NISTIR 7054

Proceedings of the LADAR Calibration Facility Workshop
June 12 - 13, 2003

Building and Fire Research Laboratory
Gaithersburg, MD 20899

United States Department of Commerce
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National Institute of Standards and Technology

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Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

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ABSTRACT

The use and scope of LADAR applications continues to expand as the technology matures, but standard protocols or procedures for calibrating and testing of LADARs have yet to be developed. While selections of LADAR instruments are generally based on the manufacturer's specifications, there are no uniform definitions of such specifications nor are there uniform guidelines for their validation. As a first step towards developing agreement on these issues, a LADAR Calibration Facility workshop was convened at NIST on June 12-13, 2003. The proceedings of the workshop are presented in this report.

Keywords: Calibration, certification, LADAR, performance evaluation, standardization, workshop

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Special thanks are extended to all speakers for their excellent presentations: Mr. Francois Blais of the National Research Council of Canada, Mr. Carlton Daniel of the U. S. Army Corps of Engineers, Mr. David Dozor of MetricVision, Dr. Gary Kamerman of FastMetrix, Inc., Mr. Eric Martin of Optech, Mr. John Palmateer of Boeing, and Dr. William Stone of NIST.

Also, very grateful thanks to Dr. David Gilsinn, Mr. Alan Lytle, Dr. Nell Sedransk, and Dr. Christoph Witzgall for their invaluable help and suggestions in planning the workshop and for their support.

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POLICY

It is NIST's policy to use the International System of Units (SI). However, some of the units used in the workshop presentations and papers are in U.S. customary units because of the intended audience. Conversions from the U. S. customary units to SI have been made where possible.

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1. INTRODUCTION

The Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST) conducted a workshop as a first step towards the establishment of a LADAR calibration facility on June 12-13, 2003 at the NIST campus in Gaithersburg, MD (LADAR is laser distance and ranging). The objectives of the workshop were:

- to provide a forum for sharing and discussing current efforts in LADAR calibration
- to determine the types of performance evaluations and test protocols required
- to identify the physical requirements of a calibration facility
- to explore potential plans for the establishment /operation /location of a LADAR test facility

At NIST, the growing use of LADAR technology and LADAR data processing underscores the necessity of an intramural test facility. In keeping with its mission as the Nation's metrology laboratory, NIST is in a position to provide metrology support to both users and manufacturers of LADARs in addition to meeting its own substantial internal calibration needs.

The workshop was organized around six presentations by leading proponents of LADAR technology. The presentations were followed by three break-out group discussions on both days. The discussions reinforced the realization that this burgeoning field of development and application requires metrology support.

These proceedings are organized as follows: Chapter 2 – workshop agenda, Chapter 3 – summaries of break-out group discussions, Chapter 4 – workshop summary and future steps, Appendix A – List of participants, and Appendices B to H – workshop presentations or papers.

2. WORKSHOP AGENDA

June 12, 2003

8:00 – 8:15	Registration	
8:15 – 8:30	Introduction	G. Cheok NIST
8:30 – 8:40	Welcome	J. Snell NIST
8:40 – 9:00	Overview: NIST/Construction Metrology and Automation's Work *The NIST Materials and Construction Research Division (MCRD) and the Intelligent Systems Division (ISD) make daily use of an extensive array of LADAR systems for such widely varying applications as real-time autonomous control of machines to tracking of manufactured components and characterization of construction sites for automated assessment of job status. Significant recurring calibration needs by the disparate LADAR user-communities at NIST has led to the concept of a joint calibration facility which, with industry input, may also serve as a neutral national calibration resource.*	B. Stone NIST
9:00 – 9:30	Calibration Activities at the National Research Council of Canada (NRCC) *The NRCC has been involved in the field of 3D Imaging for more than 20 years. Various aspects of 3D have been investigated, from laser scanner development, calibration, performance assessment, 3D geometrical processing, display, and various industrial applications. This presentation will focus on the activities related to the calibration of laser scanners and the creation of a calibration facility and tools that allow accurate modeling and evaluation of the performances of 3D systems.*	F. Blais NRCC
9:30 – 10:00	Future of Laser Radar	G. Kamerman FastMetrix
10:00 – 10:10	Break	

10:10 – 12:00	3 Break out groups	
12:00 – 12:30	Reconvene for whole group discussion	
12:30-1:30	Lunch – (Self-service NIST cafeteria)	
1:30 – 2:00	LADAR Measurements at Boeing *Current Boeing efforts in LADAR development have been directed toward systems capable of measuring parts and assemblies in a manufacturing environment. Goals include on-machine measurement and measurement during assembly for control and inspection. A national laboratory with expertise in various LADAR systems, which will ensure a better understanding of the modes of LADAR failure is envisioned.*	J. Palmateer Boeing
2:00 – 2:30	Corps of Engineers Field Measurement Requirements *The rapid assessment, development, and insertion of LADAR calibration standards into the Corps' Operations and Maintenance programs will improve the operational effectiveness of a wide range of traditional field measurement requirements. The presentation will describe the results of recent Civil Works projects where commercially available laser scanning systems have been used. A description, with illustrative examples of products from the projects, initial accuracy results, and time response-related results with future implications, are presented.*	C. Daniel USACE
2:30 – 5:00	3 Break-out groups	
5:00 – 5:45	Reconvene for whole group discussion.	
5:45	Adjourn for Day 1	

June 13, 2003

8:00 – 8:30	A Facility for Calibration of a 24 m FM Coherent Laser Radar	D. Dozor MetricVision
	The presentation describes the existing facility used to calibrate the MetricVision's Coherent Laser Radar products. These products incorporate Frequency Modulated Coherent Laser Radar, which must be precise and accurate over a wide range of operating temperatures. An overview of the product technology, and a review of the calibration laboratory and practices will be presented.	
8:30 – 9:00	Calibration Verification for Long Range Tripod-based Terrestrial Laser Scanners	E. Martin Optech
	As with other precision instruments, terrestrial laser scanners rely on the manufacturer's calibration process to ensure the product meets specification at the time of shipment. The presentation will address the calibration attributes as they pertain to long range terrestrial laser scanners range, and outline the field procedures to verify the calibration state of any scanner. The procedure outlined can be adapted to serve the needs of a wide variety of products currently available, and is based on a practical rather than theoretical approach.	
9:00 – 11:30	3 Break-out groups	
11:30 – 12:45	Reconvene for whole group discussion	
12:45 – 1:00	Wrap-up – next steps	
1:00	Adjourn	

3. SUMMARIES OF BREAK-OUT GROUP DISCUSSIONS

In the group discussions, the term "accuracy" was frequently used. There were general discussions of what is meant by "accuracy" and other metrology terms – hence, the call for common definitions in the workshop recommendations. In the following sections, "accuracy" should be taken to mean "deviation from the truth" or "uncertainty of a measurement" as these interpretations seems to meet the intent of the speaker.

3.1 June 12, 2003: Morning Session

The main question for this break-out session was: "What can we calibrate?" The following outline was given to each group as a guideline for their discussions:

- current systems
  - types of systems
  - system characteristics
  - additional steps required to accommodate future systems
  - potential problems – system specific procedures?
- what would we like to calibrate?
  - range
  - pointing accuracy → determine correlations → error propagation
  - beam divergence → resolution
- prioritize

The break out group assignments were made to so that each group had a mixture of end users, manufacturers, and researchers. This may not have occurred due to unavoidable absences.

3.1.1 Group 1 Summary

Group Participants:

John Palmateer (Chair)	*Francois Blais*	*Carlton Daniel*
Dave Dozor	*Les Elkins*	*Tyler Estler*
Maris Juberts	*Joe Liadsky*	*Alan Lytle*
Nell Sedransk		

This group considered four areas: types of LADARs, types of standards, measurement uncertainties, and priorities for a national lab.

Following an initial review of the types of LADAR systems, Group 1 then discussed the characteristics of the various LADAR systems – time-of-flight, flash, long-range low accuracy, short-range high accuracy, etc.

The group then considered standards and identified three types of standards:

1. Performance standards or commercial standards. A fundamental question is how does one compare system A with system B and have a common language so that one can make a rational decision.

2. Customer uncertainty. For an ultimate user of the data, the *xyz* value is usually the important output from the sensor. Therefore, the uncertainty for this data is crucial.

3. Researcher and developer standards. These standards deal more with specific LADAR system details to try to quantify error models and to better understand and improve performance. These standards are similar to customer uncertainty but include more details so that an evaluation of the system is possible.

The group also felt that standards were also required for the environment – outdoor, lab, factory. Seismic issues and ambient lighting were considerations to be taken into account.

Measurement uncertainty was then discussed. Potentially one needs to separate measurement uncertainty from analysis/software uncertainty (e.g., registration error). These uncertainties are usually combined and reported as a single value. There may also be other task specific uncertainties and these tasks are often intrinsic to the numerical analysis. The issue of uncertainties as a transfer function was discussed. Is this valid? What are the issues related to this?

Finally, priorities for national lab to assist users were discussed:

- issue for users
  - getting help in setting performance standards
  - participants were disappointed that NIST does not set standards
  - a lot of users would like to see performance standards developed
- developers/manufacturers need standards
  - environmental and seismic standards

3.1.2 Group 2 Summary

Group participants:

Don Channin (Chair)	*Jim Albus*	*Eric Lundberg*
Eric Martin	*Arkady Savikovsky*	*Mike Shneier*
Tony Slotwinski	*Bill Stone*	*Nicolas Vandapel*
Chris Witzgall		

This group concentrated on two topics: calibrations and accuracy.

Currently, calibrations are usually done internally by the manufacturer. Users have to interpret these reported measurements in terms of their requirements and have to understand if a given manufacturer's system, as reported in their specification sheet, meet their needs. Users have reported that this, in general, is very difficult to do. Therefore, calibration processes meant to bridge this gap between manufacturers' specifications and users' requirements are needed.

Another issue discussed was the measurement accuracy of a point in space (e.g., a target or reference). There are absolute vs. relative measurements. Different systems respond to different targets in different ways. Therefore, it was recommended that an important first step would be to develop a reference set of targets. The optics community has standard gray scales and it is important to develop something similar to this for LADAR systems. However, the development of such a standard scale for LADARs is harder as there is a wide range of LADARs – instruments which use wavelengths varying from 600 nm to 1500 nm, high precision instruments (maximum range < 10 m), factory scale (maximum range of about 50 m), outdoor scale (maximum range of 100s of meters).

Environmental factors were identified as major contributors to measurement error, and they introduce variability which is difficult to control. For LADARs used outdoors, the uncertainties of measurements will change according to environment, especially in rugged environments. Specifications are usually obtained under a controlled environment and users need to interpret how these specifications change when used in their work environment.

The group then discussed the desired level of accuracy in a test facility, that is, < 1 mm, < 10 cm, etc. What level of accuracy should a facility provide? The challenge lies in trying to deal with different levels of accuracy – a 1 mm accuracy may be sufficient for one instrument but crude for another instrument. This issue is very difficult to solve. In terms of positional accuracy, the accurate distance between 2 target points is usually not sufficient. It is important to determine what is necessary to encompass all the different applications.

3.1.3 Group 3 Summary

Group participants:

Dave Gilsinn (Chair)	*Gerry Cheok*	*Chuck Fronczek*
Joe Grobmyer	*Steve Hand*	*Dirk Langer*
Anders Ryerson	*John Sandusky*	*Dan Sawyer*

One of the main points made in this group was the need for definitions of common terms. The group could not agree on the difference between acronyms LIDAR (light distance and ranging) and LADAR. In army's point of view, the term LIDAR was associated with Doppler, aerosols, and wind measurements and LADAR was associated with mapping and hard target detection. A statement was made that if all that comes out of this workshop is a common set of terminology, it would be very helpful.

Some of the other points discussed by the group were:

- standards

    - hardware standards
    - software standards – a user may not know what software is used and the results would be different for different software
    - end users
        - want to know how well the system as a whole works
        - performance standards is preferred and more important than hardware standards
    - manufacturers
        - prefer a set standard protocols and/or artifacts which allow in-house testing in lieu of a certification procedure which would involve shipping each instrument to a neutral facility as this would be very cumbersome and expensive.
- test facilities
    - many existing facilities
    - examples
        - military facilities (Eglin, Redstone)
        - Canada (NRC)
        - private (Raytheon)
    - How many are out there?
    - Where are they?
    - How does NIST fit in?
- need for a facility
    - from a manufacturer's point of view, set of common procedures is needed, not necessarily a facility
- parameters currently being measured
    - range
    - pointing
    - beam divergence
- need to have static and dynamic scenes
- some facility properties/requirements:
    - include objects with known
        - dimensions
        - reflectance
    - need to have targets which encompass the various wavelengths used by LADARs
    - positioning for pointing
    - types of objects / artifacts have to be agreed upon
    - facility requirements
        - physical requirements will be driven by application
        - three facility sizes were considered
            - 5 m to 20 m
            - 20 m to 50 m (factory scale)
            - > 100 m (construction)
- what can NIST contribute – at the very least, a public facility

3.2 June 12, 2003: Afternoon Session

The group assignments for this break-out session were the same as for the morning session. The main question for this break out session was: "Select one or two properties for calibration. Given those properties, how would you calibrate?" The following outline was given to each group as a guideline for their discussions:

- what accuracy/resolution issues were encountered?
    - lessons learned
- what are the most important properties for calibration? for whom (manufacturers, end users)?
- can we calibrate it?
- how will this change for future LADARs?
- other insights

3.2.1 Group 1 Summary

The group had wide ranging discussions. The question as posed by the group chair was – "What properties should be calibrated?" If you want to calibrate something, what are the standards for calibration? There is a need to define the term "calibration" and other terminology. For example, one person's calibration is another person's compensation and it is very important to define what is what. There was a lot of discussion on the topic of terminology.

The group then discussed standards. The group did not discuss facility requirements or what standard the aircraft industry would look at vs. the standard used by the shipping industry as these standards vary based on the purpose of the calibration. For example, Boeing uses multilateration technique with tracking interferometers and their standards are established accordingly. Earl Morris (Redstone Arsenal) uses GPS for long range (over kilometers) measurements or they use theodolites.

Calibration issues were the next topic of group discussion. The group felt that it was very important to look at targets. What out there are you measuring? They considered target boards with different targets. For diffuse targets, the laser spot size becomes important. For range measurements – point measurement, focal plane array – the target has to be bigger than the spot size. Therefore, knowledge of the laser beam size and characteristics is needed. Likewise, the modulation transfer function, normally applied to cameras, may have utility for LADARs.

The measurement distribution and density of points for a given measurand was also discussed. For example, for a given feature and uncertainty, how many points are needed on that feature and how is the point density related to the resulting uncertainty. How many points really define a circle and does that change with the uncertainty of the measurements and the placement of the targets. This topic led to a discussion of statistical measurements. When reaching the limit of what is physically possible, you have to allow statistics to ferret out the information. Therefore, statistics need to be part of any calibration process.

Finally, calibrations have to consider the environmental factors.

3.2.2 Group 2 Summary

The group discussions primarily focused on a high level (big picture) view

- what is the purpose the calibration facility and the effort behind it
    - end users – need less detailed data
    - manufacturers – will it be a unique facility where they can test their instrument
- is it to certify equipment or to calibrate
    - certification
        - certification, to Group 2, means that the equipment is brought to a facility where specific performance tests are conducted. The result is a certification based on the test results, verifying that certain levels of performance were achieved. In some cases, performance will be determined by the manufacturer themselves, e.g., if they want their equipment to measure a standard item to a certain degree of accuracy. In other cases, the level of performance will be set by standards, e.g., use of LADARs in civil engineering. In that case, standards may be established for these applications.
    - calibration
        - equipment specific
        - difficult to find common ground to calibrate different LADAR systems.

The consensus of the group was that the certification function would be the primary function of a neutral facility with some calibration support.

The group identified 3 scales for a facility

- small
    - 2 m to 3 m range
    - 1 μm to 1 mm uncertainty
    - characterized by a single artifact
- medium
    - 3 m to 20 m range
    - millimeter to centimeter level uncertainty
    - being a single room environment
- large
    - > 20 m range
    - 1 cm to 3 cm uncertainty, at times may require 1 mm at 100 m
    - outdoors

The facility could also be characterized in terms of the kind of equipment that the LADAR unit might be replacing. For example, if replacing a CMM (coordinate measuring machine), a medium scale facility could be appropriate and measurements using a laser tracker or other surveying equipment would likely provide the required accuracy. Consideration of how the equipment is used or what equipment is being replaced may dictate the physical size of the operation. Using this criterion, the group identified some accuracy requirements for a medium size facility. For a medium size facility, there is likely a need to measure down to the level of a thousandth of an inch to be equivalent to a CMM. For civil engineering measurements, measurements down to the order of millimeters may be required for capturing information regarding object deformation while a larger scale, on the order of centimeters, may be acceptable for object placement. The facility will have operational scale limits and it was agreed that a calibration facility will have to have 10 times the accuracy of the operational limits.

The group realized that LADAR equipment measures the pointing and ranging data (although the end user only uses *xyz* data) in different ways and probably have different elements of accuracy associated with each. This once again raised the question of calibration vs. certification – if you are certifying equipment, it is probably sufficient to get the *xyz* accuracy and not worry about how the ranging and pointing accuracies contribute to the *xyz* accuracy. But if you want to calibrate a system, knowledge of component accuracies is very important. So if the facility is intended to support calibration, then you have to address this issue and the fact that various LADAR systems use different methods of addressing them. This issue does not apply for certification.

The group felt that in addition to issuing a pass/fail and certifying an instrument to a certain accuracy, it would also be helpful if a neutral facility included some information as to the source of error. This may or may not be possible.

3.2.3 Group 3 Summary

The group looked at specifics. When calibrating something, what are you going to do? Taking range as an example, how might you do it here at NIST. Currently NIST has a tape tunnel that goes out to 60 m. A rail system with a platform for targets positions the target along the 60 m track and an interferometer is available for use. There is a need for standard targets with multiple surfaces and targets with different reflectances. A target board with a sub-panel within the target that can be moved in and out of plane of the target was suggested to examine depth resolution. This test could also be used to study beam divergence – more blurring at the edges would indicate a larger beam divergence. A "stair" target was also suggested for studying depth resolution. A question was raised, "Does beam divergence have anything to do with distance?" and the answer was "Yes, it does". Examination of "phantom points" or "mixed pixels" also requires some knowledge of beam divergence. Targets for LADAR systems which record multiple returns (it was felt that this feature will become more prevalent in future systems) should have a mesh in front of the target to pick up the different return pulses.

Reflectivity, beam divergence, pulse distortion effects, and environment all affect distance measurements and should be considered.

A question was raised regarding the feasibility of establishing a kilometer range facility at NIST. It was felt that there was sufficient infrastructure at NIST to establish such a facility.

3.3 June 13, 2003: Morning Session

The main question for this break-out session was: "What is the ideal facility?" The following outline was given to each group as a guideline for their discussions:

- what would an ideal facility for ground based LADARs do
  - indoor/outdoor
  - modular/unified/consortium
- what should be required by way of calibration to cover
  - short and long range systems (meters to kilometers)
  - accuracies from microns to centimeters
- select a component of the ideal facility for a more detailed outline
- should we standardize? can we standardize?

3.3.1 Group 1 Summary

Eric Martin (Chair)	*Abdullah Qassim*	*Don Channin*
Chuck Fronczek	*Dave Gilsinn*	*Eric Lundberg*
Tony Slotwinski	*Bill Stone*	

The discussion centered on "What is going to come out of this effort?" and on trying to tie up a lot of the loose ends. There were a lot of ideas but there were few common denominators. First of all, the group acknowledged the fundamental need for an artifact-based facility – irregardless of the type instrument. Rather than talk about facilities for calibrating devices (there was some hesitancy/reluctance and legal connotations associated with the certification aspect), the group talked about a neutral performance metric that would allow for rational comparison of one LADAR against another.

The group also talked about living within the realities of budgets and financial constraints. It was felt that at present time, funding of $300 K to $500 K could be available on a pilot project basis. This amount would serve to address some of the short, medium and long range systems and to just really "get our feet wet" – to begin addressing the neutral performance concept – first thoughts and impressions of what is needed or not needed, before any large commitment of funding is made.

The types of customers were discussed. Who would benefit from having this kind of facility? The group categorized customers into 3 classes:

- 1st group – the really savvy leaders of the field who really know what they are doing and have intimate knowledge of the instruments and work with manufacturers to develop the necessary calibration specifications
- 2nd group – those who know what they need but don't necessarily have the wherewithal or a facility to test the instruments
- 3rd group – naïve customers who could be persuaded either way with a sales pitch or may not understand how to compare and evaluate the different systems

The group sees the growing need for a facility simply because as LADARs get more prevalent, more and more people will use them. The category of customers seen as growing the most is the last category or the naïve customers, and the existence of a neutral facility then becomes all the more important. The group felt that there was a need for a market survey and the need to include others (besides those represented at the workshop) as everyone needs to be on the same page at least in the initial stages. The group suggested contacting other agencies to try to avoid duplication of effort and to try to avoid, more importantly, contradictory information that could happen in a bureaucracy. Included in that contact list are specific organizations that deal in the specific areas like some of the survey groups – the metrological ones that have their own unique interests.

In terms of an action item to move forward, the group agreed with the need for a facility that performs neutral performance measurements/assessments for LADARs. The classes of performance are going to vary and the facilities themselves would vary depending on the type of devices being tested. "It is virtually impossible to come up with a single one size fits all, universal, all seeing facility to check standards that range from microns to millimeters to centimeters over ranges that may go out to kilometers – this simply becomes virtually impossible to do."

The group discussed a combination of an indoor and outdoor facility as described in the workshop presentations. There is also a need for standardized data sets for software – for software development purposes and software analysis.

In regards to the question of a facility: A facility – if there is a need for one and the group has argued that there is – should NIST build it or should someone else? This is a fundamental issue that has to be decided or at least can't be overlooked.

The need to define a neutral performance metric was felt to be a fundamental consideration if a metric is to be tested. The metric needs to defined – what are the important criteria? By having this neutral performance metric, manufacturers will be able to standardize definitions of performance for sales literature, brochures, etc. This allows the 3rd category of users (those not well versed in the technology or in the applications) to have a level playing field for comparison. The group felt that some progress was made in this regard over the last day and a half.

Also, there was agreement within the group that certain manufacturers would certainly be interested in an industry guide.

The group felt that this initiative should move forward because at least from the manufacturers' and a lot of the users' point of view, it is something that was seen as being required as LADARs become more prevalent. The group did not discuss detailed facility requirements because they felt that it is still too early in the planning phase to do so.

3.3.2 Group 2 Summary

Steve Hand (Chair)	*Gerry Cheok*	*Les Elkins*
John Sandusky	*Dirk Langer*	*Alan Lytle*
John Palmateer	*Chris Witzgall*	

The question of the day was "What kind of facility do these instruments need?" The first comment was "Who is going to operate it and who is going to use it?" Along with these discussions, the group discussion, as occurred in the past day and a half, centered on the need for common terminology or definitions. This need was felt to be essential and should be addressed early in this process of establishing a calibration/performance assessment facility.

The group discussed legalistic issues regarding calibrations vs. certifications, the identification of standards to be tested, and the use of the facility as simply a test range with a third party (e.g., NIST) oversight. These were the different concepts of what the facility would be used for and how it would be operated. It was felt that a facility would provide the means for objective tests and not necessarily a certification.

The size of the facility was discussed extensively by the group. It was pointed out that a 2-story or a high bay facility was needed. The group agreed that there has to be multiple facilities. Having a single facility for all types of LADARs is going to be very difficult.

There was also quite a bit of discussion on artifacts and the fact that the artifacts are going to have to be based on the actual parameters (application) and how to develop standard procedures. One topic during the group discussions was the discussion of the artifacts being NIST traceable. What does NIST traceable mean? Similar questions were then raised. Given that such artifacts would be available to a manufacturer or end user for loan or rent, the group felt that it was necessary to develop procedures (for care, handling, set-up, testing, environmental test conditions) for the use of the artifacts. The group also discussed how end user testing might work in such a facility.

The group also came to the conclusion that a facility is necessary. The group consciously avoided discussion of certification. They instead discussed the procedures for the use of the facility, the artifacts, and the maintenance and management the artifacts and the procedures. The group felt that the question of allocation of error should not be overlooked and should be dealt with, especially in a growing industry such as LADARs.

3.3.3 Group 3 Summary

Dave Dozor (Chair)	*Francois Blais*	*Tyler Estler*
Joe Liadsky	*Arkady Savikovsky*	*Dan Sawyer*
Nell Sedransk	*Nicolas Vandapel*	

The group began their discussions with "What does the field look like – long range systems, shorter range systems, and short range low uncertainty and long range high uncertainty type of systems?" The group talked about different types of facilities and the group chair felt that at least two facilities are required – some others thought at least three are required.

The group felt that many facilities would be required and discussed what sort of overlap they should have. The group recognized that the most expensive facility would probably be the small, highly controlled facility for the short range instruments. On the other hand, it may be less costly and actually advantageous to have many field-based facilities in different climates, different terrains to help characterization of and understanding of LADARs by the capture of the entire scene rather than identifying tooling balls as is done in industrial-type metrology.

What should be characterized? Error modes or failures? The group discussed topics and areas that required investigation, specifically for some of the pulsed laser radars – multiple objects in the field of view, calibration for <u>all</u> types of LADARs, and performance specifications/verification. For laser radar, doppler is a major issue and therefore, moving targets are something that should be included in a test facility.

A point was brought up in the group discussion concerning the relative size of an organization. The companies currently manufacturing LADARs are usually small companies – ranging from 20 to 25 people, definitely, less than 50. Some companies have had the advantage of working with and having the support of much larger companies using their instrument. However, there are those companies which don't have the benefit of such technical and financial support. These "companies that don't have billions of dollars behind them could really use a NIST facility to help them".

The group did not discuss standardization because they thought that this is a topic that required a lot more thought and time than was available in this workshop. They agreed that range, point to point positioning accuracy, different types of materials, resolutions of the combined system, impact of reflectivity on measurement, ambient lighting conditions, relative humidity, temperature, vibration, environment are all very important parameters that are first order for study and some standard procedures and methods need to be developed to examine them. A lot of these parameters extend across the different types of LADARs.

Drift tests and higher measurement resolution must be considered and that means in the entire volume. For example, MetricVision measures many tooling balls all around a given space but they don't segment the 20 000 m^3 to 30 000 m^3 space into many 1 cm^3 spots and guarantee that each point in that volume as accurate. So the question is where does the laser radar fail? Another instance was brought up whereby a serious problem could not be identified due to the lack of a sufficiently large facility. The problem was identified in the field (large manufacturing environment) and fixed; however, not before many of the instruments were already manufactured. It was felt that a NIST facility, assumed to be larger than what a small company would likely have or have access to, could help identify these problems.

The group talked about 2.5D vs. entire scene. If you have a room full of different types of artifacts, how do you ensure that all those things have the point to point accuracy that you want. The 2.5D situation is a lot easier – you can measure with a CMM or a laser tracker.

Standardization was then discussed. The types of targets that can be measured should be standardized. The group was resoundingly positive on this issue. The types of standards for measuring range could be standardized – however, it requires a lot more thought. There are probably some other things that can be standardized in the area of LADARs – certainly types of targets and range standards are two that can be addressed immediately.

4. WORKSHOP SUMMARY

The Building and Fire Research Laboratory of NIST conducted a workshop as a first step towards the establishment of a LADAR calibration facility. The workshop was held on June 12-13, 2003 at the NIST campus in Gaithersburg, MD, and was attended by a representative cross section of end users and manufacturers as well as private and government researchers from Canada and the United States.

The workshop was organized around six presentations and three break-out sessions. In each of the break out sessions, the participants were assigned to one of three groups. After each break out session, all the participants reconvened and a summary of the group's discussion was presented. Summaries of the groups' discussions are given in Chapter 3. A general workshop summary and future steps are presented in this chapter.

4.1 Summary

An underlying theme in many of the workshop discussions was how to deal with the fundamental question: "What is calibration?" More specifically "Do you really want calibration or do you want performance assessment/evaluation or do you want certification?" The terms "calibration", "performance evaluation", and "certification" have similar meanings and have been used, at times, synonymously. However, slight differences in the nuances of these terms play a crucial role when establishing a facility for calibration or performance evaluation or certification.

It was felt that <u>calibration</u> is performed to determine the hardware characteristics to enable setting or alignment of instrument parameters to optimal levels. A more formal definition of calibration given by VIM [3] is:

> *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.*

<u>Performance assessment/evaluation</u> is a voluntary assessment and would be conducted, at the request of an end user, to determine how well the instrument and the processing software would

meet the end user's specific requirements. The performance assessment could also include software analysis.

Certification has legal connotations and would involve testing of the instrument in accordance with a set of protocols and the results measured against a metric – pass/fail. The testing would, in general, be conducted in a certified laboratory. Product certification is voluntary; however, lack of certification may be interpreted negatively – rightly or wrongly.

The following example for measuring tapes is offered to help clarify the difference between certification and performance evaluation [1].

> *An American company wants to sell measuring tapes in Denmark. To do so, the tapes have to meet certain requirements. They meet the requirements and are certified, and the company is given the authority to put the official seal on their tapes. No individual tape needs to be evaluated since they have been certified.*
>
> *In the U.S., the same company simply sells the tapes. The customer either believes the numbers or not. If the accuracy of the tape is important, the customer will request traceability of the measurements. At this point, a higher authority, NIST or a laboratory traceable to NIST, will be asked to calibrate the tape.*

What then are the needs of end users and manufacturers? Because of the large investment involved in acquiring LADAR instruments, users need to have confidence in stated claims or specifications and be confident that what they are purchasing would meet their particular needs. The following measures would aid in building this confidence:

- clarification of manufacturers' specifications to enable meaningful comparisons between various commercially available instruments
- uniform guidelines for manufacturers' specifications, testing, and reporting
- performance testing of individual user-owned instrument upon request at a neutral facility

Manufacturers also expressed support for the goals of the workshop. Although many LADAR manufacturers have gone to great lengths to test and evaluate their products, they affirmed the need for quality assurance and uniform specifications such as:

- common set of terminology
- facilitation of "factory floor" calibrations through the use of NIST traceable artifacts and standard procedures
- availability to manufacturers of a climate controlled facility for testing/calibration, particularly, under extreme conditions
- uniformity of specification testing and reporting

The LADAR output of main importance to most users is the *xyz* data. However, as the LADAR output is typically a large point cloud, processing methods are to be included in the testing process to provide “end” or “total” performance evaluation. For manufacturers, however, accurate information of the hardware performance is essential for instrument improvement.

Another difference between end users and manufacturers is the apparent need for a facility. For end users, a neutral facility where one may send an instrument for performance evaluation is desirable. On the other hand, the majority of manufacturers at the workshop prefer a set of standard protocols and/or artifacts which allow in-house testing over a certification procedure. This was because certification would involve shipping each instrument to a neutral facility and this would be very cumbersome and expensive. Properties of interest to both users and manufacturers include range, beam pointing, beam size/spread, and processing multiple returns (mixed pixels or phantom points).

The general consensus was that a single facility that would encompass the entire range of LADARs would be impossible. Therefore, three kinds of testing facilities were envisioned as being necessary:

- a small, highly climate controlled indoor facility for highly accurate, short range instruments (< 10 m).
- a medium sized, climate controlled indoor facility for instruments with ranges up to 50 m.
- an outdoor testing area for long range instruments and for testing in a more realistic environment.

While the emphasis at the workshop was on ground-based LADARs, the outdoor facility could be extended for use for airborne LADARs. There was also an opinion that input from the airborne LADAR community should be sought in this “standardization” process, at least during the early stages, as there were similarities between the ground-based and airborne instruments.

The issue of “Why have standards?” was covered in the presentations and in the break-out group discussions. The participants felt that standards would:

- provide a means for uniform performance evaluation. As the use of LADAR grows and there are more “naïve” or nascent end users, the ability to fairly compare systems is invaluable. Similarly, when contracting for LADAR services, the ability to insert performance standards into contracts is very helpful.
- allow end users to do conduct their primary business, i.e., manufacture planes, build rail systems, and not have to undertake the task of designing calibration/testing procedures and protocols. Having to devote personnel to this task is costly and often financially difficult for smaller companies.

In general, there was strong support for standardization. In fact, a specific request for LADAR standards was made to the then NBS (National Bureau of Standards, now NIST) as far back as the early 1980s. However, it was recognized that standardization involves a long, arduous, and sometimes tortuous process. It was pointed out that the standardization of a process requires the implementation of proof-of-concept. This would be a potential NIST role.

In summary, the applications for LADARs are seen to be growing rapidly. These applications include commercial automation, urban planning, mapping, surveying, autonomous vehicle navigation, global climatology monitoring, bathymetry (measurement of water depth), and homeland security (possibly for chemical and biological weapon detection). This being the case, the need for some neutral facility (whether for performance assessment or calibration is yet to decided) was almost universally agreed upon. There were three common themes that ran throughout and stood out in the discussions. These recurring themes centered on the need for:

- common set of terminology
- standard targets/artifacts/standard reflectivity
- performance assessment/evaluation

It was suggested that a good starting point for developing definitions for common terminology is the VIM [3] and the Guide to the Expression of Uncertainty Measurement or the GUM [2].

4.2 Future Steps

Of the three common issues listed above was one that could and should be addressed immediately: the need for a set of definitions of common terms for LADARs. Therefore, it was suggested that NIST initiate the creation of a set of common definitions, addressing in particular, accuracy/precision/resolution to be sent to the participants for comment.

In addition, the following steps were also suggested:

- contact other professional organizations for possible collaboration/coordination
- conduct a review/inventory/benchmarking of existing facilities
- publish a definition of terms or characteristics of LADAR systems to include similarities and/or differences of systems (a survey of commercially available instruments was published by POB magazine – www.pobonline.com)
- create a list of standard targets and range standards. Possibly conduct a survey.

REFERENCES

[1] Personal communication with Mr. Charles J. Fronczek Jr., National Institute of Standards and Technology, Precision Engineering Division.

[2] *Guide to the Expression of Uncertainty in Measurement*, International Organization for Standardization, 1995

[3] *International Vocabulary of Basic and General Terms in Metrology*, International Organization for Standardization, 1993.

APPENDIX A: LIST OF WORKSHOP PARTICIPANTS

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* Was not able to attend workshop but requested to remain on the mailing list for future activities.

APPENDIX B: LADAR AT NIST

by William Stone

What is LADAR?

Scanned or Flash LADAR
LADAR = Light Distancing and Ranging

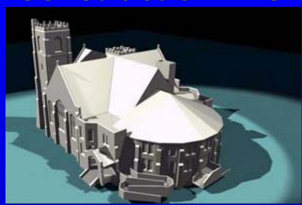
Why is it important?

Within ten years will almost completely replace traditional field survey instruments.

It will enable complete, real-time 3D representations of complex, unstructured manufacturing scenes and permit automation to take place within these regimes.

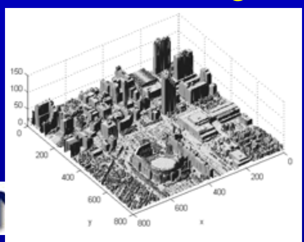
Present LADAR Use:

Construction: As-Builts

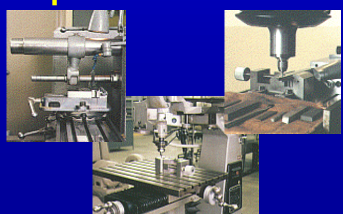


Topo Maps: Military & Civilian apps.

