NISTIR 7357

Proceedings of the 3rd NIST Workshop on the Performance Evaluation of 3D Imaging Systems – March 2 - 3, 2006

National Institute of Standards and Technology
Technology Administration, U. S. Department of Commerce

NISTIR 5357

Proceedings of the 3rd NIST Workshop on the Performance Evaluation of 3D Imaging Systems – March 2 - 3, 2006

Geraldine S. Cheok, Editor
Building and Fire Research Laboratory

October 2006

U. S. DEPARTMENT OF COMMERCE
Carlos M. Gutierrez, Secretary
TECHNOLOGY ADMINISTRATION
Robert Cresanti, Under Secretary of Commerce for Technology
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
William A. Jeffrey, Director

ABSTRACT

Two 3D Imaging Systems Performance Evaluation Workshops have been held at the National Institute of Standards and Technology (NIST) – the first in 2003 and the second in 2005. These workshops were conducted in an effort to determine the need for standard test methods for evaluating 3D imaging systems (previously referred to as LADAR - LAser Detection and Ranging - systems), to determine the types of measurements and test methods required, to provide a forum to discuss the on-going efforts in this area, and to initiate the process towards standardization of these test methods or protocols. To continue the effort, NIST conducted a 3rd Workshop on the Performance Evaluation of 3D Imaging systems on March 2-3, 2006. This report presents the proceedings from the third workshop.

Keywords: 3D imaging systems, laser scanning, LADAR, performance evaluation, standardization, terminology, test protocols, workshop.

ACKNOWLEDGEMENTS

The editor would like to thank all the participants for their time and for the stimulating discussions at the workshop.

Special thanks are extended to all speakers for their excellent presentations: Mr. Pat Picariello of ASTM International, Mr. Brent Gelhar of Optech, Dr. Steven Phillips of NIST, Mr. Steve Hand of MagLev, and Mr. Dave Ober of Metris.

Also, very grateful thanks to Dr. David Gilsinn, Mr. Alan Lytle, Dr. Kamel Saidi, and Dr. Christoph Witzgall, all of NIST, for their invaluable help in setting up the workshop and for their thoughtful discussions.

The editor also wants to thank Mr. Bruce Borchardt of NIST for his review of this report.

DISCLAIMER

Certain trade names and company products are mentioned in the text or identified in an illustration in order to adequately specify the experimental procedure and equipment used. In no case does such an identification imply recommendation or endorsement by the National Institute of Standards and Technology (NIST), nor does it imply that the products are necessarily the best available for the purpose.

The opinions expressed in the group discussions and presentations by non-NIST authors are those of the speakers and non-NIST authors and are not necessarily the opinions of NIST.

POLICY

It is NIST's policy to use the International System of Units (SI). However, some of the units used in the workshop presentations made by the invited speakers are in U.S. customary units because of the intended audience.

CONTENTS

1.0 INTRODUCTION

Two 3D Imaging Systems Performance Evaluation Workshops have been held at the National Institute of Standards and Technology (NIST) – the first in 2003 [1] and the second in 2005 [2]. These workshops were conducted in an effort to determine the need for standard test methods for evaluating 3D imaging systems [previously referred to as LADAR (LAser Detection and Ranging) systems], to determine the types of measurements and test methods required, to provide a forum to discuss the on-going efforts in this area, and to initiate the process towards standardization of these test methods or protocols.

Although fundamental technology of these systems is not new, the use of these instruments has become more established and accepted only over the past 10 years and is still considered an emerging technology in many industries. In this same time span, 3D imaging technology has seen significant advances (e.g., more accurate instruments, longer ranges, more reliable, reduction in size and cost). However, no standard test protocols exist for evaluating the performance of ground-based 3D imaging systems such as laser scanners, 3D range cameras, and flash LADAR (laser detection and ranging) instruments and no methods for assessing the accuracy of the derived output such as 3D models, volumes, or geometric dimensions.

Based on the input from the first two workshops, NIST initiated the development of a short-range, indoor, artifact-based test facility for evaluating 3D imaging systems; developed a draft document of terminology for 3D imaging systems; and drafted a test method for determining range error.

To continue the effort towards determining performance requirements and developing test methods for performance evaluation of 3D imaging systems, NIST conducted the 3rd Workshop on the Performance Evaluation of 3D Imaging systems on March 2-3, 2006.

The objectives of the 3rd NIST workshop were to:

- Select a standards development organization (SDO) for 3D imaging systems.
- Finalize the draft terminology.
- Finalize the draft ranging protocol.

This report presents the proceedings of the 3rd NIST workshop. The group discussions are presented in Chapter 3 and summarized in Chapter 4. The Terminology and Ranging Drafts are included in Appendix A and B, respectively. The workshop presentations are also included in the appendices - Appendix C to H. A list of the participants is given in Appendix I.

2.0 WORKSHOP AGENDA

March 2, 2006

8:00 – 8:30	Registration
8:30 – 8:50	Welcome and Introduction – Gerry Cheok (NIST)
8:50 – 9:15	Standards Development for 3D Imaging Systems: ASTM International – Pat Picariello (ASTM International)
9:15 – 10:00	Draft Terminology – Alan Lytle (NIST)
10:00 – 10:15	Break
10:15 – 11:30	Continue Draft Terminology – Alan Lytle (NIST)
11:30 – 12:30	Lunch
11:30 – 12:50	Verification and Calibration Process of Time-of-Flight Laser Scanners – Brent Gelhar (Optech)
12:50 – 1:10	Laser Tracker Standards Update and NIST 60 m Ranging Facility – Steve Phillips (NIST)
1:10 – 1:30	Ranging Protocol - Issues – Gerry Cheok (NIST)
1:30 – 3:15	Break-out groups - Discussion of draft ranging protocol
3:15 – 3:30	Break
3:30 – 5:00	Break-out groups - Discussion of draft ranging protocol
5:00 – 5:45	Summarize break-out group discussion
5.45	Collect SDO ballot

March 3, 2006

8:00 – 8:30	Quality Analysis and Registration of the Control Network - Steve Hand (MagLev) and Dave Ober (Metris)
8:30 – 8:50	NIST 3D Imaging Facility Update – Gerry Cheok (NIST)
8:50 – 9:10	Break-out group topics of discussion – Kamel Saidi (NIST)
9:10 – 10:00	Break-out groups - Discussion of ranging protocol
10:00 – 10:15	Break
10:15 – 11:45	Break-out groups - Discussion of ranging protocol
11:45 – 12:45	Summarize break-out group discussions
12:45 – 1:00	Results of SDO ballot. Wrap-up

3.0 BREAK-OUT GROUP DISCUSSIONS

The break-out sessions were recorded, and the material in the following sections is based on transcriptions of these tapes and on notes taken by various individuals in each group.

3.1 March 2, 2006

For the first break-out session, the three groups were asked to discuss the Ranging Protocol. Some suggested issues for consideration were:

- Evaluate absolute or relative distance.
- How many tests are needed? Need to balance between what is practical and still yield meaningful results.
- In addition to distance to target, target reflectivity, angle of incidence, and horizontal field of view (FOV), what other parameters were important? Should vertical FOV tests be included? If yes, suggest an easy method to do test this.
- Should the post-processing procedure be specified or should the test allow the user to clean data and just report the measured range?
- How is the measured distance determined - as proposed, the target is scanned and the center of the target is the centroid of measurements. Related issues - target and instrument alignment, centering of instrument over benchmark, bias caused when target is rotated at specified angle of incidence greater than 0º.
- Point density.
- Linear or random range intervals.

3.1.1 Group 1

Bruce Borchardt	*Bob Bridges*	*Carlton Daniel*
Jerry Dimsdale	*Brent Gelhar*	*Dave Gilsinn*
Steve Hand (Chair)	*Mark Klusza*	*Alan Lytle*
Jeff Mechlinski	*Pingbo Tang*	*Mitch Schefcik*
Jim Van Rens	*Kin Yen*	

The discussions for this group are organized into several general categories: intent of the protocol, targets, and procedural issues.

What is the intent of these protocols?

This topic arose when the group was trying to determine what tests were necessary or how many tests were necessary to make the protocol meaningful. An opinion was voiced that if the intent were to develop a set of instructions to assess the performance of the instrument that can be conducted by anyone, anywhere, then simpler and fewer tests would be better.

The other point of view was based on a user's need to have confidence in the instrument – that is, will the instrument perform as stated. Would the expenditure of up to 3 days to conduct the evaluation over the life of the product be too expensive? The answer was probably not. The general feeling was that the majority of the time would be spent in the set-up of the targets and instrument.

Another point was made that users need a means for "quick" field verification that the instrument is operating within specifications or to know when an instrument needed to be sent for calibration. This is often called an interim test.

For laser trackers, there is a calibration procedure, and there are interim test procedures or check procedures. The calibration procedure is supposed to be performed by any accredited calibration laboratory. The interim tests are supposed to be something that an operator can perform, relatively quickly, in a normal work environment. The interim procedures are much faster and are used to find problems quickly. It was noted that standards do not usually cover interim procedures except to state that manufacturers are responsible for them and they are supposed to have them. Manufacturers are discouraged to specify the time interval between calibrations in the tracker standard.

It was also noted that for internal quality control, some users mandate and specify that the instruments be calibrated on a periodic basis. It was pointed out that there is an ASTM standard on this issue - ISO 9000.

Targets

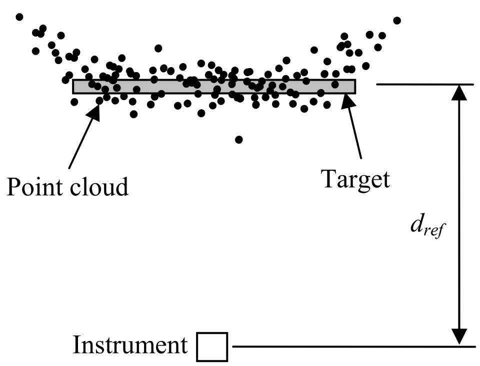
Several types of targets were discussed – plane, sphere, pyramid, box, trihedral. Spheres would eliminate the need to find the target center as would be necessary if a planar target were used. Another aspect favorable to spheres is that well-tested sphere fitting algorithms already exist in the CMM (coordinate measuring machine) community. However, the majority of the group felt that fitting spheres was more problematic and less reliable than fitting planes because finding the sphere center is very dependent on the fitting algorithm. Also, unlike the data produced by a CMM, the quality of the data is somewhat degraded by the curvature of the sphere, i.e., elongated beam spot size towards the edge of the sphere, and most fitting algorithms are adversely affected by having data points only on one side of the sphere. The consensus among the group was that a planar target would be adequate although target alignment, flatness, and edge problems need to be addressed.

The group felt that care should be taken when using reflective targets on the planar target to help define the initial target plane. This was because these reflective targets will generate strong return signals, which will "distort" and adversely affect the range measurements. A solution to this problem was to cover the reflective targets when scanning. The group also felt that filtering the data based on reflectivity was not a reliable method as reflectivity varied with different instruments. A suggestion was made to use distance as an initial filter to determine points on the target.

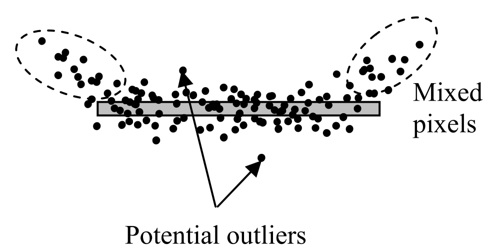
***<u>EDITOR'S NOTES</u>**: From the group's discussions, it appears that the intent of the reflective targets was not clear in the protocol. The reflective targets are **<u>only</u>** intended to be used to create the initial target plane (Plane 1 as defined in Section B5.1 in the ranging protocol) and to use this plane to remove mixed pixels and outliers, see Figure 3.1. The data associated with the reflective targets are not used after this step. Once the mixed pixels and outliers are removed, a second data filtering is specified in the ranging protocol to determine the set of points, which constitute the target plane. This second filtering is intended to identify those measurements that fall within the target center and that are not affected by the target edge and reflective targets.*

The group's point that the reflective targets distort the range measurements is well taken. Preliminary scans of a target at 100 m seem to indicate that it may be possible to objectively determine the initial target plane without the use of reflective targets.

<u>GIVEN</u>: Point cloud of target. Top view shown below.



<u>PROBLEM</u>: How to remove mixed pixels and outliers in an ***automatic*** and ***objective*** way?



<u>A SOLUTION</u>: Identify the corner points of the planar target based on the intensity values. At each corner, find the centroid of these points. Using the resulting four points to represent the target corners, define an initial target plane. Based on this initial target plane, identify points beyond a specified tolerance from that plane. These points will be considered as outliers (red, open circles below) and ignored. The remaining points, excluding the points associated with the reflective targets, are kept for further analysis.

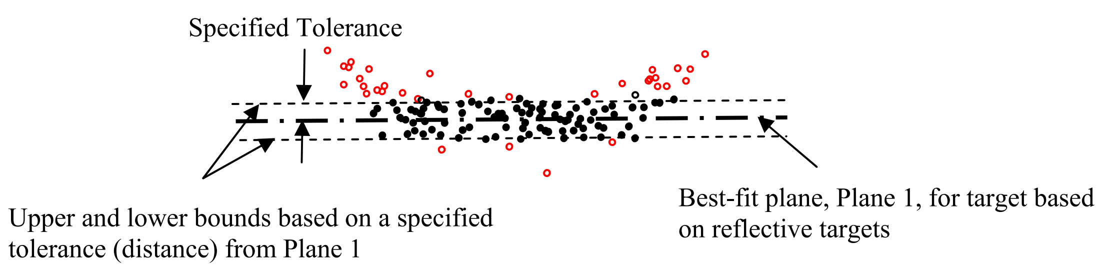


Figure 3.1. Reflective targets used for initial data filtering.

The suggestion to use the reference distance, d_{ref}, filter out mixed pixels and outliers was indeed considered when the ranging protocol was being developed. The concept would have been to ignore points whose ranges were greater than d_{ref} ± tolerance. This would have been an easy solution but would not have worked if the target were rotated as specified in the angle of incidence tests (see Figure 3.2, right image). Therefore, the method, outlined in the protocol, of defining the initial target plane was developed.

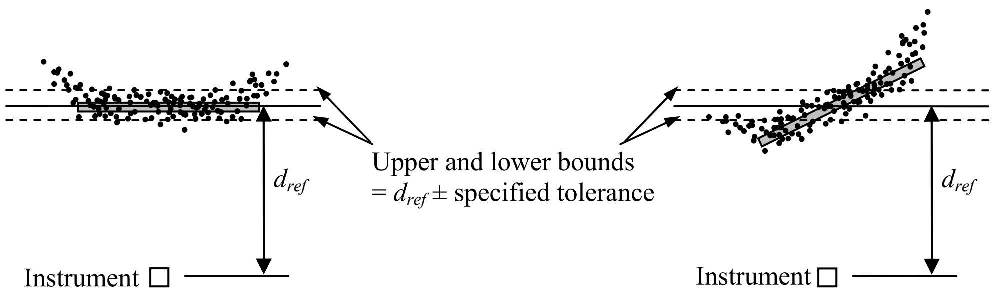


Figure 3.2. Initial data filter using nominal reference distance.

A question was raised during the discussion – is it necessary to determine target center if the purpose is to determine range?

EDITOR'S NOTE: *The determination of target center is necessary because if the target is scanned, as proposed in the protocol, the range to some point on the target is required. In the protocol, the range from the instrument to the center of the target is proposed as the measured distance,* $\mathbf{d}_m$.

Single point measurement vs. Scanning

A contentious issue in the group discussions was how the measured distance was obtained - single point measurement vs. scanning of the target. Some reasons for single point measurement were:

- Why is fitting a plane with 1000 points better than measuring a single point at the center of the target 1000 times?
- The need to have the target perpendicular to the instrument is not an issue as long as both the 3D imaging instrument and reference instrument measure the same point.

Some reasons for scanning were:

- Scanning is the primary function of the instrument – not single point measurements.
- Some instruments cannot perform single point measurements.

The question was then posed, how is a single measurement used? The answer was to measure control points.

<u>EDITOR'S NOTE</u>*: In general, measuring control points also involves scanning a reflective or cooperative target.*

With regards to data processing (plane fitting), a comment was made that neutral or consensus-based algorithms will be provided. The group felt that if data filtering was left to the manufacturer than there was the potential for data manipulation.

The issue of "raw" (range) vs. "pre-processed" (plane) data was raised, i.e., testing of the scanner or the system as a whole. The concern was that if raw data was not used, then you may get "half-cooked" data and how do you differentiate that from "fully cooked" data. After some discussion, the agreement was that "pre-processed" data would be used because a user is not concerned about the raw data and is only interested in the data as obtained from the "system".

An issue that surfaced a few times in the discussion was the difficulty in separating out "angle" from "ranging", i.e. when scanning as opposed to single point shot, there are angles involved which could affect the range measurements. A suggestion was made to use an artifact field and to report the ranges to these artifacts. The group felt that agreement on what these artifacts should be might be difficult.

There was some discussion on how to ensure that the target was perpendicular to the instrument. Other topics that were briefly mentioned included instrument tilt and a kilometer long test range.

The group decided that both single point and scanning methods be considered.

Procedural Issues

In the discussion, the question of "why develop a protocol for range?" was posed. The reply was that this characteristic was identified as being important by the participants in the previous two NIST workshops. Range accuracy is typically the "first number" on a manufacturer's specification sheet, and an instrument is often qualified by how well it could determine range. It was also noted that the ranging protocol is anticipated as the first in a series of tests to evaluate the instrument.

On the issue of absolute vs. relative distance evaluation, it was noted that relative distance was the measurement that was being evaluated in the laser tracker standard. The group decided that relative distance should be evaluated because the relative measurements would, in general, be of more use or importance to a user and finding instrument center and center of rotation would be hard to do for some instruments. The group agreed that the evaluation of the absolute distance should be a separate test.

The group was asked to consider the number of tests required. Five distances are specified in the draft protocol – would three distances be sufficient? How much set-up time is needed? Are all four azimuth angles, five reflectivities, and three target rotations specified in the draft protocol required?

A question arose on why target rotation was being evaluated. The reply was that angle of incidence was one of the factors identified in the previous workshops to affect the range measurement. The group was then asked if the incidence angle did indeed influence the range measurement, and if the test was performed outdoors as opposed to indoors, i.e., test with the incident angle of 45º outside (longer range), would it be that much different than testing indoors at 45º (shorter range)? The answer was that there would be a bigger spot size at longer range – the effect of incidence angle will be more pronounced and the return signal would be weaker. The group agreed that the angle of incidence tests were "legitimate tests" and should be part of the protocol. The group was neutral about the values (0º to 60º) specified in the protocol for the angle of incidence. An interesting question was then posed – Should the reflectivity and angle of incidence be combined, i.e., at each angle of incidence, vary the target reflectivity. There was only a brief discussion on this issue and no consensus was reached.

With regards to the tests for the horizontal FOV, i.e., varying azimuth angles, it was felt that these tests were important for laser trackers, and a user stated that there were blind spots in certain regions of his scanner. The group was uncertain if blind spots would be a factor for time-of-flight (TOF) instruments.

There was a comment that an error in horizontal FOV may be observed in an angular accuracy test or a system accuracy test that includes angle accuracy along with "everything else" and that trying to separate angles is difficult. A method suggested for a system test was to measure several targets around a room with an accurate instrument (an instrument that is more accurate than the 3D imaging system) and then measure those same targets with a 3D imaging system as a way to determine the error. An objection was made to performing the system test indoors because the same scale or error magnitude achievable in an outdoor target range was not possible in an indoor facility.

A suggestion was made that the tests for the horizontal FOV be pulled out of the ranging protocol as long as they are incorporated into another protocol that would be developed at a later time. After some discussion, the group decided that the FOV tests should be left in the ranging protocol until such time as additional tests (total system tests) make them unnecessary.

As proposed, there are no tests specified to evaluate the vertical FOV of the instrument and the group was asked if these tests were needed. The group felt that if horizontal FOV is critical, then vertical FOV is also critical and should be evaluated, but there was no discussion on practical methods to accomplish this.

There were two comments with regards to Section B6 of the draft protocol. The first dealt with environmental conditions – were the recorded values those that were reported by the sensors on-board the 3D imaging instrument? The group felt that, in general, the environmental conditions are measured by an independent instrument. The second comment was a clarification of the term "limiting conditions."

EDITOR'S NOTES: *The definition of limiting conditions was inadvertently omitted in Section B3 of the draft protocol. The following definition as given in Ref. [3] (ASME B89.4.19 - Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems) is offered and will be added to the protocol:*

> *limiting conditions – the manufacturer's specified limits on the environmental, utility, and other conditions within which an instrument may be operated safely and without damage. NOTE: the manufacturer's performance specifications are not assured over the limiting conditions.*

Other issues that were briefly discussed include:

- Instrument set-up.
- Random range selections by a user to eliminate efforts to "solve for the target placement" to get artificially improved results.
- Current protocol is written to evaluate absolute distance – need to change document to evaluate relative distance. This should be a simple change by setting one target as a reference target.
- Compensation for environmental conditions – the group felt that this information should be provided by the instrument manufacturer.

In summary, the group agreed that planar targets are acceptable and that clarification was needed on the reflective corner targets. Two issues that were contentious were single point measurement vs. scanning and the tests for horizontal FOV. The group proposed that both single point and scanning be considered – possibly in separate protocols. There were mixed feelings within the group about whether the tests to evaluate the horizontal FOV should be left in the ranging protocol or removed - "removed" only in the sense that other tests be developed to replace these tests as the ranging protocol may not be the appropriate place for them.

3.1.2 Group 2

Abdullah Qassim
Jack Cothren (Chair)
Les Elkins
Michael Garvey
Tom Greaves
Dirk Langer
George Lukes
Gabor Lukacs
Fred Persi
Kamel Saidi
Arkady Savikovsky
Omar-Pierre Soubra
Christoph Witzgall

The chair noted at the start of the discussion that the ranging protocol was just one aspect of the evaluation and other protocols would be developed in the future. The first issue the group addressed was absolute vs. relative distance evaluation. The evaluation of absolute distance is problematic, as some scanners do not have reproducible or measurable centers. As a result, centering over a benchmark may introduce an error comparable to or larger than the error that is being assessed. Possible solutions suggested were to evaluate relative distance instead of absolute and to have reference objects in the scene to enable the instrument center to be determined. With regards to the latter suggestion, comments made were that this method introduces other errors, namely, registration errors and that this method implies the use of a system that can discriminate angles well. It was suggested that the registration errors may be less than the error introduced by "guessing" the center of the instrument and that experiments were needed to verify this.

On the topic of relative distance, a comment was made that not all phase-based instruments have the ability to center over a point with any certainty and the trend of TOF systems looks to be headed in the same direction. The question then asked was "would one be willing to accept biases in the range measurements," and the reply was that relative distance is often the measurement of interest in the field.

There were some who felt that absolute measurements were needed – the need for relative or absolute distance was application dependent. A suggestion was made that the evaluation of the absolute distance not be completely discarded. It was felt that procedures to determine the instrument center may be devised to back out the instrument center. Indoors, targets spaced within a room could be used to determine the instrument center. Outdoors, a possible method would involve measuring the length of two sides of a triangle with the third side known (e.g., reference distance). In addition, a sensitivity study may be required to determine the effect on range error due to improper centering of an instrument over a point.

There was a little bit of discussion about the process/set-up to evaluate the relative distance. For 60 m, the set-up shown in Steve Phillips' presentation was feasible, but this set-up would not work outdoors and for distances between 60 m and 150 m. Manufacturers were asked what they did. One manufacturer indicated that they used a method similar to that shown by Steve Phillips – indoors.

A question was raised regarding the required accuracy of the reference measurements. Was 5 parts in 10 million necessary? Was this achievable for the systems under discussion? A response was that it depended on the application. A manufacturer indicated that they used laser trackers for indoors and a total station for outdoors to measure their targets. The use of GPS to measure control points in the kilometer range was suggested. A user stated that he used trackers for his control points in indoor industrial settings, and the suggestion of an indoor facility (as made earlier in the discussion to have both indoor and outdoor ranging facilities) would be beneficial to him.

A manufacturer was asked if they used planar boards for targets and if they rotated the boards. The response was both planar targets and spheres were used. The planar targets were measured "straight on" and at different angles. The planar target used is a square reflective target with a white circle in the middle, and these targets can be used up to 100 m. The center of the target is then the center of the circle which is found by fitting a circle to the points. A comment was made that the instrument would have to be at the same height as the target center and how was this to be ensured. The manufacturer replied that procedures were provided to align the instrument center with the target center.

Another manufacturer stated that they did not center over a known point because it would be difficult to set their instrument over a point. Alignment becomes an issue and an additional error of the set-up over a point is introduced. The distance between two known points, the relative distance, would be evaluated. A point was made that for this particular instrument, the rangefinder and the angular measurement are two completely, de-coupled systems that are based on different physics which results in slightly different characteristics and sizes of the errors. A calibration was performed on the rangefinder prior to integration into the system, similar to what was being done by another manufacturer for their instruments. This ranging calibration involved testing the rangefinder through its entire range and through the specified range of operating temperatures. After this calibration, the rangefinder was integrated into the scanning system. An angular calibration was then performed on the scanning mechanism. The manufacturer has found the ranging device to be very stable as it is an electronic system, and the errors due to temperature variations are repeatable and well defined and can be easily compensated. However, the scanning mechanism is a mechanical system that is subject to wear and other environmental conditions and requires periodic calibration; the instrument would be re-calibrated as a system and not broken down into its components.

Since the group agreed that evaluating the absolute distance was not possible for most systems, they were then asked to suggest a test method to evaluate the relative distance between targets that isolates the range from the angular measurement. One suggestion was to have the instrument between two targets. Obtain the distance to one target and rotate the instrument 180° and measure the other target. The distance between the targets would be the average of the two distances. Another suggestion was to use the set-up that was described by Steve Phillips for the 60 m facility with an interferometer at one end and the instrument at the other end. Again, the practicality of this for an outdoor facility was raised as an issue.

The group was asked about the number of tests needed in order to get a good feel for the range accuracy. A more general question was raised in reply – "What would you like to see as a result of the protocol? A single number or a spectrum of results? A manufacturer cannot put the results of the proposed protocol on the specification sheet."

In the discussion that followed, it was generally agreed that different levels of reflectivity were felt to be important. Manufacturers are often faced with inquiries from users about an instrument's performance as it relates to real world objects (e.g., wood, concrete). This led to some discussion about the need for a "NIST certified piece of wood", i.e., targets with repeatable characteristics that would be better related to real world objects; these targets would be in addition to using targets of known reflectivity. With regards to the reflectivities of real world objects, the group was asked if anyone has correlated or measured the reflectivities of concrete bridges, steel pipes, etc. Some factors that would make this difficult include the variety of woods, the surface texture – e.g., concrete could be polished, roughened, and painted, the different wavelengths employed by the various instruments, dirt – dirt on a shiny surface would often "improve" the measurements, and the ability of some materials to absorb certain wavelengths. Another factor based on experience learned the hard way dealt with the way a laser "sees" a target as opposed to how the human eyes see a target. What was not apparent to the naked human eye was apparent to the laser. In this instance, a black and white target was printed on a piece of paper. In the scan image, the reflectivities of the black and white regions were not distinguishable. After some investigation, it was found that the target was printed on rough cardboard paper and under magnification, it could be seen that the black ink was not absorbed by all the fibers and some fibers were still white – hence, the indistinct scan image. Another issue for instruments using infrared or red lasers is that measurements off of a black target may be better than those off of a green target because green is the complementary color to red and vice versa. The general recommendation was to have standardized targets (targets of known reflectivity); otherwise, comparisons between instruments would not be possible.

A suggestion was made to have a target with a high reflectivity next to a low reflectivity as some systems, AM-CW (amplitude modulated – continuous wave) systems in particular, may have some problems with a high/low contrast. The group was not able to suggest any reductions in the number of tests required as they felt that the suggested parameters were all important.

A comment was made that there needed to be a simple way to summarize the test results so that they are easily understood by the customer. A suggestion was made that a graph would be an effective way to convey the results of the 60 tests and that the number of graphs should be limited to 3 or 4 as more graphs would generally be ineffective and defeat the purpose of simplicity.

Issues common to both relative and absolute distance evaluation are finding the center of the target or the point on the target to determine a range to and aligning the target and instrument heights. The group discussed, at length, the alignment of the instrument center with the target center. Topics discussed included the use of spheres instead of planar targets (problem with the use of spheres was the required size of the spheres to get sufficient points on the sphere at 150 m) and having manufacturers provide a means for the operator to point or steer the beam to align the laser beam with the instrument center. Most manufacturers have the capability to steer the beam but for safety reasons, this capability is not provided to the user. Therefore, the test would not be able to be performed by the general user, and the manufacturer would likely want a member of their staff to operate the scanner. An argument was made that the requirement (manufacturer supplying the "key" to steer the beam) cannot be imposed on a manufacturer and if this feature is not available to the user, then reporting the ranging error based on single measurements is irrelevant.

If the instrument could be made to point at the target for alignment purposes, then the range would be the range to that point – a single point measurement rather than scanning. A comment was made that for range calibration, typically, a large number of single point measurements were made and the uncertainty is made up of the Gaussian noise and the linearity of the system which is an offset, linear or constant, from the true range over the entire range. Again, it was pointed out that even if the beam could be steered, single point measurements may still not be possible for some systems.

Since it appeared that the height of the scanner and target had to be aligned, a suggestion was made that the mounting assembly of the scanner and target should be designed so that the height is adjustable and the assembly can be leveled.

A question of parity was raised. Would the results be comparable for a scanner which allowed beam steering and focusing to one which doesn't, i.e., scanning only? It was assumed that the former case would yield better results and worse in the latter case due to errors introduced by plane fitting and other data processing. There were mixed feelings within the group about the parity.

One opinion was that the ability to point the instrument and take a single measurement was requisite to determining range error. If the target were scanned, the error would be a combination of range and angular error.

A statement was made that users are usually not concerned about the pointing accuracy but the overall accuracy or the spatial performance (from the terminology list) of the system. The interest is not in individual points but in fitting surfaces to point clouds. This sentiment was also voiced by someone else in the group – the end user would most likely be interested in the spatial performance of the system because it accounts for all the components – the angular accuracy, range accuracy, and linearity. By making a hundred or so measurements within a room, a standard deviation of the error can be obtained, and this would be the uncertainty or error of the measurement. The error obtained in this manner would be the sum of the different errors in the system and would be the worst case.

A counterpoint to these statements was that surveyors deal in individual points (total stations) and are interested in the accuracy of individual points. Also, the knowledge of the major source of error, ranging or angular, helps in the determination of the field set-up and increases job efficiency.

The end consensus of the group was that two protocols should be developed – one for pointing and one for scanning. These two protocols would be similar and if an instrument is capable of pointing and scanning, then both protocols would be used or if an instrument can only scan, then only the scanning protocol would be conducted. Although the post-processing of the data from a flash LADAR would be different, the protocols should also be applicable to these devices.

There was some discussion on the need for an indoor vs. an outdoor ranging facility. There was general agreement that both types of facilities were needed as the market was about evenly divided between indoor and outdoor usage. There appears to be a trend for service providers to have more than one type of scanner.

There were some questions among the group as to the reason for the inclusion of the horizontal FOV tests. There were some who felt that these tests should not be part of the ranging test and should, instead, be part of the angular accuracy tests. This concept was agreeable to some as long as these tests were included in the angular accuracy tests as they felt that these were important tests. An explanation was offered as to the reason why these tests were included as part of the ranging protocol; the range may be affected by where the instrument was on the horizontal encoder, and thus, would be a ranging error.

There was general agreement in the group that a circular target or a circle within a square target would be feasible. Fitting a circle to the points and finding the center of the circle would eliminate the bias introduced by a rotated target which would result in more points on the side of the target closer to the instrument. A suggestion was made not to have reflective material surrounding the circle; rather a contrasting color such as black. Another target used is a black and white checkerboard target.

As proposed, the protocol calls for the maximum point density, i.e., minimum angular increment. The group was asked if a lower point density should be specified in addition to the maximum point density – to allow a user to interpolate between these values. Suggestions included letting the manufacturer decide and specifying a point density or point spacing on the target and then back calculate the required angular increment. A point was made that the maximum point density may cause the measurements to degrade because of overlapping laser spot at the shorter ranges. This topic led to some discussion of the size of the target and the beam spot size at 150 m. The general feeling was that a (0.5 x 0.5) m target would not be large enough to yield enough points on the target at 150 m, and the proposed minimum number of points, 25, may not be sufficient to fit a circle or an ellipse.

EDITOR'S NOTE*: The draft protocol suggests minimum target dimensions of 0.5 m by 0.5 m. There is also another requirement in the protocol for a minimum of 25 points with the implication that a larger target be used if needed.*

In summary, there is a need to evaluate the relative distance as obtaining absolute distance is not possible for some instruments. The protocol should accommodate evaluation of both relative and absolute distances. The group felt that a circular target or a circle within a square target would be a good target as this involves fitting a circle through points and the center of the target would be the center of the circle. Protocols for single point measurement and scanning should be developed; it was felt that these two protocols would be similar. The flatness of the target needs to be better than 1 mm – preferably 100 μm. In reporting the results, in addition to tabulated results, the group recommended a graphical method to give the user a quick and easy way to interpret the results.

3.1.3 Group 3

Alan Aindow	*John Battaglia*	*Gerry Cheok*
Luc Cournoyer	*Chuck Fronczek*	*Francois Huard*
Darin Ingimarson	*William Keaney*	*Stephen Kyle*
David Landrecht	*Dave Ober (chair)*	*Pat Picariello*
Dan Sawyer		

A brief overview of the proposed ranging protocol was given. The draft protocol calls for 60 tests and for the use of planar targets. The test parameters were target distance, target reflectivity, angle of incidence, and horizontal FOV. The last parameter involves dividing the full extent of the horizontal FOV, *A*º, by 4. For each quadrant, the user selects a horizontal angle, θ, that is within the limits of that quadrant (e.g., $0^\circ \leq \theta \leq A^\circ/4$ or $3A^\circ/4 \leq \theta \leq A^\circ$) and obtains the measurements per the protocol. The user then selects another θ that is within the bounds of the next quadrant, rotates the instrument to this angle, and repeats the measurements.

