and objects. Though the technology has been around since the 1960's, more recent advancements have made LiDAR an effective land surveying tool for the rapid collection of topographic data in a safe, effective and non-intrusive manner. The terms Laser Scanning and LiDAR are quite often used interchangeably within the realm of land surveying.

This chapter will use the terms Stationary Terrestrial Laser Scanning (STLS), Mobile Terrestrial Laser Scanning and/or Mobile LiDAR (M-LiDAR) and Airborne LiDAR (A-LiDAR) to differentiate between the most common land surveying applications of 3D laser scanning technology.

This chapter will focus on three major survey categories which may be suitable for the application of laser scanning and/or LiDAR technology and survey methods. This is done to differentiate between the varying accuracy, control and quality assurance requirements of each category. The examples here are not intended to be exhaustive or category restrictive as the accuracy requirements of any survey are subject to the specific needs of the project. Specific project needs are to be determined prior to the commencement of the survey.

- High Accuracy Surveys (may include)
    - Pavement analysis
    - Roadway/Pavement topographic
    - Structures and bridge clearance
    - Design engineering topographic
    - As-built data
    - Deformation monitoring
    - Architectural an historic preservation
- Medium Accuracy Surveys (may include)
    - Design engineering topographic corridor study/planning
    - Urban mapping and modeling
    - Environmental
    - Sight distance analysis
    - Earthwork (stockpiles, borrow pits, landslides, etc.)
    - Coastal zone erosion analysis
    - Detailed asset inventory and management
- Low Accuracy Surveys (may include)
    - Preliminary planning
    - Transportation studies
    - General asset inventory and management

Sec. 9.01.1 Project Selection

The following are some of the key factors to consider when determining if laser scanning and/or LiDAR is appropriate for a particular survey project:

- Safety
- Project deliverables desired
- Project complexity or detail required
- Project time constraints
- Terrain and length/size of the project
- Traffic volumes and best available observation times
- Budget
- GNSS data collection environment
- System availability
- Forecast for weather and atmospheric conditions
- Ground conditions

Sec. 9.01.2 Laser Scanning & LiDAR Basics

LiDAR sensors use an active projected light signal to measure the relative position and reflective properties of a point on the earth's surface or on an object. This results in a point cloud with image qualities similar to other remote sensing technologies. This also allows the value of a point cloud to be extended when it is mined for topographic features and information beyond what was required for the originally intended survey. However, the origin and accuracy of the extended point cloud data must be supported by the survey documentation for it to be used with confidence and to ensure the survey information is not misused.

The 3D point data collected through the use of LiDAR technologies consist of a point cloud usually in the industry standard LAS (LASer) file format. This format is an open, binary format specified by the American Society for Photogrammetry and Remote Sensing (ASPRS) to be used for the interchange and archiving of LiDAR point cloud data. Point clouds from a single observation may be merged with other point clouds to form a larger composite point cloud to cover greater area and/or to achieve greater detail within a specified area.

All points in the point cloud have an X, Y and Z coordinate as well as a Laser Return Intensity value (XYZI). They may also have Red, Green and Blue color values if image overlay data is available (XYZIRGB). When the point clouds include values for scanned control points that are georeferenced to a known coordinate system, the entire point cloud can then be oriented to the same coordinate system. The positional error of any point in the cloud is then equal to the accumulation of any errors present within the scanning control, positional errors of the scanning equipment and errors in the individual point measurements. Proper quality control measures must be adhered to and standard operating procedures followed to ensure the accuracy and integrity of the final datasets.

Similar to a reflectorless total station, laser scanning measurements that are perpendicular to a surface will produce better accuracies than those with a larger angle of incidence to the surface. The larger the incidence angle (see Figure 9-1), the more the beam can elongate, which produces errors in the distance returned. Data points will also become more widely spaced as distance from the scanner increases and less laser energy is returned. At a certain distance the error will exceed project standards and beyond that no usable data will be returned. Atmospheric factors such as heat radiation, rain, snow, silt, dust, and fog will also limit the effective range of the scanner. Similar degradation will occur with mobile LiDAR, where the sensors are mounted on the top of a vehicle – the further away from the drive path, the angle of incidence will increase, effectively producing data that is less dense and potential errors in the data points. Although less frequently seen, the same may be said of aerial LiDAR, where the points contained in the dataset is pushed too far beyond the flight line.

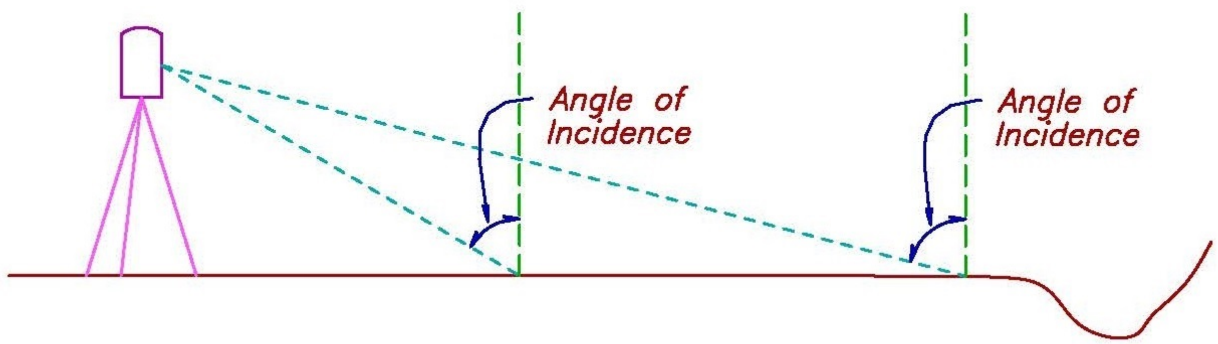


Figure 9.1 Angle of Incidence

Sec. 9.02 Eye Safety

Generally, commercially sold LiDAR products must conform to the International Electrotechnical Commission ("IEC") 60825 and 60825-1 standards. Sensors designed to meet these eye safety standards can be used safely by properly trained personnel. However, under certain conditions, some wavelengths of light operating at a higher power level can still cause corneal damage and potential damage to the eye lens.

