15 Terrestrial Laser Scanning Specifications

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15 Terrestrial 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. Terrestrial LiDAR or Terrestrial Laser Scanning (TLS) as discussed in this chapter does not pertain to airborne LiDAR or Airborne Laser Scanning (ALS), which will be addressed in a revision of the *Caltrans Surveys Manual (CSM)*, Chapter 13, Photogrammetry.

Survey specifications describe the methods and procedures needed to attain a desired survey accuracy standard. For complete accuracy standards, refer to *CSM* Chapter 5[1], "Classifications of Accuracy and Standards." Caltrans survey specifications shall be used for all Caltrans-involved transportation improvement projects, including special-funded projects.

[1] http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/05_Surveys.pdf

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15.1 Stationary Terrestrial Laser

Stationary Terrestrial Laser Scanning (STLS) refers to laser scanning applications that are performed from a static vantage point on the surface of the earth.

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, 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). The points may be in an XYZIRGB (X, Y, Z coordinates, return Intensity, and Red, Green, Blue color values) if image overlay data is available. 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.

Just as with reflectorless total stations, 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 (see Figure 15-1), the more the beam can elongate, producing 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 standards and beyond that no data will be returned. Atmospheric factors such as heat radiation, rain, dust, and fog will also limit scanner effective range.

For in-depth discussions of stationary laser scanning, see the AHMCT Research Center reports "Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects"[2] and "Accelerated Project Delivery: Case Studies and Field Use of 3D Terrestrial Laser Scanning in Caltrans Projects: Phase I - Training and Materials."[3]

[2] http://ahmct.ucdavis.edu/pdf/UCD-ARR-07-06-30-01-B.pdf
[3] http://ahmct.ucdavis.edu/pdf/UCD-ARR-09-02-28-02.pdf

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15.2 STLS Applications

Two types of Terrestrial Laser Scanning (TLS) specification groups have been described to differentiate between TLS surveys have varying accuracy, control, and range requirements. "Type A" TLS surveys are hard surface topographic surveys with data collected at engineering-level accuracy. "Type B" TLS surveys are topographic surveys with data collected at lower-level accuracy. See *CSM* Chapter 11, "Engineering Surveys,"[4] for tolerances and accuracy standards for types of surveys.

15.2-1 Type A - Hard surface topographic surveys:

- Pavement Analysis Scans
- Roadway/pavement topographic surveys
- Structures and bridge clearance surveys
- Engineering topographic surveys
- Detailed Archaeological surveys
- Architectural and Historical Preservation surveys
- Deformation and Monitoring surveys
- As-built surveys
- Forensic surveys

15.2-2 Type B - Earthwork and lower-accuracy topographic surveys:

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

[4] http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/11_Surveys.pdf

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15.3 STLS Project Selection

STLS equipment is available for State Highway System (SHS) project work. The following are factors to consider when planning use of STLS on a particular SHS project:

- Safety
- 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
    - Accuracy required
    - Technology best suited to the project and desired final products

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15.4 STLS Equipment and Use

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 from the stated specifications for the equipment by the manufacturer. STLS accessories include tripods, tribrachs, targets, and target poles. Tall tripods with dual-clamp lock on its legs are recommended for the scanner instrument. All survey equipment must be properly maintained and regularly checked for accuracy and proper function (refer to *CSM* Chapter 3[5], "Survey Equipment").

15.4-1 Eye Safety

Follow OSHA Regulation 1926.54 and manufacturers' recommendations when using any laser equipment. Never stare into the laser beam or view laser beams through magnifying optics, such as telescopes or binoculars. STLS equipment operators should never direct the laser toward personnel operating instruments with magnifying optics such as total stations or levels. 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.

15.4-2 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 individual 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. Surface properties including color, albedo or surface reflectivity, surface texture, and angle of incidence can limit scanner useful range.

15.4-3 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. Vendor-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.

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[5] http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/03_Surveys.pdf

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15.5 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 15-2).

