March 2022

Guidelines for the Use of Terrestrial LiDAR Scanners in Criminal Justice Applications

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Acknowledgments

The Terrestrial LiDAR Scanning Working Group includes forensic practitioners and researchers with extensive backgrounds in crime scene documentation and reconstruction and experience in providing expert testimony on bloodstain pattern analysis and trajectory reconstruction. The working group includes representatives from federal, state, county, and local jurisdictions and representatives from the Crime Scene Subcommittee of the National Institute of Standards and Technology (NIST) Organization of Scientific Area Committees (OSAC) and the National Institute of Justice's (NIJ's) Forensic Science Research and Development Technology Working Group.

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The FTCoE would also like to thank the following individuals and entities for their thoughtful review:

Anderson Shelton (Supervisor, Critical Response Team 4, Tennessee Highway Patrol); The Digital Imaging Technical Advisory Group (DITAG) supported by the Australia and New Zealand Policing Advisory Agency National Institute of Forensic Science; Jason Barr (Senior Forensic Scientist, Auckland Service Center, Institute of Environmental Science and Research Limited); and Christopher Flight (Senior Sergeant, Education and Training Group, Office of the Chief Forensic Scientist, Forensic Services Department, Victoria Police) who coordinated the DITAG response.

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Suggested Citation

Forensic Technology Center of Excellence. (2022). *Guidelines for use of terrestrial LiDAR scanners in criminal justice applications*. Research Triangle Park, NC: RTI International.

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Foreword

Terrestrial LiDAR scanning devices (also known as terrestrial laser scanning devices, TLS) acquire complex geometric data that capture a three-dimensional representation of a scene; this technology is used in criminal justice applications such as documenting a scene. Although the use of this technology is increasing in criminal justice applications, no standardized, vendor-neutral guidelines for use are currently available for end users.

The NIJ, in partnership with the FTCoE, convened the Terrestrial LiDAR Scanning Working Group to create consensus-based best practices to standardize and improve the use and application of TLS in scene documentation and reconstruction. This guidance document intends to establish a minimum standard for capturing, processing, analyzing, visualizing, presenting, and storing TLS data in a forensic context. This resource was built to promote uniform implementation and use of TLS technology in practice. This will ultimately improve the practitioners' ability to attain scientifically supportable conclusions from TLS data, ensure effective quality management procedures, and improve presentation of this information to stakeholders, including law enforcement, investigators, and the courts (e.g., prosecutors and defense attorneys, judges, and juries).

Scope

This guidance document intends to establish a minimum standard for capturing, processing, analyzing, visualizing, presenting, and storing Terrestrial LiDAR Scanner (TLS) data used for forensic applications. Although this document was created for TLS operators, analysts, technologists, and agency procurement/decision makers, it can also be helpful to the legal community and product manufacturers. Through this guidance document, the Terrestrial LiDAR Scanning Working Group ultimately strives to improve practitioners' ability to formulate conclusions from TLS data with lower measurement uncertainty and error, ensure effective quality management procedures, and improve presentation of this information to stakeholders.

The resource was built from the collective experience and knowledge of TLS experts across local, state, and federal jurisdictions. The guidance document provides considerations for procurement, data capture, training, processing, data management, reporting, and disclosure that are "vendor neutral": Any TLS user can apply these recommendations, regardless of the brand of instrument they are using. The guidance in this document should not supersede instrument vendor instructions or your agency's policies and procedures.

1. Terms and Definitions

For the purposes of this document, the following definitions apply.

3D Imaging System

A non-contact measurement instrument used to produce a three-dimensional (3D) representation (e.g., a point cloud) of an object or a site (ASTM E2544-11a).

Accuracy (of measurement)

The closeness of the agreement between the result of a measurement and a true value of the measurand (ASTM E2544-11a).

Artificial Common Reference Object

Strategically placed objects in the scan area to serve as reference points between scan positions to enable registration. Also called "targets."

Calibration

A set of operations that establish the relationship between values of quantities indicated by a measuring instrument or measuring system under specified conditions, or values represented by a material measure or a reference material and the corresponding values realized by standards (ASTM E2544-11a).

Error (of measurement)

The result of a measurement minus the true value of the measurand (ASTM E2544-11a).

Hash Algorithms

The use of complex mathematics to create a value that is typically represented as a string of hexadecimal characteristics (called a hash) on a given set of data. If the data change, so will the hash (SWGDE 2019).

Hash Function

A function that maps a bit string of arbitrary length to a bit string of fixed length. The function is expected to have the following three properties: (1) collision resistance, (2) preimage resistance, and (3) second preimage resistance (NIST 2012).

Intensity

A measure of the reflected signal from a surface, which is related to the amount of light that was able to return to the instrument. A higher intensity value appears brighter and is proportional to a surface that reflects light whereas a lower intensity values appears darker and is proportional to objects that absorb light.

Known Length Artifact

An item with a known size that is introduced into the scan area to allow for an accuracy check of the individual scan data. Also called an "artifact."

LASER

Light amplification by stimulated emission of radiation; a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation (RTI International, 2016).

Laser Scanning

The act of using a laser device that collects 3D coordinates of a given region of a surface automatically in a systematic pattern at a high rate (in excess of hundreds or thousands of points per second) achieving the results in (near) real time (Boardman & Bryan, 2018). Laser scanning is a method of non-contact measurement.

Light Detection and Ranging (LiDAR)

A remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light (RTI International, 2016).

Measurement Uncertainty

Measurement uncertainty is an estimate of the magnitude of systematic and random measurement errors that may be reported along with the measurement result. An uncertainty statement relates to a particular result obtained in a laboratory carrying out the test method, as opposed to precision and bias statements, which are mandatory parts of the method itself and normally derived from an interlaboratory study conducted during development of the test method (ASTM International 2005).

NIST Traceable Artifact

An object that is metrologically traceable to the National Institute of Standards and Technology's (NIST's) practical realization of the International System of Units (SI) unit of length, the meter (NIST), and used as a known distance artifact.

Phase-Based Measurement

A method of determining the distance to a point on a surface by measuring the phase shift of emitted waves and the returning/reflected waves.

Point

An abstract concept describing a location in space that is specified by its coordinates or other attributes (ASTM E2544-11a).

Point Cloud

A collection of data points in 3D space (frequently in the hundreds of thousands), obtained, for example, using a 3D imaging system (ASTM E2544-11a). Each point is a measurement with coordinates relative to the instrument origin. With the abundance of points, the point cloud not only contains measurements for each point, but the point cloud itself is a visual rendering of the scanned object or location.

Precision

The measure of closeness of agreement between a series of measurements obtained from multiple samplings of the same homogeneous sample. It is expressed numerically as imprecision (OSAC Lexicon).

Pulse-Based Time-of-Flight Principle

A method of determining the distance to a point on a surface by measuring the time of an emitted laser pulse to the surface and the time the reflected pulse is detected. The distance, d, is equal to (c*t) /2 where c is the speed of light.

Range

The distance, in units of length, between a point in space and an origin fixed to the 3D imaging system that is measuring that point (ASTM E2544-11a).

Range Resolution

The smallest change in range that causes a perceptible change in the corresponding range measurement indication (ASTM E2544-11a).

Reference Measurement Standard

A measurement standard designated for the calibration of other measurement standards for quantities of a given kind in a given organization or at a given location (JCGM 200:2012).

Registration

The process of determining and applying to two or more data sets the transformations that locate each dataset in a common coordinate system so that the data sets are aligned relative to each other (ASTM E2544-11a). Registration combines the point clouds captured at multiple scanning locations at a site into a single, common point cloud representing the entire site that was scanned.

Terrestrial LiDAR Scanning

A method for surveying tasks that acquires complex geometric data where each point is determined by the position (X, Y, Z) and the intensity (i) of the returning signal, also known as terrestrial laser scanning (RTI International, 2016). This method differs from a total station in its ability to automatically capture a large number of points in a predefined window.

Total Station

A surveying instrument that uses a theodolite with an electronic distance meter to read slope distances from the instrument to a particular point (RTI International, 2016).

2. Technology Overview

This section introduces TLS technology and the types of instruments covered in the guidance document. Light detection and ranging, or LiDAR, is a remote sensing technology that enables accurate and precise measurement of the distance of objects at a scene. LiDAR instruments measure distance by illuminating a target with a laser and analyzing the reflected light on an X, Y, Z plane, creating a high-resolution 3D documentation of a scene. LiDAR is commonly used in applications such as surveying, archaeology, and geology and is increasingly used in forensic science applications.

Appropriately trained users may leverage TLS data to document or "reconstruct" scenes. Through accurate and precise scene documentation, scene capture using TLS can do the following:

- Enable investigation of important and specific measurements for applications such as trajectory analysis, bloodstain pattern analysis, height analysis, position analysis, and vehicle dimensions, among others.
- Generate an interactive 3D image which can be used to help the courts "step into" and visualize the scene, understand a witness's vantage point or perspective, and place an involved participant back into the scene to help them recall key points and convey what transpired at a scene.
- Demonstrate viewpoints and perspectives that are not usually possible to document comprehensively (i.e., top-down view of a house to show a floorplan, with the ceiling hidden).
- Capture a spatially accurate representation of the scene quickly and with a level of detail and completeness beyond photographs or video. These scans can capture the scene under any light conditions.
- Integrate results from various instruments or analyses, allowing spatial relationships to be better understood.

This document provides guidance for consistent implementation of TLS for scenes and is meant to be used while operating the instrument in accordance with the vendor's guidelines. It covers instrument use topics such as equipment calibration and validation; capabilities, training, experience, and qualification of persons with functional levels of practice; considerations for TLS data capture from preparing scans to operating the instrument at the scene; and processing, reporting, and disclosing TLS data.

There are several different types and configurations of TLS devices on the market, and their design and capabilities vary widely. There are three broad types of TLS devices: tripod-mounted laser scanners, Simultaneous Localization and Mapping (SLAM) laser scanners, and handheld laser scanners. Tripod-mounted laser scanners are the most well-recognized and broadly capable category and serve as the primary focus for this guidance document. In general, tripod-mounted devices tend to be capable of longer-range and more accurate measurements and more durable. These instruments can be valuable for a variety of scenes, especially those where accuracy is critical. SLAM laser scanners are field-portable mapping devices that capture and utilize 3D data. Whether in the form of a backpack-mounted or handheld device, SLAM devices are typically best suited for large volume data captures where the relative accuracy and quality of the laser scan data are not critical (e.g., large scenes, an entire building). Handheld laser scanners are small devices that are typically used for short-range measurements (<2 m). Some handheld devices can produce detailed, accurate 3D data, and provide value in small areas. **Appendix A** offers additional points of comparison for the different types of TLS devices.