Follow OSHA Standard 1926.54 and the manufacturer's recommendations when operating any laser equipment. Never stare into the laser beam or view laser beams through magnifying optics, such as telescopes or binoculars. Survey personnel should also guard against curious members of the public looking directly into the beams. STLS equipment operators should never direct the laser toward personnel operating instruments with magnifying optics such as total stations or surveyor's levels. The STLS equipment should never be intentionally directed toward any aircraft or into any occupied vehicle. Additionally, 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.

Sec. 9.03 Useful Range of Scanner

Since a laser is capable of scanning features over long distances, and since the accuracy of the scan data diminishes 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 scanner. The useful range is influenced by factors such as the range and accuracy specifications of the scanner as well as the accuracy requirements of the final survey products. Methods for accomplishing this might include the implementation of range and/or intensity filtering during data collection or culling any out-of-useful range data during post processing. Since VDOT may choose to mine the survey data for additional information, it is imperative that the final dataset contain only data collected within the useful range of the scanner. Surface properties including color, surface reflectivity (albedo), surface texture, weather and angle of incidence can limit scanner useful range. When using a Mobile Terrestrial Laser Scanner system (M-LiDAR) the range and accuracy may also be limited by GNSS signal reception during data collection. Care should be taken to properly plan the mobile LiDAR drive paths and mobile control placement to capitalize on accuracy of the dataset.

Sec. 9.04 STLS Equipment

All of the equipment used to collect STLS data, to control the data, and to collect the quality control validation (check) points should be able to collect the data at the accuracy standards required for the project. This determination will be made from the manufacturer's stated specifications for the equipment to be used. STLS equipment and accessories may include the laser scanner, a laptop or tablet computer, various cables, tripods, tribrachs, panels, target poles and batteries. Tall tripods with dual-clamping mechanisms on the legs are generally recommended for the scanner instrument. All survey equipment used for STLS operations must be properly maintained and regularly checked for accuracy and proper function.

Laser scanning panels or fixed control decals are designed for a specific range of distance and most laser scanners do not have telescopes to orient the instrument to a backsight. STLS panels must be scanned with a sufficient density to model their reference locations. The size of the panel or fixed control decal, laser spot size, distance from the scanner, and scan resolution determine how precisely the reference locations can be determined. If the distance from the scanner to the control exceeds the manufacturer's recommended distance, the error may increase dramatically. Vendor specific recommended control panels may differ in size and shape. The operator should follow the manufacturer's recommended panel configurations, distance for placement to scanner location, and scan resolution.

Sec. 9.05 STLS Guidelines and Procedures

STLS collected survey data points are to be checked by various means including:

1. Comparing the scan to the quality control validation points,
2. Reviewing the DTM and data terrain lines in the profile,
3. Redundant measurements. Redundant measurements with a laser scanning system can only be accomplished by multiple scans, either from the same set-up, or from a subsequent set-up that offers an adequate amount of overlapping coverage.
4. Conventional or other types of cross-section on hard surfaces at regular intervals to confirm point cloud accuracies

Sec. 9.05.1 STLS Project Planning

Before the STLS project commences, the project area shall be reconnoitered to determine the optimum conditions in which to collect data to minimize excessive "artifacts" from traffic or other factors, and to identify obstructions that may cause data voids or shadows. Artifacts, or phantom points, are 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, including water 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. These erroneous data points must be clipped out of the processed point cloud and the void areas collected through alternate methods.

Check weather forecast for fog, rain, snow, fire smoke, or blowing dust. Tall tripod set-ups may be used to help reduce artifacts and obstructions from traffic and pedestrians, and to reduce incident angles. Areas within the project area that will be difficult to scan should be identified and a plan developed to minimize the effect on the final data, through additional set-ups or alternate methods of data collection. Safety should always be taken into consideration when selecting set-up locations.

Site conditions should be considered to determine scanning distance limitations and required scan density to adequately model the subject area. High accuracy surveys such as pavement analysis scans to identify issues like surface irregularities and drainage problems require more dense scanning, usually 0.1' or less, unless stated otherwise in the project scoping documents. Some scanners can maintain a constant desired point density throughout their effective range. Most high accuracy surveys and detailed analysis scans also require shorter maximum scanning distances and closer spacing of scanner control and validation points than other topographic survey applications.

Sec. 9.05.2 STLS Project Control and Placement

When performing STLS topographic surveys, the STLS control points for **scanner occupation stations and targeted control points** that will be used to control the point cloud adjustment and the validation points that will be used to check the point cloud adjustment of the STLS data, **shall meet 0.07' local network accuracy or better horizontally and vertical accuracy standards as defined in Chapter 5 of this VDOT Survey Manual**. Briefly, the following accuracy requirements must be met, based on the project needs and type as described in Section 9.01:

- High Accuracy Surveys – validation points shall meet surveyed local positional accuracies of X, Y (horizontal) ≤ 0.04' and Z (vertical) ≤ 0.03'
- Medium Accuracy Surveys – validation points shall meet surveyed local positional accuracies of X, Y (horizontal) ≤ 0.07' and Z (vertical) ≤ 0.06'
- Lower Accuracy Surveys – validation points shall meet surveyed local positional accuracies of X, Y & Z (horizontal and vertical) ≤ 0.10'

All STLS control and validation points shall be on the project datum and epoch. Best results are typically seen when the control stations are evenly spaced horizontally throughout the scan. Variation in control elevations is also desirable. Control should be placed at the recommended optimal distance from the scanner and scanned at the density as recommended by the STLS manufacturer. Maximum scanner range and accuracy capabilities may limit effective scanning coverage.