Table 15-1 lists the specifications required to achieve STLS general order accuracy.

15.5-1 Planning

Before the STLS project commences, the project area shall be reconnoitered to determine the best time to collect data to minimize excessive "artifacts" from traffic or other factors, and to identify obstructions that may cause data voids or shadows. 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 angle (see Figure 15-1). Areas in the project 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 setup locations.

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 15-1). Some scanners can maintain a constant desired point density throughout their effective range. Pavement analysis scans also require shorter maximum scanning distances and closer spacing of scanner control and validation points (see Figure 15-2) than other Scan Type A applications.

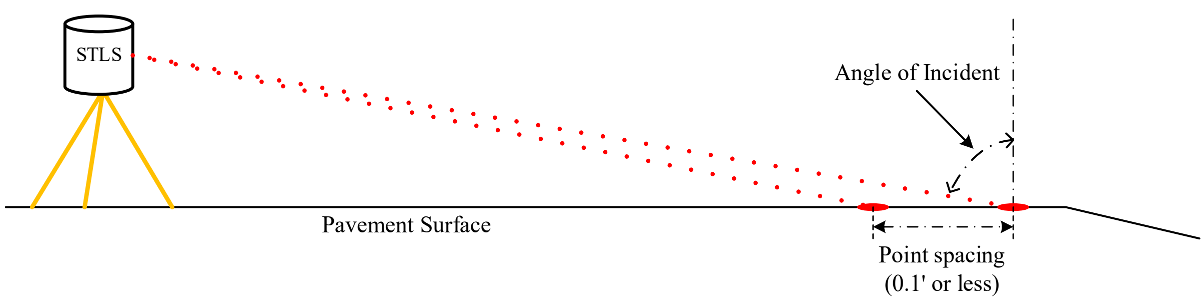

Figure 15-1 Scan Point Density for Pavement Plane surveys

15.5-2 Project Control Establishment 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 0.07’ local network accuracy or better horizontal and third order vertical accuracy standards as defined in Chapter 5 of the *CSM*. 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 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 15-2).

All Type A, hard surface topographic STLS surveys require control meet the 0.07’ 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’[6]. 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 15-1). All STLS control and validation points shall be on the project datum and epoch.

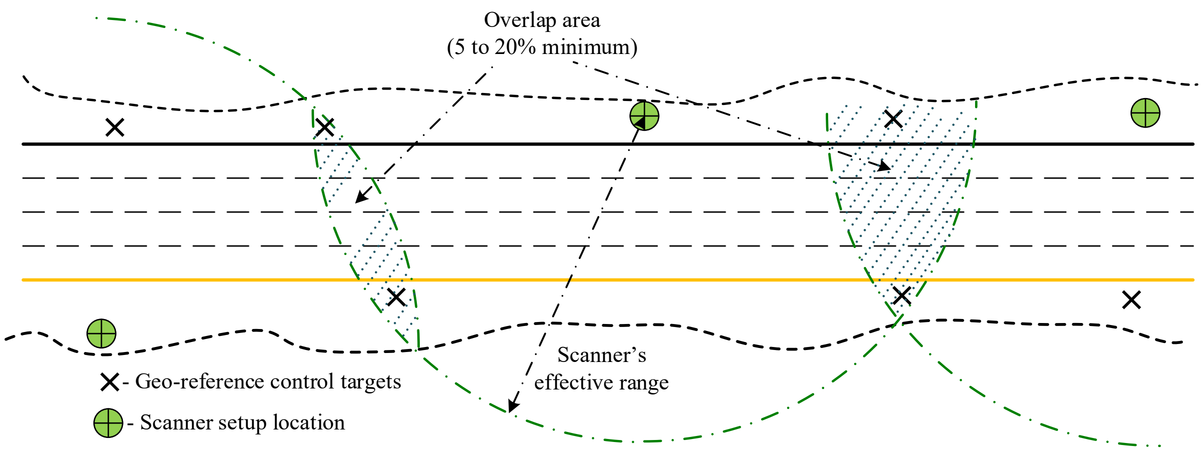

Figure 15-2 Target Placement and Scan Coverage - other Scan Type A applications Fewer targets may be required. Care must be taken not to exceed other limitations.

