A Ranging Protocol for 3D Imaging Instruments

1. SCOPE

The performance of three-dimensional (3D) imaging systems may be evaluated based on many different criteria. One such criterion is the range uncertainty of the system for which a protocol is proposed in this standard. This protocol provides a basis for performance comparisons among such systems based on the range uncertainty.

The protocol establishes requirements and methods for specifying and testing the performance of a class of spatial coordinate measurement systems called 3D imaging systems. A 3D imaging system is a measurement instrument that is used to rapidly measure (on the order of thousands of measurements per second or faster) the range and bearing to or the 3D coordinates of points on an object or within a scene. The information gathered by a 3D imaging system is provided in the form of "point clouds" with color and intensity data often associated with each point within the cloud. These systems include laser scanners, 3D optical scanners, 3D range cameras, LADARs (laser detection and ranging instruments), and 3D flash LADARs.

The sub-classes of these instruments for which the proposed standard applies include those that are ground-based and are capable of capturing information of a scene that is on the order of a large capital project such as process plants, construction sites, buildings, and bridges.

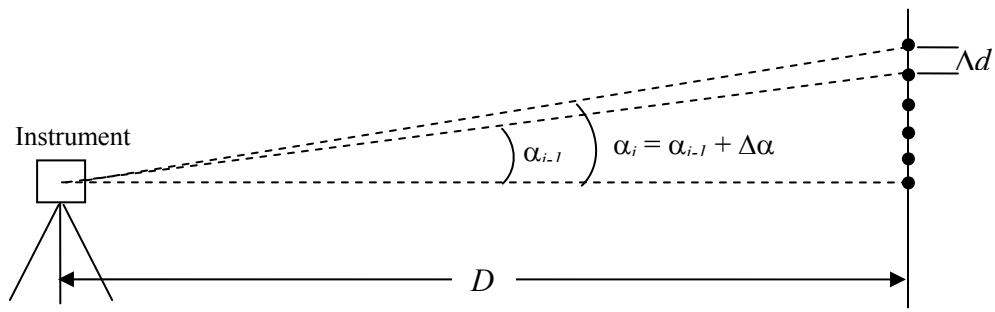
2. INTRODUCTION

In addition to providing for the performance evaluation of 3D imaging instruments based on range uncertainty, this protocol facilitates performance comparisons among different instruments by unifying terminology and the treatment of environmental factors. It defines a test method appropriate for providing a baseline to evaluate the range uncertainty of a majority of such instruments and is not intended to replace more complete tests that may be required for special applications.

The range uncertainty protocol proposed in this standard provides a method to evaluate an instrument up to a maximum range of 150 m. There are commercially available instruments with maximum ranges greater than 150 m (over a kilometer for some instruments). However, the ranges for most of the current applications are within 150 m for the sub-classes of instruments described in the scope. Protocols for longer ranges, while deemed important, were not considered at this time for reasons of feasibility and practicality, but may be considered at a later time based on expressed interest from the 3D imaging community.

3. DEFINITIONS

angular increment – for a scanning instrument, the angular increment is the angle between contiguous measurements, $\Delta\alpha$, where $\Delta\alpha = \alpha_i - \alpha_{i-1}$, in either the horizontal or vertical directions. The angular increment may also be known as the angle step size.



Distance between points = $\Delta d \cong D\,(1 + \tan^2 \alpha)\,\Delta\alpha$

The angular increment, specified by the instrument manufacturer, is typically a minimum value, and the achievable point density may be inferred from this value. A smaller angular increment results in a denser point cloud. The angular increment can be used to determine the distance, $\Delta\, d$, between contiguous pixels or points as shown above.

For a scan, the angular increment is often set equal in both the horizontal and vertical directions, and the value usually cannot be changed during a scan.

maximum permissible error (MPE) – extreme values of an error permitted by specification, regulations, etc. for a given measuring instrument [VIM 5.21m Ref. 1].

mixed pixels – mixed pixels or phantom points are result of the way most instruments process multiple returns. When a laser beam hits the edge of an object, the beam is split. Part of the beam is reflected by the object and the other part is reflected by another object beyond. Thus, the reflected signal contains multiple returns. Typically, the reported range measurements in such cases are the averages of the multiple returns which often fall between the two objects; hence, recording points that do not exist and are referred to as mixed pixels or phantom points.

The number of mixed pixels may be reduced by having a smaller beam spot size, smaller beam divergence, and the capability of the 3D imaging system to record multiple returns from a single transmitted pulse.

rated conditions – the manufacturer specified limits on the environmental and other conditions within which the manufacturer's performance specifications are guaranteed at the time of installation of the instrument.

reference distance – the calibrated value of the distance between two points in space at the time and conditions when a test is performed.