Urban Planning



Manufacturing Inspection/Automation



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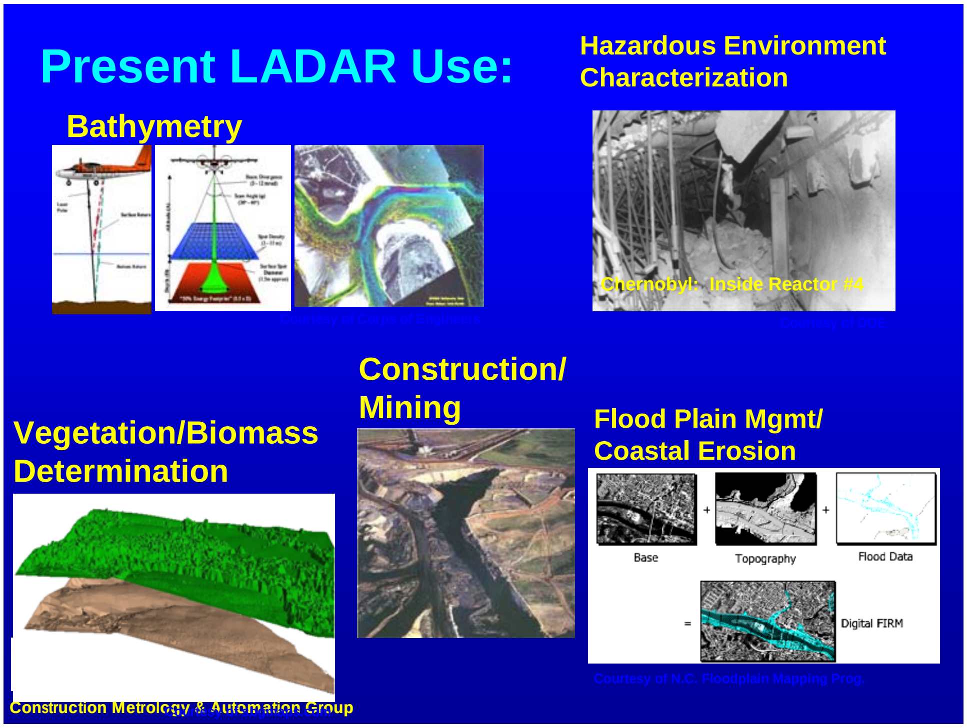
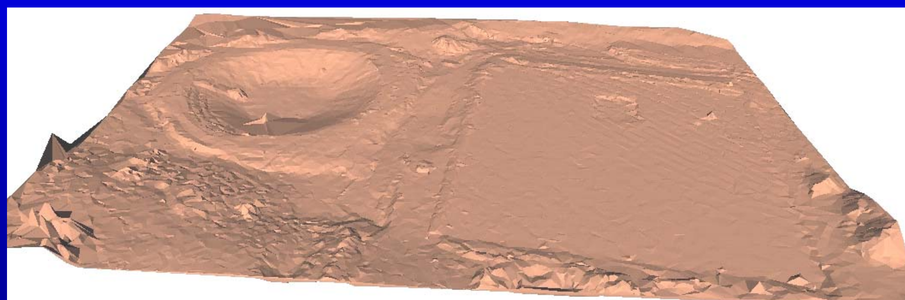


Present LADAR Use:
Bathymetry
Courtesy of Corps of Engineers
Hazardous Environment Characterization
Chernobyl: Inside Reactor #4
Courtesy of DOE
Vegetation/Biomass Determination
Construction Metrology & Automation Group
Construction/ Mining
Flood Plain Mgmt/ Coastal Erosion
Base
Topography
Flood Data
Digital FIRM
Courtesy of N.C. Floodplain Mapping Prog.

Nomenclature


PRO TUFF BIN


NIST
March 7, 2000
Construction Metrology & Automation Group



March 9, 2000

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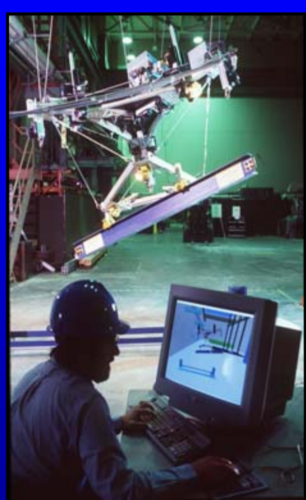
Automated Steel Construction



NIST Role

- Provide Industry Forum for Design of Innovative Steel Connections
- Provide neutral testing lab for evaluation of novel connections
- Provide Robotic Testbed for Design and Performance Evaluation of automated placement systems
- Explore radical automation architectures for steel

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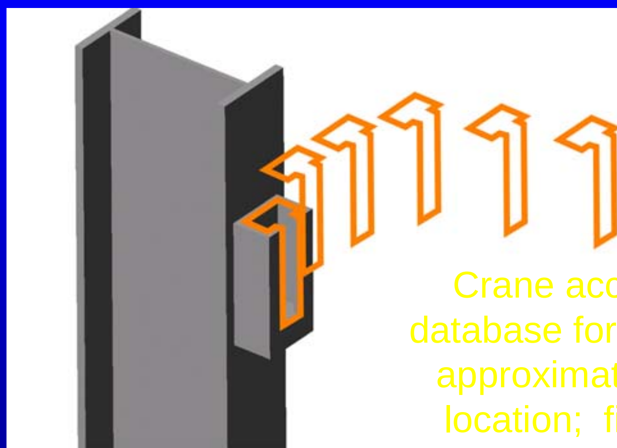
LADAR-machine vision fusion for auto-docking trajectory generation



Crane accesses 4D site database for sequencing and approximate "seed" target location; final placement control is via real-time sensor lock.

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ASC TESTBED

Future Efforts – Long Term

- LONG TERM:
  - Sensor package (Vision/LADAR) for final docking
  - Upgrade controller to current 4D/RCS standard
  - Integrate with commercial PIMS
  - Full Scale outdoor test facility
  - Investigate new connection concepts

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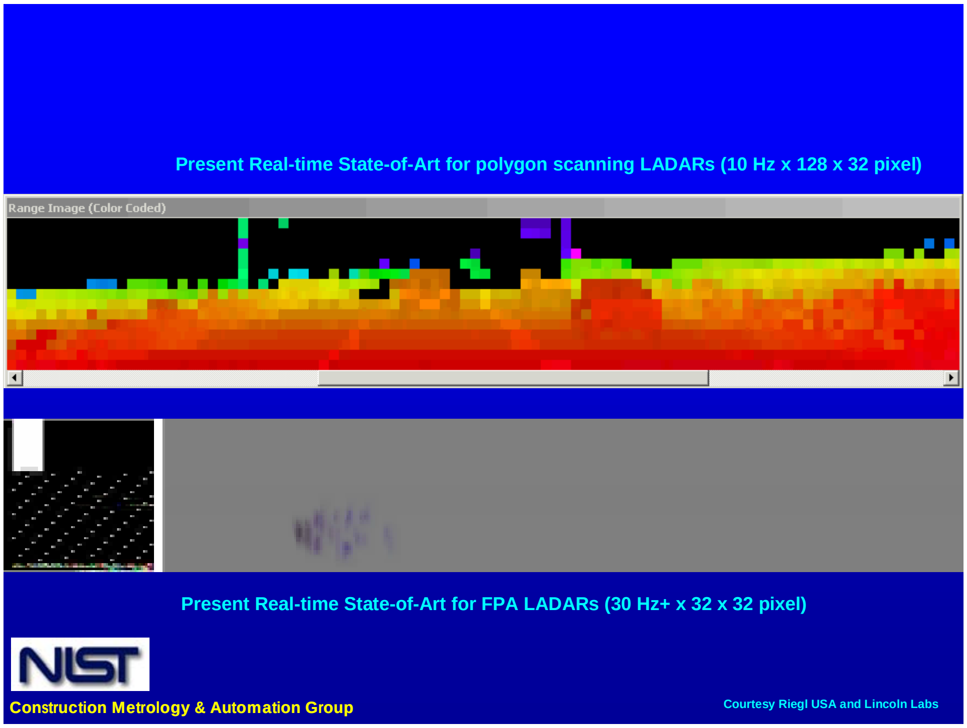
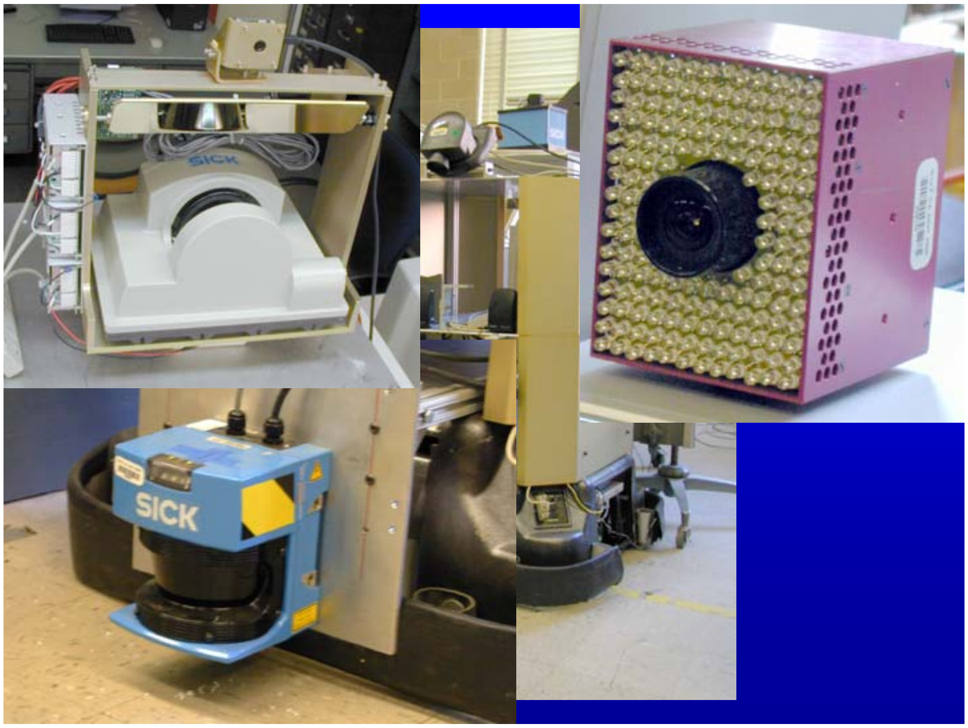

Present Real-time State-of-Art for polygon scanning LADARs (10 Hz x 128 x 32 pixel)
Range Image (Color Coded)
Present Real-time State-of-Art for FPA LADARs (30 Hz+ x 32 x 32 pixel)
Construction Metrology & Automation Group
Courtesy Riegl USA and Lincoln Labs


ROBOCRANE
Construction Metrology & Automation Group



Solving the Auto-placement Problem: learning from Autonomous Mobility

HMMWV

XUV

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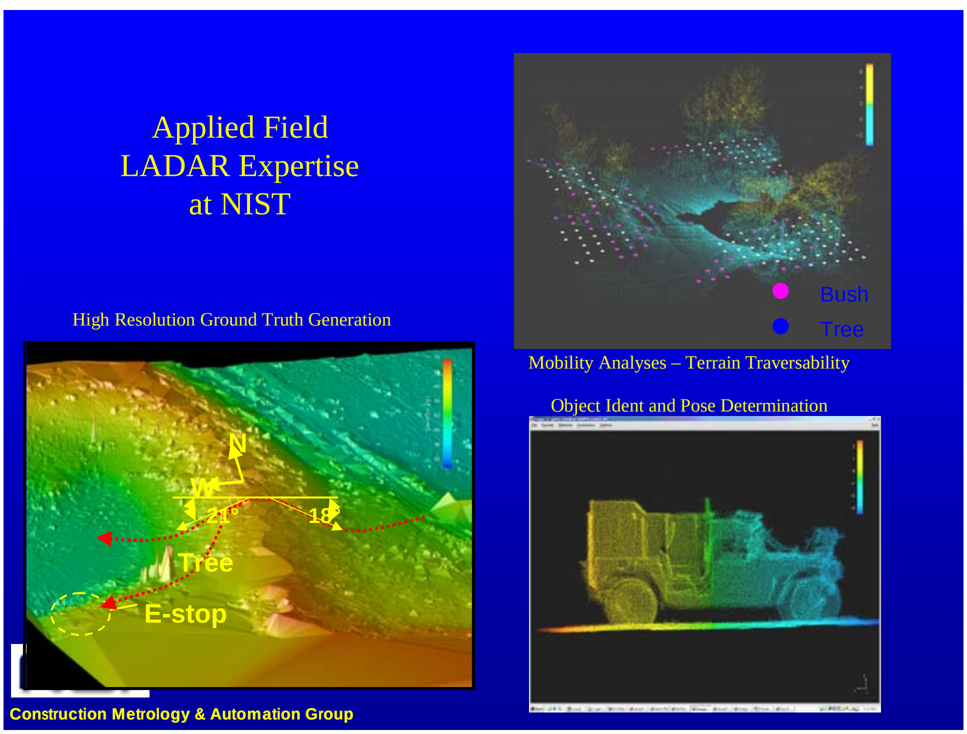
Applied Field
LADAR Expertise
at NIST
Bush
Tree
Mobility Analyses – Terrain Traversability
High Resolution Ground Truth Generation
N
W
Tree
E-stop
Object Ident and Pose Determination
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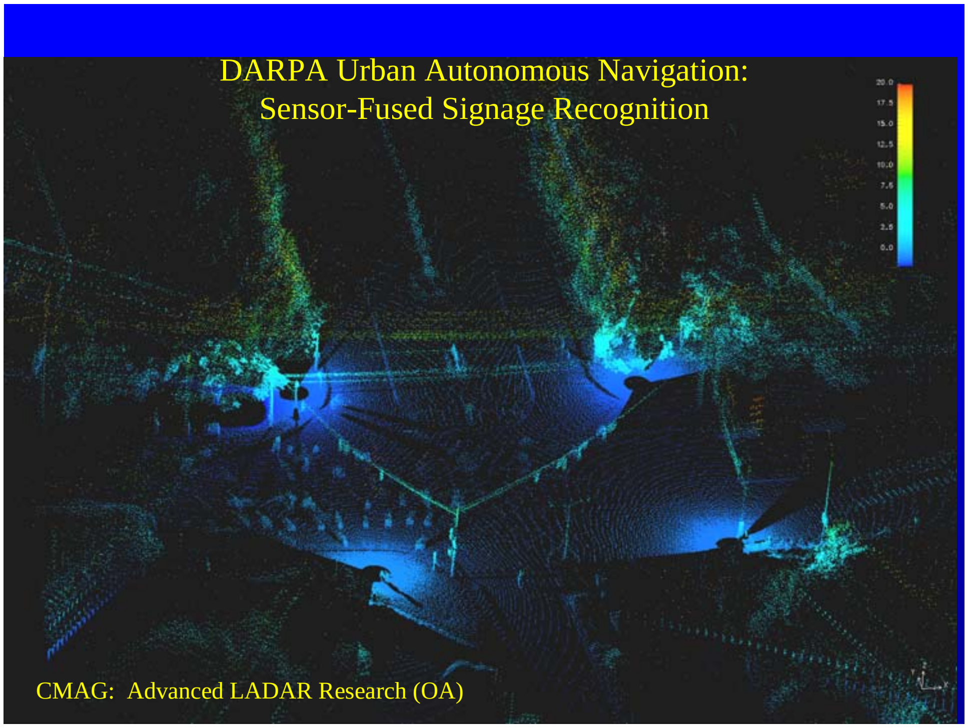
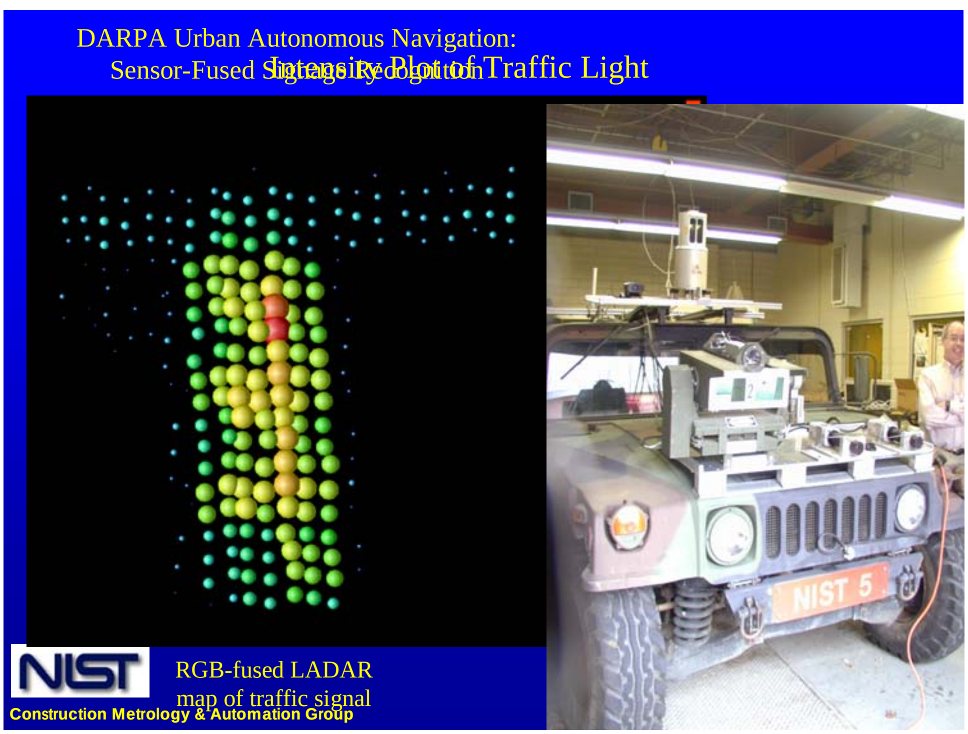
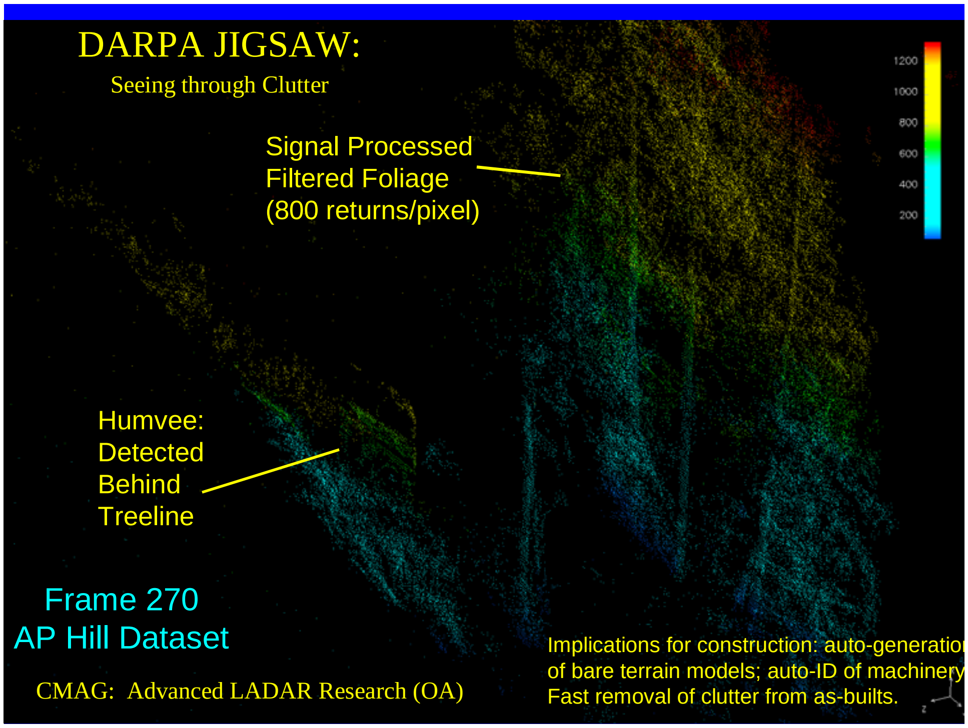

DARPA Urban Autonomous Navigation:
Sensor-Fused Signage Recognition
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
CMAG: Advanced LADAR Research (OA)


DARPA Urban Autonomous Navigation:
Sensor-Fused Signage Recognition
Intensity Plot of Traffic Light
NIST
RGB-fused LADAR
map of traffic signal
Construction Metrology & Automation Group
NIST 5


DARPA JIGSAW:
Seeing through Clutter
Signal Processed
Filtered Foliage
(800 returns/pixel)
1200
1000
800
600
400
200
Humvee:
Detected
Behind
Treeline
Frame 270
AP Hill Dataset
CMAG: Advanced LADAR Research (OA)
Implications for construction: auto-generation
of bare terrain models; auto-ID of machinery.
Fast removal of clutter from as-builts.


Accuracy: 1 mm
Range: 100 m
Speed: 10 Hz
Size: << "coffee cup"
Cost: < $1000
MEMS-based
Meso-scale
Integration
Next Generation LADAR
NGL
Objective: To establish the critical
measurement technologies necessary for the
development of compact, low-cost, accurate,
real-time laser ranging systems

Nomenclature

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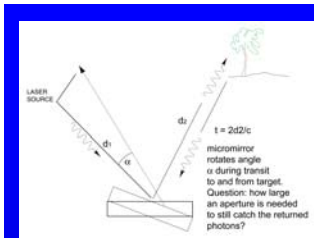

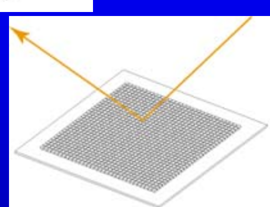

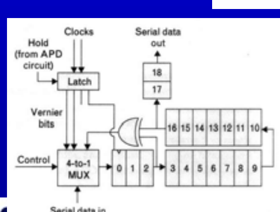

FY02/03 Accomplishments

FANDANGO:
Fast ANgular Deflection Experiment At NIST.GOV Expected to characterize range measurement behavior at angular deflection rates of (10)^6 degrees per second and frame FY04 research directed to achieving feedback-loop control of new MEMs DMD devices.

PHASER: Pico-second High-reliability Sensor Readout -- collaboration established with NIST Time & Frequency Division (Boulder)

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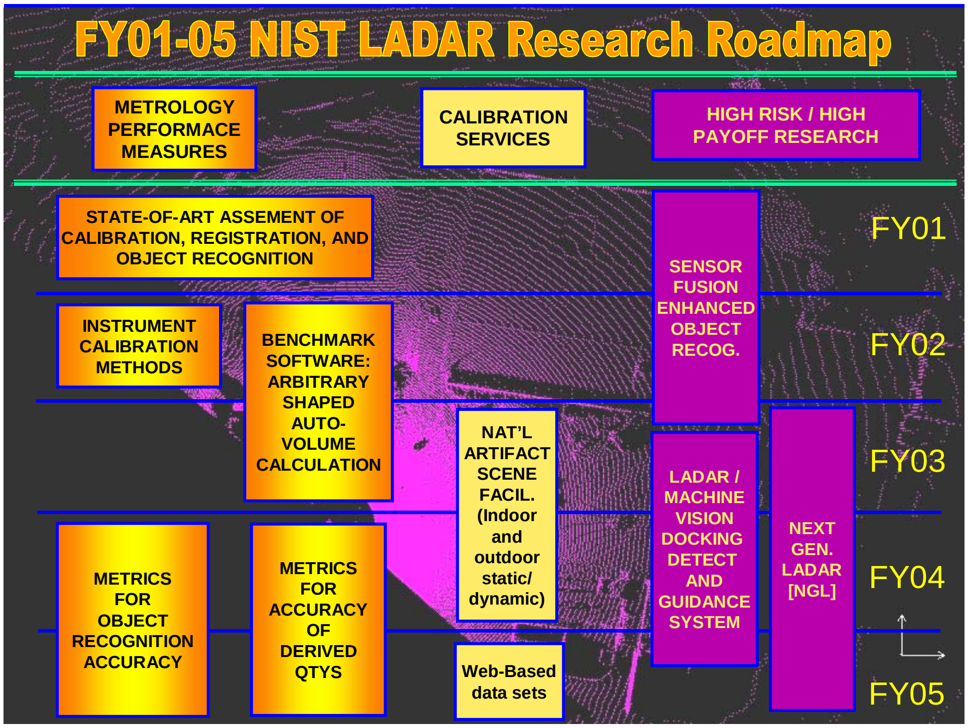
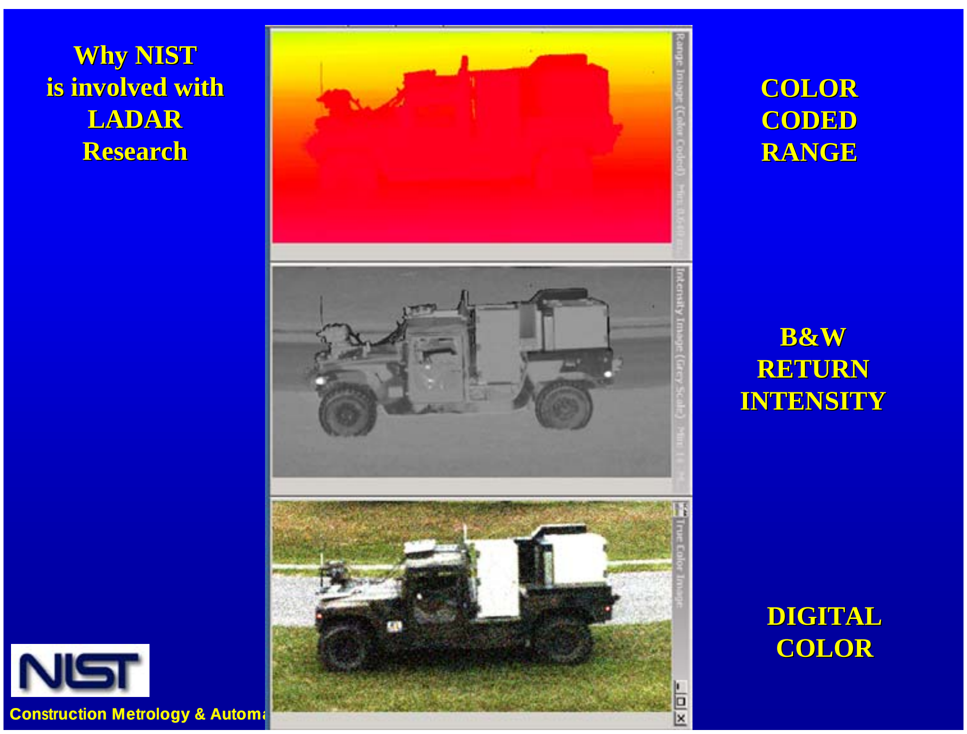
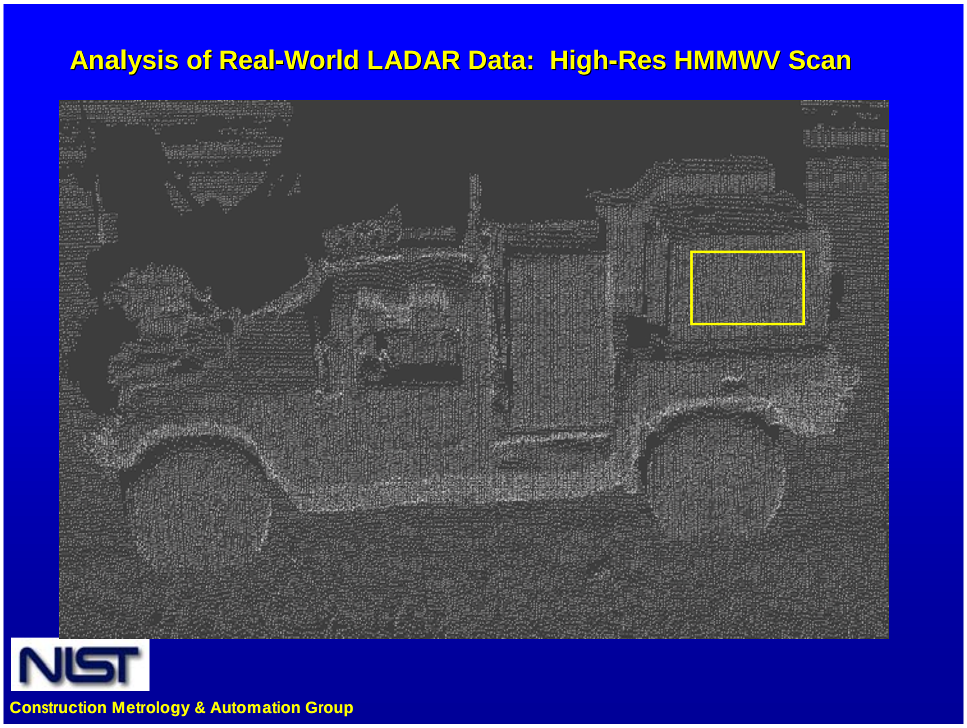

FY01-05 NIST LADAR Research Roadmap
METROLOGY PERFORMACE MEASURES
CALIBRATION SERVICES
HIGH RISK / HIGH PAYOFF RESEARCH
STATE-OF-ART ASSEMENT OF CALIBRATION, REGISTRATION, AND OBJECT RECOGNITION
SENSOR FUSION ENHANCED OBJECT RECOG.
FY01
INSTRUMENT CALIBRATION METHODS
BENCHMARK SOFTWARE: ARBITRARY SHAPED AUTO-VOLUME CALCULATION
FY02
NAT'L ARTIFACT SCENE FACIL. (Indoor and outdoor static/ dynamic)
LADAR / MACHINE VISION DOCKING DETECT AND GUIDANCE SYSTEM
NEXT GEN. LADAR [NGL]
FY03
METRICS FOR OBJECT RECOGNITION ACCURACY
METRICS FOR ACCURACY OF DERIVED QTYS
FY04
Web-Based data sets
FY05


Why NIST is involved with LADAR Research
COLOR CODED RANGE
B&W RETURN INTENSITY
DIGITAL COLOR
NIST
Construction Metrology & Autom


Analysis of Real-World LADAR Data: High-Res HMMWV Scan
NIST
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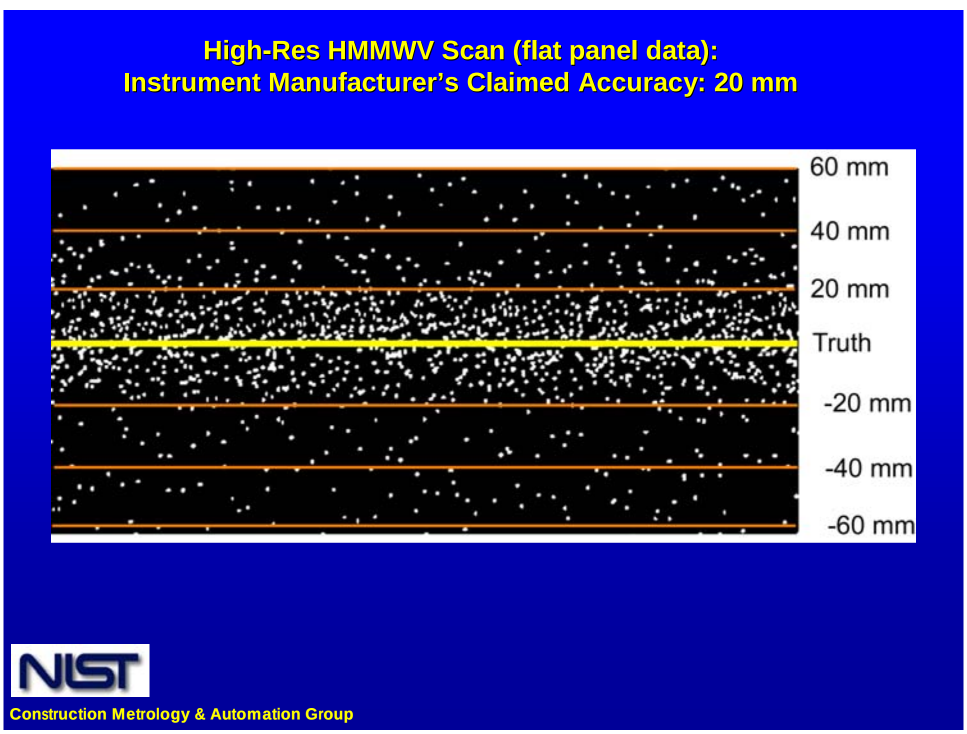
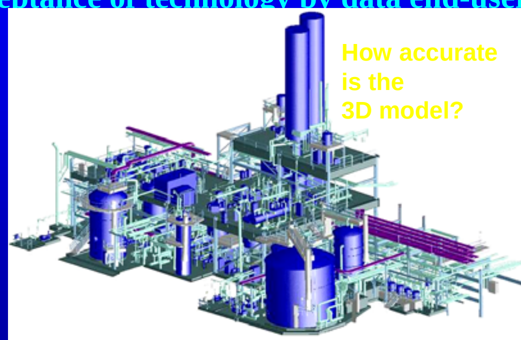

High-Res HMMWV Scan (flat panel data):
Instrument Manufacturer's Claimed Accuracy: 20 mm
60 mm
40 mm
20 mm
Truth
-20 mm
-40 mm
-60 mm
NIST
Construction Metrology & Automation Group

Why NIST is Involved:

"Process and Procedure: Wild, wild west at the moment. Instrument calibration, independent accuracy assessments, operational issues all need guidance from recognized experts to increase acceptance of technology by data end-users."

