Chapter 7 – LiDAR Surveys

Policy Statement
Any survey which incorporates LiDAR data shall conform to the specifications as defined in this document.

General Statement
The term "LiDAR" is short for Light Detection and Ranging and is also commonly referred to as "Laser Scanning". A LiDAR survey can be performed from many platforms, including fixed-wing aircraft, Unmanned Aerial Systems (UAS, "drones"), and ground based systems (stationary or mobile). The purpose of this document is to define standards for the use of ground based LiDAR only. See ***Chapter 10 – Small Unmanned Aerial Vehicle (sUAV) Surveys*** for alternate methods of LiDAR data collection.

Applications for LiDAR
LiDAR is an efficient tool for the following types of surveys:

- Engineering topographic surveys including roadways, channels, and structures
- As-built surveys
- Determination of vertical clearances (bridges, overhead power lines, etc.)
- Deformation monitoring
- Volumetric Surveys
- Architectural or archaeological surveys

Benefits of LiDAR
The benefits of a LiDAR survey as compared with conventional methods of data collection are as follows:

- Unsafe conditions inherent to high traffic zones or other hazardous environments may be mitigated
- Massive amounts of data can be collected in a very short period of time
- The same data set may be used for multiple projects with multiple delivery formats
- Go-backs are virtually eliminated

Challenges Inherent to LiDAR
LiDAR is not the perfect tool for all applications. Following are some of the challenges inherent to a LiDAR survey:

- Office processing time is increased substantially as compared to conventionally collected data sets
- Control network must be of a higher density than that of conventional data collection methods
- Equipment currently available barely meets required accuracy standards; extra care must be taken to create ideal conditions for data capture, e.g.: densification of the

control network, shortening sighting distances, maximizing incidence angles, increasing overlap, etc.

- Features obscured by dirt or foliage are essentially invisible to the scan and must be collected conventionally
- Laser equipment presents a potential for eye injury; operators of laser equipment must follow OSHA Regulation 1926.54 entitled "Nonionizing Radiation"

Preparation

Before planning the survey, a meeting between the Party Chief and the Requestor shall be conducted on the job site. During this meeting, the Requestor will explain specific project requirements. It is the responsibility of the Party Chief to listen attentively and take notes, and to bring up any questions or concerns. Any changes to the scope of the project agreed upon during this meeting must be documented by the Requestor in the form of an amended "***Request for Survey.***"

Accuracy Requirements

Topographic data points, regardless of their source, should be located within the following tolerances, relative to project control ("local accuracy"):

- Data points representing hardscape features (concrete, asphalt, underground vaults) should be located within +/- 0.03 feet horizontally and +/- 0.02 feet vertically
- Data points representing utility appurtenances (pull boxes, manholes, fire hydrants) should be located within +/- 0.15 feet horizontally and +/- 0.02 feet vertically
- Data points representing original ground features (dirt breaklines, spot elevations) should be located within +/- 0.15 feet horizontally and +/- 0.1 feet vertically
- Data points representing landscaping features (trees, shrubs) should be located within +/- 0.5 feet horizontally and +/- 0.1 feet vertically

Based upon the accuracy requirements defined above and the ultimate purpose of the survey, a determination must be made as to the density and distance limits of the scan. A ***"Fine Scan"*** will result in data point spacing of ≤ 25mm at 50 meters. A ***"Coarse Scan"*** will result in data point spacing of ≤ 50mm at 50 meters. When capturing hardscape features, a Fine Scan is required and scan distances should be limited to 150 feet. When capturing utility appurtenances, original ground features, landscaping features, or for volumetric surveys, a Coarse Scan may be used and scan distances should be limited to 300 feet.

Stationary Scans

A stationary scan is one in which the scanning instrument is mounted on a fixed platform, typically a tripod. Field procedures are outlined below:

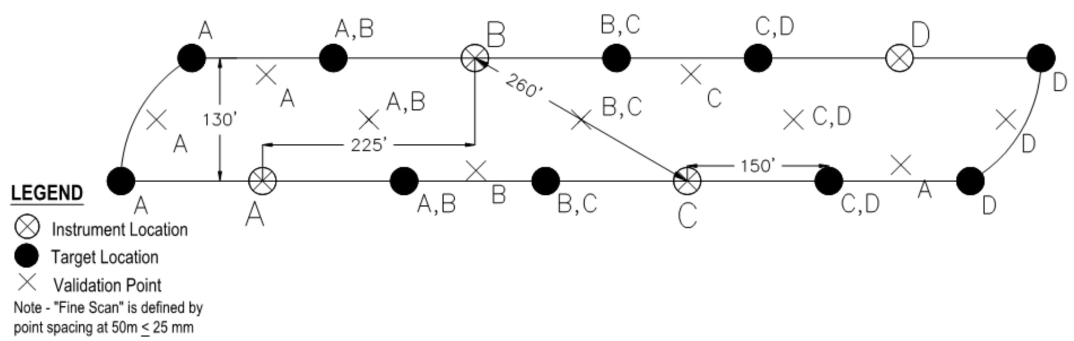
Instrument Positioning and Target/Validation Point Layout:

Instrument positioning and target/validation point layout will vary depending on the type of equipment selected and the desired density of the scan. Details are provided below:

- The Senior Land Surveyor shall approve the control scheme and target layout prior to execution of the scan

- The scanning instrument shall be positioned so as to achieve a 15% overlap with adjacent scans
- The sections below entitled ***"Establishing Horizontal Control"*** and ***"Establishing Vertical Control"*** provide detailed requirements for the establishment of positions on the control, target, and validation points upon which the LiDAR survey is to be based
- Control and target points must be integrated into the project control network; validation points may be established as "sideshots" to the control network
- Refer to ***Figure 1a*** and ***Figure 1b*** below for typical distribution of instrument, target, and validation points
- If the scanning instrument cannot be set up over a known control point and oriented towards a known backsight point, the instrument position shall be determined by resection from a minimum of four target points
- If the scanning instrument can be set up over a known control point and oriented towards a known backsight point, the additional target points shown in Figure 1a and Figure 1b may be eliminated, and a third known control point shall be staked-out and stored before execution of the scan
- Depending upon the type of equipment used, target points shall be occupied by either a conventional prism assembly or a spherical/planar type target designed specifically for LiDAR scans
- A minimum of three validation points shall be included in each scan
- Validation points may consist of painted targets or clearly discernable existing features, such as the intersection of traffic stripes, an angle point of a concrete feature, etc.

Figure 1a - Target Layout for Fine Scan



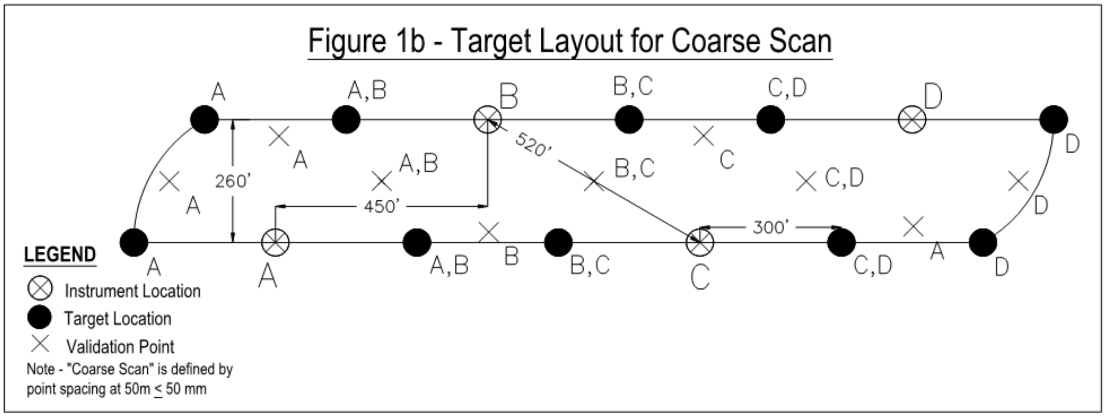


Figure 1b - Target Layout for Coarse Scan

Conducting the Scan:
The following notes relate to the workflow of stationary scans:

- Calibration of the scanning instrument shall be performed daily throughout the duration of the project
- When capturing non-vertical features, the scanning instrument should be set up as high as is practical, so as to maximize the angle of incidence with reflective surfaces
- Instrument set-up information shall be logged on the relevant setup sheet (***"LiDAR Set-Up Sheet – Known Point"*** or ***"LiDAR Set-Up Sheet – Random Position"***), including a sketch of the control targets and validation points to be scanned
- Instrument and target heights shall be measured and recorded in both metric and imperial units, with a unit conversion calculation performed before collection of data
- If possible, a maximum scanning distance should be assigned in order to avoid capturing data beyond desired limits
- Control targets are scanned at maximum density and the scan is registered to project control, either by resection or by occupation of known control
- At this point the remainder of the scan is conducted at the desired density
- The point cloud shall be reviewed before the scanner is moved, and any features which may not have been accurately captured shall be described on the set-up sheet; these features must later be collected by an alternate method