15.5-3 Equipment Set-up 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. Setting up the laser scanner as high as practical on a

[6] See Chapter 11 Section 11.7-3 of the Caltrans Survey Manual

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.

15.5-4 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 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%.

15.5-5 Monitoring STLS Operation

Monitoring STLS operation during the scan session is an important step in the scanning process. The system operator should note if and when the STLS system encountered difficulty and be prepared to take appropriate action to ensure data quality.

15.5-6 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 (refer to *CSM* Chapter 9.6-3[7], "Project Control Report").
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 15-2).
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.

[7] http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/09_Surveys.pdf

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15.6 STLS Deliverables and Documentation

The desired deliverables from a 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 beyond its initial intended use.

15.6-1 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 Caltrans Roadway Design Software files
- Current Caltrans Drafting Software files
- Digital photo mosaic files
- 3D printing technology physical scale models of the subject
- Survey narrative report and QA/QC files

15.6-2 STLS Documentation

Documentation of surveys is an essential part of surveying work. 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 (typically the Party Chief), shall contain the following general information, the specific information required by each survey method, and any appropriate supplemental information.

- Project name and identification: County, Route, Postmile, E.A. or Project Identification, 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 (see Section 15.5-6)
- Dated signature and seal of the Party Chief or other person in responsible charge

Table 15-1 Stationary Terrestrial Laser Scanning Specifications

Operation/Specification	STLS Scan Application (See Section 15. 2)	
	Scan Type A	Scan Type B
Level compensator should be turned ON unless unusual situations[8] 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	H ≤ 0.03 foot V ≤ 0.02 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 60º ≤ α ≤ 120º	Recommended 40º ≤ α ≤ 140º
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)	5% to 20% [9]	
Registration of multiple scans in post-processing	Required	
Post-processing software registration error report	Required	
Registration errors not to exceed in any horizontal dimension	0.03 foot	0.15 foot
Registration errors not to exceed in vertical dimension	0.02 foot	0.10 foot
Independent validation points from conventional survey to confirm registration	Minimum of three (3) per mile	Minimum of two (2) per mile

[8] Unusual situations could include bridge set-up with heavy truck traffic or high winds which cause excessive instrument vibration.
[9] When using cloud to cloud registration overlap can be as much as 75%

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15.7 Mobile Terrestrial Laser Scanning

Mobile terrestrial laser scanning (MTLS) 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, hi-rail vehicles, boats, and other types of vehicles. MTLS improves the safety and efficiency of data collection. In addition, the MTLS 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 and GNSS base stations occupying project control (or continuously operating GNSS 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, and may be combined with digital imagery sensor data in proprietary software. The point cloud and imagery information provides a very detailed data set.

GNSS has vertical accuracy limitations and will not meet Caltrans Engineering Survey standards for pavement elevation surveys. Additional control points (local transformation points) within the MTLS 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.

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15.8 MTLS Applications

NCHRP's Report 748 "Guidelines for the Use of Mobile LIDAR in Transportation Applications"[10] provides a detailed list of the types of project suitable for MTLS. See *CSM* Chapter 11[11], "Engineering Surveys," for tolerances and accuracy standards for specific types of surveys.

15.8-1 Type A - Hard surface topographic surveys:

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

15.8-2 Type B - Earthwork and low-accuracy topographic surveys:

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

10 http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_748.pdf
11 http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/11_Surveys.pdf

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15.9 MTLS Project Selection

The following are factors to consider when determining if MTLS is appropriate for a particular SHS project:

- Safety
- Project deliverables desired
- Project time constraints
- GNSS data collection environment
- Length/size of project
- MTLS system availability
- Traffic volumes and available observation times

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15.10 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.