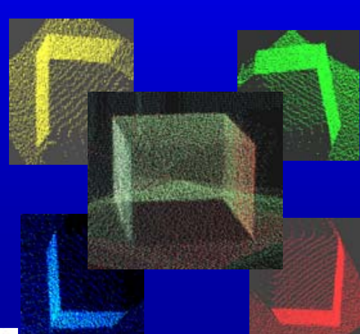


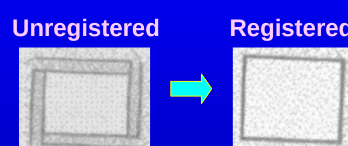
– Martin Flood, Airborne1, Presentation at Internat'l Society of Photogrammetry and Remote

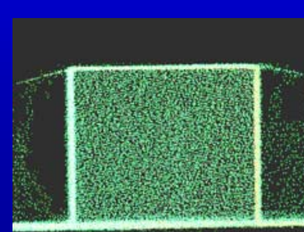
Construction Metrology & Automation Group

Meshing and Registration

- Current Efforts
  - Propagation of instrument errors
  - Accountability for computations and confidence in results







Phantom points

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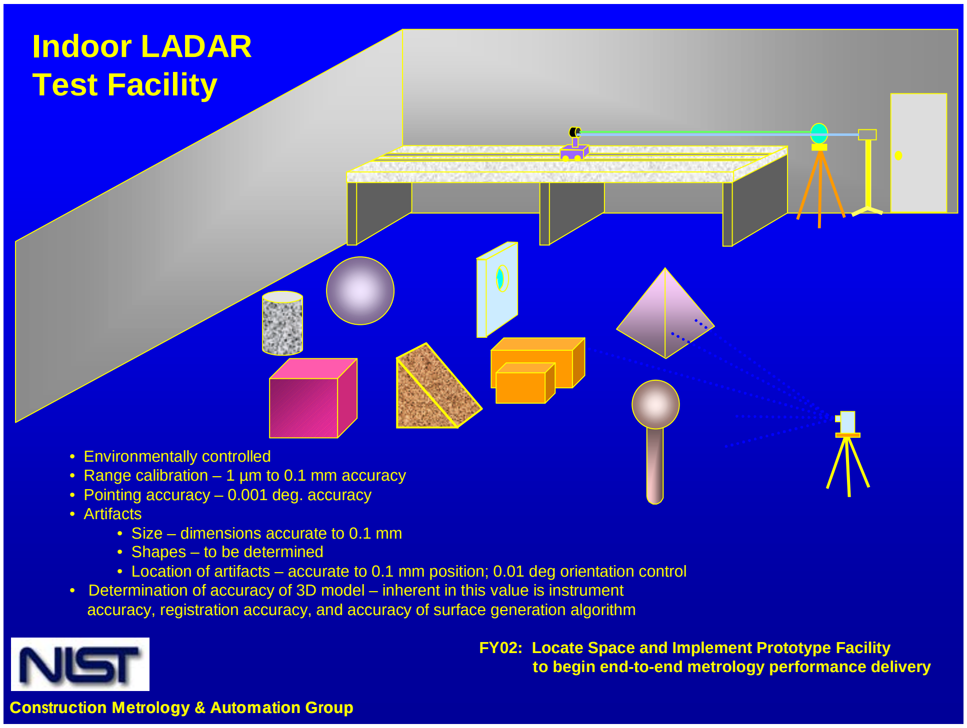
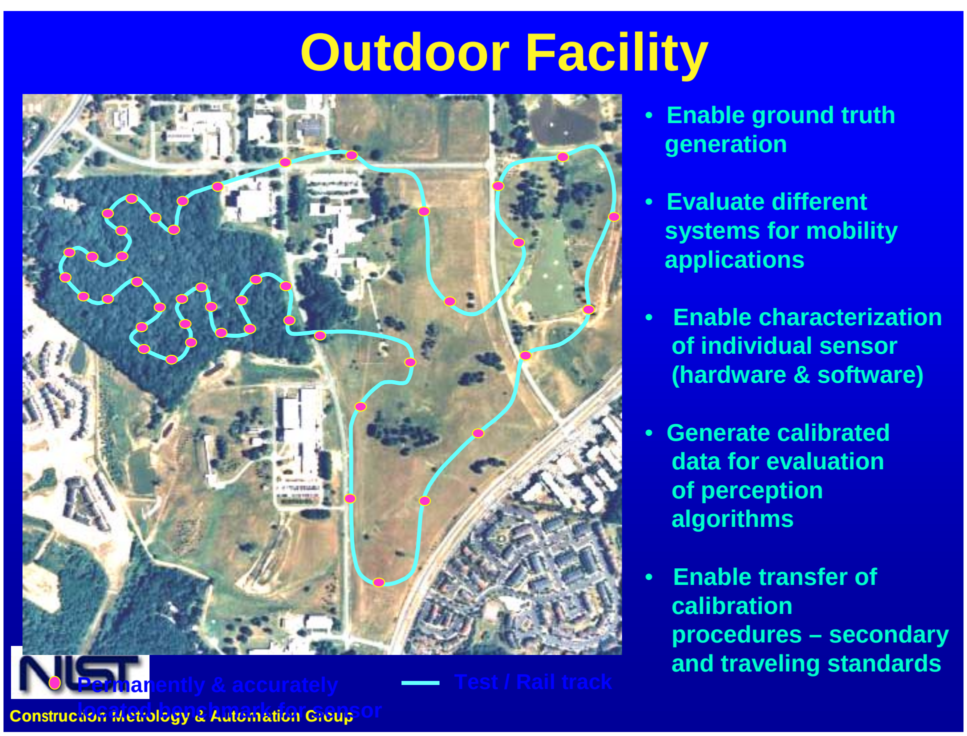

Indoor LADAR
Test Facility
• Environmentally controlled
• Range calibration – 1 µm to 0.1 mm accuracy
• Pointing accuracy – 0.001 deg. accuracy
• Artifacts
• Size – dimensions accurate to 0.1 mm
• Shapes – to be determined
• Location of artifacts – accurate to 0.1 mm position; 0.01 deg orientation control
• Determination of accuracy of 3D model – inherent in this value is instrument accuracy, registration accuracy, and accuracy of surface generation algorithm
NIST
FY02: Locate Space and Implement Prototype Facility
to begin end-to-end metrology performance delivery
Construction Metrology & Automation Group


Outdoor Facility
• Enable ground truth generation
• Evaluate different systems for mobility applications
• Enable characterization of individual sensor (hardware & software)
• Generate calibrated data for evaluation of perception algorithms
• Enable transfer of calibration procedures – secondary and traveling standards
Permanently & accurately
Test / Rail track
NIST
Construction Metrology & Automation Group

Nomenclature

- Lidar = single point laser ranging system
- LADAR = device that acquires a range image

Some Implemented LADAR Designs

- Pan/Tilt Scanner
- Rotating Mirror Scanners
- Flash LADAR

NIST
Construction Metrology & Automation Group

APPENDIX C: CALIBRATION ACTIVITIES AT THE NATIONAL RESEARCH COUNCIL OF CANADA

by Francois Blais

NIST: LADAR Calibration Workshop
June 12 - 13, 2003
National Institute of Standards and Technology, Gaithersburg, MD

Calibration Activities at the National Research Council of Canada

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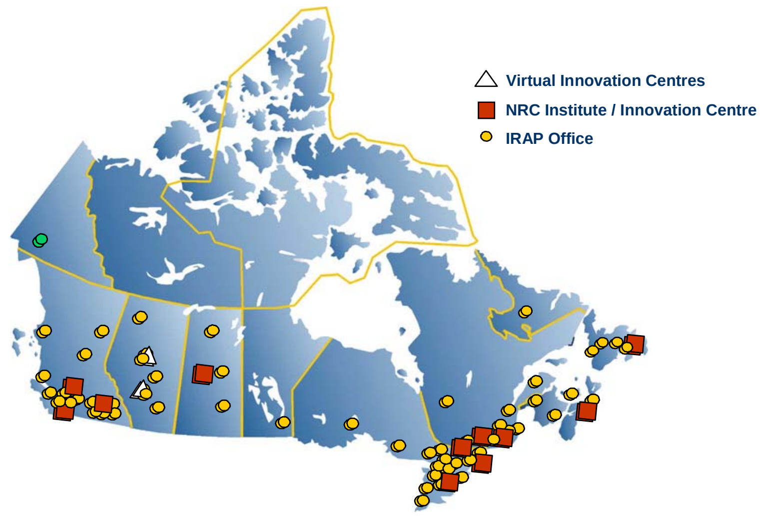
CNRC·NRC

Outline

- The NRC – National Research Council of Canada
- Active 3D Techniques – examples
- Calibration
  - Modelling and Calibration procedure
  - Practical considerations – methodology
  - Field Calibration
  - Assessing the accuracy
- Conclusion: the need for standards

Calibration Activities at the NRC *NIST Calibration Workshop 2003* CNRC·NRC 1

NRC – A National Institution



Calibration Activities at the NRC — NIST Calibration Workshop 2003 — CNRC·NRC — 2

Visual Information Technology Group Research activities

- Virtualizing reality and visualization
  - 3D laser sensors - metrology
  - Shape and colour modeling
  - Modeling from 2D images
  - Advanced visualization systems
- 3D data mining & management
  - 3D Search Engine
  - Advanced interfaces for 3D searching
- Collaborative Virtual Environments (CVE)

Calibration Activities at the NRC — NIST Calibration Workshop 2003 — CNRC·NRC — 3

3D Acquisition Systems at NRC

- 3D sensor development
  - Active triangulation (Biris + Auto-synchronized)
  - Range: 10 cm to 20 m
  - Accuracy: 10 um to a few cm
  - Data: range + registered intensity (color)
- Calibration
  - 3D Geometrical (LUT, model based, hybrid)
  - Color reflectance
  - Accuracy assessment: Triangulation, Pattern Projection , TOF
- Processing software
  - ICP, Segmentation, model reconstruction, characterisation
  - Perspective projection (2D->3D)
- Applications

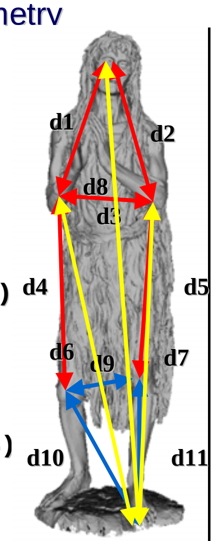
Dimensional inspection – Modeling

3D pattern projection and photogrammetry

d1 – d5
Agreement between the two models

d6 – d8
Positive deviations
vorst case**: 4.3 mm (0.25 %)**

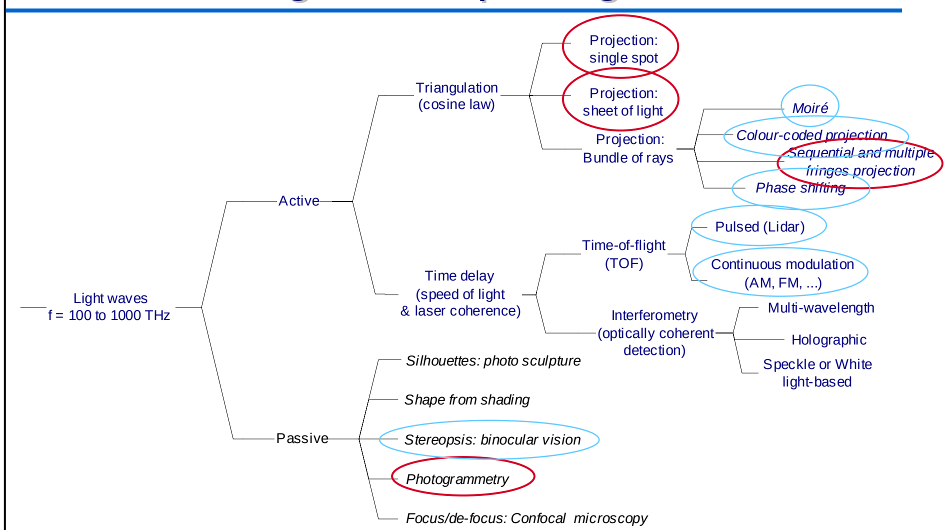
d9 – d11
Negative deviations
vorst case **: -4.2 mm (1.66 %)**



Active 3D Techniques at NRC

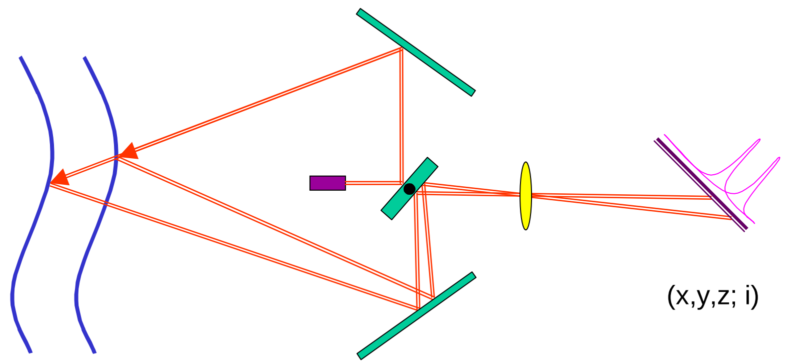
and some examples

Measuring 3D shape: Light waves

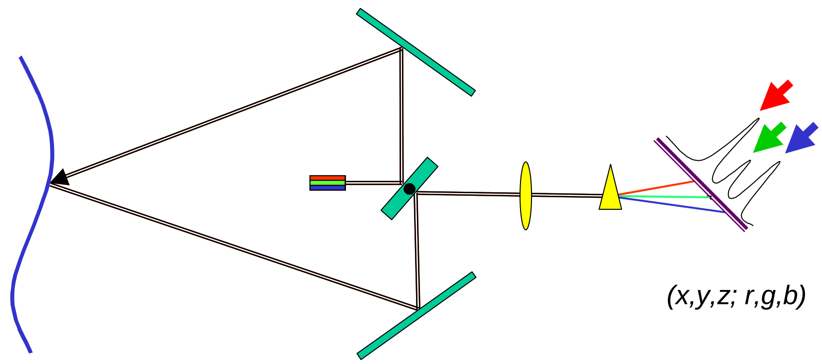


see also D. Nitzan PAMI, v.10, n.3, 1988

Auto-synchronization: mono-chrome



Auto-synchronization : 3D + colour



High-resolution scanner for 3D & colour

Simultaneous colour & range digitizing

- high resolution: $\sigma_z \sim 10\ \mu m$, $\Delta_x \sim 50\ \mu m$
- Small volumes **10-20 cm**
- Intrinsic reflectance measurement

Calibration Activities at the NRC *NIST Calibration Workshop 2003* CNRC·NRC *10*

From Reality to Virtualized Reality

Calibration Activities at the NRC *NIST Calibration Workshop 2003* CNRC·NRC *11*

From Reality to Virtualized Reality (movie)

Large Field of View Laser Scanner

- monochrome system (532 nm, 820 nm, 1.5 um)
- dual-axis scanning galvanometer mirrors
- for digitizing large structures
- operates on a conventional tripod or telescopic tripod
- range 50 cm to 10 m, resolution: 70 µm at 50 cm

Mission STS-105 International Space Station August 2001

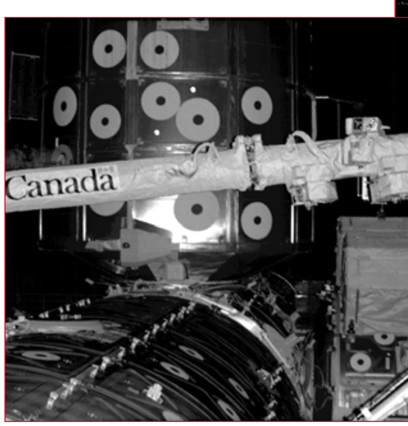
- Neptec Design Group (under license)
- Collaboration Neptec-NASA-CSA-NRC

Photo NASA

Calibration Activities at the NRC   NIST Calibration Workshop 2003   CNRC·NRC   14

Reflectance and Shape Information

- Mission STS-105



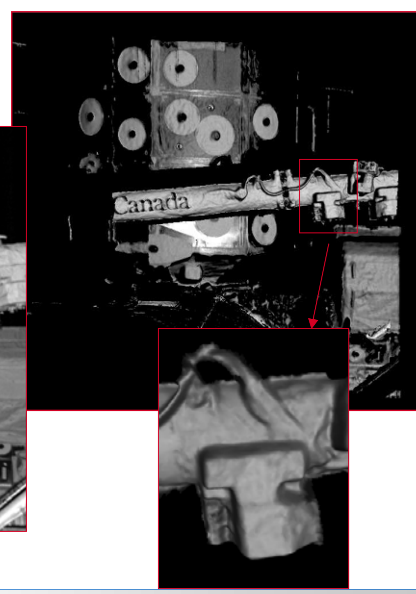
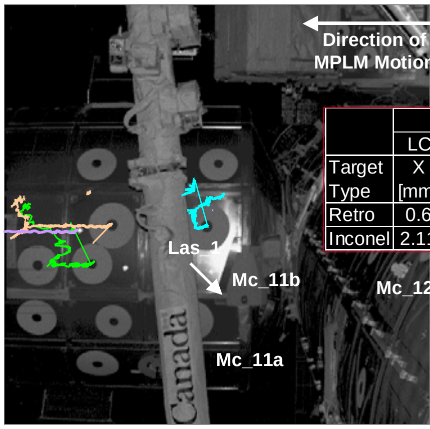


Photo Neptec

Calibration Activities at the NRC   NIST Calibration Workshop 2003   CNRC·NRC   15

Tracking Moving Targets during MPLM Demate

- Produces real-time pose estimates for assembling the ISS elements



	Standard Deviation								
	LCS Centroids			Pose (Photosolution)					
Target Type	X [mm]	Y [mm]	Z [mm]	X [mm]	Y [mm]	Z [mm]	Yaw [deg]	Pitch [deg]	Roll [deg]
Retro	0.6	1.51	8.79	0.76	0.25	0.25	0.02	0.02	0.01
Inconel	2.11	2.42	3.6	3.05	1.27	0.51	0.09	0.09	0.05

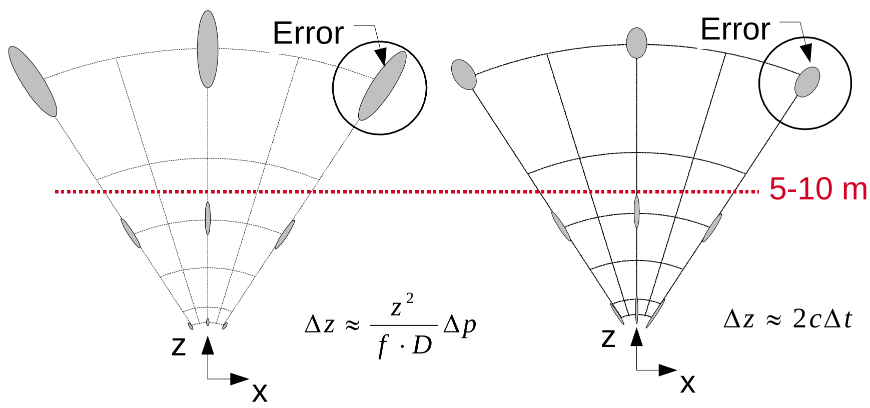
Courtesy Neptec

Calibration
-
Modeling and Calibrating a 3D Laser Scanner

Error distribution: laser spot scanning

The measurement error distributions of a triangulation/TOF based laser scanner are ***inhomogeous*** and ***anisotropic*** in behavior.

Triangulation *TOF*



$$\Delta z \approx \frac{z^2}{f \cdot D}\Delta p \qquad \Delta z \approx 2c\Delta t$$

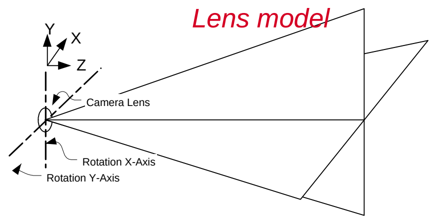
Sensor Calibration

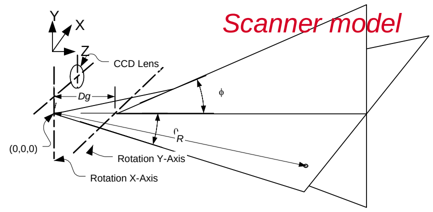
- LUT based calibration (1986)
  - $[x \quad y \quad z]^T = [LUTx[p,\theta,\varphi] \quad LUTy[p,\theta,\varphi] \quad LUTz[p,\theta,\varphi]]^T$
  - Large memory tables
  - Not practical for large volumes
- Hybrid Calibration (1988-90)
  - $[x \quad y \quad z]^T = [fx(z,\theta,\varphi) \quad fy(z,\theta,\varphi) \quad fz(p;[\theta,\varphi])]^T$
  - LUT of simplified models
- Model based calibration (1992s – 2000s)
  - $[x \quad y \quad z]^T = f(p,\theta,\varphi)$
  - Strong astigmatism + high correlation in XYZ
  - Mechanical model: non-linear (unstable)
  - Optical “virtual” model + observability: (stable)

$$[u \quad v \quad w]^T = f(p,\theta,\varphi) \;\Rightarrow\; [x \quad y \quad z]^T = [u/w \quad v/w \quad 1/w]^T$$

Model Based Calibration

- Lens model does not apply
  - Strong astigmatism
  - Non-linear correlation between rotation axis
  - Scanning mirrors: non-symmetric distortions
  - Distortions vary with range Z
- Minimization of errors:
  - High correlation in XYZ
  - Origin of the scanner (x_0,y_0,z_0) undefined

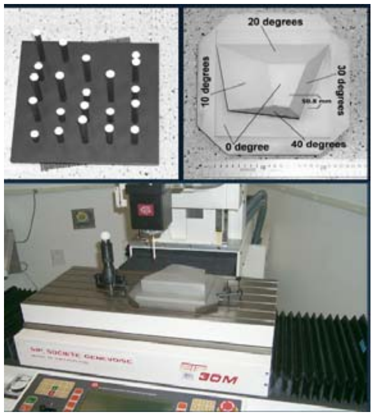




Calibration
-
Calibrating a Laser Scanner Practical considerations

(0.4 m to 20 m)

Metrology laboratory

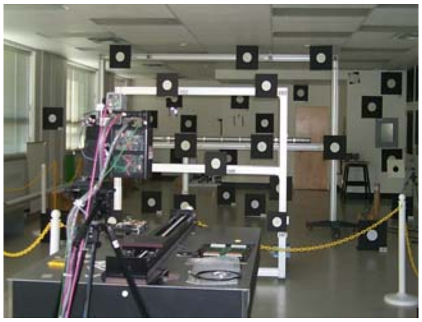


Example of Equipment

- Temperature controlled environment
- Anti-vibration tables
- Theodolites and photogrammetry equipment
- Optical measurement and alignment tools (e.g interferometers)
- High precision reference objects
- Optical quality reference surfaces
- Accurate linear and rotation stages
- Inspection software (e.g. Polyworks)
- Access to high precision CMM and other measuring capabilities through other Institute and partners
- …

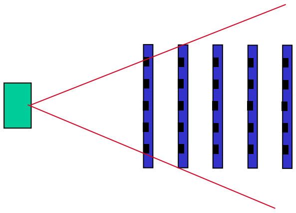
Calibration Experimental Set-up (old)

- Structure originally used for model calibration
  - Require accurate survey of the targets
- Complexity
  - Cost
  - Can't be used for simultaneous calibration of small and large volumes
  - Small number of targets (accuracy)
  - Occlusions and obstructions
- Good to verify the calibration not to calibrate scanners



Calibration with a Target Array

- Known positions
- Accurately machined target array
- Range limited by the translation stage
- Does not cover the full FOV
- Wobble, jitter, backlash, orthogonal motions
  - E.g. 20 urad wobble = 200 um XYZ error
- A mechanical "challenge"



High Precision Calibration using Target Array

- Space Vision System (NASA)

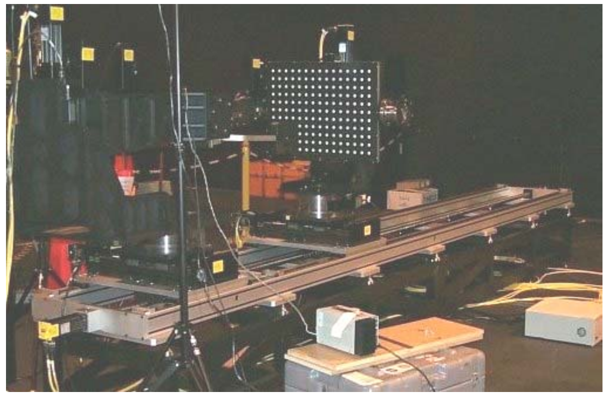
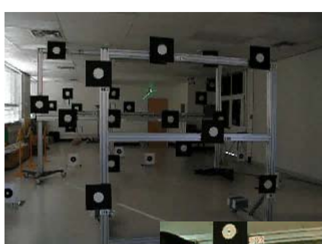


Photo Neptec

Calibration Activities at the NRC *NIST Calibration Workshop 2003* CNRC·NRC *26*

Acquiring Calibration Data

- As many point as possible
- Automated: to reduce user errors



Lissajous Imaging

Raster Imaging + ROI

Geometrical tracking

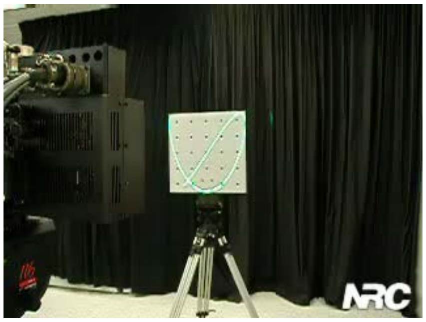
Calibration Activities at the NRC *NIST Calibration Workshop 2003* CNRC·NRC *27*

How can we solve for the "Absolute Reference" ?

- Several XYZ coordinate systems: one for each reference object
- Must accurately measure the absolute position of the camera vs. these reference systems
  - All 6 DOF (translation+rotation)
  - Camera optical reference : a hidden "virtual" point inside the camera mechanical enclosure
  - Camera enclosure (assembly tolerance)
  - Absolute location for each target array, object, or structures used during the calibration

Example: Calibration Procedure

- Field calibration
- Large number of measurement = better statistics
- Redundancy = detect misaligned references
- Semi-Automated = reduced user errors
- Fast procedure
- User friendly

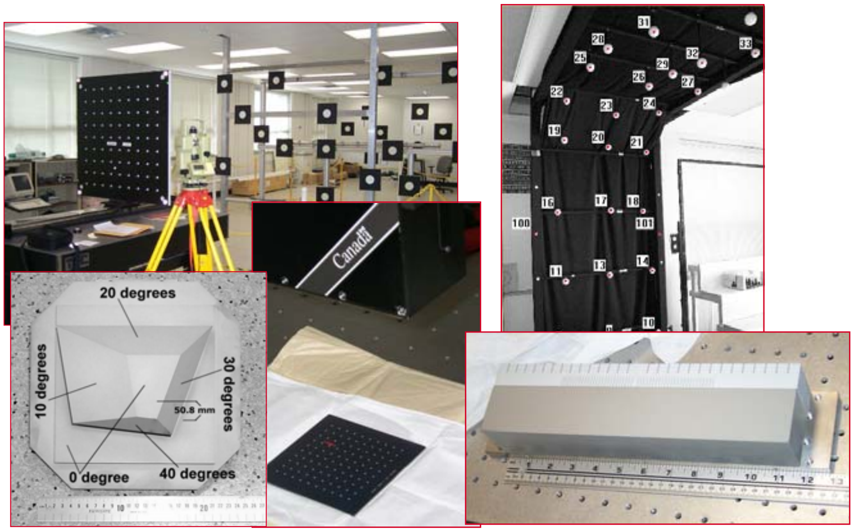


Calibration
-
Assessing the Accuracy

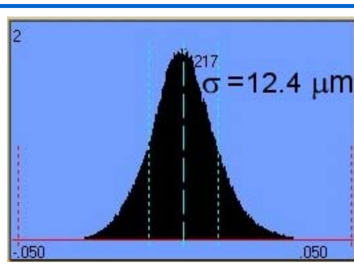
Verification

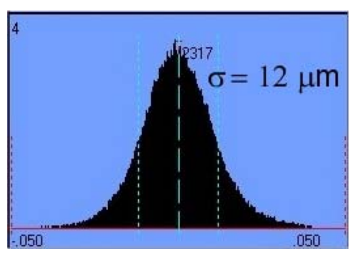
- Using independent methods and/or reference object
  - Different calibration plates
  - Reference objects acquired from different orientations + differential inspection
  - Using another 3D scanner
  - Other systems and methods
    - Photogrammetry, theodolites, CMM

Calibrate, verify & compare



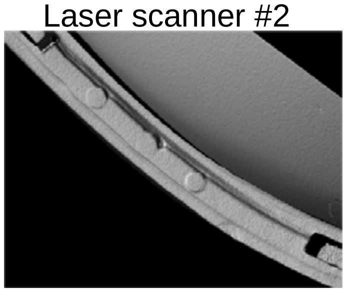
Uncertainty: align 2 overlapping scans

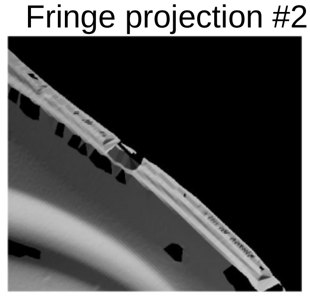




Laser scanner #2

Fringe projection #2





$\Delta x,y$=0.2mm

$\Delta x,y$=0.05mm

Calibration

-

The need for standards

What means accurate 3D ?

- Single point, surface deviation, or edge
- Single view or reconstructed object
- Accuracy vs. spatial resolution and volume (z_{min},z_{max},z^2)
- Processing software rarely considered when assessing accuracy
  - Noise reduction: $1/\sqrt{N}$
    - Fit, smoothing, dithering, and time averaging
    - Affects spatial resolution (blur)
  - May not necessarily increase accuracy
    - Correlated XYZ, bias
    - Can induce distortion,and shifts (bias)

About standards

- Definitions: VIM 1993
- Theodolites: section 3, German standard DIN 18723
- CMM manufacturers use ISO standard 10360-2:1994 for assessing their measuring machines
- Guideline called VDI/VDE 2634 is being prepared in Germany for optical 3-D vision systems
  - testing and monitoring procedures
  - area scanning

Certification: NIST, NRC ...

- Procedures
- Certification 2D or 3D: NIST (US), NRC (CAD), ISO (Italia), PTB (DE), ASME B89.4.1-1997 ...
- For 3D systems based upon pattern projection: VDI/VDE 2634 (DE)
- Definitions of specifications: Vocabulaire International de Métrologie (VIM)
  - Resolution, Uncertainty, Accuracy

Conclusion

- Calibration is a complex iterative process
  - Understanding the scanner / model
  - Calibration methodology, equipment, reference
  - Independent accuracy assessment
- Experience shows that many errors are often related to the reference object
  - Assumption that the reference object is accurate
  - Machining tolerance
- Calibration procedure must be carefully followed
  - Still very prone to human errors, manipulation, and procedural errors

Conclusion (cont.)

- Need “good” standards to avoid misleading “claims”
  - Current comparisons are based solely on “specifications” from manufacturers …
  - Different standards are needed, adapted for a given type of application
    - Edges, surface, or closed models
    - Data smoothness vs. spatial resolution
    - The non-linear properties of 3D scanners
    - Operating conditions

Terminology (1) – from VIM

- *Accuracy*: closeness of the agreement between the result of a measurement and a true value of the measurand. *If one wishes to measure absolute quantities then this is important.*
- *Reproducibility:* closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. *One needs this feature if the same artefact has to be measured, let say, at different times or by a different user.*
- *Uncertainty* characterizes the dispersion of the values that could reasonably be attributed to the measurand. *The measurement uncertainty can be further decomposed in a systematic and a random part.* (σ)

Calibration Activities at the NRC | NIST Calibration Workshop 2003 | CNRC·NRC | 40

Terminology (2)

- *Systematic errors*: 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. *This type of error can be due to poor calibration, range measurement artefact, ambient light conditions, reflectance properties of surface etc. Can be reduced by modeling the errors.*
- *Random errors*: this type of error originates from stochastic temporal and spatial variations of influence quantities. *One has to lower this quantity if nice synthetic shadings of surfaces are required without resorting to excessive filtering.*
- *Resolution*: smallest difference between indications that can be meaningfully distinguished. *One needs this feature in order to avoid being limited by quantification noise, CCD resolution, spot size, etc.*

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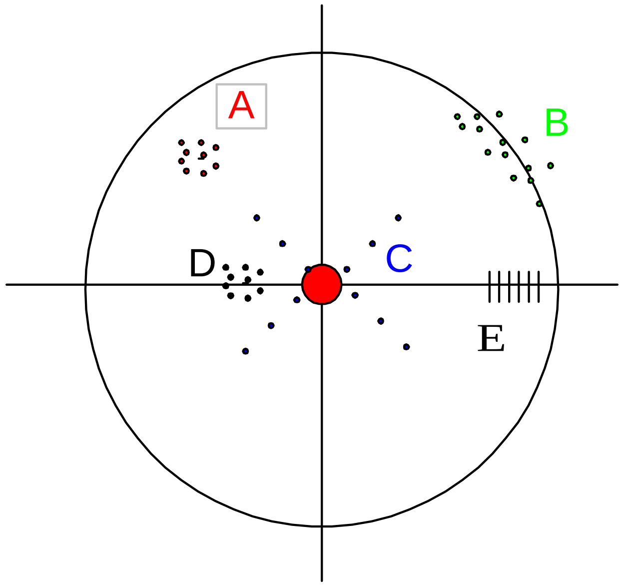
Example



Calibration Activities at the NRC   NIST Calibration Workshop 2003   CNRC·NRC   42

APPENDIX D: FUTURE OF LASER RADAR

by Gary Kamerman

Future of Laser Radar

Presentation to the
LADAR Calibration Facility Workshop
held at the
National Institute for Science & Technology

12 June 2003

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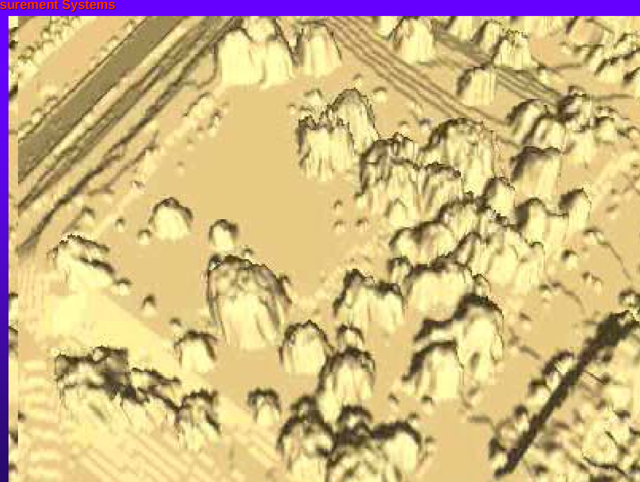
DTED 5 of Baltimore, MD

FastMetrix, Inc.
Precision Measurement Systems



2

FastMetrix, Inc.
Precision Measurement Systems

Questions?

- Why are we here?
- Who will benefit from calibration standards?
- Why should the research community care?
- What standards?