4. PERFORMANCE TESTS

In this Section and in Section 5, values such as target dimensions, valid scan region, and angular increments and procedures for determining valid measurements and determining target distances are based on best judgment. Experiments will have to be conducted to determine if these values and procedures are feasible and workable.

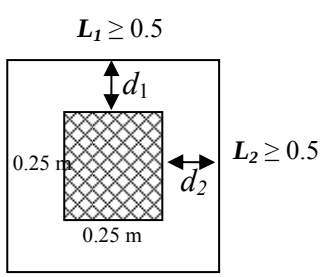
In Table 4.1, a total of 60 tests are suggested and the shaded cells indicate potential tests that may be eliminated to reduce the number of tests. Further reduction will likely be necessary for practicality.

4.1 Targets and sampling

4.1.1 Targets

Planar targets of known reflectivity shall be used for the ranging tests. These targets should be flat within 1 mm over the entire target area.

The target dimensions should be at least 0.5 m by 0.5 m, see Figure 1. To eliminate the mixed pixel effect caused by target's edges, measurements are considered valid only if they fall within a (0.25 m x 0.25 m) area centered on the target. This valid scan area is depicted as the hatched region in Figure 1. Measurements outside of this area will be ignored.



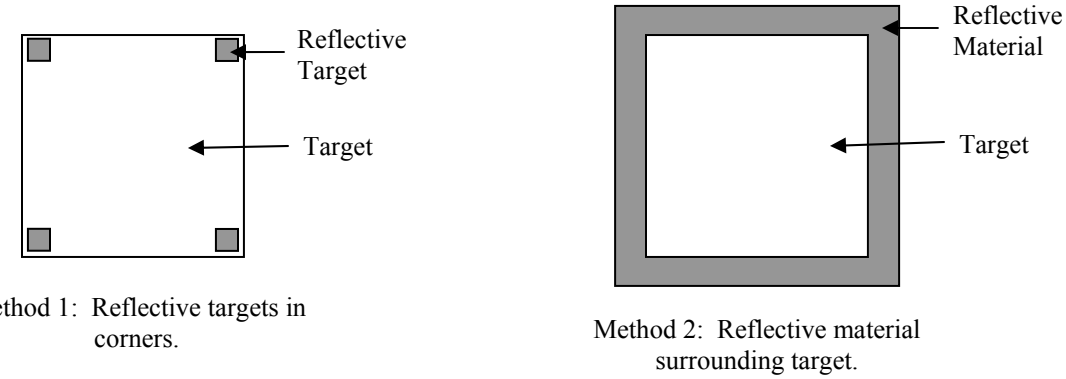
Target area: L_1 x L_2 ≥ 0.25 m^2

Valid scan area : $(0.25)^2 = 0.0625$ m^2

Distance to edge: d_1 , $d_2 \geq 0.125$ m

Figure 1. Target Dimensions and Valid Scan Area.

To identify the outliers in the data, two potential methods are suggested (Figure 2): Method 1 - Attach four reflective targets to the corners of planar target, Method 2 – surround the planar target with reflective material. Use of these auxiliary reflectors in outlier removal is discussed in Section 5.1.



Method 1: Reflective targets in corners.

Method 2: Reflective material surrounding target.

Figure 2. Two Methods to Determine Target Plane.

4.1.2 Sampling Procedures

For scanning instruments, the horizontal and vertical angular increments between points should both be set to the larger of the minimum value for either the horizontal or vertical directions. For example,

> Given Instrument A with specified minimum angular increments of $\delta_{horizontal}$ = 0.005º and $\delta_{vertical}$ = 0.008º, then the angular increment setting for the ranging tests should be 0.008º.

If the angular increments cannot be set equal, then the point spacing in the horizontal and vertical directions should be set as close to being equal as possible.

The resulting scan pattern should produce an equal number of measurements in the horizontal and vertical directions, with a minimum of 5 valid measurements in each direction resulting in a minimum of 5 x 5 = 25 total valid measurements (see Section 4.1.1).

The center of the scan area should approximately coincide with the center of the target (Section 4.2.2).

4.2 Ranging Tests

4.2.1 Reference distance

The reference distance between the scanner and the target may be obtained either by measuring the distance between these two positions or by placing the scanner and target over known benchmarks. If the reference distance is measured, the instrument used to obtain those measurements should have an uncertainty less than or equal to *** (to be decided by stds.

committee). If benchmarks are used, the uncertainty of the benchmark locations should be less than or equal to *** (to be decided by stds. committee).