As an additional caveat, it is important to note that manufacturers' reporting of TLS specifications is not uniform. Users should pay special attention to specification sheets and documents to be certain that these topics are well understood and suited to their applications.

3. Equipment Calibration

This section provides an overview of TLS instrument calibration considerations.

3.1 Overview

Instrument calibration will necessitate on-going costs and downtime for the agency owners. The costs for certified calibrations will be significant and should be budgeted in advance. Procurement teams should have a clear understanding of the cost of calibration and the agency's plan for the frequency of the calibrations.

TLS devices are complex measurement devices that are susceptible to degradations in their precision and accuracy over time. The rate of measurement degradation depends on several factors including quality of the instrument construction, design, and components, frequency of use, care in handling and storage, and exposure to harsh elements. Over time, these will affect the instrument's ability to produce measurements within the vendor's specifications. Most importantly, the TLS operator and 3D analysts must know the measurement of uncertainty associated with the data they capture and exploit. This is critical to the ultimate admissibility of 3D evidence produced by the TLS.

3.2 Calibration Frequency

Vendors will specify an interval between instrument calibration—usually a period of 1–2 years—based on the instrument's design and expected deployment environments. In most circumstances, the vendor conducts all instrument calibrations. Most TLS device users operate in the architectural, engineering, and construction or land surveying industries and calibration recommendations are set for these specialties. As a result, TLS manufacturer recommendations for calibration may not be suitable for forensic applications.

3.3 Self-Calibration

TLS devices with internal collimation checks have recently been developed and made available for purchase. These devices purportedly do not need calibration and are described as self-calibrating. More research and validation are required to substantiate these claims. Manufacturers' white papers are available on this topic and represent a good starting point for further research. As of the publication of this document, calibration is only recognized as described in this section, and TLS performance should always be compared against an external reference.

4. Equipment Validation

This section provides an overview of TLS equipment validation considerations. Performance of a forensic TLS device should include an instrument validation at periodic intervals for monitoring and traceability purposes.

An instrument validation involves a series of processes through which an instrument is tested to verify or validate the performance specifications published by the manufacturer of the instrument. Instrument validations can be performed in between calibrations to ensure the instrument is ready to perform within the expected tolerances. Two of the most burdensome and overlooked challenges to the on-going success of a TLS program are the recurring costs and instrument downtime associated with adhering to some manufacturers' prescribed period for calibrations and maintenance. Implementing a method that can be used to demonstrate that the instrument(s) used to collect data were functioning within the instrument's published tolerances, even in the absence of a manufacturer's calibration certificate, could help reduce instrument down time and maintenance costs associated with recurrent calibration. This in-house validation method (referenced below as a "periodic calibration verification" could be a replacement for equipment calibration depending on the scanner's frequency of use, storage, and handling conditions (e.g., if the instrument was dropped). For more information on performance checks in the field, see section 6.2.7 (Reference Measurement Protocol).

4.1 Periodic Calibration Verification (PCV): ISO 17123-9

The International Organization for Standardization (ISO) 17123-9 standard for PCV is as follows:

> Field procedures for determining and evaluating the precision (repeatability) of terrestrial laser scanners and their ancillary equipment when used in building, civil engineering, and surveying measurements. Primarily, these tests are intended to be field verifications of the suitability of a particular instrument for the immediate task at hand, and to satisfy the requirements of other standards. They are not proposed as tests for acceptance or performance evaluations that are more comprehensive in nature.

Some limitations of ISO 17123-9 reduce its applicability to this task. Notably, the layout of the test field described in the standard is based on the maximum manufacturer-recommended distance for capturing targets. For an instrument with a 75-meter target capture distance, the target used to create the vertical triangle in the test field would be placed 37.5 meters above the heights of other targets. This requirement limits the locations in which a test field can be placed (e.g., buildings without this clearance). Additionally, reference values for target distances are not captured as part of the test; therefore, scale errors in the instrument being tested cannot be evaluated.

4.2 Manufacturer-Specific Procedures

Manufacturers may include tools and procedures to facilitate periodic user verification that measurements taken by a TLS meet specifications. Users should verify with the manufacturer of their specific TLS that use of such tools and procedures are suitable for extending recommended service intervals for devices that are functioning properly.

5. Personnel Capabilities, Training, Experience, and Qualifications

This section describes the different functional practice levels of personnel when capturing and using TLS data, provides the suggested or recommended minimum educational and training requirements for each level of functional practice, and recommends training content and proficiency testing intervals.

5.1 Functional Levels of Practice with TLS Data

5.1.1 Operator

- Operates instrument(s) to capture TLS data that are acceptable for a particular analysis.
- Selects the appropriate instrument settings to capture the required details and placement of the instrument to cover the scene with minimal occlusions and with the minimum number of scans required.
- Qualified to testify about instrument operation and how it was used to capture TLS.
- Maintains the instrument, which includes having the instrument calibrated at appropriate intervals.

5.1.2 Technologist

- Has the qualifications of an Operator and those listed in this section.
- Processes TLS data using the native or non-native software to produce data for forensic analyses and to produce demonstrative exhibits.

- Has the ability to integrate TLS data with data from other devices or sources to produce demonstrative exhibits, including measurements.
- Qualified to testify about how the applicable software was employed to process the data into a demonstrable product and can provide measurements from that data, as needed.

5.1.3 Analyst

- Has the qualifications of a Technologist and those listed in this section.
- Uses TLS data or other applicable sources of data to complete specific forensic analysis and renders expert opinions or forensic reconstructions.
- Qualified to explain their reconstruction methodology and render expert opinions or conclusions about their reconstruction in their respective discipline(s).

5.2 Minimum Training Requirements

5.2.1 Operator

- Has received a manufacturer-prescribed course of training (or equivalent) in the operation of a specific TLS instrument and has demonstrated a level of competency in the proper operation of that instrument to collect TLS data that also meets standards established by the organization (e.g., number of training exercises with expected outcomes, completion of a written or oral assessment).
- Should be proficiency tested in instrument operation as a part of an on-going quality assurance program.

5.2.2 Technologist

- Has received a manufacturer-prescribed course of training (or equivalent) in the operation of a specific TLS instrument and has demonstrated a level of competency in the proper operation of that instrument to collect TLS data that also meets standards established by the organization (e.g., number of training exercises with expected outcomes, completion of a written or oral assessment).
- May have received an additional manufacturer-prescribed course of training (or equivalent) in the operation of non-TLS devices or instruments whose data may be used in conjunction with TLS data and has demonstrated competency in the proper integration of non-TLS data sources.
- Has received a manufacturer-prescribed course of training (or equivalent) in the use of native or non-native software and has demonstrated competency in the use of their available software to produce demonstrable renderings of the scene using single or multi-source instrument data.
- Should be proficiency tested in both instrument operation and software use as a part of an on-going quality assurance program.

5.2.3 Analyst

- Has received a manufacturer-prescribed course of training (or equivalent) in the operation of a specific TLS instrument and has demonstrated a level of competency in the proper operation of that instrument to collect TLS data that also meets standards established by the organization (e.g., number of training exercises with expected outcomes, completion of a written or oral assessment).

- May have received an additional manufacturer-prescribed course of training (or equivalent) in the operation of non-TLS devices or instruments whose data may be used in conjunction with TLS data and has demonstrated competency in the proper operation of those non-TLS devices or instruments.
- Has received a manufacturer-prescribed course of training (or equivalent) in the use of native or non-native software and has demonstrated competency in the usage of their available software to produce demonstrable renderings of the scene using single or multi-source instrument data.
- Should be proficiency tested in both instrument operation, software use, and reconstruction methodology as a part of an on-going quality assurance program.
- Has received requisite training in the particular area of forensic analysis in which conclusions and/or opinions are being drawn from the data.

5.3 Proficiency testing

Operators, Technologists, and Analysts should be proficiency tested to their level of competency every year as part of an ongoing agency or employer quality assurance program. Proficiency testing should be tests that are representative of casework where the result is known or casework that is directly observed and monitored by personnel qualified at the same or higher level. Results of proficiency tests should be maintained by the agency in accordance with agency procedures and guidelines.

6. TLS Data Capture

This section provides an overview of TLS applications and considerations for scanning scenes in a field setting.

6.1 Applications for 3D Data

TLS are used to capture a scene by documenting evidence and its location with respect to other items in a scene. The location of evidence in relationship to other objects is often important such as in shooting scenes or when bloodstain patterns are considered. Items of interest may include the following:

- Bloodstain patterns
- Bullet impacts
- Environmental topography and surrounding environment
- Footwear impressions
- Location and positioning of decedent(s)
- Tire marks
- Vehicle or property damage
- Wounds
- Weapons
- Witness viewpoints

More specifically, TLS can provide measurements for three types of applications:

Critical Measurements: Critical measurements require a high level of accuracy and are used to inform an expert opinion in areas such as bloodstain pattern analysis, crush analysis, and trajectory analysis.

General Analysis: General analysis is used to take overall measurements where a rigorous level of accuracy is not required such as skid marks and sightline distance. Demonstrative Use: Demonstrative use is when measurements are not the primary consideration, and the data are simply being displayed to show the overall “lay of the land.”

6.2 Considerations for Preparing for a TLS Scan

Before using a TLS instrument in a scene, operators should note the following considerations for preparing for a TLS scan.

6.2.1 Establish security of the scene

Scanning records the scene elements as closely as possible to how they appeared at the time of the incident and, when possible, the scene should be secured before it is scanned. One technique to secure a scene is constructing two perimeters: an outer perimeter for staging equipment and personnel and an inner perimeter surrounding the area to be documented. To the best of the operator’s ability, the inner perimeter should be kept free of people until the scanning is complete to ensure evidence and the surrounding environment is not disturbed or obscured.

6.2.2 Understand scanning order of operations

Laser scanning is one step in the overall process of scene documentation. Because laser scanning has a low impact on the scene, it is recommended that laser scanning occur earlier in the documentation process. Once experts have photographed and marked the scene and evidence, it should be scanned before anything is moved. All known evidence must be marked before scanning.