The maximum range proposed was 150 m as most of the capital projects (e.g., new facility, modernization/improvement/decommissioning of an existing facility) fell within this range - protocols for longer ranges would be developed in the future if needed. The protocol involves scanning the target and fitting a plane through valid points (determination of valid points is described in the protocol). The measured range is then the distance to the centroid of the plane. The error, measured distance minus true distance, is then compared to the MPE (maximum permissible error). The group was asked to determine if the proposed procedures were the most suitable method or if other methods would be better. A practical way to evaluate the vertical FOV was also sought as some instruments cannot easily be turned on their side.

A user commented that the protocol should allow him to know if the instrument is performing within manufacturer's specifications. Also, errors from data processing and software have to be determined.

Someone asked if MPEs were reported by manufacturers. MPEs are reported for laser trackers but not for 3D imaging systems. However, the point was made that this was not the case for laser trackers until users made a point of requiring it of the manufacturers. For 3D imaging systems, the reported accuracy of the system is set to multiples of the standard deviation, σ, of the range error - 1σ in most cases.

Another comment was that some scanners obtained a "cluster" of range measurements of a point and the average of these ranges is reported as the range to that point. Another piece of information that is therefore necessary in the report is the time to obtain that measurement.

Instead of using a square target, someone in the group used circular targets for his applications and suggested using circular targets as it is easier to find the center of a circle than a square.

Knowledge of the instrument center or (0,0,0) position, was debated at length. A question raised was what professions used 3D imaging systems or who were the primary users. The reply was surveyors, mechanical contractors, and engineering firms. In a surveying job, the 3D imaging system is often referenced to a traverse, and it would be useful to be able to determine an instrument's center. If this were the case, users need to convey these requirements to the manufacturers. A counter point was that knowledge of the instrument center was not necessary as long as there was a method to transform the scan data to the traverse via measurement of common targets. In the process of evaluating several instruments for purchase, a user stated that the ability to set up over a point and sight to another point to obtain the orientation instantly was a benefit for him.

The questions then were "can the center of the scanner be determined?" and "how accurately can the instrument and target be centered over the benchmark?" An alternative suggested was the use of calibrated objects with known dimensions placed on reference points or calibrated bars.

On the topic of absolute vs. relative distance, a point of view was that the protocol should evaluate relative distance and therefore knowing the instrument center would not be necessary. Another method, yet to be developed, should be used to determine the instrument offset error. One method would be to place an instrument between two targets. It was also suggested that the existence of an offset error can be detected in an "angle test" (test to determine the pointing accuracy of the instrument). A suggestion was made that the relative range error be called "displacement error" as the laser tracker community had adopted this terminology.

Another suggestion was to scan each target, fit planes through each of the point clouds, and create a best-fit line that goes through the plane centers. The assumptions made were that the centroid of the points is the center of the target and that the targets are all inline. The relative distance between the targets would then be the distance between the targets along that line. A suggestion was made to select one target as the "zero" and all other target distances are relative to this selected target. This distance would then be compared to the reference relative distance. This method would eliminate the need to align the target and the instrument centers. There was some discussion that if the height of the scanner was known and the target was placed over a benchmark at the same height, then it may be possible to calculate the angle that the best-fit line makes with the target plane. The group did not have any issue with the use of planar targets (square or circles) and felt that the details of this procedure, best-fit line through all the targets, have to be more carefully considered and clarified to address the following:

- Would this method be feasible?
- Do the targets need to be in a line? Multiple targets set up in a row or single target moved from one position to another.
- Mechanism to hold and move the targets.
- Technique to ensure that targets are parallel to each other and perpendicular to the laser beam and how to measure that.
- Need to conduct sensitivity analysis on the "out-of-perpendicularity" of the target and laser beam, i.e., if the target is not perpendicular (angle of incidence, $\gamma = 0^{o}$) to the laser beam, what is the upper limit of γ at which there is an effect on the range measurement?
- Target design that is both simple and inexpensive and which allows alignment of instrument to target center - one suggestion was to have a small mirror in the center of the target.
- When aligning targets and instrument, do you adjust the target or the instrument?

Regarding range intervals, a suggestion was to include testing at the minimum and maximum ranges at the very least.

The possibility of having one protocol to evaluate range, angles, and range offset instead of separate protocols was raised. The evaluation protocol would make use of a 3D test range (i.e., targets not in a straight line) with the targets in place and with known distances between the targets. The instrument would be placed at different locations (3 minimum) throughout the range and at various heights. Someone in the group stated that this procedure was similar to the methodology used in the Unified Spatial Metrology Network (USMN). In brief, USMN is commercially available software used to quantify the uncertainty fields of coordinate data comprised of measurements from one instrument from different vantage points or from different systems. USMN is used to determine the uncertainty of the instrument in terms of the two angles and the range. Range offset and angle errors can be detected by USMN but not scale error.

Some comments about the use of USMN were the error is reduced by using more parameters and there is a need to trace back to the unit of length. Also, the Large Scale Metrology Group at NIST is working on a similar problem but with a 3D ball array. A basic but important aspect was the ability to determine the actual position of the spheres in 3D space. A potential solution may be the use of a laser tracker using multi-lateration technique because what was required was the true position and not a derived position from “a bundle adjustment.”

A question raised was whether the measured distance would be compared to a distance obtained using a more accurate instrument. It was agreed that a more accurate instrument, e.g., a laser tracker, would be used to obtain the reference distances, and the instrument would be traceable to NIST.

After some discussion on a combined protocol, the discussion returned to the intent of the break-out group - was it to develop a protocol to characterize the whole system or separate protocols for range, angles, reflectance? The feeling was that developing an all-inclusive protocol may be difficult but possible.

The group was asked if the parameters suggested in the protocol are relevant. The group agreed that range-to-target, target reflectivity, angle of incidence, and horizontal FOV were variables that should be left in the protocol.

Two points for discussion were brought up. First, the number of points used to scan the targets needs to be decided as the accuracy of the plane defining the target depends on this number. Second, the background radiation on the target is not covered in the protocol. Laser systems are susceptible to background radiation and the noise appears as uncertainty. The suggestion was to standardize the lighting conditions. The group was unsure how “sunlight” could be standardized, but felt that some measure could be used to “quantify” sunlight. Rather than quantifying sunlight, a binary type solution was suggested – test in sunlight and test in dark or inside and outside.

EDITOR’S NOTE*: A pyranometer measures the solar irradiance on a planar surface and can be used to “quantify” sunlight.*

Another topic of discussion was testing the vertical FOV. Turning an instrument on its side would not be possible as some instruments cannot be tuned on its side or not easily. Additionally, some disadvantages of testing the instrument this way are 1) this is not the way the instrument would be used in the field, 2) turning the instrument on its side may create other issues due to the force of gravity on sensitive/critical parts, and 3) some instruments need to be leveled. One solution was to use targets on a stand at positioned at three levels - floor, mid, and high, and the stand would be relatively close to the instrument to maximize the range of vertical FOV to be evaluated. This method is used to evaluate laser trackers, but laser trackers have shorter ranges than most of the 3D imaging systems; thus, this method would be viable only if the error is scalable to longer ranges. The use of mirrors was another idea that was discussed but was deemed not feasible. The reasons being that some instruments cannot measure through a mirror, and this method would not really test the vertical FOV of the instrument as it would be the mirror that would be rotated and not the instrument. The group felt that the vertical FOV test may be an optional test left to the discretion of the manufacturer.

Besides the range errors as a function of the specified parameters, other reported results should include the plane fit, the residual error of the plane fit, and the time to scan. The need to report the last statistic was questioned as the end results from all instruments are basically the same. The feeling was that most users want to know how slow or fast an instrument is as this statistic can be equated to efficiency and productivity. The time to scan would also give the user an idea of the tradeoffs between time and accuracy as users have different accuracy requirements, and these requirements may vary from project to project. Some felt that this protocol "cannot consider everything" and should only evaluate range and not speed of the instrument. A counterpoint would be that the range error is dependent on the time to acquire the measurements. It was mentioned that someone in 1986 had computed a "figure of merit" for scanners that took into account instrument specifications, time, and instrument cost.

The group agreed that the parameters to be varied in the protocol were distance to target, target reflectivity, angle of incidence, horizontal FOV, optional vertical FOV, and background light. The group was asked to rank the importance of these parameters. Distance to target was ranked as the most important - minimum range, maximum or 80 % of maximum range, and two other values in between.

The next topic was target reflectivity, a manufacturer observed that the reflectivities encountered in the real world are typically on the low end - about 20 %. On a similar note, another researcher observed that there is not much change between 20 % and 99 % reflectivity and that problems arose for reflectivities between 1 % and 20 %. Therefore, the protocol should be biased towards the lower reflectivities. The use of standardized targets, targets with known or calibrated reflectivity, was agreed upon, and standard diffuse targets with known reflectivities for wavelengths from 250 nm to 2500 nm are commercially available. Mention was made of other studies which used a wall with different color patches. Another suggestion was the ability to relate the standard reflectivities back to the real world objects (e.g., wood, concrete, grass) as this is very helpful to users. The group ended the discussion on this topic by suggesting that the levels of reflectivities for evaluation be 5 %, 10 %, 20 %, and 90 %.

While discussing the angle of incidence, an interesting observation was made about the possible biases associated with the different reflectivities and the fact that the protocol evaluates relative distances. It is possible that the systematic error for a 5 % reflective target and a 90 % reflective target is different, but this systematic error will not show up when evaluating relative distances. A possible solution would be to have a target with different reflectivities on it. The question then was "do you fit four separate planes or one plane?" Four fits would be required, and although it may lengthen the test, it would yield useful information. A separate test may be required using a target with multiple reflectivities.

This led to the issue of target size. If the target were divided into fourths, would there be sufficient hits within each of these regions at the longer distances? As written, the draft protocol allows larger targets to be used so that a minimum of 25 points is available for the plane fit. There was some discussion on the number of points for the plane fit. The issue was whether increasing the number of points 1) reduces standard error (the point was made that standard error was not standard deviation) and the standard deviation would remain the same for the plane fit or 2) reduce the standard deviation but not the error of the plane fit. The issue was not resolved, but the group agreed that this issue required further study.

Angle of incidence was the next topic discussed, and a question raised was how critical is this factor. A manufacturer stated that the range noise increased by about 200 % when the target was rotated from 0º to 65º. Another manufacturer concurred that angle of incidence was important. For imaging instruments such as triangulation systems, angle of incidence is an important factor. The suggestion was to specify three values of angle of incidence - 0º, 30º, and 60º with 0º being normal to the line of sight.

For the horizontal FOV, three specified values were reasonable to the group - divide the maximum horizontal FOV by 3 and rotate the instrument head so that it lies within each of these regions. Again, the feeling was that for some instruments this evaluation of this parameter would not be problematic but may be for others.

On the topic of background light, the group's experience was that all active systems work in the dark. A suggestion was to make this an optional parameter as a manufacturer may be unwilling to state outright that their systems do not work well in sunlight. From a user's standpoint, knowledge of whether an instrument operates outdoors under all conditions is important, and the results from tests in sunlight are very useful. In a user's experience, the standard deviation for fitting a wall ranged from 10 mm on a cloudy day to 30 mm on a sunny day. A question posed was whether the problem was because the wall was in the sun or because the instrument was in the sun. Background radiation does contribute to the shot noise and how this is filtered out depends on the manufacturer. On the other hand, some users only work indoors (e.g., process plants) and outdoor operation is not required. Some kind of differentiation needs to be made - universal (indoors and outdoors) or indoors.

The protocol was written for outdoor evaluation. If the protocol required testing on a sunny day, and it was partly cloudy, would you need to wait for a sunny day? The response was that the manufacturer has to state the rated conditions. These conditions include all conditions under which the specifications hold. From a user's standpoint, if the user decides to check the manufacturer's specification, it does not matter what the conditions are, as long as it is within the rated conditions, those specifications have to hold. This is a way around not being able to control all the environmental factors, as this is not possible. A remark was made that the specifications state that the instrument can operate at 0 ºC, but most users don't normally verify that this is the case. The point, however, of the rated conditions is that the manufacturer has to meet their specification as one user may indeed decide to verify that the instrument functioned properly at 40 ºC, another at 20 ºC, and yet another at 0 ºC. Therefore, a manufacturer has to be careful when stating specifications for an instrument as the instrument has to pass the test when tested anywhere within the rated conditions. It was pointed out that the protocol does require that the Rated and Limiting conditions be specified - Form B6.1 (Appendix B).

***EDITOR'S NOTE**: The definitions of rated and limiting conditions were inadvertently omitted in Section B3 of the protocol. The following definition as given in Ref. [3] (ASME B89.4.19-2006) is offered and will be added to the protocol:*

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

The definition for limiting conditions is also taken from ASME B89.4.19-2006 and is given in Section 3.1.1.

A statement was made that a lot of manufacturers choose to leave certain information out of the specifications as they may not reflect positively on their instrument. The question was, is the purpose of the tests then to make the manufacturers accountable unless the test was optional? If the test were optional, would manufacturers have to state that they opted not to do that part of the test? The response was that it was the user's responsibility to ask for the inclusion of the tests while the manufacturers will try to ignore them. If a manufacturer decided to opt out of a test, it can be assumed that they fail it or won't pass. A point made was that when a protocol is adopted as an ASTM standard, manufacturers are not required to meet the standard, but users can choose not to buy an instrument unless it can be shown that it meets the ASTM standard.

Eye safety was another topic that was discussed and if the standard would include eye safety. This could be an issue inside manufacturing plants. Someone in the group stated that there is already a committee on laser safety. Also, manufacturers are required to state what class laser is being used in their instrument.

Other remarks included:

- Target alignment needs to be specified, e.g., are the targets going to be in a straight line, how is that line going to be established. The group agreed that this needs to be addressed but not at this time.
- A target mount that allows for easy adjustment of target height so that the target center can be aligned with the instrument center.

A summary of the group's discussion was given:

- Spheres vs. circles and planes: leaning towards circle or plane.
- Absolute vs displacement: decision to go with displacement. Instrument offset would be determined with another test.
- Range intervals: minimum, maximum, and 2 ranges in between the minimum and maximum values.
- Target reflectivity:
    - 5 %, 10 %, 20 %, and 90 %
    - May need a separate test for a multi-reflective target
    - Relate the reflectivity to real world objects
- Angle of incidence: 0º, 30º, 60º

- Horizontal FOV: (max. horizontal FOV)/3 and randomly choose angles within each of the three regions.
- Vertical FOV:
  - Optional test.
  - Potential methods.
    - Use mirrors.
    - Lay instrument on its side.
    - Stand set at close range with targets on stand set at low, medium, high.
  - Rated conditions: manufacturer must specify the range of operating ambient lighting conditions.
- Additional reported results:
  - Time to scan.
  - Standard deviation of plane fit.
  - Number of points per scan.

3.2 March 3, 2006

For the second break-out session, the groups were asked to continue their discussions of the ranging protocol but to concentrate on varying the horizontal FOV, pointing vs. scanning, instrument and target alignment, and how the measured range is determined.

3.2.1 Group 1

Horizontal FOV

The first issue that the group discussed was whether the tests to evaluate the horizontal FOV should remain in the ranging protocol. There was one vote to leave the tests in. The reasoning being that even if the tests were lengthened by an extra day or two, it was inconsequential compared to the life of an instrument. Another opinion was that the horizontal FOV tests would be completely irrelevant for some instruments. However, the group felt that this scenario would always be true – where the protocol would apply to some instruments but not to others.

There was also the opinion that if there were a small region that is problematic, it would be unlikely that the proposed test procedures would detect it. An observation was made that in the B89.4 standard, the user was allowed to choose any two additional points (select any azimuth and range) to evaluate. The various combinations of angles, ranges, and measurement conditions would result in numerous tests, and it would not be possible to specify all the cases in an effort to detect the error. By allowing the user to select any two additional points for evaluation, the protocol will provide the user a means of recourse - to demonstrate that the instrument is faulty in a particular region.

A question was asked about who would conduct the tests, and there was general agreement that the tests would be performed by any user or any calibration lab. It was argued then that it would not be possible to develop a test that detects all the potential problems – current or future. While true, the counterpoint was that the test should not limit the ability to find a particular or potential problem with the technology.

A user stated that he wanted to have a standard that he has confidence in and that would produce results that he trusts, and a secondary need is to use the standard to re-qualify an instrument. That is, if the specifications states that they meet ASTM "XXX", he would have a certain level of comfort in believing the specifications and would be able to purchase the instrument without "too much heartburn." If a manufacturer does not perform the test rigorously enough (the expectation was that the standard was rigorous enough in the first place), the problem may not be detected, but the existence of a standard would give a user a means of recourse.

The question raised then was "as a user, when reviewing the specifications on the website, do you expect that the manufacturer has tested the range at every single/potential azimuth angle?" The reply was "I don't but I would have a comfort level that they did".

The rebuttal to this was that it is not possible – that there will still be some tests omitted. A manufacturer will try to ensure to the extent possible that the claims made with regards to their product in terms of FOV, range accuracy, etc. are true. The question then is "how many tests are necessary to give the user a sense of confidence that the test is valid?"

For a manufacturer, the desire is to have standards so that fair comparisons are possible. The need to continually prove that his (the manufacturer's) specifications are "correct" (better or equivalent to) when compared to a competitor's specifications results in lost of both time and revenue.

The discussion then went back to "how many angles need to be specified". One opinion was that a single set-up range test is sufficient (no horizontal angles) – otherwise, there are potential situations where the results could be "faked" or where the results may not be the same, thereby devaluing the test. The opposing opinion was that there needed to be some provision for being able to test at other angles if it is going to be a potential error or failure source. In the CMM community, this was a very contentious issue between the users and the manufacturers. However, in general, manufacturers want to keep their customers happy and give them what they want, and they will fix their problems. Regarding the standards, they are often written in such a way that if there is a problem, there is recourse for the user – "I tested this and this thing fails. I want a refund."

The issue that the problem is not universal to all instruments resurfaced. The group, however, felt that the protocol has to be "global" or inclusive and be applicable for any new technology that may be developed. If the specifications were well written, the instrument can be tested if what is specified is within the instrument's capabilities. The same should also apply to relative vs. absolute distance – some instrument may be able to measure absolute distance and the protocol should be written to allow for that possibility.

After some discussion, the general agreement among the group was that a basic set of measurements was necessary - from a start point the distance was incrementally increased. Again, it was reiterated that ranging problems as a function of the horizontal FOV was not common, but some provision should be made to allow the user to evaluate the instrument at two extra positions at user specified angles that is within the instrument's allowable horizontal FOV.

From a user's perspective, a user expects that if the specifications state that the instrument has been checked for its full range and rotation, then the understanding is that the manufacturer has "worked within the standard test" to know the instrument performs as stated within the entire range of motion. If a problem were encountered at a particular position in the course of using the instrument, then a user would have a means of recourse for resolving the problem.

A perspective based on experience with developing standard tests for CMMs was given. For CMMs, the manufacturers developed their own formula for MPE. "If you shoot straight down, is your MPE the same as if you rotated the instrument? If yes, then you don't even bother to report the rotation – you say it is valid for entire range of rotation. Initially, a manufacturer would check a small number of instruments over the full range of values for all conditions. Then in production mode, the manufacturer wants to check all the instruments as quickly as possible according to some set of criteria, and at this point, the manufacturer is probably not looking for any more of 'these problems'. So the problem could 'creep up' but the manufacturer is not aware of it, and this is possible as the manufacturer is not checking everything at this stage."

As another point of reference regarding a user's needs, for some tests currently being conducted for the Department of Transportation (DOT), the DOT requested that ranging tests include testing the range as a function of the horizontal FOV.

A point was made that the standards are being developed to give the user confidence in the instrument and as the users have raised this issue as a concern, it was suggested that it be included and the discussion move on to other topics. Therefore, there was group consensus on the protocol as currently written, but the protocol should be modified to allow the user two user-selected points within the horizontal FOV as applicable. Also, the protocol should evaluate relative distance.

EDITOR'S NOTE: *The draft protocol allows the user to select four points within the horizontal FOV. Given* $\mathbf{A}$ *= the maximum horizontal FOV of an instrument, the user evaluates the instrument at four selected horizontal angles,* $\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3, \mathbf{a}_4$, *with the following constraint:*

$$0 \le \mathbf{a}_1 \le \mathbf{A}/4, \quad \mathbf{A}/4 \le \mathbf{a}_2 \le \mathbf{A/2}, \quad \mathbf{A/2} \le \mathbf{a}_3 \le (3/4)\,\mathbf{A}, \quad (3/4)\,A \le \mathbf{a}_4 \le \mathbf{A}$$

Other Topics

On the topic of single point measurement vs. scanning a target, the group decided that separate protocols should be developed for both methods. If an instrument can perform both, then both protocols have to be carried out and if not, then the manufacturer has to state why the protocol is not applicable.

It was cautioned that there is a need to be clear about what is applicable – that it would be part of a manufacturer's specifications. A manufacturer conducts the evaluations under certain conditions, and if these aren't the conditions under which the user conducts the evaluations, then of course, those conditions are not applicable. It would be up to the manufacturer to state that these are the published standards, and this is what the instrument is able to conform to and these are not applicable. The feeling was that if a manufacturer keeps stating "not applicable" to everything, then the manufacturer will not be selling many instruments – "it is a market force issue."

A comment was made that some scanners may not be able to yield single point measurements – the method it uses may involve scanning a surface and then reporting a distance to that surface and it may not necessarily be the distance to the center of the surface.

It was then suggested that the manufacturer/user choose the measurement method, report the measured distance and then compare this measured distance to the reference distance. The procedure would then only specify *X* number of targets, reflectivities, distances, etc. The amount of time it took to obtain the measurements has to be reported in addition to the number of points, and if single point measurements were obtained or if it was scanned. Also, if the instrument does not have software to process the data, then the software used has to be stated.

A point was made that the sample rate should be included along with the time for data acquisition. Clarification of "data acquisition" time was sought.

- Does the time it takes to setup the scan count towards the total scan time? For example, to narrow the field of view down to the target, it would take at least a couple of scans – is that time to be included?
- At what point is the data acquisition considered done?
- Also, an instrument may scan very rapidly but take a lot of time to display the data or vice versa.
- For an instrument like a range finder that has a sample rate, for example, 100 000 points/s, it is relatively easy to measure the data collection time. It may not be as easy to test a total system and if this information was actually needed.

A user explained that what was important to him was the noise at given ranges and the time to collect the data. The noise will give a general indication of how much uncertainty he can expect in a job. Also, if that noise varies significantly with distance, then based on the job, one instrument may be more appropriate than another and the ability to determine that from the specifications is important to him. Additionally, the amount of time to collect the data is important as that would enable him give a more accurate estimate of the costs involved when developing a job proposal.

Another issue raised was that the method used to obtain the measurement in the evaluation test may not be how it is obtained in the field. For example, an instrument may sample at 40 000 points/s and get 40 000 measurements for a point. However, the output is one measurement of the point – the average of 40 000 measurements.

A user commented that what he wants to know is: "What is the range? What is the number of points that you output to me to calculate that range – not how many measurements did you use to calculate the points that you gave to me, and how long did it take to collect this set of points that you delivered to me."

There was some discussion about getting "skewed results" if the manufacturer changed the sample rate and the need to collect the measurements in the same manner as is done in the field.

The discussion then came back to an earlier suggestion that the manufacturer/user provides the test procedure, test results, time to test, process the data, and MPE at given ranges. The group was divided about whether the test procedures should be specified or not. If the procedures were specified, then it would be technology specific. The feeling was that the procedures should be as general as possible.

The group felt that the results from a protocol include:

- What is the range?
- How many points were used to calculate the range?
- What is the point acquisition/sample rate?
- What is the MPE?

3.2.2 Group 2

The discussion began with the topic of relative vs. absolute distance. The evaluation of relative distances using a track system although feasible for indoors, may not be viable for outdoors. The difficulty involved in moving targets around (weight and size of the targets), and the errors introduced from target set-up were mentioned. In the discussion, some suggestions made included the use of permanent pillars, the use GPS and a total station to obtain the reference distances, and the use of instrument mounts that allowed height adjustment and adjustments in 6 degrees of freedom (DOFs). A couple methods of determining or backing out the instrument center were briefly mentioned. Some questions raised were 1) Will a user be able to align the instrument in the field as well as is possible in a lab? 2) Is it necessary to align the instrument to the target? A response for the second question was that alignment is necessary to avoid abbé errors. A suggestion was made that for instruments where alignment was possible, i.e., instruments that had the capability of pointing, the absolute and relative distance protocols be used, and for instruments where alignment is not possible, then only the relative distance protocol be used. If an instrument can only perform the relative distance protocol then that instrument should not be viewed negatively as the application may not require absolute measurements. A cautionary note was inserted that while users require sufficient information to allow them to make sound decisions when purchasing an instrument, the protocols should not be overly restrictive to inhibit or impede the development of the instrument or make it too expensive for the vendor to manufacture the instrument. The group decided that the set of tests that is required depends on the instrument's capabilities. That is, a 2 x 2 matrix (see Fig. 3.1) with four possible tests an instrument can perform.

EDITOR'S NOTE*: The following example is included for clarification.*

	Pointing	*Scanning*
Absolute Distance	*A*	*A, B*
Relative Distance	*A, C*	*A, B, C, D*

Figure 3.1. Test matrix for range tests depending on an instrument's capabilities. A, B, C, and D are different instruments.

The assumption is that all instruments can scan.

Instrument A can obtain single point measurements and has a known instrument center that can be centered over a known point.
Instrument B cannot obtain single point measurements and has a known instrument center that can be centered over a known point.
Instrument C can obtain single point measurements and does not have a known instrument center.
Instrument D cannot obtain single point measurements and does not have a known instrument center.

A suggestion was made that the number of tests for outdoor evaluations be reduced because outdoor evaluations were felt to be more time consuming.

A test facility, operated by the National Geodetic Survey in Corbin, VA, with a range of 1.5 km or 1.4 km was mentioned as a possibility for instrument evaluation at longer ranges. However, in addition to this facility, it was felt that a similar facility at NIST would be beneficial.

The group revisited the issue of evaluating the range at various horizontal FOVs as there were mixed opinions as to whether these tests were required. It was mentioned that the practice of making a measurement, rotating the instrument, and making the measurement again is commonly done by surveyors. A user stated that the tests involving the horizontal FOVs evaluate the system rather than just the range. To this user, system evaluation is a very important issue and more valuable than knowledge of the individual errors. The system evaluation will yield the final performance of the instrument with all the errors combined. The ambiguity within the group about whether to include the horizontal FOV tests in the ranging protocol resulted from how these tests were viewed. One view is that the range protocol evaluates range errors as a function of distance, target reflectivity, angle of incidence, and horizontal FOV. The other view is that once angles are introduced, it is not a pure ranging test anymore but a system test. The group felt that the confusion arose from the assumption that elevation, azimuth, and range are uncorrelated when perhaps they were. As a concession to the possible limited ability to determine the elevation and azimuth errors and possible correlation of the range and angle measurements, the group felt that errors from varying FOVs could be grouped under the range error.

There was some discussion on software and having standardized software. There was some confusion among the group regarding which software was standardized. Most systems include software that at a minimum allows a user to control the instrument and specify output data. However, it is not this software that would be standardized but rather the fitting software (e.g., planes, spheres) - standardized in the sense that there would be agreement on which software to use - either open source code or a commercial software package. In addition to the standard fitting software, there is a need for standard software to process the data, e.g., identification and handling of outliers. This standard software will provide an objective means of determining which points are selected for the fit and which points are outliers.

Some of the confusion was also attributed to the need for fitting software. If the output is point clouds and there seems to be more situations where just the point cloud is all that is needed, i.e., no models created from the point clouds, then why is there a need for fitting software? The response was that fitting was required because for instruments that cannot obtain single point measurements, a plane had to be fitted through the points to obtain a range to that plane. Additionally, for future protocols, if distances between objects or the dimensions of an object are required then some fitting algorithm is needed.

The group decided to re-visit the topic of target configuration and size. The group felt that a circular planar target was a good choice because it had an identifiable or calculable center. However, this configuration may not yield sufficient points at 150 m to fit a circle, and a square, planar target may have to suffice. Another target used by someone in the group was a black and white target, and the center was determined by edge detection and line fitting. The group did not have sufficient information to determine the advantages/disadvantages of a circular target vs. a black and white target. A suggestion to use the median of the ranges as the measured range was made because this would not require as many points as is needed in the methods involving fitting - circle and plane fitting. Using the median value, however, would not account for the bias introduced when the target is rotated away from the instrument. It was pointed out that at 150 m the errors due to misalignment of the target and instrument would not be as significant as those at the shorter ranges. Another method offered to determine the center of the target was to have some type of detector or CCD photodiode in the center of the target which would give the operator some indication when it was hit by the laser. Other issues discussed were the number of points required to do edge detection. The minimum of 25 points as proposed in the protocol would not be sufficient. The number of points used to determine the range should be included as part of the report. The discussion went back and forth from black and white checkerboard targets and circular targets. The group ended their discussion with the conclusion that a planar square target may not be the optimal target but may be feasible.

3.2.3 Group 3

The group started their discussion with the horizontal FOV. Some issues raised include evaluation of systems with maximum ranges of 10 m and triangulation-based vs. TOF based instruments. The two issues were related in that most of the longer range systems are TOF systems, and for these systems, the horizontal FOV would not be a critical issue. Basically, “range is range”, i.e., no angles are involved in computing the range, and since only small angles are involved when scanning the target, the contribution to range error from angle error would not be significant. Evaluation of the horizontal FOV for triangulation-based systems may be necessary as angles are used to obtain the range, and an error associated with the FOV is possible if the system is not calibrated. Categorization of instruments would be helpful to users, and the applicability of the protocol to the various classes of instruments would be necessary.

Clarification of pointing vs. scanning was sought. Scanning, as the group discussed the previous day, involved scanning the target (25 points minimum), reducing the number points measured to calculate the target center. Pointing involved setting up the instrument and shooting one point continuously like a total station. Some instruments do not have this capability. A strong opinion was that the systems being evaluated are "scanning" systems and as such, they should be evaluated in the manner in which they will be operated in the real world. This is also the same rationale for why scanning a target was proposed in the protocol, and the fact that some instruments could not yield single point measurements. Another opinion was that most manufacturers scan a target to acquire the target, and if this was how the instrument was being operated, then it should be tested in the same way.

A statement was made that scanning the target would be less noisy than taking multiple single measurements because speckle noise, a systematic error, is reduced when scanning. A belief voiced was scanning and fitting a plane would yield a better estimate of the range than averaging repeated measurements of the same point. Scanning, however, introduces errors associated with fitting a plane and estimating the target center. A comment made was that the manufacturers had different software for plane fitting and this would introduce more uncertainty. The reply was that the manufacturer's software would not be used. The data would be exported to a standard fitting algorithm - a committee will have to agree on which algorithm is appropriate.

Another issue that was briefly touched upon was that some instruments could filter data based on the strength of the returned signal, e.g., a quality filter, and how would this be handled. In short, any filtering performed would be reported in the rated conditions. The error contribution from the angle error introduced by scanning a target, as discussed earlier, would not be significant. However, if the target was rotated to 30º or 60º, this contribution could be significant. A suggestion was made to put a restriction on the angle that is subtended by the target – this restriction indicates recognition that there is a spread of the measurements but it was agreed that to a large extent it doesn't have a significant geometric effect. It is a compromise between trying to get pure range error and the need to evaluate the sensor in the scanning mode, and the group felt that it was an acceptable compromise.

Based on the groups discussion from the previous day, the protocol should evaluate four levels of ranges, four levels of reflectivities, three levels of angles of incidence, and three levels of horizontal FOV – a total of 144 tests. The question was "do all these tests need to be performed?" The general feeling was "no". One suggestion was to do subsets – for example, for a given range, evaluate three levels of angles of incidence to determine the effect of angle of incidence. However, some users felt that it was important to know the relationships between range error and all of the parameters. Also, some important information may be omitted by doing subsets of tests. For example, an instrument may be able to get a measurement on a 2 % reflective target at a 0° incident angle, but it may not be able to get a measurement on a 2 %

reflective target at a 30° incident angle. Another comment was that the number of tests will depend on the intent of the test – will the tests be conducted daily, monthly, yearly? Is it an acceptance test? If it were an acceptance test, then it would be acceptable to spend two or three days conducting the tests. A suggestion was that the full set of tests be required for acceptance testing but a subset of tests (conducted at various time intervals) be used to determine major problems with instrument. Another suggestion was that the manufacturer conduct the full set of tests for new models – models where the inner workings were changed or if the internal software were changed and not if the packaging was changed.

EDITOR'S NOTE*: In the draft protocol, the effect of horizontal FOV is evaluated only as a function of range, i.e., the target reflectivity is set at > 90 % and the angle of incidence is 0º.*

There was a question regarding the minimum number of points required for the plane fit. It was felt that more points were required to get a better estimate of the RMS (root mean square) of the plane fit. The suggested range of points was 200 points to 400 points. The issue then was can most scanners get 200 points to 400 points on the target at 150 m. Clarification was sought on why would there be a limit on the number of points. The protocol does not have a limit on the maximum number of points – scanning is performed at maximum achievable density. The minimum limit is set so that if a scanner cannot return at least 25 measurements, then no measurement would be recorded for that range. Most manufacturers have a method that they use to acquire targets, and a suggestion was to use this method, regardless of number of points or time, to acquire the target. The drawback was that most of the targets that are used are special reflective targets – not the 2 % reflective targets.

The group felt that the specified flatness of the target plane, 1 mm over 1 m^2, was not adequate and should be ten times better. Another concern dealt with the target surface as the ranges would be different for different surfaces due to the absorption of the laser by the target. In one user's experience, the use of Spectralon target produced noisy results. Spectralon is a good diffuse material, but the laser penetrates the material. An appropriate material will have to be chosen based on depth of absorption, uniformly diffuse, etc. If the depth of penetration were small (micrometers), then it may not matter but the penetration depth will have to be determined. Marble and ceramic were also mentioned as problematic materials for some scanners. A person in the group had attended a conference where there was general agreement that bare aluminum would be good target material – glass would be better but expensive. The plate would be machined and painted with Spectralon or Kodak paint. Since the layer of paint would not be very thick, the penetration issue is minimized. It was noted that the issue of material penetration may not be an issue if the depth of penetration was constant and displacement (relative) measurements were to be evaluated.

