Chapter 8 - Terrestrial Laser Scanning

8.1 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, it will take less time to collect the data and longer time to process the data, however the overall time could 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 8-1

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/m² (>9 pts/ft²)	• 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/m² (3 to 9 pts/ft²)	• 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/m² (<3 pts/ft²)	• *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. Although the guidelines in the above table were developed for Mobile LiDAR. They can also serve as a guideline for Stationary Terrestrial Laser Scanning (STLS) as well. 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

8.2 Stationary Terrestrial Laser Scanning (STLS)

Stationary Terrestrial Laser Scanning (STLS) refers to laser scans that are performed from a static location(s).

The raw data product of a laser scan survey is a point cloud. When the scanning control points are georeferenced to a known coordinate system (i.e. NJSPCS), the entire point cloud can be oriented to the same coordinate system. All points within the point cloud have X, Y, and Z coordinates and Laser Return Intensity values (XYZI). If image overlay is available the points may be in an XYZIRGB (X, Y, Z coordinates, return Intensity, and Red, Green, Blue color values). The positional error of any point in a point cloud is equal to the accumulation of the errors of the scanning control and errors in the individual point measurements.

Laser scan measurements that are perpendicular to a surface will produce better accuracies than those with a large angle of incidence to the surface. The larger the incidence angle, longer distances, (see Figure 8-1), the more the beam can elongate resulting in divergence of the laser, producing errors in the distance returned. Data points will also become more widely spaced as distance from the scanner increases and reflect off a larger area the less laser energy is returned. At a certain distance, the error will exceed standards and beyond that no data will be returned. Atmospheric factors such as heat radiation, rain, snow, dust, and fog will also limit scanner effective range. It is recommended that the surveyor refer to the manufacturer specifications regarding the acceptable distance for any scanner.

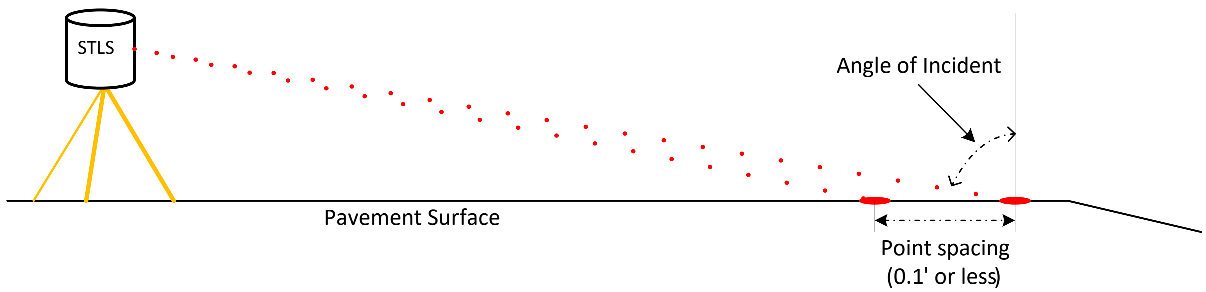


Figure 8-1 Example of Incidence Angle
Image Courtesy of California Department of Transportation.

8.3 Applications

There are many different applications for this technology. This section will deal with what is required for NJDOT projects. As indicated in Table 8-1 there are many different applications for laser scanning. Some of the major uses this technology could be used for are pavement evaluation, drainage issues, bridge inspection, evaluation and clearance, intersection improvements, traffic signal, and controller locations and clearance. The type of project and the accuracy required will determine the density of the point cloud and number of targets.

8.4 Selecting a Project

Not every project will be suited for this technology. Below are some factors that should be considered when determining whether the project is suitable or not.

- 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
- Traffic volumes and best available observation times
- Forecast weather and atmospheric conditions at planned observation time
- STLS 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)

Some significant advantages of STLS is the minimizing the effects on traffic and the safety of the survey crew.

8.5 STLS Types of Scans

In general, there are two types of scans, Type A and Type B. 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.