The measurands in the protocol are the observed errors when measuring calibrated reference lengths. For any particular measurement, the observed error is $e = d_m - d_{ref}$. In testing measuring instruments, the reported measured value d_m is taken to be a fixed constant with no uncertainty. Then the standard uncertainty associated with the measured error is $u(e) = u(d_{ref})$. This uncertainty in realizing the reference length has to be considered in deciding whether the observed error meets the manufacturer's *MPE* specification with an acceptable level of confidence.

The latest ASME B89 Standards (Ref. 2) address this issue by use of the **measurement capability index** C_m defined by

$$C_m = \frac{MPE}{2\,u(e)} = \frac{MPE}{2\,u(d_{ref})} = \frac{MPE}{U},$$

where U is the $k = 2$ expanded uncertainty.

A commonly used decision rule, called 4:1 simple acceptance, accepts an observed error $e < MPE$ as conforming with the *MPE* specification, and non-conforming otherwise, provided that $C_m \geq 4$. This constrains the reference length uncertainty to satisfy $u(d_{ref}) \leq MPE/8$. Thus if a manufacturer claimed an *MPE* of 5 mm in measuring a 100 m length, the reference length would have to be calibrated to within a standard uncertainty of $u(d_{ref}) \leq 0.63\ \text{mm}$.

Using the measurement capability index is a convenient, readily understood way of setting requirements on the realization of reference lengths.

4.2.2 Instrument set-up

The instrument should be leveled in both the horizontal and vertical directions using the manufacturer's procedures if provided. The intersection point of a line from the instrument center that is orthogonal to the target plane should approximately coincide with the center of the target. This will result in the instrument being set-up as shown in Figure 3.

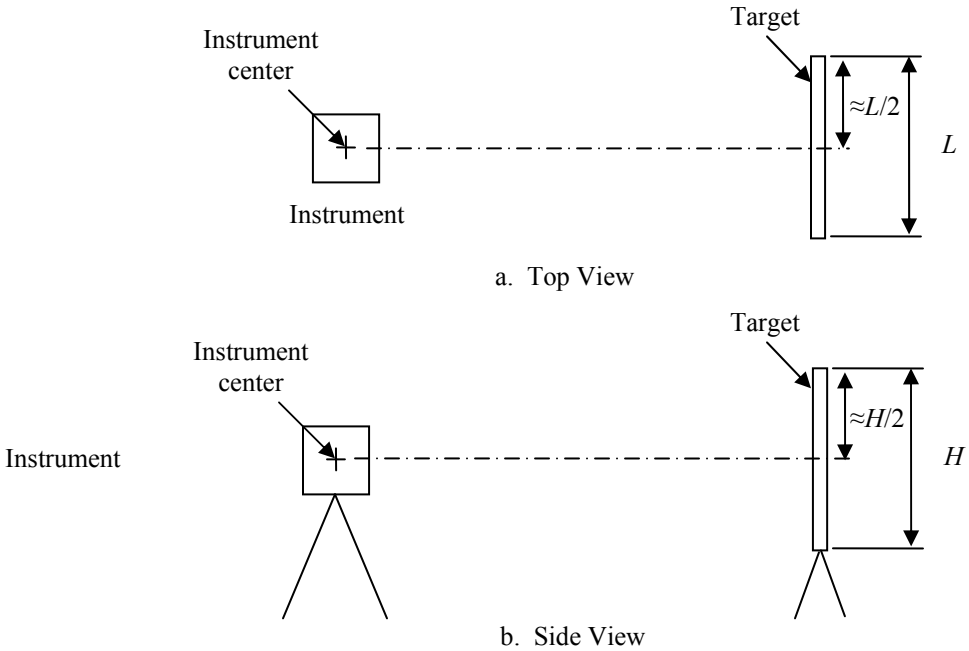


Figure 3. Instrument Set-up

If benchmarks are used, the manufacturer's procedures for centering of the instrument over the benchmark should be followed.

4.2.3 Test procedures

Measurements are made with the instrument and target positioned and oriented as described in the Table 4.1. Three measurements shall be performed for each position in Table 4.1. The tests are proposed to evaluate the effects of distance, target reflectivity, and angle of incidence on range error.