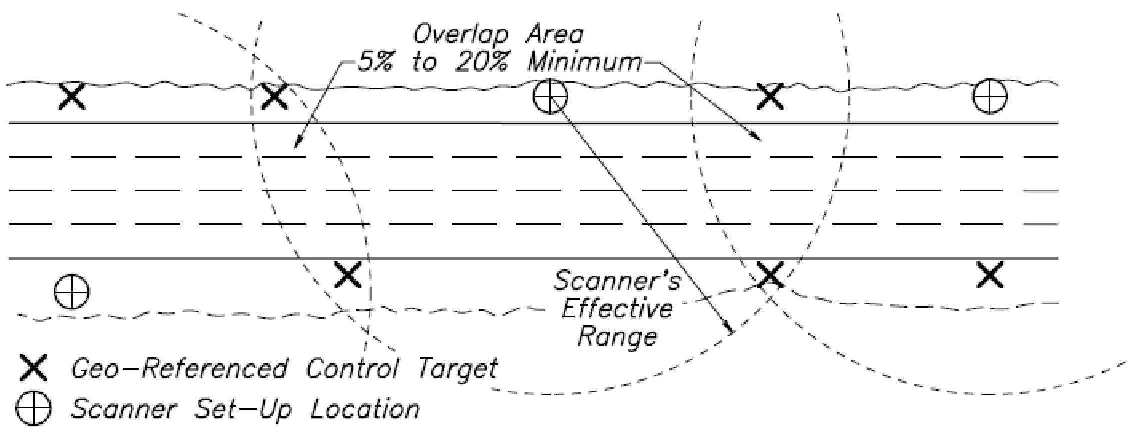


Figure 9.2 Control Placement & Scan Coverage

Sec. 9.05.3 Equipment Set-up & Calibration

When occupying a known control point, ensure the instrument is level and over the point, measure and record the height of instrument and height of control points at the beginning of each set-up. It is advisable to check the plummet position for targets at the completion of each set-up. Scanners that do not have the ability to occupy known points require additional control points incorporating good strength of figure to control each scan and establish scanner position by resection. Setting up the laser scanner as high as practical on a tall tripod will reduce the angle of incidence and consequently improve the scanner's effective range and accuracy of points on the pavement surface. Ensure automatic STLS system calibration routines are functioning per the manufacturer's specifications and that the scanner goes through the calibration process at startup. Strong winds or vibrations, such as on bridge surfaces can interfere with this process and care should be taken to choose a set-up location in an area of little or no vibration and use only during periods of low wind conditions.

Pavement conditions can greatly affect the distance a scanner can measure. Newer black pavement will return less energy to the scanner than older, graying asphalt and thus limit the distance measured. A sample scan on typical pavement conditions should be done before setting out scan control on a long project. Due to high-reflectivity concerns, do not attempt to perform scanning operations in wet conditions. Check the tribrach bubble level and check for centering error on a regular basis. Never carry a laser scanner on the tripod and check the tripod for tightness on a regular basis.

Sec. 9.05.4 Redundancy & Quality Control

STLS data collection shall be conducted in such a manner as to ensure redundancy of the data through overlapping scans. The data should be collected so that there is a minimum 5% to 20% overlap (percentage of scanner's useful range) from one scan to the next adjacent scan. When using cloud to cloud registration overlap can be as much as 75%.

Survey data points collected using STLS data are checked by various means including comparing scan points to validation points, reviewing the digital terrain model, reviewing data terrain lines in both plan and profile, examination of select cross-sections, and by comparing redundant measurements. Redundant measurements with STLS can only be accomplished by scanner set-ups that offer overlapping coverage. Plan and profile views of overlapping registered point clouds should indicate precise alignment and data density of less than 0.03 ft vertical at scan seams. Elevation comparison may be performed using profile, Digital Elevation Model (DEM) differences determined from the point grid, Triangular Interpolation Network (TIN) data or other Digital Terrain Model (DTM) aspects.

Monitoring STLS operation during the scan session is an important step in the scanning process. The system operator should make note if (and when) the STLS system encountered difficulty and be prepared to take appropriate action to ensure data quality. The operator shall keep a written record of any such difficulties encountered, the corrective action taken, and the time the issue was first noticed and the time the corrections were completed. The troublesome scan my require repeating to provide accurate data collection.

An STLS Quality Management Plan (QMP) shall include descriptions of the proposed quality control (QC) and/or quality assurance (QA) plan. The QMP shall address the requirements set forth in this document and any other project-specific QA/QC measures.

The project Survey Report shall include the following QA/QC Report information when using STLS to perform all or part of the project:

1. Project control report(s) and project control diagram(s), report(s) may include:
   a. Project identification and VDOT district
   b. Key Personnel to include Project Surveyor & License #
   c. Specifications: a statement regarding the specifications and standards used for the survey, referenced datums, horizontal & vertical orders of accuracy
   d. Dates: dates the field work began and ended, date the final adjustments were completed
   e. Horizontal Survey Method: conventional, static GPS, rapid static GPS or kinematic GPS with observation times, OPUS or OPUS projects solution, number and type of primary instrumentation used
   f. Vertical Survey Method: automatic or digital level, total station system, static GPS, rapid static GPS or kinematic GPS with observation times, OPUS or OPUS projects solutions, number and type of primary instrumentation used
   g. Horizontal and/or Vertical Monument Types: general descriptions of any monuments set or used, attach any applicable datasheets
   h. Software: name and version of all software used (specify use of each)
   i. Adjustments: i.e. least squares, general comments regarding the consistencies of the accuracy(ies) achieved, explanations of any large residuals, etc.
   j. Field & Office Comments: i.e. pertinent comments regarding right of entry, observation problems, augmentation surveys required for obscured areas, data processing and adjustments, unique situations encountered, etc.
2. STLS registration reports that contains registration errors reported from the registration software.
3. Elevation comparisons of two or more point clouds from overlapping scan area (see Figure 9-2).
4. Statistical comparison of point cloud data and redundant control point(s) if available.
5. Statistical comparison of registered point cloud data with validation points from conventional surveys if available.
6. Either item 4 or 5 shall be performed for Quality Control purposes. Completing both item 4 and 5 is highly recommended.

Sec. 9.06 STLS Deliverables & Documentation

The desired deliverables from a stationary terrestrial laser scanning project should be identified in the planning stage. The ultimate value of the STLS collected data is multiplied when it is “mined” for data for various uses and customers (end users) beyond its initial intended use. Different projects and customers may require different types of deliverables which can range from standard CADD products to a physical three-dimensional scale model of the project.