8.5.1 Type A – Hard Surface and High Accuracy – Topographic Surveys

- Engineering topographic surveys
- As-built surveys
- Structures and bridge clearance surveys
- Pavement analysis
- Forensic surveys

8.5.2 Type B – Earthwork and Low 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

Type A and B list Courtesy of California Department of Transportation

8.6 STLS Equipment and Uses

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 from the stated specifications for the equipment by the manufacturer. It is recommended that all survey equipment be properly maintained and regularly checked for accuracy and proper function. Ancillary equipment may include tribrachs, tripods, targets, target poles, etc.

8.7 Eye Safety

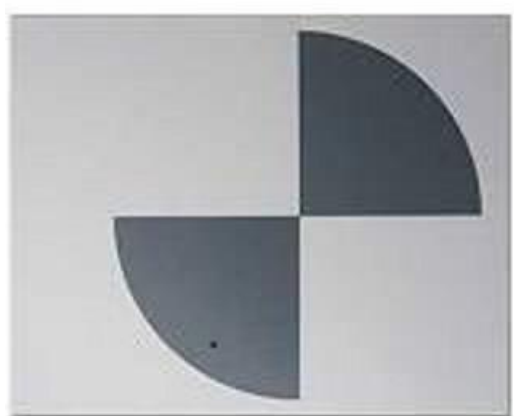
One major concern is that of eye safety for both the survey crew and the general public. The survey crew should follow all appropriate OSHA, State and manufacturers' recommendations when using any laser equipment. Never stare into the laser beam or view laser beams through magnifying optics, such as telescopes or binoculars. STLS 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 and refer to the manufacturer specifications.

8.8 Useful Range of Scanner

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 individual scanner as well as the accuracy requirements of the final survey. Methods for accomplishing this might include the implementation of range and/or intensity filtering during data collection or removal of any out-of-useful range data during post-processing. Surface properties including color, surface reflectivity, surface texture, and angle of incidence can limit scanner useful range, divergence and low angular accuracy.

8.9 Scanner Targets

Total station targets reduce pointing error when placed at long distances. Laser scanning targets, however, are designed for a specific range of distance. Most laser scanners do not have telescopes to orient the instrument to a backsight. STLS targets must be scanned with a sufficient density to model their target reference locations. The size of the target, laser spot size, distance from the scanner, and target scan resolution determine how precisely the target reference locations can be determined. If the distance from the scanner to the target exceeds the manufacturer’s recommended distance, the error may increase dramatically. Manufacturer specific recommended targets may differ in size and shape. The operator should follow the manufacturer’s recommended targets, distance for placement of targets, and target scan resolution.

Sample STLS Targets

8.10 STLS Specifications and Procedures

STLS collected survey data points are 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. and 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 overlapping coverage (see Figure X-2).

8.10.1 Planning

Before the STLS project commences, the project area shall be inspected to determine the best time to collect data to minimize excessive interference from traffic or other factors, and to identify obstructions that may cause data voids or shadows. Check weather forecast for fog, rain, snow, 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 angle (see Figure 8-1). Areas in the project that will be difficult to scan should be identified including standing water, 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 setup locations. If additional safety is required, the surveyor should follow the guidelines in the NJDOT Safety Manual and the MUTCD.

Site conditions should be considered to determine expected scanning distance limitations and required scan density to adequately model the subject area. Pavement analysis scans to identify issues such as surface irregularities and drainage problems require a scan point density of 0.10′ or less (see Figure 8-1). Typically, density diminishes over the scanners effective range. Pavement analysis scans also require shorter maximum scanning distances and closer spacing of scanner control and validation points (see Figure X-2) than other Scan Type A applications.