Again, the point was made that the RMS error of the plane fit should be reported as it was very useful not only for knowledge of the spread but also useful when creating 3D models.

Methods to align the target and instrument were discussed. A method, used by surveyors, called "bucking in" was mentioned and described. The basic procedure was to look at the angles to the target, move the instrument over, and repeat the procedure. The alignment of target and instrument can be done quite easily indoors. An outdoor environment poses different problems, but the problems should not be insurmountable as the required accuracy is probably on the order of a degree or two. There was a suggestion to use a target with a small hole, where a mirror can be inserted, in the center of the target to help align the instrument and target. When testing for angle of incidence, it is also important to ensure that the planes remain parallel as it moved down the rail – or at least determine how much the orientation can differ from the nominal value without having a significant effect. A point was made that a facility where targets and benchmarks are permanently and accurately located could be established, and users could then bring their instruments to the facility to be evaluated. The implication was if the tests were meant to be reproduced at different facilities, then the cost associated with each set up may be a factor. Total stations rather than interferometers would likely be used to determine the reference distances when outdoors.

The following points are a summary of the group's discussions as noted by the chair:

- Triangulation system determines ranges based on angles; hence, range errors may be dependent on the horizontal FOV. TOF systems do not use angles to determine range so horizontal FOV is less critical.
- The instruments of interest are scanning instruments. Therefore, the data must be collected in a manner similar to how they will be operated.
- To understand the RMS of the range error, the RMS of the plane fit is desired.
- The group realizes that the range error cannot be easily decoupled from the angle error at non-zero incident angles, and a note of some sort needs to be included in the protocol.
- Approximately 300 measurements are needed to see the "true" RMS error of the plane fit.
- The flatness of the planar target should be ≈1/10 of the smallest uncertainty of the instrument being evaluated.
- The optical penetration of the target needs to be determined. However, if it were constant with range, then the error from penetration into the target will cancel out for displacement measurements. There was a suggestion to use an aluminum target with Spectralon paint.

A suggested alignment procedure for a pointing instrument was:

- Place a target at the center of the planar target - at the point to which the interferometer is measuring range and buck in the instrument so that the Δ AZ (azimuth) and Δ EL (elevation) is within a specified tolerance for the ranges to be measured. (For a non pointing scanner, derive the centroid of the target and then use the known relationship of the location of the interferometer point to the centroid and correct).
- Measure the AZ, EL coordinate to the center of the flat target at each range.
- Scan the flat target and create a plane in the instrument's reference frame.
- Using the AZ, EL vector from the instrument origin, intersect that ray with the best fit plane to get an X,Y,Z point on the plane.
- Repeat for each range (using the a priori AZ, EL associated value).
- Compare the Δ Range against the Δ Range from the interferometer
- For each plane, determine the number of points on the plane and the RMS value of the best fit plane.

Alternatively, the instrument alignment can be done mechanically as follows:

- Buck in the instrument so that the Δ AZ and Δ EL are zero as the target moves along a rail.
- Make sure the rotation axis is centered on the surface of the flat target.
- The flat surface targets must be parallel to within a specified tolerance for all the incident angles (the incident angles is based on the line-of-sight angle of the instrument/interferometer with the planar surface).

4.0 SUMMARY

The 3rd NIST Workshop on Performance Evaluation of 3D Imaging Systems was held on March 2-3, 2006 at NIST. The objectives of the workshop were:

- Select an SDO for 3D imaging systems.
- Finalize the draft terminology.
- Finalize the draft ranging protocol.

The terminology was discussed by all the participants as a single group. As the terminology was discussed at the 2nd NIST workshop in 2005, discussion time for each of the definitions was limited, and as each definition was presented, the participants were asked to note issues and concerns only. The list of terminology, issues raised, and new terms suggested for inclusion are given in Appendix A.

The ranging protocol is given in Appendix B. Section 4.2 presents summaries of common issues in the group discussions of the ranging protocol. In brief, the participants agreed on the following:

- A ranging protocol is required.
- The use of planar targets - circular or square.
- Evaluation of relative distance (displacement) - develop separate protocols to evaluate absolute distance and instrument offset.
- The importance of the test parameters - distance to target, target reflectivity, angle of incidence, and horizontal FOV. The tests involving the horizontal FOV may be replaced when protocols are developed to evaluate angle accuracy.

4.1 SDO Selection and Activity

Prior to the workshop, two SDOs, ASTM International and IEEE (Institute of Electrical and Electronics Engineers), were asked about their interest in developing standards for 3D imaging systems. Both expressed interest and were asked to respond to a questionnaire seeking general information on how their organization operated and how the standard developing process worked in their respective organizations. The responses to these questionnaires were sent to the participants prior to the workshop. Both SDOs were invited to make presentations at the workshop, but unfortunately, IEEE was unable to make a presentation at the workshop.

Following the ASTM presentation and a review of IEEE's responses, the participants were asked to vote for an SDO: ASTM, IEEE or No Preference. The vast majority of the participants selected ASTM as the SDO.

Following the workshop, ASTM held an organizational meeting on June 7, 2006 to establish a committee for 3D Imaging Systems. At this meeting, ASTM E-57[1], 3D Imaging Systems, was formally established. The scope of the committee was developed at the meeting and three subcommittees were established: Terminology, Test Methods, and Best Practices. After the June 7 meeting, committee officers were nominated and balloted: Committee Chair - Alan Lytle (NIST), Vice Chair - Alan Aindow (LeicaHDS), Membership Secretary - Tom Greaves (SparPoint), Recording Secretary - Steve Hand (MagLev). The first meeting of this committee will be in January 2007.

4.2 Summary of Group Discussions

The participants were divided into three groups to discuss the ranging protocol. Although the discussions took different paths, similar issues surfaced in the different groups and similar resolutions were reached.

A common issue was the intent of the protocol. The basic questions were:

- Who will use the protocol - manufacturers, users, or both?
- Will the instrument be sent to an evaluation/calibration facility or will the tests be conducted by anyone at their own facility?
- Will the tests be conducted daily, monthly, yearly? Is it an acceptance test?

The answers to these questions will provide guidance when developing the protocol. For example, if it were an acceptance test, then two or three days is a reasonable length of time to conduct the tests. Users also wanted a means for quick field verification, and if the tests were intended for periodic verification, then fewer and simpler tests were needed. A suggestion was that the full set of tests be required for acceptance testing, but for periodic or field verification, a subset of tests be used - where the subset will be defined in the protocol. In reference to the second bulleted question, if the tests were meant to be conducted by anyone, anywhere, then the test set-up cannot be overly elaborate and complex requiring costly expenditures in time and capital equipment.

Related to the intent of the protocol is the question of a user's expectations when reviewing an instrument's specifications. As with any test protocol, the protocol evaluates a system at discrete points. For example, when evaluating range error as a function of horizontal FOV, a user selects three or four angles (out of an infinite number of values) to test. Therefore, the probability of selecting the angles which cause problems is low, and the question is does the user expect that manufacturer has conducted tests at every potential azimuth angle. From a user's standpoint, the feeling was "probably not", but the hope is that the manufacturer has conducted more rigorous testing of the instrument. There was also a general sense that manufacturers do endeavor to be diligent when developing specifications for their instruments as this was in their best interests. The solution to this issue is the specification of rated conditions in the protocol. The rated conditions guarantee that the instrument will perform within the stated specifications.

[1] http://www.astm.org/COMMIT/E57

Specification of the rated conditions also addresses the issue of the inability to control the environmental factors outdoors.

Separation of the range error and the angle error was another common issue and was deemed a difficult problem. The need to determine the error contribution from both sources arises if the protocol required that the target be scanned rather than acquiring single point measurements. There was a suggestion to impose a restriction on the angle subtended by the target – this restriction indicates recognition that there is a spread of the measurements, but it was agreed that the angle error would not be significant due to the small angles involved when scanning the target. It is a compromise between trying to get pure range error and the need to evaluate the sensor in the scanning mode.

As implied in the previous paragraph, the combined range and angle error relates to the issue of pointing (single point measurement) vs. scanning a target. There was general consensus that the instrument should be evaluated in the manner in which it will be operated, that is, scanning mode. There are two major advantages of determining range error from single point measurements. First, no angles are involved and it would be "pure range error". Second, it eliminates the need to fit a plane and to determine a point on that plane to which the measured distance is derived. However, not all instruments have the ability to point the instrument and acquire single point measurements. Therefore, there was agreement that two protocols be developed - one for pointing and another for scanning. The ability to compare the results from these two tests was raised. The participants did not know if the results from these two tests would be comparable. There were mixed feelings about which test would yield a lower standard deviation - scanning a point 1000 times (standard deviation of the 1000 points) or scanning a target with 1000 points and fitting a plane through the 1000 points (RMS of the plane fit).

As the centers of some instruments are unknown or cannot be easily determined, there was general agreement that the relative distance be evaluated. It was also agreed that another test be developed to evaluate both absolute distance and any instrument offset. In two of the groups, scanning of calibrated artifacts was raised as an option, but there was no in-depth discussion of this option.

Target reflectivity was felt to be an important factor. There were several interesting and informative discussions on this topic. Some observations made were the reflectivities of most real world objects tend to be on the lower end - about 20 %, most of the problems occurred for reflectivities between 1 % and 20 %, and range error did not vary greatly for reflectivities between 20 % and 99 %. However, depending on the laser used, a lower reflectivity target may not be as problematic. For instance, if the instrument uses infrared or red lasers, a green target may result in greater range error than a black target because red and green are complementary colors. In two of the groups, there was a suggestion to have multiple reflectivities on a single target. Some systems, AM-CW systems in particular, may have some problems with a high/low contrast. In two of the groups, users have often asked manufacturers about the performance of their instrument for certain materials, e.g., concrete, wood. There was a suggestion to somehow relate the reflectivities of the targets used in the protocol to real world objects. Penetration of the target by the laser was also raised as an issue and further investigation was suggested.

Some of the participants questioned the inclusion of the tests to evaluate the range error as a function of the horizontal FOV. The feeling was that the horizontal FOV tests evaluated angle error and not range error, and these tests may not be problematic for some systems. A comment was made that if users raised this issue and if the protocol were meant to increase a user's confidence in the instrument, then these tests should be included. After some discussion, the consensus was to leave these tests in the range protocol until protocols to evaluate the angle error were developed. A part of this issue was the users' desire to have tests that evaluate the system as a whole - not just range error or angle error, but a single value that combined all the errors resulting from the system hardware and internal software. There was a suggestion in one of the groups to use a 3D target field.

The general feeling was that if horizontal FOV was considered important, then tests of the vertical FOV should also be included. One method to test the vertical FOV was to scan three targets on a stand relatively close to the instrument - this would maximize the range of vertical FOV to be tested. Several methods to test the full range of the vertical FOV at longer distances was discussed, but no simple method resulted from the discussions.

There was some discussion of the need for an indoor vs. an outdoor ranging facility. Both types of facilities were needed as users were about evenly divided between indoor and outdoor operation. Most service providers also have more than one type of scanner.

It was also discussed that there was a need to summarize the test results so that they can be easily understood by the customer. Using a limited number of graphs was suggested. The RMS of the plane fit should also be included in the results.

Some discussion on the specific details in the protocol included:

1. Highly reflective targets at the corners or surrounding the target, as suggested in the protocol, should not be used. The reason being these targets distort and adversely affect the range measurements.
2. There was general consensus on the use of planar targets - either circular or square.
3. Most participants did not feel that a 0.5 m by 0.5 m target would be large enough to yield sufficient points at 150 m.
4. The suggested planarity of the target, 1 mm over 1 m^2, was insufficient and a more stringent tolerance was recommended.
5. The suggested minimum number of points, 25, may be too small. More points may be required to fit a circle and more points may be needed to get a better estimate of the RMS of the plane fit.
6. Most participants felt that the design of the mounting assembly for the instrument and target should allow for easy height adjustment.

REFERENCES

1. Cheok, G. S., Ed. [2003], "Proceedings of the LADAR Calibration Facility Workshop, June 12-13, 2003," *NISTIR 7054* (CD-ROM), National Institute of Standards and Technology, Gaithersburg, MD, October.

2. Cheok, G. S., Ed. [2005]**,** "Proceedings of the 2nd NIST LADAR Performance Evaluation Workshop – March 15 - 16, 2005," NISTIR 7266, National Institute of Standards and Technology, Gaithersburg, MD, October.

3. American Society of Mechanical Engineers, "Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems," ASME B89.4.19-2006.

APPENDIX A: Draft Terminology

The Draft Terminology in this Appendix was presented at the 3rd NIST Workshop on the Performance Evaluation of 3D Imaging Systems. Based on the workshop discussions, some new terms were suggested for inclusion and some issues were raised for some definitions. The new terms and issues are included in this Appendix and are so indicated or if color is available, the new terms and issues are also highlighted in blue. Suggested definitions are offered for some of the new terms.

STANDARD DEFINITIONS OF TERMINOLOGY FOR 3D IMAGING SYSTEMS

PREFACE

In an effort to standardize terminology used for 3D imaging systems, the National Institute of Standards and Technology in conjunction with input from instrument manufacturers and users has developed a common terminology for 3D imaging systems. We are pleased to present this edition of a terminology pre-standard. We expect that the standard terminology document will expand on this pre-standard to include additional common terms and nomenclature.

A1.0 Referenced Definitions

The definitions of the terms presented in this section were obtained from various standard documents [1.1, and 1.3] developed by various standards developing organizations. The intent is not to change these universally accepted definitions but to gather, in a single document, terms and their definitions that may be used in current or future standard documents for 3D imaging systems.

In some cases, definitions of the same term from two standards have been presented to provide additional reference. The text between the square brackets to the right of each defined term is the name (as well as, in some cases, the specific section) of the source of the definition associated with that term.

Accuracy of measurement [VIM 3.5]:

Closeness of the agreement between the result of a measurement and a true value of the measurand

NOTES:

1. "Accuracy" is a qualitative concept.
2. The term "precision" should not be used for "accuracy".

Bias (of a measuring instrument) [VIM 3.25]:

Systematic error of the indication of a measuring instrument.

NOTE: The bias of a measuring instrument is normally estimated by averaging the error of indication over an appropriate number of repeated measurements.

Bias [Engineering Statistics Handbook]:

The difference between the average or expected value of a distribution, and the true value. In metrology, the difference between precision and accuracy is that measures of precision are not affected by bias, whereas accuracy measures degrade as bias increases.

Calibration [VIM 6.11]:

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

NOTES:

1. The result of a calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.
2. A calibration may also determine other metrological properties such as the effect of influence quantities.
3. The result of a calibration may be recorded in a document, sometimes called a calibration certificate or a calibration report.

Conventional true value (of a quantity) [VIM 1.20]:

Value attributed to a particular quantity and accepted, sometimes by convention, as having an uncertainty appropriate for a given purpose.

EXAMPLES:

a) At a given location, the value assigned to the quantity realized by a reference standard may be taken as a conventional true value;
b) The CODATA (1986) recommended value for the Avogadro constant, N_A: 6,022 136 7 x 10^{23} mol^{-1}

NOTES:

1. "Conventional true value" is sometimes called assigned value, best estimate of the value, conventional value or reference value. […]
2. Frequently, a number of results of measurements of a quantity is used to establish a conventional true value

Error (of measurement) [VIM 3.10]:

Result of a measurement minus a true value of the measurand.

NOTES:

1. Since a true value cannot be determined, in practice a conventional true value is used (see true value and conventional true value).
2. When it is necessary to distinguish "error" from "relative error", the former is sometimes called "absolute error of measurement". This should not be confused with the "absolute value of error", which is the modulus of error.

Indicating (measuring) instrument [VIM 4.6]

Measuring instrument that displays an indication

EXAMPLES:

a) analog indicating voltmeter;
b) digital frequency meter;
c) micrometer.

NOTES:

1. The display may be analog (continuous or discontinuous) or digital.
2. Values of more than one quantity may be displayed simultaneously.
3. A displaying measuring instrument may also provide a record.

Maximum Permissible Error (MPE) [VIM 5.21]

Extreme values of an error permitted by specification, regulations, etc. for a given measuring instrument.

Measurand [VIM 2.6]:

Particular quantity subject to measurement.

EXAMPLE: vapor pressure of a given sample of water at 20° C.

NOTE: The specification of a measurand may require statements about quantities such as time, temperature and pressure.

Precision [ASTM E456-02]

The closeness of agreement between independent test results obtained under stipulated conditions.

NOTES:

1. Precision depends on random errors and does not relate to the true value or the specified value.
2. The measure of precision is usually expressed in terms of imprecision and computed as a standard deviation of the test results. Less precision is reflected by a larger standard deviation.
3. "Independent test results" means results obtained in a manner not influenced by any previous result on the same or similar test object. Quantitative measures of precision depend critically on the stipulated conditions. Repeatability and reproducibility conditions are particular sets of extreme stipulated conditions.

Precision [Engineering Statistics Handbook]:

1. In metrology, the variability of a measurement process around its average value. Precision is usually distinguished from accuracy, the variability of a measurement process around the true value. Precision, in turn, can be decomposed further into short term variation or repeatability, and long term variation, or reproducibility.

2. A fuzzy concept term for the general notion that one knows more or has shorter confidence intervals if one has more data; that is, more data gives greater precision in answers and decisions.

Random Error [VIM 3.13]:

Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions:

NOTES:

1. Random error is equal to error minus systematic error.
2. Because only a finite number of measurements can be made, it is possible to determine only an estimate of random error.

Relative Error [VIM 3.12]:

Error of measurement divided by a true value of the measurand.

NOTE: Since a true value cannot be determined, it practice a conventional true value is used.

Repeatability (of results of measurements) [VIM 3.6]:

Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement.

NOTES:

1. These conditions are called repeatability conditions.
2. Repeatability conditions include:
    - the same measurement procedure
    - the same observer
    - the same measuring instrument, used under the same conditions
    - the same location
    - repetition over a short period of time
3. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.

Reproducibility (of results of measurements) [VIM 3.7]:

Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement.

NOTES:

1. A value statement of reproducibility requires specification of the conditions changed.
2. The changed conditions may include:
    - principle of measurement
    - method of measurement
    - observer
    - measuring instrument
    - reference standard
    - location
    - conditions of use
    - time.
3. Reproducibility may be expressed quantitatively in terms of the dispersion characteristics of the results.
4. Results are here usually understood to be corrected results.

Systematic Error [VIM 3.14]:

Mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus a true value of the measurand.

NOTES:

1. Systematic error is equal to error minus random error.
2. Like true value, systematic error and its causes cannot be completely known.
3. For a measuring instrument, see “bias”.

Uncertainty of measurement [VIM 3.9]:

Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.

NOTES:

1. The parameter may be, for example, a standard deviation (or a given multiple of it), or the half-width of an interval having a stated level of confidence.
2. Uncertainty of measurement comprises, in general, many components. Some of these components may be evaluated from the statistical distribution of the results of series of measurements and can be characterized by experimental standard deviations. The other components, which can also be characterized by standard deviations, are evaluated from assumed probability distributions based on experience or other information.
3. It is understood that the result of the measurement is the best estimate of the value of the measurand, and that all components of uncertainty, including those arising from systematic effects, such as components associated with corrections and reference standards, contribute to the dispersion.

True value (of a quantity) [VIM 1.19]:

Value consistent with the definition of a given particular quantity

NOTES:

1. This is a value that would be obtained by a perfect measurement.
2. True values are by nature indeterminate.
3. The indefinite article “a”, rather than the definite article “the”, is used in conjunction with “true value” because there may be many values consistent with the definition of a given particular quantity.

A1.1. REFERENCES

1.1 ASTM International, ASTM E456-02, “Standard Terminology Relating to Quality and Statistics,” American Society of Testing and Materials.

1.2. Engineering Statistics Handbook, http://www.itl.nist.gov/div898/handbook/glossary.htm

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

A2.0 Standard Definitions for 3D Imaging Systems

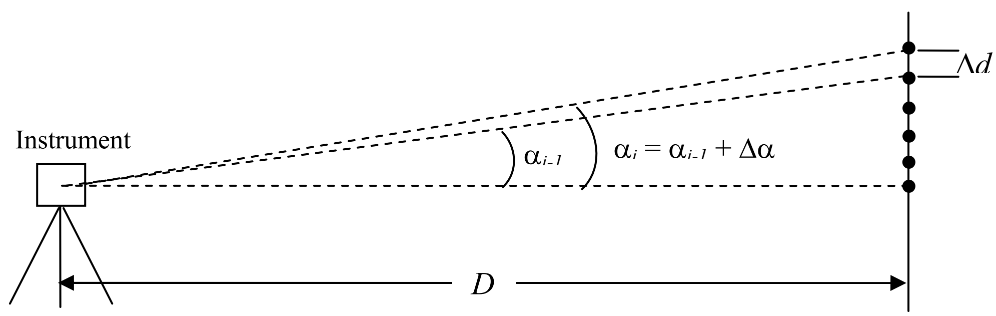
3D Imaging System

A three-dimensional (3D) imaging system is an indicating instrument that is used to rapidly measure (on the order of thousands of measurements per second or faster) the range and bearing to and/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, and 3D flash LADARs.

***Issues**:* Care has to be taken when identifying which systems are to be included or excluded. Should photogrammetry be included/excluded? What about medical and short range imaging systems? Suggest rewording the sentence "These systems include laser scanners, 3D optical scanners, 3D range cameras, LADARs, and 3D flash LADARs." to "These systems include but are not limited to laser scanners, 3D optical scanners, 3D range cameras, LADARs, and 3D flash LADARs."

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 is also known as the angle step size.



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

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 between contiguous pixels or points, Δd, as shown above.

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

Angular resolution

See *Resolution*

Beam Spot Size (New term)

Size of the light or laser beam as it hits a plane perpendicular to its travel path.

Control points

Visible or recoverable reference points common to both an independent source of higher accuracy and the product itself (point-cloud). An example of a recoverable reference point is the center of a sphere, while not visible, it can be obtained by processing suitable data. Control points are sometimes referred to as fiduciaries.

Control points may be used to:

- register two or more point clouds into a common reference coordinate system
- infer the accuracy of the derived output of a 3D imaging system.

Example: Control points are designated in a scan region and the locations of these control points (reference locations) are obtained by an instrument (such as a total station) of higher accuracy than the 3D imaging system used. The distances between any two of these control points (reference distances) can be calculated using the reference locations. Similarly, the distances between corresponding control points (measured distances) in the point cloud or model can also be calculated using the data obtained by the 3D imaging system. The differences between the measured and reference distances or the errors may be used to infer the accuracy of the point cloud or model. However, the errors are only known at the control points and may or may not be representative of the entire point cloud or model.

Cross-talk or crosstalk (New term)

see Pixel cross-talk

First return

The first return is the first reflected signal that is detected by the 3D imaging system for a given sampling position (i.e., azimuth and elevation angle).

Flash LADAR

A 3D imaging system comprised of a broad field illumination source (commonly a laser, but for close proximity it can be a bank of LEDs) and a focal plane array (FPA) detector, such that the range image is acquired simultaneously in one burst. This allows for the achievement of high frame rates (on the order of 30 frames per second or faster) which is critical for real time applications.

Frame

A frame is equivalent to a region of interest where data is to be acquired. The size of the frame is generally user specified with the maximum size of a frame equivalent to the field of view (FOV) of the instrument.

Issues*:* The term frame is often used to refer to a coordinate system – suggest using a different term. Consider the concept an area or volume of interest?

Frame Rate

The frame rate is the number of frames that can be acquired per second. For example, if 10 frames could be acquired in one second, the frame rate would be 10 Hz. This is generally a metric that is mainly applicable to real-time systems such as flash LADARs, since most commercial scanning 3D imaging systems have update rates on the order of minutes and are dependent on the laser pulse repetition rate, selected FOV, and selected angular increment. However, for non-real time instruments, knowledge of the frame rate is useful when comparing instruments as a higher frame rate could mean increased productivity.

In the case of non-real time systems, an appropriate description of the frame rate should include the time, FOV, and angular increment. For example, "the time to acquire a frame for a FOV of 360° x 90°, at an angular increment of 0.2° (horizontal and vertical) is 180 s." Note that the frame rate for a FOV of 90° x 360°, at an angular increment of 0.2° (horizontal and vertical) may be different if the mechanical speeds of the horizontal and vertical movements are different.

Instrument Center

The instrument center is the point within or on the surface of an instrument from which all instrument measurements are referenced, i.e., instrument origin (0, 0, 0).

Last return

The last return is the last reflected signal that is detected by the 3D imaging system for a given sampling position (i.e., azimuth and elevation angle).

Mixed Pixels

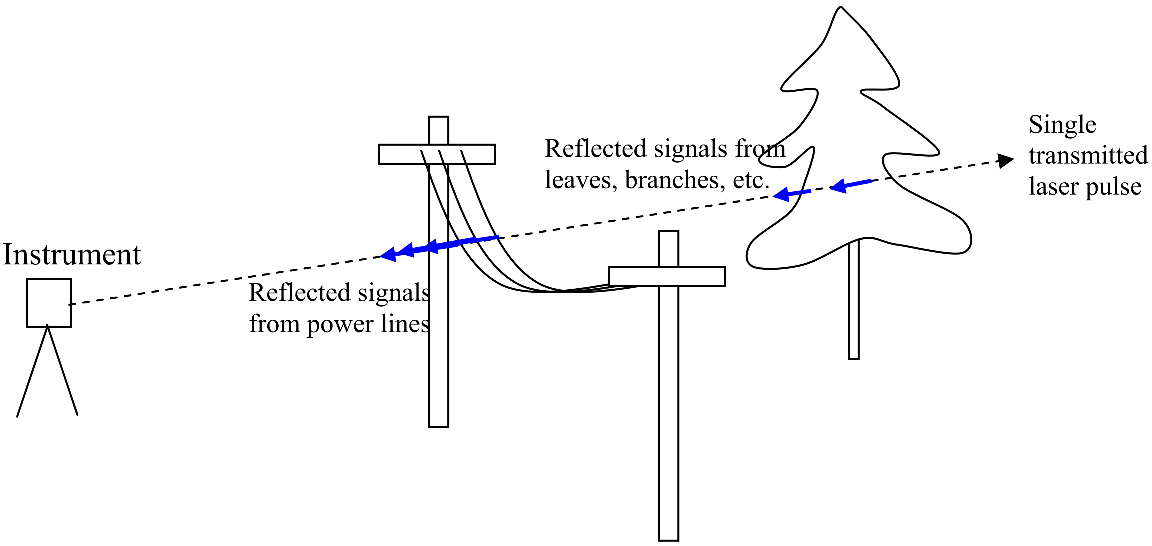
Mixed pixels or phantom points are a result of the way most instruments process multiple returns. When a laser beam hits the edge of an object, the beam is split. Part of the beam is reflected by the object and the other part is reflected by another object beyond. Thus, the reflected signal contains 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 initial beam spot size, smaller beam divergence, and the capability of the 3D imaging system to record multiple returns.

Modular transfer function (New Term)

Multiple returns

Multiple returns occur when the laser beam hits multiple objects separated in range. When this occurs, the beam is split and multiple signals are detected by the 3D imaging system, see figure below.



***Outlier (New term)* [*NIST/SEMATECH e-Handbook*]**

An observation that lies an abnormal distance from other values in a random sample from a population. In a sense, this definition leaves it up to a consensus process to decide what will be considered abnormal. Before abnormal observations can be singled out, it is necessary to characterize normal observations. Outliers should be investigated carefully. Often they contain valuable information about the process under investigation or the data gathering and recording process. Before considering the possible elimination of these points from the data, one should try to understand why they appeared and whether it is likely similar values will continue to appear. Of course, outliers are often bad data points.

***Issue*:** Do we leave this term in this section or move it to Section A1.0? Reason to leave in this section - if a definition of what are "normal" observations is included. Since the definition of "normal" observations would probably vary for different instruments (instruments other than 3D imaging systems), it is suggested that the term be left in this section. Reason to move to Section A1.0 - if no definitions are offered for "abnormal" or "normal" observations. If outliers are defined in the individual test protocols, then move this term to Section A1.0.

Panoramic imaging (New term)

Phantom Points

See "mixed pixels."

Pixel cross-talk (New term)

The fraction, often expressed as a percentage or a ratio (often expressed in decibels for power ratios), of the received signal amplitude (e.g., optical power, current, voltage, or electrical power) in a pixel when that pixel and only that pixel is supposed to be illuminated with the transmitted signal to the signal amplitude in any other pixel not supposed to be illuminated nor in any way supposed to receive the signal.

The cross-talk may not be constant across the array as the amount of cross-talk from one pixel to another pixel may depend on which pixel in an array is being illuminated and which other pixel is being measured to determine the cross-talk.

The pixel cross-talk may be 1) due to optical cross-talk (due to signal light scattered into other pixels), 2) produced by some re-emission process in a detector or other component in the ladar transceiver, and propagated to other detectors [as occurs in some silicon Geiger-mode Avalanche Photodiodes (APDs)], or 3) due to electronic cross-talk which is caused by the electronic signal produced from either the laser source or when the electrical signal produced by the light illuminating one pixel is coupled into another pixel (through induction, capacitance, radiation, or ground loop currents).

Point Cloud

A point cloud is a collection of 3D points, frequently in the hundreds of thousands, as obtained using a 3D imaging system.

Point Density

Point density is the number of points per unit area.

EXAMPLE:

$$\text{Point density at distance } r = \frac{a \times b}{x \times y}$$

$$x = 2 \times r \tan\left(\frac{\theta}{2}\right)$$

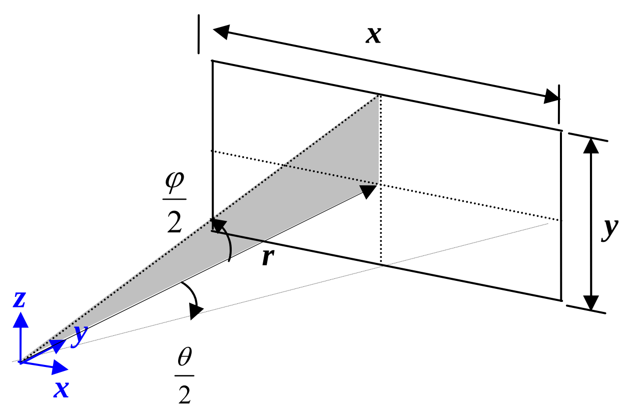
$$y = 2 \times r \tan\left(\frac{\varphi}{2}\right)$$

a = nominal number of points in row

$$= \frac{\theta}{\Delta\theta} + 1$$

b = nominal number of points in a column

$$= \frac{\varphi}{\Delta\varphi} + 1$$



θ, φ = user specified field of view for a scan

$\Delta\theta, \Delta\varphi$ = angular increment in the horizontal and vertical directions, respectively.

Suggested r: 20 m, 50 m, and 100 m

Issues: Consider row/line and column point spacing and report both values individually instead of points per unit area. Point density is dependent on beam spot size – what happens when beam spot size on an object is large? Other possible terms instead of point density are "cloud point density", "captured point density", and "displayed point density". Should point density be decoupled from angular resolution?

Registration

Registration is required when two or more sets of coordinate data are obtained with each data set having its own frame of reference or local reference frame. The task of registration involves determining a set of rigid body transformations and applying those transformations to a data set to transform that set into another reference frame or to a global reference frame.

Registration Error

Local registration error: deviation from spatial agreement of registered point clouds at a location in an overlap region.

Global registration error: combination of local registration errors based on a vector norm such as RMS $\left(\sqrt{\frac{\sum e^2}{n}}\right)$.

Resolution

Range or depth resolution: The smallest distance or separation, in range or depth, between two distinct objects that can be detected in a single scan.

Horizontal resolution: The smallest horizontal distance or separation between two distinct objects that can be detected in a single scan at a specified distance from the instrument.

For example, given a statement "The instrument has a horizontal resolution of 30 mm at 100 m." A user may infer that two objects, located at a maximum distance of 100 m from the instrument, are distinguishable if they are separated by 30 mm.

To eliminate the need to associate the horizontal resolution with a given distance, a *horizontal angular resolution* may be specified. The horizontal angular resolution will be based on the horizontal resolution.

For example, given a horizontal resolution of 30 mm at 100 m, the horizontal angular resolution is equal to

$$\arctan\left(\frac{30}{100 \times 1000}\right) = 0.017^{\circ}$$

It is suggested that several angular resolutions be calculated based on the horizontal resolutions at various distances from the instrument and that the specified horizontal resolution be, conservatively, set equal to largest value.

For example, given the following information,

$$\text{horiz. resolution of 14 mm at 50 m} \Rightarrow \text{angular resolution} = \arctan\left(\frac{14}{50000}\right) = 0.016^{o}$$

$$\text{horiz. resolution of 29 mm at 100 m} \Rightarrow \text{angular resolution} = \arctan\left(\frac{29}{100000}\right) = 0.017^{o}$$

$$\text{horiz. resolution of 49 mm at 150 m} \Rightarrow \text{angular resolution} = \arctan\left(\frac{49}{150000}\right) = 0.019^{o}$$

then the specified horizontal angular resolution would be 0.019^{o}.

Vertical resolution: The smallest vertical distance or separation between two distinct objects that can be detected in a single scan at a specified distance from the instrument.

In a similar manner to the horizontal angular resolution, the *vertical angular resolution* may be specified.

***Issues**:* The range or depth resolution requires further thought. Instead of horizontal and vertical resolution consider replacing with lateral resolutions.