The environment may play a significant role in how a scene is captured. Factors such as poor lighting, tight spaces, rain, fog, or other weather conditions will dictate the scan settings, and the capture method should be adjusted accordingly. High and low temperature can affect an instrument’s measurement accuracy or ability to capture data at all; operators must ensure their instrument is functioning as designed in the current conditions or take proactive steps to mitigate those impacts. Rain, depending on this instrument’s IP rating and rain-fall rate, can damage the instrument and or add extraneous noise to the captured data. Rapid changes in barometric pressure can also produce errors in some instrument’s elevation calculations. In cases where weather or other factors such as rapidly deteriorating evidence (e.g., fire, explosion, chemical spills) are a factor, the capture settings may need to be adjusted to record as much of the evidence as possible while it is safe to do so. When scanning on a steep slope, operator safety and instrument stability will also need to be considered.

6.2.3 Prepare reflective objects

Reflective surfaces or objects can introduce artifacts due to reflection and/or refraction when scanned by a TLS. Therefore, there are multiple ways to prepare reflective surfaces to ensure they can be measured. A large mirror can be covered with a sheet or paper if there is no evidence on the mirror. Sterilized surgical drapes may also be used in place of paper as a contamination minimization measure at scenes. Other reflective surfaces can be sprayed with a substance that will leave a residue. Dry shampoo, fingerprint powder, and aerosol deodorant that contains baking powder are three examples of easily available products that will leave a residue to assist the scanner with collecting the data. If the surface is going to be prepared this way, ensure any forensic evidence is collected and photographs have been taken before preparing the surface. A list of additional equipment that can help visualize these objects can be found in **Appendix B**.

6.2.4 Understand the intended use of laser scan data

In many cases, understanding the end use of the captured laser scan data is important because it will dictate the necessary instrument settings and area to be scanned. For example, scenes requiring precise measurement analyses such as bullet trajectories or bloodstain patterns require scanning with high resolution instrument settings. Whereas cases requiring only general measurements or plan drawing, color data or high-resolution scan settings may not be required. In addition, the desired end visualization should be considered because camera flythroughs, animations, and virtual tours or models are better served with higher resolution color scans.

6.2.5 Mount the scanner appropriately

TLS can be mounted in several different ways to ensure proper coverage of a scene. The incidence angle that the laser beam makes with a surface affects the instrument's ability to correctly sample the surface. The measurement precision error increases as the angle between the laser beam and the surface decreases; there is less measurement error if the laser beam is more perpendicular to the surface being measured. A list of equipment that may help ensure instrument stability can be found in **Appendix B.**

6.2.6 Set the appropriate point density for data needs

For data used to obtain critical measurements, the point spacing should generally range from 1–3 mm at the location of the measurements. For general indoor analysis, the point spacing should be less than 3 cm at the location of measurement. For general outdoor scenes (for demonstrative purposes), the point spacing should be no more than 15 cm at the point of reference. Because each scanner has different settings and different scan modes, the operator should ensure the point spacing meets or exceeds the manufacturer's guidelines when performing the scans. The operators should thoroughly know how their instrument functions and its capabilities at the range in question. Recommendations for critical measurements across TLS applications are found in **Appendix C**, and resources to support recommendations for critical measurements can be found in **Appendix D**. Guidance on calculating point spacing can be found in **Appendix E**.

6.2.7 Incorporate reference measurements

The Reference Measurement Protocol (RMP) is an on-site validation that should be performed every time the TLS device is deployed during a forensic investigation. There are several acceptable methods for performing the RMP. The RMP process compares the TLS measurement to the same measurement taken with a separate instrument. Often, this comparison is done using a known length artifact that is introduced into the scene such as a set of targets or prism pole or an easily characterized distance in the environment. A corner-to-corner room measurement that is measured by both the TLS and a handheld laser electrical discharge machine device would be one example of an acceptable RMP. A NIST traceable length artifact measured by the TLS and compared against the certified length of that artifact is another acceptable RMP that has the added assurance of using an object calibrated through an accredited third party.

While scanning at scenes, one or more reference measurements should be made, at a minimum, to ensure that the instrument is functioning properly. A reference measurement may be taken by using known points such as the length of walls, markings on the ground, or other natural features in the scene.

These reference measurements should be accomplished using a NIST traceable standard object. There are multiple ways to accomplish this measurement. A NIST-certified tape measure can be used to measure between two easily identifiable points in the scene, which can then be compared with the measurements in the scan data. An object that has been measured with a NIST-certified tape measure or a manufacturer-specific NIST-certified measurement device can be placed in the scene, and its known measurement can be compared with the measurement in the scan data. TLS manufacturers may market these devices specific to scanning. Objects placed in the scene should be placed in the first and last scans in areas that are out of the areas of evidentiary value. They should be placed in such a way that the measurements test the accuracy in all three measurement planes (i.e., the reference object should be placed at an angle to the scanner position and sloped away from the scanner).

6.3 Operating the TLS Instrument at the Scene

6.3.1 Understand capabilities of line-of-sight instruments

TLS are line-of-sight instruments; objects closer to the scanner may occlude objects behind it. The operator must ensure that the scanners are placed to minimize occlusions in areas of interest. The operator should understand what the scanner will see and use the scanner's perspective to ensure the scene is properly documented. In some circumstances, scan locations do not need to be far away from each other to achieve full documentation of the scene. In other circumstances, the scanner location may only require a change in elevation to ensure this is accomplished.

6.3.2 Scan overlap

When the data are to be registered using cloud-to-cloud registration, there should be sufficient overlap between scans. Certain scanning environments will require the use of artificial common reference objects, more commonly referred to as "targets." Scanning environments that are devoid of rectangular architecture or planar (flat) objects will need the addition of targets to register individual scans together. If the data are going to be registered using targets, there should be a minimum of three targets in common between each scan (though some manufacturers require four; check your equipment requirements). Avoid placing targets colinearly or co-planarly, meaning the heights and surfaces upon which targets are placed or the heights of the tripods supporting the spherical targets should vary. Multiple types of targets can be used for registration (i.e., spherical targets can be combined with checkerboard targets). Figures 1 and 2 provide examples of proper target placement indoors with areas of repeating patterns such as a hotel hallway or stairwell. Figure 3 provides suggested scan positions and spherical target placement around the exterior of a vehicle when targeted registration is utilized.

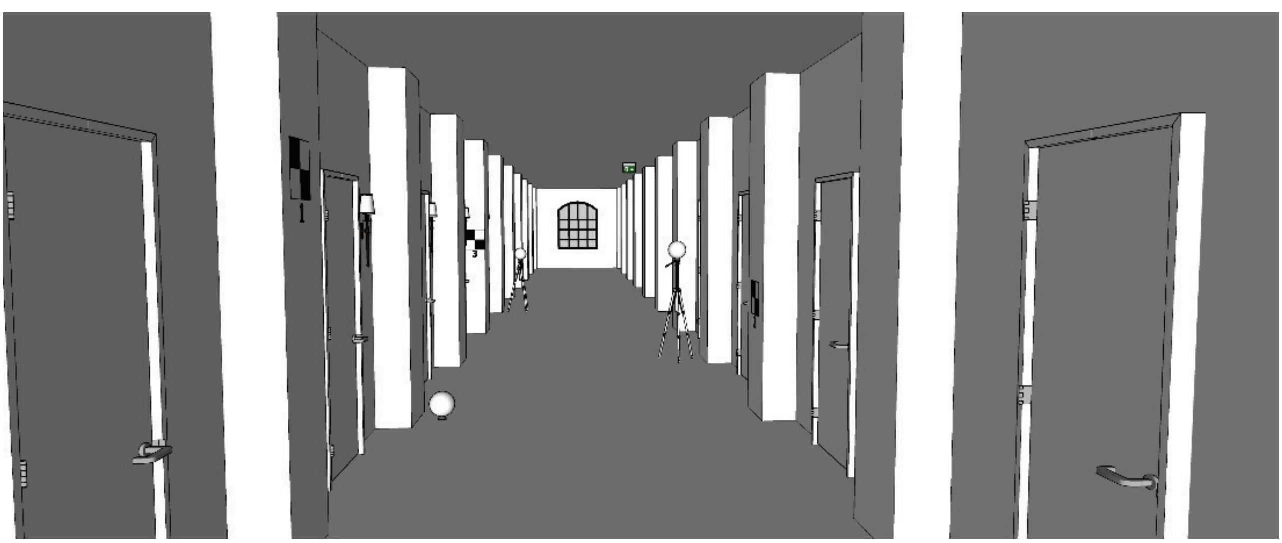


Figure 1. Appropriate placement of checkerboard and spherical targets at differing heights along a hallway of repeating structural elements.

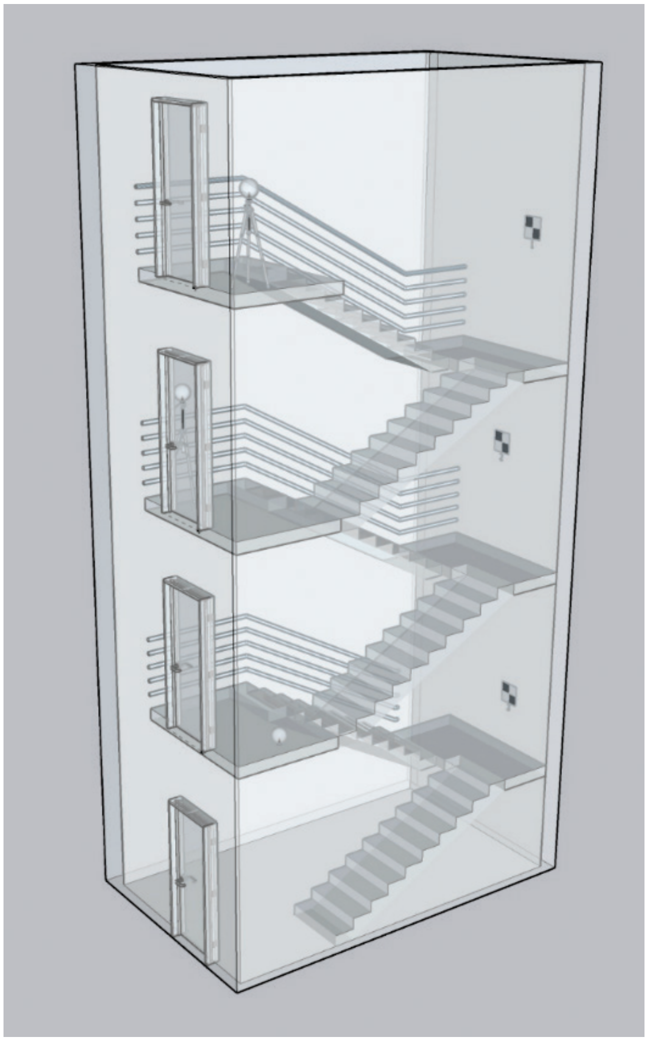


Figure 2. Appropriate placement of checkerboard and spherical targets on multiple levels of a stairwell.