15.10-1 Eye Safety

Follow OSHA Regulation 1926.54, ASTM standard E2641-09, and manufacturers' recommendations when using any laser equipment. Never stare into the laser beam or view laser beams through magnifying optics, such as telescopes or binoculars. Additionally, the eye safety of the traveling public and other people should be considered at all times and the equipment operated in a way to ensure the eye safety of all.

15.10-2 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.

15.10-3 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 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. See Section 15.11-6 for more details.

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15.11 MTLS Specifications and Procedures

MTLS GNSS equipment must correspond with the requirements stated in *CSM* Chapter 6, "GNSS Surveys". MTLS kinematic post-processing must comply with these specifications or applicable Caltrans 0.07' (Horizontal) GNSS Survey Specifications; whichever is more restrictive. MTLS kinematic GNSS/IMU data must be post-processed in forward and reverse directions (from beginning-to-end and end-to-beginning). Table 15-2 lists the specifications required to achieve general order MTLS accuracy.

15.11-1 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)

15.11-2 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 base station data (L1 and L2 frequency) shall be logged at 1 Hz with GPS and GLONASS enabled. If GNSS/IMU post-processing software supports other GNSS signals such as Galileo and/or GPS L5, L2C, and L1C, these additional GNSS signal data shall be logged at 1 Hz.

The GNSS baseline shall not exceed 12.5 miles (20 km) 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.

15.11-3 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.

15.11-4 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 on the SHS project, overlapping passes in opposite directions, or both shall be collected. Overlap dimensions: minimum of 25% sidelap (see Figure 15-3). The redundant overlap data provides data for quality control.

15.11-5 Monitoring Equipment during 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.

15.11-6 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 15-3).

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 15-3). 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 Caltrans 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 15-2).

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.

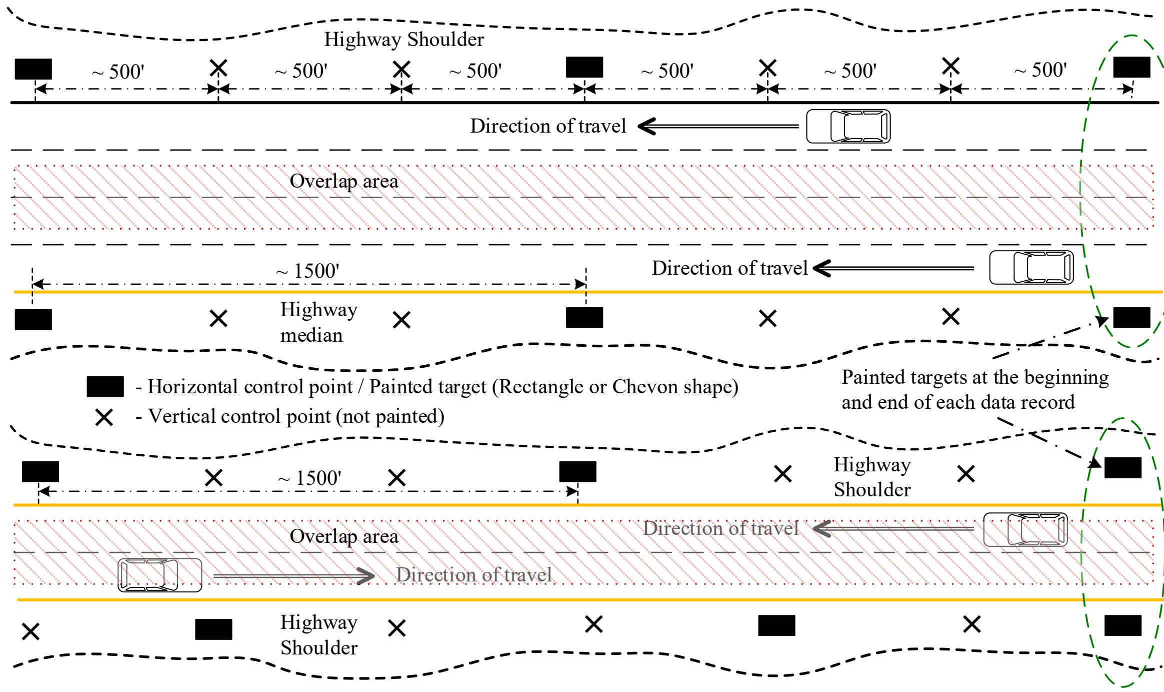

Figure 15-3 Typical MTLS Type A Local Transformation Layout

15.11-7 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. Engineering 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 (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 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.