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

- Registered point clouds in XYZI or XYZIRGB files in ASCII, CSV, LAS, LAZ, ASTM E57 3D Imaging Data Exchange Format (E2761), or other manufacturer's specific format
- DTM file(s) in current VDOT format, 3D MicroStation (breaklines and points)
- Contour file(s) in current VDOT format, 2D MicroStation (contour interval as required, provide edge to edge match between "cut" contour files, No Overlap)
- Planimetric file(s) in current VDOT format, 2D MicroStation (provide edge to edge match between "cut" planimetric files, No Overlap)
- Digital photo files (if available)
- Survey narrative report and QA/QC data

Documentation of surveys is an essential part of any surveying task. 3D data not properly documented is susceptible to imbedded mistakes and is difficult to adjust or modify to reflect changes in control. An additional concern is that poorly documented data may not be legally supportable.

The survey narrative report, completed by the person in responsible charge of the survey, may contain the following general information, the specific information required by each survey method, and any appropriate supplemental information.

- Project identification and VDOT district
- Survey date, limits, and purpose
- Horizontal Datum, Vertical Datum, epoch, and units
- Control found, held, and set for the survey
- Personnel, equipment, and surveying methods used
- Field notes including scan diagrams, control geometry, instrument and target heights, atmospheric conditions, etc.
- Problems encountered and corrective actions taken
- Any other pertinent information
- QA/QC reports
- Dated signature and seal of the person in responsible charge

Table 9-1 Stationary Terrestrial Laser Scanning Guidelines

Operation/Guidelines	STLS Scan Application		
	High Acc	**Medium Acc**	**Lower Acc**
Level compensator should be turned ON unless unusual situations require that it be turned OFF (specify in survey report)	Each set-up		
Minimum number of targeted control points required per manufacturer's recommendations	Additional targeted control points are recommended (redundancy/densification)		
STLS control and validation point surveyed local positional accuracy	H ≤ 0.04 foot V ≤ 0.03 foot	H ≤ 0.07 foot V ≤ 0.06 foot	H and V ≤ 0.10 foot
Strength of figure: α is the angle between each pair of adjacent control targets measured from the scanner position	Recommended $60^\circ \leq \alpha \leq 120^\circ$	Recommended $40^\circ \leq \alpha \leq 140^\circ$	Recommended $40^\circ \leq \alpha \leq 140^\circ$
Control placed at optimal distances to produce desired results	Each set-up		
Control scanned at density recommended by vendor	Required		
Measure instrument height and target heights	Required		
Fixed height targets	Recommended		
Check plummet position of instrument and targets over occupied control points	Beginning and end of each set-up		
Be aware of equipment limitations when used in rain, fog, snow, smoke or blowing dust, or on wet pavement	Each set-up		
Distance to object scanned not to exceed best practices for laser scanner and conditions - Equipment dependent	Manufacturer's specification		
Distance to object scanned not to exceed scanner capabilities to achieve required accuracy and point density	Each set-up		
Observation point density	Sufficient density for feature extraction		
Overlapping adjacent scans (percentage of scan distance)	5% to 20%		
Registration of multiple scans in post-processing	Required		
Post-processing software registration error report	Required		
Registration errors not to exceed in any horizontal dimension	0.04 foot	0.08 foot	0.15 foot
Registration errors not to exceed in vertical dimension	0.03 foot	0.06 foot	0.10 foot
Independent validation points from conventional survey to confirm registration	Minimum of three (3) per mile	Minimum of three (3) per mile	Minimum of two (2) per mile

Since all projects are different, these model STLS guidelines and/or specifications are not individually restrictive requirements though, taken as a whole, the specifications used on any VDOT project should be in substantial accordance with these guidelines. Significant deviations from the guidelines described herein should be reviewed by VDOT's GeoSpatial Program Manager or their assignee prior to implementation. The final determination of the proper standard of care to be employed remains the sole responsibility of the Land Surveyor in charge.

All STLS produced topographic survey submittals must comply with the Model Virginia Map Accuracy Standards and the National Map Standards.

Sec. 9.07 Mobile LiDAR (M-LiDAR)

Mobile laser scanning or Mobile LiDAR (M-LiDAR) uses LiDAR technology in combination with Global Navigation Satellite Systems (GNSS), Distance Measuring Instrument/Indicator (DMI), and Inertial Measurement Unit (IMU) to produce accurate and precise georeferenced point cloud data and digital imagery from a moving vehicle. Many systems also incorporate digital cameras to aid in visualization and may be in the form of still photos or streaming video similar to video logging equipment. M-LiDAR platforms may include Sport Utility Vehicles, pick-up trucks, hi-rail vehicles, boats, or other types of vehicles. M-LiDAR may improve the safety and efficiency of data collection. In addition, the M-LiDAR collected data may be “mined” for various uses beyond its initial intended use.

The scanner(s) position is determined by post-processed kinematic GNSS procedures using data collected by GNSS antenna(s) mounted on the vehicle, GNSS base stations occupying project control (or continuously operating GNSS stations) throughout the project area and potentially painted control points along the shoulders and/or sidewalks of the project corridor. 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. This data may also be combined with digital imagery sensor data in proprietary software. The point cloud and imagery information can provide a very detailed data set.

GNSS has vertical accuracy limitations and may not meet VDOT Engineering Survey standards for pavement elevation surveys. For this reason, additional control points (local transformation points) within the M-LiDAR scan area are required to register the point cloud data by adjusting point cloud elevations. 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 purposes.

Sec. 9.08 M-LiDAR Guidelines & Procedures

M-LiDAR GNSS equipment must correspond with the requirements stated in Chapter 5, “GNSS & Control” of this manual. M-LiDAR kinematic post-processing must comply with these guidelines and specifications or other applicable guidelines obtaining a minimum of 0.07’ local network accuracy, or project specific requirements; whichever is more restrictive. M-LiDAR kinematic GNSS/IMU data must be post-processed in forward and reverse directions (from beginning-to-end and end-to-beginning). Table 9-2 herein lists the specifications required to achieve the necessary order M-LiDAR accuracy.

Sec. 9.08.1 M-LiDAR Mission Planning

Before the M-LiDAR project data collection commences, a mission planning session should be conducted to ensure adequate GNSS satellite 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 times 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.