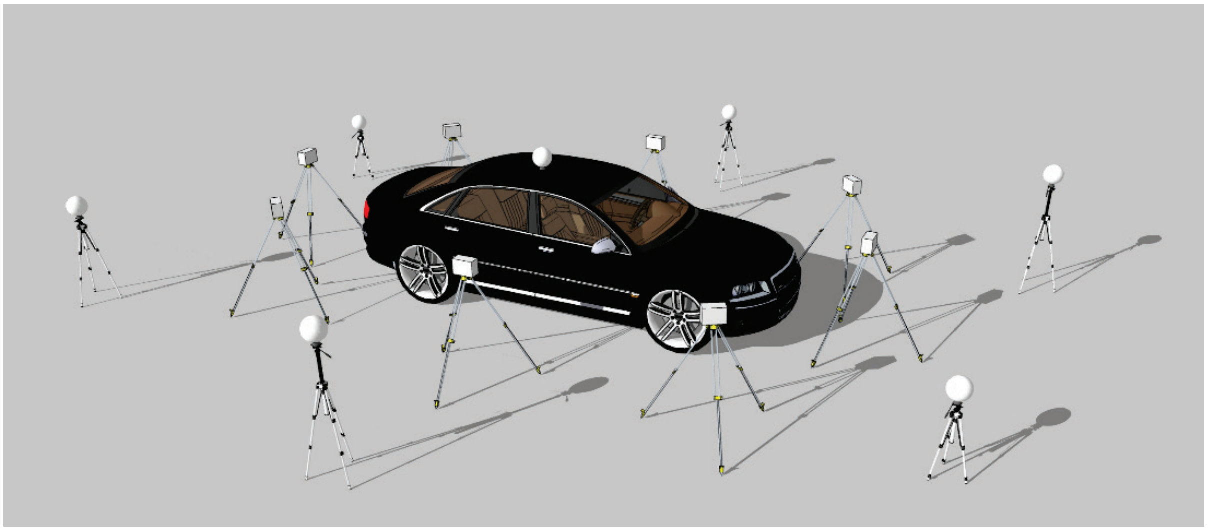


Figure 3. Appropriate placement of spherical targets and suggested scan positions around the exterior of a vehicle.

6.3.3 Scanning with color and the use of external lighting:

When using external lighting to capture color, avoid shining lights directly into the laser scanner which may cause the color to wash out. Ideally, external lighting is placed under the scanner or in a manner that does not cause the color to be overexposed.

6.3.4 Field Notes

Scanning operators should document their actions in field notes. These notes should record any information that is important to the scene, including the following:

- Date
- Time
- Case number
- Name of operator
- Weather
- Scanner
- Make and model
- Scanner serial number
- Date of last calibration
- Scanner settings
- Types of targets used
- Reference measurement used
- Location of any reference, GPS, or other control objects
- Scene diagram or photos showing scanner positions or target positions (Figures 4 and 5 provide examples of interior and exterior scan projects)
- Location of known critical measurements
- Anything that might have an impact on the collection of data
- Reference of scan positions to landmarks
- Scan plan/reference sketch
- Position/location of reference ties (survey stakes/nails) for repeatability

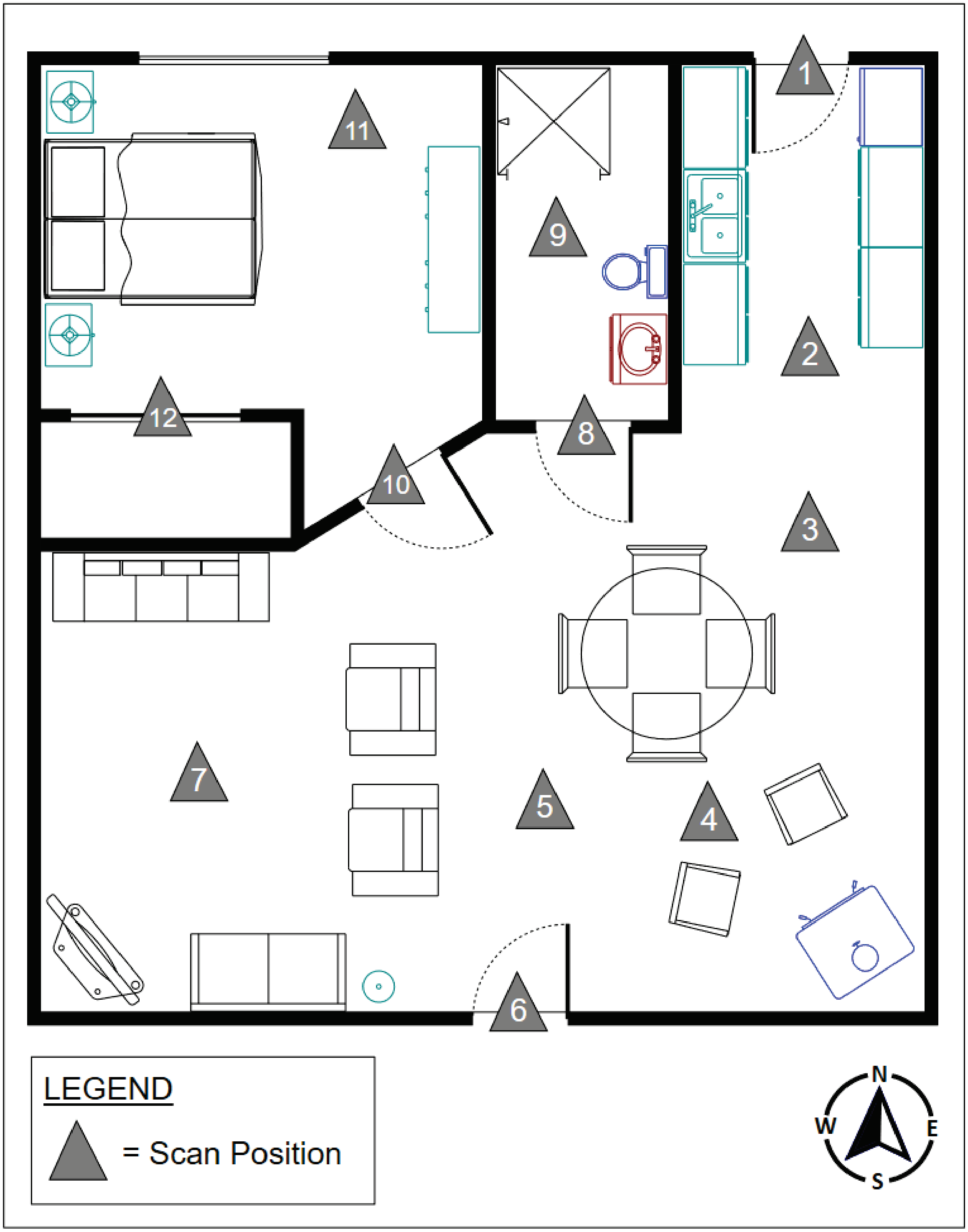


Figure 4. Example scene diagram depicting scan positions for interior scan project.

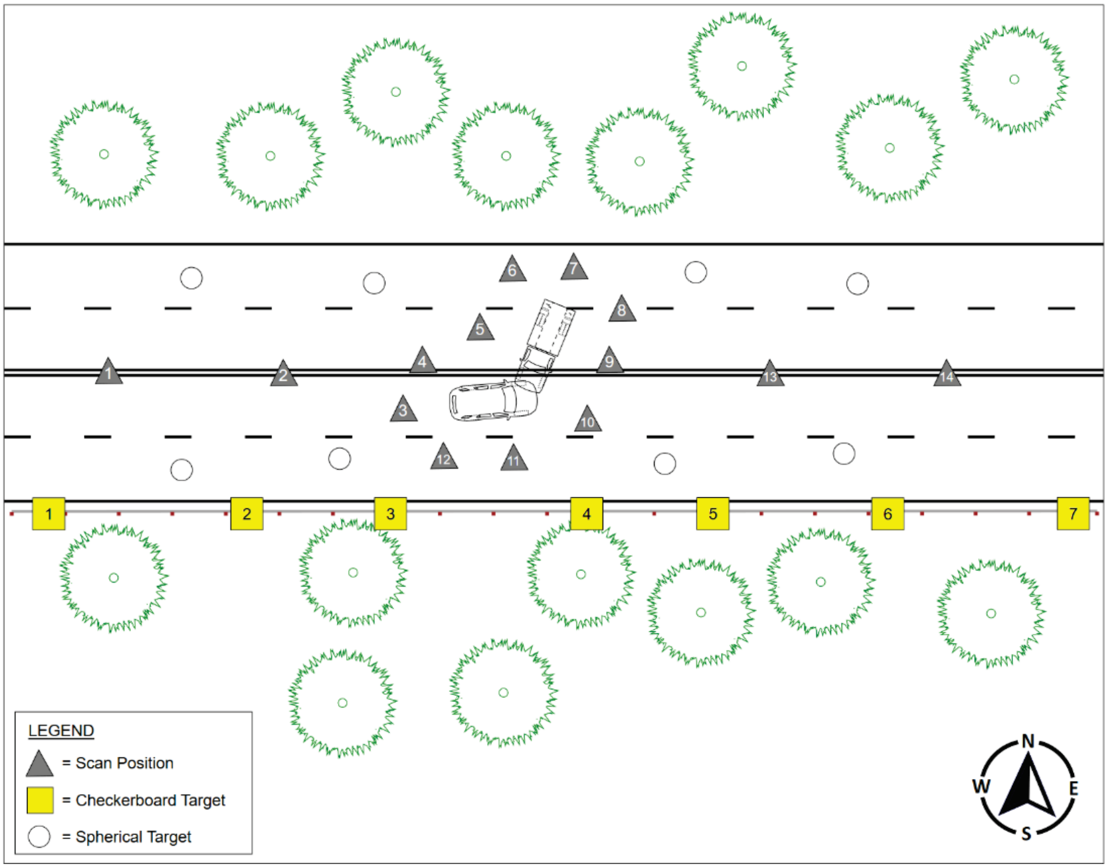


Figure 5. Example scene diagram depicting scan positions and target locations for exterior scan project. The checkerboard targets (in yellow) are placed alongside a fence or guardrail next to the road.

7. Data Processing

Data collected with TLS must be processed for use by analysts. The degree to which the data is processed will depend on its intended use, but common steps must be taken to obtain repeatable outputs that accurately reflect the scanned subjects.