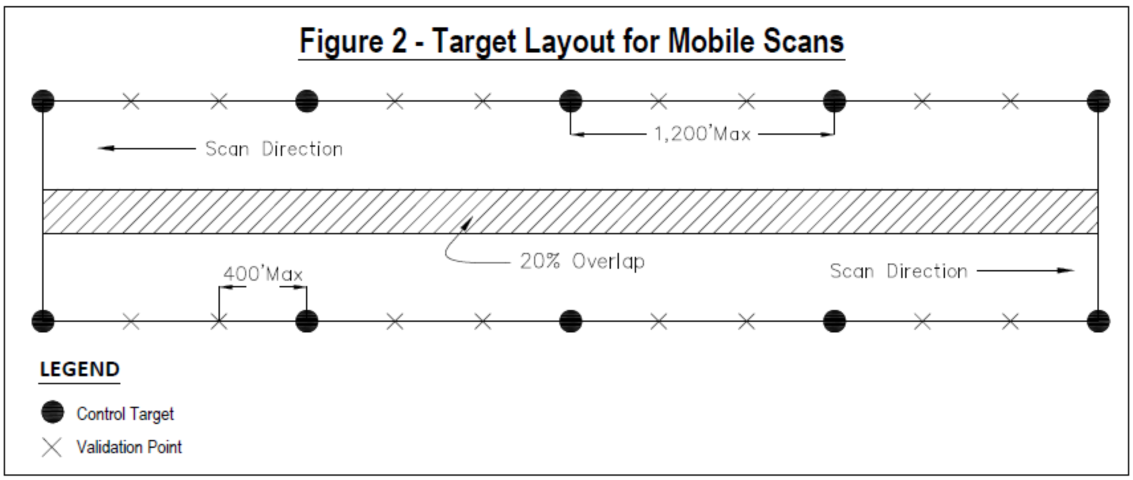
Mobile Scans

A mobile scan is one in which one or more scanning instruments are mounted on a mobile platform, such as a motor vehicle. The scanning instrument collects data continuously as the position of the vehicle is determined by a combination of control targets, GPS receivers, and an Inertial Measurement Unit (IMU). Field procedures are outlined below:

Control Target/Validation Point Layout:
Control target and validation point layout will vary depending on existing field conditions. Details are provided below:

- The Senior Land Surveyor shall approve the control scheme and control target/validation point layout prior to execution of the scan

- The sections below entitled ***"Establishing Horizontal Control"*** and ***"Establishing Vertical Control"*** provide detailed requirements for the establishment of positions on the control targets and validation points upon which the LiDAR survey is to be based
- Control targets must be integrated into the project control network; validation points may be established as "sideshots" to the control network
- Control targets shall consist of painted targets; validation points may consist of painted targets or clearly discernable existing features, such as the intersection of traffic stripes, an angle point of a concrete feature, etc.
- Refer to ***Figure 2*** below for typical distribution of control targets and validation points
- Spacing of control targets and validation points should be decreased in areas where GPS signal may be lost or degraded due to tree canopy, steep embankments, overpasses, etc.



GPS Requirements:
Following are requirements for collection and processing of GPS data:

- GPS data is collected with a conventional base/rover configuration, with base receivers located within the project area and rover receiver(s) mounted on the vehicle
- GPS base stations shall be located at a maximum of 6 mile intervals in order to ensure that no baselines over 3 miles in length are used in the solution; projects 6 miles or less in length should have a base station at each end of the project
- Due to the 3 mile maximum baseline length requirement, OCRTN CGPS stations are typically not to be used as GPS base stations
- Selection of GPS base station locations should be based on actual field conditions: avoid nearby trees, overhead powerlines, and other obstructions or sources of multipath
- GPS receivers shall be dual frequency, and data shall be collected at 0.5 second or 1 second intervals
- Satellite visibility and PDOP forecasts shall be reviewed prior to scheduling the scan
- A minimum of 5 satellites common to the base and rover receivers should be observed
- PDOP should not exceed 5.0
- Maximum duration of GPS signal loss or degradation is 60 seconds or 0.6 miles travelled, during which time the IMU must be operational within the following parameters:

maximum uncorrected horizontal drift error of 0.33 feet; maximum uncorrected vertical drift error of 0.23 feet; maximum uncorrected roll and pitch error of 0.020 degrees RMS; maximum uncorrected true heading error of 0.020 degrees RMS (this data was copied from Chapter 15 of the Caltrans Surveys Manual)
- Kinematic GPS data shall be post processed in both forward and reverse directions