M-LiDAR systems may 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 M-LiDAR 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 obstructions 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 an open sky view suitable for a static session nearby should be identified. The M-LiDAR operator should stop in an open sky area for a short static session (5 to 7 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
- M-LiDAR data collection drive route plan/paths
- Identify "static session" areas of open sky
- Safety plan
- Traffic control plan (if traffic control is required)

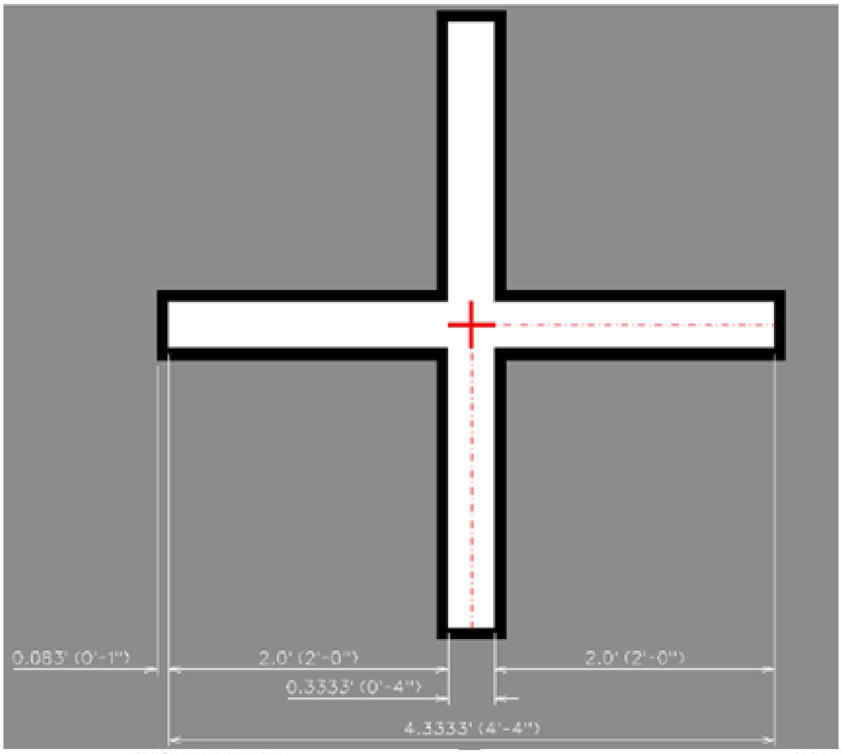
Sec. 9.08.2 M-LiDAR Local Registration & Validation

Local registration points serve as control for adjustment of the point clouds. Validation points allow for Quality Control checks of the adjusted scan data. Local registration and validation points may be painted control points, recognizable features, or coordinate positions within the scans.

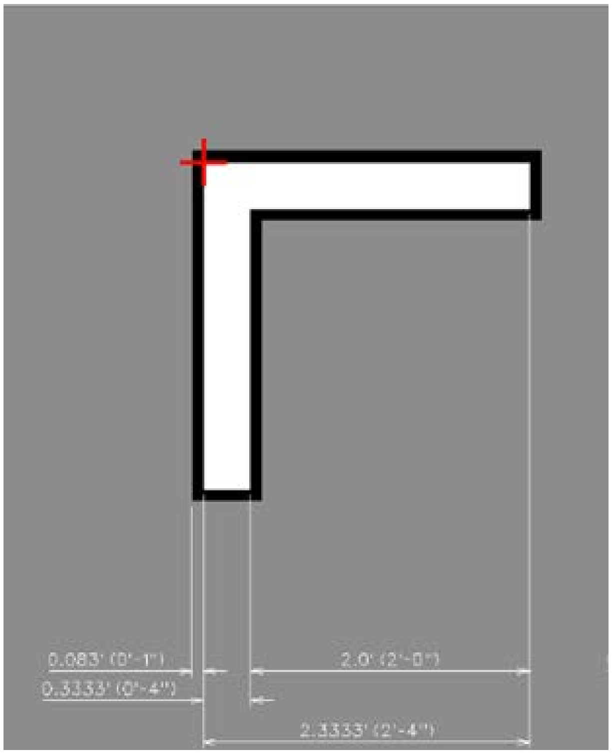
When used, highly reflective control points should be located within 20 feet of the center of the road lane or planned M-LiDAR vehicle trajectory without compromising safety of the ground crew surveying or marking the locations. The control points may be marked by reflective tape, white or yellow paint with glass beads, reflective thermoplastic, or other means as recommended by the scanner's manufacturer. The M-LiDAR vehicle operator(s) should adjust the vehicle speed so that the control point(s) will be scanned at sufficient density to ensure good target recognition. See Figure 9.3 for appropriate control point installation.

Figure 9.3 Examples of M-LiDAR Panel Installation

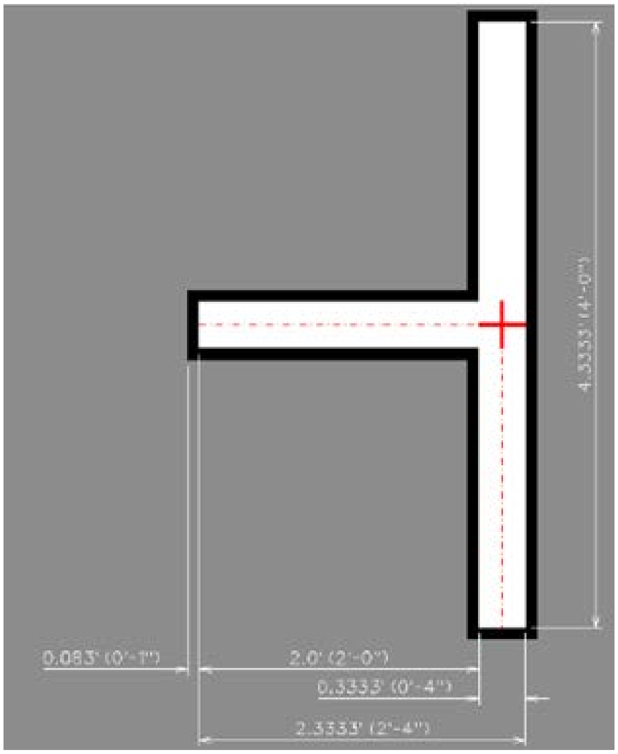
Cross



Chevron



Tee



Control panel placement guidelines:

- Should be placed at a 45-degree angle facing the road
- Shall be placed on flat, clean surface (cleared of small rocks and road debris by using a whisk broom)
- Should not be placed on multi-level objects such as sewer grates, nor up against curbs
- If the panel must be placed more than 2’ from the white stripe, an additional outer border of black gorilla tape is required to improve contrast
- Panels shall not be placed closer than 6” to the existing road striping
- Panels shall not be placed on a rumble strip
- Panels should ideally be placed out of direct drive paths whenever possible to prevent tire damage to the panel
- When measuring the point for survey, capture a photo of the selected point showing where the survey point is set, and where the panel is located in relation to nearby objects. Two pictures are required.
- Photos shall be included in survey reports as part of the project deliverable
- If a shoulder does not exist or its surface cannot be cleaned of rocks or gravel, placing panels inside a drive lane is acceptable, however crew safety is paramount. If the panel cannot be placed in the shoulder, and the travel lane is deemed unsafe, the panel may be placed on an adjacent shoulder, sidewalk, driveway, etc., but not more than 4’ from the drive lane.

Control PIDs (Photo Identifiable Points)

- Choose a location of high contrast for better imaging of the LiDAR, i.e. corner of concrete block, existing paint striping, center of structure, etc. Ensure the survey point is at a sharp corner and if on existing paint striping the paint is in good condition
- Area of PID shall be cleared of small rocks and road debris
- When measuring the point for survey, capture a photo of the selected point showing where the survey point is set on the PID and where the PID is located in relation to nearby objects.
- Photos shall be included in survey reports as part of the project deliverable

Control PIDs Inside Lanes (Skip Lines)

For safety and access reasons, often control panels cannot be placed on the inside highway shoulders. In this scenario, a panel is placed on the outside shoulder of the roadway and then utilizing a conventional total station with direct reflect (DR) technology, PID points can be measured at the center of the end of the highway dashed line paint stripes, preferably as in line with the outside shoulder panels as possible.

In order to increase the accuracy of the collected and adjusted geospatial data, a local registration of the M-LiDAR 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 M-LiDAR manufacturer's painted target recommendations and specifications (size and shape) should always be followed. Painted local registration point targets shall be located at the beginning, end, and evenly spaced throughout the project of each M-LiDAR data recording or pass. Vertical registration points shall be located evenly spaced in between the painted local registration point targets.

For medium accuracy M-LiDAR 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. M-LiDAR missions performed for high accuracy surveys such as pavement analysis to identify issues such as surface irregularities and drainage problems may require local registration point targets at a maximum of 1000-foot spacing. High accuracy M-LiDAR surveys require local transformation points and validation points to have surveyed local positional accuracies of $H \leq 0.04$ foot and $V \leq 0.03$ foot or better whereas medium accuracy M-LiDAR surveys require local transformation points and validation points to have surveyed local positional accuracies of $H \leq 0.07$ foot and $V \leq 0.6$ foot or better. The preferred method of establishing M-LiDAR local transformation point elevations for high and medium accuracy surveys is differential leveling per VDOT leveling specifications or project specific requirements, whichever is more restrictive.

For earthwork or other lower accuracy M-LiDAR surveys, bracket the scanned area on both sides of the roadway with 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). Earthwork and other lower accuracy M-LiDAR surveys require local transformation and validation points to have surveyed local positional accuracies (horizontal and vertical) of ≤ 0.10 foot or better.

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. GNSS-challenged areas include tunnels, steep valleys, large ravines and urban canyons.