Spatial performance

Spatial performance may be quantified using several different types of measures. The measure that is often used is based on the deviation of corresponding control points. These deviations are frequently combined using the RMS method. Adopting this method, the spatial performance is calculated as follows:

$$\sqrt{\frac{\sum_{i=1}^{n}\left[\left(x_{m,cp\,i} - x_{ref,cp\,i}\right)^2 + \left(y_{m,cp\,i} - y_{ref,cp\,i}\right)^2 + \left(z_{m,cp\,i} - z_{ref,cp\,i}\right)^2\right]^2}{n}}$$

where

$x_{m,cp\,i}$, $y_{m,cp\,i}$, $z_{m,cp\,i}$ = coordinates of control point *i* as measured by the 3D imaging system

$x_{ref,cp\,i}$, $y_{ref,cp\,i}$, $z_{ref,cp\,i}$ = coordinates of control point *i* as measured by an instrument of higher accuracy than the 3D imaging system used

Issue: The consensus was that the term is necessary but requires a new definition.

A3.0 Standard Acronyms for 3D Imaging Systems

APD

An acronym for "Avalanche Photo Diode".

CCD

An acronym for "Charge Coupled Device". An imaging sensor where individual pixels in an array are allowed to transport, store, and accumulate optically-generated charge carriers to defined sites within the device. CCD principles, combined with on-chip timers for each pixel can be used to create a time-of-flight focal plane array.

FOV

An acronym for "Field of View". The angular coverage of a scene and the units normally associated with FOV are degrees, e.g., The LADAR has an FOV of 300° (horizontal) x 80° (vertical).

FPA

An acronym for "Focal Plane Array". A 2D "chip" in which individually addressable photo sensitive "pixels" can be accessed.

LADAR

An acronym for a laser (light) detection and ranging (LADAR) system. A LADAR is a system that is used to obtain multiple distance measurements of a scene. These measurements, several thousand to several million, are commonly referred to as a "point cloud". The distances are measured by measuring the time-of-flight of a laser pulse, the phase difference of a laser pulse, or by triangulation.

The term LIDAR has been commonly associated with airborne laser radars while the term LADAR has been commonly associated with ground-based laser radars.

LIDAR

An acronym for a light detection and ranging (LIDAR) system. Similar to the term LADAR, a LIDAR system is used to obtain multiple measurements (e.g., distances, velocities, chemical concentrations) of a scene.

The term LIDAR has been commonly associated with airborne laser radars and those systems that perform remote sensing of the atmosphere.

APPENDIX B: Draft Ranging Protocol

A Ranging Protocol for 3D Imaging Instruments

B1. 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.

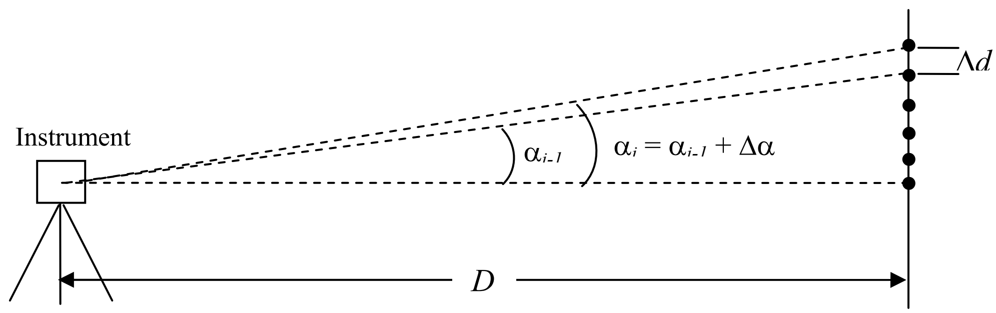
B2. INTRODUCTION

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.

B3. 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 = $\Delta d \approx D\,(1 + \tan^2 \alpha)\,\Delta\alpha$

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. B1].

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.

B4. PERFORMANCE TESTS

In this Section and in Section B5, 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 B4.1, 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.

B4.1 Targets and sampling

B4.1.1 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 B1. 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 B1. Measurements outside of this area will be ignored.

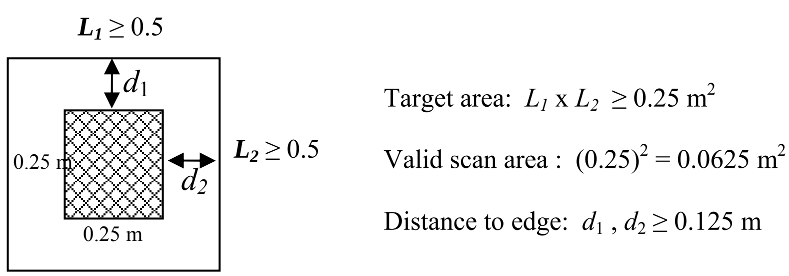
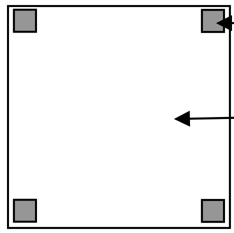


Figure B1. Target Dimensions and Valid Scan Area.

To identify the outliers in the data, two potential methods are suggested (Figure B2): 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 B5.1.



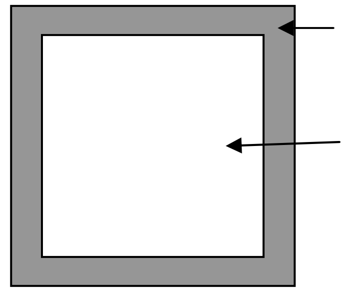


Figure B2. Two Methods to Determine Target Plane.

B4.1.2 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 B4.1.1).

The center of the scan area should approximately coincide with the center of the target (Section B4.2.2).

B4.2 Ranging Tests

B4.2.1 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 X (value to be decided by standards committee). If benchmarks are used, the uncertainty of the benchmark locations should be less than or equal to Y (value to be decided by standards 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. B2) 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 $u(d_{ref}) \leq 0.63$ mm.

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

B4.2.2 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 B3.

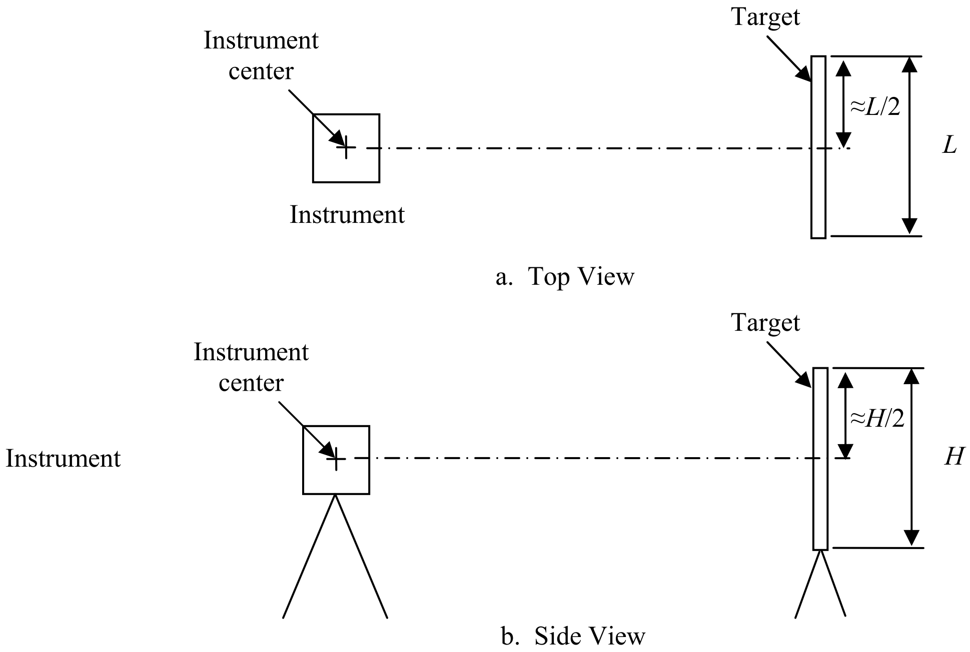


Figure B3. Instrument Set-

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

B4.2.3 Test procedures

Measurements are made with the instrument and target positioned and oriented as described in the Table B4.1. Three measurements shall be performed for each position in Table B4.1. The tests are proposed to evaluate the effects of distance, target reflectivity, and angle of incidence on range error.

Table B4.1. Ranging Test Positions

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

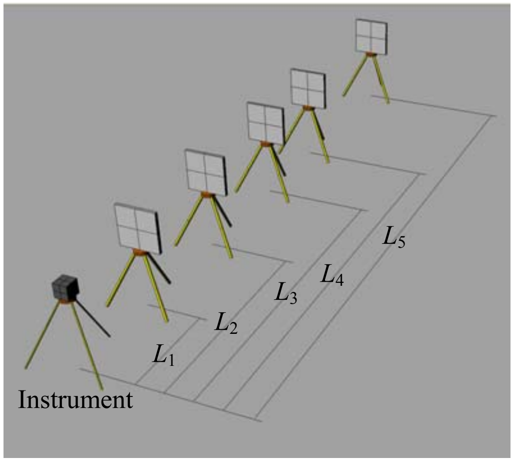
4	Smaller of: 1. $10\%\ \boldsymbol{R} \le L_1 \le 20\%\ \boldsymbol{R}$ or 2. 30 m	0	$3\boldsymbol{A}/4 < \theta \le \boldsymbol{A}$	> 90%	0
5	Smaller of: 1. $20\%\ \boldsymbol{R} < L_2 \le 40\%\ \boldsymbol{R}$ or 2. 60m	0	$0 \le \theta \le \boldsymbol{A}/4$	> 90%	0
6	Smaller of: 1. $20\%\ \boldsymbol{R}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

22	Smaller of: 1. 20% ***R*** < $L_2 \leq$ 40% ***R*** or 2. 60m	0	Any	> 90%	20
23	Smaller of: 1. 40% ***R*** < $L_3 \leq$ 60% ***R*** or 2. 90 m	0	Any	> 90%	20
24	Smaller of: 1. 60% ***R*** < $L_4 \leq$ 80% ***R*** 2. 120 m	0	Any	> 90%	20
25	Smaller of: 1. 80% ***R*** ≤ L_5 100% ***R*** 2. 150 m	0	Any	> 90%	20
26	Smaller of: 1. 10% ***R*** ≤ $L_1 \leq$ 20% ***R*** or 2. 30 m	0	Any	> 90%	40
27	Smaller of: 1. 20% ***R*** < $L_2 \leq$ 40% ***R*** or 2. 60m	0	Any	> 90%	40
28	Smaller of: 1. 40% ***R*** < $L_3 \leq$ 60% ***R*** or 2. 90 m	0	Any	> 90%	40
29	Smaller of: 1. 60% ***R*** < $L_4 \leq$ 80% ***R*** 2. 120 m	0	Any	> 90%	40
30	Smaller of: 1. 80% ***R*** ≤ L_5 100% ***R*** 2. 150 m	0	Any	> 90%	40
31	Smaller of: 1. 10% ***R*** ≤ $L_1 \leq$ 20% ***R*** or 2. 30 m	0	Any	> 90%	60
32	Smaller of: 1. 20% ***R*** < $L_2 \leq$ 40% ***R*** or 2. 60m	0	Any	> 90%	60
33	Smaller of: 1. 40% ***R*** < $L_3 \leq$ 60% ***R*** or 2. 90 m	0	Any	> 90%	60
34	Smaller of: 1. 60% ***R*** < $L_4 \leq$ 80% ***R*** 2. 120 m	0	Any	> 90%	60
35	Smaller of: 1. 80% ***R*** ≤ L_5 100% ***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 ***R*** or 10 m	0	Any	> 90%	0
37	smaller of ≈0.4 ***R*** or 20 m	0	Any	> 90%	0
38	smaller of ≈0.6 ***R*** or 30 m	0	Any	> 90%	0
39	smaller of ≈0.8 ***R*** or 40 m	0	Any	> 90%	0
40	smaller of ≈1.0 ***R*** or 50 m	0	Any	> 90%	0
41	smaller of ≈0.2 ***R*** or 10 m	0	Any	60% to 80%	0

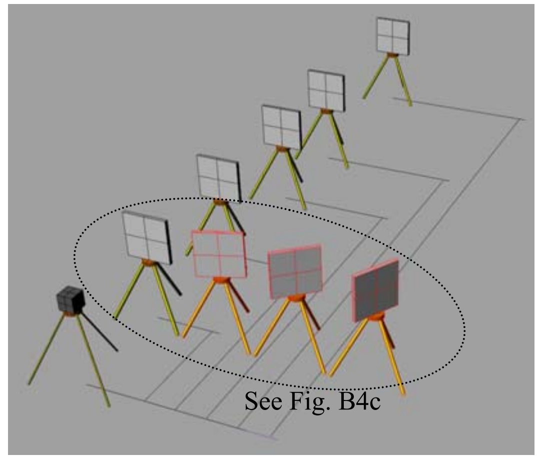
42	smaller of ≈0.4 ***R*** or 20 m	0	Any	60% to 80%	0
43	smaller of ≈0.6 ***R*** or 30 m	0	Any	60% to 80%	0
44	smaller of ≈0.8 ***R*** or 40 m	0	Any	60% to 80%	0
45	smaller of ≈1.0 ***R*** or 50 m	0	Any	60% to 80%	0
46	smaller of ≈0.2 ***R*** or 10 m	0	Any	40% to 60%	0
47	smaller of ≈0.4 ***R*** or 20 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 B4 for corresponding target orientation.

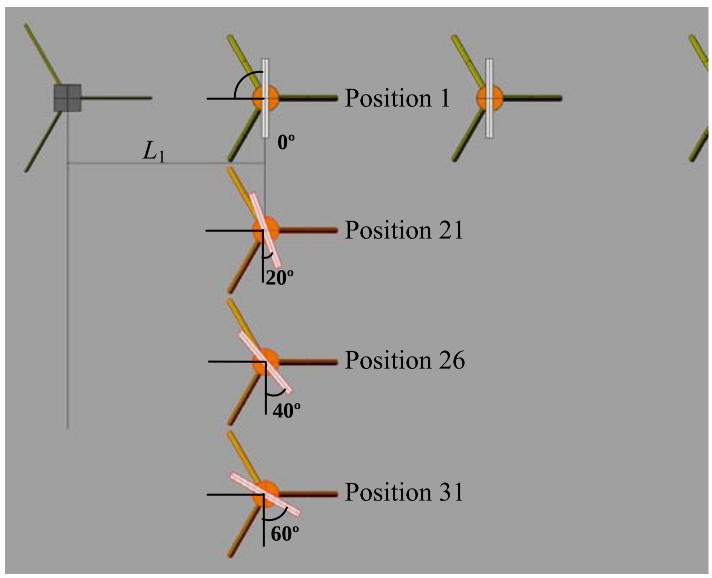
The shaded cells are potential tests that may be eliminated to reduce the number of tests required.



a.



b.



c. Top view of Figure B4b showing target orientation.

Figure B4. Ranging test set-up showing various target positions and orientations.

B5. DATA PROCESSING

B5.1 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.

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

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 B5).

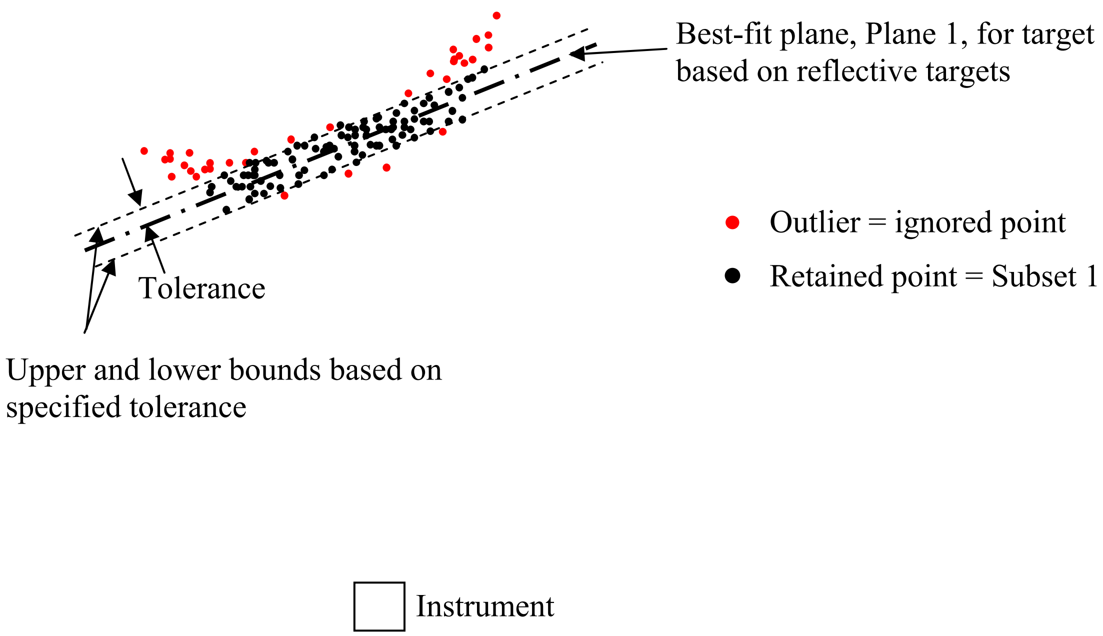


Figure B5. Top View showing segmentation of outliers.

B5.2 Determining Valid Measurements

The center of the points (x_c, y_c, z_c) in Subset 1 (Section B5.1) 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 B6): 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 B5.1.

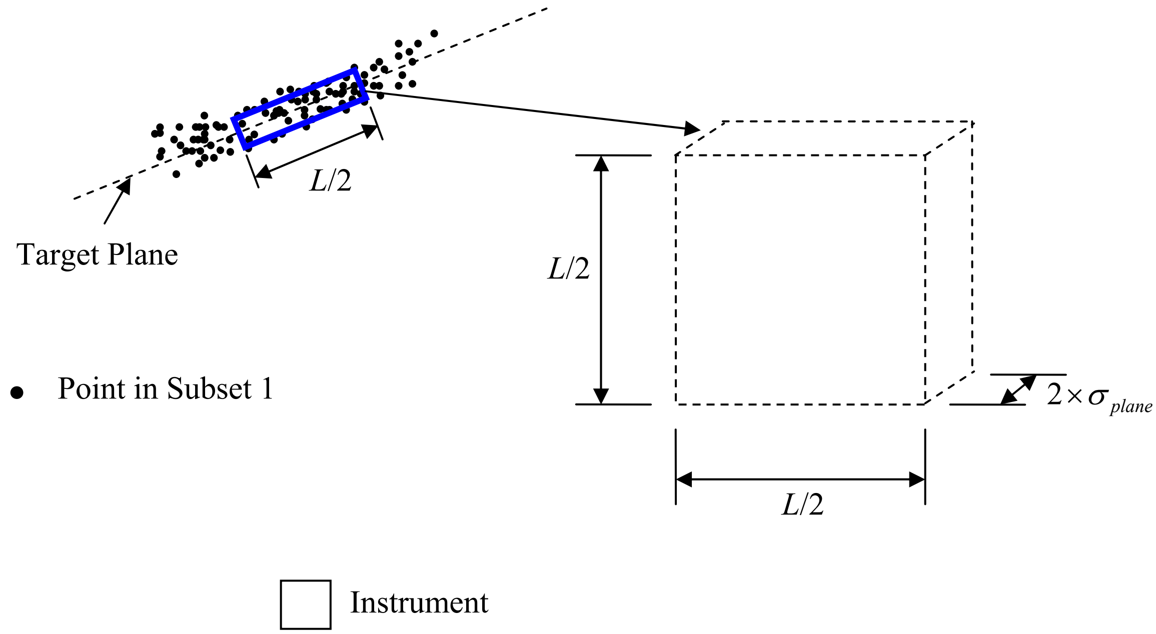


Figure B6. Top view showing bounding box for determining valid measurements.

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.

B5.3 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 = number of valid measurements as determined in Section B5.1

For the target distance to be valid, n has to be greater than 25 as per Section B4.1.2.

B6. REPORTING RESULTS

For each day of testing, a General Specifications and Rated Conditions Form, Form B6.1, shall be completed.

Form B6.1. 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 B5.4) and d_{ref} (Section B4.2.1) 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 B6.2.

Form B6.2. 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							

B7. REFERENCES

B1. International Organization for Standardization, International Vocabulary *of Basic and General Terms in Metrology*, 1993. (VIM)

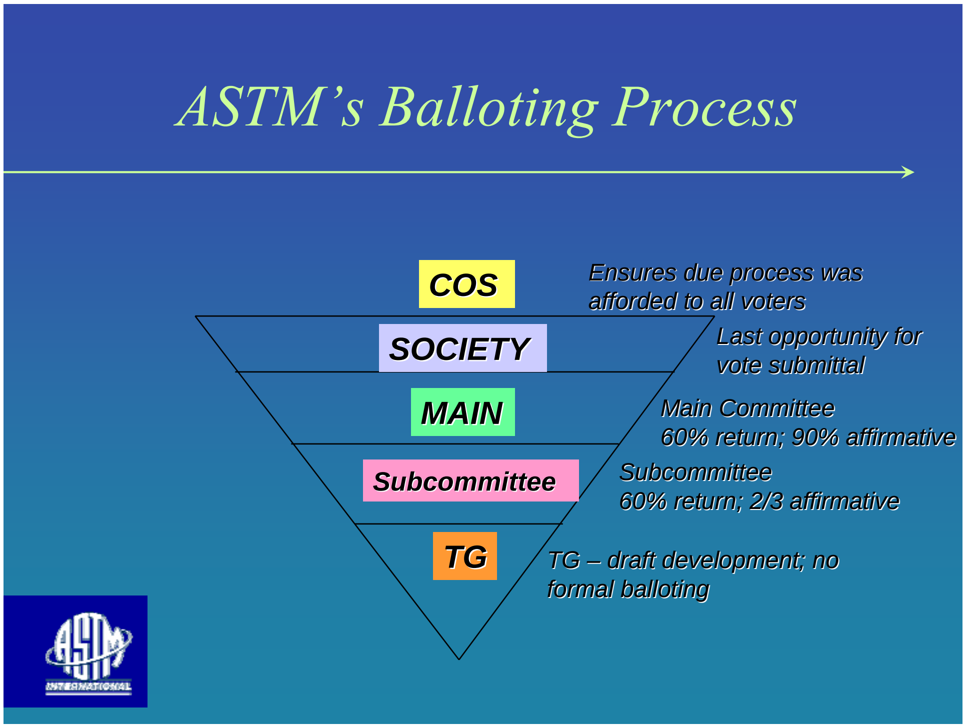
B2. American Society of Mechanical Engineers, "Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems," ASME B89.4.19-2006.

APPENDIX C: Standards Development for 3D Imaging Systems: ASTM International – Pat Picariello (ASTM International)

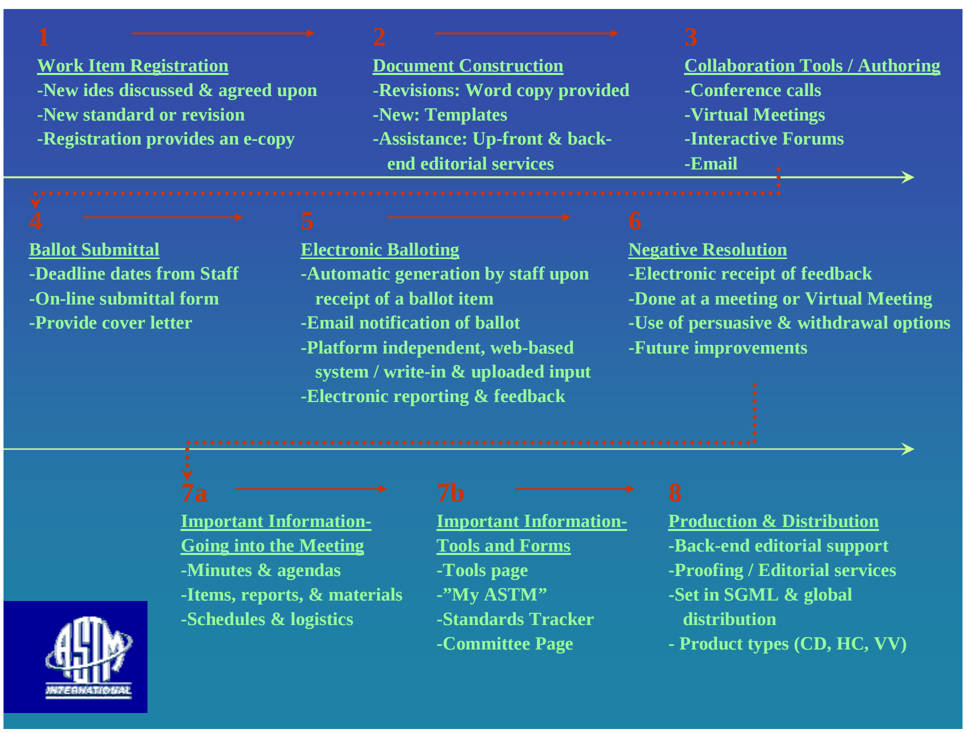
Reproduced with permission from Pat Picariello

Slide C1

Slide C2



Slide C3



Slide C4

Time Frame - Development

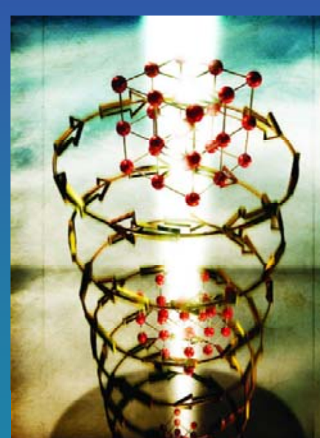
- Complexity of the job
- Urgency of needs
- Time devoted by members
- Utilization of new informational technologies

Slide C5

138 Technical Committees

Examples

- A1 on Steel, Stainless Steel, and Related Alloys
- B1 on Electrical Conductors
- D1 on Paint
- D2 on Petroleum Products and Lubricants
- D4 on Road and Paving Systems
- E28 on Mechanical Testing
- E17 on Vehicle Pavement Systems
- E29 on Particle Size Characterization
- E30 on Forensic Science
- E50 on Environmental Assessment
- E54 on Homeland Security Applications
- E55 on Pharmaceutical Application of PAT
- E56 on Nanotechnology
- F1 on Electronics
- F4 on Medical & Surgical Materials & Devices
- F5 on Business Imaging Products
- F8 on Sports Equipment and Facilities
- F15 on Consumer Products
- F24 on Amusement Rides and Devices
- F25 on Ships and Marine Technology
- F29 on Anesthetic & Respiratory Equipment
- F37 on Light Sport Aircraft
- F38 on Unmanned Air Vehicle Systems
- F40 on Declarable Substances in Materials
- F41 on Unmanned Undersea Vehicle Systems

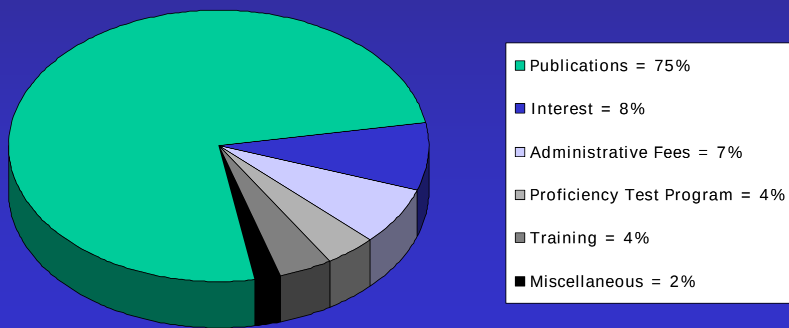


Slide C6

ASTM's Business Model

Annual Budget of $35 Million

Revenue Sources 2005



Slide C7

Related ASTM Activity

- Computer Assisted Orthopedic Surgery
- Computed Tomographic (CT) Examination and Imaging Systems
- Digital Imaging and Communication in Nondestructive Evaluation (DICONDE)
- Interferometric Laser Imaging Nondestructive Inspection Systems

Slide C8

Foundation ASTM Activity

- Construction
  - Engineering & Dimensional Analysis
  - Reverse Engineering
- Manufacturing
  - Process Control
  - Tooling Verification
- Design/Prototyping
- Animation
- Industrial Metrology
- Forensics/Anthropology
- Wear Analysis

Slide C9

Organization Process: New Activity

- Mirrors Standards Development Process
- Industry Driven
- 3-Stage
  - Exploratory
    - Post initial request, due diligence, market research
  - Planning*
    - Live meeting of <u>key stakeholders</u>, education, formal agreement to proceed
  - Organizational
    - Live meeting of <u>all interested stakeholders</u>, agreement on title, scope, structure, formal agreement to organize within ASTM International

*Standards development should have commenced by this point

Slide C10

Questions?

Pat Picariello
610.832.9720
ppicarie@astm.org

ASTM Website
www.astm.org

Slide C11

APPENDIX D: Verification and Calibration Process of Time-of-flight Laser Scanners – Brent Gelhar (Optech)

Reproduced with permission from Brent Gelhar.

Slide D1

Slide D2

Optech

Optech Overview

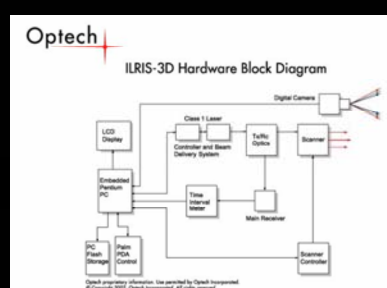
Optech is the pioneer and worldwide leading manufacturer of LIDAR systems offering a diversity of platforms catering to different industries and applications

Slide D3

Optech

Laser Scanning System Calibration: An Overview

1. Scanning System Sub-components:
   - Scanner Calibration
   - Timing Electronics Calibration
   - Waveform Calibration
   - Thermal Calibration
2. System Level Calibration Verification
   - Facilities and procedures



Slide D4

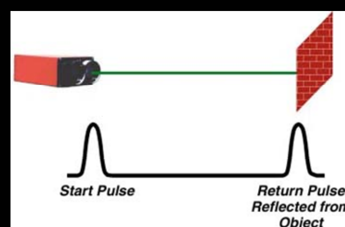
Optech

Lidar Overview

A sequence of events occur to define the operational theory behind Lidar

1. Laser generates and optical pulse (pulse of light)
2. Pulse is reflected off an object and returns to the system receiver
3. High-speed counter measures the time of flight from the start pulse to the return pulse.
4. Time measurement is converted using the constant speed of light formula

Range = (Speed of Light x Time of Flight) / 2



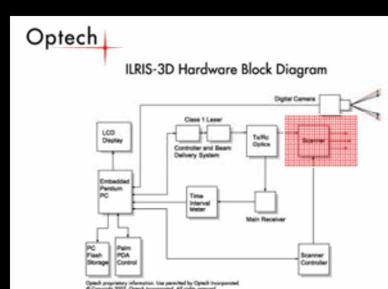
Slide D5

Optech

Scanner Calibration

Calibrating Scanner Mirrors

- ILRIS uses two oscillating scanner mirrors
- These mirrors oscillate at non linear speeds
- The encoder readout and the actual scanner position can have an offset
- The offset and the non-linearity are calibrated out of the system



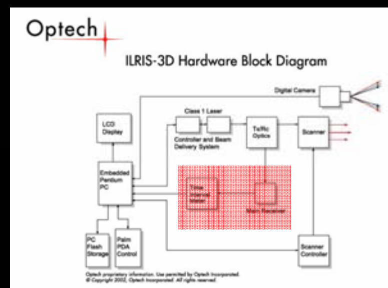
Slide D6

Optech

Timing Electronics

Calibrating the Range

- The timing electronics while accurate, can have a fixed offset between the actual distance and the calculated distance.
- This offset is calibrated out of the system using targets at known distances.

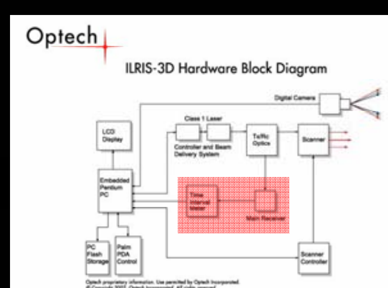


Slide D7

Optech

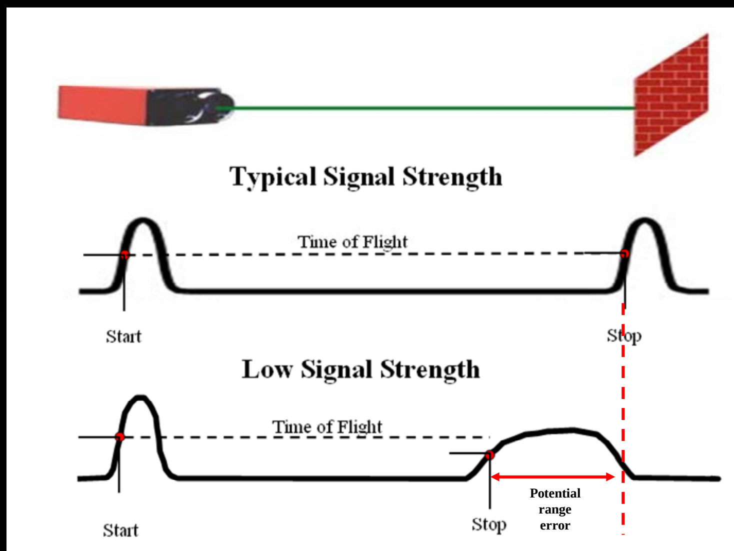
Waveform Calibration

- The electronic timing counter is started and stopped based on the detection of light
- The waveform of the pulse of light is never uniform
- The non-uniformity of the return signal shape must be calibrated to avoid ranging errors



Slide D8

Waveform Calibration



Slide D9

Thermal Calibration

- Varying thermal conditions will effect the performance of several system sub-components
- The effect on each of the sub-components must be characteristics by testing the system in varying conditions
- Includes varying temperature, humidity and air pressure

Slide D10

Publicly Available Verification Facilities

MINIMUM CONSTRAINT ADJUSTMENT ANALYSIS

BASELINE NAME: DOWNSVIEW, ONTARIO

* PASSES
X FAILS

VARIANCE FACTOR V.F.
GOODNESS-OF-FIT G.F.