Table 4.1. Ranging Test Positions

Position Number	Reference Distances (***R***=Maximum Ranging Distance) (m)	Measured elevation angle, φ (°)	Measured azimuth angle, θ (***A*** = Full extent of horiz. FOV) (°)	Target Reflectivity	Target Rotation[§] (°)
1	Smaller of: 1. 10% $\boldsymbol{R} \leq L_1 \leq$ 20% ***R*** or 2. 30 m	0	$0 \leq \theta \leq \boldsymbol{A}/4$	> 90%	0
2	Smaller of: 1. 10% $\boldsymbol{R} \leq L_1 \leq$ 20% ***R*** or 2. 30 m	0	$\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}/2$	> 90%	0
3	Smaller of: 1. 10% $\boldsymbol{R} \leq L_1 \leq$ 20% ***R*** or	0	$\boldsymbol{A}/2 < \theta \leq 3\boldsymbol{A}/4$	> 90%	0

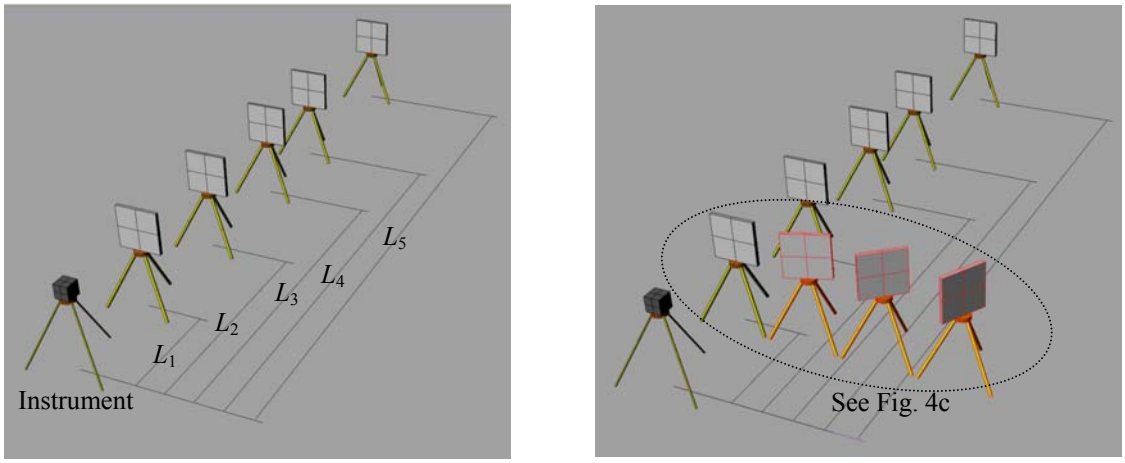
	2. 30 m				
4	Smaller of: 1. 10% $\boldsymbol{R} \leq L_1 \leq$ 20% $\boldsymbol{R}$ or 2. 30 m	0	$3\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}$	> 90%	0
5	Smaller of: 1. 20% $\boldsymbol{R} < L_2 \leq$ 40% $\boldsymbol{R}$ or 2. 60m	0	$0 \leq \theta \leq \boldsymbol{A}/4$	> 90%	0
6	Smaller of: 1. 20% $\boldsymbol{R} < L_2 \leq$ 40% $\boldsymbol{R}$ or 2. 60m	0	$\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}/2$	> 90%	0
7	Smaller of: 1. 20% $\boldsymbol{R} < L_2 \leq$ 40% $\boldsymbol{R}$ or 2. 60m	0	$\boldsymbol{A}/2 < \theta \leq 3\boldsymbol{A}/4$	> 90%	0
8	Smaller of: 1. 20% $\boldsymbol{R} < L_2 \leq$ 40% $\boldsymbol{R}$ or 2. 60m	0	$3\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}$	> 90%	0
9	Smaller of: 1. 40% $\boldsymbol{R} < L_3 \leq$ 60% $\boldsymbol{R}$ or 2. 90 m	0	$0 \leq \theta \leq \boldsymbol{A}/4$	> 90%	0
10	Smaller of: 1. 40% $\boldsymbol{R} < L_3 \leq$ 60% $\boldsymbol{R}$ or 2. 90 m	0	$\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}/2$	> 90%	0
11	Smaller of: 1. 40% $\boldsymbol{R} < L_3 \leq$ 60% $\boldsymbol{R}$ or 2. 90 m	0	$\boldsymbol{A}/2 < \theta \leq 3\boldsymbol{A}/4$	> 90%	0
12	Smaller of: 1. 40% $\boldsymbol{R} < L_3 \leq$ 60% $\boldsymbol{R}$ or 2. 90 m	0	$3\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}$	> 90%	0
13	Smaller of: 1. 60% $\boldsymbol{R} < L_4 \leq$ 80% $\boldsymbol{R}$ 2. 120 m	0	$0 \leq \theta \leq \boldsymbol{A}/4$	> 90%	0
14	Smaller of: 1. 60% $\boldsymbol{R} < L_4 \leq$ 80% $\boldsymbol{R}$ 2. 120 m	0	$\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}/2$	> 90%	0
15	Smaller of: 1. 60% $\boldsymbol{R} < L_4 \leq$ 80% $\boldsymbol{R}$ 2. 120 m	0	$\boldsymbol{A}/2 < \theta \leq 3\boldsymbol{A}/4$	> 90%	0
16	Smaller of: 1. 60% $\boldsymbol{R} < L_4 \leq$ 80% $\boldsymbol{R}$ 2. 120 m	0	$3\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}$	> 90%	0
17	Smaller of: 1. 80% $\boldsymbol{R} \leq L_5$ 100% $\boldsymbol{R}$ 2. 150 m	0	$0 \leq \theta \leq \boldsymbol{A}/4$	> 90%	0
18	Smaller of: 1. 80% $\boldsymbol{R} \leq L_5$ 100% $\boldsymbol{R}$ 2. 150 m	0	$\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}/2$	> 90%	0
19	Smaller of: 1. 80% $\boldsymbol{R} \leq L_5$ 100% $\boldsymbol{R}$ 2. 150 m	0	$\boldsymbol{A}/2 < \theta \leq 3\boldsymbol{A}/4$	> 90%	0
20	Smaller of: 1. 80% $\boldsymbol{R} \leq L_5$ 100% $\boldsymbol{R}$ 2. 150 m	0	$3\boldsymbol{A}/4 < \theta \leq \boldsymbol{A}$	> 90%	0
21	Smaller of: 1. 10% $\boldsymbol{R} \leq L_1 \leq$ 20% $\boldsymbol{R}$ or	0	Any	> 90%	20