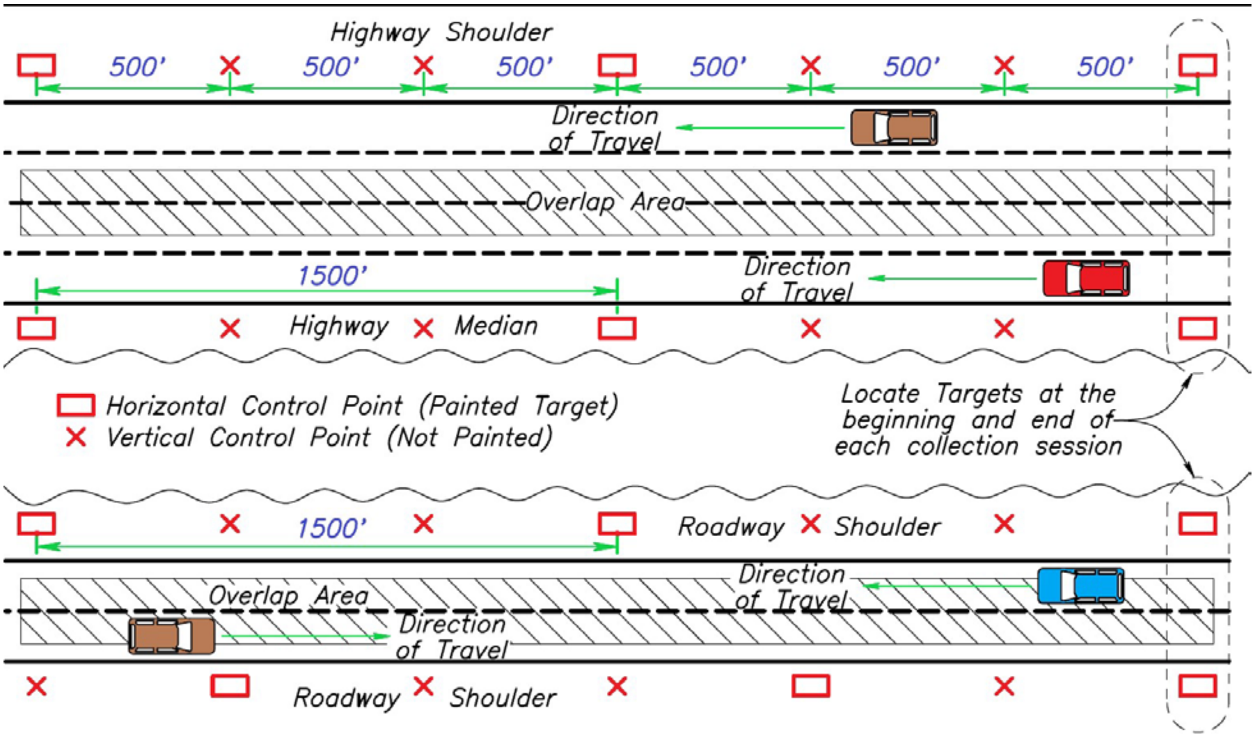


Figure 9.4 Examples of M-LiDAR Panel Placement & Scan Coverage
(ground conditions, specific survey requirements, traffic patterns and safety concerns may preclude use of the panel placements shown above; for instance no panels on the interior shoulder, spacing of mobile panels, use of skip lines, etcetera. The person in responsible charge shall make the final determination concerning panel placement in accordance with project needs, existing conditions and the manufacturer's recommendations)

Sec. 9.08.3 M-LiDAR Quality Control

Quality Control (QC) measures must be performed to ensure the accuracy of the registered M-LiDAR point clouds meets the required accuracy of the project. Engineering survey data points collected using M-LiDAR are checked by various means including comparing scan points to validation points, reviewing the digital terrain model, reviewing data terrain lines in both plan and profile, examination of select cross-sections, and by comparing redundant measurements. Elevation comparison may be performed using profile, Digital Elevation Model (DEM) differences determined from the point grid or Triangular Interpolation Network (TIN) data. Redundant measurements with M-LiDAR can only be accomplished by multiple scanning runs or passes that offer adequate amounts of overlapping coverage.

The M-LiDAR 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 or exceeds the required accuracy of the project.

There are three common Quality Control methods for M-LiDAR 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 a 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 a conventional survey to check the (XY 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, included in the survey report, shall list the results of the M-LiDAR mission 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(s) 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 M-LiDAR 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 M-LiDAR registered point cloud

   b. Comparison of elevation data from overlapping (side-lap) runs

   c. Comparison of points at the area of overlap (end-lap) 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

Sec. 9.09 M-LiDAR Deliverables & Documentation

Different projects and customers (end users) require different types of deliverables. One of the inherent features and fundamental advantages of laser scan data such as M-LiDAR is that it is acquired, processed and delivered in a 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 an M-LiDAR project should be specified during the planning phase and/or the contract task order.

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

- Registered point clouds in XYZI or XYZIRGB files in ASCII, CSV, LAS, LAZ, ASTM E57 3D Imaging Data Exchange Format (E2761), or other manufacturer's specific format
- M-LiDAR raw data files
- DTM file(s) in current VDOT format, 3D MicroStation (breaklines and points)
- Contour file(s) in current VDOT format, 2D MicroStation (contour interval as required, provide edge to edge match between "cut" contour files, No Overlap)
- Planimetric file(s) in current VDOT format, 2D MicroStation (provide edge to edge match between "cut" planimetric files, No Overlap)
- Digital video or photo files with data files currently supported by VDOT software
- Survey narrative report including project metadata and GNSS base station data sheet
- M-LiDAR project QC report (see section 9.08-3)

The documentation of M-LiDAR projects is an essential part of the surveying work. The data path of the entire process must be defined, documented, assessable, and allow for identifying adjustment or modification. 3D data without a proper documentation is susceptible to imbedded mistakes and is difficult to adjust or modify to reflect changes in control. An additional concern is that poorly documented data may not be legally supportable.

The survey narrative report, completed by the person in responsible charge of the survey, may contain the following general information, the specific information required by each survey method, and any appropriate supplemental information, including GeoSpatial metadata files conforming to the current VDOT standards.

1. Survey narrative report:
    a. Project identification & VDOT district
    b. Survey date, limits, and purpose
    c. Horizontal Datum, Vertical Datum, epoch, and units
    d. Control found, held, and set for the survey
    e. Personnel, equipment, and surveying methods used
    f. Field notes including diagrams, control geometry, positions and/or elevations of horizontal and vertical control points, atmospheric conditions, etc.
    g. Problems encountered and corrective actions taken
    h. Any other pertinent information
2. M-LiDAR QC report (see section 9.08-3)
3. Dated signature and seal of the person in responsible charge

Table 9-2 M-LiDAR General Guidelines

Operation / Specification	M-LiDAR Scan Application		
	High Acc	Medium Acc	Low Acc
M-LiDAR equipment must be capable of collecting data at the intended accuracy and precision for the project	Required		
Initial calibration of all M-LiDAR system (per manufacturer's specifications)	As Required		
Boresight calibration of M-LiDAR system (per manufacturer's specifications) should be performed before and after project data collection	As Required		
Dual-frequency GNSS recording data at a rate of 1 Hz or faster	Required (See Note #6)		
DMI (Distance Measurement Instrument and/or Indicator)	Required (See Note #6)		
IMU (Inertial Measurement Unit)	Required (See Note #6) (See Note #10)		
Minimum IMU uncorrected positioning capability due to lost or degraded GNSS signal	GNSS outage of 60 seconds or 0.6 miles distance travelled		
Maximum duration or distance travelled with degraded or lost GNSS signal resulting in uncorrected IMU positioning	GNSS outage of 60 seconds or 0.6 miles distance travelled		
Maximum uncorrected IMU X-Y positioning drift error for 60 second duration or 0.6 miles distance travelled of GNSS outage	0.33 foot (0.100 m)		
Maximum uncorrected IMU Z positioning drift error for 60 second duration or 0.6 miles distance travelled of GNSS outage	0.23 foot (0.070 m)		
Maximum uncorrected IMU roll and pitch error/variation for 60 second duration or 0.6 miles distance travelled of GNSS outage	0.020° RMS		
Maximum uncorrected IMU true heading error/variation for 60 second duration or 0.6 miles distance travelled of GNSS outage	0.020° RMS		
Project control should be the constraint for GNSS positioning	Yes		
Minimum NSSDA horizontal and vertical check points (See Note #7)	20 points		
Minimum number of project transformation points required	4		
Minimum order of accuracy for GNSS base station horizontal (H) and vertical (V) project control points	Horizontal 0.07' local network accuracy & Vertical accuracy per Chapter 5 or project specific requirements if more restrictive		