7.1 Data Import

For most TLS, data from a scan project must be imported into proprietary software for processing. During import, filtering options may be available. The user must understand the effects of these settings on the quality of data and select the appropriate level of filtering for the intended use of the data.

7.2 Registration

Registration is defined as "the process of determining and applying to two or more data sets the transformations that locate each dataset in a common coordinate system so that the data sets are aligned relative to each other (ASTM E2544-11a)." Registration combines the point clouds captured at multiple scanning locations at a site into a single, common point cloud representing the entire site that was scanned.

Registration may be automated or may require manual alignment of scan position data or manual matching of points that are common in the different scan positions. The registration software may provide feedback on the quality of the registration, but the user must visually verify the quality of the registration accuracy by examining the alignment of common surfaces or the correspondence of common points. Regardless of the density of the data collected, errors in registration may significantly reduce the accuracy of distances measured between points scanned from different positions.

7.3 Outlier Removal

Because a TLS will collect data for any object within its range, including people and vehicles moving around the scanner, it may be necessary to remove points from transient objects to improve visibility of evidence or the environment. Care must be taken not to remove data of evidentiary value from the point cloud. The point cloud includes all reliable data points to present the most accurate depiction of the scene. Important clarifying language for data reporting or presentation should include caveats such as “Extraneous and unreliable data recorded during the scanning process such as artifacts caused by reflection, edge artifacts, people, and objects moving within the scene during the scanning process have been removed for clarity. Data that have been removed are available for examination upon request.”

7.4 Revision History

While processing, registering, and removing outlying points, each major step in the process should be documented. A brief description of the actions taken prior to the save point should be recorded for later review and repeatability. The raw data should always be saved prior to any processing and each processing step should be documented external to the software or within the registration software itself. Ideally, the manufacturer’s software would automatically record user’s input and processing of the dataset; however, at the time of publication, this feature is not available by any manufacturer known to the authors.

7.5 Data Export

Exporting point cloud data from the software allows for analysis of the data using external software and sharing files with other analysts who may not have access to the proprietary software. Some TLS instruments generate export file types that cannot be opened in software from other sources. When choosing the format of exported registered and unregistered point cloud, several factors should be considered such as file size, software compatibility, and potential deliverables.

A few file types have been found to be usable in a variety of software, including the proprietary software from multiple TLS manufacturers:

- E57
- PTS/PTZ
- XYZ
- LAS/LAZ
- OBJ
- PLY
- TXT

8. Data Management

This section describes the types of data produced by the TLS and methods for confirming and maintaining data integrity. It recommends how the data should be managed and stored in a forensic context to be compliant with the Scientific Working Group on Digital Evidence's "Best Practices for Archiving Digital and Multimedia Evidence" (SWGDE, 2020).

8.1 Types of Data Managed

Laser scanning data must be handled and stored in a manner that ensures the integrity of the outputs and their acceptance in court. Data must be protected from loss or modification. When considering the data, the following terms, established for forensic digital imaging workflows, are utilized:

8.1.1 Primary data

Primary data refers to the first instance in which an image is recorded onto any media that is a separate identifiable object or objects. The primary data files are generated at the time of capture. The primary data, also known as raw data, are typically written to a memory card or hard drive associated with the device.

8.1.2 Original data

Original data are generated when an exact binary copy is made directly from the primary data. The original data are evidence and should be stored in a secure location and retained unaltered. They serve as the original record of the data recorded from the scene. Access to these data should be protected, ensuring they cannot be altered or removed without consent. Original data should be backed up to prevent loss due to hardware failure.

8.1.3 Working data

Working data are a copy of the original data set that is used for processing, analyzing, or editing. Working data ensures that an unaltered original record is retained should unedited data be needed. Working copy data can be made available to other parties upon request.

8.1.4 Hash checking

Open-source software exists that allows for data fidelity to be checked to ensure they have not been altered. Immediately upon transferring the TLS data to a computer, a hash value should be calculated using the software to provide a baseline value. This baseline value will then be maintained for later comparison should the data fidelity ever be questioned.

8.1.5 Data storage

Redundant storage of TLS data should adhere to state laws and department standard operating procedures. SWGDE suggests that at least two copies of the primary TLS data are created in case one fails (SWGDE, 2019). One copy should be kept at an off-site storage space to better protect the data. When that is not possible, the data should be stored on archive-quality media to ensure proper protection.

8.1.6 Data accessibility

TLS data are often subject to retention periods of 99 years or more. Therefore, best practices recommend an additional copy of the data be created in. e57 format, which is generally considered to be a generic format. Possessing a copy of the data in. e57 will ensure it is readable in the future.

8.1.7 Data reporting

The reporting of TLS data may vary depending upon the data's purpose, application, audience, and venue. However, accurately reporting the methods and equipment used, procedures followed for the acquisition and post-processing of the data, and quality measures utilized to ensure data accuracy will help ensure TLS data are admissible and understood by consumers of the resulting product. Section C of **Appendix F**, "Legal Considerations and Recommendations for Use of Terrestrial LiDAR Scanning for U.S. Criminal Justice Applications," provides an overview of legal requirements for admissibility of TLS evidence. Legal requirements may vary depending on jurisdiction.

8.2 Reporting Requirements

This section includes suggested required reporting parameters for TLS data.

8.2.1 Terms and definitions

Technical terms used throughout the report should be defined and sources should be cited for the definition. Technical terms can be defined in the body of the report, a footnote, or an appended glossary. Sources should be cited in a footnote or appended citation list.

8.2.2 Equipment

- Make/model
- Scanner specifications sheet
- Scanner calibration certificate

8.2.3 Data collection

- Date/time/operator
- Scan plan
- Total number of scans
- Variables specific to scan project (e.g., color/no color; targets/no targets; scanner locations)
- Environmental conditions throughout the data capture process

8.2.4 On-site calibration/verification

- Reference measurement device used
- Reference measurement device certificate (if applicable)
- Comparison between scan data vs. reference measurement

8.2.5 Data archival

- Data transfer
- Hash value generation
- Hash comparison
- Submission into evidence archive (e.g., property room no.)

8.2.6 Registration

- Registration methods used (targeted, cloud-to-cloud, manual)
- Registration results/report: details level of overlap and accuracy between scan positions

8.2.7 Post-processing

- Filters applied
- Data cleanup

8.2.8 Final deliverable production

- Method for creating final deliverable
- Instructions for navigating deliverable

9. Disclosure of Data

This section provides an overview of best practices for disclosing TLS data and preparing for trials that include TLS data as evidence.

9.1 Legal Requirements

Timely and thorough disclosure of TLS data and reporting are subject to legal requirements, which may vary by jurisdiction and venue. The disclosure of TLS data may be made pursuant to a legal request for discovery by the opposing party. As such, the appropriate information or data format requested may be dictated by the specific request.

9.2 Information Disclosure

Making information available to all parties involved in an investigation is an important aspect of supporting a fair and open judicial process. The disclosure of a thorough statement, report, or data output should be made at the earliest possible time. In some circumstances, the disclosure of working notes and original data may be requested by the parties involved in an investigation to enable them to understand how a particular output was produced.

9.3 Trial Preparation

Trial preparation with involved parties is important. Litigators should understand the necessary questions to be asked to lay the foundation for the technology. Section E of **Appendix F**, "Legal Considerations and Recommendations for the Use of Terrestrial LiDAR Scanning for U.S. Criminal Justice Applications," provides guidance on educating attorneys and judges on the use of TLS data in court.

The scanner operator who is called to testify as a fact witness needs to have a competent working knowledge of the technology; including how the TLS works and the underlying principles of the data collection, processing, and registration. When a courtroom demonstration is conducted, all TLS equipment, computers, and software should be charged and up to date before trial date. Any demonstrations should be rehearsed in advance with the attorney presenting the TLS data for admission.

If necessary, higher-level technical questions about the TLS technology itself, including those related to the underlying algorithms in proprietary registration software, should be directed to a representative from the scanner manufacturer for accuracy and detailed explanation.

Well in advance of trial, the scanner operator should thoroughly discuss with the attorney the purpose and scope of the TLS evidence being presented in court to ensure the attorney's questioning is within the operator's qualifications. When the attorney is seeking expert opinion beyond the operator's qualifications, an appropriately qualified expert should also be subpoenaed to testify.

Appendix A: Comparison of Laser Scanner Device Types

This table offers additional points of comparison for the different types of TLS devices. Please note that these are generalized statements about these categories of TLS devices. There are devices on the market that span across categories in their capabilities and others that may have design advantages that overcome the generally accepted limitations of their categories.

Category	Tripod-Mounted Laser Scanners	SLAM Laser Scanners	Handheld Laser Scanners
Data Collection and Purpose	Data collection is done while mounted on a stable and rigid platform in the field. The instrument is repositioned as necessary to fully document a scene and enable registration of point cloud.	Data collection is done in motion—walking or vehicle mounted—and quality of data capture depends on the speed and trajectory of the motion and environment.	Data collection is done in controlled environments—typically in a laboratory or workshop—or in small scenes.
Use Case	Coverage of small to large areas when accuracy is the most important need	Rapid data collection for larger areas	Obtaining detailed 3D point clouds of small objects or coverage of smaller areas or scenes. Rapid data collection, used for areas that are difficult to document (tight spaces) or have line of sight limitations.
Measurement Technology	Time-of-flight, phase-based	Simultaneous localization and mapping	Structured light
Set-ups	Multiple set-ups are required for large or complex environments	Multiple “walks” or “loops” may be required for complex environments	Usually used for modeling objects that can fit on an indexed table or rotating platform or for capturing smaller scenes
Operator Skill	Less dependent on operator technique—most equipment gives no feedback until you register later	Highly dependent on operator technique—get instant feedback on SLAM devices while scanning	Moderately dependent on operator technique
Potential Applications	All around use where millimeter accuracy is required. Evidence capture: trajectory analysis, bloodstain pattern analysis, crash investigation, height estimation.	Best used for large geographic areas or buildings where millimeter to centimeter accuracy is required. Tactical planning and response—limited to no processing needed.	Best used for measuring minute detail on objects or small surfaces for millimeter range accuracy. Crash investigation, small area scans (especially where TLS cannot fit—e.g., vehicle), crush analysis.

Appendix B: Suggested Equipment List

This table lists general equipment that can help operators easily and effectively conduct TLS scans in a field setting.