	2. 30 m				
22	Smaller of: 1. 20% $\boldsymbol{R} < L_2 \leq$ 40% $\boldsymbol{R}$ or 2. 60m	0	Any	> 90%	20
23	Smaller of: 1. 40% $\boldsymbol{R} < L_3 \leq$ 60% $\boldsymbol{R}$ or 2. 90 m	0	Any	> 90%	20
24	Smaller of: 1. 60% $\boldsymbol{R} < L_4 \leq$ 80% $\boldsymbol{R}$ 2. 120 m	0	Any	> 90%	20
25	Smaller of: 1. 80% $\boldsymbol{R} \leq L_5$ 100% $\boldsymbol{R}$ 2. 150 m	0	Any	> 90%	20
26	Smaller of: 1. 10% $\boldsymbol{R} \leq L_1 \leq$ 20% $\boldsymbol{R}$ or 2. 30 m	0	Any	> 90%	40
27	Smaller of: 1. 20% $\boldsymbol{R} < L_2 \leq$ 40% $\boldsymbol{R}$ or 2. 60m	0	Any	> 90%	40
28	Smaller of: 1. 40% $\boldsymbol{R} < L_3 \leq$ 60% $\boldsymbol{R}$ or 2. 90 m	0	Any	> 90%	40
29	Smaller of: 1. 60% $\boldsymbol{R} < L_4 \leq$ 80% $\boldsymbol{R}$ 2. 120 m	0	Any	> 90%	40
30	Smaller of: 1. 80% $\boldsymbol{R} \leq L_5$ 100% $\boldsymbol{R}$ 2. 150 m	0	Any	> 90%	40
31	Smaller of: 1. 10% $\boldsymbol{R} \leq L_1 \leq$ 20% $\boldsymbol{R}$ or 2. 30 m	0	Any	> 90%	60
32	Smaller of: 1. 20% $\boldsymbol{R} < L_2 \leq$ 40% $\boldsymbol{R}$ or 2. 60m	0	Any	> 90%	60
33	Smaller of: 1. 40% $\boldsymbol{R} < L_3 \leq$ 60% $\boldsymbol{R}$ or 2. 90 m	0	Any	> 90%	60
34	Smaller of: 1. 60% $\boldsymbol{R} < L_4 \leq$ 80% $\boldsymbol{R}$ 2. 120 m	0	Any	> 90%	60
35	Smaller of: 1. 80% $\boldsymbol{R} \leq L_5$ 100% $\boldsymbol{R}$ 2. 150 m	0	Any	> 90%	60
Positions 36 – 60 are meant to be performed in an indoor facility.					
36	smaller of ≈0.2 $\boldsymbol{R}$ or 10 m	0	Any	> 90%	0
37	smaller of ≈0.4 $\boldsymbol{R}$ or 20 m	0	Any	> 90%	0
38	smaller of ≈0.6 $\boldsymbol{R}$ or 30 m	0	Any	> 90%	0
39	smaller of ≈0.8 $\boldsymbol{R}$ or 40 m	0	Any	> 90%	0
40	smaller of ≈1.0 $\boldsymbol{R}$ or 50 m	0	Any	> 90%	0