Observation Period	Variance Factor	Degrees of Freedom	Statistical Tests		Inst. Constant mm [S.D.]	Calibration Constant mm [S.D.]	Calibration Scale ppm [S.D.]	Input Coordinates	Pier Movement mm [SD]		Average Scale Difference ppm [SD]
			V.F.	G.F.					At	Amount	
1991 July 31-Aug 2	1.499	34	*	*	+1.5 [0.1]	+1.5 [0.1] +1.5 [0.1]	-0.6 [0.2]	1987	3	-3.0 [0.1]	-3.1 [0.8]
1991	1.499	34	*	*	+1.5 [0.1]	+1.5 [0.1] +1.5 [0.1]	-0.6 [0.2]	1988	3	-2.8 [0.4]	-3.8 [5.7]
1991	1.499	34	*	*	+1.5 [0.1]	+1.5 [0.1] +1.5 [0.1]	-0.6 [0.2]	1989	3	-1.8 [0.3]	-5.4 [3.7]
1987,88,89, 91 COMBINED	2.099	178	X	*	+2.0 [0.1] +2.2 [0.1] +1.9 [0.1] +1.5 [0.1]		-1.1 [0.2] -0.3 [0.2] +0.8 [0.3] -0.6 [0.2]	Pier 3 identified as 3(88), 3(89), 3(91) in 1987/88, 1989, 1991 respectively.			

Slide D11

Summary of Publicly Available Facilities

ADVANTAGES

- Freely available and accessible to the public
- A good standard verification for quick equipment checks
- Provides a Government control over the area of some level of standard

DISADVANTAGES

- Always oriented to single point survey measurement devices
- Environments not always well controlled or physically maintained

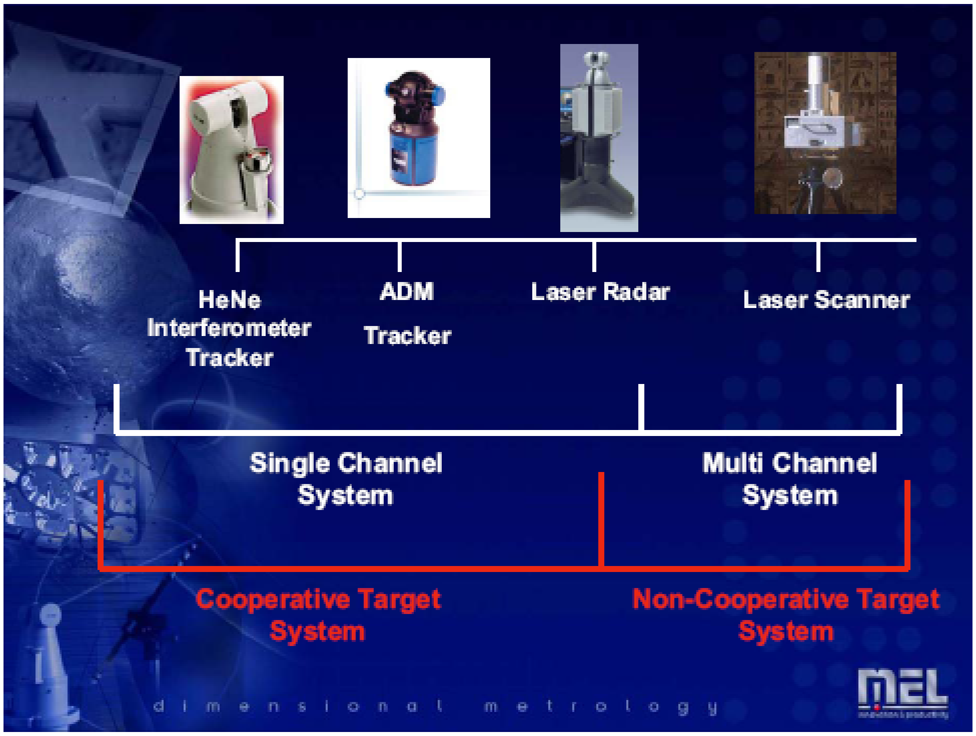
Slide D12

APPENDIX E: Laser Tracker Standards Update and NIST 60 m Ranging Facility – Steve Phillips (NIST).

Reproduced with permission from Steve Phillips.

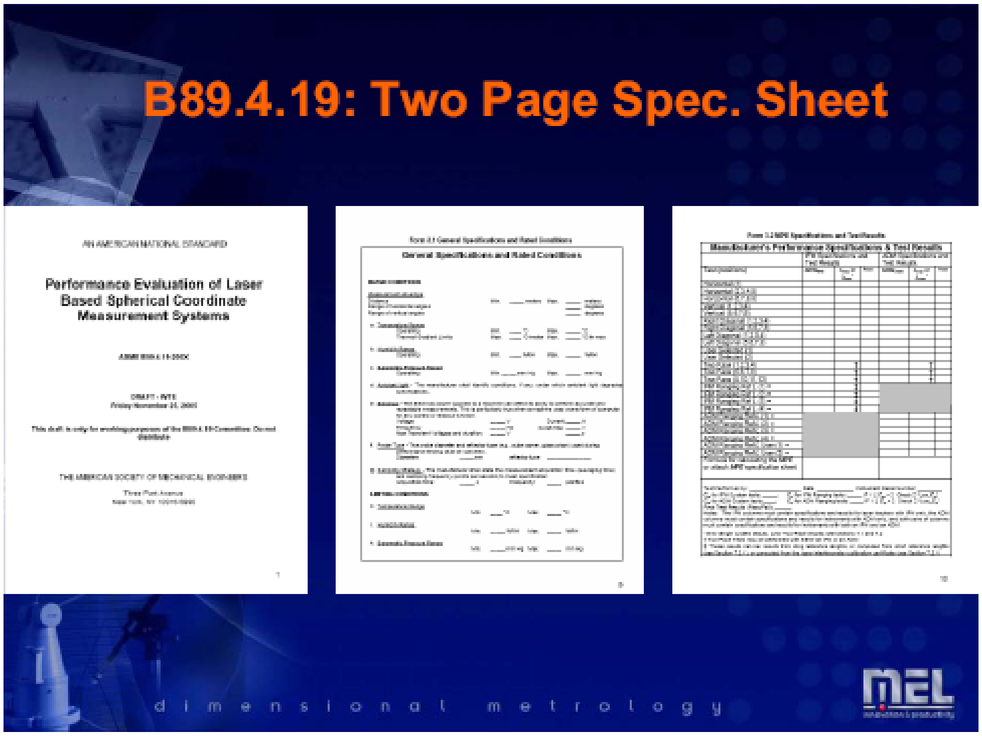
Slide E1

Slide E2

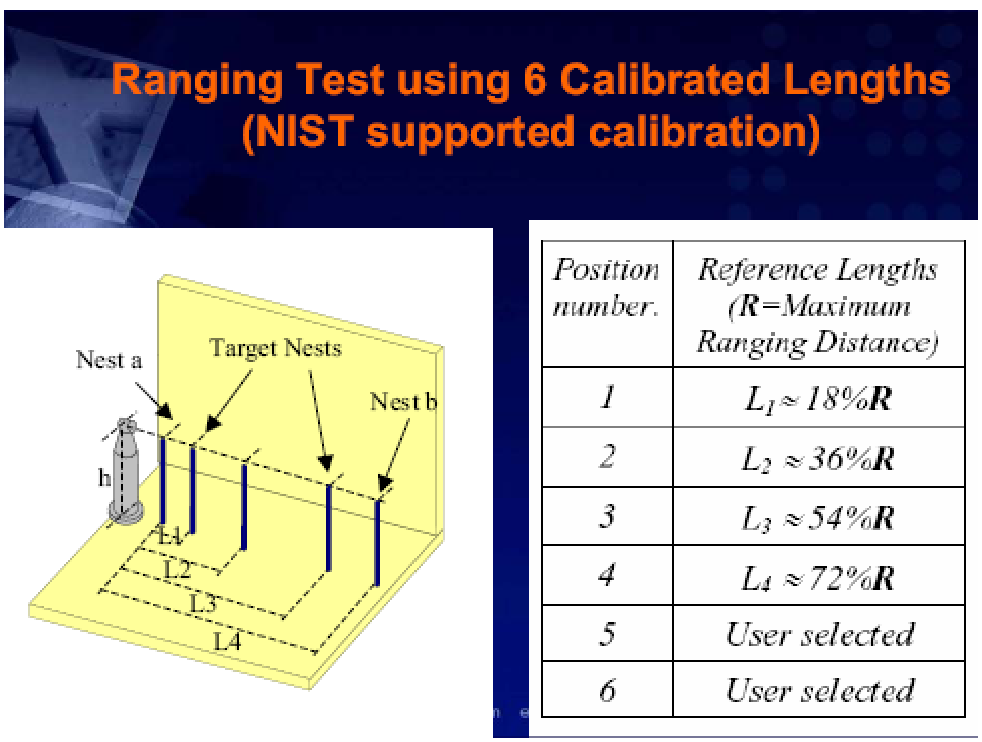


Slide E3

Slide E4

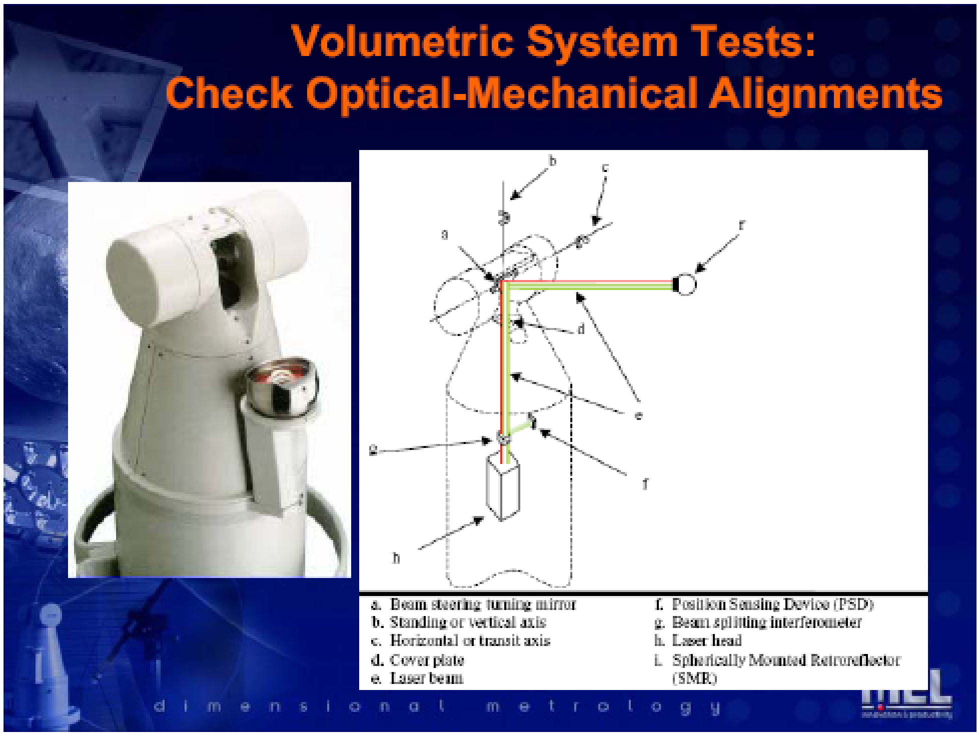


Slide E5

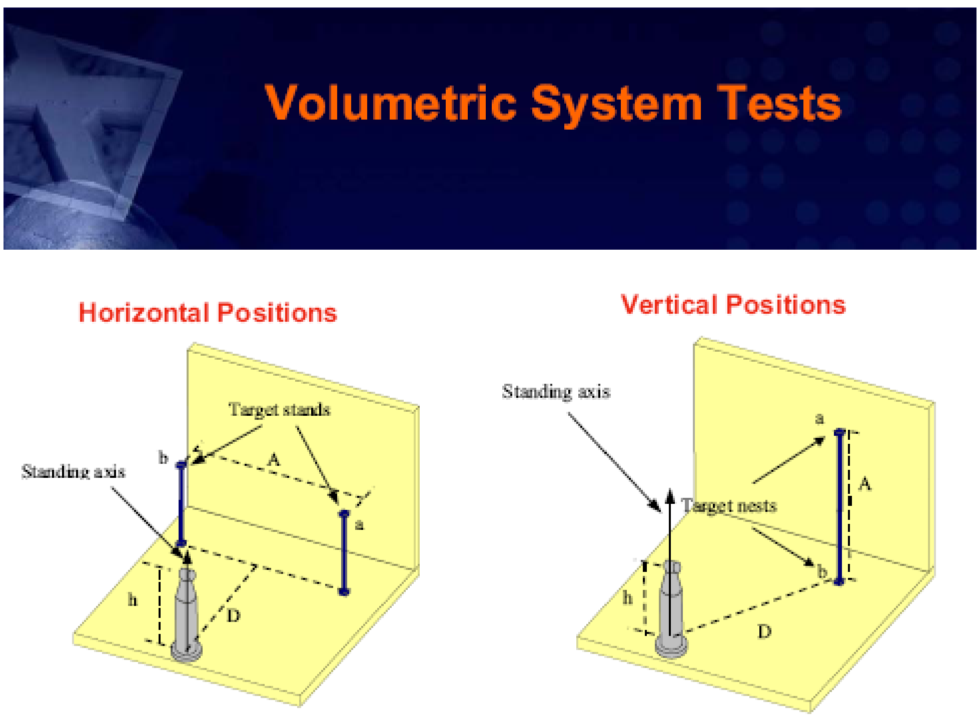


Position number.	*Reference Lengths (**R**=Maximum Ranging Distance)*
1	$L_1 \approx 18\%\mathbf{R}$
2	$L_2 \approx 36\%\mathbf{R}$
3	$L_3 \approx 54\%\mathbf{R}$
4	$L_4 \approx 72\%\mathbf{R}$
5	*User selected*
6	*User selected*