Inertial Measurement Unit (IMU) Requirements:
Following are requirements for the IMU associated with the scanning project (this data was copied from Chapter 15 of the Caltrans Surveys Manual):
- Minimum positioning data sampling rate of 100 Hz
- Maximum gyro rate bias of 1 degree per hour
- Maximum gyro rate scale factor of 150 ppm
- Maximum Angular Random Walk of 0.125 degree per √hour
- Minimum uncorrected positioning capability due to loss or degradation of GPS signal of 60 seconds or 0.6 miles

Conducting the Scan:
The following notes relate to the workflow of mobile scans:

- Calibration of the scanning instrument and IMU shall be performed daily throughout the duration of the project
- GPS receivers should be set up and collecting data at all base station locations throughout the scanning operation
- GPS signal shall be monitored continuously during the scanning operation, and the duration of any loss or degraded signal shall be documented for verification of compliance with this document
- The IMU system must be monitored continuously during the scanning operation
- Vehicle speed is to be adjusted so as to ensure desired data point density is achieved
- Multiple scans shall be collected - in both directions or with two passes in the same direction - with a planned side overlap (sidelap) of 20%

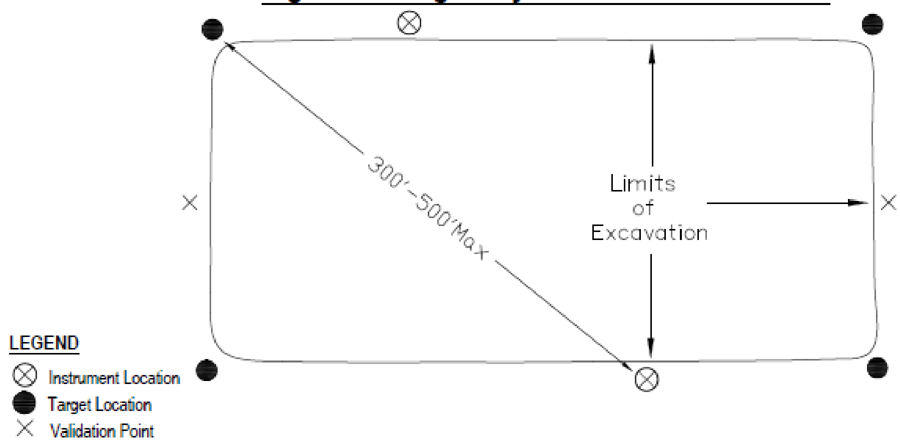
Volumetric Scans
A volumetric scan is one which facilitates calculation of earthwork volumes, e.g.: stockpiles, keyway removal areas, etc. Although volumetric surveys are often conducted by UAS (see ***Chapter 10 – Small Unmanned Aircraft System (sUAS) Surveys***), the purpose of this section is to define standards for the use of ground based scans only. Field procedures are outlined below:

Instrument Positioning and Target/Validation Point Layout:
The same basic standards defined above for stationary scans apply to volumetric scans. Variations from these standards and further explanation are defined below:

- Volumetric scans may be captured at a low point density (course scans)
- Scan distances should be limited to 300 feet but may be extended to 500 feet at the discretion of the party chief, with approval from the Senior Land Surveyor
- Regardless of the size of the stockpile or excavation, the scanning instrument shall be set up in at least two locations in order to capture all faces of the earthwork and to provide the required overlap between scans

- A minimum of two validation points shall be included in each scan
- Elevations of instrument, target, and validation points may be derived by trigonometric principles.
- Refer to ***Figure 3*** below for typical distribution of target and validation points

Figure 3 - Target Layout for Volumetric Scan



Monumentation

Monuments set as control points during the course of a LiDAR survey shall meet the following criteria:

- Monuments which fall on concrete curbs or in the surface of concrete paving shall consist of a tag secured in a lead plug or set in epoxy.
- Monuments which fall on asphalt dikes or in the surface of asphalt paving shall consist of a spike or "MAG" nail with a washer.
- Monuments which fall in non-paved areas shall consist of an iron pipe with a tag or disk, or a rebar with an aluminum cap. Rebar must be set a minimum of 3 inches below the ground surface.
- All tags/washers/disks/caps referenced above shall be stamped with the agency name or the license number of the surveyor in responsible charge, and shall also be stamped "CP" or "CONTROL POINT".
- Tags set in iron pipes shall be of a diameter less than that of the inside diameter of the pipe. Disks affixed to iron pipes shall be of a diameter equal to that of the outside diameter of the pipe.
- Under no circumstances are plastic plugs to be used with iron pipe or rebar.