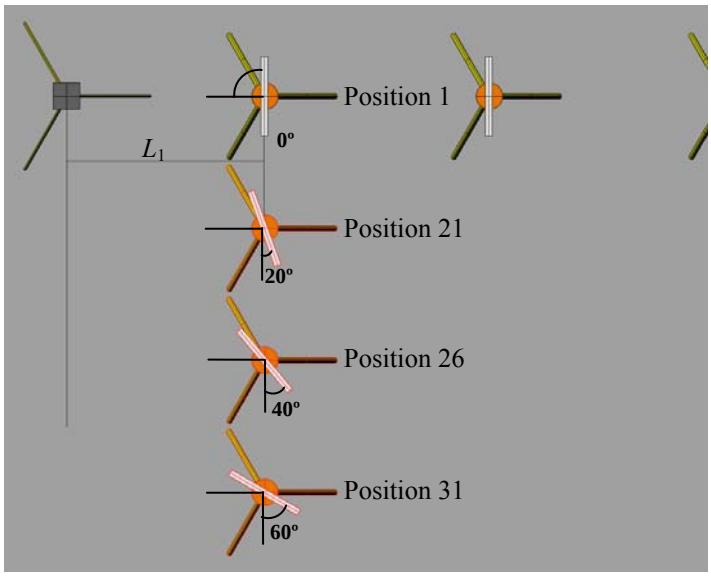
41	smaller of ≈0.2 ***R*** or 10 m	0	Any	60% to 80%	0
42	smaller of ≈0.4 ***R*** or 20 m	0	Any	60% to 80%	0
43	smaller of ≈0.6 ***R*** or 30 m	0	Any	60% to 80%	0
44	smaller of ≈0.8 ***R*** or 40 m	0	Any	60% to 80%	0
45	smaller of ≈1.0 ***R*** or 50 m	0	Any	60% to 80%	0
46	smaller of ≈0.2 ***R*** or 10 m	0	Any	40% to 60%	0
47	smaller of ≈0.4 ***R*** or 20 m	0	Any	40% to 60%	0
48	smaller of ≈0.6 ***R*** or 30 m	0	Any	40% to 60%	0
49	smaller of ≈0.8 ***R*** or 40 m	0	Any	40% to 60%	0
50	smaller of ≈1.0 ***R*** or 50 m	0	Any	40% to 60%	0
51	smaller of ≈0.2 ***R*** or 10 m	0	Any	20% to 40%	0
52	smaller of ≈0.4 ***R*** or 20 m	0	Any	20% to 40%	0
53	smaller of ≈0.6 ***R*** or 30 m	0	Any	20% to 40%	0
54	smaller of ≈0.8 ***R*** or 40 m	0	Any	20% to 40%	0
55	smaller of ≈1.0 ***R*** or 50 m	0	Any	20% to 40%	0
56	smaller of ≈0.2 ***R*** or 10 m	0	Any	0% to 20%	0
57	smaller of ≈0.4 ***R*** or 20 m	0	Any	0% to 20%	0
58	smaller of ≈0.6 ***R*** or 30 m	0	Any	0% to 20%	0
59	smaller of ≈0.8 ***R*** or 40 m	0	Any	0% to 20%	0
60	smaller of ≈1.0 ***R*** or 50 m	0	Any	0% to 20%	0

Notes:
[§] See Figure 4 for corresponding target orientation.

The shaded cells are potential tests that may be eliminated to reduce the number of tests required.



a. b.



c. Top view of Figure 4b showing target orientation

Figure 4. Ranging test set-up showing various target positions and orientations.

5. DATA PROCESSING

5.1 Removing Outliers

To remove the outliers using Method 1, the target plane is determined using the four reflective targets. The intensity data is used to extract the points that are associated with the four reflective targets. The reflective target centers are then set equal to the centroids of these four groups of points. The target plane is determined by fitting a plane (Plane 1) through these four points. A standard plane fitting algorithm (provided by NIST or other openly available software)

which minimizes the sum of squares of the orthogonal distances of four points to that plane should be used. The standard deviation, σ_{plane}, of the orthogonal distances is also calculated.

Any point, (x_i, y_i, z_i) whose distance d_i from the target plane is greater than a specified *tolerance* is ignored.

$$d_i = \frac{|\, ax_i + by_i + cz_i + d \,|}{\sqrt{a^2 + b^2 + c^2}} \quad \geq \quad tolerance \quad \Rightarrow \text{ignore point}$$

where the equation of the plane is given by $ax + by + cz = d$. Some suggestions for the tolerance: [3 x (manufacturer specified uncertainty)], MPE, or 10 cm.

Method 2 differs from Method 1 only in the manner in which the points that constitute the target plane are initially determined. In Method 2, points associated with the reflective material and the target may be separated using the intensity data. A boundary around the target points is generated and points that lie outside of this boundary are ignored. The points that lie inside the boundary are used to determine the target plane (Plane 1). The fitting of the target plane and determination of outliers are as described in Method 1.