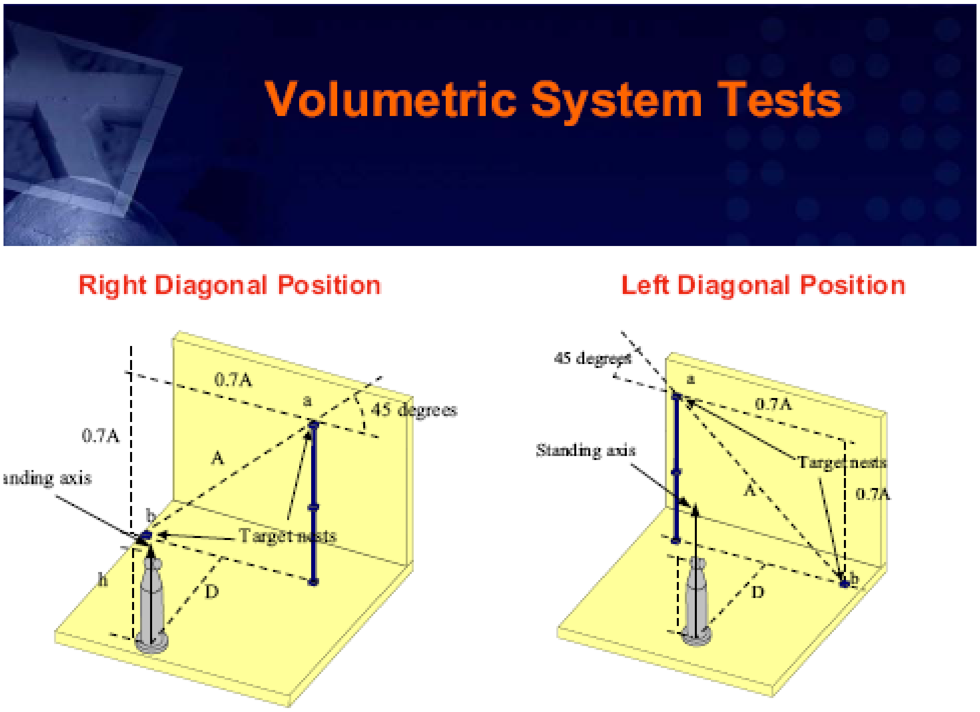
Slide E6



Slide E7

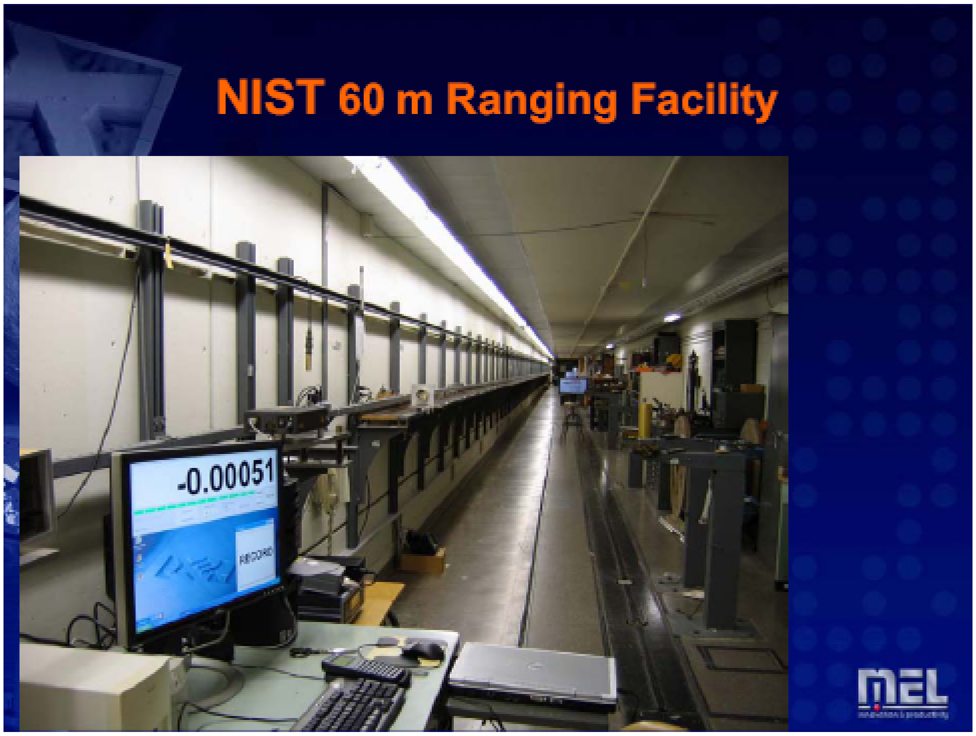


Slide E8

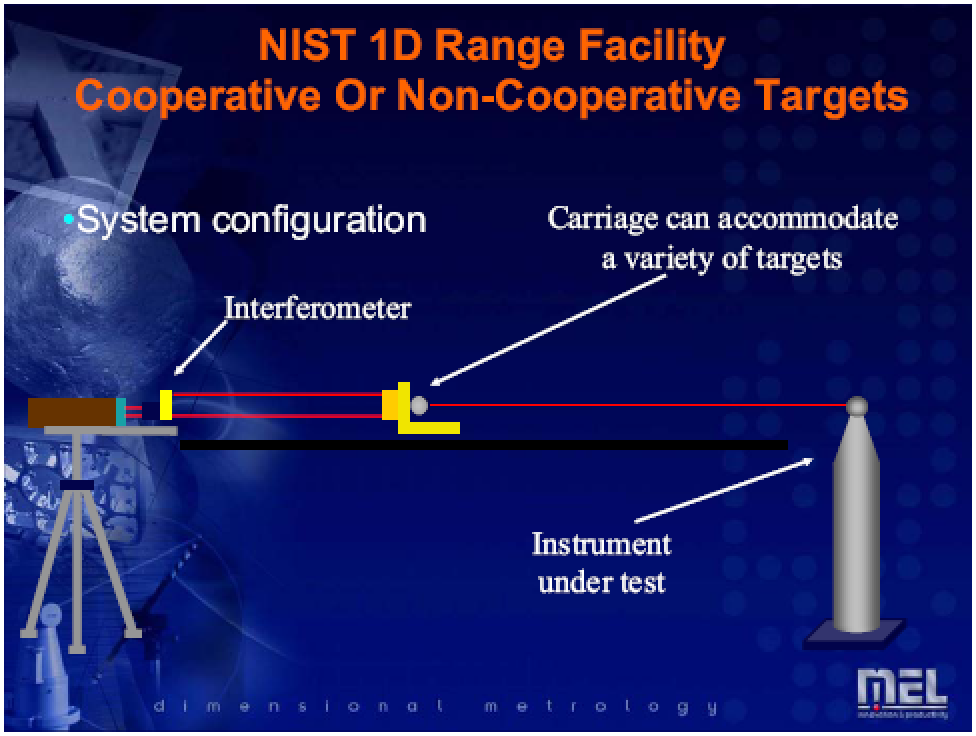


Slide E9

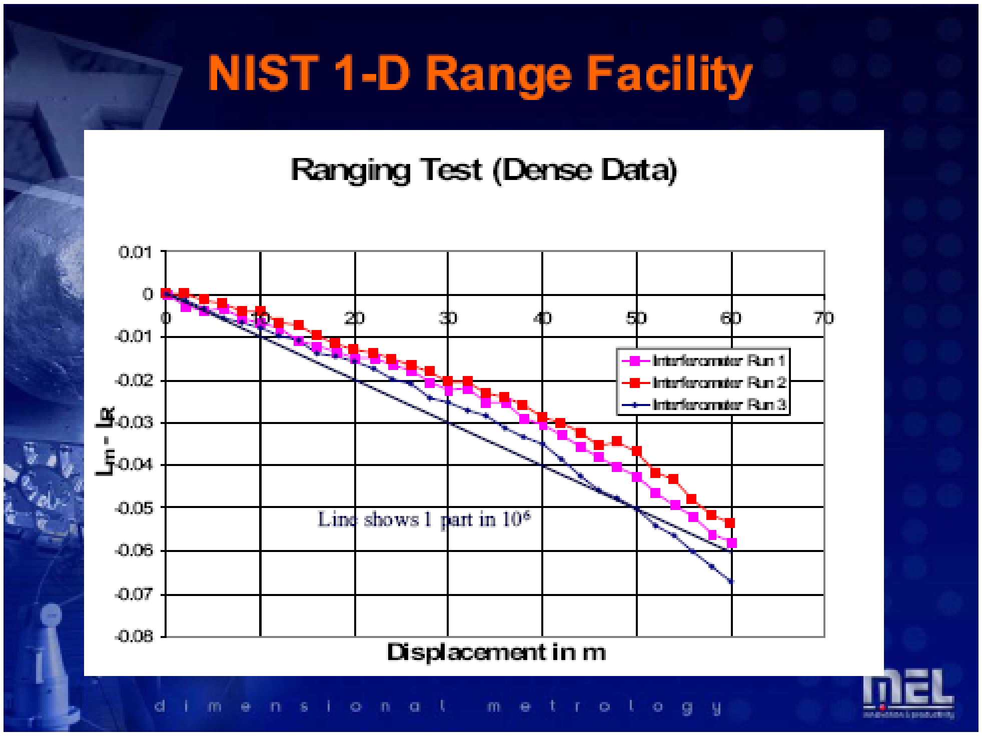
Slide E10



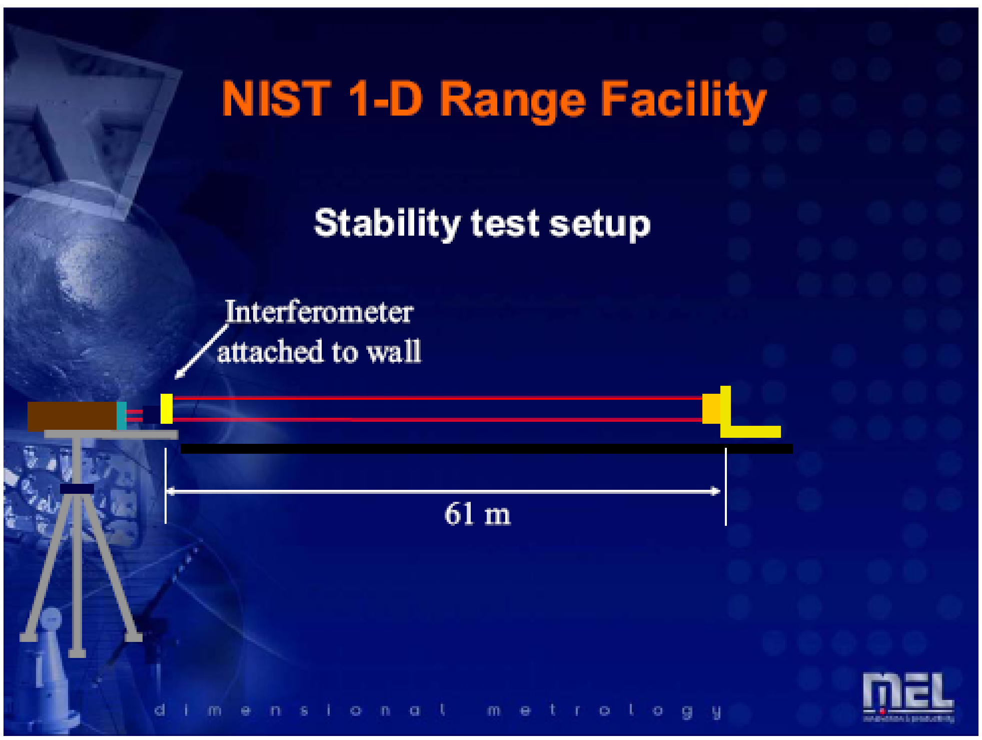
Slide E11



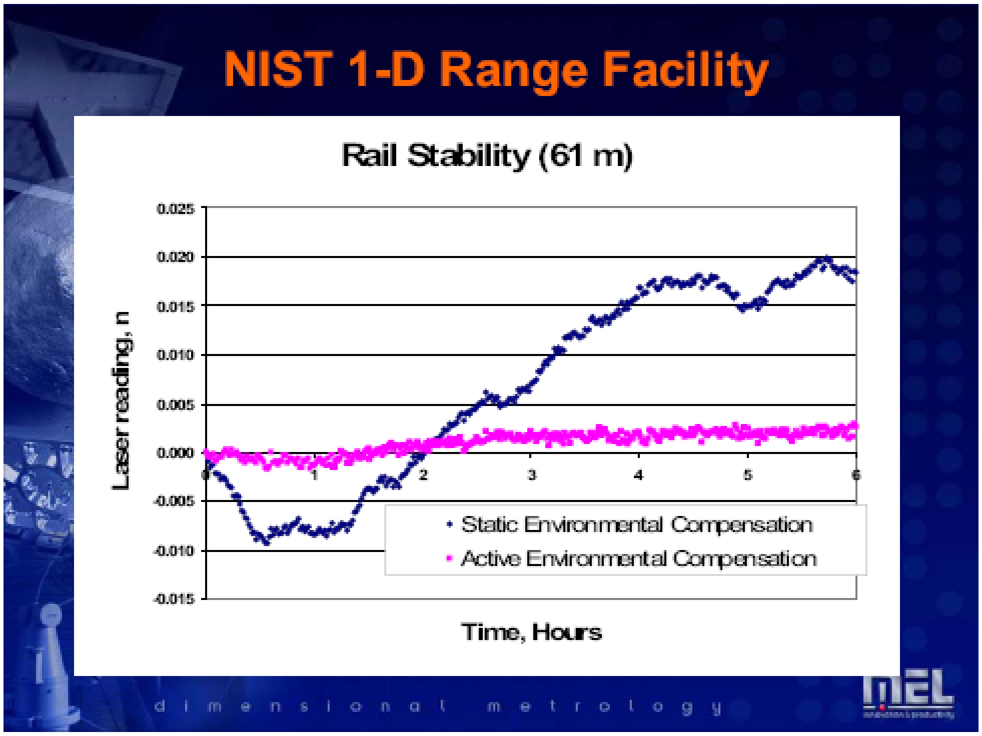
Slide E12



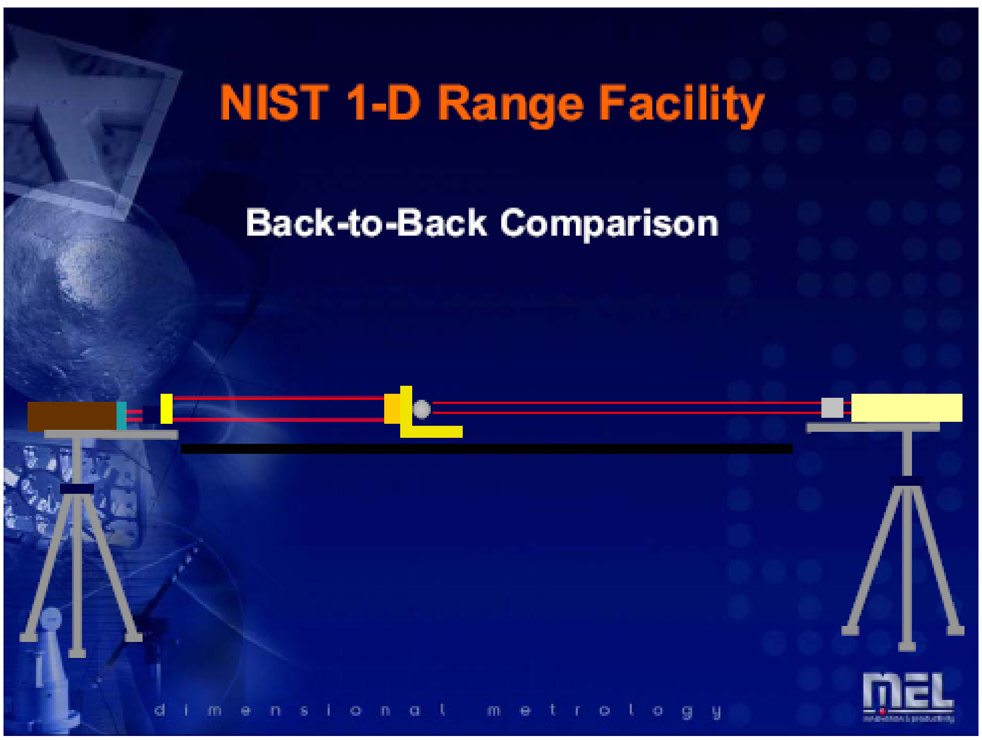
Slide E13



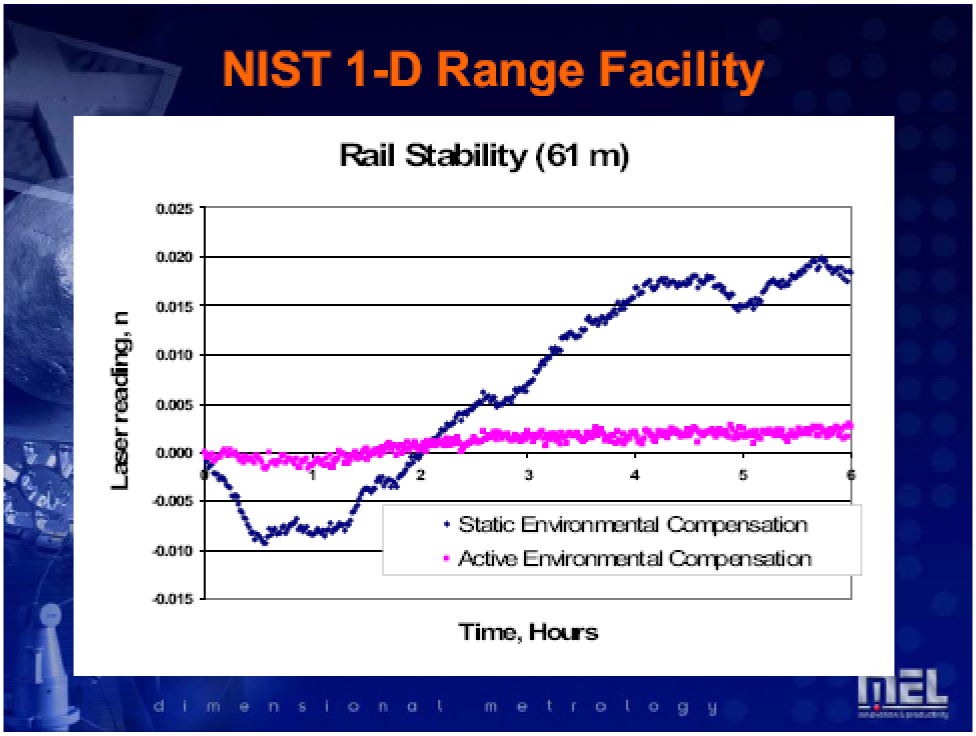
Slide E14



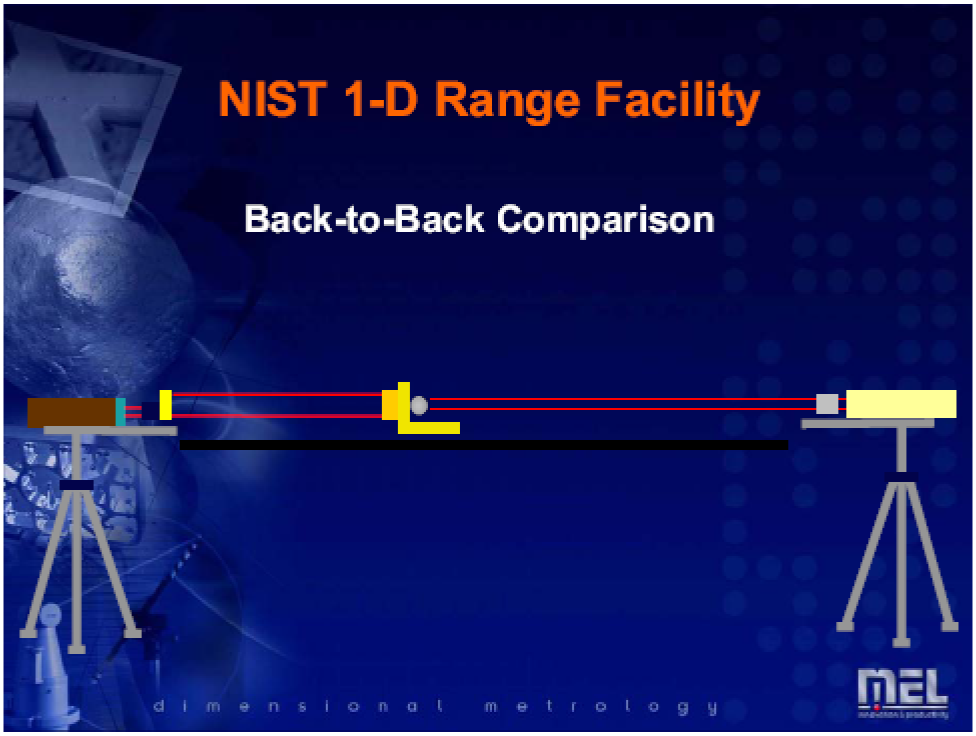
Slide E15



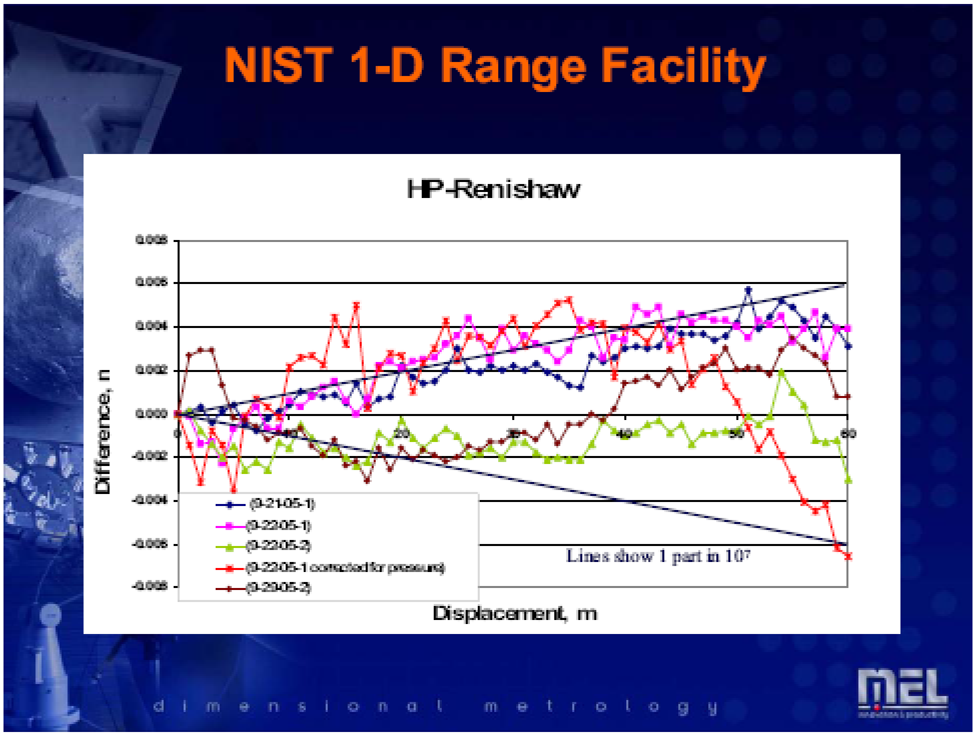
Slide E16



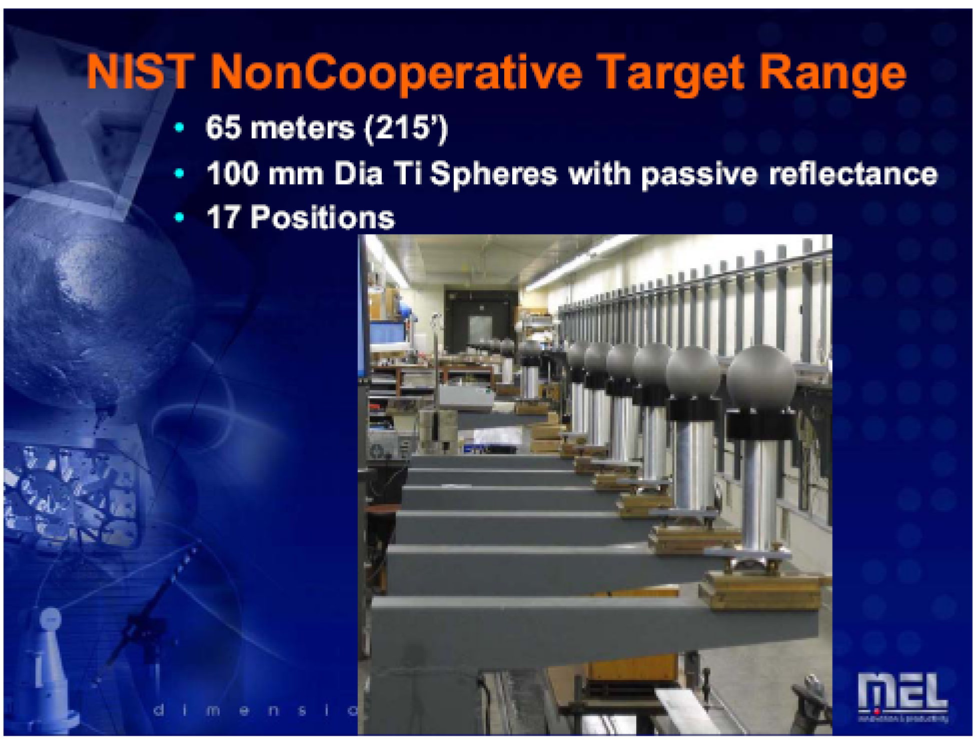
Slide E17



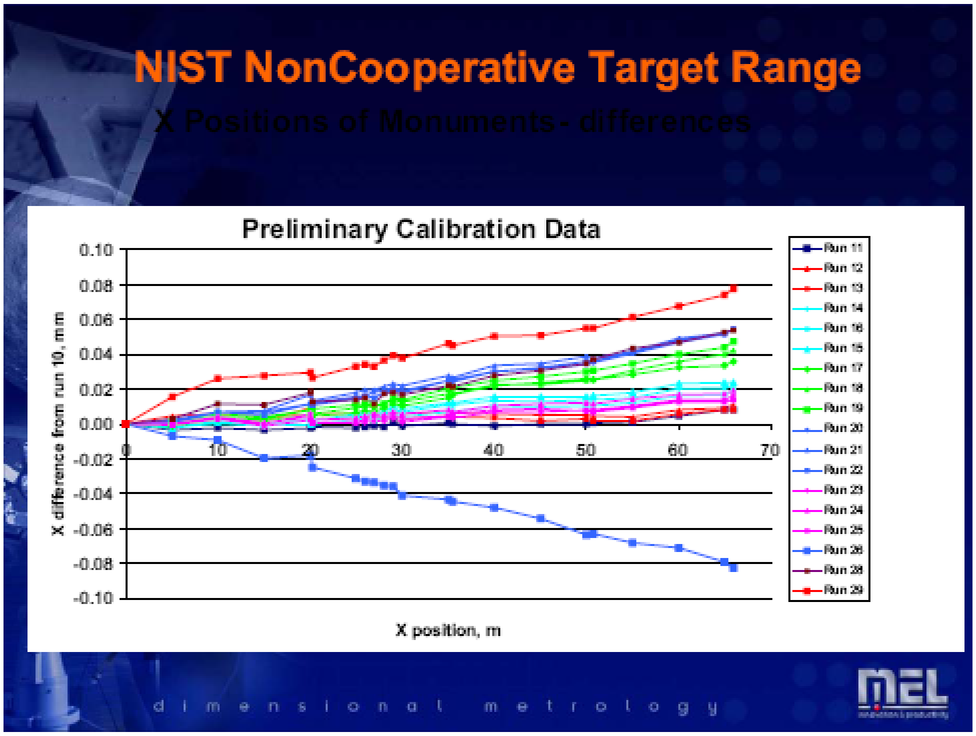
Slide E18



Slide E19

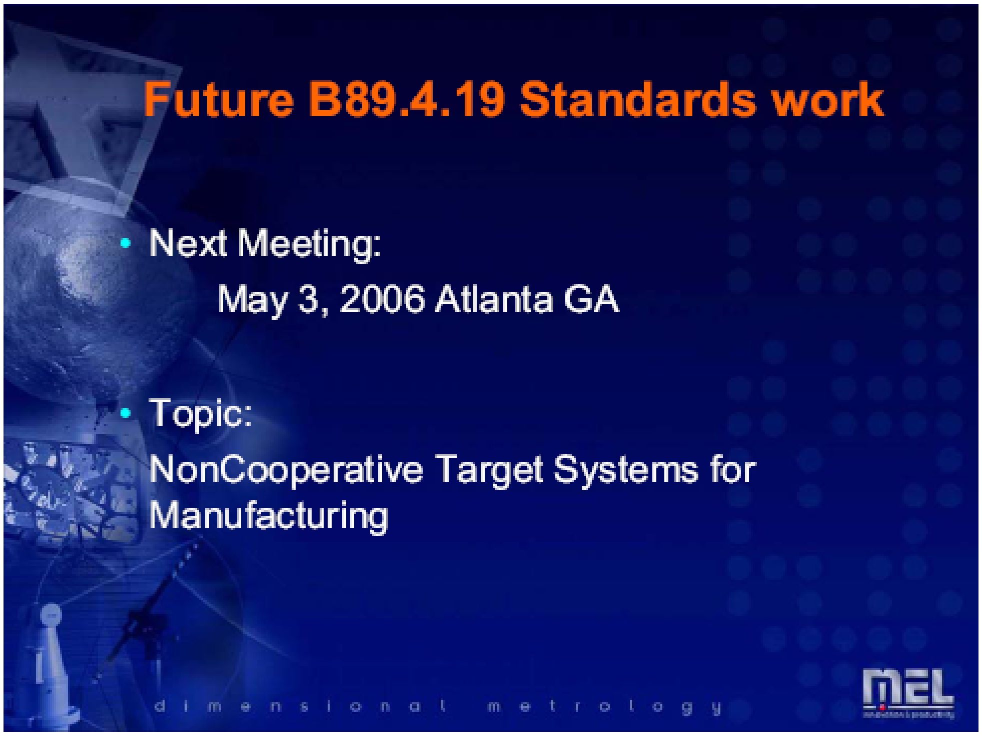


Slide E20

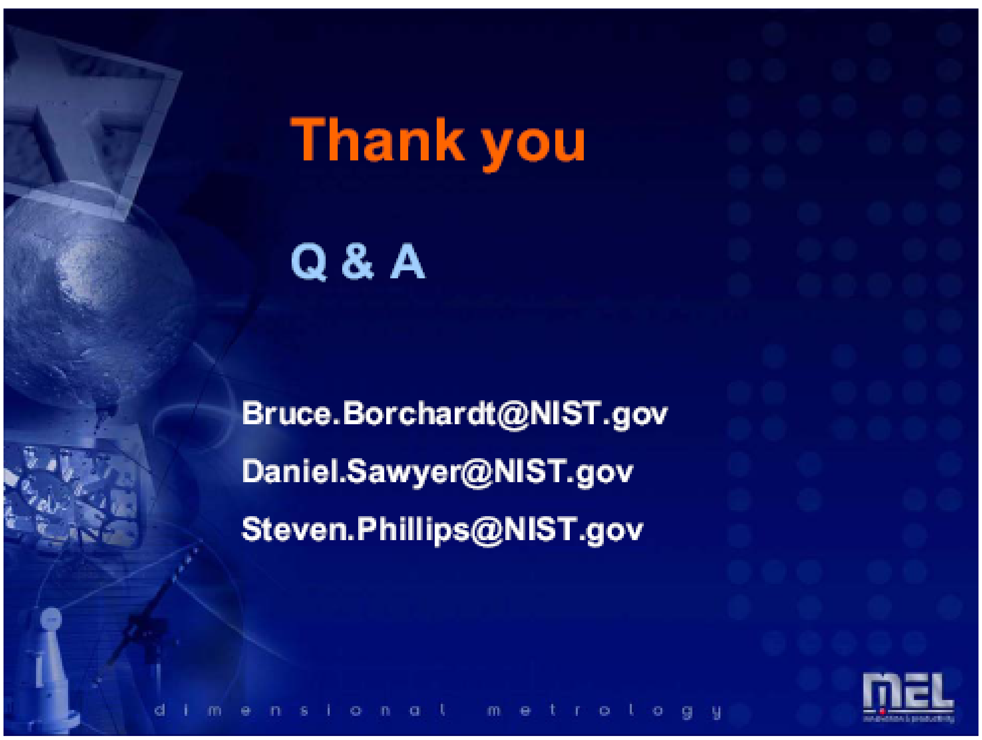


Slide E21

Slide E22



Slide E23



Slide E24

APPENDIX F: Quality Analysis and Registration of the Control Network - Steve Hand (MagLev)

Reproduced with permission from Steve Hand.

Slide F1

Office of Naval Research

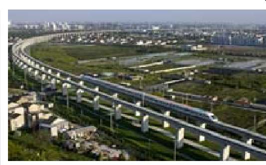
MAGLEV INC.

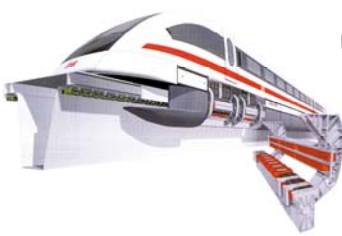
Quality Analysis and Registration of the Control Network

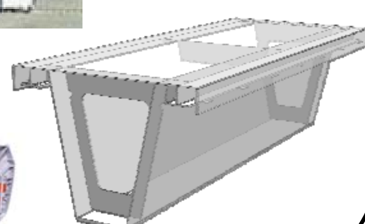
NIST Workshop

March 3rd, 2006

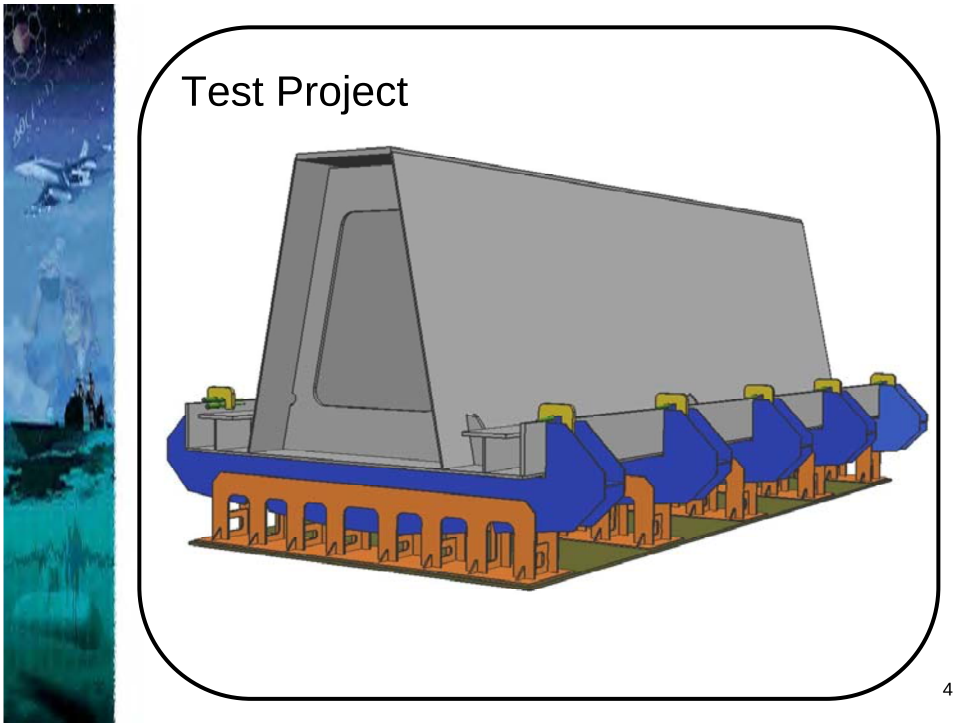
2 **Slide F2**



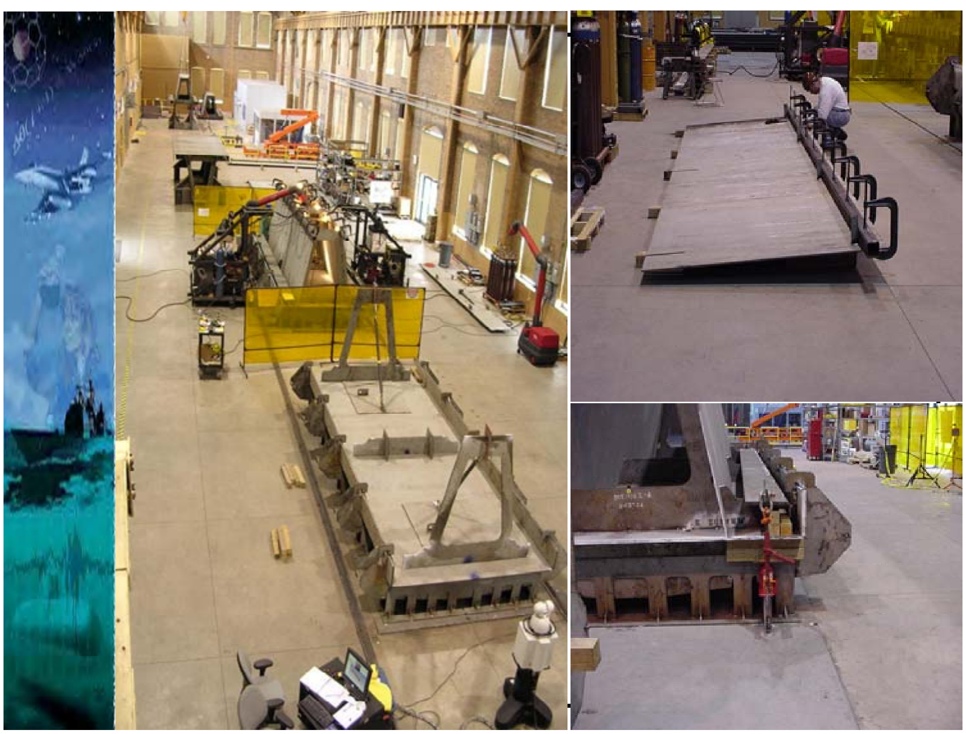




3 **Slide F3**

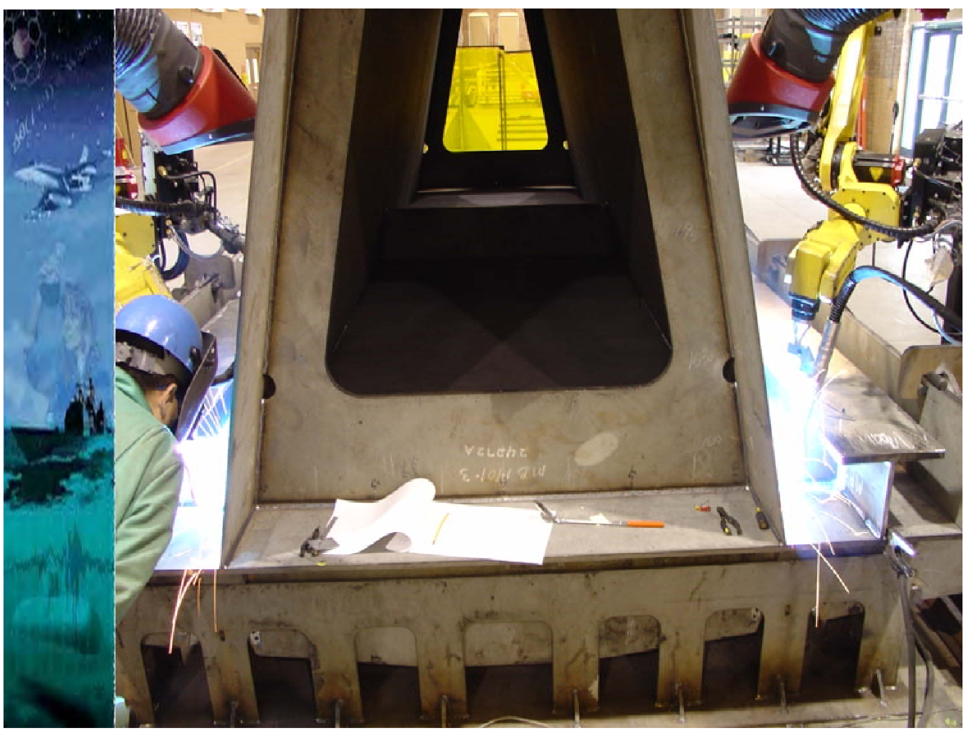


Slide F4

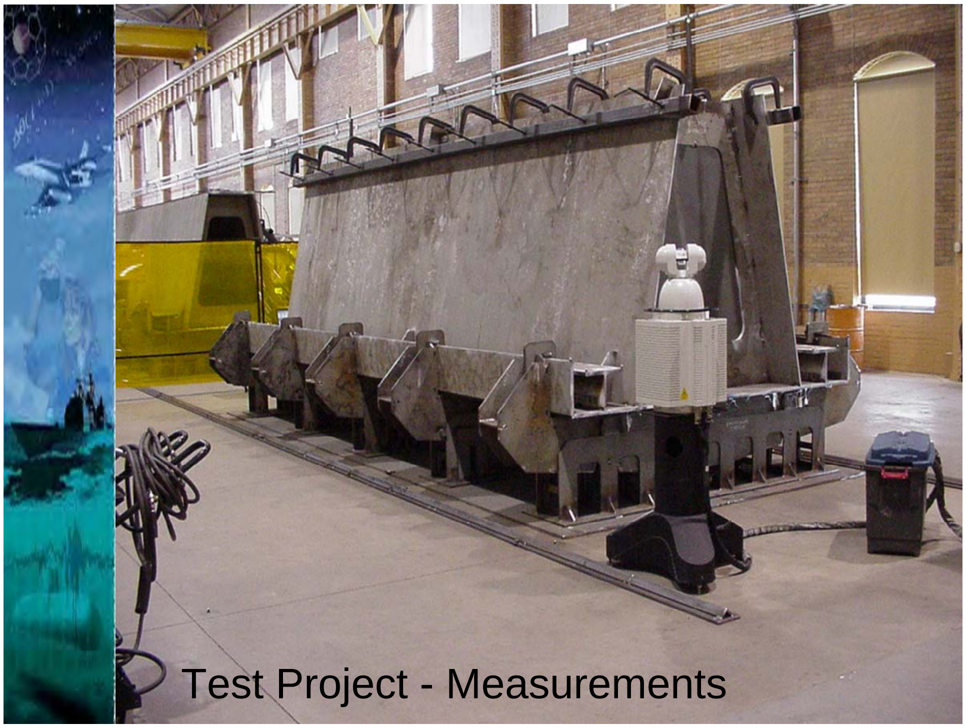


Slide F5

Slide F6

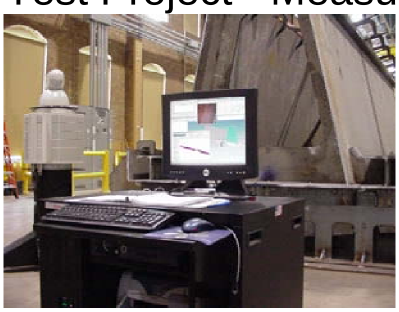


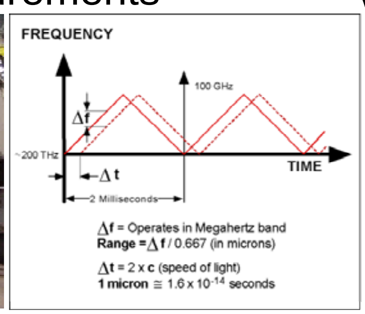
Slide F7



Slide F8

Test Project - Measurements





Coherent Laser Radar (CLR)

Leica LR-200 (Metris MV-200)

Performs both Single Point and Scanning Measurements

Uncertainty at 2 Sigma = ± 50 Microns [± 0.002 in.]