Quality Assurance/Quality Control Report

Prior to commencement of field activities, a Quality Assurance/Quality Control (QA/QC) plan, developed by the Senior Land Surveyor, must be in place. Once the field survey and data processing have been completed, the QA/QC Report is prepared, which shall include the following:

- Statistical summary of the control network (Star*Net adjustment)

- Registration reports which reflect registration statistics, control target and validation point comparison statistics, scan seam comparison of overlap areas, etc.
- Log of PDOP values (mobile scan)
- Log of IMU statistics (mobile scan)
- Separation between the results of forward and reverse processing of kinematic GPS data (mobile scan)

Deliverables – Consultant to OC Survey

A consultant performing a LiDAR survey for OC Survey shall provide the following list of deliverables:

- QA/QC Report
- Project control schematic, including the associated Star*Net adjustment report
- Differential leveling notes
- LiDAR set-up sheets, field sketches, etc.
- Registered point cloud data in XYZI (or XYZIRGB) format
- Image overlay data
- Civil 3D files

The format of each of these items shall be agreed upon by all parties prior to commencement of scanning operations.

Deliverables – OC Survey to OC Design

A list of deliverables and formats shall be defined on the "***Request for Survey"*** form received from the Requestor and should be verified during the meeting discussed above in the section entitled **"Preparation"**. Typical deliverables are listed below:

- Registered point cloud data in XYZI (or XYZIRGB) format
- Image overlay data
- Civil 3D files

Establishing Horizontal Control

Computed positions of control and target points shall conform to a minimum combined (relative) positional accuracy* of **1:10,000** (at a 95% confidence level, or 2 sigma), or a combined distance error of **≤ 0.033 feet** for connection distances shorter than **330 feet**. Positions of base stations used in mobile LiDAR applications shall conform to a minimum combined (relative) positional accuracy of **1:20,000**. In addition, each base station shall have a computed network accuracy (error ellipse semi-major axis) **≤ 0.033 feet**. This relative positional accuracy standard shall be met whether the survey is conducted by GPS (static or RTK), conventional traverse (total station), or any combination thereof.

*Relative positional accuracy is a measure of the accuracy of point positions in relation to each other, and is not to be confused with the measure of traverse closure expressed as a ratio.

The following are guidelines for GPS and conventional traverse methodology:

Static GPS:
Control for a LiDAR survey project may be established by static (or fast-static) GPS procedures. While a network adjustment may be performed using only GPS vectors (stand-alone), combining conventional traverse data with GPS vectors will sometimes result in a network with higher relative positional accuracy.

Design of the network and occupation scheme will be determined by the Party Chief in conformance with ***Chapter 1 – Static GPS*** When selecting points to be included in the static network, consideration must be given as to strength of figure and adequate spacing. The minimum allowable spacing for points in stand-alone networks shall be dictated by the following criteria:

- Trimble R10 receivers, rated for static surveys at 3mm + 0.5 ppm at 68% confidence level (1 sigma): a minimum spacing of **500 feet** when tied to CGPS stations at an average distance of 32,000 feet, and a minimum spacing of **300 feet** when tied to primary project control or legacy control at an average distance of 4,000 feet
- Minimum spacing for GPS receivers with static survey ratings different from those listed above can be computed using the formula shown in "***Appendix A, Section 1***"

RTK GPS:
RTK is generally not to be used as a stand-alone measurement tool when performing a control survey. RTK is best used to bolster the control network, not define it. In order to ensure realization of the **1:10,000** criteria, the network shall be adjusted using RTK measurements together with conventional traverse data.