The points that are not ignored constitute the subset of points called Subset 1 (Figure 5).

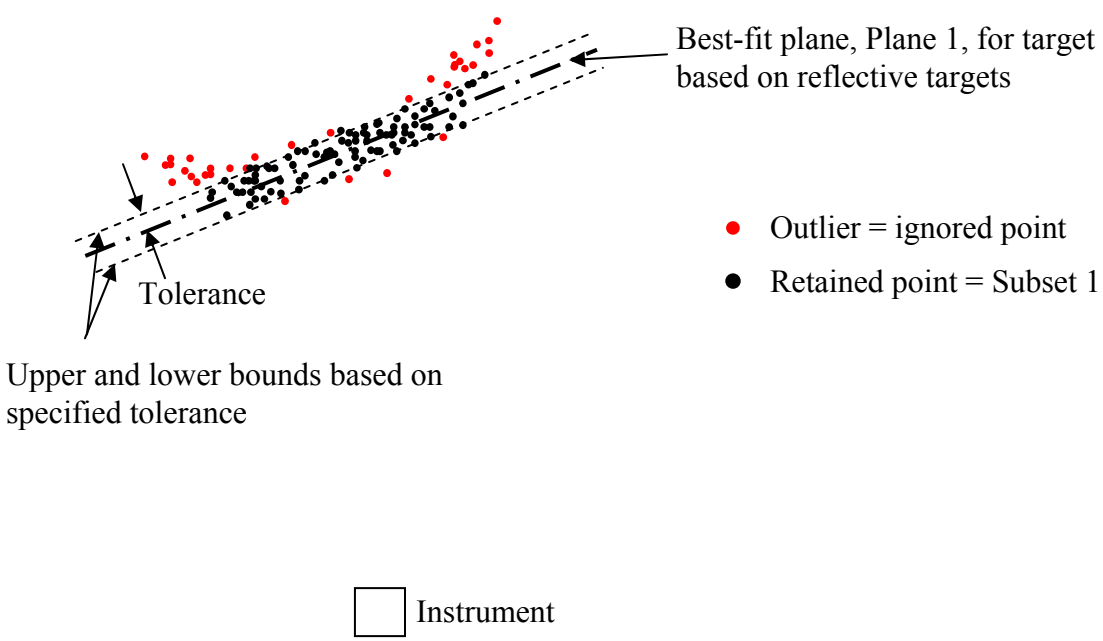


Figure 5. Top View showing segmentation of outliers.

5.2 Determining Valid Measurements

The center of the points (x_c, y_c, z_c) in Subset 1 (Section 5.1) is equal to the centroid of all the points in Subset 1. Points within a box whose center is at (x_c, y_c, z_c) are considered valid. The box has the following dimensions (Figure 6): dimensions in the target plane equal to $L/2$ and whose thickness is equal to $2 \times \sigma_{plane}$ where σ_{plane} is as determined in Section 5.1.