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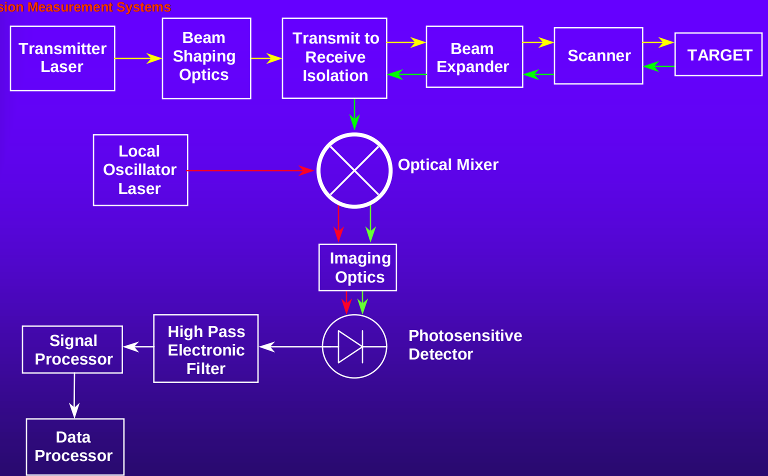
Precision Measurement Systems

General Laser Radar Architecture



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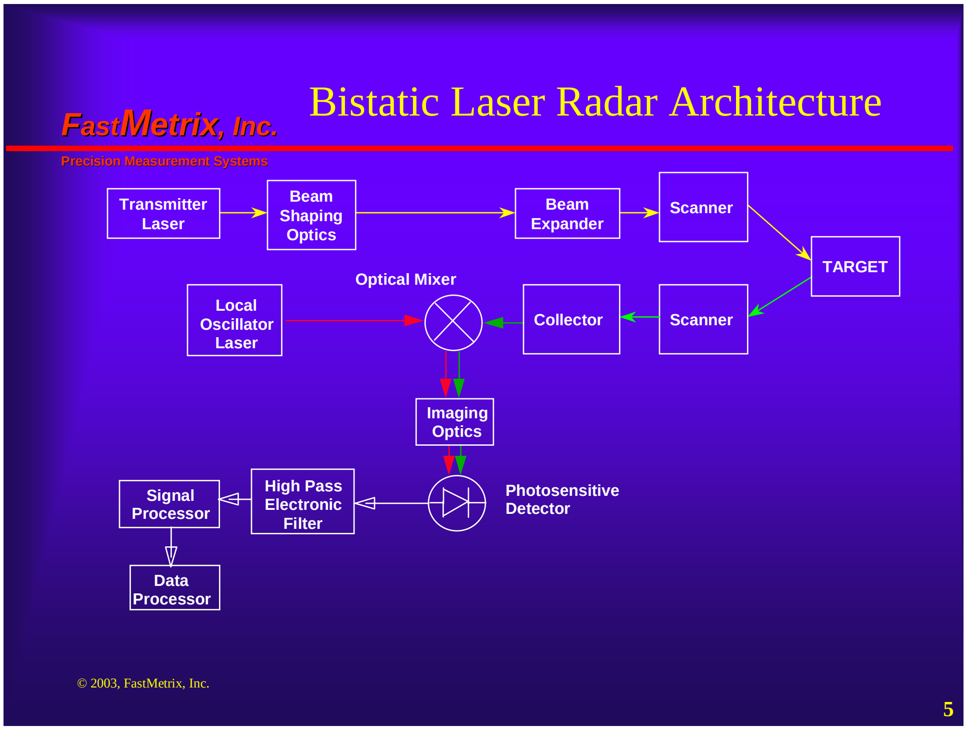
FastMetrix, Inc.
Precision Measurement Systems
Bistatic Laser Radar Architecture
Transmitter Laser
Beam Shaping Optics
Beam Expander
Scanner
TARGET
Optical Mixer
Local Oscillator Laser
Collector
Scanner
Imaging Optics
Signal Processor
High Pass Electronic Filter
Photosensitive Detector
Data Processor
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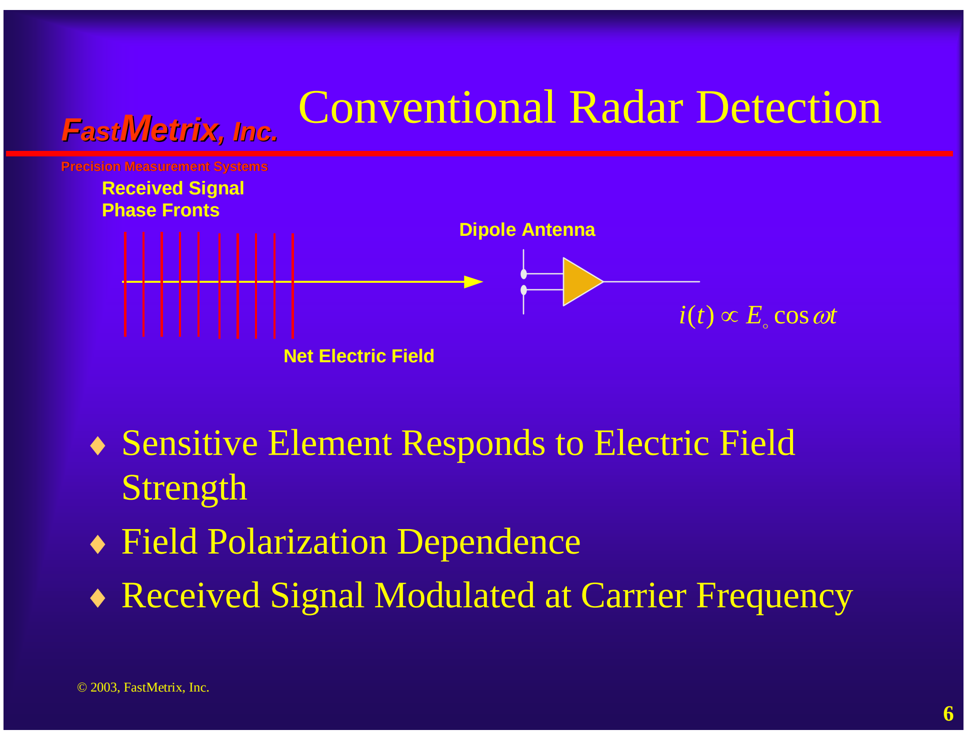
FastMetrix, Inc.
Precision Measurement Systems
Conventional Radar Detection
Received Signal Phase Fronts
Dipole Antenna
$i(t) \propto E_o \cos \omega t$
Net Electric Field
♦ Sensitive Element Responds to Electric Field Strength
♦ Field Polarization Dependence
♦ Received Signal Modulated at Carrier Frequency
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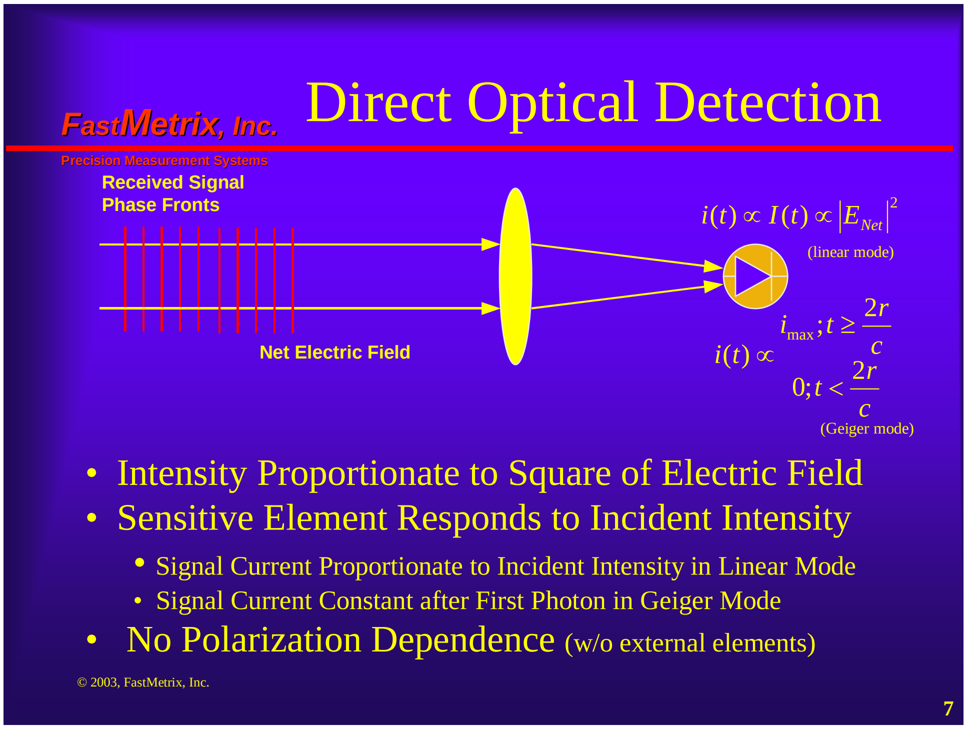
FastMetrix, Inc.
Precision Measurement Systems
Direct Optical Detection
Received Signal Phase Fronts
Net Electric Field
$i(t) \propto I(t) \propto |E_{Net}|^2$
(linear mode)
$i(t) \propto \begin{cases} i_{max}; t \geq \frac{2r}{c} \\ 0; t < \frac{2r}{c} \end{cases}$
(Geiger mode)
• Intensity Proportionate to Square of Electric Field
• Sensitive Element Responds to Incident Intensity
• Signal Current Proportionate to Incident Intensity in Linear Mode
• Signal Current Constant after First Photon in Geiger Mode
• No Polarization Dependence (w/o external elements)
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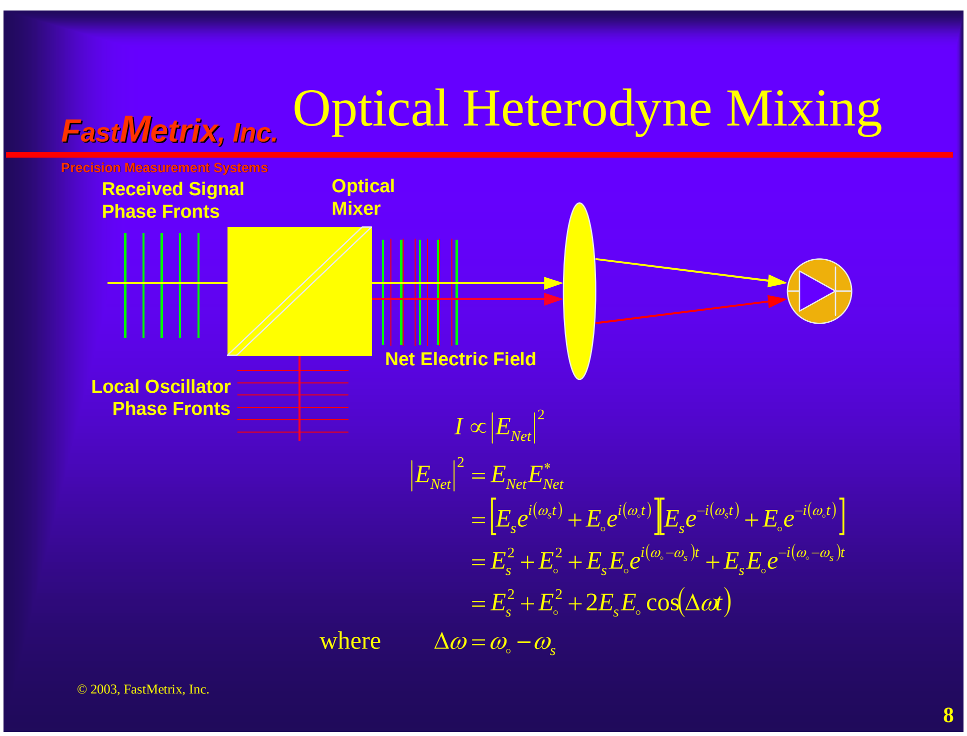
FastMetrix, Inc.
Precision Measurement Systems
Optical Heterodyne Mixing
Received Signal Phase Fronts
Optical Mixer
Net Electric Field
Local Oscillator Phase Fronts
$I \propto |E_{Net}|^2$
$|E_{Net}|^2 = E_{Net}E^*_{Net}$
$= [E_s e^{i(\omega_s t)} + E_\circ e^{i(\omega_\circ t)}][E_s e^{-i(\omega_s t)} + E_\circ e^{-i(\omega_\circ t)}]$
$= E_s^2 + E_\circ^2 + E_s E_\circ e^{i(\omega_\circ - \omega_s)t} + E_s E_\circ e^{-i(\omega_\circ - \omega_s)t}$
$= E_s^2 + E_\circ^2 + 2E_s E_\circ \cos(\Delta\omega t)$
where $\Delta\omega = \omega_\circ - \omega_s$
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8

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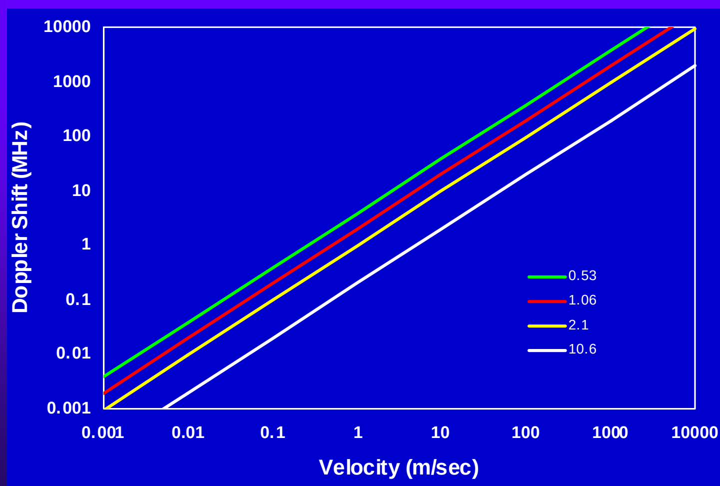
Doppler Shift for Various Lasers



9

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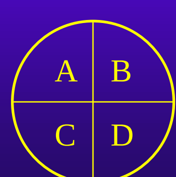
Metric Extraction

Range $$r = \frac{ct}{2}$$

Velocity by Differential Range $$v = \frac{r_2 - r_1}{\Delta t} = \frac{c(t_2 - t_1)}{2\Delta t}$$

Velocity by Doppler Shift $$v = \frac{\lambda \upsilon_D}{2}$$

Angular Position
$$\psi_{el} = \frac{(A+B)-(C+D)}{A+B+C+D}$$
$$\psi_{az} = \frac{(A+C)-(B+D)}{A+B+C+D}$$



10

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Measurement Definitions

- **Resolution*** is the ability to identify the presence of two, separate sources (or targets) in a single signal (or laser radar return)
- **Precision*** is the deviation about the mean. Precision is an indication of the repeatability of the measurements. It is the square root of the variance of an ensemble of measurements.
- **Accuracy*** is the deviation about the expectation (i.e., true) value. The accuracy is a measure of how far an individual measurement can be expected to be from the correct value.
- **Error*** is the difference between the measured value and the expectation value. It is not a statistical quantity.
- **Ambiguity**** is the result of cyclic or repetitive waveforms that produce identical returns from well separated (and otherwise resolved) objects.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N}}$$

$$\kappa = \sqrt{\frac{\sum_{i=1}^{N}(x_i - x)^2}{N}}$$

where σ = precision

κ = accuracy

x_i = measured values

x = expectation value

$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N}$, and

N = number of measurements.

* Applies to range, velocity, amplitude or angular measurements

**Applies to range and velocity measurements

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Field of View Definitions

- **Beamwidth** is the angular extent of the transmitted laser beam profile
- **Instantaneous Field of View (IFOV)** is the angular subtense of a single detector element
- **Field of View (FOV)** is the total angular extent of the receiver detector array in a staring system or the total angular coverage of the receiver detector element(s) during a complete frame cycle for a scanned system
- **Field of Regard (FOR)** is the total angular extent over which the FOV may be positioned

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Applications of Laser Radars

- Weapon Delivery
  - Rangefinders
  - Monopulse Tracking
  - Moving Target Identification
- Object Identification
  - 3-D Range Imaging
  - Vibration Signature
  - Range-Doppler Imaging
  - Range Histogram
- Optical Metrology and Inspection
- Environmental Monitoring
  - Aerosol Backscatter
  - Wind Mapping
  - Chemical Analysis
    - Differential Absorption LIDAR
    - Raman LIDAR
  - Topographic Mapping
  - Bathymetry
- Robotics

5
13

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Types of Laser Radars

Types of Lasers (typical)	Carrier Wavelength
CO_2	10.6 µm
Tm,Ho:YLF	2.1 µm
Er:Glass	1.55 µm
Nd:YAG	1.06 µm
Frequency Doubled Nd:YAG (2xNd:YAG)	0.53 µm
GaAlAs	0.8 to 0.904 µm
HeNe	0.63 µm

Detection Technique	Interferometer Type	Modulation Technique
Direct	Not Applicable	Pulsed AM
Coherent	Heterodyne Homodyne Offset Homodyne Three Frequency Heterodyne	Pulsed AM FM Hybrid None (CW)

Functions	Measurements
Tracking	Amplitude
Moving Target Indication (MTI)	Range
Machine Vision	Angular Position
Velocimetry	Velocity
Wind Shear Detection	Vibration Spectra
Target Identification	Imaging

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Initial Investigations

1960's

- NASA & Academia
  - Tank Ullage Measurements (early LDV)
  - Ruby Lunar Ranging
  - Apollo Laser Altimeter
- Limited Military Usage
  - First Laser Guided Bombs
  - Laser Rangefinders

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Early Developments

1970's

- Maturing Technology
  - Nd:YAG Laser Rangefinders
  - Nd:YAG Laser Designators & Semi-Active Seekers
- New Technology Exploration
  - Air-to-Air Missile Laser Radar Seeker
  - AM/CW CO_2 Heterodyne Optical Radar
  - CW CO_2 Homodyne Doppler Wind Lidar
- Broad Based Research
  - ERIM, NASA MSFC, MIT/LL, BMDO, Army (NVL), Air Force (ATL), Navy (China Lake)

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Seemingly Recent Developments

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1980's

- CO_2 Imaging
  - Autonomous Terminal Homing (ATH)
  - Backbreaker / Optionbreaker
  - Cruise Missile Advanced Guidance (CMAG)
  - Advanced Terminal Laser Seeker (ATLAS)
- Doppler Navigation
  - EN6 (Bear Claw)
- Laser Gated Imaging
  - AC-130 Gunship Fire Control Active TV
- Laser Rangefinders & Designated Seekers
  - Tanks
  - Paveway III

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Transverse Flow Laser Velocimeter

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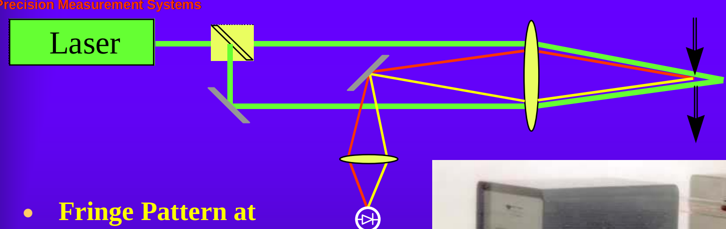

- **Fringe Pattern at Focal Region**
- **Particle in focal region scatters light into receiver**
- **Transverse motion moves particle from fringe to fringe**
- **Rate of change of modulated signal is a measure of velocity**
- **Radial motion does not modulate signal**
- **Near field operation only**

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Lunar Laser Ranging
• 1969
• 60 Joule Ruby Laser
• 3 cm range precision
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Paveway Laser Guided Bomb
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Laser Radar Missile Seeker

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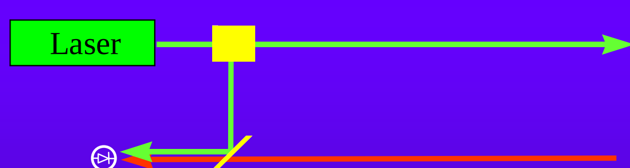
Radial Laser Doppler Velocimeter



- Particle in beam scatters light into receiver
- Radial motion Doppler shifts scattered radiation
- Optical heterodyne mixing generates modulated signal at Doppler frequency in receiver
- Doppler frequency is a measure of velocity
- Near or far field operation

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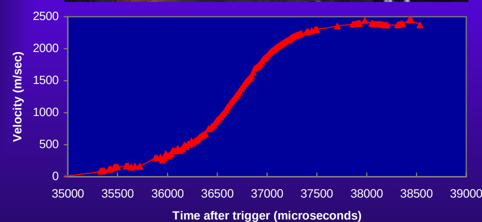
Radial Velocimetry Application



- Interior Ballistics Instrumentation
  - Coherent CO_2 Laser Radar
  - Acousto-Optic Signal Processor
  - Digital Data Acquisition
- Harsh Environment
  - Blast, Shock, Debris
  - EMP
  - Ambient Conditions
- High Performance
  - 5 km/sec maximum velocity
  - 1 m/sec velocity accuracy
  - 25 μsec time resolution
  - 1500 millisec event duration

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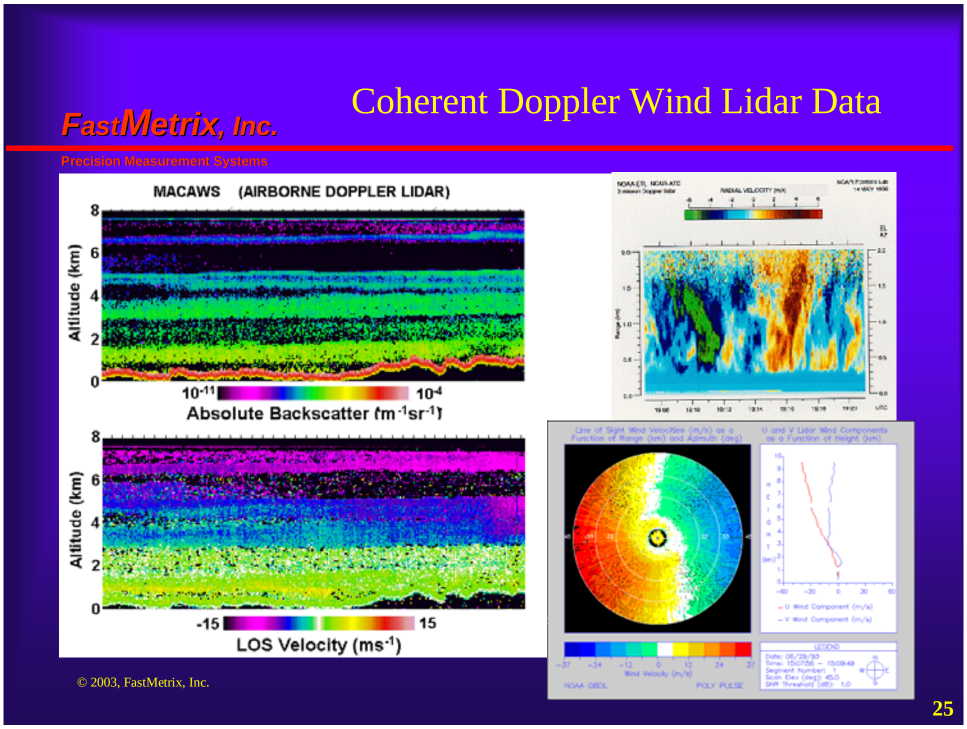
MACAWS Hardware

(Multi-Center Airborne Coherent Atmospheric Wind Sounder)

- Pulse CO_2 Transverse Excitation Atmosphere
  - 0.6 to 1 Joule per Pulse
  - 20 Hertz Pulse Repetition Frequency
- Heterodyne Receiver
  - liquid N_2 cooled HgCdTe Detector
  - 20 centimeter clear aperture

24


Coherent Doppler Wind Lidar Data
FastMetrix, Inc.
Precision Measurement Systems
MACAWS (AIRBORNE DOPPLER LIDAR)
Altitude (km)
Absolute Backscatter (m-1sr-1)
LOS Velocity (ms-1)
© 2003, FastMetrix, Inc.
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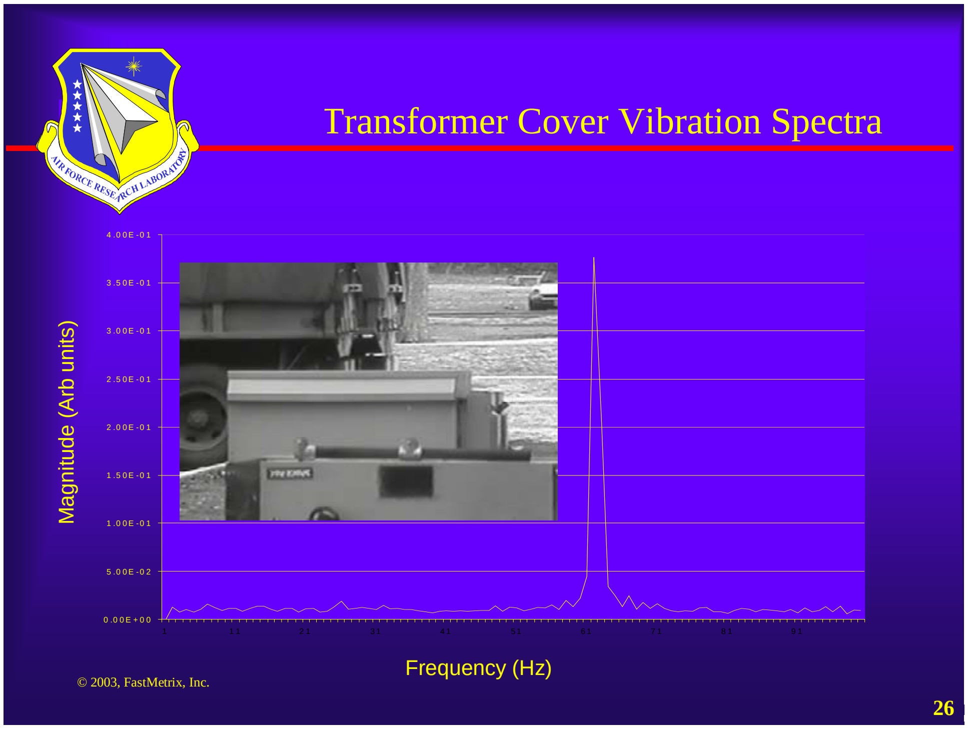
Transformer Cover Vibration Spectra
AIR FORCE RESEARCH LABORATORY
Magnitude (Arb units)
Frequency (Hz)
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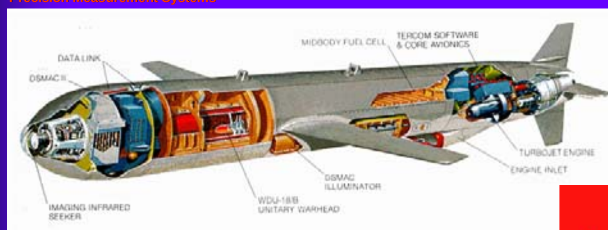
Cruise Missile Guidance



27

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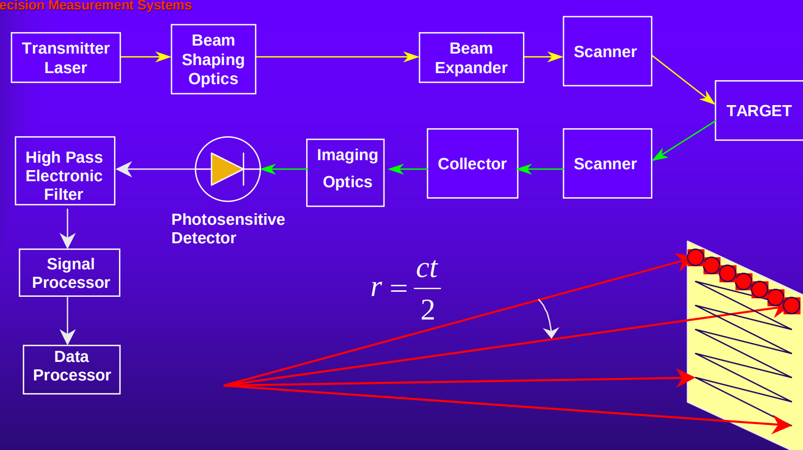
Typical Laser Radar Architecture



$$r = \frac{ct}{2}$$

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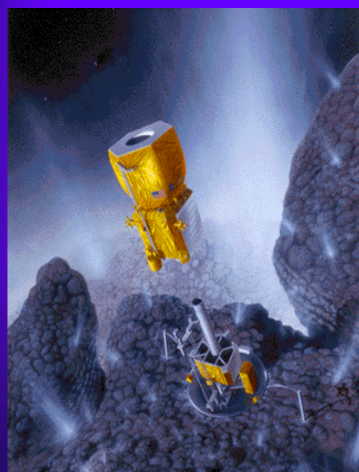
Angle Resolved Range Imagery



- Champollion/Deep Space 4
  - Autonomous Operation
  - Topographic Survey of Comet
  - Landing Site Selection on Tempel 1
  - Flight Control and Hazard Detection
  - Landing Control
  - Rendezvous and Docking
- 3-D Topographic Mapping
  - 10° x 10° FOV
  - 1 mradian resolution
  - 1 cm range accuracy
- Space Qualified
  - 4 kilograms
  - 3 liters
  - 20 Watts
  - 20 kilorads

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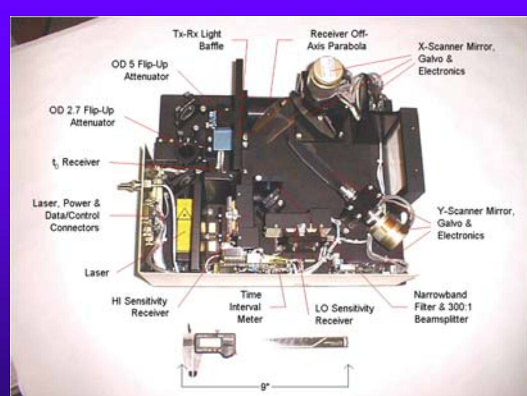
Champollion/DS4 Breadboard



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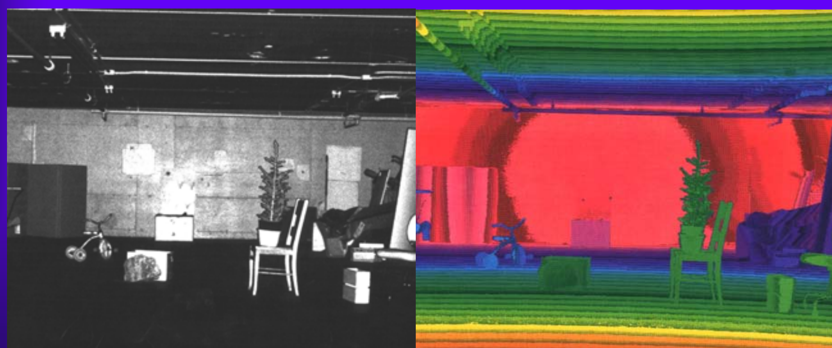
Angle Resolved Range Image

Intensity | Range



Courtesy of Optech

31

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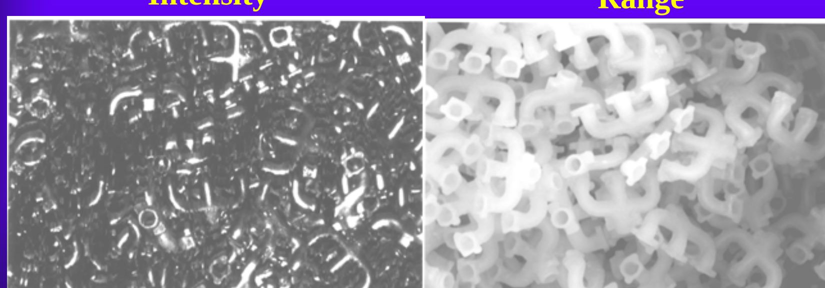
3-D Imaging in Manufacturing

V6 Exhaust Manifolds

Intensity | **Range**



Courtesy of Perceptron

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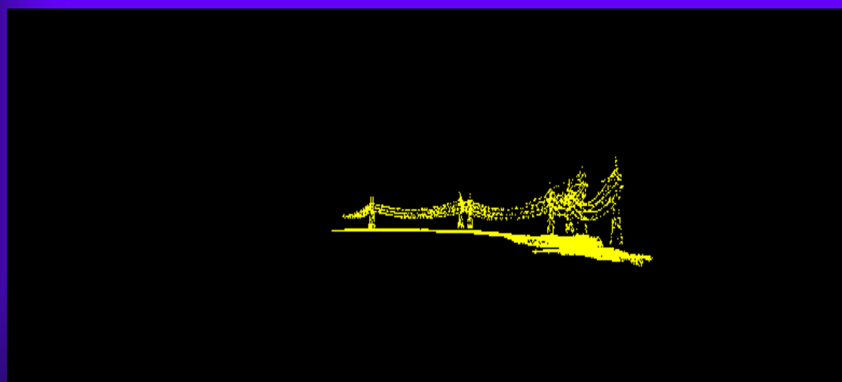
3-D Wire Detection

Power Lines



Courtesy of LaserMap Image Plus Incorporated

33

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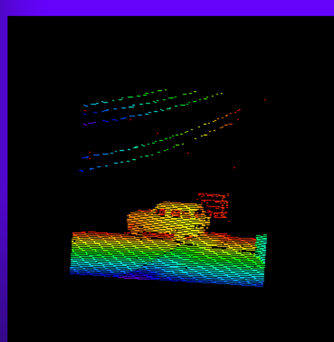
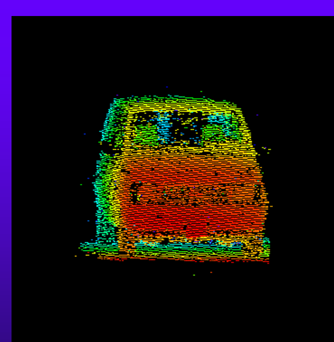
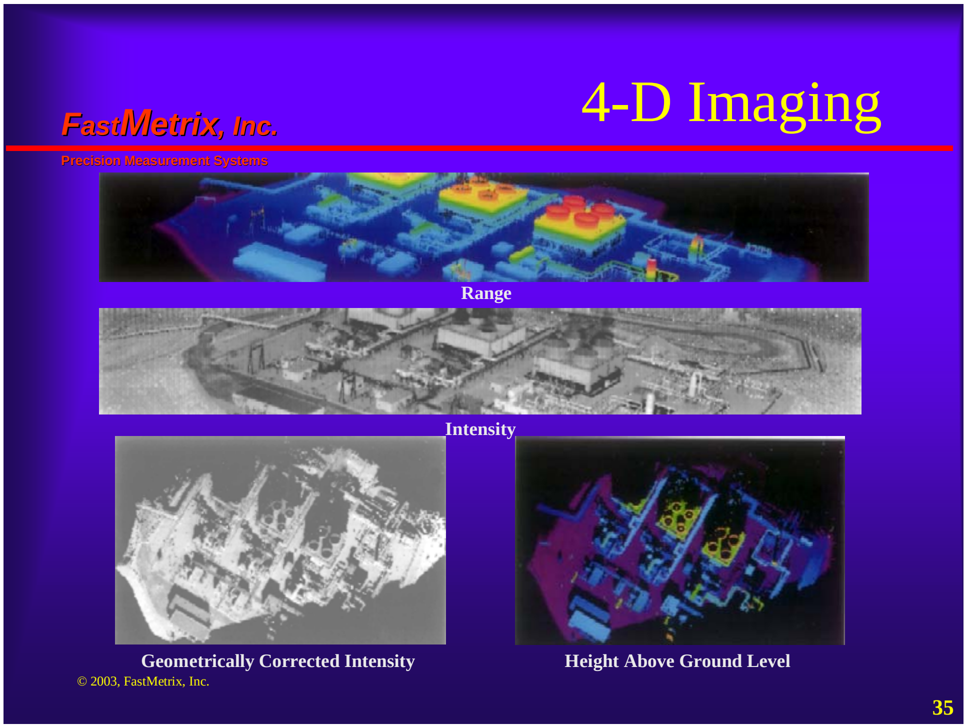




34


FastMetrix, Inc.
Precision Measurement Systems
4-D Imaging
Range
Intensity
Geometrically Corrected Intensity
Height Above Ground Level
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Geosurvey Lidar
Baltimore, Maryland
• 1m GSR
• 0.3 m height accuracy
• Airborne Sensor
Courtesy of Optech and the U.S. Army
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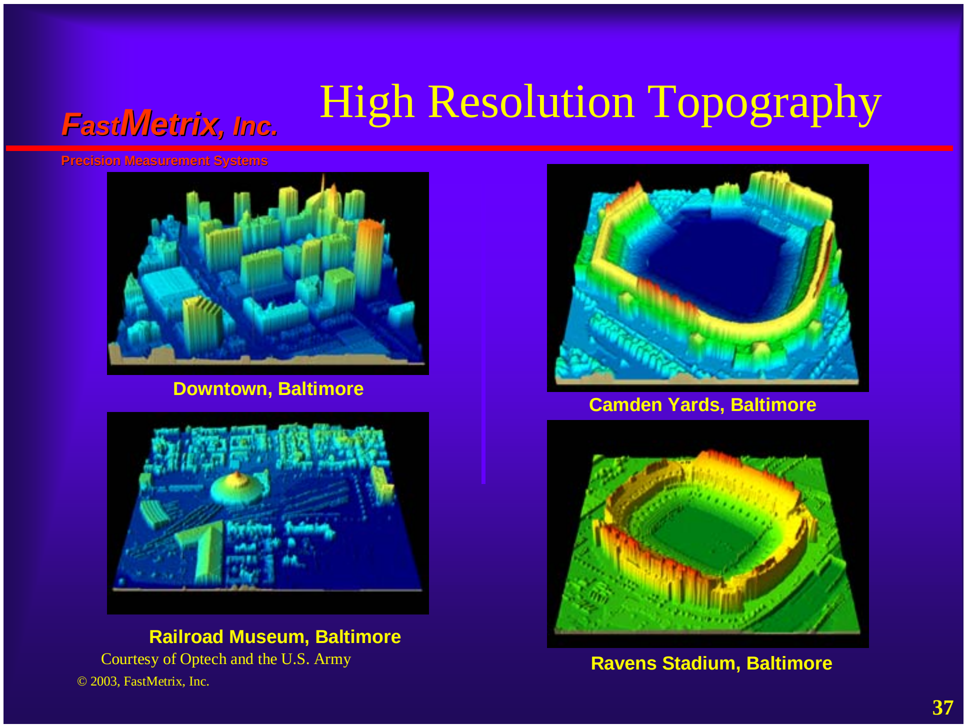
FastMetrix, Inc.
Precision Measurement Systems
High Resolution Topography
Downtown, Baltimore
Camden Yards, Baltimore
Railroad Museum, Baltimore
Courtesy of Optech and the U.S. Army
Ravens Stadium, Baltimore
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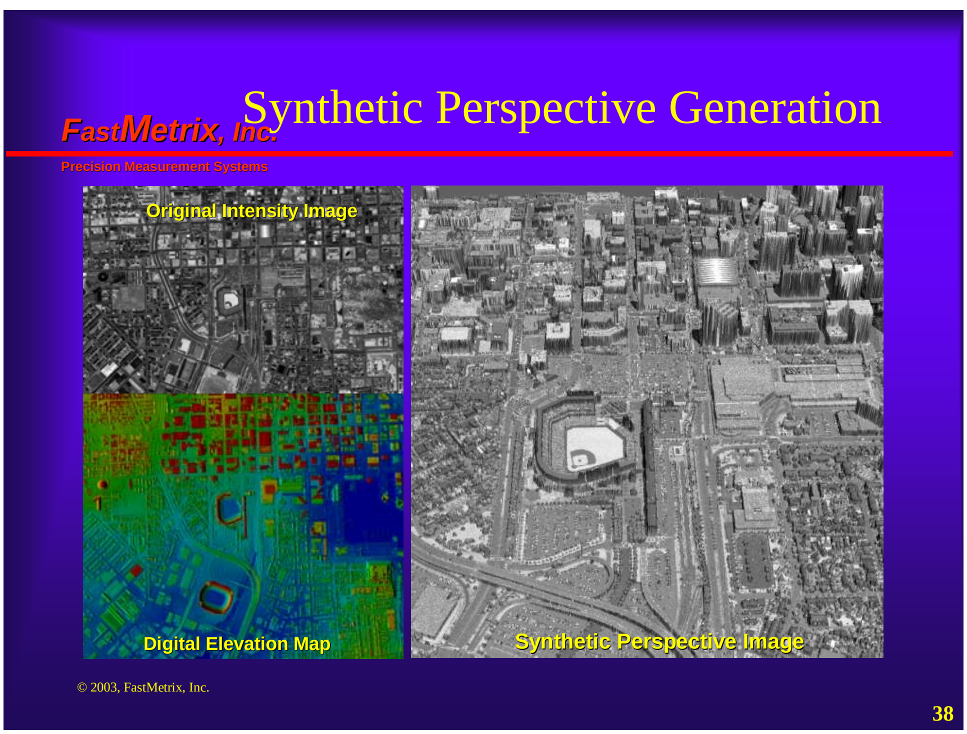
FastMetrix, Inc.
Precision Measurement Systems
Synthetic Perspective Generation
Original Intensity Image
Digital Elevation Map
Synthetic Perspective Image
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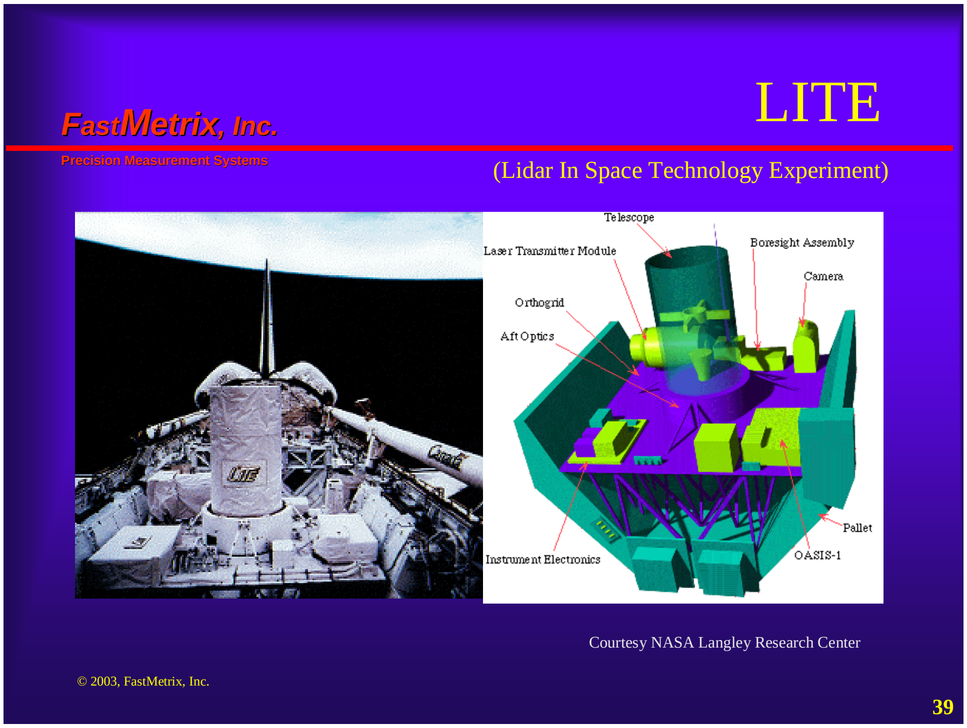