RTK occupation points are selected in such a way as to maximize strength of figure, while leaving the bulk of the data to be captured by conventional traverse. The occupation scheme will be determined by the Party Chief in conformance with ***Chapter 2 – RTK GPS.***

The minimum recommended spacing for points in RTK surveys shall be dictated by the following criteria:

- Trimble R10 receivers, rated for RTK surveys at 8mm + 1 ppm at 68% confidence level (1 sigma): a minimum spacing of **1200 feet** when tied to OCRTN stations at an average distance of 32,000 feet; a minimum spacing of **700 feet** when tied to local project control in a base-rover configuration at an average distance of 4,000 feet
- Minimum spacing for GPS receivers with static survey ratings different from those listed above can be computed using the formula shown in "***Appendix A, Section 1***"

Conventional Traverse (Total Station):
Conventional traversing may be used either as a stand-alone method or in combination with GPS vectors when establishing control networks for topographic surveys.

Field measurements shall meet the following specifications:

- Horizontal Angles: Minimum of two direct (face 1) and two reverse (face 2) with a maximum residual of 5 seconds; exception granted for sights closer than 300 feet.
- Distances: Measured to backsight and foresight; minimum of two direct and two reverse with a maximum residual of 0.007 feet.

Establishing Vertical Control

For LiDAR surveys representing hardscape features (concrete, asphalt), elevations of control , target, and validation points shall be established using differential leveling procedures, meeting 3rd order (or better) accuracy requirements. Leveling shall be referenced to a minimum of two vertical control points (benchmarks) and be in conformance with ***Chapter 4 – Differential Leveling***. For LiDAR surveys representing original ground features, landscaping features, or for volumetric surveys, elevations of control points, target points, and validation points may be derived by trigonometric principles.

Adjustment of the Control Network

All LiDAR control data shall be adjusted by least squares adjustment software, in conformance with ***Chapter 12 – Network Processing***.

Statistical analysis of the network adjustment shall be performed to ensure that a minimum combined (relative) positional accuracy of **1:10,000** (1:20,000 for GPS base station points used for mobile scans) has been achieved for all connected monument pairs. Although this computation is automatically performed in most network adjustment software, the formula for this computation is shown in "***Appendix A, Section 2.***"

Connections of very short distances often will not meet this **1:10,000** standard. An alternative standard for distances of less than **330 feet** is shown in "***Appendix A, Section 3.***"

In the event one or more pairs of monuments fail to pass these relative positional accuracy criteria, the network adjustment shall be reviewed and a determination made by the Senior Land Surveyor (or Project Manager) as to whether or not additional observations will made in order to improve geometry, increase redundancy, or further isolate errors.

Important Note:
Once a network has been adjusted and coordinates are reported to another entity (e.g.: Mapping Unit), these coordinates shall be deemed final. Should supplemental control or boundary ties be needed, the primary coordinates shall be fixed in subsequent adjustments. Only in the event that erroneous data is discovered will previously reported coordinate values be changed.

Additional Resources:

Chapter 15 of the Caltrans Surveys Manual is a valuable resource which should be consulted before planning a LiDAR survey.

Appendix A – Formulas

1. Minimum spacing for new control points to be positioned using GPS can be computed using the following formula:

   $$D = 10{,}000 \times \sqrt{(2 \times \{ [(1.96)(a)]^2 + [(1.96)(b)]^2 + c^2 \})}$$

   where:

   - D = minimum spacing (in feet) between static or RTK occupation stations
   - a = manufacturer's millimeter rating at a 68% confidence level, (converted to feet)
   - b = manufacturer's ppm rating at a 68% confidence level, times the average distance (in feet) from legacy control stations, and divided by 1,000,000
   - c = estimated receiver positioning error (rod plumb or tribrach errors), commonly estimated to be 0.007 feet
   - 1.96 = the multiplier from a 68% confidence level (1 sigma) to a 95% confidence level (2 sigma)

2. All connected monument pairs shall pass the following mathematical test:

   $$D \div \sqrt{(x^2 + y^2)} \geq 10{,}000$$ (or ≥ 20,000 where required above)

   where:

   - D = distance (in feet) between the pair of monuments being examined
   - x = error ellipse semi-major axis for monument #1 (at 95% confidence)
   - y = error ellipse semi-major axis for monument #2 (at 95% confidence)

3. Connections of very short distances often will not meet the **1:10,000** standard defined by the formula in Section 2 above. An alternative standard for distances of less than 330 feet follows:

   $$\sqrt{(x^2 + y^2)} \leq 0.033 \text{ feet}$$

   where:

   - x = error ellipse semi-major axis for monument #1 (at 95% confidence)
   - y = error ellipse semi-major axis for monument #2 (at 95% confidence)