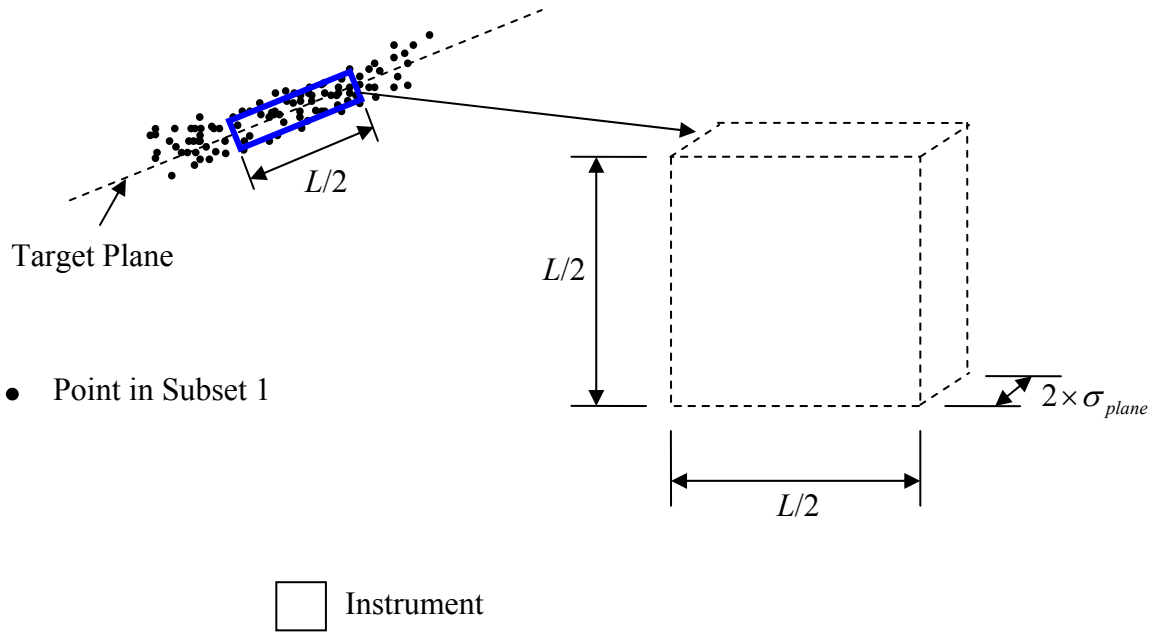


Figure 6. Top view showing bounding box for determining valid measurements.

For a target that is rotated, a drawback in Method 1 is that the box center (x_c, y_c, z_c) may be biased towards the side of the target that is closer to the instrument due the larger number of points on this side of the target. The box center may be adjusted to account for this bias.

5.3 Determining Target Distance

The target distance, d_m, is set equal to the distance from the centroid of the all valid measurements to the instrument center, and is computed as follows:

$$d_m = \sqrt{(x_m - x_0)^2 + (y_m - y_0)^2 + (z_m - z_0)^2}$$

$$= \sqrt{x_m{}^2 + y_m{}^2 + z_m{}^2}$$

$$\text{for } (x_0, y_0, z_0) = \text{instrument center} = (0, 0, 0)$$

where

$$x_m = \frac{\sum_{i=1}^{n} x_i}{n}, \quad y_m = \frac{\sum_{i=1}^{n} y_i}{n}, \quad z_m = \frac{\sum_{i=1}^{n} z_i}{n}$$

$$n = \text{number of valid measurements as determined in Section 5.1}$$

For the target distance to be valid, n has to be greater than 25 as per Section 4.1.2.

6. REPORTING RESULTS

For each day of testing, a General Specifications and Rated Conditions Form, Form 6.1, shall be completed.

Form 6.1. General Specifications and Rated Conditions

RATED CONDITIONS

Measurement envelope

Distance	Min. _____ meters	Max. _____ meters
Range of horizontal angles		_____ degrees
Range of vertical angles		_____ degrees

a. Temperature Range

Operating	Min. ____ °C	Max. _____ °C

b. Humidity Range

Operating	Min. ____ %RH	Max. _____ %RH

c. Barometric Pressure Range

Operating	Min. _____ mm Hg	Max. _____ mm Hg

d. Electrical - The electrical power supplied to a machine can affect its ability to perform accurate and repeatable measurements. This is particularly true when a machine uses some form of computer for any control or readout function.

Voltage	_____ V	Current _____ A

e. Sampling Strategy - The manufacturer shall state the measurement acquisition time (averaging time) and sampling frequency (points per second) to meet specification.

Acquisition time:	_____ s	Frequency: _____ points/s

LIMITING CONDITIONS

f. Temperature Range	Min. ____ °C	Max. _____ °C
g. Humidity Range	Min. _____ %RH	Max. _____ %RH
h. Barometric Pressure Range	Min. _____ mm Hg	Max. _____ mm Hg

The ranging tests are evaluated by calculating the magnitude of the difference between the measured target distance and the reference distance using the following equation.

$$e = \left| d_m - d_{ref} \right| ,$$

where d_m is the distance measured by the 3D imaging system (Section 5.4) and d_{ref} (Section 4.2.1) is the reference distance. There are three values (e_1, e_2, e_3) for each test position corresponding to the three repeated measurements. The averages of these values, e_{avg}, are reported in the Performance Test Results Form, Form 6.2.

Form 6.2. Performance Test Results

TEST DATE: _____

INSTRUMENT: _____

OPERATOR: _____

WEATHER CONDITIONS (Outdoors only): _____

_____

_____

LIGHTING CONDITIONS (Indoors only): _____

_____

_____

TEST CONDITIONS

a. Temperature Range Min. ____ °C Max. _____ °C

b. Humidity Range Min. _____ %RH Max. _____ %RH

c. Barometric Pressure Range Min. _____ mm Hg Max. _____ mm Hg

Test Positions	Reference Distance (m)	e_{avg} (mm)	Target Reflectivity (%)	FOV Horiz. by Vert. (°)	Angular Increment (°)	# of Valid Meas.	Scan Time (s)
1							
…							
…							
60							

REFERENCES

1. International Organization for Standardization, International Vocabulary *of Basic and General Terms in Metrology*, 1993. (VIM)

2. American Society of Mechanical Engineers, "Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems," ASME B89.4.19-200X.