FastMetrix, Inc.
Precision Measurement Systems
LITE
(Lidar In Space Technology Experiment)
Telescope
Laser Transmitter Module
Boresight Assembly
Camera
Orthogrid
Aft Optics
Pallet
OASIS-1
Instrument Electronics
Courtesy NASA Langley Research Center
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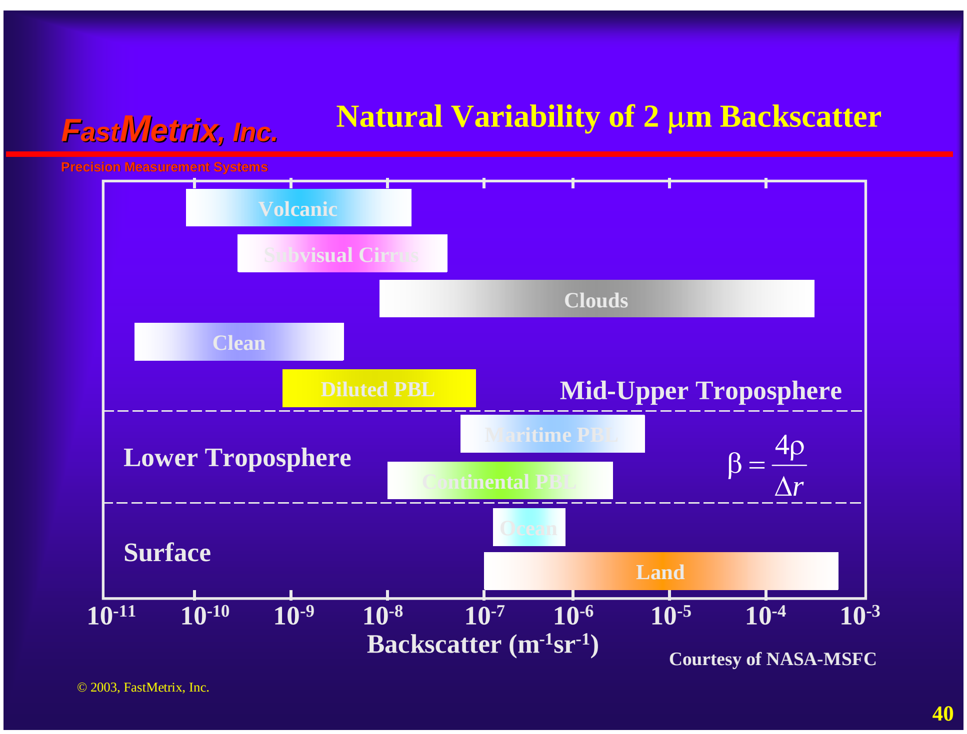

FastMetrix, Inc.
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Natural Variability of 2 μm Backscatter
Volcanic
Clouds
Clean
Diluted PBL
Mid-Upper Troposphere
Lower Troposphere
$\beta = \frac{4\rho}{\Delta r}$
Surface
Land
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3}
Backscatter ($m^{-1}sr^{-1}$)
Courtesy of NASA-MSFC
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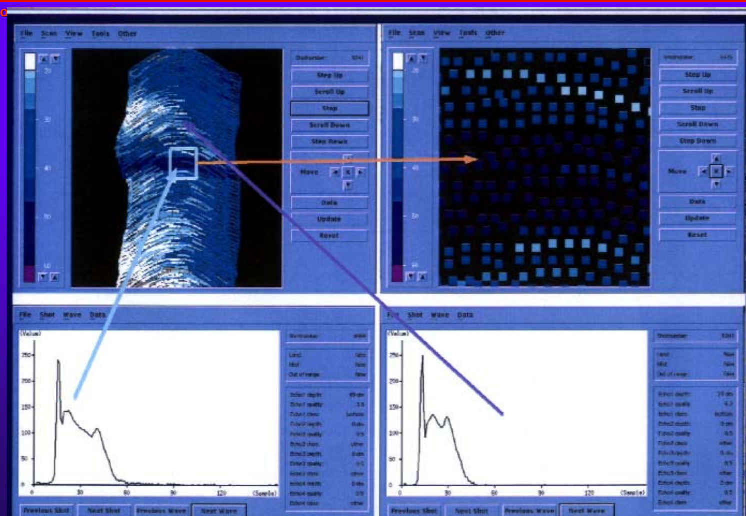
Laser Bathymeter



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Courtesy of the Swedish Defense Research Establishment (FOA)

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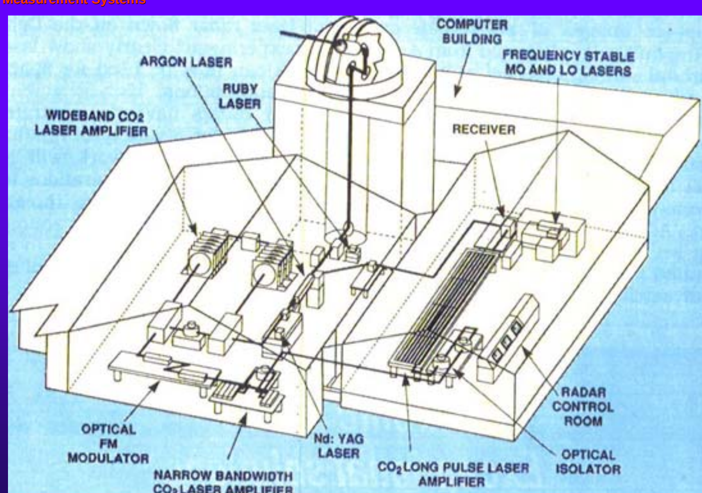
Firepond Laser Radar



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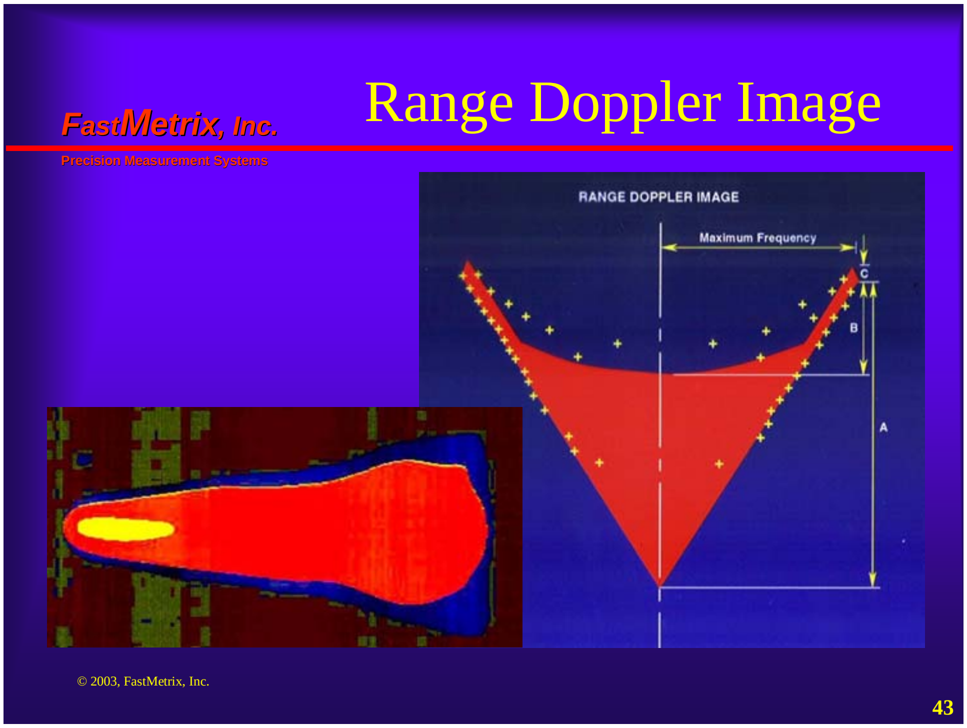
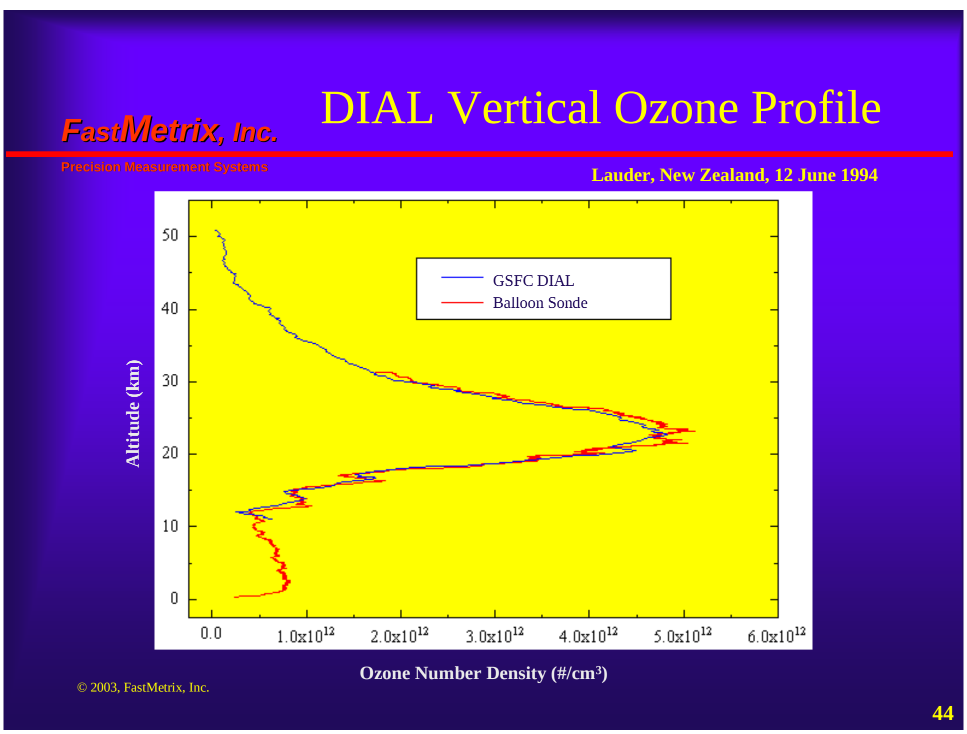

FastMetrix, Inc.
Precision Measurement Systems
Range Doppler Image
RANGE DOPPLER IMAGE
Maximum Frequency
C
B
A
© 2003, FastMetrix, Inc.
43


FastMetrix, Inc.
Precision Measurement Systems
DIAL Vertical Ozone Profile
Lauder, New Zealand, 12 June 1994
GSFC DIAL
Balloon Sonde
Altitude (km)
0
10
20
30
40
50
0.0
1.0x10^12
2.0x10^12
3.0x10^12
4.0x10^12
5.0x10^12
6.0x10^12
Ozone Number Density (#/cm³)
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Raman Lidar

- Independent of Excitation Frequency
  - Small Cross Sections
  - Isotropic Scattering
- Cross Section scales with 4th Power of Frequency
- Distinctive Line Structure based upon Vibrational and Rotational Energy States of Molecular Species
  - water vapor & ozone
  - Temperature
  - optical extinction
  - optical backscatter

Courtesy of Dr. Russell Philbrick, Pennsylvania State University

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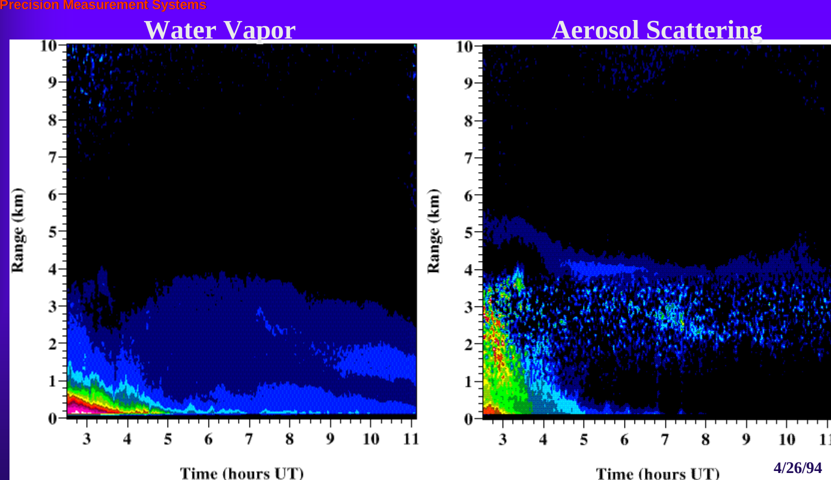
Raman Lidar Image of Dry Line



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The Raman Effect

	DMMP	DIMP	GB	GA	N_2	O_2	H_2	CO_2	CO_2	SO_2
Shift (cm^{-1})	712	719	725	2198	2330	1556	4160	1366	1285	1151
Wavelength (nm)	(Raman Cross Section x 10^{-30} cm^2/molecule/steradian)									
532					0.37					2.05
514.5	12	7.4	6.0	7.6	0.54	0.75	1.1	.70	0.52	2.9
488.0	18	13	8.2	13	0.68	0.95	1.5	.87	0.66	3.6
457.9	22	15	11	19	0.91	1.2	2.0	1.1	0.85	4.7
363.8	58	70	44	72						
337					3.5	4.6	8.7	4.2	3.1	17
308					5.2	6.7	13	6.1	4.5	25
248					13	17	35	15	11	60

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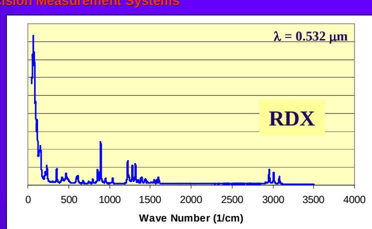
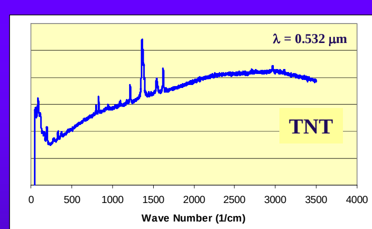
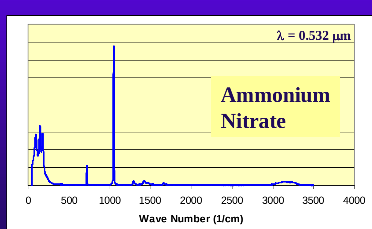
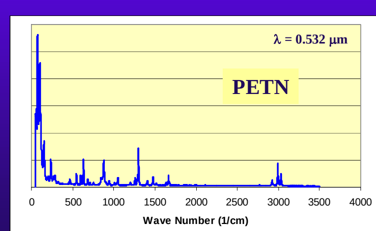
Raman Spectra of Explosives









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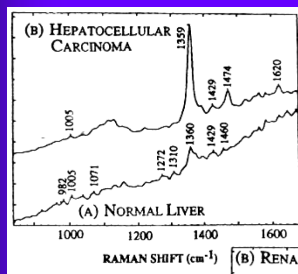
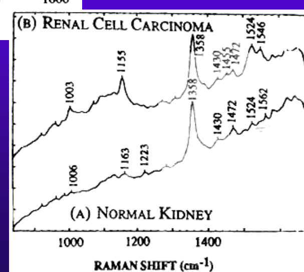
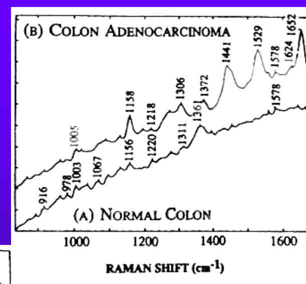
Raman Spectra of Malignant Tissues







- 406.7 nm Excitation
- 5 cm^{-1} resolution

Douglas C Redd, Christopher J. Frank, Zhe-Chuan Feng, Ted S.Gansler, Richard L. McCreery, "Raman spectrosopic characterization of human malignant tissues: implications for a percutaneous optical biopsy technique for in-situ tissue Diagnosis," *Optical Biopsy*, SPIE Press, Vol. 2081, pp. 185-191, 1993.

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Target Laser Cross Section Definition

- **Radar Convention**
  - Cross-sectional area of a perfectly reflecting sphere that produces a reflected energy density at the laser radar receiver equal to that produced by the target
- **Lambertian Convention**
  - Cross-sectional area of a perfectly reflecting flat Lambertian surface, oriented normal to the line of sight from the transmitter, that produces a reflected energy density at the laser radar receiver equal to that produced by the target
- **Isotropic Convention**
  - Cross-sectional area of a perfectly reflecting flat isotropic surface, oriented normal to the transmitter, that produces a reflected energy density at the laser radar receiver equal to that produced by the target

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Laser Radar Cross Sections

Type	Γ	Notes
Sphere	$\pi\rho z^2$	$z << \frac{r\varphi}{2}$
Cube Corner Reflector	$\pi\rho\frac{l^4}{3\lambda^2}$	$l << r\varphi$ $r \geq \frac{D^2}{\lambda}$
Flat Lambertian Disk	$4\pi\rho z^2 \cos\theta$	$z << \frac{r\varphi}{2}$
Long Wires	$2\rho z r\varphi$	$l \geq r\varphi$
Extended Lambertian Surface	$\pi\rho r^2\varphi^2$	$z \geq r\varphi$
Volumetric Scatterer	$\frac{\pi\varphi^2 r^2 \Delta r\beta}{4}$	
Raman	$\frac{\pi}{10^4}\Gamma_R N\Delta r\varphi^2 r^2$	Γ_R = Raman cross section (cm^2 / sr / molecule), N = density of Raman species (molecules / m^3), Δr = range resolution of the lidar (m) $\approx \frac{c\tau}{2}$,

z = sphere, disk or wire radius (m)
l = length of wire or cube edge (m)

ρ = total hemispherical reflectance
β = aerosol backscatter coefficient (m^{-1})

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FastMetrix, Inc.
Precision Measurement Systems

Target Signature Models

- **CALIBER III (obsolete)**
  - Faceted Target Surface Model
  - Uniform Illumination (Continuous Plane Waves)
  - No Shadowing
  - Single Scattering
- **IRMA**
  - Faceted Target Surface Model
  - Arbitrary Illumination (Ray Casting)
  - Shadowing
  - Single Scattering
- **DELTAS (No Longer Supported)**
  - Continuous Target Surface Model
  - Arbitrary Illumination (Ray Casting)
  - Shadowing
  - Multiple Scattering

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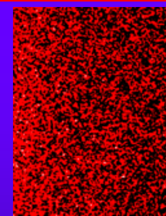
FastMetrix, Inc.
Precision Measurement Systems

Target Speckle



- Constructive and Destructive Interference
  - Coherent Illumination
  - Optically Rough Target
    - Large Ensemble of Independent Scattering Site
    - Phase Uncorrelated between Sites
- Produces Random Array of Bright and Dark Spots at Receiver Aperture
  - Amplitude Described by Rayleigh Statistics
  - Coherent Phase within Spots (i.e., rms OPD < ~λ/4)
  - Random Phase difference between Spots (Speckle Lobes)

$$D_{\text{speckle lobe}} \approx \frac{2.5\lambda r}{z}$$

λ = wavelength, r = range, z = target size

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FastMetrix, Inc.
Precision Measurement Systems

Reflectivity Standards

- Specular Reflectors
  - Spheres and Sphere Segments
  - Cube Corner Reflectors
- Diffuse Reflectors
  - High Reflectivity
    - $BaSO_4$
    - Compacted PTFE Teflon
    - Spectralon™
    - Flowers of Sulphur
    - Nextel™ White Velvet
    - Snow
  - Low Reflectivity
    - SiC Sandpaper
    - Nextel™ Black Velvet
    - Optoblack™

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FastMetrix, Inc.
Precision Measurement Systems

Calibration Standards

- Specular Sphere and Sphere Segments
  - Convex Mirrors
  - Commercial Ball Bearings

$$\Gamma = \pi \rho z^2$$

- Cube Corner Reflectors
  - Glass Prisms
  - Orthogonal Reflectors

$$\Gamma = \frac{0.289^2 l^4}{\lambda^2}$$

- Diffuse Reflectors
  - SiC Sandpaper
  - Gold Coated Sandpaper
  - 3M Black Velvet Paint
  - 3M White Velvet Paint
  - Snow
  - Flowers of Sulfur

$$\Gamma = 4\pi \rho z^2$$

55

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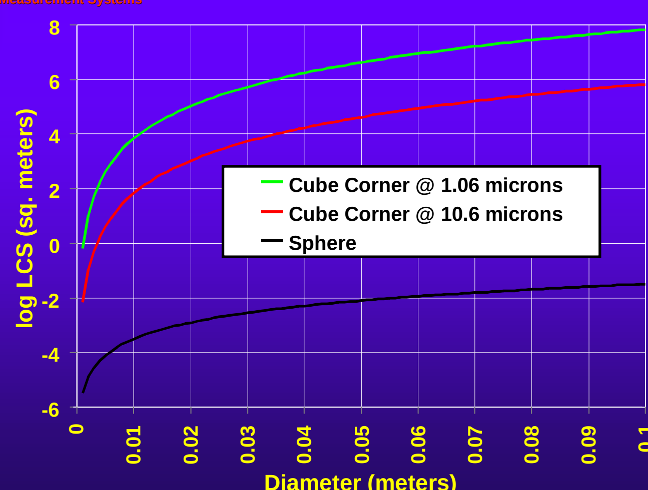
Precision Measurement Systems

LCS of Cube Corners and Spheres



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FastMetrix, Inc.
Precision Measurement Systems

Image Quality

- Modulation Transfer Function (MTF)
- Point Spread Function
- MTF Area (MTFA)
- Square Root Integral
- National Imagery Interpretability Rating Scale (NIIRS)

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Modulation Transfer Function

$$M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

$$MTF(\omega, \upsilon) = \frac{M_o(\omega, \upsilon)}{M_i(\omega, \upsilon)}$$

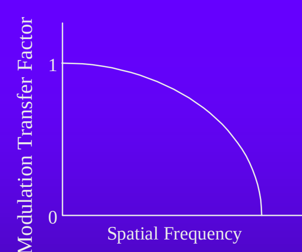
where M = modulation depth

L_{max} = maximum image luminance

L_{min} = minimum image luminance

ω, υ = vertical and horizontal spatial frequencies

o, i = output and input, respectively



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Precision Measurement Systems

Contrast Threshold Function

$$CTF(\omega) = b_0 e^{b_1\omega + b_2\omega^2 + b_3\omega^3}$$

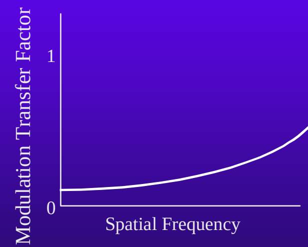
$$b_0 = 1.7062 \times 10^{-3}$$

$$b_1 = 201.6188 \times 10^{-3}$$

$$b_2 = -2.31616 \times 10^{-3}$$

$$b_3 = 0.20000 \times 10^{-3}$$

- Empirically Derived
  - Human Monochromatic Response
  - Young Eyes
  - >18 inches



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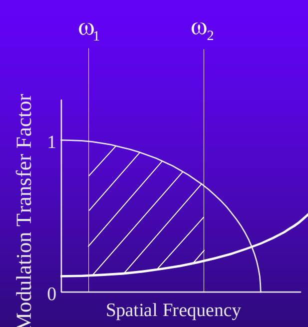
MTFA

- Modulation Transfer Function Area

$$MTFA = \int_{\omega_1}^{\omega_2} MTF(\omega) - CTF(\omega)\, d\omega$$



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Precision Measurement Systems

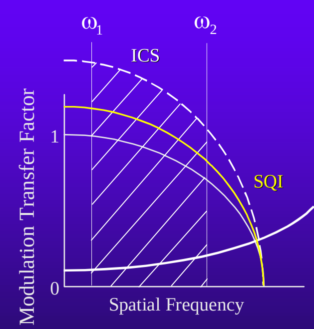
Other Integral Metrics

- Integrated Contrast Sensitivity Function

$$ICS = \int_{\omega_1}^{\omega_2} \frac{MTF(\omega)}{CTF(\omega)} d\omega$$

- Square Root Integral

$$SQRI = \frac{1}{\ln 2} \int_{\omega_1}^{\omega_2} \sqrt{\frac{MTF(\omega)}{CTF(\omega)}} \frac{d\omega}{\omega}$$



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FastMetrix, Inc.
Precision Measurement Systems

What Standards?

- Metrics
  - Precision
  - Resolution
  - Accuracy
  - Ambiguity
  - Error
  - Laser Cross Section

  } Range, Velocity, Angle, Amplitude, Concentration
- Targets
  - Specular Reflectivity
  - Diffuse (Lambertian) Refelctivity
  - Geometric Targets
  - Chemical and Aerosol Cross Sections
- Image Quality

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APPENDIX E.1: LADAR MEASUREMENTS AT BOEING

by John Palmateer

Ladar Measurements at Boeing

John Palmateer
Technical Fellow, Metrology
Boeing Commercial Airplanes

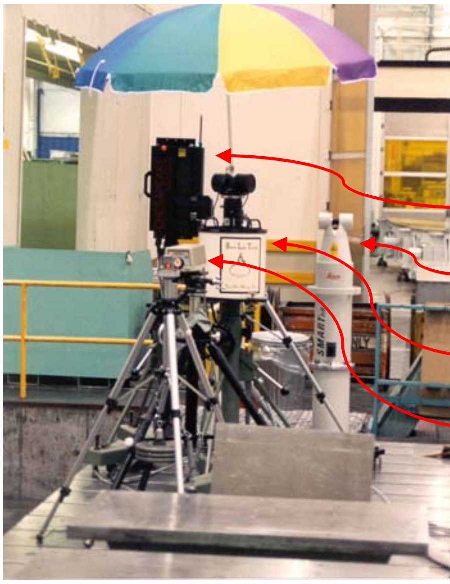
Boeing High Tech Center

- Developed both AM and FM ladar
  - Worked with Digital Optronics, now MetricVision
- Boeing continues work on AM
  - Boeing Laser Tracker (BLT)
    - 11 systems used for 737 assembly
    - Corner cubes required
  - Doppler velocimeter
    - Non contact, fast
  - Currently adapting velocimeter for ranging up to 20ft

BOEING

Applications at Boeing

MR&D
Manufacturing Research & Development



- Testing of BLT and Trackers

FARO (SMX) Tracker

Leica Tracker

BLT

HP Differential Interferometer

BOEING

Applications at Boeing

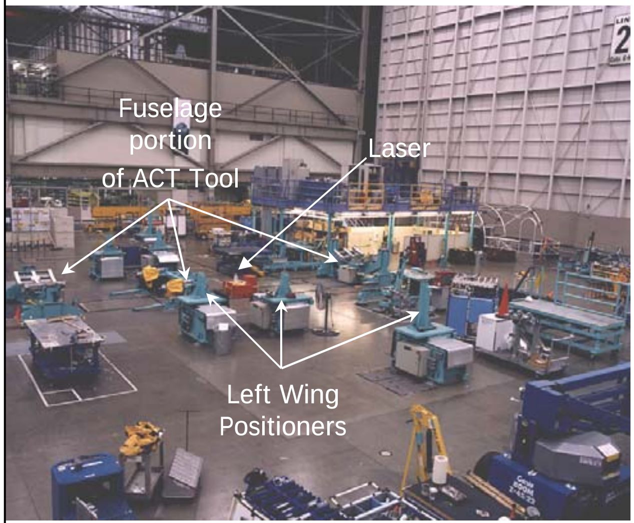
MR&D
Manufacturing Research & Development

- Assembly Jigs on tracks
- Adjust dihedral and sweepback relative to floor!
- Not shown
  - Plumb bob
  - Pogo stick
  - Come-along

BOEING

Applications at Boeing

MR&D
Manufacturing Research & Development

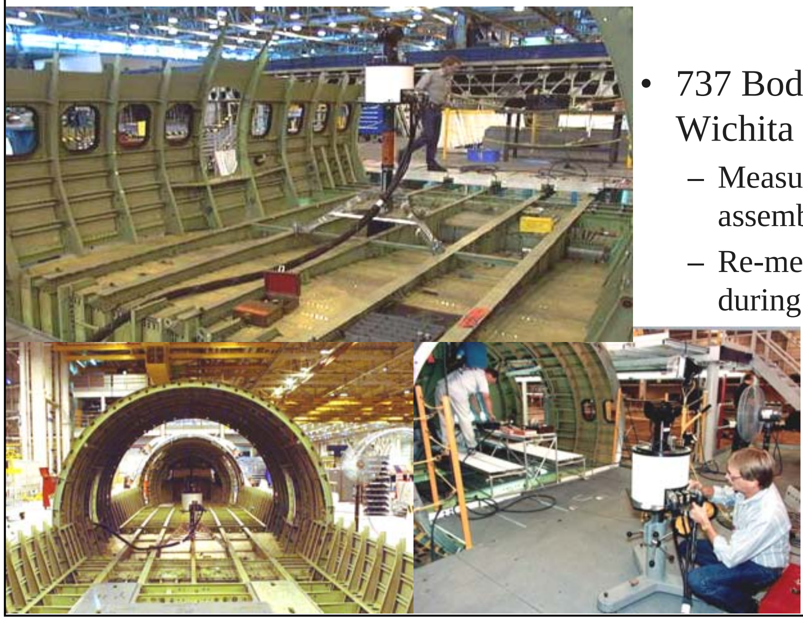


- 737 Wing-Body Join
  - Simplified tooling for final assembly using determinate assembly
  - Optimizes dihedral and sweepback of wings relative to fuselage

BOEING

Application at Boeing

MR&D
Manufacturing Research & Development

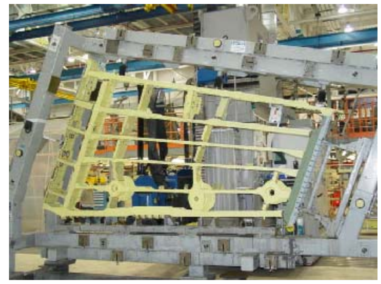


- 737 Body Join in Wichita
  - Measure sub-assembly
  - Re-measure during assembly

F/A-18 Inner Wing Applications

Scan Wing Substructure Metallic Features

MV200 Laser Radar



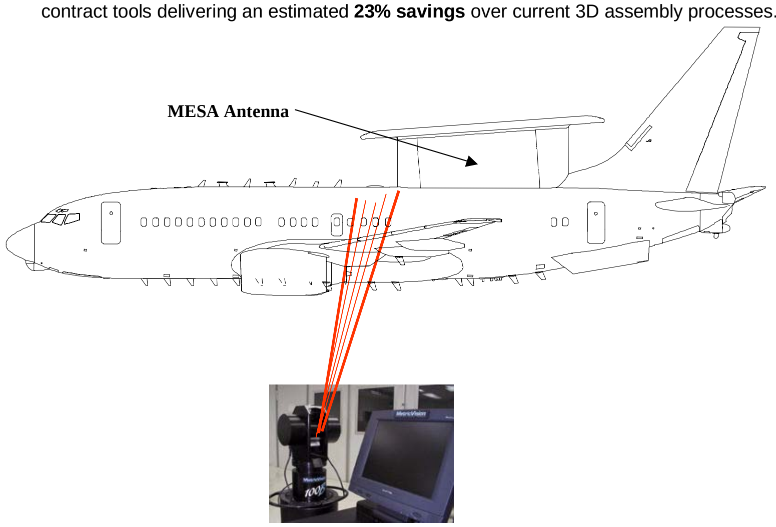
Determine Actual Skin Thickness

System has passed acceptance testing and is qualified for production development

Application at Boeing

Airframe Modifications

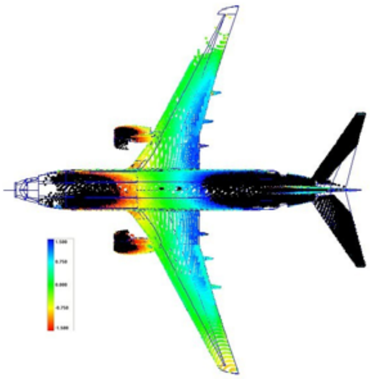
The LR-200 laser scanner will be used to map and install airframe components without costly locator jig contract tools delivering an estimated **23% savings** over current 3D assembly processes.