M-LIDAR Local Transformation Point and Validation Point surveyed local positional accuracy requirements	H ≤ 0.04 foot V ≤ 0.03 foot	H ≤ 0.07 foot V ≤ 0.06 foot	H and V ≤ 0.10 foot
Maximum post-processed baseline length	5 miles	8 miles	12.5 miles
Minimum overlapping coverage between adjacent scanning runs	25% side-lap	20% side-lap	
Monitor M-LIDAR system operation for GNSS reception (See Notes #1 through #4)	Throughout each pass		
Monitor for minimum number of common healthy satellites in view for GNSS base stations and the mobile scanner (Notes #1 through #4)	Throughout each pass		
Maximum GDOP during data acquisition	6		
Allow sufficient time between overlapping data collection passes to ensure change in satellite constellation; recommend at least 3 different satellites per overlapping pass	Each overlapping pass		
Monitor M-LIDAR system operation for proper IMU and DMI operation and for distance and duration of any uncorrected drift	Throughout each pass		
Monitor M-LIDAR laser scanner operation for proper function	Throughout each pass		
Minimum orbit ephemeris for kinematic post-processing	Broadcast		
Monitor vehicle speed – limit to maintain required point density and a sufficient density required for accurate target recognition	Each pass		
Filter data to exclude measurements exceeding scanner range	Each pass		
Observations – ensure sufficient point density to model objects	Each pass		
M-LiDAR point density requirements (See Note #8)	≥ 20 pts/ft²	≥ 10 pts/ft²	(See Note # 9)
Transformation point maximum spacing along the project corridor, transformation points may be located on each side of the scanned roadway as safety conditions permit (See Note #11)	1000 foot intervals	1500 foot intervals	3000 foot intervals
Validation point maximum spacing throughout the project on each side of scanned roadway for QC purposes as safety conditions permit (See Note # 11)	700 foot intervals	1000 foot intervals	2000 foot intervals

Since all projects are different, these model M-LiDAR general guidelines and/or specifications are not individually restrictive requirements though, taken as a whole, the specifications used on any VDOT project should be in substantial accordance with these general guidelines. Significant deviations from the guidelines described herein should be reviewed by VDOT's GeoSpatial Program Manager or their assign prior to implementation. The final determination of the proper standard of care to be employed remains the sole responsibility of the Land Surveyor in charge.

All M-LiDAR produced topographic survey submittals must comply with the *Model Virginia Map Accuracy Standards* and the *National Map Standards.*

M-LiDAR survey guideline 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 prior to the survey onset.
2. If necessary, the 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, roadside parking or other factors.
3. If safety conditions permit, additional Validation Points should be added in challenging GNSS environments such as tunnels and urban canyons.
4. GNSS coverage of less than 5 satellites in view at the vehicle must not exceed the uncorrected position time or distance travelled capabilities of the M-LiDAR system IMU. (GNSS Base Stations must have 6 satellites at all times)
5. The Land Surveyor in responsible charge of the M-LiDAR must choose the appropriate accuracy and geometry of the Project Control Points, Transformation Points and Validation Points to ensure the M-LiDAR survey data and products meet or surpass accuracy requirements of the project.
6. Manufacturer's specifications for precision must be sufficient for M-LiDAR system to meet or surpass the 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. The Land Surveyor in responsible charge must ensure the M-LiDAR collection achieves sufficient point density to support the required detail and accuracy of M-LiDAR survey data and products. Point density should be verified through sample point spacing analysis using the formula:

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

9. Large surveys requiring less accuracy that do not have designated project control, may use other appropriate published control upon approval by VDOT.

10. IMU (Inertial Measurement Unit) recommended capabilities:

    - Minimum IMU positioning data sampling rate of 200 Hz
    - Maximum IMU Gyro Rate Bias of 1° per hour
    - Maximum IMU Angular Random Walk of 0.125° per √hour
    - Maximum IMU Gyro Rate Scale Factor of 150 ppm

11. These are general guidelines and project specific requirements may, based upon the professional's judgement, dictate use of different methodologies and layouts. For example, placing painted panels every 1000' to 1200', skips lines in tandem, and cross-section every 2000' to 3000' (or as warranted to meet the project needs). Primary control doesn't necessarily need to be set throughout the project as the example diagrams indicate provided that project tolerances are not exceeded and are verified by proper QA/QC reporting.

Sec. 9.10 **Airborne LiDAR (A-LiDAR)**

See Chapter 6, "Photogrammetric Surveys", for specific guidelines relating to Aerial Photogrammetry and the use of A-LiDAR to complement and enhance traditional photogrammetric surveys.

Airborne Light Detection and Ranging (A-LiDAR) data may be used for certain VDOT projects. Such projects include corridor location studies, and any other preliminary engineering projects that require a digital terrain model (DTM) at a lower level of accuracy than traditional location surveys. The A-LiDAR platform must include a fully functioning airborne global positioning system (A-GNSS) and an inertial measurement unit (IMU.) GNSS base stations must also be utilized. Post processed A-GNSS/IMU data shall be used when processing the A-LiDAR point clouds.

VDOT does demand that any consultant performing A-LiDAR work for the department have the necessary hardware, software, and experience that will provide a consistent, accurate, and reliable product. A-LiDAR procedures must include appropriate data filtering and editing to eliminate incorrect, non-surface readings, and reduce the file to a manageable size. Development of break lines may use a combination of aerial photography and A-LiDAR data for horizontal location (aerial) and vertical location (A-LiDAR) at the professional's discretion. Photogrammetry must be utilized during the development of break lines for the DTM and to provide a means for quality control of the A-LiDAR data.

A-LiDAR *will not* be obtained as a standalone deliverable without aerial photography on VDOT projects without express written approval granting an exception and the use of A-LiDAR in advance of the data collection.

Obtaining A-LiDAR data is *standard practice* on all aerial photogrammetry projects unless written approval is given by the GeoSpatial Program Manager or the State Photogrammetry Supervisor to exclude it.