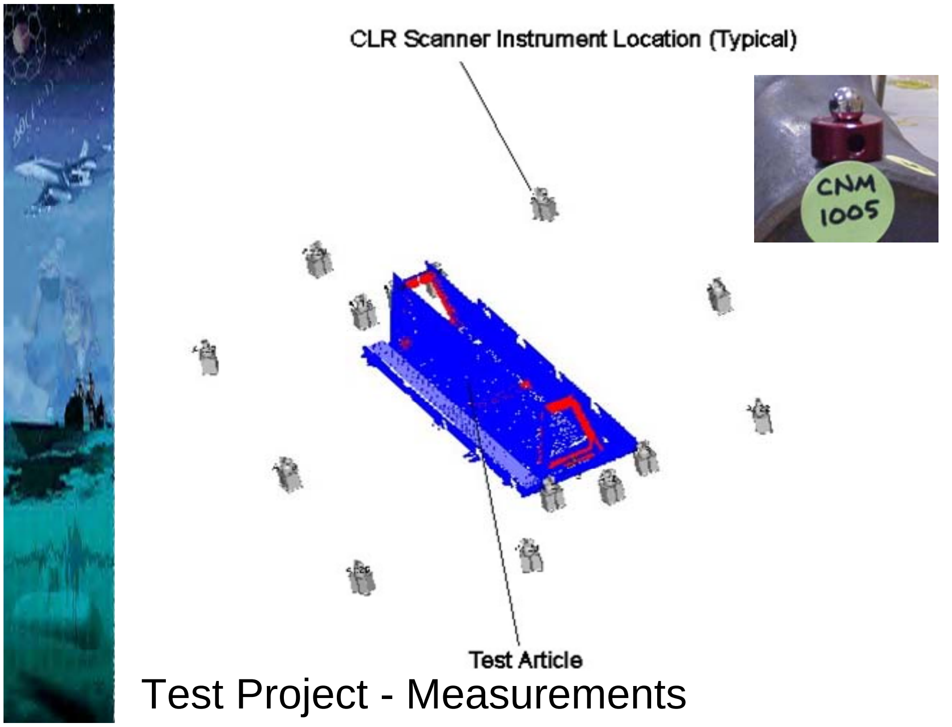
At Range 24 meters

Operating Software: Spatial Analyzer™

Processing Software: Polyworks™

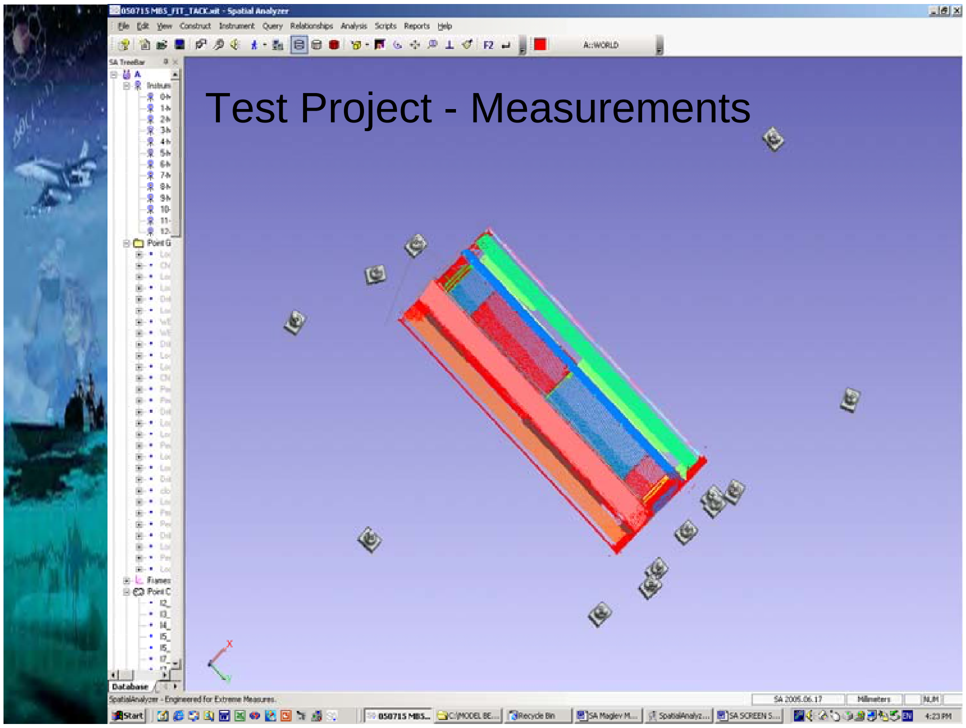
9

Slide F9

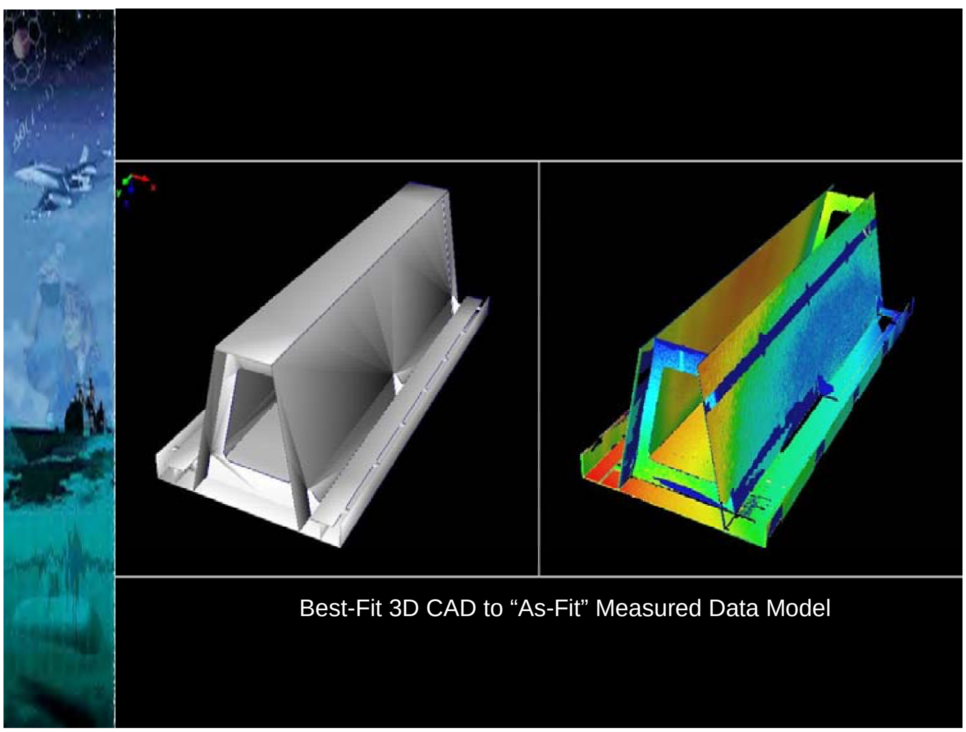


Slide F10

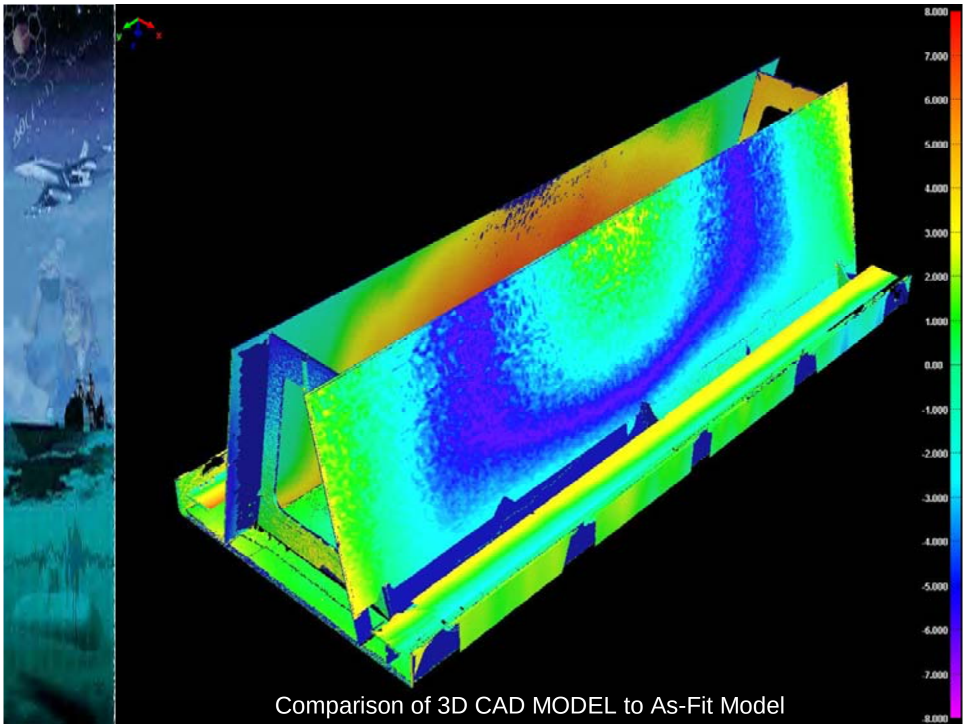
Slide F11



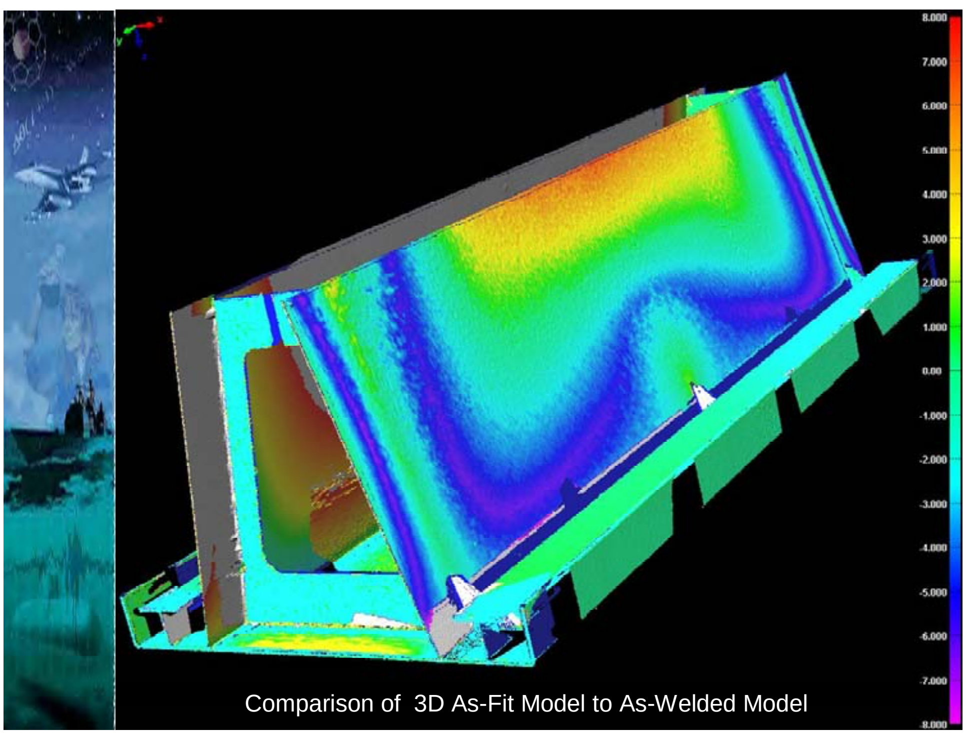
Slide F12



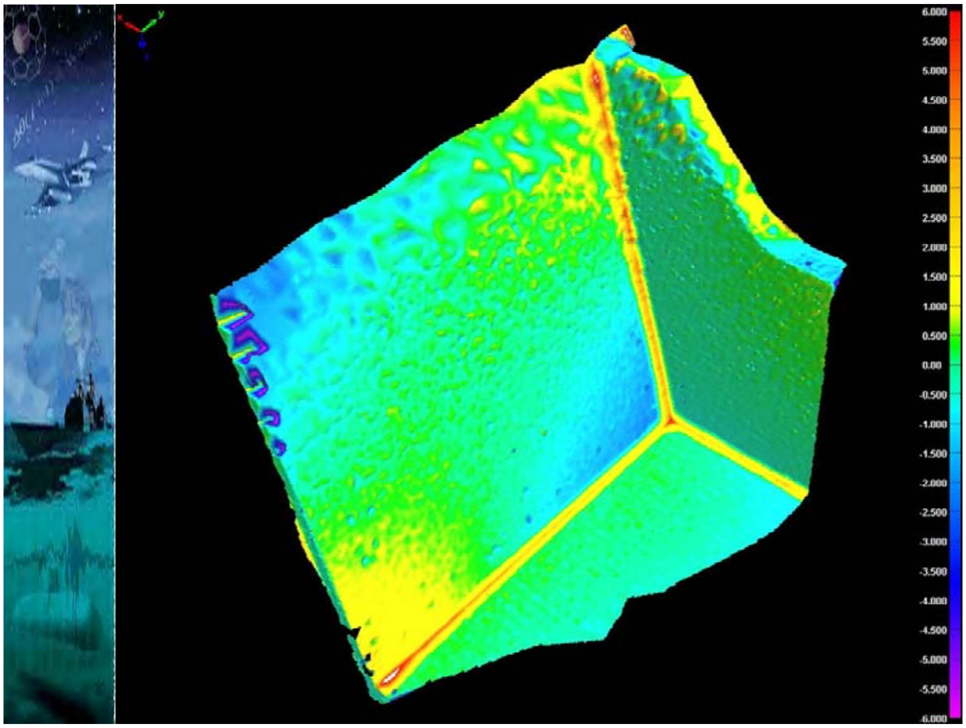
Slide F13



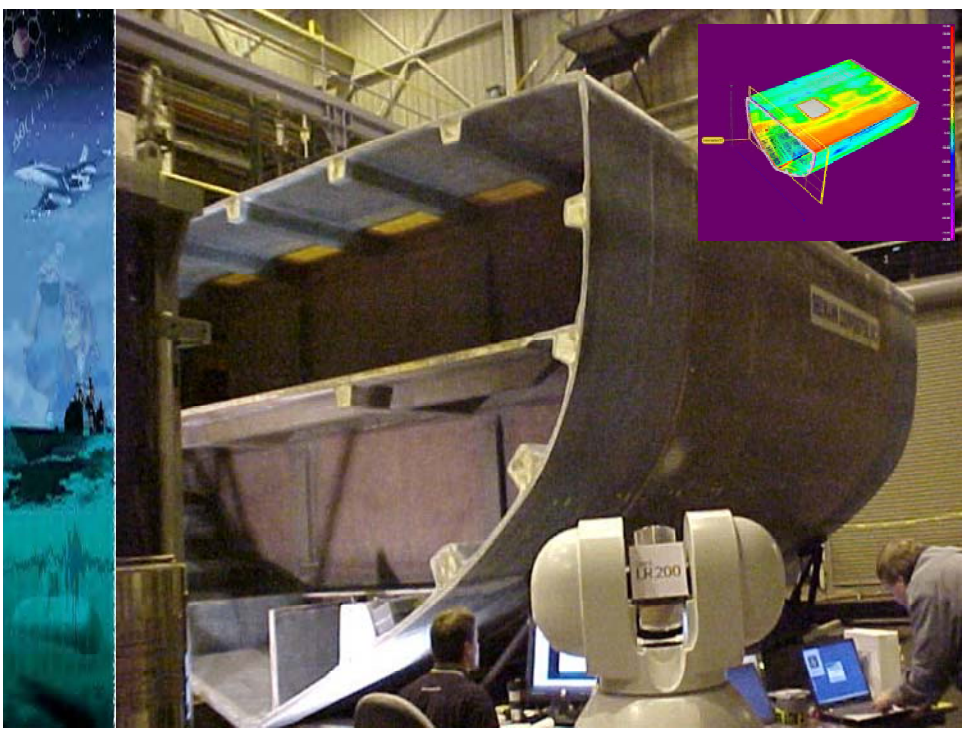
Slide F14



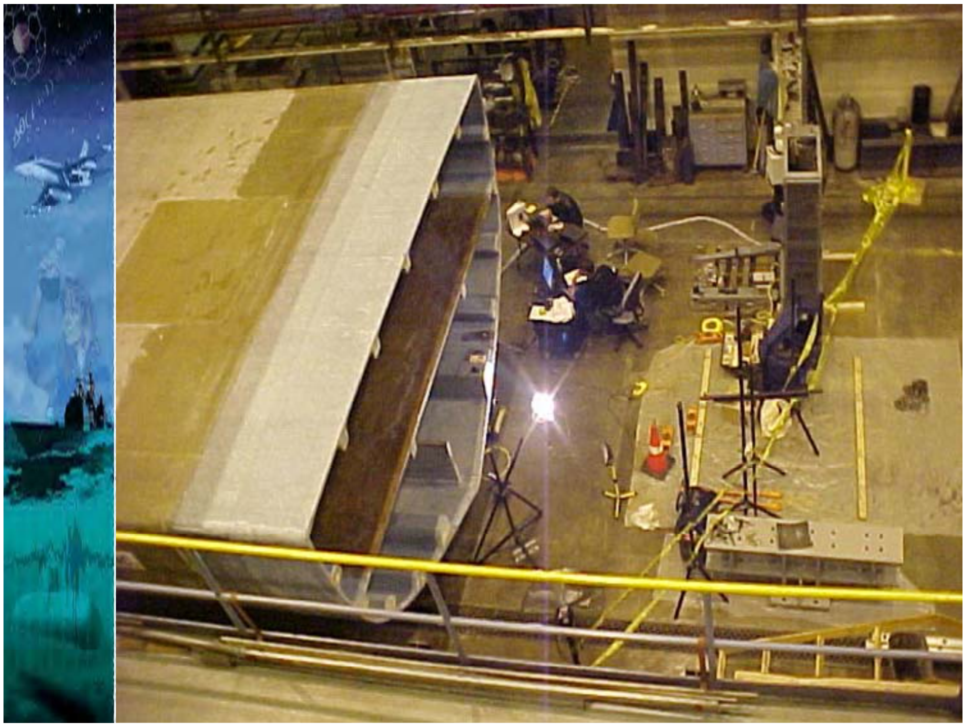
Slide F15



Slide F16

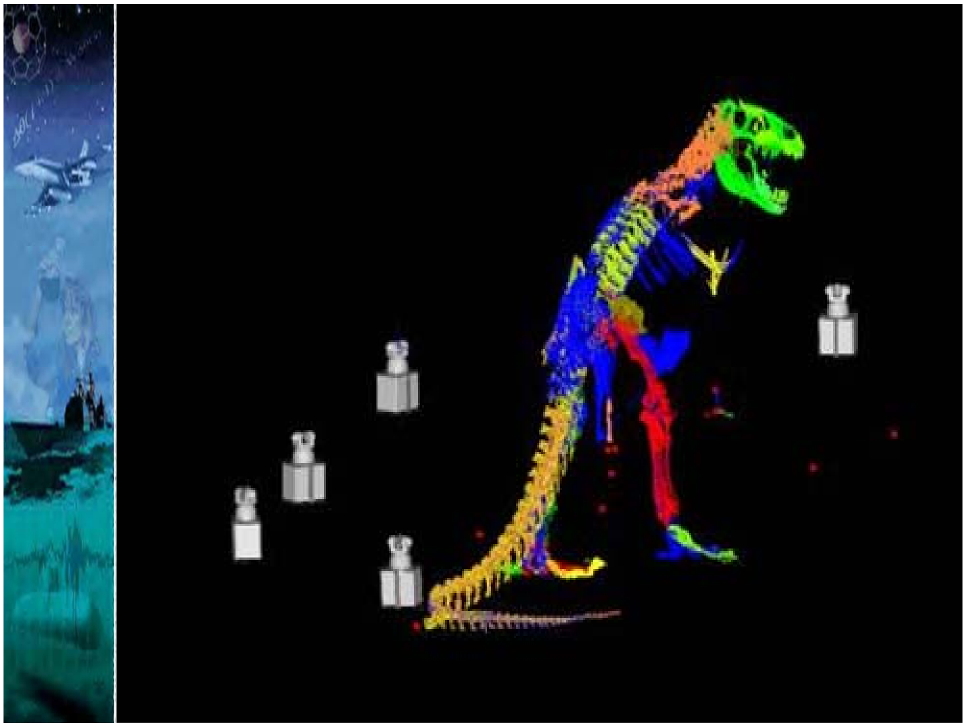


Slide F17



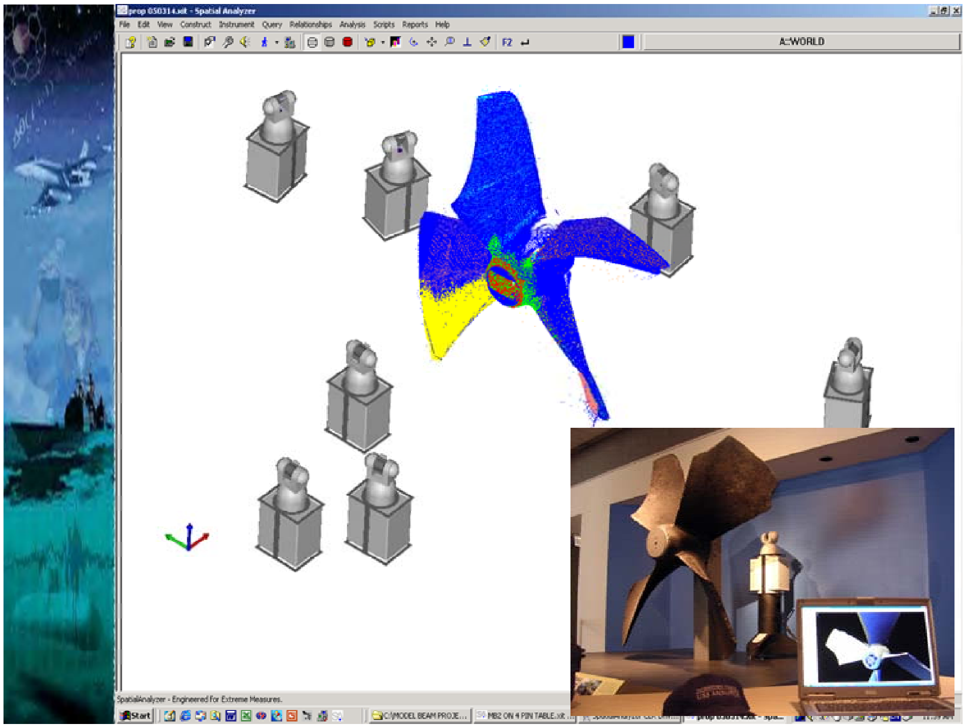
Slide F18

Slide F19

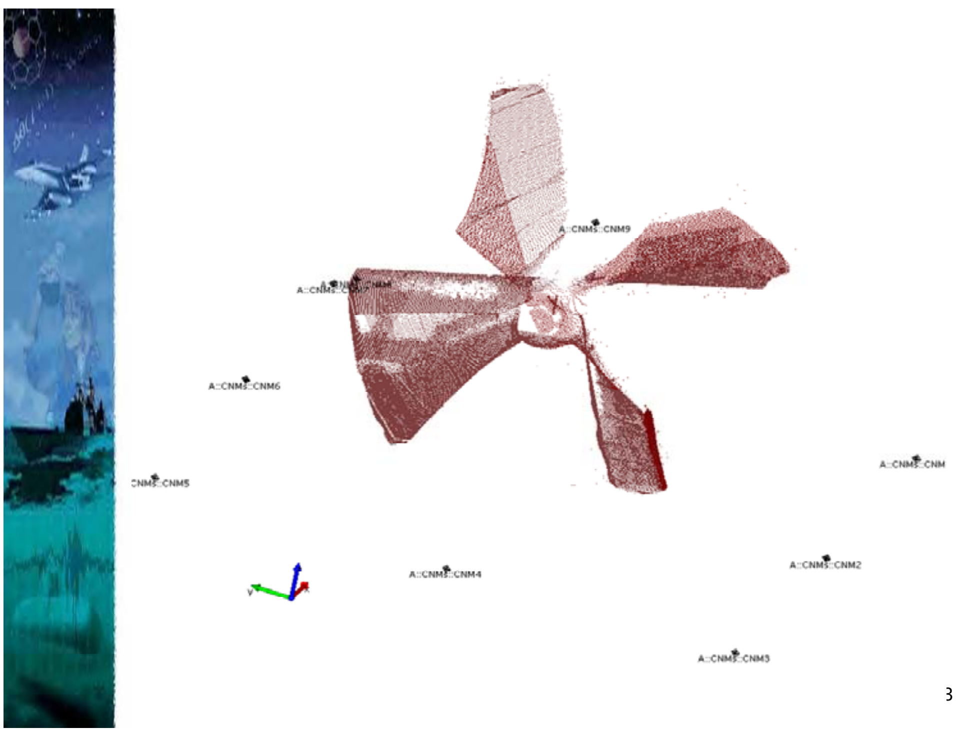


Slide F20

Slide F21



Slide F22



3 **Slide F23**

APPENDIX G: Unified Spatial Metrology Network - Dave Ober (Metris)

Unified Spatial Metrology Network

Steve Hand: MAGLEV INC.

David Ober: Metris USA

9/7/2006 1

Slide G1

Unified Spatial Metrology Network (Developed by New River Kinematics)

SpatialAnalyzer

- Spherical Coordinate Uncertainty
- Best Fit in Cartesian vs. Spherical Space Simulation
- USMN Goals
- SA Best Fit vs. USMN Simulation & Results
- USMN Network Measurement Uncertainty
- Checking Instrument Operation
- USMN Considerations

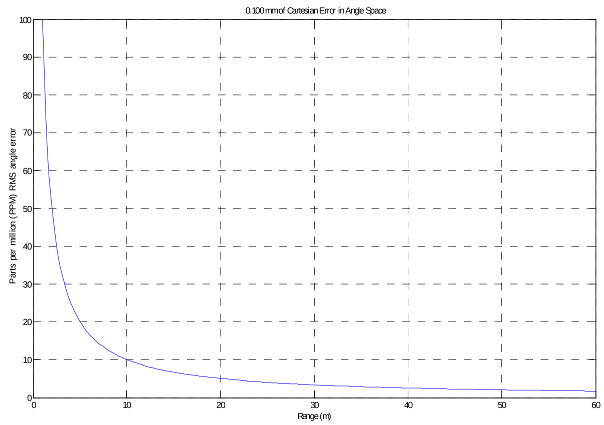
9/7/2006 2

Slide G2

Cartesian uncertainty in Spherical/Polar coordinates

Question: What is the "goodness" of an instruments angle encoder that has 0.100 mm of RMS of residual error to 20 repeated measurements?

Answer: It depends on the range of the instrument to the measurand.



1 PPM = 1 µRad = 0.21 arc-sec = 0.057 mdeg

9/7/2006 3

Slide G3

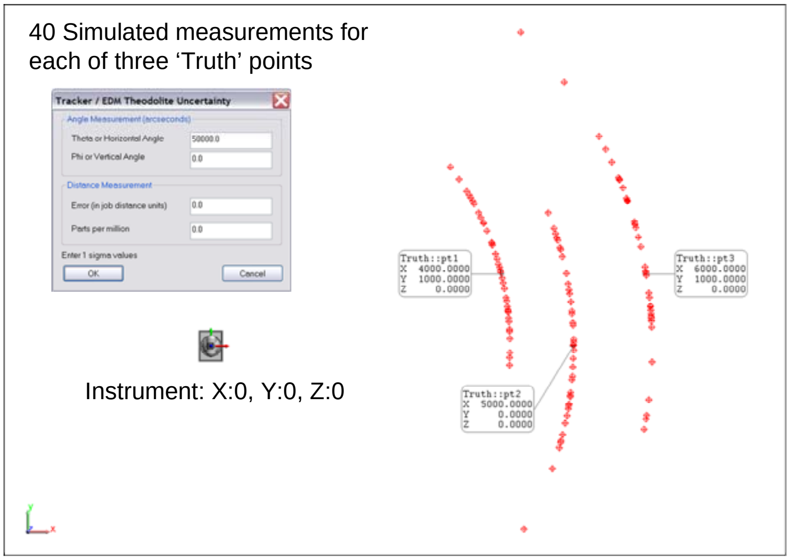
Spherical Coordinate Uncertainty

Constant spherical uncertainty ***is not constant*** in Cartesian space.
The uncertainty point cloud size & orientation changes in Cartesian space

9/7/2006 4

Slide G4

Simulated Spherical Measurements



9/7/2006 5

Slide G5

Cartesian & Spherical Best Fit Functions

For the 40 simulated measurements
(for each of the three 'Truth' points)

- Cartesian Best Fit

  XAvgC = mean(X(i)), YAvgC = mean(Y(i)), ZAvgC = mean(Z(i))

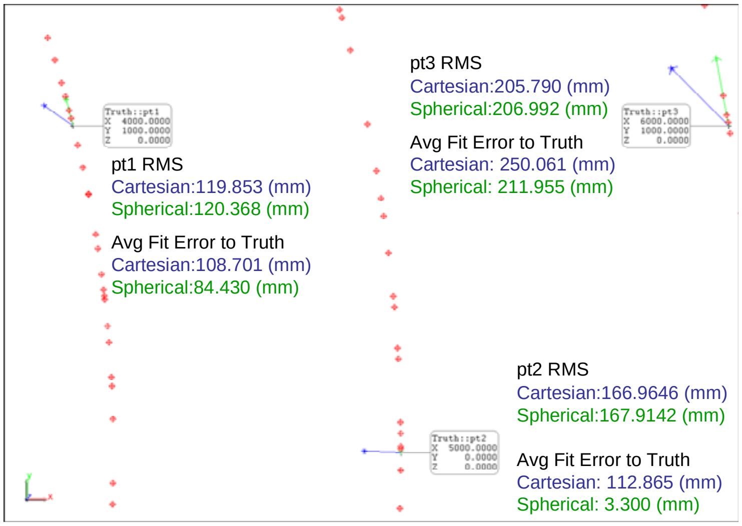
- Spherical Best Fit

  RgAvg = mean(Rg(i)), AzAvg = mean(Az(i)), ElAvg = mean(El(i))
  [XAvgS, YAvgS, ZAvgS] = Sph2CartCLR(RgAvg, AzAvg, ElAvg)

9/7/2006 6

Slide G6

Cartesian vs. Spherical Best Fit Results



9/7/2006 7

Slide G7

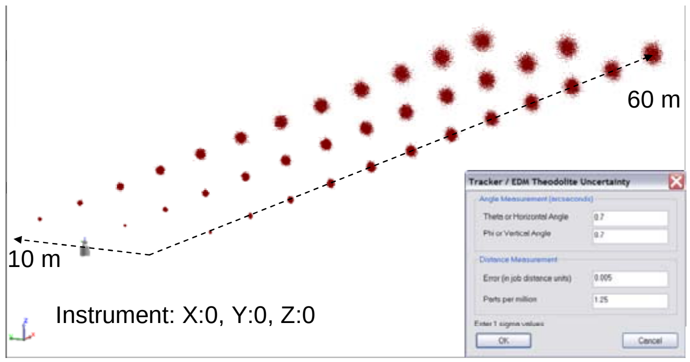
USMN Goals

- To provide the best estimate of measured points in the global reference frame by employing *weighted* Least Squares solutions of all measurements *in each instruments own reference frame*
- To provide a more accurate estimate of each measurements uncertainty based on the tie-in network topology
  (can be completed before the job begins)
- To provide an analysis of the working instruments total uncertainty in the working environment
  (during the job or for determining calibration)

9/7/2006 8

Slide G8

USMN vs. Best Fit Simulation



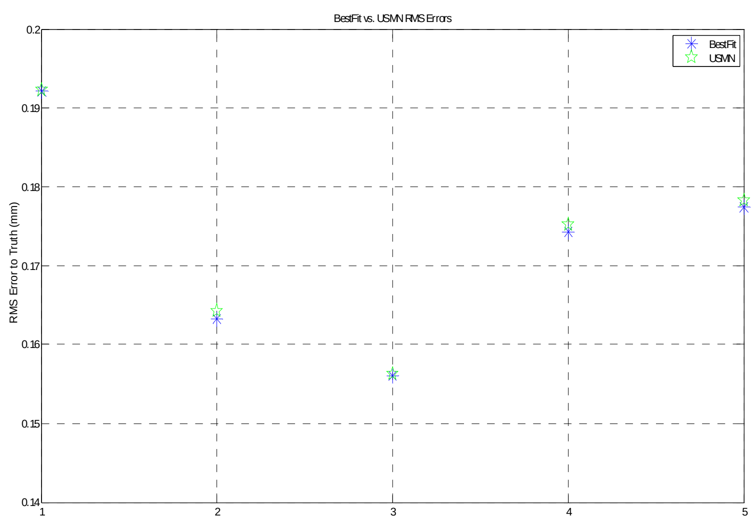
Simulate five separate measurement sets (with simulated errors) at 36 truth points spaced from five to sixty meters in range & ten meters wide.

Use Spatial Analyzer's Best-Fit & USMN to locate the instrument to the 'true' points and see how much error is introduced at the instruments location (translation & orientation) for each of the five measurement sets.

9/7/2006 9

Slide G9

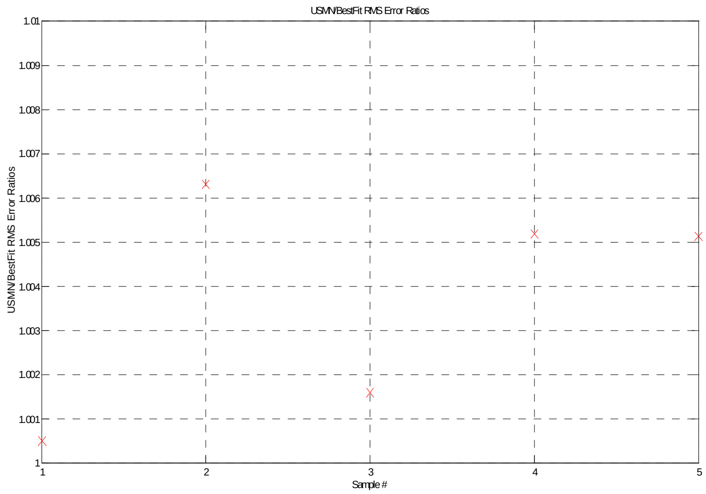
RMS Errors from True Points to Measurements after SA BestFit & USMN



9/7/2006 10

Slide G10

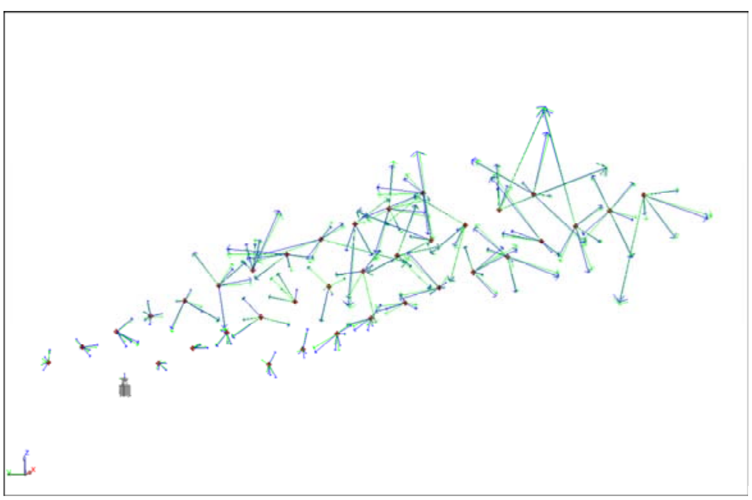
USMN/BestFit RMS Error Ratios



The USMN RMS error is ~0.04% Larger than the Best Fit RMS Error

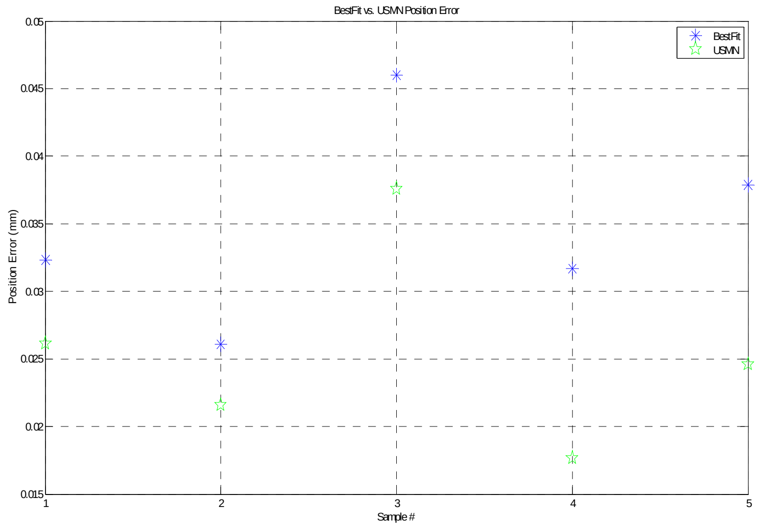
Slide G11

Vector Errors from True Points to Measurements after SA BestFit & USMN



Slide G12

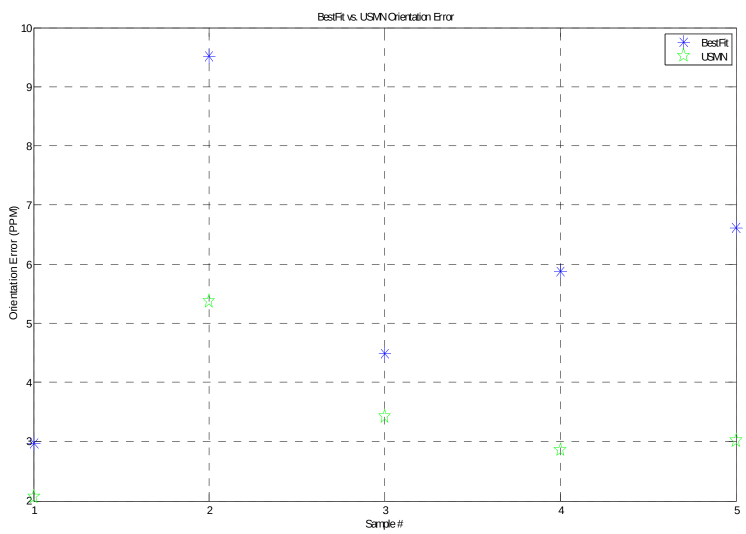
Instrument Position Error



9/7/2006 13

Slide G13

Instrument Orientation Error

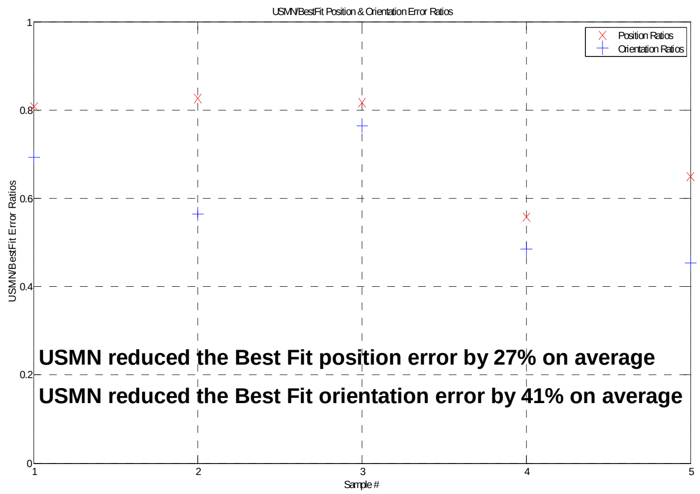


1 PPM = 1 µRad = 0.21 arc-sec = 0.057 mdeg

9/7/2006 14

Slide G14

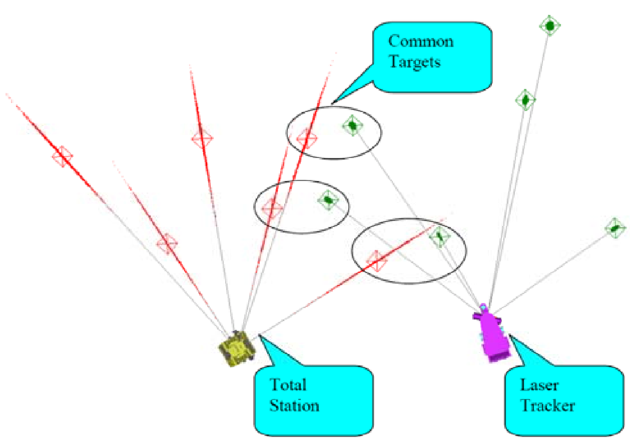
Instrument USMN/BestFit Position & Orientation Error Ratios



9/7/2006 15

Slide G15

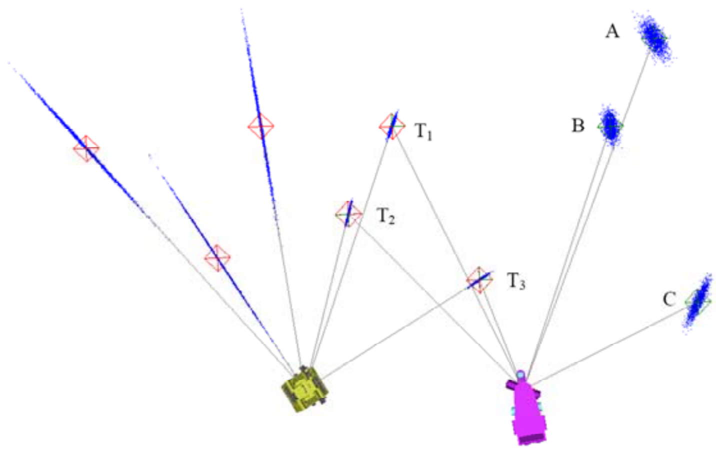
Uncertainty Clouds Before Tie-In



9/7/2006 "SA USMN Manual.pdf": p101 16

Slide G16

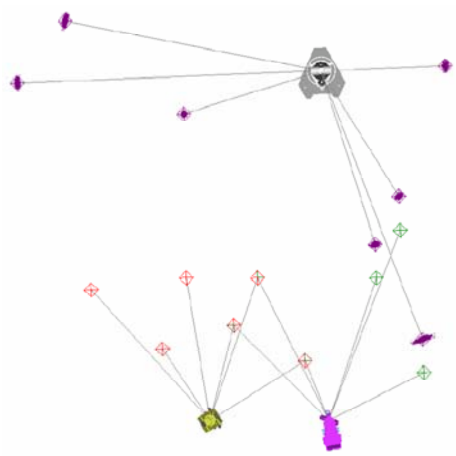
Uncertainty Clouds after Tie-In



9/7/2006 "SA USMN Manual.pdf": p103 17

Slide G17

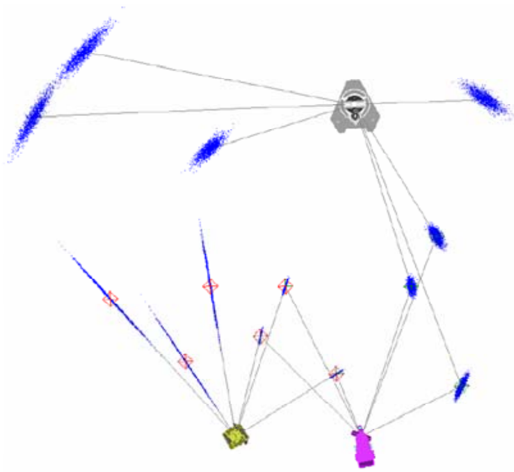
New Instrument for Network Tie-In



9/7/2006 "SA USMN Manual.pdf": p105 18

Slide G18

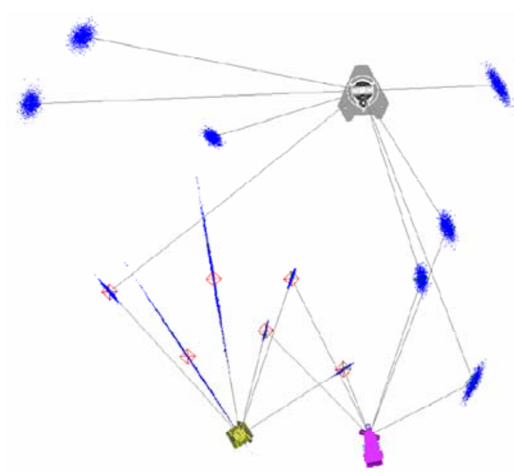
New Uncertainty Clouds after New Instrument Tie-In