Application at Boeing

- Low accuracy ladar
  - Measurement of fuselage, dorsal fin, and wings
  - Separately fit fuselage, and wings
  - Minimize asymmetry

Application at Boeing

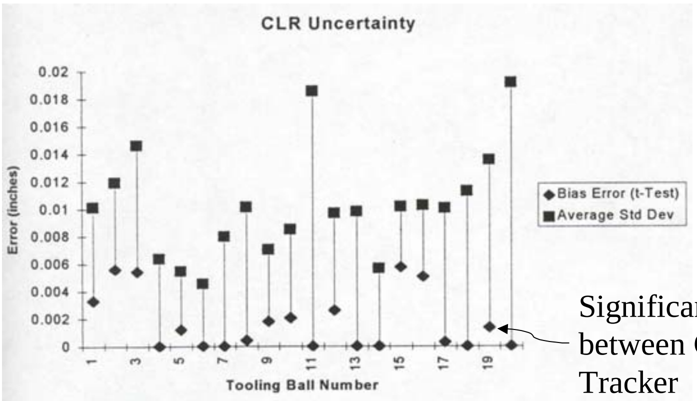


- Low accuracy ladar
  - Establish symmetry during final assembly
  - Average over surfaces
    - Standard deviation of the mean "improves" raw uncertainty
    - Perturbation studies indicate ~0.01 degree
  - Reverse Engineering of facilities

Early Calibration Effort

- Examine calibration in large volume
  - Use tracker as standard
  - Use t-Test for estimate of significant error
    - Concern over relative uncertainties between standard and CLR100
    - Simple way to guardband
    - $t_{\nu,\alpha} < \dfrac{\bar{x}_1 - \bar{x}_2 - (\mu_1 - \mu_2)}{\sqrt{\dfrac{s_1^2}{n_1} + \dfrac{s_2^2}{n_2}}}$

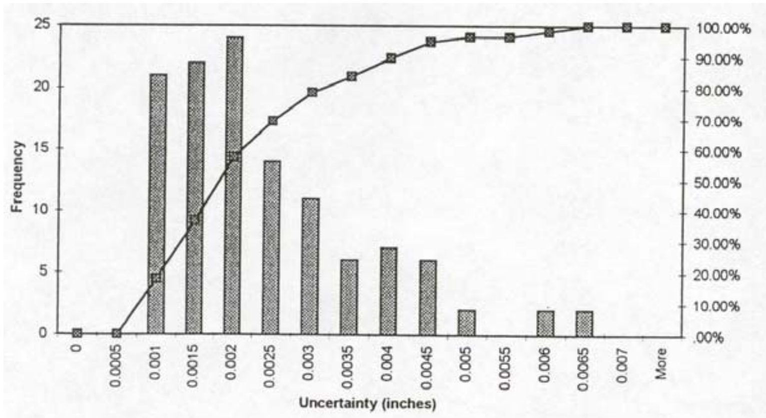
Early Calibration Effort



Significant μ_1-μ_2 between CLR and Tracker

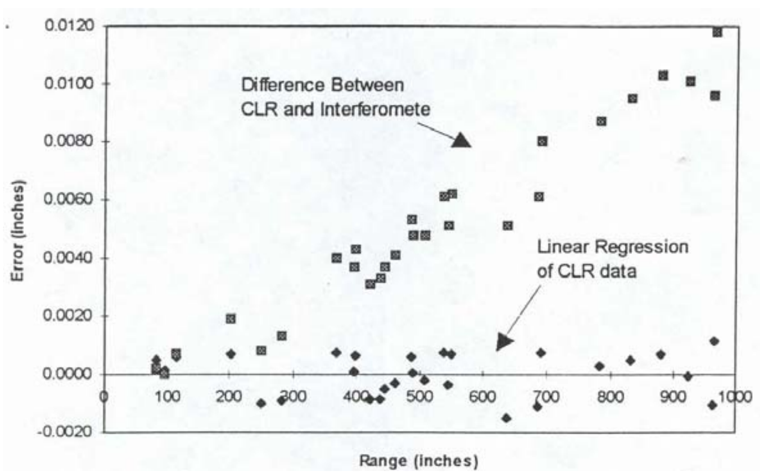
Early version of the T-Test Computation

Early Calibration Effort



- Histogram from final acceptance test
- The uncertainty added the standard deviation and mean

Early Calibration Effort



- The primary concern was that the range error would be non-linear
- Discontinuity between three local oscillators

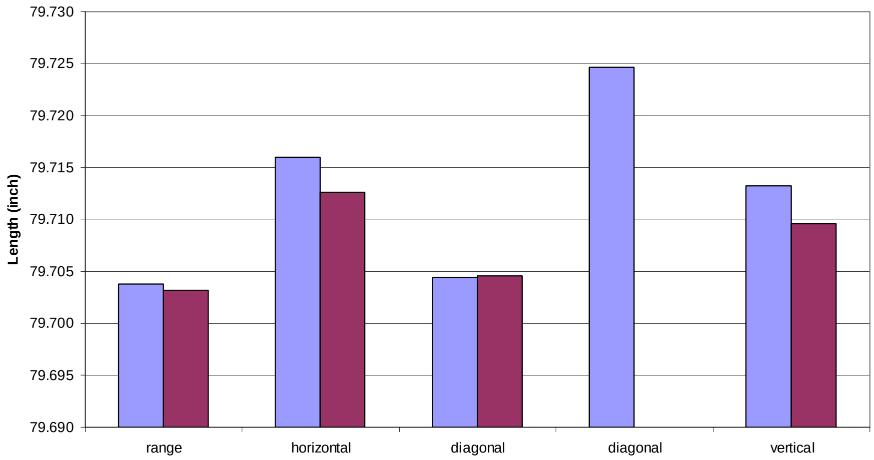
Recent Calibration Effort

- More experience with ladar measurements
  - BLT
  - Trackers with ADM
- ASME B89.4.17 - Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems
- Effort to simplify calibration
  - Eliminate need for moving equipment to calibration lab
  - Reduce support equipment costs

Recent Calibration Effort

- Calibration of transverse measurements in the near field
  - Standard can create large angles (reduce common mode errors)
  - Near field includes lateral and angular errors

Recent Calibration Effort



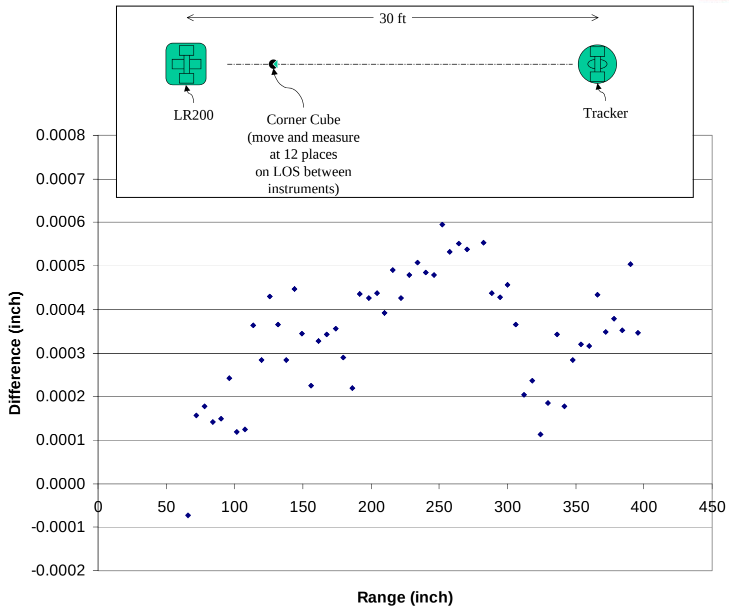
Recent Calibration Effort

- Range calibration
  - Many different ranging schemes with different modes of failure
- Two calibration methods being examined
  - Using tracking interferometer as standard
  - Using invariant distances in conjunction with known distance

BOEING

Recent Calibration Effort

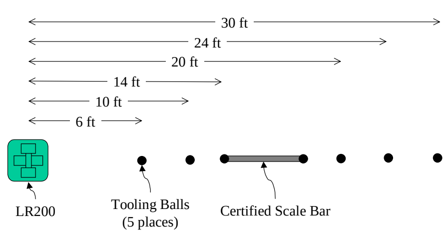
MR&D Manufacturing Research & Development



BOEING

Recent Calibration Effort

MR&D Manufacturing Research & Development



- Method 2 (being tested) – Invariant distance with absolute scale
- Change position of ladar and look for changes on intervals
  - Hope non-linearity moves from one interval to another
  - Maintaining invariance is a problem

Recent Calibration Effort

- Shop floor compensation / calibration
  - Increase equipment utilization
  - Increased uncertainty balance with compensation in measurement environment
    - Reduced thermal-mechanical errors
    - Calibration of measurements as used
- Separate measurement calibration from software accreditation

Conclusion

- 3D non-contact measurement using ladar is a quantum leap ahead of triangulation and vision systems
  - More expensive
- Current challenges include
  - System architecture – CAD driven measurement, analysis and reporting
- A calibration standard is an important step that needs doing now
- NIST as a neutral clearing house for ladar technology
  - Error budgets
  - Modes of failure
- NIST continuing to organize technology workshops

APPENDIX E.2

Ladar Measurements at Boeing

John Palmateer
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253-931-4636

Abstract:

The use of laser radar (ladar) measurement at Boeing is minimal. Nonetheless, Boeing perceives the need for non-contact ladar measurement and has been funding research toward this goal since the late 1980s. The current efforts in ladar development have been directed toward systems capable of measuring parts and assemblies in a manufacturing environment. Goals include on-machine measurement and measurement during assembly for control and inspection. Calibration is performed in a shop environment. Calibration compares a measurement to a length standard, whereby both range and angle measurements are examined as a system. Because of the less certain nature of ladar (e.g., varying modes of failure), the range device is also calibrated separately. Shop practices also include steps that help to validate the measurement process, such as closure measurement and measurement / verification of a length standard. This paper envisions a national laboratory with expertise in various ladar systems, which will ensure a better understanding of the modes of ladar failure.

Introduction

The extent of ladar measurements at Boeing is minimal, so in that respect the title is misleading. Nonetheless, Boeing perceives the need for non-contact laser radar measurements and has been funding research toward this goal since the late 1980. Initial efforts centered at the Boeing High Tech Center, and examined both AM and FM systems. Through those efforts and in conjunction a partner, Digital Optronics which has since morphed into MetricVision, two systems evolved: the Boeing Laser Tracker (BLT), an AM laser radar requiring cooperative target to achieve adequate signal to noise; and the MetricVision's CLR100, an FM ladar capable of measuring directly off surfaces. The current errors in laser radar have been oriented toward laser radar measurement systems capable of measuring parts and assemblies in a manufacturing environment. Since that time, both systems have been evolving and improving. Boeing has since developed a high speed, lower accuracy laser radar pointed by galvanometers and accoustoptics that can track cooperative targets on rapidly moving objects (e.g., a vehicle aligning for refueling). We have also used laser radar for mapping of vibrations (measurement of Doppler). MetricVision likewise has continued development of laser ladar including an array system for inspection of surfaces in hazardous environments (inside nuclear waste storage tanks).

Applications

The initial application for ladar in commercial airplanes was wing-body join (WBJ) for 737. The goal was to eliminate the large floor assembly jigs that “precisely” hold the orientation of the wings to the body during the join operation. This was to be replaced with a jacking system on the fuselage and wings, whose relative orientation was controlled by measurement of those assemblies. Prior to the advent of ladar, this task was not feasible because Boeing would have needed to use tracking interferometers. The requirement for carrying a retro-reflector from point-to-point and the likelihood of breaking the laser beam was very high, so use in a production process was not feasible. The BLT and CLR100 were both prime candidates for this measurement task. Ultimately the CLR was selected for the 737 wing-body join. The BLT was later selected for 737 body-body join in Wichita. One of the crucial (and less than satisfactory) aspects for both these applications has been seamless integration of measurement, controls and CAD. This continues as a hot topic within Boeing.

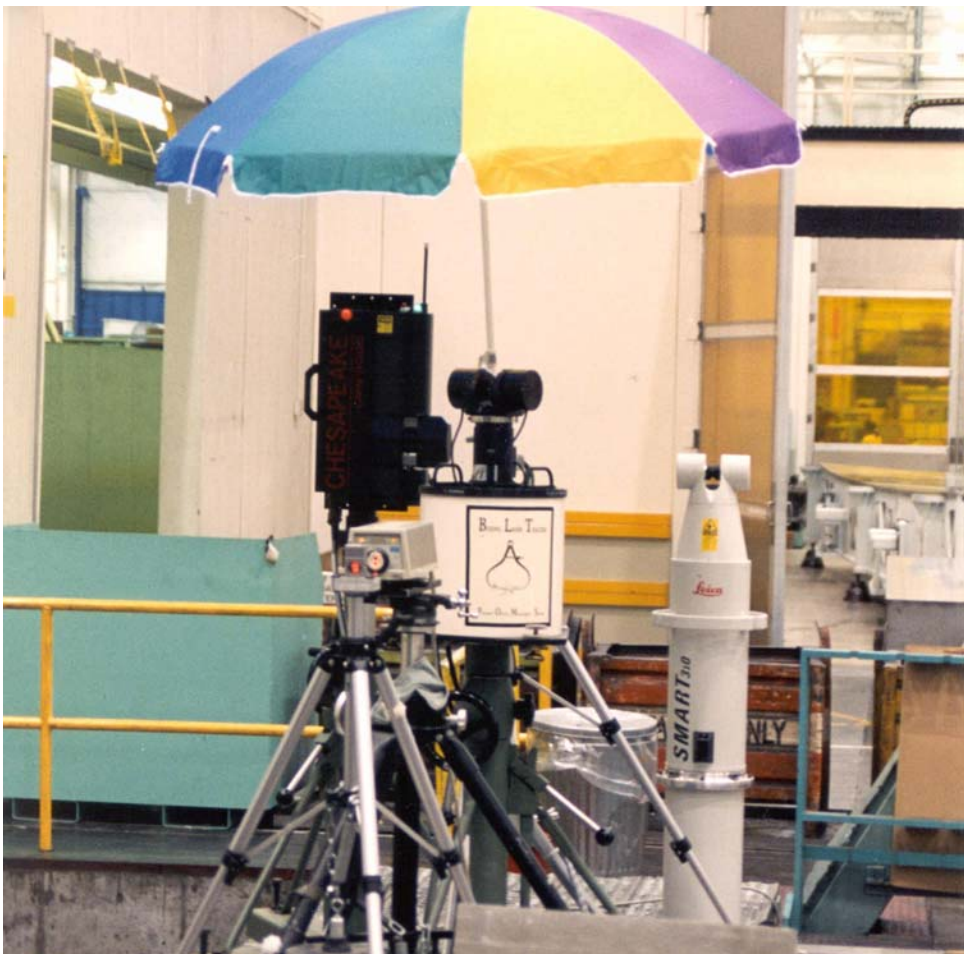

Figure 1. Testing of Boeing Laser Tracker, and other Tracking Interferometers

Recently Boeing has applied ladar measurements to the FA-18 (St. Louis) and Wedge Tail (Seattle). Again the need was for a targetless point and measure system was deemed important. For the FA-18 application, the need is to measure the wing thickness at all drill locations on the wing for drilling of blind holes. The wing thickness is affected by liquid shim material and variance in the graphite. WEDGE TAIL.

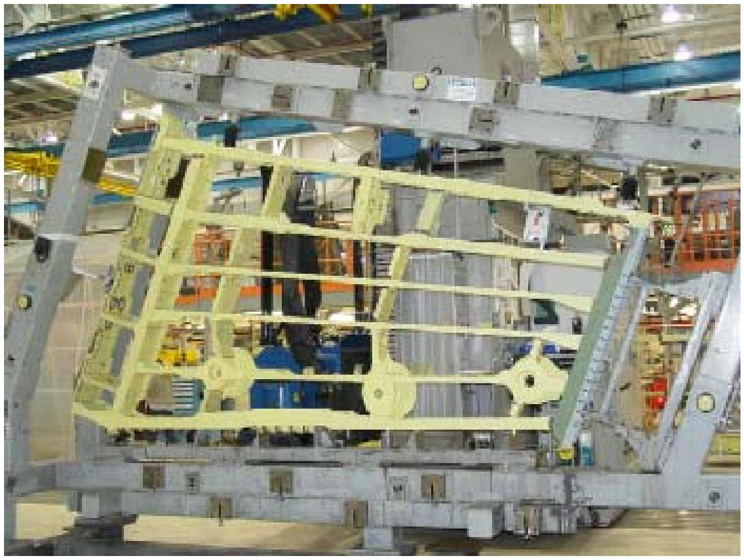

Figure 2. Wing Substructure

Calibration

A major concern during the development and application of the CLR100 to the 737 WBJ was the allocation of calibration risk between Boeing and MetricVision. Confidence in the CLR100 had not developed. The compensation processes for both the pointing head and ranging system were being developed and proven. From Boeing's perspective the calibration requirement looked at measurements accuracy and reliability in a large volume as would be required during WBJ. MetricVision did not want the anomalous measurements, typical in a development project, disqualifying the system, and more important, creeping criteria changing the measurement requirements and costing extra time and development dollars. Furthermore, as part of a purchase contract, these concerns had to balance before the system was ready for prime time and fix those criteria in the contract writing.

The standard for the calibration was the tracking interferometer.[1] Targets in a 40 meter volume were mapped using measurements from at least four tracking interferometer positions. These were "bundled" using Boeing written software. A Student-T criteria, using the computed standard deviation from the tracker measurements and estimated uncertainty of the CLR100 (15 ppm) to balance the uncertainties between the tracking interferometer and CLR100. Additionally, certain number of measurements needed to be within the accuracy requirements. The acceptance criteria did not look at the angle

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[1] Palmateer, J., "Uncertainty Characterization for Portable Variable Geometry Coordinate Measurement Systems", Proceedings 8th International Metrology Congress, October 1997, Bordeaux, FRANCE.

encoding accuracy. Acceptance criteria did not explicitly examine range accuracy, though it did get examined separately on several occasions.

The most recent calibration document (handout) is very different from the prior concept. First, Boeing has more experience and confidence with ladar system (e.g., the Leica and Faro tracking interferometers with absolute distance measurement). Second, the ASME B89.4.19, Performance Evaluation of Laser Based Spherical Coordinate Measurement Systems, has been looking at calibration issues and procedures related to tracking interferometers. Discussions between developers, users and interested scientists have resulted in several key ideas: transverse calibration in the near field when characterizing measurement uncertainty; and calibration of the ranging system since these systems vary greatly and are probably the least well known and stable aspect of the measurement system. Third, is an effort to get the calibration process out of calibration labs and into the factory. This increases equipment utilization time and makes the measurement closer to a process specific calibration.

APPENDIX E.3

Calibration of Structured Light Metrology Systems

John.W.Palmateer@Boeing.com

1.0 INTRODUCTION

This document outlines a generalized procedure for calibrating[2] structured light (a.k.a. Moiré) metrology systems. This calibration may also apply to other metrology systems that perform non-contact surface measurements such as laser and scanning-laser spot triangulation. It is anticipated that calibration procedures for specific systems will be written based on tests and criteria herein and as well as other operational requirements. It is strongly recommended that a performance evaluation be performed for any system and application. The performance evaluation should include tests not normally found in a calibration related to fitness of use such as the ability to discriminate between good and bad data, and various methods that assist the operator in this assessment.

The calibration uses a ball plate artifact (see Appendix E.3-A) and optionally a ball bar. The artifact is made of several (e.g., 20) precision balls held in stable (i.e., three-point) mounts. The inclusion of the ball bar is designed to augment the artifact in the event that it is substantially smaller than (less than 50 %) the field of view of the system under test. The ball bar, when used, should span approximately 80 % of the system under test's field of view. The calibration of measurements must be separated from calibration of analysis routines that fit measured objects. When calibrating a complex object using CAD it becomes difficult to distinguish the measurement uncertainty, CAD model uncertainty, and the uncertainty in the fitting process. Thus this calibration routine uses spheres whose analysis is well-understood and published. [3]

This calibration is from a single vantage point. It estimates the uncertainty for the basic unit of measurement (a.k.a., X-, Y-, Z-triplet, the measurement triplet, or voxel) and the

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[2] ISO International Vocabulary of Basic and General Terms defines calibration as comparison to a standard.
[3] Shakarji, C., "Least-Square Fitting Algorithms of the NIST Algorithm Testing Service", J. Res. Natl. Inst. Stand. Technol. 103, 633 (1998).

distortion across the field-of-view (FOV). One must distinguish between the FOV of the camera and projector, a 2-D space, and the measurement volume, a 3-D space. Distortions in the 2-D space create measurement errors in the 3-D space. It is important to fill the FOV of the camera and projector system so that lens distortions are maximized in the 3-D volume. In general, metrology systems where physical movement of the metrology sensor is not required, measurement of the artifact in a portion of the volume captures the entire volumetric measurement uncertainty. That is, projection and reconstruction of structured light extend via lines-of-sight through the measurement volume. Thus the uncertainty is not strong function of the volume. So unless there is some mechanism that interacts with the measurement volume (e.g., focus mechanism or gantry movement of the sensor), absence of distortion in one FOV of the volume implies absence of distortion throughout the volume. Thus calibration can use a "flat" artifact, such as a ball plate, that fills the FOV but does not fill the measurement volume.[4] If the sensor requires movement by a gantry or similar device, as in the case of some line scan cameras, then the uncertainty of motion through the volume must be characterized and added to the sensor uncertainty.

A typical measurement of a feature is often constructed from many individual X-, Y-, Z-triplets. In the case of this standard, the feature is the center of a sphere. Clearly, the process of fitting X-, Y-, Z-triplets to complex surfaces and determining that fitting's confidence interval will be a complicated function of X-, Y-and Z-triplet locations, triplet uncertainty, data density, and surface contour. The role played by triplet uncertainty is typical of any value that is being averaged, in that it influences the uncertainty of that average by $\sigma_{Triplet} / \sqrt{\text{number of measurement}}$.[5] Thus, while the triplet uncertainty primarily influences the uncertainty of a feature being extracted, increasing the number of measurements (as well as other geometry considerations) ameliorates this influence.

[4] Calibrations using "flat" artifacts: J. Zhang and A. Djordjevich, Study on laser strip sensor, Sensors and Actuators (72) 1999; K. Harding, Calibration methods for 3D measurement systems, Proc of SPIE, Vol., 4189 (2001); G. Sansoni, M. Carocci & R. Rodella, Calibration and performance evaluation of a 3D imaging sensor based on the projection of structured light, IEEE Trans. on Instrumentation and Measurement, Vol. 49, No. 3 (2000)

[5] Box, G.E.P., Hunter, G.W. and Hunter, J.S., Statistics for Experimenters, John Wiley & Sons (1978).

Thus, the triplet uncertainty must be known for subsequent uses of the data but is not part of the systems immutable uncertainty.

The distortion across the FOV is not a value that is reduces with additional measurements. Rather, the distortion across the FOV affects the measurements between features in the usual manner that is expected of measurement uncertainty. The single vantage point estimates the uncertainty of a point-to-point measurement via comparison to a ball plate. Thus, the triplet uncertainty is independent of the instrument uncertainty, and not explicitly in its uncertainty computation. The triplet uncertainty is contained in the location in the spheres, which in turn estimate the distortion across the FOV. Increasing the number of measurement reduces the distortion only because the estimates for the sphere centers are improved. Thus, the distortion across the FOV is the true point-to-point instrument uncertainty.

As the volume is expanded, the uncertainty becomes the RSS of the point-to-point uncertainty plus the mechanism used to expand the volume. In this manner, the uncertainty is propagated when combining images into a larger survey. For example, if photogrammetry is used to stitch vantage points together, the resulting uncertainty is a combination of the point-to-point uncertainty ($U_{pt\text{-}pt}$), as determined by this calibration process, and the photogrammetry uncertainty ($U_{Photogrammetry}$): $\sqrt{(U_{Photogrammetry})^2 + U_{pt-pt}^2}$. Additionally the grid of photogrammetry points throughout the survey also serves as the check for distortion as the data is subsequently manipulated. An alternative example is a line scan camera mounted on a certified gantry where the uncertainty of individual line scans are adjusted by the uncertainty of the coordinate frame of that certified gantry. Note that in this case, the pointing of the gantry's coordinate frame should be the dominant contributor. Once determined, the uncertainty can be propagated into application software when generating surfaces, extracting features, etc.

Thus, the single vantage point calibration allows comparison of similar equipment. It is likely that different products will have different procedures for collecting, evaluating and combining data, so use of a single vantage point provides a common denominator between all processes so that any system's fundamental unit of measure can be compared.

Procedures for calibrating a *fixed* structured light installation that includes a translation or rotation stage should also include these translation and rotation stages when designing a calibration procedure. It is relatively simple to modify the single vantage point procedure for multiple vantage points and obtain an uncertainty for the fixed installation. When the structured light system is used in an unstructured manner, that is, combining vantage points is *ad-hoc*, it may not be practical to include the mechanism for combining the vantage points into the calibration procedure. It is strongly recommended that the mechanism for combining vantage points be included as part of the performance evaluation for the application, but not the calibration of the structured light system since it is easier and more versatile to handle these calibrations separately.

2.0 SURVEY

The single vantage point for the calibration plate should be off a corner of the plate and diagonally across the plate (as shown in the figure A1 in Appendix E.3-A). The sample size for any object in the survey, (e.g., sphere on a ball plate) must include at least 100 measurement points. If the calibration plate subtends less than 50 % of the metrology system's field of view, supplement the calibration with a ball bar whose length subtends at least 80 % of the metrology system's field of view. Additionally, if the depth of field for the metrology system is sufficiently large that it generates a significant change in uncertainty, then measurements of the calibration plate at several positions within the field of view are required. Often the depth of field is small and this is not an issue. Alternatively, the depth of field may be large, but only the worst case uncertainty is desired, so only one measurement in that worst case region should be required. If this process rejects any data, the rationale for rejection must be documented including whether data rejection is automated or operator invoked.

3.0 ANALYSIS

The measuring and fitting of single spheres shows errors which estimates the X-, Y- and Z-triplet uncertainty. Measurements between independent balls quantify the distortion across the field of view. These two values are estimated separately, the former for use in estimating uncertainty in feature extraction and the latter for estimating the point-to-point measurement uncertainty.

Compute a sphere fit with unconstrained radius for all points on each hemisphere on the ball plate (see Appendix E.3-B). Record the computed radius and 1-sigma standard deviation for each sphere. The localized uncertainty from sphere measurements is the sum of the radial errors and 2-sigma standard deviation for these measurements (see Table 1). Make a whisker plot of the residual errors for the sphere fit. Alternatively, plot the residuals of the sphere fit as a function of angle of incidence between the central line-of-sight for the system-under-test and the normal vector on the sphere (see Appendix E.3-B) and compute the regression line for this data.

If any of the measured points fall in a forbidden zone, that is, physically impossible regions such as between the sphere and surface of the ball plate due to measurement device physics, etc., these points should also be reported.

Table 1. Best Fit Sphere

	Computed Radius	*Nominal Radius*	*Standard Deviation (stdev)*	*Uncertainty radial error + 2 $\times$stdev*
Sphere 1				
Sphere 2				
Sphere 3				
Sphere 4				
Sphere 5				
⋮				
Ave. Triplet Uncertainty				

Compute the point-to-point distance between independent balls (i.e., use each ball only once in the computation) on opposite sides of the calibration plate (and between the ends of the ball bar if used) using the center values of the sphere fit. The scale is the ratio of the longest nominal distance to the current distance. This is used to normalize the differences to the longest interball distance. Compute the standard deviation of the scaled difference (see Table 2). Alternatively, compute the least square fit (6-degrees of freedom)of all computed sphere center locations with the nominal center locations. The standard deviation of the fit is the standard deviation for the distortion across the field.

Table 2. Distance Between Spheres

Distance Between Spheres					
	Measured	*Nominal*	*Difference*	*Scale*	*Normalized Difference*
Sphere 1 and sphere 2[6]					
Sphere 3 and sphere 4					
Sphere 5 and sphere 6					
⋮					
Ball Bar					
Standard Deviation					

4.0 RESULTS

The standard deviation of the sphere fits estimates the X-, Y-, Z-triplet uncertainty, u_{xyz}. All Max-Min deviation from the ideal spheres must be within the maximum permissible triplet error (MPE), if one is provided. In the event that the specification is in terms of expanded uncertainty (2-sigma), at most, 5 % of the measured deviations to the sphere can be outside the expanded uncertainty. Note any significant structure to the sphere fit such as oblateness and ellipticity. If the regression line was plotted, then the slope must be less than 0.05. Error may be due to asymmetry in the structured light on the surface of the hemisphere, as seen by the camera, as the incidence angle gets larger. Error may also be due to power loss as the incidence angle gets larger. This test may identify the presence of a potential problem but does not diagnose the source.

The standard deviation for the normalized distances between spheres estimates the distortion in the volume measurement, $u_{pt\text{-}pt}$. All normalized differences must be within the maximum permissible error for point to-point measurements, if one is supplied. Alternatively, the normalized difference must be less than the single point uncertainty multiplied by $\sqrt{2}$ (this assumes the pair has equivalent and spherical uncertainties). In the event that the specification is in terms of expanded uncertainty, (2-sigma), twice the standard deviation for the normalized difference must be less than the expanded uncertainty.

The uncertainty of the calibration plate in this procedure has been ignored. Thermal expansion of the balls and calibration plate are generally very small over a wide range of

[6] The sphere numbers are examples. The actual choice of spheres should span the ball plate.

temperatures (see Appendix E.3-C), therefore calibration can be performed in a factory environment. Thermal errors, when they occur, will most likely affect the mechanical stability of the orientation between the structured light generator and the camera system. The system performance evaluation should identify the extended validity conditions for temperature of use.

5.0 CONCLUSION

The calibration process must separately identify the triplet uncertainty and the instrument uncertainty:

u_{xyz}

$u_{pt\text{-}pt}$

and the temperature range over which the measurements are valid.

If the structured light system is part of a fixed installation, then the instrument uncertainty should include any uncertainty associated with translation and rotation stages.

Appendix E.3-A Calibration Artifact

The artifact shown in figure A1 is a ball plate, 406.4 mm (16 in.) on the long side with 20 hemispheres held in three-point mounts. The roundness of the hemispheres is better than 0.00254 mm (0.0001 in.). The locations of the hemispheres are calibrated less than 0.0127 mm (0.0005 in.). Some methods for computing ball plate calibration artifact parameters automatically rely on random placement of the balls so correlation can be used to match nominal separations with actual measurements.

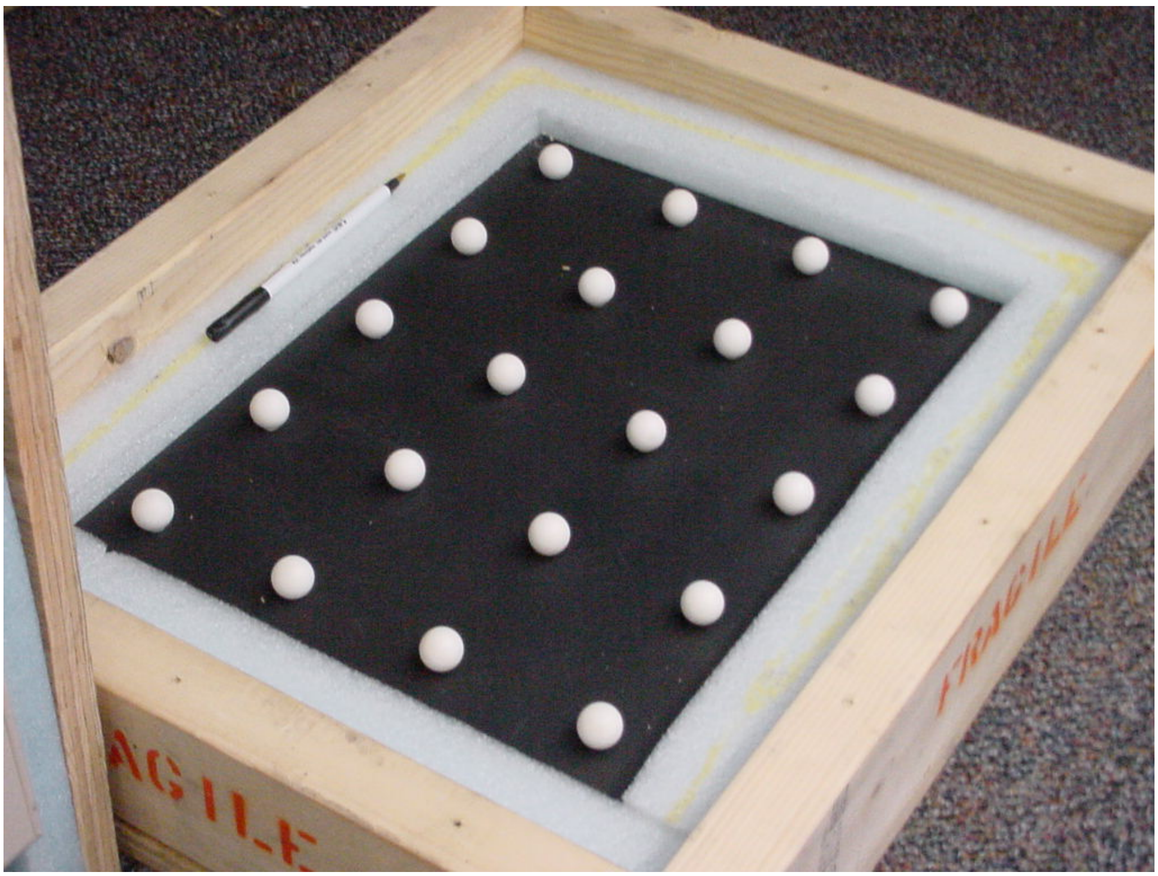


Figure A1. Diagram of Ball Plate

Appendix E.3-B Sphere Fit and Angle of Incidence Calculation

The plotting of data as a function of angle of incidence is described (see figure B1).

Compute the errors for each measurement to a sphere, using constrained (true) radius: δ_i

Compute the center of the sphere based on all measured data: **C**

Compute the vector for the origin of the metrology system to the sphere center: **OC**.

Compute the normal vector for each measured point: **PC**.

Compute the incidence angle, θ, from the dot product of the vectors **OC** and **PC**:

$$\theta = \arccos\left(\frac{\overrightarrow{OC} \cdot \overrightarrow{PC}}{|OC||PC|}\right)$$

Plot the sphere error, δ_i, with respect to the incidence angle (see figure B2). Ideally, the slope of any linear regression through all of the points should be "flat".

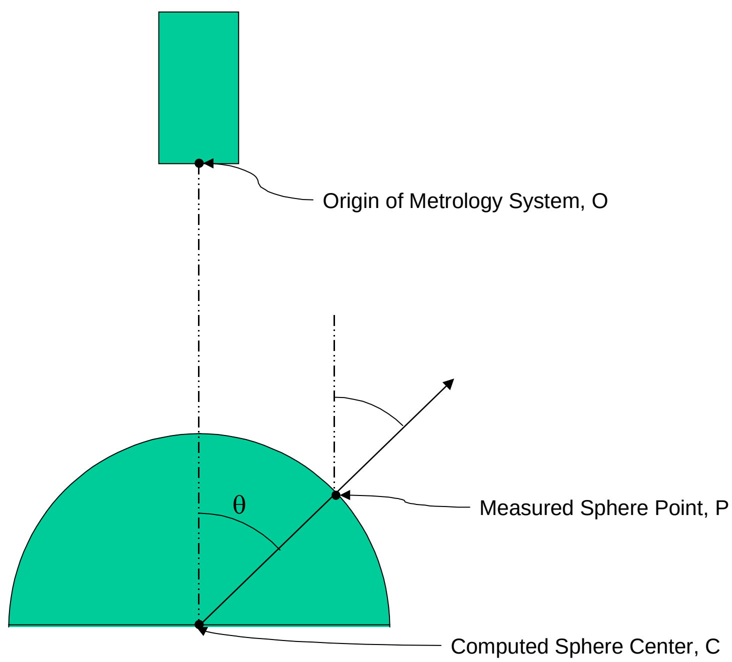


Figure B1. Diagram of Sphere Measurement

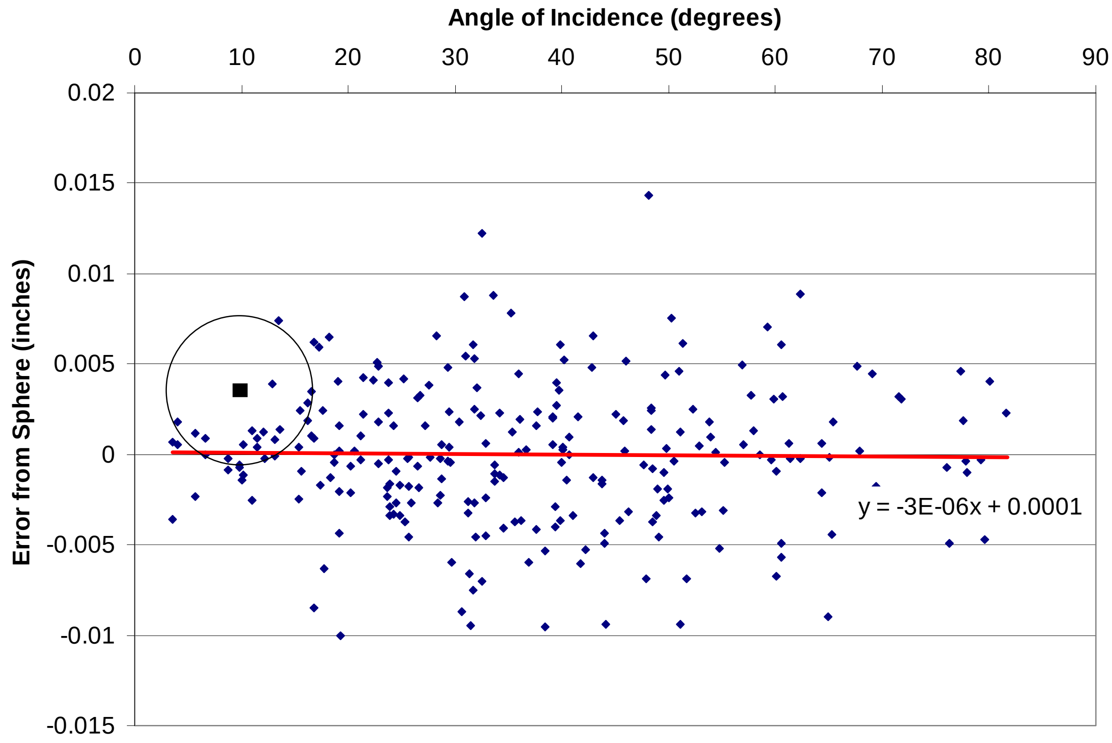


Figure B2. Typical Plot of Incidence Angle Versus Error.