Description	Purpose
Blu-ray Burner/Reader	For transference of data from laptop to elsewhere and official copies of data (if not integrated into laptop).
Checkerboard Target Stickers (50)	Targets for use during scanning operations.
D-100 Nonaqueous Developer	For reducing the reflectivity of reflective surfaces such as glass and mirrors.
Door Stops	To wedge doors open between rooms/areas to provide for connector scans.
Dump Pouch (belt worn)	For carrying and easily accessing multiple items on body while scanning on scene.
External Lighting (video mounts on scanner), Large Floodlights	Helps capture color data.
Flexi Reference Sphere Set in a Backpack	Spherical targets for use during scanning operations.
High Capacity (gaming) laptop with GPU	Laptop for portable processing of scans.
Laser Scanning Backpack	Customized rolling backpack to carry all scanning equipment and accessories.
LED Headlamps	For working in low light scenes.
Magnetic Checkerboard Reference Target Set	Magnetic Checkerboard Targets for use during scanner operations.
Memory Card Safe	For maintaining SD cards during transit and non-use.
Mini Flashlight	For working in low light scenes.
Platform Tripod	Stable platform for scanner when used on soft surfaces or on ground.
Platform Tripod Adapter	Threaded adapter for using different scanner types.
Pocket Rod	For placing in first scan as an internal calibration.
Reflective Chalk	May provide value with time-of-flight scanners.
SD card reader	For transference of data from scanner to laptop (if not integrated into laptop).
Single Flexi Reference Sphere	Single Sphere target for use during scanning operations.
Software Dongle	Licensure to operate scanner processing software on laptop.
Stylus Pens	To write with and to use as stylus on scanner graphical user interface/touch screen.
Travel Chair	Small chair to sit in during long scans that is small enough to pack.
Tripod Leg (Seat Belt Cover) (1 each)	Hi Viz covers for tripod legs so tripod and scanner are visible in scene to other personnel.
Tripod-Mounted Clipboard	For maintaining the scan position map.
4TB Portable External Hard Drive	For secondary/backup storage of project files and scan files.
32GB Memory Card (2-pack)	For recording of scanner projects and movement of files between personnel/agencies.
50 GB Blu-ray (25-pack)	For transference of large project files or scan files and official copies.
150W Car Power Inverter	For charging batteries and accessories if a vehicle is only available for power.

Appendix C: Measurement Accuracy and Resolution Guide

This table provides a guide for recommended accuracy and resolution across scenes for different TLS applications.

Application	Recommended Accuracy	Recommended Resolution-Point Spacing
Crush and Vehicle Damage	±1 cm (Max ±2 cm)	10 mm
General Scene—Indoor	±0.5 cm (Max ±3 cm)	<3 cm
General Scene—Outdoor	±3 cm (Max ±3)	<15 cm
Crash Scene Mapping	±3 cm (Max ±6)	<15 cm
Blood Pattern Analysis	<3 mm	<1 mm
Bullet Trajectory	<3 mm	1–3 mm
Subject Height (Area of Interest)	<3 mm	1–3 mm

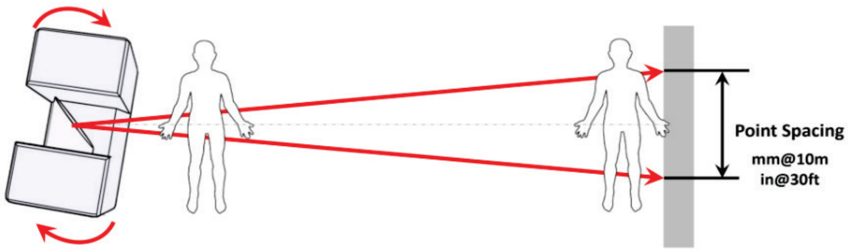
Appendix D: Literature Recommendations for Critical Measurements Across TLS Applications

This table provides resources supporting the critical measurement suggestions in **Appendix C**.

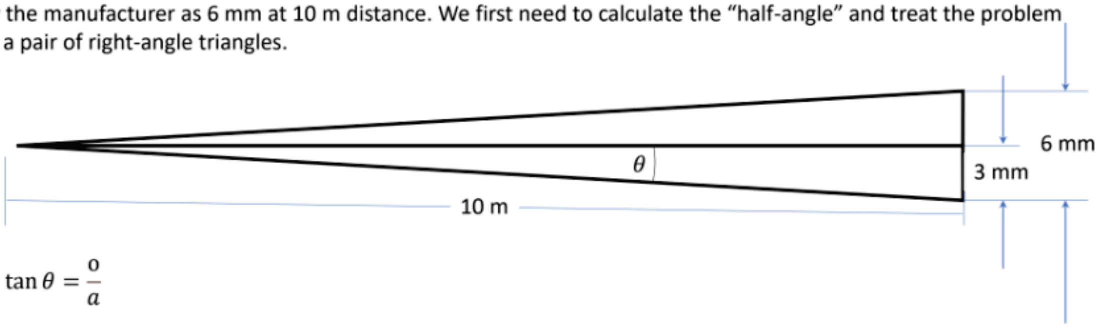
Application	Resources
Crush and Vehicle Damage	• Jones, B., Welcher, J., Szabo, T., Elliot, D., & MacAdams, C. (2010). *The accuracy of photogrammetry vs. hands-on measurement techniques used in accident reconstruction* (2019-01-0065). SAE International. https://www.photomodeler.com/downloads/documents/applications/2010-01-0065.pdf • Mills, D., & Carty, G. *Coordinated crush determination using coded and non-coded targets with close range photogrammetry.* DCM Technical Services, Inc. https://www.photomodeler.com/downloads/documents/applications/MillsCodedTargetsCrush.pdf • Comeau, J.-L., Dalmotas, D. J., German, A., Monk, B., & Trépanier, D. (1996). Crush measurement for side impacts using a total station. *SAE Transactions*, *105*, 47–52. https://www.jstor.org/stable/44720720 • Chapman, M., & Mills, D. (2003, June 8–11). *Vehicle crush measurements using high resolution terrestrial LIDAR*. Proceedings of the Canadian Multidisciplinary Road Safety Conference XIII, Banff, Alberta. http://www.dcmtechservices.com/forensics/publications/Chapman%20Mills%20Vehicle%20Crush%20Using%20Lidar.pdf • Tandy, D., Coleman, C., Colborn, J., Hoover, T. & Bae, J. (2012). *Benefits and methodology for dimensioning a vehicle using a 3D scanner for accident reconstruction purposes* (2012-01-0617). SAE International. https://doi.org/10.4271/2012-01-0617.
General Scene Mapping	• Dustin, D., & Liscio, E. (2016). Accuracy and repeatability of the laser scanner and total station for crime and accident scene documentation. *Journal of the Association for Crime Scene Reconstruction*, *20*, 57–67.
Blood Pattern Analysis	• Esaias, O., Noonan, G. W., Everist, S., Roberts, M., Thompson, C., & Krosch, M. N. (2019). Improved area of origin estimation for bloodstain pattern analysis using 3D scanning. *Forensic Science*, *65*(3). https://doi.org/10.1111/1556-4029.14250 • Liscio, E., Bozek, P., Guryn, H., & Le, Q. (2020). Observations and analysis of cast-off stains. *Journal of Forensic Sciences*. https://doi.org/10.1111/1556-4029.14301 • Liscio, E., Bortrot, S., Frankcom, J. Hackenbrook, T., Inch Lamarche, R. (2015). A preliminary validation of the use of 3D scanning for bloodstain pattern analysis. *Journal of Bloodstain Pattern Analysis*, *31*(3), 3–10. • Lee, R., & Liscio, E. (2016). The accuracy of laser scanning technology on the determination of bloodstain origin. *Canadian Society of Forensic Science Journal*, *49*, 38–51. • Kwan, N., Liscio, E., & Rogers, T. (2016). 3D bloodstain pattern analysis on complex surfaces using the FARO focus laser scanner. *Journal of Bloodstain Pattern Analysis*, *32*(2), 21–27.
Bullet Trajectory	• A Comparison of Bullet Trajectory Rod Measurement Methods, Eugene Liscio, P. Eng., Identification Canada, Volume 38, No 3, September 2015 • Accuracy and Repeatability of Trajectory Rod Measurement Using Laser Scanners, Eugene Liscio,1,2 P.Eng.; Helen Guryn,1 H.B.Sc.; and Daniella Stoewner,1 H.B.Sc. J Forensic Sci, 2017 https://onlinelibrary.wiley.com/doi/abs/10.1111/1556-4029.13719 • Liscio, E., Le, Q., & Guryn, H. (2020). Accuracy and reproducibility of bullet trajectories in FARO zone 3D. *Journal of Forensic Sciences*, *65*, 214–220. https://doi.org/10.1111/1556-4029.14144

Application	Resources
Subject Height	• Liscio, E., Guryn, H., Le, Q., & Olver, A. (2021). A comparison of reverse projection and PhotoModeler for suspect height analysis. *Forensic Science International*, *320*, 110690. • Olver, A., Guryn, H., & Liscio, E. (2021). The effects of camera resolution and distance on suspect height analysis using PhotoModeler. *Forensic Science International*, *318*, 110601. https://doi.org/10.1016/j.forsciint.2020.110601 • Johnson, M. & Liscio, E. (2015). Suspect height estimation using The Faro Focus 3D Laser Scanner. *Journal of Forensic Sciences*. https://onlinelibrary.wiley.com/doi/abs/10.1111/1556-4029.12829

Appendix E: Point Spacing Calculation



We can reduce the point spacing calculation to a trigonometric relationship. Assume the point spacing is provided by the manufacturer as 6 mm at 10 m distance. We first need to calculate the "half-angle" and treat the problem as a pair of right-angle triangles.



$$\tan\theta = \frac{o}{a}$$

$$\tan\theta = \frac{0.003}{10}$$

$$\tan\theta = 0.0003$$

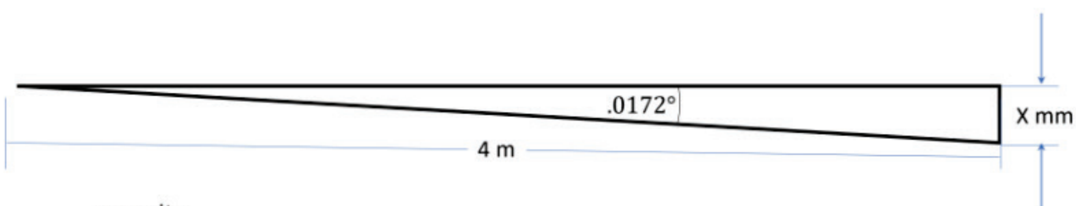
$$\tan\theta = 0.0003$$

$$\theta = arctan(0.0003)$$

$$\theta = 0.0172°$$

Thus, 0.0172° is the half angle and the total angle is 0.0344°

In order to calculate the point spacing at a lesser or greater distance, we use the same relationship. Let's assume we want the point spacing at 4 meters distance. We know that the half angle at the specified resolution is 0.0172°.



$$\tan\theta = \frac{\text{opposite}}{adjacent}$$

$$\tan(0.0172°) = \frac{X}{4}$$

X = $\tan(0.0172°)\, x\, 4$

X =0.0012 m

However, this is only half the point spacing so multiplying by 2, we get 0.0024 m or 2.4 mm.