8.10.2 Project Control and Target Placement

When performing Type A STLS surveys, the STLS control (scanner occupation and targeted control stations) points that will be used to control the point-cloud adjustment and validation points that will be used to check the point-cloud adjustment of the STLS data, shall meet 0.05′ local network accuracy or better horizontal and third order or better vertical accuracy standards as defined in Chapter 3 of the NJDOT Survey Manual. Best results are typically seen when the targeted control stations are evenly spaced horizontally throughout the scan. Variation in target elevations is also desirable. Targets should be placed at the recommended optimal distance from the scanner and scanned at high-density as recommended by the STLS manufacturer. Maximum scanner range and accuracy capabilities may limit effective scan coverage.

Pavement analysis survey scans to identify issues such as surface irregularities, such as rutting and drainage problems, may require shorter maximum scanning distances and closer spacing of scanner control and validation points than other Scan Type A applications (see Figure 8-2).

All Type A, hard surface topographic STLS surveys require control meet the 0.05′ local network accuracy and third order vertical accuracy, and validation point surveyed local positional accuracies of X, Y, (horizontal) ≤ 0.03′ & Z (vertical) ≤ 0.02′. Scan Type B, earthwork and other lower-accuracy topographic surveys require validation point surveyed local positional accuracies of X, Y, & Z ≤ 0.10′ (see Table X-1). All STLS control and validation points shall be on the project datum and epoch.

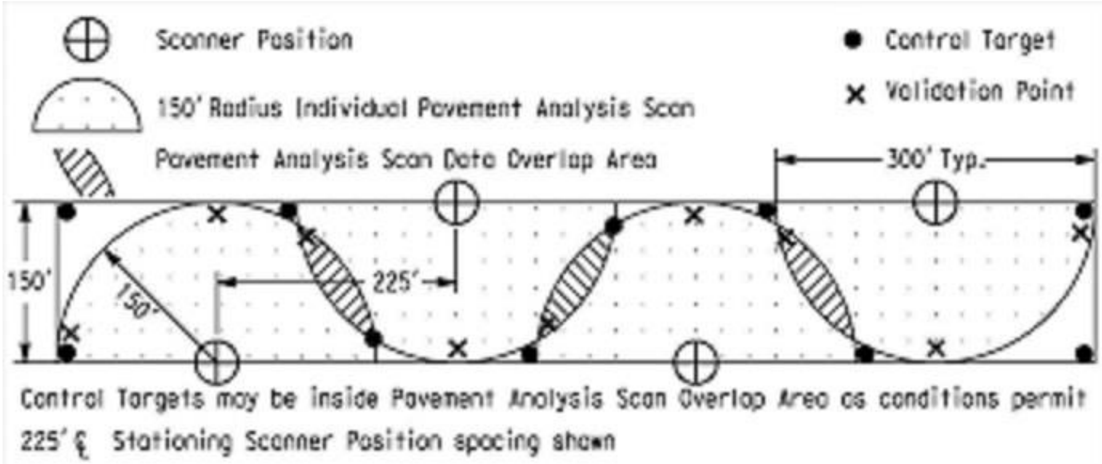


Figure 8-2 Target Placement and Scan Coverage – Type A Applications
Image Courtesy of California Department of Transportation.

8.10.3 Equipment Setup and Calibration

When occupying a known control point, ensure the instrument is over the point, measure and record the height of instrument (if required) and height of targets (if required) 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 targets incorporating good strength of figure to control each scan and establish scanner position by resection. Three targets per resection is preferred, although less may be utilized if cloud – cloud registration is used in areas of hardscape. Setting up the laser scanner as high as practical on a tall tripod would reduce the angle of incidence and consequently improve scanner's effective range and accuracy points on the pavement surface. Ensure automatic STLS system calibration routines are functioning per the manufacturer's specifications before beginning any scanning.

8.10.4 Redundancy

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 10% 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%.

8.10.5 Monitoring During the STLS Operation

Monitoring STLS operations during the scanning session is a critical step in the process. The operator should note if and when the STLS system encountered difficulties and be prepared to take appropriate action to ensure data quality. These could include significant change in weather conditions, temporary obstructions between the scanner and the target (i.e. large parked vehicle) that could interrupt the scan. When obstructions do occur, it is recommended that the scanning occur twice from the same location before moving, otherwise additional setups may be required.