Appendix E.3-C Calibration Plate Uncertainty

The compensation / calibration for structured light measurement systems is designed to take place in a shop environment. The accuracy of this calibration is contingent on the accuracy of the standard used for the calibration. The calibration plate is provided with a certification at a specific temperature and must be adjusted for the temperature in the shop during the compensation / calibration process. The calibration ball plate purchased from Bal Tec is fabricated with a cast base, meaning that the thermal expansion is reasonably isotropic, therefore the linear thermal expansion model can be extended to three dimensions.

Given that the CTE and uncertainties for dimension and temperature when the calibration ball plate is used:

CTE_{Plate} = 12 ppm / ºF
L_{Plate} = 406.4 mm (16 in.)
U_{Plate} = 0.00127 mm (0.00005 in.)
DiameterBalls = 19.1 mm (0.750 in.)
CTE_{ZrO2} = 12 ppm / ºF
U_{Balls} = 0.00127 mm (0.00005 in.)
U_{Temp} = 0.1 ºC (0.2 ºF)

The dimensional correction is shown in figure C1:

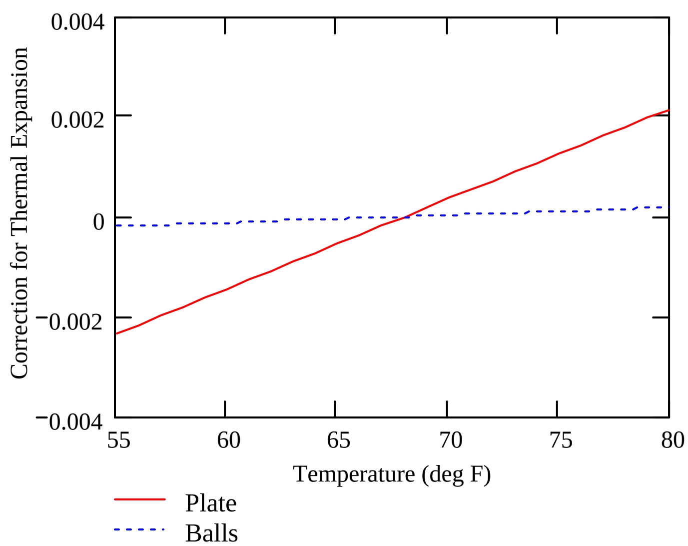


Figure C1. Temperature Correction to Dimensions

There is no need to thermally correct for ball diameter since the uncertainty is much less than the uncertainty of the structured light system under test. For a temperature change of 2.2 ºC (4 ºF) there is also no need to correct for thermal expansion of the ball plate (though advisable since it is so simple), since its thermal expansion is also much less than uncertainty of the structure light system under test.

The corresponding dimensional uncertainty is shown in figure C2:

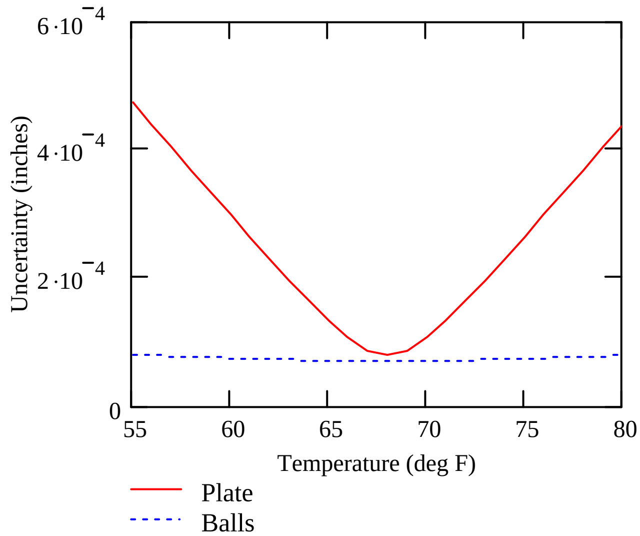


Figure C2. Calibration Ball Plate Uncertainty

The uncertainties are substantially less than the uncertainty of the measurement system under test for a ±10º temperature range, roughly a factor of 10 less than the measurement uncertainty. Thus, the calibration standard will maintain acceptable uncertainty for a wide range of shop temperatures.

APPENDIX E.3-D Uncertainty of Surface Objects

When measuring a single point location several times, the usual procedure is to compute the average point location, the standard deviation. When the confidence interval for the average location is desired the standard deviation of the mean is computed. The standard deviation of the mean for a group of points on a number line is expressed as:

$$\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}} \qquad [1]$$

where σ is the standard deviation for the group of points and n is the number of points in the group. So, given $\sigma = 0.010$ and n=100, the standard deviation of the mean (i.e., the confidence interval for the mean) is 0.0254 mm (0.001 in.). It is also easy to see that halving the standard deviation for the group of points is equivalent to using four times the number of points. Thus, as the number of measurements increases, the confidence in the average value improves.

This concept holds true for any average, regardless of the shape of the distribution forming the average. And since the extraction of an object from a cloud of points is, in effect, an average, increasing numbers of measurements or increasing the area will improve the estimation of that surface object. Clearly, the point distribution over the surface in addition to the uncertainty of the individual measurements will affect the confidence in any estimation. This appendix derives rules of thumb for the "standard deviation of the mean" for surface objects given the triplet uncertainty, number of points, and area of measurements.

The technique used in this paper is a Monte Carlo (perturbation) method. A cloud of points representing a typical surface object, i.e., plane or hemisphere, is generated using random number generators. A random uniform distribution is used over the surface of the object, and random normal distributions are used in and out of the object's surface. Then that cloud of points is fit using a least squares method to its particular object. This process is repeated hundreds of times for a particular set of parameter, e.g., surface area, number of points, and measurement uncertainty for the cloud of points. From the hundreds of fittings the confidence for locating the surface object can be computed. For example, in the case of the plane, the separation of two planes that bound 68 % and 95 %

of all planes computed was determined (Appendix E.3-A). For the hemisphere, the radius of the sphere containing 68 % and 95 % the center locations was computed (Appendix E.3-B).

Figures D1–D3 show the results for fitting point clouds to planes. As might be anticipated, increasing the number of points and making the measurement uncertainty smaller improves the confidence in the location of the plane. Increasing the area of the plane does not increase the confidence in the location of the plane. This latter observation seems reasonable—the larger area makes the orientation of the plane more certain, while the increasing radius of rotation increases the displacement of the plane, thereby counteracting each other.

The plots labeled "theory" were empirically derived—i.e., fitting equations to the 68 % data. Thus, given the nominal planar bounds for one plot location, the planar bounds can be estimated at all other points, including the 95 % data. These equations are:

$$\sigma_{\overline{P2}} = \sigma_{\overline{P1}} \times \sqrt{\frac{n_1}{n_2}} \qquad [2]$$

$$\sigma_{\overline{P2}} = \sigma_{\overline{P1}} \times \frac{\sigma_2}{\sigma_1} \qquad [3]$$

From these equations, the effects of increasing the number of points in the cloud and improving the measurement uncertainty can be estimated. For example, increasing the number of measurements in a cloud by a factor of four halves the uncertainty of the computed plane. This is similar to the standard deviation of the mean at a point.

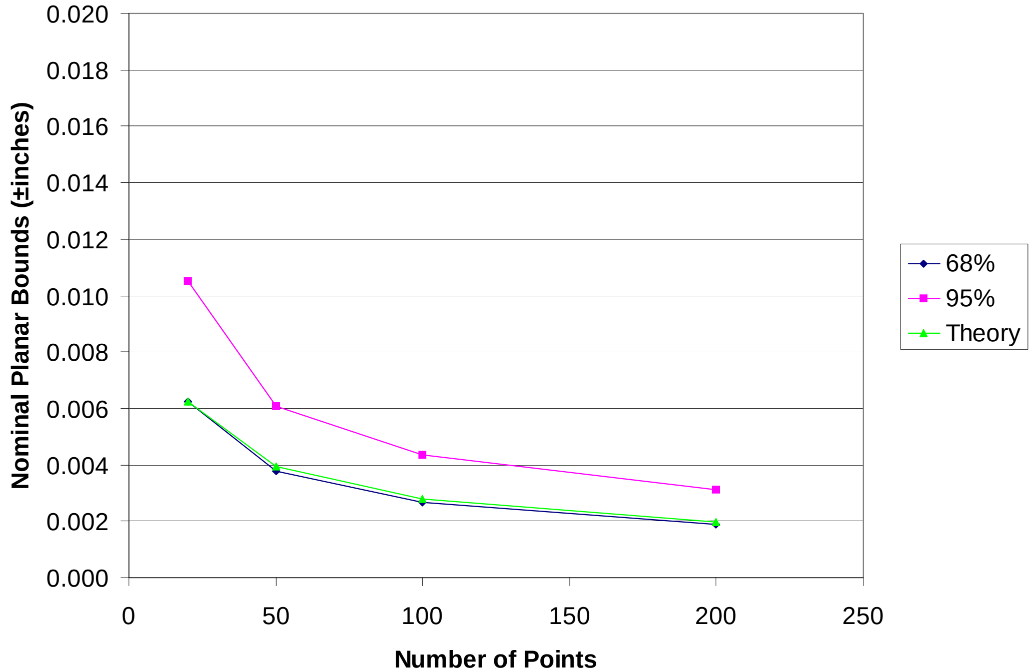


Figure D1. ±0.01 in. Measurement Uncertainty, 400 in.^{2} Area

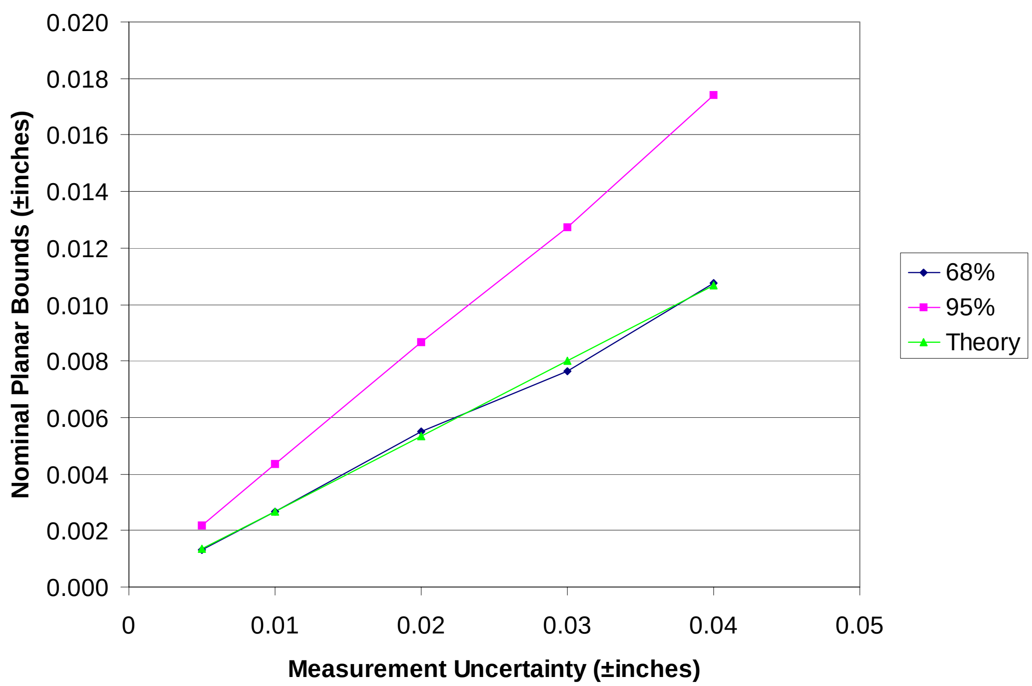


Figure D2. 100 Points, 400 in.^{2} Area

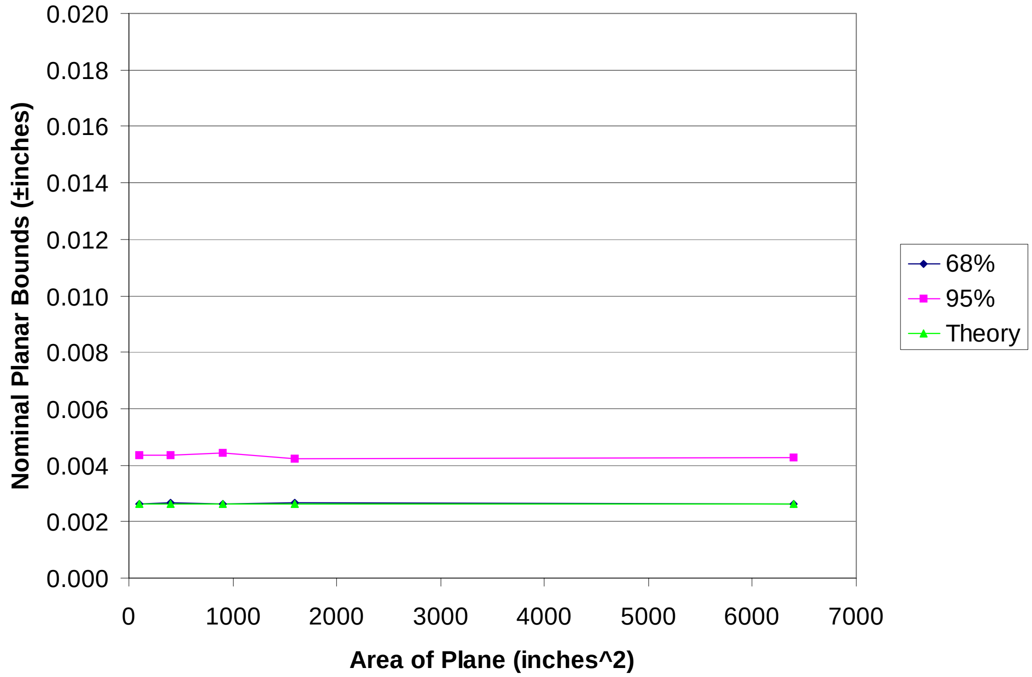


Figure D3. 100 Points, ±0.01 in. Measurement Uncertainty

It should be noted that the 95 % bounds are not twice the 68 % bounds, as might be expected for the relationship between 1-sigma and 2-sigma values. Figure D4 is a typical histogram for a set of 1000 planes with a particular set of parameters. A goodness-of-fit evaluation proves the distribution is not chi squared either, too much data are shifted toward cone axis.

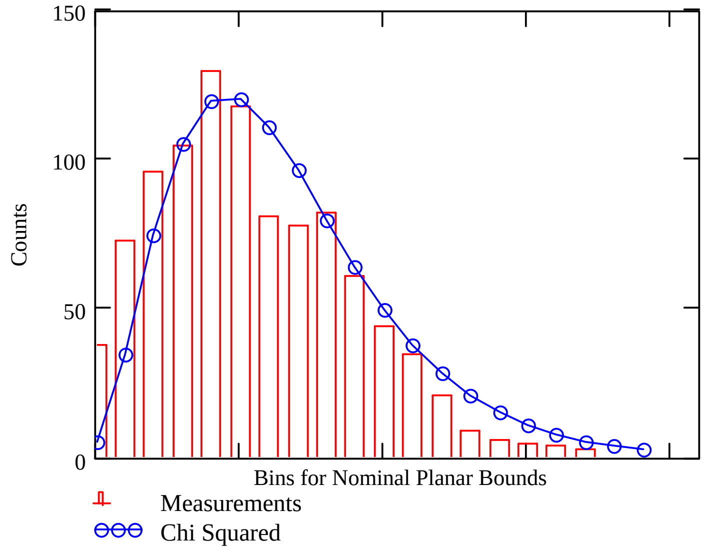


Figure D4. Typical Histogram of Bins for Bounding Planes

Figures D5–D7 show the results for fitting point clouds to hemispheres. The region of points on the hemisphere is controlled by an intersecting cone and identified by the cone angle (i.e., the angle between the cone axis and the generatrix). Again, as expected, increasing the number of points and making the measurement uncertainty smaller improves the confidence in locating the center of the hemisphere. This time, however, increasing the area of the point cloud over the hemisphere increases the confidence in the location of the center of the hemisphere.

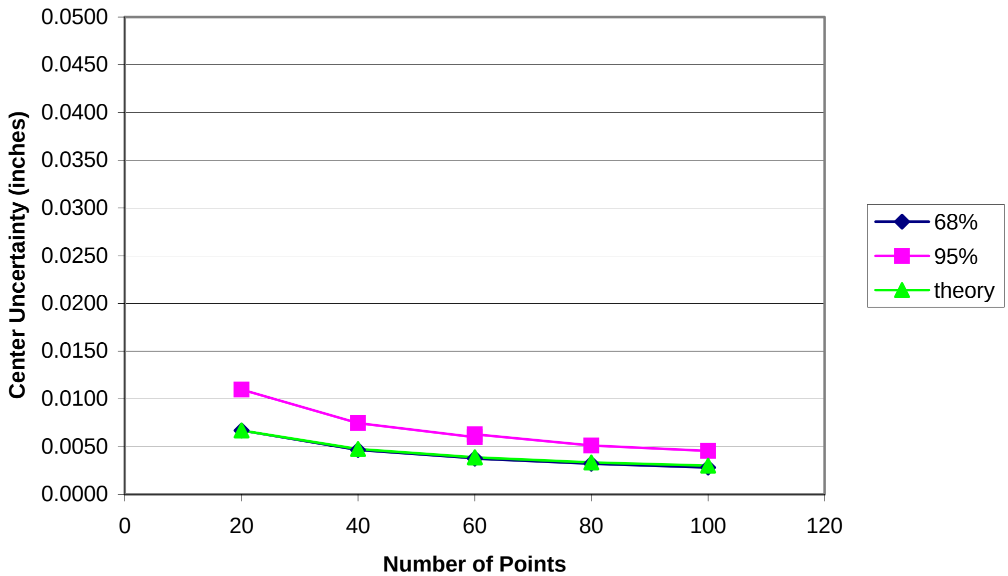


Figure D5. ±0.005 Measurement Uncertainty, 40º Cone Angle

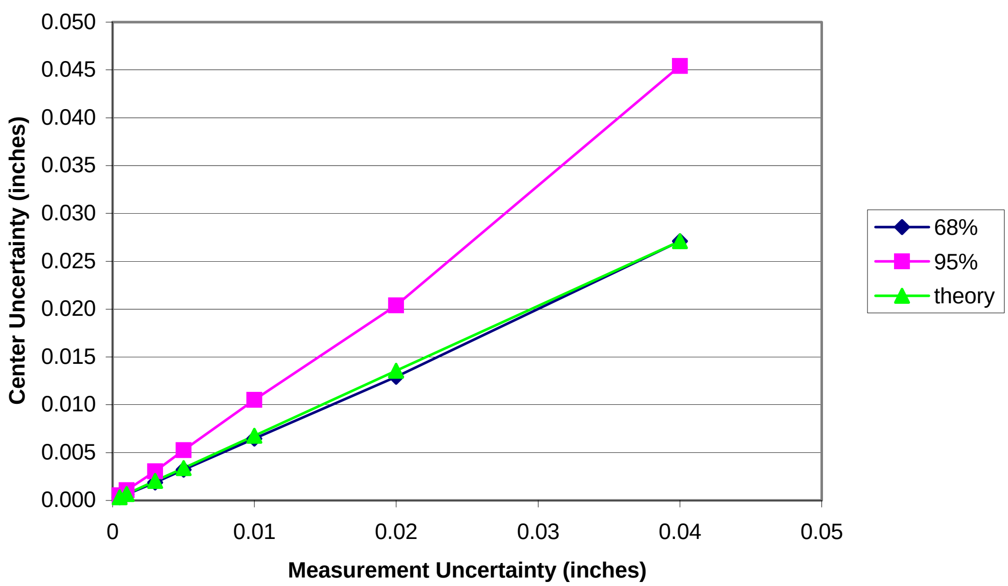


Figure D6. = 40º Cone Angle, 80 Points

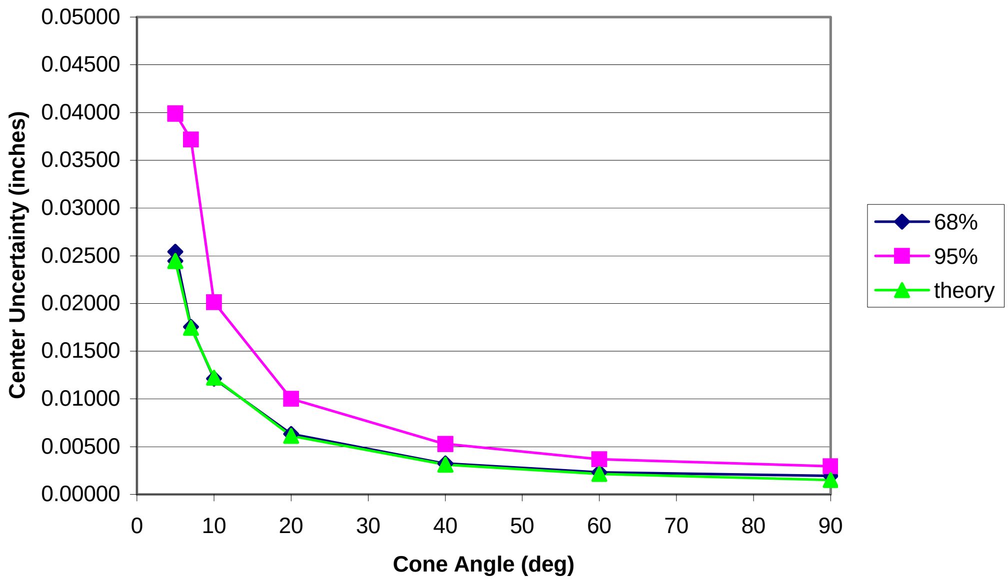


Figure D7. ±0.005 Measurement Uncertainty, 80 Points

The "theory" values were generated with the following equations:

$$\sigma_{\overline{C2}} = \sigma_{\overline{C1}} \times \sqrt{\frac{n_1}{n_2}} \qquad [4]$$

$$\sigma_{\overline{C2}} = \sigma_{\overline{C1}} \times \frac{\sigma_2}{\sigma_1} \qquad [5]$$

$$\sigma_{\overline{C2}} = \sigma_{\overline{C1}} \times \sqrt{\frac{Area_1}{Area_2}} \qquad [6]$$

where the area is computed from the zenith angle: $2\pi \cdot (\cos(0) - \cos(\phi))$. Equations [4] and [5] are the same as their corresponding equations for a plane, [2] and [3]. Increasing area decreases the uncertainty of the hemisphere center point as shown in equation [6]. It is hypothesized that the area of the surface becomes a factor as the curvature is increased. For a plane, there is no curvature, so area does not affect the outcome. Or stated another way, greater curvature causes vectors from the measured locations to the surface to have greater variation, thus improving the fitting process.

For the hemisphere, equations [4] through [6] can be combined:

$$\sigma_{\overline{C2}} = \sigma_{\overline{C1}} \times \frac{\sigma_2}{\sigma_1} \sqrt{\frac{n_1 \cdot Area_1}{n_2 \cdot Area_2}} \qquad [7]$$

This equation shows the interesting result that given an arbitrarily small region of a sphere, if sufficient numbers of points are measured, the uncertainty of the center can also be arbitrarily small! Whereas the usual thought is that measurement of small regions of a sphere cannot accurately identify the center position.

From the above, it appears that the rules of thumb are largely contained in equations [2] and [3]:

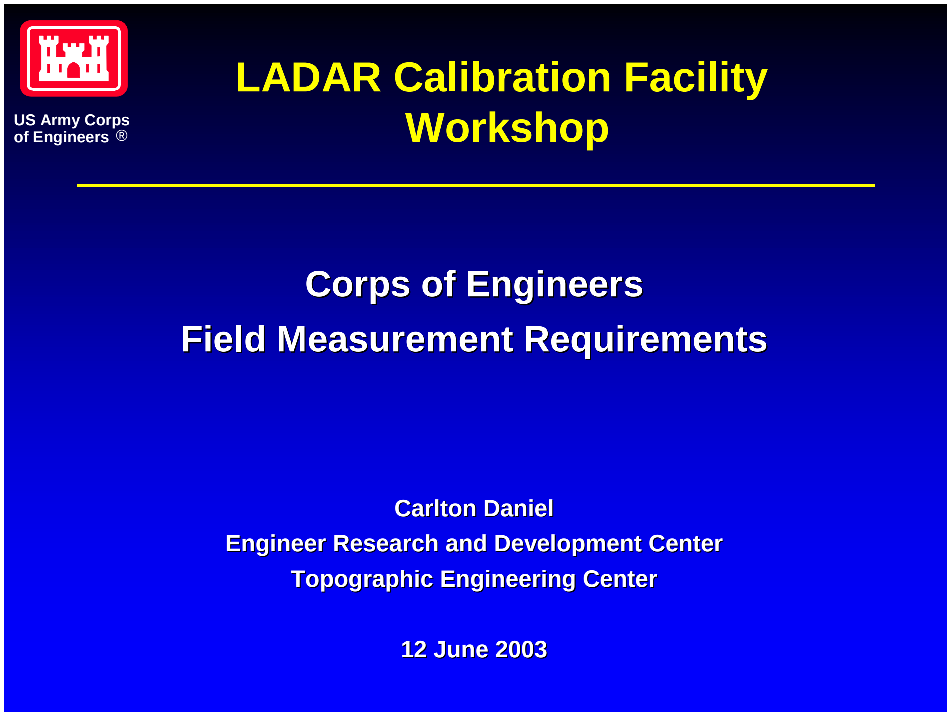
- Increasing the number of points decreases the mean location of the object by the square root of the ratio of points.
- Changing the ratio of measurement uncertainty changes the mean location of the object proportionally.

Obtaining a rule of thumb for an arbitrary surface area may not be feasible due to the confounding of area and curvature.[7] Likewise, estimating a nominal $\sigma_{\overline{SURFACE}}$ for a surface measured by a minimal number of points (i.e., n=3 for a plane, n=4 for a sphere) and unit area based on the measurement uncertainty does not appear feasible because of confounding of area and curvature.

[7] Need a little help here with ideas.

APPENDIX F: CORPS OF ENGINEERS FIELD MEASUREMENT REQUIREMENTS

by Carlton Daniel



US Army Corps of Engineers ®

Corps Civil Works Program

Provides direct public service benefits for

- Water Control Structures
- Pumping Stations
- Navigational Locks & Dams
- Hydroelectric Power Plants

US Army Corps of Engineers ®

Operations and Maintenance Challenges

- Almost half of the U.S. inland waterway facilities are nearing or extending their 50-year planned design life
- Ensuring expected performance levels will require rebuilding or replacing many existing locks, dams, hydropower and water supply facilities
- The future challenge will be to integrate and utilize laser scanning technologies and emerging calibration standards into the redesign of these structural systems

US Army Corps of Engineers ®

Port St. Lucie Lock and Dam Florida

US Army Corps of Engineers ®

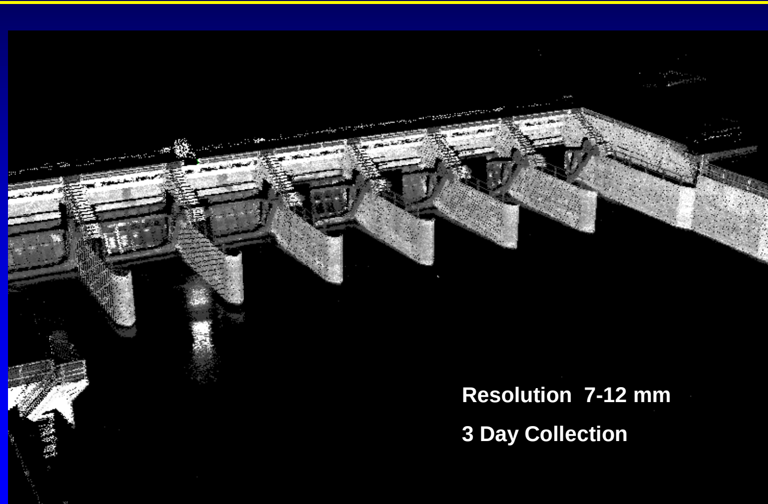
Port St. Lucie Navigational Lock

US Army Corps
of Engineers ®

Port St. Lucie Flood Gates

US Army Corps
of Engineers ®

Laser XYZ Point Cloud Image

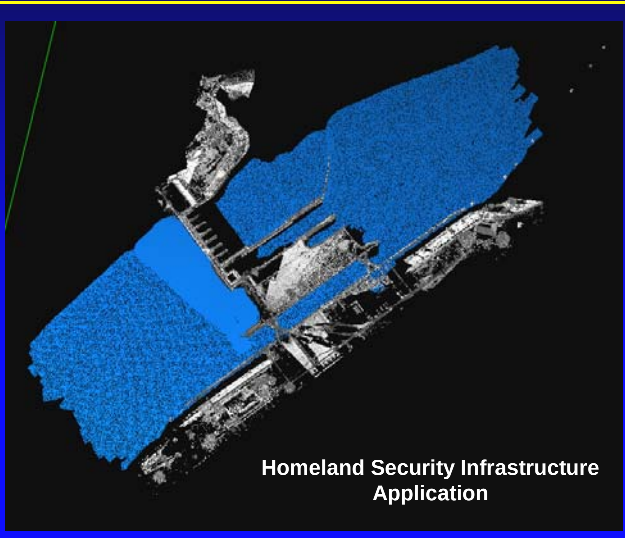


US Army Corps of Engineers ®

3-D Rendering from Laser Data

US Army Corps of Engineers ®

Multibeam Soundings & Laser Image Data Fusion



US Army Corps of Engineers ®

Historical Preservation

US Army Corps of Engineers ®

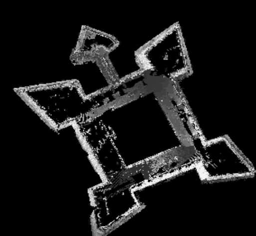
Laser Scanning Operation

US Army Corps of Engineers ®

All Scans Referenced to XYZ Geodetic Coordinates

US Army Corps of Engineers ®

Three Dimensional Point Cloud Data

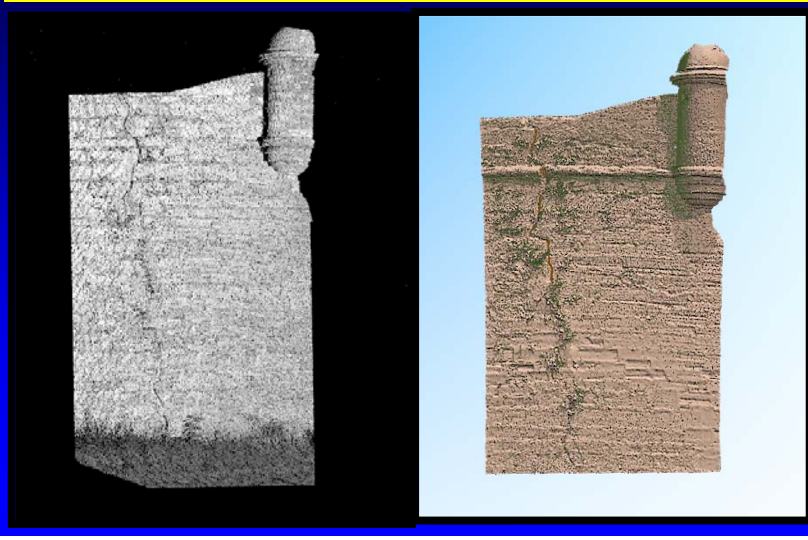


1.5 Day Collection

20 Million Data Points

US Army Corps of Engineers ®

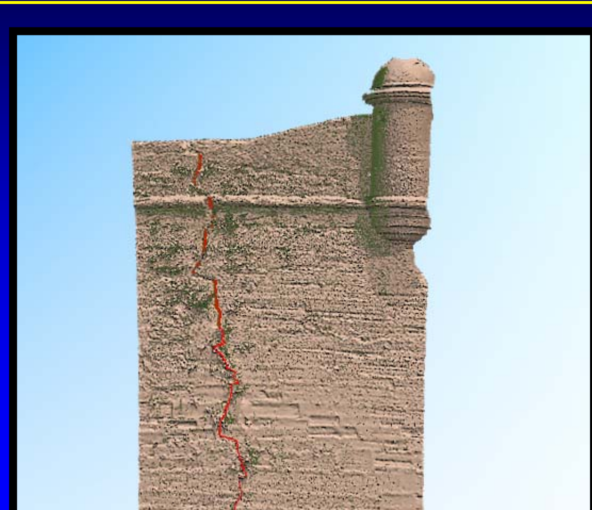
7 mm Resolution Scanned and Rendered Image



US Army Corps of Engineers ®

Structural Assessment

- Length 26 Ft.
- Average width 2.5 In.