Figures and formulae provided by Eugene Liscio.

Appendix F: Legal Considerations and Recommendations for Use of Terrestrial LiDAR Scanning for U.S. Criminal Justice Applications

Jonathan W. Hak, Q.C., Dipl., B.Sc., LL.B., LL.M., PhD Candidate[1]

Table of Contents

1 Introduction

Accurate and detailed depictions of scenes, areas of interest, and objects provide investigators, counsel, and the court with data necessary to comprehend available evidence more fulsomely and to understand what occurred.[2] Scene measurements, including the location of objects and features within the scene, are central to a proper scene reconstruction, especially given that scenes are transient and ephemeral. What may seem unimportant at the outset could take on great significance at trial.[3] The work of the Terrestrial LiDAR Scanning Working Group for Criminal Justice Applications is intended to support the joint National Institute of Justice—Forensic Technology Center of Excellence's goals of improving practice and strengthening the impact of forensic science through rigorous technology corroboration, evaluation, and best practices dissemination. This paper provides an overview of the use of terrestrial LiDAR scanning devices for scene measurement and reconstruction and focuses on legal considerations and recommendations for the use of such evidence in a criminal trial. This paper should be read in conjunction with the overall work of the Working Group.

A. What is Terrestrial LiDAR Scanning?

Light detection and ranging (LiDAR) technology is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. Terrestrial LiDAR scanning devices, also referred to as terrestrial laser scanning (TLS) devices, emit laser beams into the selected environment while rotating

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[2] Agosto, E., Ajmar, A., Boccardo, P., Tonolo, F. G., & Lingua, A. (2008) Crime scene reconstruction using a fully geomatic approach. *Sensors*, 8, 6280–6302.

[3] Sheppard, K., Cassella, J.P., & Fieldhouse, S. (2017). A comparative study of photogrammetric methods using panoramic photography in a forensic context. *Forensic Science International*, 273, 29–38.

horizontally and vertically. The scanner measures the distances and angles from the intensity of the reflected beams and computes the three-dimensional (3D) coordinates of all reflected targets to create a 3D point cloud consisting of millions of points. These points produce a detailed and highly accurate 3D depiction of the scene.[4]

Two-dimensional scene depictions limit the ability of the viewer to accurately assess spatial relationships of the overall scene and features and objects located within it.[5] Also, they are less suitable for reconstructing scenes and events using computer-generated animations or virtual reality walkthroughs.[6] 3D laser scanning allows investigators to capture the entire geometry of a scene, including objects and other relevant aspects that may not have been noted when the evidence was gathered, thus ensuring the longevity and preservation of the scene for a subsequent comprehensive examination.[7] The efficiency that TLS affords in documenting a scene saves investigators valuable time at the scene and records data that may not initially appear relevant but may take on significance later.[8]

B. The Use of TLS in Criminal Justice Applications

TLS can be used to capture extensive scene details for later analysis and visualization and is used most commonly, though not exclusively, with crime scenes and motor vehicle collisions.[9] Multiple scanning technologies can be used to accurately measure outdoor and indoor scenes, as well as vehicles and other objects. Combining different tiers of scanning technology provides a varied perspectival view of an event, maximizing the data that can be obtained.[10] TLS has also been used for bloodstain pattern analysis and violent crime reconstruction[11] and to examine solar irradiance for cadaver decomposition in forested environments.[12]

Scenes can be documented three-dimensionally in addition to other conventional methods.[13] TLS devices can quickly scan large areas, buildings, rooms, and vehicles, generating point clouds with millions of points with accuracy ranges up to 1 mm.[14] These data can be used to create a virtual reality application for virtual scene

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4 Buck, U., Kneubuehl, B., Näther, S., Albertini, N., Schmidt, L., & Thali, M. (2011). 3D bloodstain pattern analysis: Ballistic reconstruction of the trajectories of blood drops and determination of the centres of origin of the bloodstains. *Forensic Science International*, 206, 22–28; Forensic Technology Center of Excellence. (2020, July). Meeting Report: Terrestrial LiDAR Scanning Working Group for Criminal Justice Applications, First Meeting. https://forensiccoe.org/terrestrial-lidar-scanning-working-group-for-criminal-justice-applications-first-meeting-report/

5 Urbanová, P., Jurda, M., Vojtisek, T., & Krajsa, J. (2017). Using drone-mounted cameras for on-site body documentation: 3D mapping and active survey. *Forensic Science International*, *281*, 52–62.

6 Ibid, 53.

7 Forensic Technology Center of Excellence. *Landscape study on 3D crime scene scanning devices (with 2018 update)*. National Institute of Justice. https://forensiccoe.org/private/5dd6ad2d0ffeb

8 Mullins, R. A. (2016). *Virtual views: Exploring the utility and impact of terrestrial laser scanners in forensics and law* [M.A. thesis]. University of Windsor.

9 Baier, W., Donnelly, M. J., Payne, M., & Williams, M. A. (2020). A holistic multi-scale approach to using 3D scanning technology in accident reconstruction. *Journal of Forensic Sciences*, *65*, 1774–1778; Bucheli, S. R., Pan, Z., Glennie, C. L., Lynne, A. M., Haarman, D. P., & Hill, J. M. (2014). Terrestrial laser scanning to model sunlight irradiance on cadavers under conditions of natural decomposition. *International Journal of Legal Medicine*, *128*, 725–732.

10 Baier, *supra* note 9, at 1776.

11 Buck, *supra* note 4.

12 Bucheli, *supra* note 9.

13 Sieberth, T. Dobay, A., Affolter, R., & Ebert, L. C. (2018). Applying virtual reality in forensics—A Virtual scene walkthrough. *Forensic Science, Medicine and Pathology*, *15*, 41–47.

14 Ibid, at 41.

walkthroughs.[15] Virtual walkthroughs are valuable because scenes cannot be held indefinitely and deteriorate with time. Furthermore, virtual walkthroughs can be conducted anywhere and anytime, without the danger and inconvenience that may accompany scene visits. Virtual walkthroughs depicting the witness's first-person view are particularly helpful as they show the scene from the witness's perspective,[16] though it should be noted that researchers report that distances in virtual reality are underestimated for larger spaces, and viewers need to be cautioned accordingly.[17]

C. Legal Requirements for Admissibility

Judges are required to act as gatekeepers and to ensure that technical evidence is admitted only upon a showing of scientific validity and reliability by its proponent.[18] Therefore, for TLS evidence to be ruled admissible, the court must be satisfied that the tests of scientific validity and reliability have been met. It follows that witnesses presenting this evidence must be adequately trained and fully qualified to address these critical issues. It is not sufficient to simply know how to use the instrument. The TLS device operator must be fully qualified to operate the instrument and must have a working knowledge of it, including how it works and what it is designed to do. This level of knowledge is required of any witness who presents computer-generated evidence in court.[19] Errors in measurement, calibration, forensic workflow, and insufficient technical knowledge by operators can result in the irreversible loss of evidence.[20] When working in an ISO 17020 environment, competency testing is required for all work conducted at a scene. Furthermore, all measuring devices must be calibrated within approved tolerances with a clearly defined limit of accuracy.[21]

TLS device operators who collect but do not analyze the data are required to testify and may be called as fact or technical witnesses, as opposed to expert witnesses, if they are not called upon for their opinion on the meaning of the data. If the operator is likely to be asked involved questions about the operation of the instrument, the accuracy of the data, whether all requisite data was captured, or similar, then it is preferable to have the operator qualified as an expert witness to allow those opinions to be given, although there must be a clear demarcation between the role of the operator and the analyst, assuming these functions are split. If the operator is also the analyst, this demarcation is not necessary.

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[15] Agosto, *supra* note 2, at 6281.
[16] Sieberth, *supra* note 13, at 46.
[17] Ibid.
[18] *Daubert v. Merrell Dow Pharmaceuticals Inc.*, 113 S. Ct. 2786 (US Supreme Court); *Federal Rules of Evidence*, Rule 702.
[19] *State of Connecticut v. Swinton*, 268 Conn. 781; 2004 Conn. LEXIS 190 (Connecticut Supreme Court 2004).
[20] Urbanová, *supra* note 5, at 59.
[21] Sheppard, *supra* note 3, at 30.

All data gathered from digital scanning requires interpretation by an expert.[22] Where data are gathered by an operator and then given to an analyst for detailed evaluation and further processing for presentation, the analyst must be qualified as an expert witness, specifically in evaluating, interpreting, and processing data gathered by TLS devices. Before this step can be taken, the analyst must have sufficient targeted education, training, skill, and experience to rise to the level expected of an expert witness. No specific minimum legal standards have been set for TLS device operators or TLS data analysts. Oversight agencies and agencies who use TLS devices must establish robust training programs to ensure that only qualified personnel engage in this highly technical scientific work.

Data generated by TLS devices must be authenticated to be admissible. Authentication requires that the party seeking to introduce technical data must establish that the data are in fact what they purport to be and that the data are accurate and reliable. This requirement is set out in *Federal Rules of Evidence* Rule 901, equivalent provisions in state codes of evidence, and by common law. Technical evidence is prone to exclusion because of lack of authentication, not because it is incapable of being authenticated but because the attorney leading the evidence has not adequately prepared with the technical or expert witness to meet this requirement.

Interestingly, there exists a lack of standards for how digital measurement data should be recorded, preserved, processed, and presented.[23] Proper standards and standard operating procedures are essential components of forensic science.[24] Agencies who use TLS devices should utilize uniform, scientifically valid procedures so that the evidence gathered will withstand robust technical and legal challenges in court.

TLS data errors can result from systematic error and human error. Systematic errors involve erroneous coordinate values whereas human error concerns the generation of inaccurate measurements.[25] Furthermore, digital evidence is fragile and may fall prey to intentional or inadvertent alteration during acquisition or subsequent processing.[26] Accuracy and reliability are the cornerstones of electronic scene measurement and recreation; therefore, the collection of digital scene data must be accomplished in a forensically sound manner. To present a strong case for admissibility, the following procedures should be followed:[27]

- Details regarding the capture, storage, and transmission of digital scene data must be adequately documented, preserved, and available for review by interested parties.
- Digital scene data should not be altered between the time of collection and itsuse in court, and should any alteration occur, it must be fully documented.
- Access to original data must be restricted to qualified individuals who understand the need to preserve the integrity of the data.