9/7/2006 "SA USMN Manual.pdf": p106 19

Slide G19

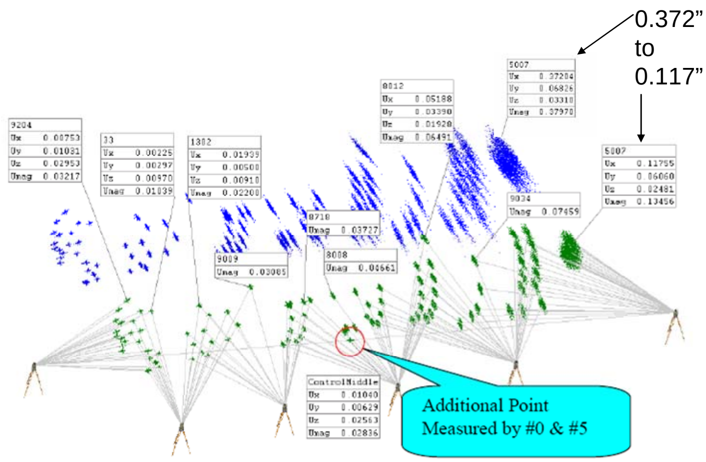
New Instrument Tie-In back to Ground Greatly Reduces Network Uncertainty



9/7/2006 "SA USMN Manual.pdf": p107 20

Slide G20

Steam Turbine Tie-in With Additional Grounding Point

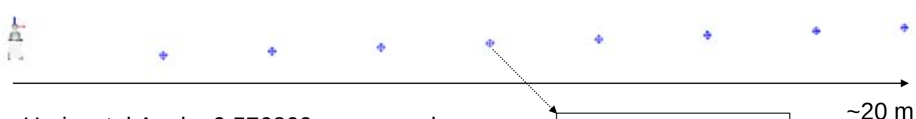


9/7/2006 “SA USMN Manual.pdf”: p171 21

Slide G21

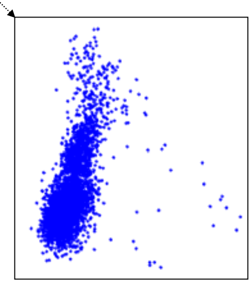
Using USMN to Detect Motion on Repeatability Measurements

66 hours (2 ¾ days) data collection time on eight tooling balls



Horizontal Angle 0.576809 arcseconds
Vertical Angle 0.856319 arcseconds
Distance 0.007225 [Millimeters]

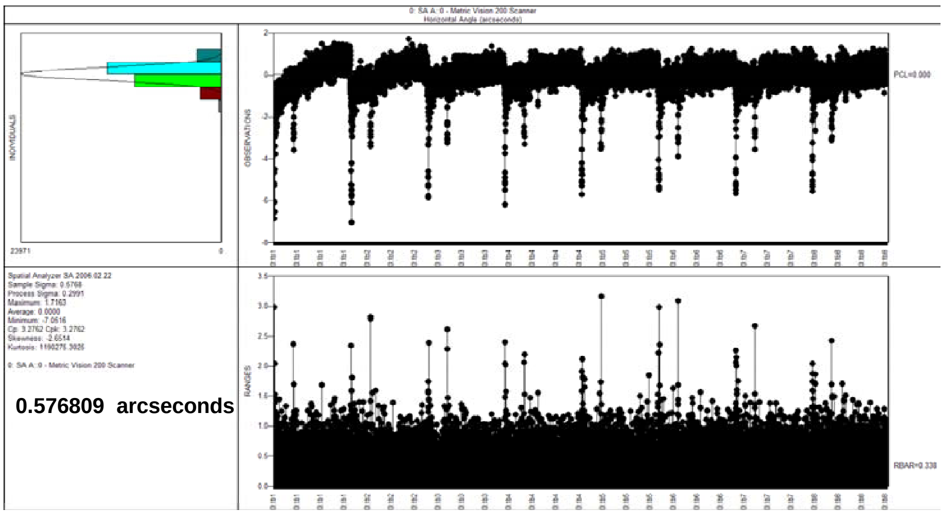
30408 measurements



9/7/2006 22

Slide G22

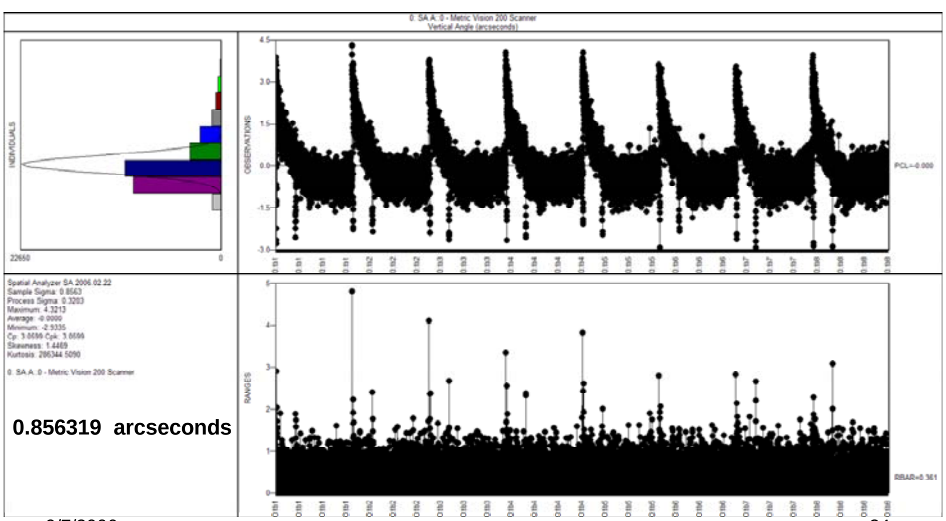
66 Hour Azimuth Repeatability



9/7/2006 23

Slide G23

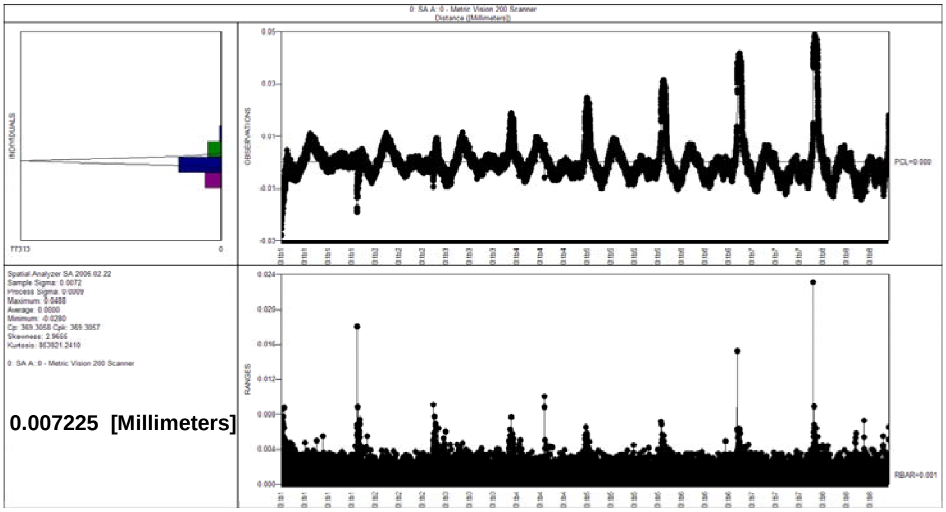
66 Hour Elevation Repeatability



9/7/2006 24

Slide G24

66 Hour Range Repeatability

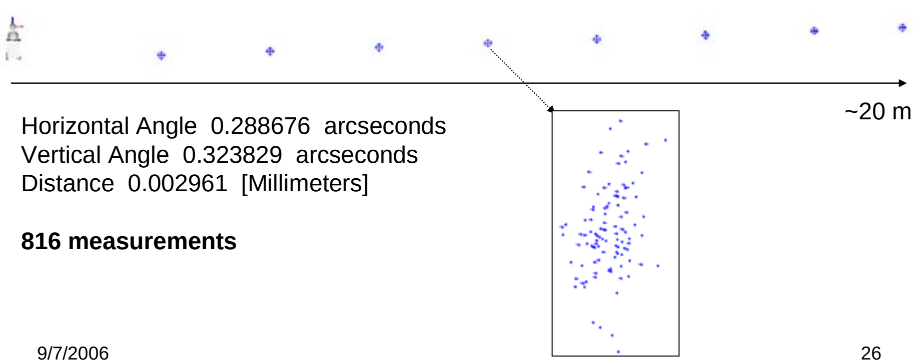


9/7/2006 25

Slide G25

Using USMN to Detect Motion on Repeatability Measurements

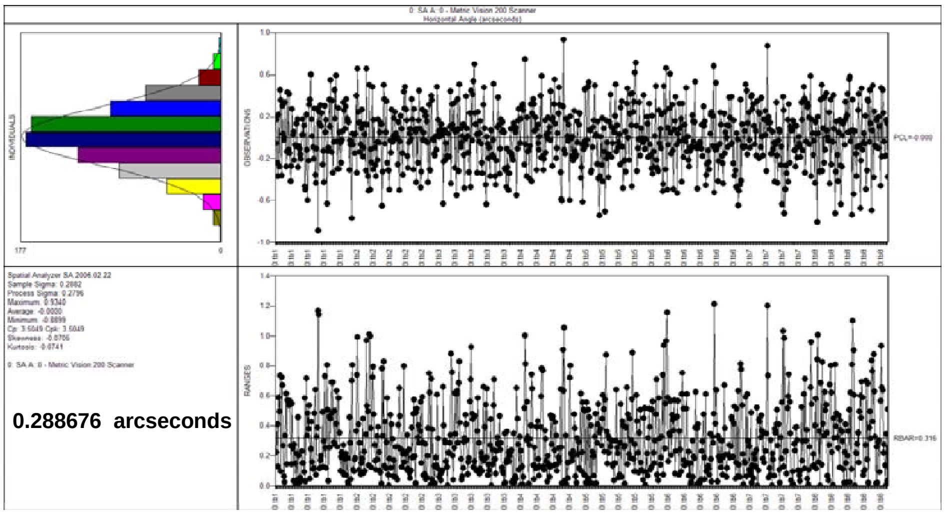
Final 100 minutes data collection time on eight tooling balls



9/7/2006 26

Slide G26

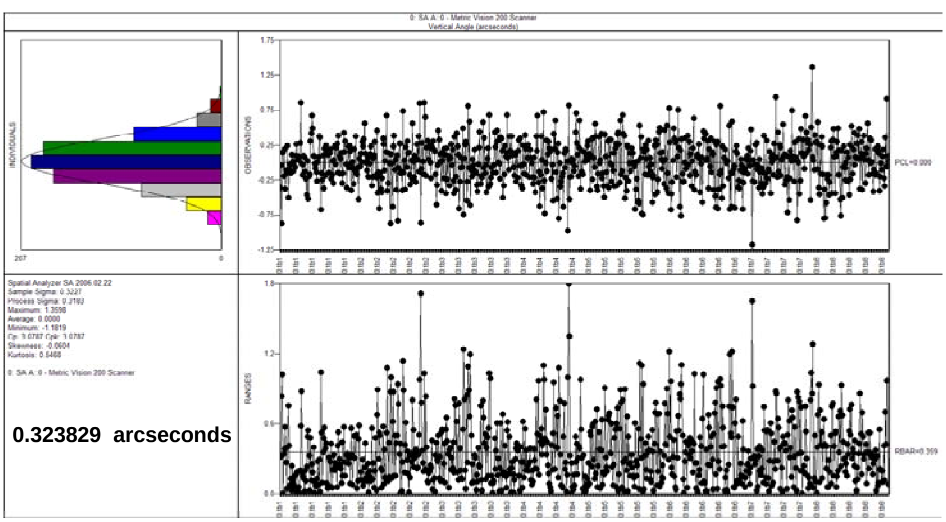
100 Minute Azimuth Repeatability



9/7/2006 27

Slide G27

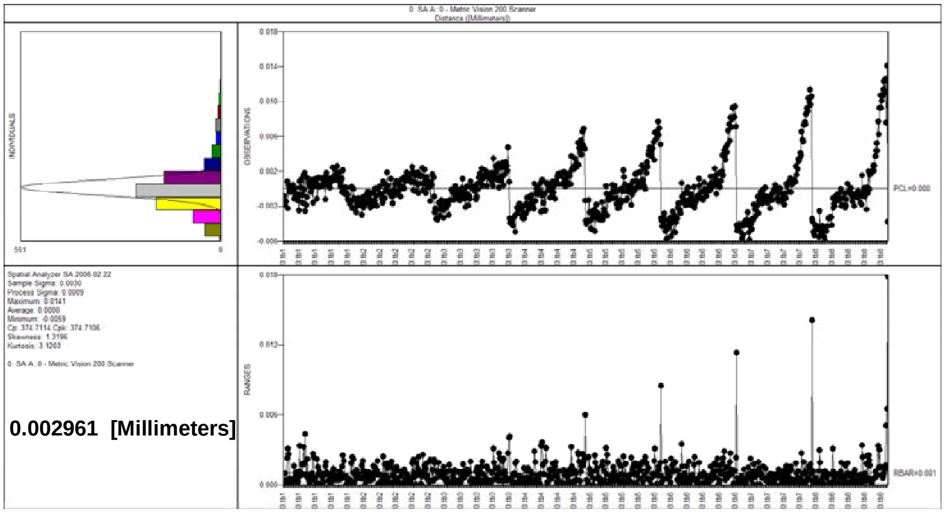
100 Minute Elevation Repeatability



9/7/2006 28

Slide G28

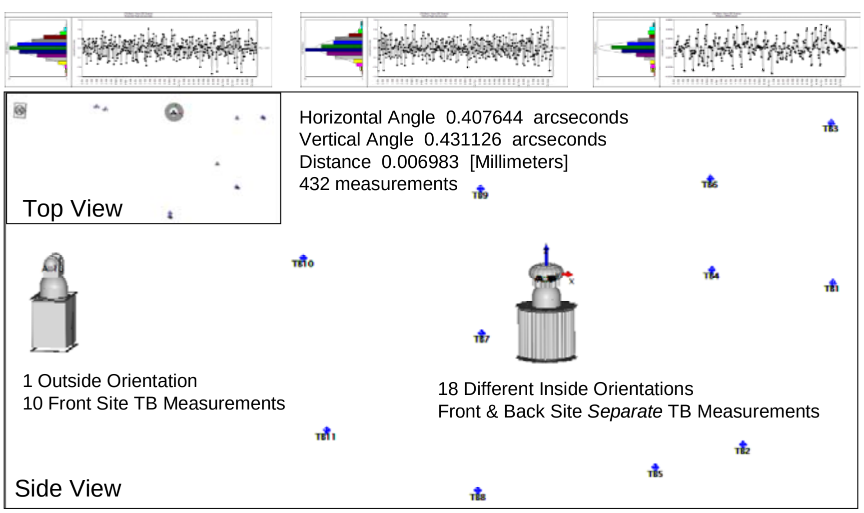
100 Minute Range Repeatability



9/7/2006 29

Slide G29

USMN Global Instrument Uncertainty



9/7/2006 30

Slide G30

USMN Considerations

- The *local* error distribution is assumed to be Gaussian ***noise*** when it is typically a combination of bias & noise
- The Least Squares uncertainty weightings are based on the user/manufacturer inputs and not based on the reality of the uncertainty of the instrument (or environment) at a specific point in time
- USMN can not separate instrument uncertainty from the uncertainty induced by the environment (temperature changes, vibrations, drift, etc.)
- SA Spherical/Polar angle uncertainty formulations do not allow for uncertainty variation with range
- The uncertainty clouds are centered about the measurements when the measurement may in reality be on the tail distribution

9/7/2006 31

Slide G31

Questions?

9/7/2006 32

Slide G32

APPENDIX H: NIST 3D Imaging Facility Update – Gerry Cheok (NIST)

NIST 3D Imaging Facility: An Update

Gerry Cheok
National Institute of Standards and Technology

National Institute of Standards and Technology 1

Slide H1

NIST 3D Imaging Workshops (1)

- Workshops in 2003 and 2005
- Objectives:
  - to provide a forum for sharing and discussing efforts in evaluation of 3D imaging systems
  - to determine the needs of the 3D imaging community
- General consensus:
  - neutral facility for performance evaluation
  - need for some form of standardization
    - Terminology
    - Standard evaluation protocols

National Institute of Standards and Technology 2

Slide H2

3D Imaging System Performance Evaluation Facility

Why:

- A national performance evaluation facility will provide much needed means to independently evaluate performance of 3D imaging systems – a capability that does not currently exist
- Standard protocols will allow
  - Fair comparisons of instruments
  - Method to verify manufacturer's claims
- Provide the basis for secondary field calibration standards

NIST National Institute of Standards and Technology 3

Slide H3

Facility (1)

- Purpose of facility
  - Performance evaluation
  - Test bed for developing evaluation metrics and test protocols
- Types of facility
  - Small indoor facility
    - Evaluate short range, very accurate instruments
    - Artifact based
  - Medium range facility
    - Allows for longer range (~ 50 m) evaluations
    - Rail system for positioning target
  - Outdoor facility
    - Long range evaluations
    - Evaluation in
      - Field conditions
      - Varying environment and seasons
    - Permanent benchmarks

NIST National Institute of Standards and Technology 4

Slide H4

Indoor Artifact-Based Facility (1)

- Facility
  - 17 m (L) x 5 m (W)
- Environment
  - Not temperature controlled but monitored. Temperature ~20.0 ºC ± 0.2 ºC
  - Humidity is monitored

National Institute of Standards and Technology

5

Slide H5

Indoor Artifact-Based Facility (2)

- Hardware
  - 4 – 3D imaging systems
  - Rotation stage
    - 1000 lbs capacity
    - 1.6 second incremental move
  - Targets
    - 18” x 18”: Multi – Step
      - ~12%, ~25%, ~50%, ~98%
    - 24” x 24”:
      - ~2%
      - ~22%
      - ~45%,
      - ~75%
      - ~99%
    - 1 m x 1 m: ~98%

National Institute of Standards and Technology

6

Slide H6

Indoor Artifact-Based Facility (3)

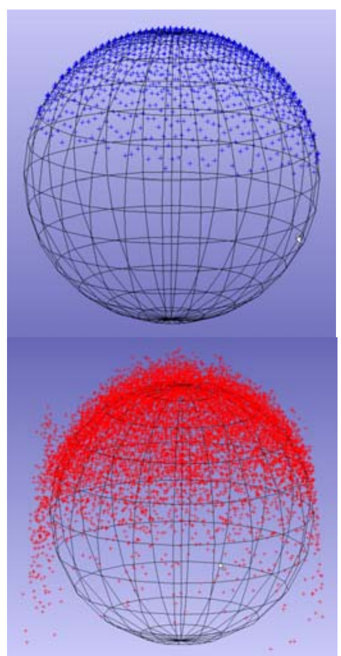
- Prototype artifacts
  - 6” and 8” diameter spheres
  - Slotted disc
  - Stair
  - Ball bar

National Institute of Standards and Technology 7

Slide H7

Artifact: 8 in. Sphere

- Anodized aluminum
- Registration
- Evaluate fitting algorithms

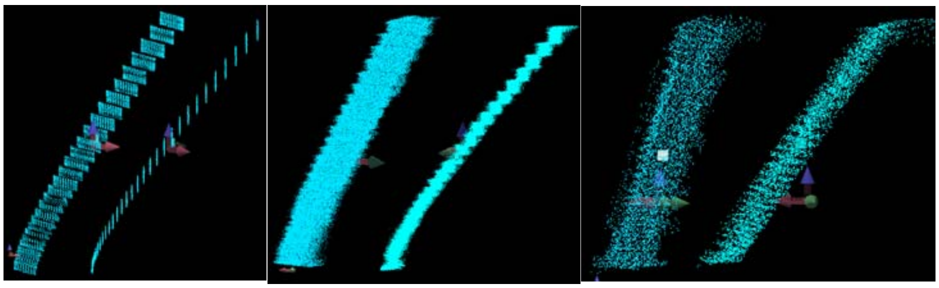


National Institute of Standards and Technology 8

Slide H8

Artifact: Stair

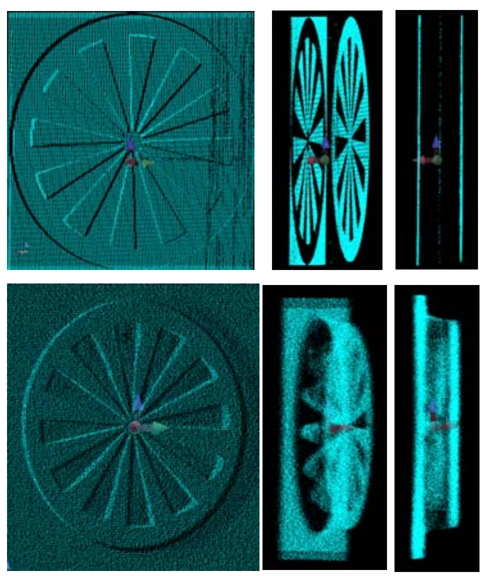
- Aluminum
- Step height 1 mm difference
- Resolution



National Institute of Standards and Technology 9

Slide H9

Artifact: Slotted Disc

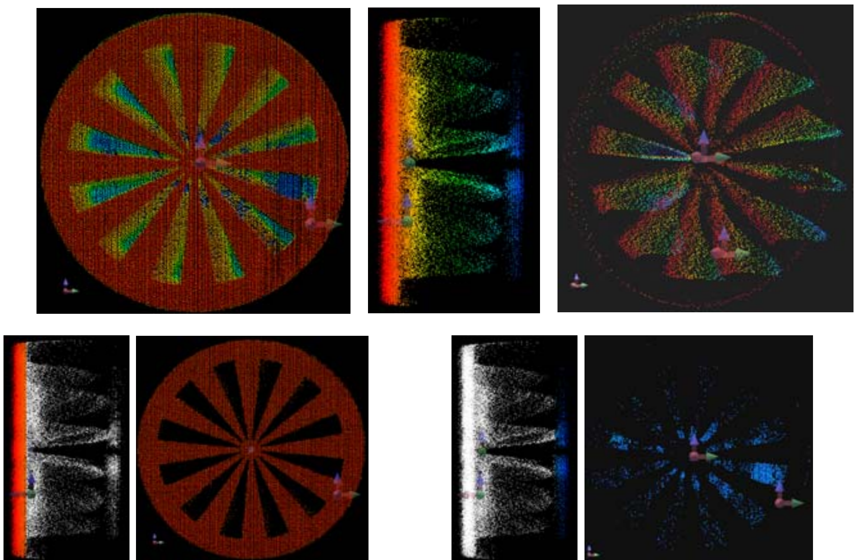


- Disc anodized aluminum
- Resolution
- Vary slot angles 0° to 15°
- Vary distance betw’n disc and back plane

National Institute of Standards and Technology 10

Slide H10

Fan: 14 m, 0.01 deg, 10 in back plane

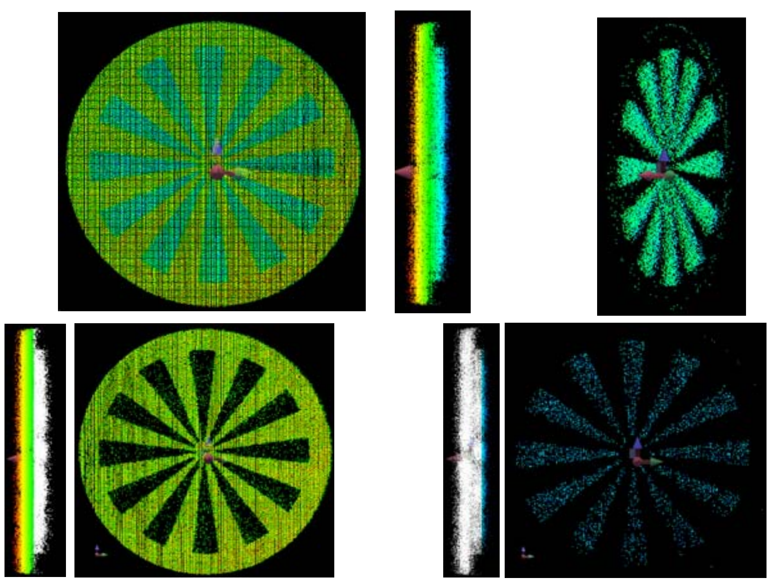


National Institute of Standards and Technology

11

Slide H11

Fan: 14 m, 0.01 deg, 1 in back plane

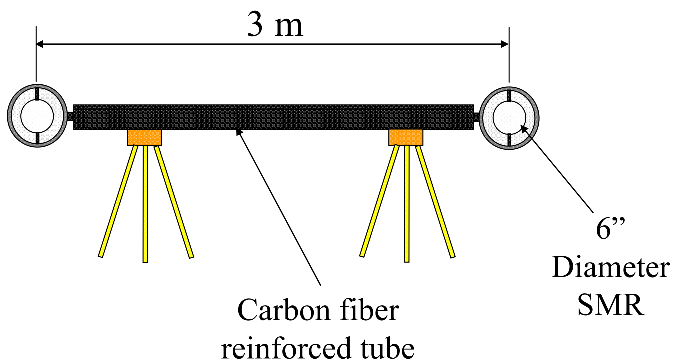


National Institute of Standards and Technology

12

Slide H12

Ball Bar

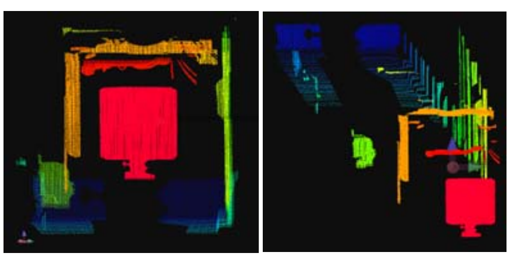


National Institute of Standards and Technology

13

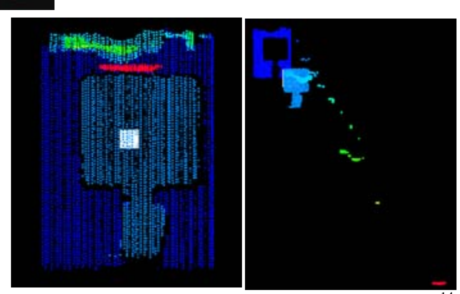
Slide H13

Ranging Protocol (1) - Initial Data Filtering



30 m

100 m



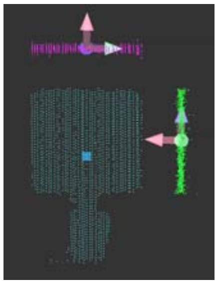
National Institute of Standards and Technology

14

Slide H14

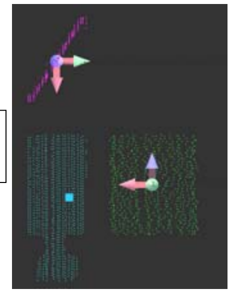
Ranging Protocol (1)

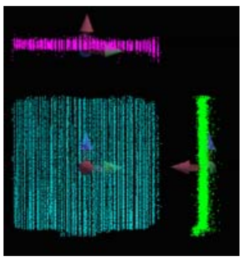
Distance = 100 m
Target reflectivity = 99 %



Rotation: 0º
Ang. incr.: 0.01º
No. pts: 1,800

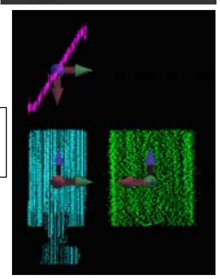
Rotation: 60º
Ang. incr.: 0.01º
No. pts: 800





Rotation: 0º
Ang. incr.: 0.004º
No. pts: 11,000

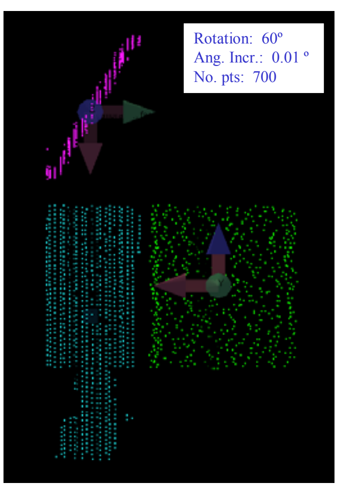
Rotation: 60º
Ang. incr.: 0.004º
No. pts: 5,500

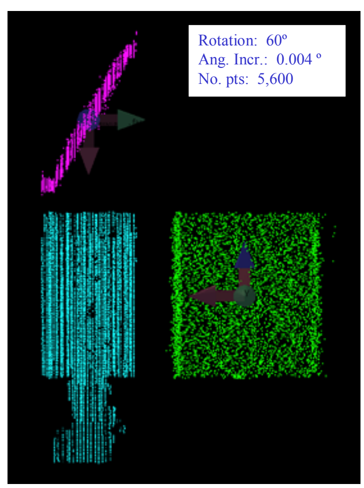


Slide H15

Ranging Protocol (2)

Distance = 100 m
Target reflectivity = 2 %





Slide H16

Future Tasks

- Test the ranging protocol
- Conduct experiments to determine registration uncertainty
  - Experiments using 6” SMRs and “box”
  - Test sphere fitting algorithm
- Conduct experiments using the slotted disc and stair artifacts
- Acquire linear stage for resolution
- Determine benchmarks for outdoor facility

National Institute of Standards and Technology

17

Slide H17

APPENDIX I: List of Workshop Participants

Registered Workshop Participants

Last Name	*First Name*	*Affiliation*	*Address*	*City*	*State*	*Zip Code*
Abdullah	Qassim	EarthData	7320 Executive Way	Frederick	MD	21704
Aindow	Alan	Leica HDS	4550 Norris Canyon Road	San Ramon	CA	94583
Battaglia	John	Bentley	20201 Century Blvd., Suite 420	Germantown	MD	20874
Borchardt	Bruce	NIST - MEL/PED	100 Bureau Drive, Stop 8211	Gaithersburg	MD	20899-8211
Bridges	Bob	FARO Technologies	222 Gale Lane	Kennett Square	PA	19348
Cheok	Gerry	NIST - BFRL/CMAG	100 Bureau Drive, Stop 8611	Gaithersburg	MD	20899-8611
Cothren	Jack	Univ. of Arkansas	Department of Geosciences, Center for Advanced Spatial	Fayetteville	AR	72701
Cournoyer	Luc	National Research Council of Canada	1200 Montreal Rd.	Ottawa	Ontario	K1A OR6
Daniel	Carlton	Army Testing and Evaluation Command	4501 Ford Ave	Alexandria	VA	22302
Dimsdale	Jerry	Voxis Inc.	1150 Brickyard Cove Road	Point Richmond	CA	94801
Elkins	Les	Spatial Integrated Systems	7564 Standish Place, Suite 100	Rockville	MD	20855
Fronczek	Chuck	Private consultant	17632 Charity Lane	Germantown	MD	20874
Garvey	Michael	M-7 Technologies	1019 Ohio Works Drive	Youngstown	OH	44510-1078
Gelhar	Brent	Optech	100 Wildcat Road	Toronto	Ontatrio	L5M 4G2

Last Name	*First Name*	*Affiliation*	*Address*	*City*	*State*	*Zip Code*
Gilsinn	Dave	NIST - ITL/MCSD	100 Bureau Drive, Stop 8910	Gaithersburg	MD	20899-8910
Greaves	Tom	Spar Point Research	85 Constitution Lane, Suite 2E	Danvers	MA	01923-3630
Hand	Steve	MagLevInc	1905 Tecnology Center, 1100 Industry Road, Box 11	McKeesport	PA	15132
Huard	Francois	Trimble	30 rue de Fontaine du vaisseau	Fontenay sous Bois		94120
Ingimarson	Darin	Quantapoint	275 Curry Hollow Road, Ste M100	Pittsburgh	PA	15236
Jackson	Ric	FIATECH	3925 West Braker Lane	Austin	TX	78759-5316
Keaney	William	Woolpert & Company	1314 Oakview Drive	Columbus	OH	43235
Klusza	Mark	Bitwyse	35 Congress Street, Suite 406	Salem	MA	09170
Kozlowski	Jesse	Taylor Wiseman & Taylor	124 Gaither Drive, Suite 150	Mount Laurel	NJ	08054
Kyle	Stephen	Metrology3+	University of College London, Gower St.	London		WC1E 6BT
Landrecht	David	Taylor Wiseman & Taylor	602 Brandywine Parkway	West Chester	PA	19380
Langer	Dirk	Z & F	1 Library Place, #203	Pittsburgh	PA	15110
Lukacs	Gabor	Geomagic, Inc	6408 Lakeland Dr.	Raleigh	NC	27612
Lukes	George	Institute of Defense Analyses	4850 Mark Center Drive	Alexandria	VA	22311
Lytle	Alan	NIST - BFRL/CMAG	100 Bureau Drive, Stop 8611	Gaithersburg	MD	20899-8611
Mechlinski	Jeff	Direct Dimensions	10310 S. Dolfield Rd	Owings Mills	MD	21117
Ober	Dave	Metris	8500 Cinder Bed Road, Suite 150	Newington	VA	22122
Persi	Fred	Quantapoint	Arbor Professional Centre, 275 Curry Hollow Road, M100	Pittsburgh	PA	15236
Phillips	Steven	NIST - MEL/PED	100 Bureau Drive, Stop 8211	Gaithersburg	MD	20899-8211

Last Name	*First Name*	*Affiliation*	*Address*	*City*	*State*	*Zip Code*
Picariello	Pat	ASTM International	100 Barr Harbor Drive	West Conshohocken	PA	19428
Pingbo	Tang	Carnegie Mellon University	4910 Centre Avenue, Apt E10	Pittsburgh	PA	15213
Raphael	Michael	Direct Dimensions Inc	10310 S. Dolfield Road	Owings Mills	MD	21117
Saidi	Kam	NIST - BFRL/ CMAG	100 Bureau Drive, Stop 8611	Gaithersburg	MD	20899-8611
Savikovsky	Arkady	Laser Projection Technologies	8 Delta Drive	Londonderry	NH	03053
Sawyer	Dan	NIST - MEL / PED	100 Bureau Drive, Stop 8211	Gaithersburg	MD	20899-8211
Schefcik	Mitch	Optira, Inc.	13335 A Street	Omaha	NE	68144
Soubra	Omar-Pierre	Trimble	7401 Church Ranch Boulevard	Westminster	CO	80021
Testa	Nicole	FIATECH	3925 W. Braker Lane (R4500)	Austin	TX	78759-5316
Van Rens	Jim	Riegl USA	7035 Grand National Drive, Suite 100	Orlando	FL	32819
Witzgall	Christoph	NIST - ITL/MCSD	20 Walker Ave	Gaithersburg	MD	20877
Yen	Kin	Mech. & Aero Engr., Univ. of California, Davis	2132 Bainer Hall, 1 Shield Ave	Davis	CA	95616-5294