15.12 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 Caltrans Survey Request or contract task order.

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

- Registered point clouds in ASCII CSV (XYZI or XYZIRGB files), LAS, LAZ, or other specified format.
- MTLS raw data files
- Current Caltrans Roadway Design Software files including project limits if available
- Current Caltrans Drafting Software files including project limits if available
- 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 (refer to *CSM* Chapter 9.6-3, "Project Control Report")
- MTLS QC report (see 15.11-7)

15.12-1 MTLS Documentation

The documentation of MTLS projects is an essential part of 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 difficult to adjust or modify to reflect changes in control. An additional concern is that a poorly documented data would not be legally supportable.

The survey narrative report, completed by the person in responsible charge of the survey (typically the Party Chief), shall 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 Caltrans standard.

1. Survey narrative report
   a. Project name & identification: County, Route, Postmile (begin and end), Expenditure Authorization (EA) or Project Identification number, etc.
   b. Survey date, limits, and purpose
   c. Datum, vertical Datum, epoch, and units
   d. Control found, held, and set for the survey
   e. Personnel, equipment, and surveying methods used
   f. Problems encountered

   g. Any other pertinent information
2. Project Control report (see *CSM* Chapter 9.6-3)
3. MTLS QC report (see 15.11-7)
4. Dated signature and seal of the Party Chief or other person in responsible charge

Table 15-2 Mobile Terrestrial Laser Scanning Specifications

Operation/Specification	MTLS Scan Application (See Section 15.8)	
	Scan Type A	Scan Type B
MTLS equipment must be capable of collecting data at the intended accuracy and precision for the project	Required	
Initial calibration of MTLS system (per manufacturers specs)	As Required	
Dual-frequency GNSS recording data at 1 Hz or faster	Required	
Minimum IMU positioning data sampling rate capability	200 Hz	
Maximum IMU Gyro Rate Bias	1 degree per hour	
Maximum IMU Angular Random Walk	0.125 degree per √hour	
Maximum IMU Gyro Rate Scale Factor	150 ppm	
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 mile distance of GNSS outage	0.33 foot (0.100 m)	
Maximum uncorrected IMU Z positioning drift error for 60 second duration or 0.6 mile distance of GNSS outage	0.23 foot (0.070 m)	
Maximum uncorrected IMU roll and pitch error/variation for 60 second duration or 0.6 mile distance of GNSS outage	0.020 degrees RMS	
Maximum uncorrected IMU true heading error/variation for 60 second duration or 0.6 mile distance of GNSS outage	0.020 degrees RMS	
Project control should be the constraint for GNSS positioning	Yes	
Minimum order of accuracy for GNSS base station horizontal (H) and vertical (V) project control	Horizontal 0.07' local network accuracy Vertical – Third Order	
MTLS Local Transformation Point and Validation Point surveyed positional accuracy requirements	H ≤ 0.03 foot V ≤ 0.02 foot	H and V ≤ 0.10 foot
Maximum post-processed baseline length	12.5 miles (20 kilometers)	