8.10.6 Quality Control

Engineering 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 plan and profile, and 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 point grid or Triangular Interpolation Network (TIN) data. An STLS Quality Management Plan (QMP) shall include descriptions of the proposed quality control (QC) and quality assurance (QA) plan. The QMP shall address the requirements set forth in this document and any other project-specific QA/QC measures. The QA/QC report shall list the results of the STLS including but not limited to the following documentation:

1. Project Control reports (see NJDOT Survey Manual Chapter 11).
2. STLS registration reports that contains registration errors reported from the registration software (cloud – cloud and target areas).
3. Elevation comparisons of two or more point clouds from overlapping scan area (see Figure 8-2).
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 QC. Completing both item 4 and 5 is highly recommended.

8.11 STLS Deliverables and Documentation

The desired deliverables from a scanning project should be identified in the planning stage. The mapping consultant should refer to the NJDOT CADD Standards available online and contact the CADD Manager if they have any questions regarding the CADD Standards and CADD deliverables.

Any use of the data other than its intended use should be approved by the NJDOT CADD Manager and NJDOT PM before any other use of the data.

8.11.1 STLS Deliverables

Different projects and customers require different types of deliverables, which can range from a standard CADD product to a physical three-dimensional (3D) scale model of the actual subject.

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 specified format
- Current NJDOT CADD Standards for Roadway, Bridge, Electrical
- Current NJDOT Drafting Software files
- Digital photo mosaic files
- 3D printing technology physical scale models of the subject

- Survey narrative report (refer to Chapter 11 of the NJDOT Survey Manual)
- QA/QC Files

8.11.2 STLS Documentation

Documentation of surveys is an essential part of surveying work. Survey data not properly documented could result in additional field and office time to redo or correct what was not performed or documented properly.

The survey narrative report (refer to Chapter 11 of the NJDOT Survey Manual), completed by the PLS in responsible charge of the survey, shall contain the following general information, the specific information required by each survey method, and any appropriate supplemental information.

- Project Name and UPC Number: Route, Beginning and Ending Milepost, Project UPC Identification, Municipality, County, etc.
- Survey date, limits, and purpose
- 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
- Any other pertinent information
- QA/QC reports
- Dated signature and seal of the Professional Land Surveyor in responsible charge

Table 8 – 2 Stationary Terrestrial Laser Scanning Specifications

Table Courtesy of California Department of Transportation

As revised by NJDOT

Operation/Specification	**STLS Scan Application (See Section XX)**	
	Scan Type A	**Scan Type B**
Level compensator should be turned ON unless unusual situations require that it be turned OFF	Each set-up	
Minimum number of targeted control points required	Follow manufacturer's recommendations	
STLS control and validation point surveyed positional local accuracy. (See note 1 below)	H ≤ 0.02 foot V ≤ 0.03 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 $40^{\circ} \leq \alpha \leq 140^{\circ}$
Target placed at optimal distance to produce desired results	Each set-up	

Control targets scanned at density recommended by vendor	Required	
Measure instrument height and target heights	If required	
Fixed height targets	Recommended	
Check plummet position of instrument and targets over occupied control points	Begin 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)	10% to 20%	
Registration of multiple scans in post-processing	Required	
Registration errors not to exceed in any horizontal dimension. (See note 1 below)	0.03 foot	0.15 foot
Registration errors not to exceed in vertical dimension. (See note 1 below)	0.04 foot	0.10 foot
Independent validation points from conventional survey to confirm registration Not including BM's or Control tie points used in registration * (See note 1 below)	Minimum of 3 per mile	Minimum of 2 per mile

* This refers to Target Registration

Notes:

1. These values have been revised to meet NJDOT requirements. They do not match the original values in the California DOT Survey Manual.