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[22] Baier, *supra* note 9, at 1776.

[23] Church, E. (2019). *The forensic utility of photogrammetry in surface scene documentation*. [M.Sc. thesis]. Boston University School of Medicine.

[24] Chisum, W. J., & Turvey, B. E. (2007). *Crime reconstruction*. Elsevier Academic Press.

[25] Mullins, *supra* note 8, at 14.

[26] Bulbul, H. I., Yavuzcan, H. G., & Ozel, M. (2013). Digital forensics: An analytical crime scene procedure model. *Forensic Science International*, *233*, 244–256.

[27] Ibid, 245.

- Integrity verification is an essential precondition.
- Proper chain of custody documentation requires an accounting of the chronological history of the evidence, with all steps from creation to presentation noted. Therefore, a comprehensive audit trail recording the digital lifespan of the measurement data should be maintained and available for review.

A further consideration regarding the evaluation, interpretation, and presentation of TLS data is that of peer review. The US Supreme Court stated in *Daubert v. Merrell Dow Pharmaceuticals Inc*.[28] that peer review is one of the factors trial judges should consider when assessing admissibility. Peer review by a qualified, competent reviewer is not a legal requirement but is a valuable component of proper forensic practice. In cases where an analyst has formed opinions about a scene based upon the evaluation and interpretation of TLS data, it is recommended that a meaningful, thorough, and documented peer review be conducted.

D. Judicial Reception of TLS Data

TLS data can be used as real evidence or demonstrative evidence. Real evidence has evidential value and can be used to determine the facts in a case. Demonstrative evidence is designed to illustrate *viva voce* and other forms of evidence by way of a visual recreation.[29] It may take the form of photographs, video, diagrams, charts, 3D models, 3D laser scans, and other computer-generated animations. As a matter of law, it has no independent evidential or probative value. To make the most use of TLS data, counsel tendering such evidence should seek to have it admitted as real evidence, accompanied by expert evidence authenticating it and interpreting the data for the court.

There is limited jurisprudence on the use of TLS data in criminal and civil cases in the United States. Reported case law refers to the use of TLS data and intimates that it was used as part of the judicial analysis. Though most of the reported cases are civil cases, the rulings are equally applicable in the criminal realm. A particularly helpful case is *Cyr et al. v. Weber*,[30] a negligence action arising out of a motor vehicle collision. An expert in highway safety, accident reconstruction, and traffic engineering presented TLS evidence that he had obtained from the scene and from which he produced 3D images and animations for use in court. The expert testified that he created an accurate 3D environment using the TLS scans, the dimensional specifications of the vehicles, and the relative placement of the vehicles. The court found the TLS methodology, including the scanner, the 3D software, and the analysis to be generally accepted within the scientific community. The court further found that the scanner used had been tested and subjected to peer review. The evidence was found to be scientifically valid and reliable. Utilizing a *Swinton* analysis, the court found that the computer-generated evidence presented was

[28] *Supra* note 18.

[29] Sainato, V.A. (2009). Evidentiary Presentations and Forensic Technologies in the Courtroom, The Director's Cut. *Journal of the Institute of Justice and International Studies*, 9, 38-52; Mnookin, J. (1998). The Image of Truth: Photographic Evidence and the Power of Analogy, *Yale Journal of Law and the Humanities*, 10(1), 1-74, at 67-70.

[30] *Cyr et al. v. Weber*, 2016 WL 3202426 (Superior Court of Connecticut).

suitable for the purpose tendered and that the technology was reliable. At the request of the party presenting the TLS evidence, the evidence was offered for illustrative purposes only.

In *United States v. Slager*,[31] during the sentencing hearing of a former police officer being sentenced for the fatal shooting of a man, the defendant presented expert evidence from a forensic analyst who created a 3D digital model of the crime scene using video evidence and TLS data obtained by investigators. The 3D model allowed the court to see the defendant and the man from different angles and to examine varying theories about what happened. The court admitted the expert evidence generally but did not accept the expert's interpretation of the data. The data and the technology used were not challenged, only the expert's interpretation of it, which the court found not to be credible given other evidence in the case.

TLS devices and the use of TLS data to create a 3D environment to examine a scene was further endorsed in *Gecker as Trustee for Collins v. Menard, Inc.*,[32] a case involving a shopping cart–related injury. The plaintiff sought to have the defendant's experts prevented from testifying in the case. One of the defendant's experts utilized 3D scans of the store entrance and created 3D digital models of the shopping cart train, which allowed him to recreate how the shopping cart train struck the plaintiff. The plaintiff challenged the reliability of photogrammetry and the TLS point clouds used to create the 3D model. In rejecting the plaintiff's argument, the court found that the photogrammetry and TLS data used by the expert were not "new techniques." The court found the expert evidence to be standard, peer-reviewed, and tested techniques and that the data and methodology used constituted reliable science. Accordingly, the expert was permitted to testify at trial.

In *Koenig and Everett v. Johnson*,[33] a motor vehicle-pedestrian collision case, the defendant sought to present evidence from an expert in engineering and accident reconstruction. The expert utilized TLS data obtained from the scene, together withother evidence, to produce a 3D reconstruction of the scene and event. The court found the expert evidence sufficiently reliable to warrant admission, noting that the plaintiffs could challenge the expert's opinions at trial.

The author has not located any cases wherein the court criticized TLS data or the use of it in the case, nor have the authors found any cases where there were serious challenges to the evidence. Unless the parties disagree on the admissibility or use of the data and present opposing expert evidence, there is often little need for the judge to comment on it, hence the paucity of case law. For example, in *Stapleton v. Union Pacific Railroad Company*,[34] 3D laser scanning was utilized to examine a low-speed locomotive collision, but little detail was given about how it was used in the application to exclude expert testimony. The TLS evidence was not excluded in this pre-trial

[31] *United States v. Slager*, 2018 WL 445497 (US District Court, South Carolina).
[32] *Gecker as Trustee for Collins v. Menard, Inc.*, 2019 WL 3778071 (US District Court, N.D. Illinois, Eastern Division).
[33] *Koenig and Everett v. Johnson*, 2020 WL 2308305 (US District Court, South Carolina).
[34] *Stapleton v. Union Pacific Railroad Company*, 2020 WL 2796707 (US District Court, N.D. Illinois, Eastern Division).

motion. Similarly, in *State v. Odum*,[35] the defendant presented testimony from two members of a private forensics company who utilized a 3D laser scanning instrument to reconstruct the crime scene. They testified that as a result of their work, they determined that the police had erred in their measurements regarding bullet trajectory and impact location. This was confirmed by an expert in ballistics, crime scene reconstruction, and bullet trajectory. It does not appear that the TLS evidence was challenged. Furthermore, no details were given in the appellate judgment regarding the work of police investigators nor did the measurement variance have any impact on the convictions registered at trial. However, the case has some valuebecause it is an example of TLS evidence being admitted at trial and referred to by an appellate court. Finally, in *Dalton v. USA*,[36] 3D laser scanning was used to reconstruct the events leading up to a fatal motor vehicle collision. The court found the evidence of value in understanding the actions of each of the vehicles involved. None of the above cited cases are determinative although *Cyr et al. v. Weber* is a reasonably strong endorsement of TLS evidence and 3D scene reconstruction being used as demonstrative evidence. It will take time to develop a robust body of case law on the use of TLS data in litigation.

E. Educating Attorneys and Judges on the Use of TLS Data in Court

As with most technical evidence that is new or relatively new to the courtroom, it is essential that attorneys who present TLS evidence have a sufficient understanding of the basics of TLS scanning and the creation of 3D scene depictions so that they can lead and defend the evidence with confidence. They must also possess the requisite legal knowledge to address the need for authentication and the proper classification and use of the evidence in the courtroom. Attorneys leading evidence they do not understand risk adverse judicial rulings that can have a ripple affect across the jurisprudence. Accordingly, a seminar designed to achieve these objectives is worthy of consideration.

Providing training to the judiciary would also be valuable, but this is entirely dependent upon whether the judiciary wishes to receive training. Judicial independence issues sometime limit the ability of outside parties to provide training that might be viewed as partisan, even though it is not. Training the judiciary, although helpful, is not an essential component of using TLS data in court because judges are required to learn about the case, case data, and the technology used through evidence called by the parties. That is the role of expert witnesses, with the assistance of attorneys who lead and argue the evidence. Judges are not permitted to take judicial notice of technology that is outside the realm of common knowledge, and TLS devices and data would not be classified as common knowledge.

[35] *State v. Odum*, 2017 WL 5565629 (Court of Criminal Appeals of Tennessee).

[36] *Dalton v. USA*, 2014 WL 7423760 (US District Court, E.D. New York).

2 Conclusion

The use of TLS devices to obtain detailed and accurate measurements of scenes, areas of interest, and objects is an important adjunct in the search for the truth. The ability to view locations of interest in a 3D environment can be very helpful to counsel and the court in visualizing an event and different theories as to how it occurred. Central to the use of TLS devices and TLS data are qualified and properly trained device operators and data analysts. TLS device operators and data analysts must have a thorough understanding of the technology being used, an understanding of the acceptable parameters for the use of such technology in court, and the ability to effectively communicate their evidence in court, especially when being challenged. TLS device operators and data analysts should consider themselves teachers whose role it is to educate attorneys, judges, and jurors.

From the limited reported case law in the United States, some trends can be discerned. Courts are expressing epistemic value in TLS evidence. For the evidence to be admitted, there must be a robust showing of scientific validity, including data accuracy and presentation reliability. The court will assess the weight to be given to the evidence, similar to the way it will assess all scientific evidence. Whether TLS evidence is accepted as real evidence or demonstrative evidence is dependent upon the approach taken by counsel and the expert evidence presented.

Appendix G: References

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Appendix H: Additional Resources

ASTM E620-11 Standard Practice for Reporting Opinions of Scientific or Technical Experts
ASTM E678-07 Standard Practice for Evaluation of Scientific or Technical Data
ASTM E1020-13 Standard Practice for Reporting Incidents that May Involve Criminal or Civil Litigation
ASTM E1459 Guide for Physical Evidence Labeling and Related Documentation
ASTM E1188-11 Standard Practice for Collection and Preservation of Information and Physical Items by a Technical Investigator

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