Continued

Table 15-2 Mobile Terrestrial Scanning Specifications - Continued

Operation/Specification	MTLS Scan Application (See Section 15.8)	
	Scan Type A	Scan Type B
Minimum overlapping coverage between adjacent runs	25% sidelap	
Monitor MTLS system operation for GNSS reception	Throughout each pass	
Monitor MTLS system operation for IMU operation and distance and duration of any uncorrected drift	Throughout each pass	
Monitor MTLS laser scanner operation for proper function	Throughout each pass	
Monitor MTLS system vehicle speed	Throughout each pass	
Minimum orbit ephemeris for kinematic post-processing	Rapid	
Observations – sufficient point density to model objects	Each pass	
Vehicle speed – limit to maintain required point density (density required for accurate target recognition)	Each pass	
Filter data to exclude measurements exceeding scanner range	Each pass	
Local transformation point maximum stationing spacing throughout the project on each side of scanned roadway	1500 foot intervals	3000 foot intervals
Validation point maximum stationing spacing throughout the project on each side of scanned roadway for QC purposes as safety conditions permit	500 foot intervals	1500 foot intervals

Appendix 15A: Glossary

ASCII (American Standard Code for Information Interchange) – text file.

Albedo – The fraction of light energy reflected by a surface, usually expressed as a percentage; also called the reflection coefficient.

Artifacts – Erroneous data points that do not correctly depict the scanned area. Objects moving through the scanner's field of view, temporary obstructions, highly reflective surfaces, and erroneous measurements at edges of objects (also known as "Edge Effects") can cause artifacts. Erroneous depiction of features can be due to inadequate or uneven scan point density.

ASTM E57 Standard - ASTM (American Society for Testing and Materials) E57 (3D Imaging data format) see links: http://www.libe57.org/, and https://www.astm.org/COMMITTEE/E57.htm

CSV (comma-separated values) – comma-separated text file.

Data Voids – Gaps in scan data caused by temporary obstructions or inadequate scanner occupation positions. Overlapping scans and awareness of factors causing data shadows can help mitigate data voids. Some data voids are caused by temporary obstructions such as pedestrians and vehicles.

Decimation – Reduction of the density of the point cloud.

Distance Measuring Instrument (DMI) – A device that precisely measures vehicle wheel rotation and hence measures the distance traveled by the vehicle wheel.

GNSS (Global Navigation Satellite System) – Satellite navigation systems including the United States' Global Positioning System (GPS), Russia's GLONASS, the European Union's Galileo, and China's BeiDou Navigation Satellite System.

Inertial Measurement Unit (IMU) – A device that senses and quantifies motion by measuring the forces of acceleration and changes in attitude in the pitch, roll, and yaw axes using accelerometers and gyroscopes.

Intensity – A value indicating the amount of laser light energy reflected back to the scanner.

Noise – Erroneous measurement data resulting from random errors.

Phantom Points – See "Artifacts" above.

Point Cloud – The 3D point data collected by a laser scanner from a single observation session. A point cloud may be merged with other point clouds to form a larger composite point cloud. Data from within a point cloud may be used to produce traditional survey products. Point clouds can be specified as a deliverable.

Point Density – The average distance between XYZ coordinates in a point cloud, typically at a specified distance from the scanner. The ***point density*** specified by the client or selected by the contractor should be understood as the maximum value for the subject in question and should be dense enough to achieve extraction of detail at the scales specified for the project.

Registration – The process of joining point clouds together or transforming them onto a common coordinate system. Registration can be by use of a) known coordinates and orientations b) target transformation or c) surface-matching algorithms.

Resolution – The ability to detect small objects or object features in the point cloud.

Scan – The acquiring of point cloud data by a LiDAR system.

Detail Scan – A higher point density scan.

Overview Scan – A scan to gather general details of an area.

Scan Density – See "Point Density" above.

Scan Speed – The rate at which individual points are measured and recorded.

XYZI – Scanner file format showing X & Y coordinates, Z elevation, and reflection Intensity values.

XYZIRGB– Scanner file format showing X & Y coordinates, Z elevation, reflection Intensity, and Red, Green, and Blue color values.