US Army Corps
of Engineers ®

Conclusions

- Laser scanning technologies are expediting results and increasing completeness of coverage
- Calibration standards will improve the effectiveness of a wide range of field measurement requirements
- Using laser scanning technology to redesign and rebuild inland waterway facilities will significantly reduced future operational field costs

APPENDIX G: METRICVISION FACILITY FOR CALIBRATION OF 24 m FREQUENCY MODULATED COHERENT LASER RADAR

by Dave Dozor

NIST LADAR Calibration Workshop

MetricVision Facility for Calibration of 24m Frequency Modulated Coherent Laser Radar

June 12-13, 2003

Gaithersburg, MD

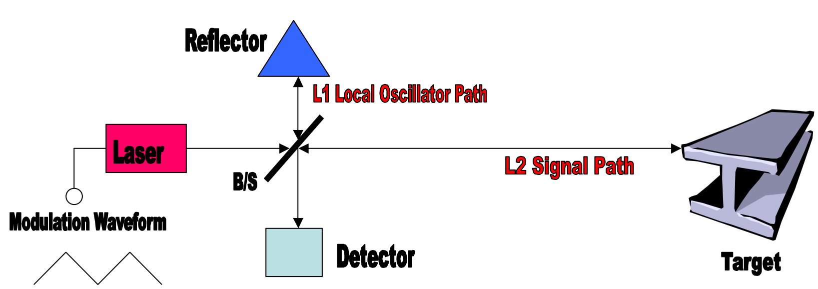
Overview

- FM Coherent Laser Radar
- MV200 Product
- Temperature Controlled Laboratory
- Range Calibration/Verification
- Angle Calibration/Verification
- Future Needs for Calibration

FM Coherent Laser Radar

- MetricVision Laser Radar uses:
  - An Infra-Red (λ_{nom}=1550nm) Laser Diode
    - Frequency Modulated about $f_{nom} = c/\lambda_{nom}$
    - Modulation is linear
  - Local Oscillators of controlled length
    - Used to compare with Measurement arm
  - Reference Arm of controlled length
    - Used as an internal "reference length"
  - Detectors

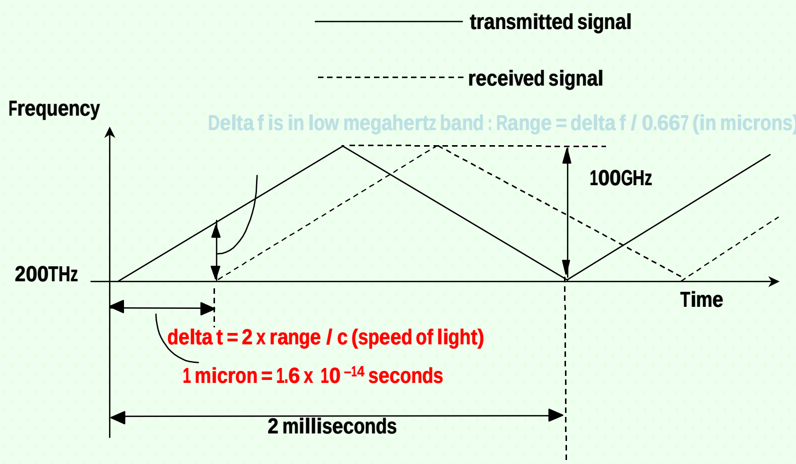
Basic FM Laser Radar Concept



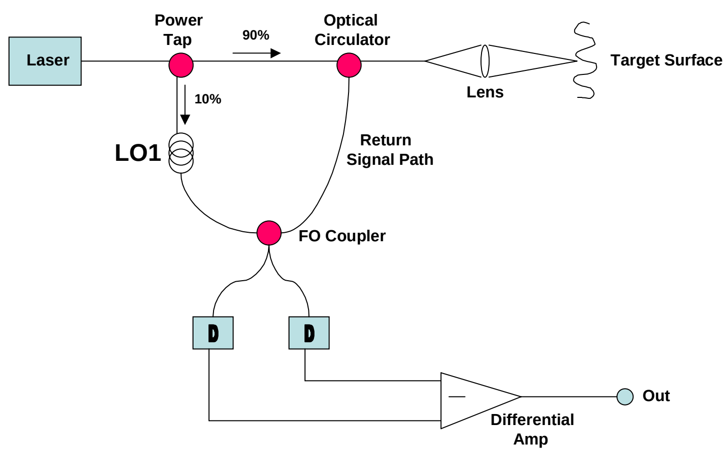
Laser frequency (wavelength) is linearly modulated. The light from the two paths of different length are heterodyned. The resulting difference frequency is proportional to the OPLD (and therefore range).

Optical Path Length Difference: OPLD = 2*L2 - 2*L1

Laser Tuning/Chirping

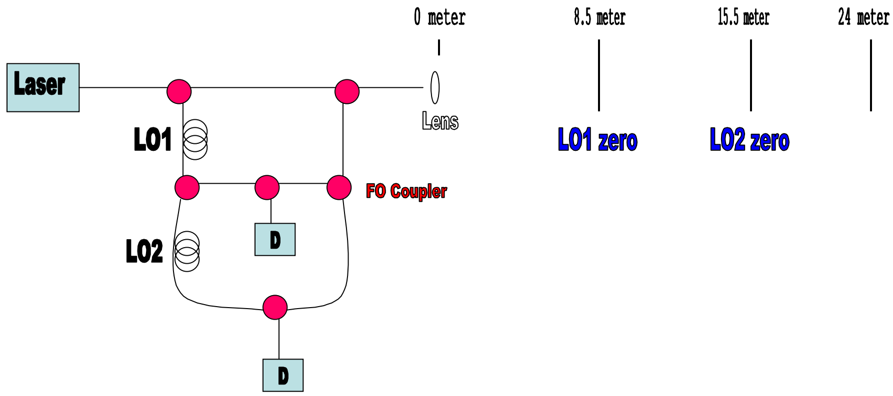


Basic FM CLR Configuration

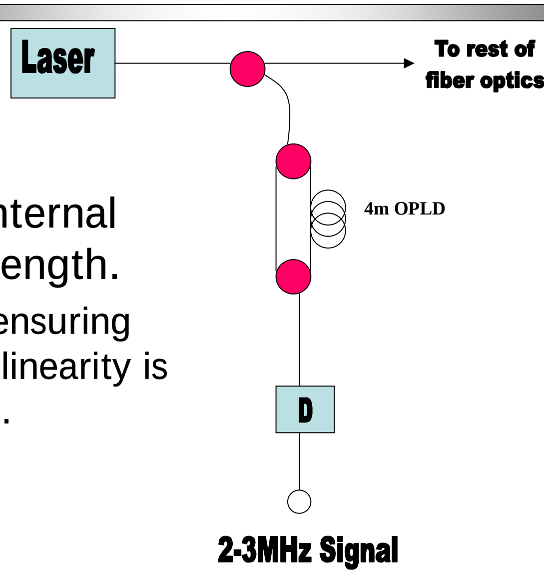


Enhanced FM CLR Configuration

- Diode Lasers are not single wavelength sources.
  - Places a limit on the practically measurable range.



The Reference Arm



- Serves as Internal Reference Length.
  - Useful for ensuring laser chirp linearity is maintained.

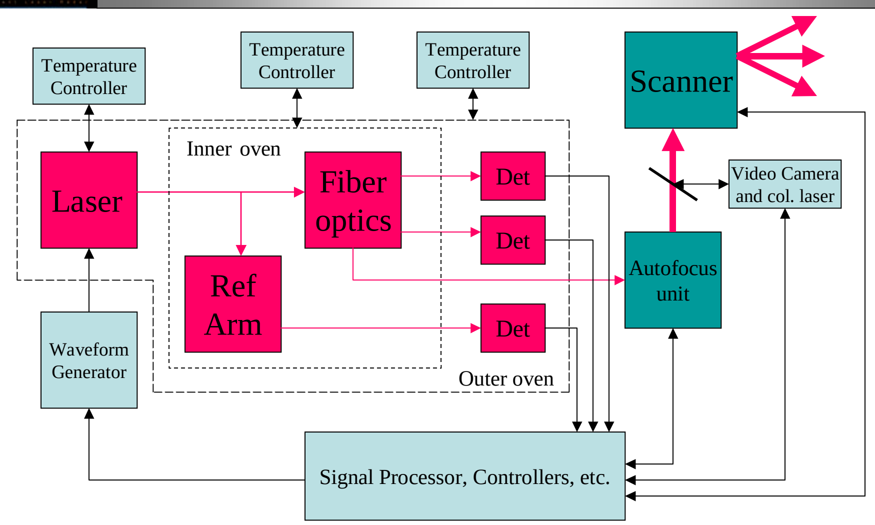
The Laser Radar System

- Basic Concept provides:
  1) Single transmit and return path, no shadowing
  2) Non-contact measurements off any surface
  3) Simultaneous range and velocity measurements
  4) Precise measurements (micron precision)
  5) Immunity to background lighting

2), 3) Coherent Detection

4), 5) Large Tuning BW

Photonics Block Diagram



FM Laser Radar Product

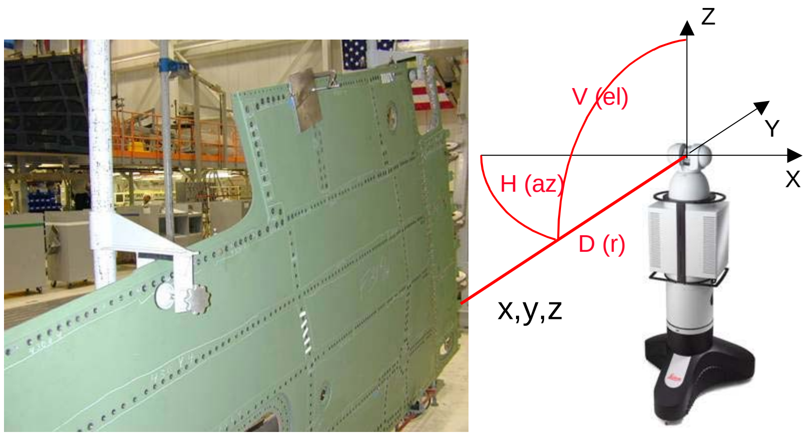
- Prior diagram indicates;
  - Need for Temperature Stability
  - Need for Beam Focusing
  - Need for Beam Pointing
- Other affects must also be compensated.
  - Temperature, Humidity, and Pressure of air.
  - Pointing and Focusing imperfections.
    - PMA and AF Kinematics (Angle Compensation)

MV200 Product

- Final Integration:
  - PMA
  - Laser Radar
  - IOA/Autofocus
- Must compensate for non-ideal integration
- 3-D Prec.<2ppm$_{rms}$
- 5°C < T_{op} < 40°C
  - Temperature Comp'd

MV200 Basic Principles

- MV200 acquires (R, Az, El) data to <2ppm$_{rms}$ precision.



MV200 Basic Principles

- Range, Azimuth, Elevation (spherical) Data must be corrected before conversion to X,Y,Z (cartesian) 3-D coordinates.
  - Range comp'd for:
    - Temp., Humidity Press.
    - LO length settings
    - LO1, LO2 cross-over
  - Azimuth, Elevation comp'd for:
    - Temperature
    - Machine Kinematic Parameters

Range Compensation

- Index of Refraction (n) of Air (Meas. Arm)

$$\left.\frac{\partial n_{air}}{\partial T}\right|_{P,RH} \cong 1ppm$$

$$\left.\frac{\partial n_{air}}{\partial P}\right|_{T,RH} \cong 0.3ppm$$

$$\left.\frac{\partial n_{air}}{\partial RH}\right|_{T,P} \cong 0.01ppm$$

  - Above are approximate figures (rules of thumb)
  - T in °C, P in mBar, RH in %

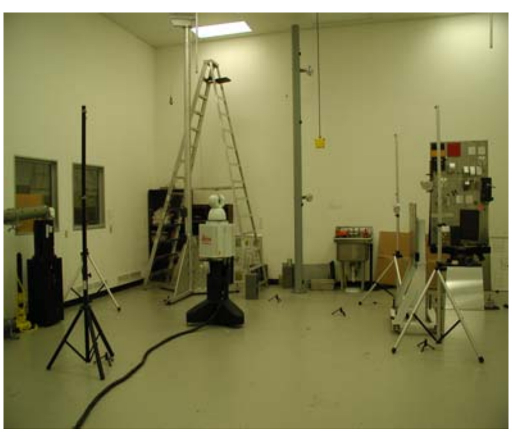
Angle Compensation

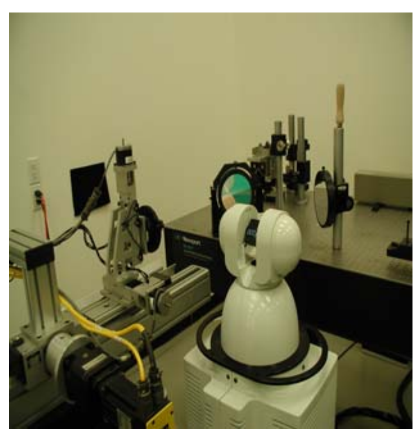
- At constant temperature, parameters:
  - Perpendicularity of axes
  - Coincidence of axes
  - Encoder cycle error
  - Many others
- These parameters are determined at a set of temperatures and "scheduled" based on RTD feedback.

Temperature Controlled Lab

- MetricVision’s Temperature Controlled Lab
  - Volume: 22,000 ft^3 (623 m^3)
  - Class: 100,000
  - Temp Rng: 50°F to 110°F (10°C to 43°C)
  - Temp Tol.: ±0.5°F (0.3°C)
  - Personnel: 8 people (max)
  - Heat Load: $50kW_{max}$ ($36HP_{max}$)
  - Humidity: ≅±5% (Estimate/Not Controlled)
  - Pressure: ≅±2mbar (Estimate/Not Controlled)

Temperature Controlled Lab





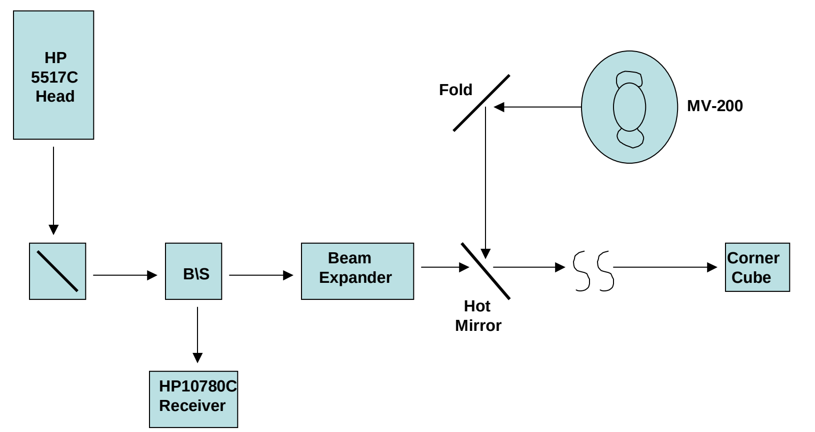
Range Calibration

- Range is calibrated against an Environmentally compensated:
  - Hewlett-Packard 5517C Head (He-Ne Tube)
  - Hewlett-Packard 10780C Receiver
- Laser Radar and Beam expanded HeNe are retroreflected off of a movable platform and compared at various ranges.

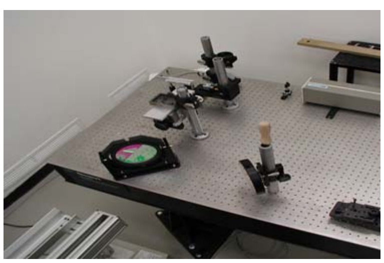
Range Calibration Parameters

- The range calibration parameters are used to calibrate the photonic circuit.
  - $L_{reference\_arm}$ (4.0m EOWA typ.)
  - $L_{local\_oscillator\_1}$ (8.5m EOWA typ.)
  - $L_{local\_oscillator\_2}$ (15.5m EOWA typ.)

Range Calibration Set-up



Range Calibration Photo

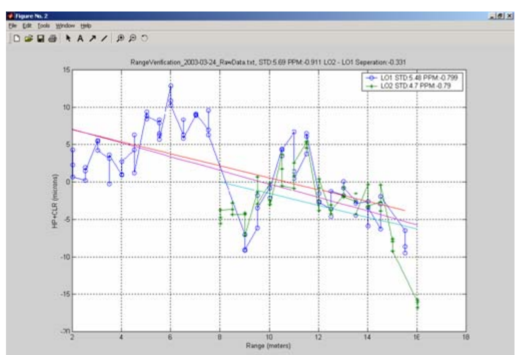


Range Verification

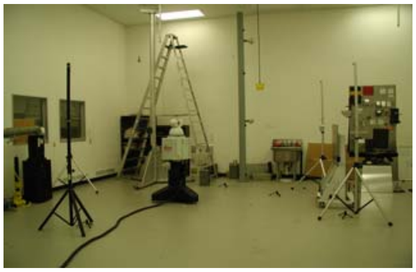
- The Range Calibration must be verified over the operating range.
  - Data is collected on LO1 and LO2 and compared to the HeNe Interferometer Data.
  - 2 – 16m at 0.5m intervals
- Figures of Merit include:
  - STD (RMS error to HeNe $\Rightarrow$ All sources included)
  - PPM (slope wrt HeNe $\Rightarrow$ uncorrected systematic error)
  - Sep (average seperation between the Los)
- STD must be less than 12.5um over full range

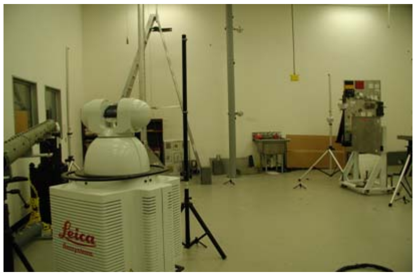
Range Verification Results

- A Typical FM CLR
  - STD = -5.69um
  - Slope = -0.911ppm
  - Sep. = -0.331um
- Range Verification for:
  - Unit 35



Angle Compensation Photo





Angle Compensation

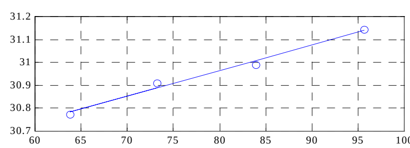
- Angle Compensation purpose:
  - Determine mechanism kinematic parameters.
- Utilizes ranging ability of the FM CLR to measure tooling balls.
  - Based on interball distance being constant:
    - Geometry can be used to find parameters
  - Various views are recorded and model applied
    - Results show corrected interball distances

Angle Compensation

- This Extensive Angle Comp is performed at various temperature to schedule the parameters.
  - Most parameters exhibit no temp dependence
  - The slope is determined for others
  - Our embedded software compensates

Angle Comp/T-dependence

- Top plot shows:
  - Perp of axes (SN33)
  - 200nrad/°F
  - Very good fit
- Bottom plot shows:
  - Max error ~0.5µrad



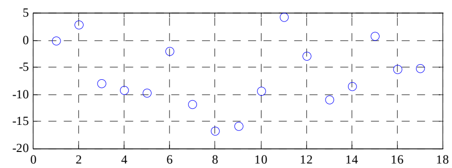
Angle Verification Photo

Angle Comp Verification

- After compensating, verification is done
  - Performed over a range of temperatures
  - Performed on 5 to 8 views
- Interball distances computed to assess
  - With calibrated/compensated CLR
    - End-on ball pipe measurement to get “truth”
    - Comparison with measured interball distances
  - Must show <50µm RMS error over all meas.

Angle Comp Verification

- Top plot shows:
  - RMS error = 11µm
  - Max error = 31µm
- Bottom plot shows:
  - Error before comp
- View centered at:
  - (Az,El) = (45°,-69°)
  - Range ≅ 3m
- One View/One Temp



Summary of Calibration Facility

- MetricVision has established a Laser Radar Calibration Facility.
  - Used for Calibration and Verification of MV200 Large-Volume Coordinate Metrology Instrument
  - Temperature Controlled in 8 zones to 0.5°F
  - Utilizes a HeNe Reference and Constant interball distance artifacts for calibration of instrument for 3D measurements.

Next-Gen LADAR Facility

- Range Calibration over full (Az, El)
  - Precision Electromechanics to position scanner
- Very Large, Accurate Truth Model
  - ~15m radius artifact with appropriate features
  - Scanner can measure in/out at diff locations
- Rail Upgrades (longer, lateral motion trim)
- Non-vertical Position Calibration
- Larger Temperature Range on Facility

Next-Gen LADAR Facility

- Range Precision vs. Reflected Energy
- Continuous Range Monitoring
- Environmental & Seismic Effects
  - Air Turbulance
  - Temperature Gradients
  - Vibration Amplitude and Frequency effects on LADAR (chirp frequency, doppler, etc.)

APPENDIX H: CALIBRATION VERIFICATION FOR LONG RANGE TRIPOD-BASED TERRESTRIAL LASER SCANNERS

by Eric Martin

Optech

Abstract / Intro

- Terrestrial laser scanners, like all pieces of measuring equipment rely on the manufacturer's calibration process to ensure the product meets specification at the time of shipment.
- While the actual calibration procedures may vary between manufacturer, users can verify instrument calibration in the field, providing they understand the scanner requirements, and have the proper facilities and tools available.

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Abstract / Intro

- This presentation will address the important calibration attributes as they pertain to long range terrestrial laser scanners (>150m) range, and outline the field procedures that can be employed by a typical user to verify the calibration state of any particular scanner.
- This procedure is not meant to be used as with a type or brand of scanner; rather it can be adapted to serve the needs of a wide variety of products currently available.
- It is based on a practical rather than theoretical approach.

Tripod-based Terrestrial Laser Scanners

- General attributes – Long range (several hundred to >1000m range), cm to mm accuracy, various classes of eyesafety.
- Typically send a Light pulse (vis or IR) through a beam steering system, direct it to a target, collect and focus the scattered return to a receiver / detector.
- For time-of-flight systems, a time interval is calculated and the range is computed from the known speed of light for the wavelength used at a given atmospheric condition.
- No matter what the complexity of the system, most scanners of this class have a single common element – they produce XYZ point cloud data from diffuse surfaces, and include a measure of intensity of the signal return.

Major Markets for Tripod-based Terrestrial Scanners

- Used primarily to scan either:
  - Engineered structures
    - Bridges, Roadways, Buildings, Dams, Towers, or Process Plants
  - Landscape / Terrain
    - Open pit mines, golf courses greens / fairways, urban planning, DTM / DEM applications.

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Chief Attributes

- Tripod based terrestrial lidar systems are not designed for a single fixed range
  They have hundreds or even thousands of meters of ranging capability
  Their versatility is extended by being able to operate at relatively short range (indoor applications)

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Chief Attributes - Differences From Conventional Instruments

- Total stations are typically the first instruments that come to mind when thinking of a method to verify scanner calibration.
  Although most scanners do use 2 angles and a range as their source polar data, they do not output this in a useable format.
- The format that is output, used and manipulated by the customer are Cartesian XYZ point clouds.
- In addition, totalstations do not record the intensity of the return (as intended to be processed as part of a point cloud), which is oftentimes a very valuable element of a laser scanner's output.

Data Output

- It makes the most sense for users to confine their analysis to the XYZi or XYZRGB Cartesian output from a laser scanner.
- It is the fundamental output from the scanner, It is the only data used in post processing, and direct cross-comparisons between scanner types can be made regardless of the make, model or architecture.
- Cartesian output is not dependent on the internal architecture of the hardware; future scanners deploying non-traditional technologies can be evaluated and compared directly to legacy systems.

Accuracy Elements

- Accuracy (as defined by the manufacturer) is the single most significant element of calibration requiring verification. It is non-trivial to assess accuracy of such scanning system, due to a large number of factors that are not present in conventional instruments. These error sources include

  Angular, long range,large image space, variations in material reflectivity, beam incidence to the target, etc…

Definition of Terms

- Rather than apply generic or statistical definitions to these terms, the ones below are defined to best address the condition that applies in to a laser scanner in actual field use conditions.
- They are based on analysis of the full amount of data produced by the system, using the available analysis tools. Bearing this in mind, the following definitions apply to ILRIS-3D in typical field use.

Target Registration Accuracy

- The RMS error of scan comparing scanner derived target locations to corresponding survey locations.
- The total error is the sum of all of the error of the instrument, and includes all error groundtruth as well. This is expressed as a sphere of error in XYZ space.

  This is a foundation element in dealing with scanner accuracy, as it typically has the most significant effect when scanning over large field-of-view and large dynamic ranges.

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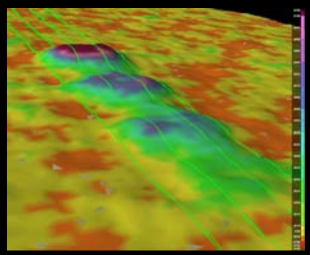
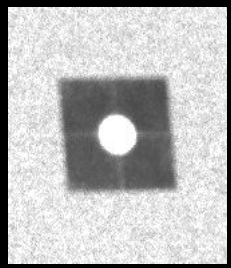
Other Terms (cont'd)

- *Modeling Accuracy*
  - The error in 3D object reconstruction (real vs reconstructed). May include multiple scan alignment errors, and may be based on either primitive or surface (polygonal) modeling.
- *Resolution*
  - The minimum distinguishable feature in all 3 dimensions (or in a direction specified by the manufacturer).





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Other Terms (cont'd)

- *Precision*
  - Measure of consistency in output. Just as a chronometer can keep very good time, and is therefore precise, if it is offset from the atomic timeserver by some bias error, it is not accurate. So too can the output from a scanner can be very precise but have a bias error that affects its accuracy

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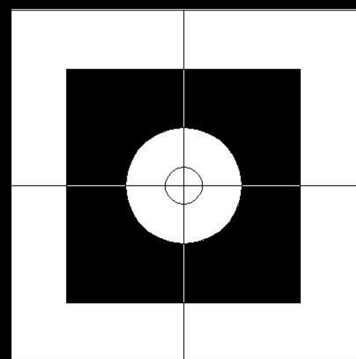
Typical Indoor Target Wall – Attributes and Procedure

- Targets used must conform to the manufacturer's recommendation
  Targets are very accurately surveyed by traditional means, and processed into XYZ Cartesian groundtruth.



- User mounts scanner at a point that allows for the scan to cover the instruments entire field of regard

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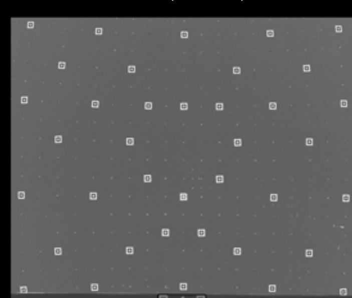
Method of Verifying Target Registration Accuracy

- *Indoor Facility*
  Many indoor facilities already exist for calibrating 2D cameras. With additional modifications, the same facilities can be used as a partial verification of scanner calibration
- They can be made to address other issues such as angle of incidence of beam to target, as well as range / intensity errors due to material reflectance (color).



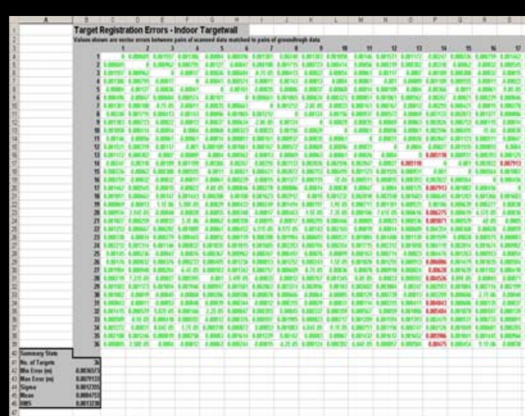
Data Collection and Analysis

- The manufacturer's supplied software is used to extract and compute the centroid of the target locations based either on intensity, geometry, or both.
- Target centroids from scanner (coordinate system A) are then compared with survey data (coordinate system B) by one of 2 methods

	A	B	C	D	E	F	G
1	Survey Coordinates			Target Number	Scanner Coordinates		
2	975.296	1033.345	102.8185	107	-7.1583	49.27624	-3.44275
3	974.4452	1032.961	104.2426	109	-8.10749	49.43924	-2.03358
4	975.3555	1033.357	104.2666	110	-7.11651	49.45157	-2.00324
5	975.3547	1033.369	106.5816	111	-7.13201	49.75393	0.292347
6	974.4677	1032.98	106.6037	112	-8.10331	49.74834	0.306826
7	981.6755	1034.152	113.2288	122	-1.07853	48.81769	7.172873
8	976.6299	1031.915	106.3563	123	-6.53102	47.89778	0.305569
9	980.4254	1033.587	104.263	128	-2.36289	47.68354	-1.73717
10	980.4258	1033.589	105.2429	129	-2.36827	47.80681	-0.76409
11	980.4384	1033.596	106.1101	130	-2.36416	47.91673	0.097853
12	980.3416	1035.566	106.3201	131	-1.67594	49.77769	0.08205
13	981.1917	1035.94	106.3299	132	-0.75196	49.79157	0.096887
14	981.2134	1035.939	104.3024	133	-0.71158	49.53348	-1.91633
15	980.2331	1035.503	104.295	134	-1.78536	49.50807	-1.93036
16	984.0301	1033.438	103.0287	145	0.901398	45.98118	-2.73449
17	984.8125	1035.53	112.9334	154	2.344776	48.81561	6.905362
18	986.3123	1036.174	104.2406	174	4.066215	47.74414	-1.70384
19	985.0993	1037.649	104.3074	175	3.529551	49.57114	-1.87186
20	984.2763	1037.286	104.2529	176	2.635033	49.55283	-1.93285
21	984.2491	1037.285	106.2301	177	2.587547	49.81296	0.028017
22	985.1914	1037.696	106.1864	178	3.614107	49.81181	-0.00598
23	986.3128	1036.174	106.3236	179	4.042927	48.00133	0.363253
24	989.9886	1039.813	106.6811	181	8.8567	49.93555	0.52926
25	990.888	1040.207	106.591	182	9.84028	49.93146	0.441061
26	990.962	1040.24	104.297	183	9.943687	49.64213	-1.82964
27	989.9625	1039.795	104.2776	184	8.848544	49.62377	-1.85879
28	990.881	1040.205	102.622	187	9.869857	49.42716	-3.49266
29	978.4036	1033.818	114.7978	1x1	-4.23552	49.98279	8.570018
30	983.2722	1035.437	115.0325	1x2	0.878858	49.58817	8.902187
31	987.6435	1037.892	114.8003	1x3	5.860096	50.08525	8.656613

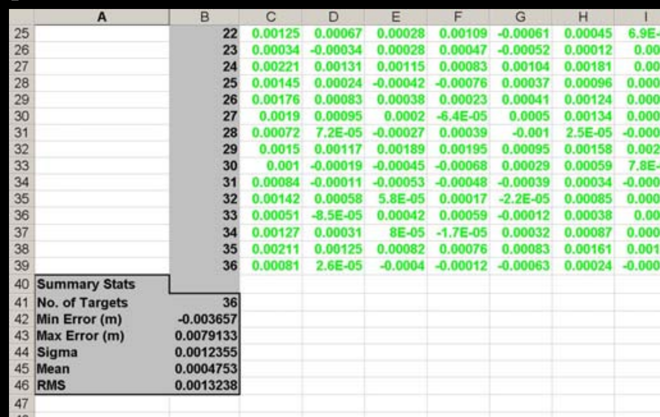
Data Collection and Analysis (cont'd)

1) Resection
   - Resecting coordinate system A-B (or B-A) using a least-squared adjustment on all targets
2) Vector Comparison
   - Leaving the datasets in their native coordinate system, and comparing pairs of points in one set to corresponding pairs points in the other.



Data Collection and Analysis (cont’d)

- Whichever method is used, the following criteria should be analyzed to ensure it falls within the manufacturer’s specs:



	A	B	C	D	E	F	G	H	I
25		22	0.00125	0.00067	0.00028	0.00109	-0.00061	0.00045	6.9E-0
26		23	0.00034	-0.00034	0.00028	0.00047	-0.00052	0.00012	0.000
27		24	0.00221	0.00131	0.00115	0.00083	0.00104	0.00181	0.001
28		25	0.00145	0.00024	-0.00042	-0.00076	0.00037	0.00096	0.0002
29		26	0.00176	0.00083	0.00038	0.00023	0.00041	0.00124	0.0008
30		27	0.0019	0.00095	0.0002	-6.4E-05	0.0005	0.00134	0.0007
31		28	0.00072	7.2E-05	-0.00027	0.00039	-0.001	2.5E-05	-0.0003
32		29	0.0015	0.00117	0.00189	0.00195	0.00095	0.00158	0.0020
33		30	0.001	-0.00019	-0.00045	-0.00068	0.00029	0.00059	7.8E-0
34		31	0.00084	-0.00011	-0.00053	-0.00048	-0.00039	0.00034	-0.0001
35		32	0.00142	0.00058	5.8E-05	0.00017	-2.2E-05	0.00085	0.0003
36		33	0.00051	-8.5E-05	0.00042	0.00059	-0.00012	0.00038	0.000
37		34	0.00127	0.00031	8E-05	-1.7E-05	0.00032	0.00087	0.0005
38		35	0.00211	0.00125	0.00082	0.00076	0.00083	0.00161	0.0012
39		36	0.00081	2.6E-05	-0.0004	-0.00012	-0.00063	0.00024	-0.0001
40	Summary Stats								
41	No. of Targets	36							
42	Min Error (m)	-0.003657							
43	Max Error (m)	0.0079133							
44	Sigma	0.0012355							
45	Mean	0.0004753							
46	RMS	0.0013238							
47									

Typical Outdoor Facility

- Chosen correctly, Outdoor facilities have the advantage of increased range, wider dynamic range and use of oblique surfaces, and provide real-world field operating conditions.

- Data collection and analysis is typically the same as des

Calibrated EDM Baseline

- Calibrated EDM baselines have the advantage of having very accurate (sub-mm) slope distances over greater ranges, and typically serve as total station calibration checks.
- Typical baselines certified by government are in the 200-500m range employing 4 to 6 reference pillars.

Ontario Ministry of Natural Resources

EDM Baseline Utility

- An EDM baseline is not a replacement for target registration accuracy verification, but has complimentary advantages, as a calibrated EDM baseline can be used to:

  1) Identify errors over a longer range than can be typically found elsewhere

  2) Identify errors in the scanner zero position, by setting up over a known point

EDM Baseline – Attributes

- Monuments consist of 12” dia. concrete pillars anchored 6’ below grade spaced over several hundred meters
- Bronze cap with 5/8-11 UNC screw thread mounted on top for positive target center.
- Very accurate known slope distance between pillars

EDM Baseline – Typical Procedure

- Position targets on center over monument
- Set instrument on center over reference pillar
- Scan an area bounded by the target
- Analyze data using appropriate software tools.

EDM Baseline – Data Analysis

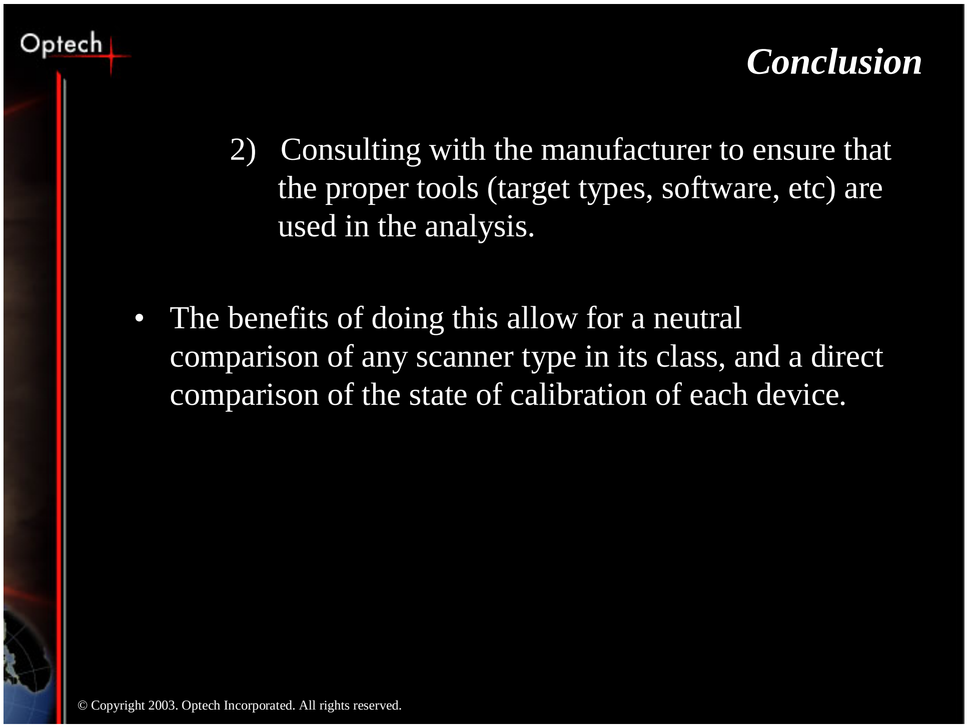
- Slope distance corrections must be made to compensate any height deltas between the target end and the reference scanner if they are present
- Two sets of comparisons can be made
  - Slope groundtruth error from the absolute scanner position to target
  - Slope groundtruth error from relative from one target to the next.

Absolute Range Error Summary										
Nominal Range (m)	Polar			Cartesian				Groundtruth and Errors	
	R-TFF	R-TFF'	Delta	X	Y	Z	R	Groundtruth Slope Range	Error from Groundtruth Slope (mm)
72	7272.516602	72.61332258	0.057477416	-4.97976	72.46915	2.068031	72.66948	72.6708	1.3
154	0	-0.111843436	0.111843436	0	0	0	0	153.9696	
226	22669.64648	226.5846214	-72.6152214	-15.5442	225.9975	7.03934	226.6408	226.6402	-0.6
Relative Range Error Summary									
							153.9713	153.9696	-1.7

Conclusion

- Although long-range tripod based terrestrial laser scanners share some common attributes, the actual procedure for calibration varies to address specific elements of each system.
  - However, all systems provide a common data product - Cartesian XYZ point cloud data. Users of any system should be able to readily validate the scanner's calibration condition by a combination of:

    1) Understanding the specification being tested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Conclusion
2) Consulting with the manufacturer to ensure that the proper tools (target types, software, etc) are used in the analysis.
• The benefits of doing this allow for a neutral comparison of any scanner type in its class, and a direct comparison of the state of calibration of each device.
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measurement at the
speed of light