Appendix 15B: STLS Checklist

A. Materials needed BEFORE scanning:

- ☐ 1. Purpose of mapping project? Caltrans Project Number: ___________
- ☐ 2. Project Manager name: _________________________
- ☐ 3. Map Units: ☐ U.S. Survey Foot ☐ Metric
- ☐ 4. Control: ☐ STLS ☐ Conventional
- ☐ 5. Project Datum: Horizontal (including epoch) and Vertical ___________________
- ☐ 6. Scanner calibration report (dated).
- ☐ 7. Flight plan showing flight lines, flying heights, and average photo scale.
- ☐ 8. Proposed scanner control plan
- ☐ 9. Proposed scanner occupation plan
- ☐ 10. Proposed safety plan
- ☐ 11. Proposed validation points
- ☐ 12. Proposed schedule for delivery of Item B and C materials to the district.

B. Materials needed AFTER scanning and registration and BEFORE feature extraction

- ☐ 1. The Project Control Report (see *CSM* Chapter 9 Section 6-3)
- ☐ 2. The Project QC Report (see 15.5-6)
  - ☐ a. STLS registration reports that contains registration errors reported from the registration software.
  - ☐ b. Elevation comparison of two or more point clouds from overlapping scan area
  - ☐ c. Statistical comparison of point cloud data and redundant control point(s) if available.
  - ☐ d. Statistical comparison of registered point cloud data with validation points from conventional surveys if available.
  - ☐ e. Either item c or d shall be performed for QC. Completing both item c and d are highly recommended.
- ☐ 3. Registered point cloud (LAS, LAZ, ASTM E57, or other specified format files).
- ☐ 4. Georeferenced digital photographs if available

C. Materials needed AFTER feature extraction has been completed:

- ☐ 1. Registered point cloud (LAS, LAZ, ASTM E57, or other specified format files).
- ☐ 2. Georeferenced digital photographs if available
- ☐ 3. CADD files
- ☐ 4. 3D printing technology physical scale models of the subject if required
- ☐ 5. Survey control report
- ☐ 6. Survey narrative report
- ☐ 7. QC report

Appendix 15C: MTLS Checklist

A. Materials needed BEFORE the MTLS data collection:

- ☐ 1. Purpose of mapping project? Caltrans Project Number: ___________
- ☐ 2. Name of the Caltrans Project Manager? ___________________________
- ☐ 3. Map Units: ☐ U.S. Survey Foot ☐ Metric
- ☐ 4. Control: ☐ MTLS ☐ Conventional
- ☐ 5. Project Datum: Horizontal (including epoch) and Vertical ___________________
- ☐ 6. Scanner(s) alignment calibration report (dated).
- ☐ 7. Proposed safety plan.
- ☐ 8. Proposed drive route plan
- ☐ 9. Pre-op MTLS vehicle check
- ☐ 10. GNSS satellite visibility and PDOP forecasts
- ☐ 11. Proposed GNSS base station location(s)
- ☐ 12. Quality Management Plan
- ☐ 13. MTLS control target plan including target spacing and control target layout diagram
- ☐ 14. Proposed schedule for delivery of Item B and C materials to the district
- ☐ 15. Name and contact information for the MTLS operator.

B. Materials needed AFTER the data collection and registration and BEFORE feature extraction:

- ☐ 1. MTLS QC report should contain the following:
  - ☐ a. The GNSS / IMU post-processing accuracy report
  - ☐ b. Registration report
  - ☐ c. QC results
- ☐ 2. List of required features to be extracted and survey request with project limit
- ☐ 3. Registered point cloud (LAS, LAZ, or other specified format files) with description
- ☐ of each file with file name, readme.txt file, kml file, or shp file
- ☐ 4. Georeferenced digital photographs with data files supported by TopoDOT
- ☐ 5. MTLS Raw data files if requested
- ☐ 6. Control points file(s)
- ☐ 7. Conventional survey data file(s)
- ☐ 8. Survey narrative report including description of any anomalies
- ☐ 9. Survey control report

C. Materials needed AFTER feature extraction:

- ☐ 1. All items in **A** and **B**.
- ☐ 2. Current Caltrans Roadway Design and Caltrans Drafting Software files