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MacKinnon, David Kenneth

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NRC Experiments for ASTM E57.02 Medium Range Measurement Error Standards Development

David MacKinnon, Ph.D., P.Eng.
NRC Canada: Measurement Science and Standards
ASTM E57 Executive Committee member

July 24, 2014

Executive Summary

- Standards are needed to ensure…
  - …that materials, products, processes, and services are fit for their intended purpose(s), and
  - …that personnel are competent
- Standards for non-contact 3D imaging systems are slowly beginning to emerge
  - ASTM standards for medium-range (2 to 150 m range) systems under development
  - ISO active in non-contact CMM and laser tracker standard development
- The National Research Council Canada (NRCC) has been working closely with NIST and other partners in the development of two proposed ASTM standards for medium-range 3D imaging systems

Presentation Format

- Background on NRCC and ASTM
- Importance of standards for non-contact 3D imaging systems
- Current status of 3D imaging standards development
- NRCC contributions to ASTM medium-range standards development
- Concluding remarks
- Questions

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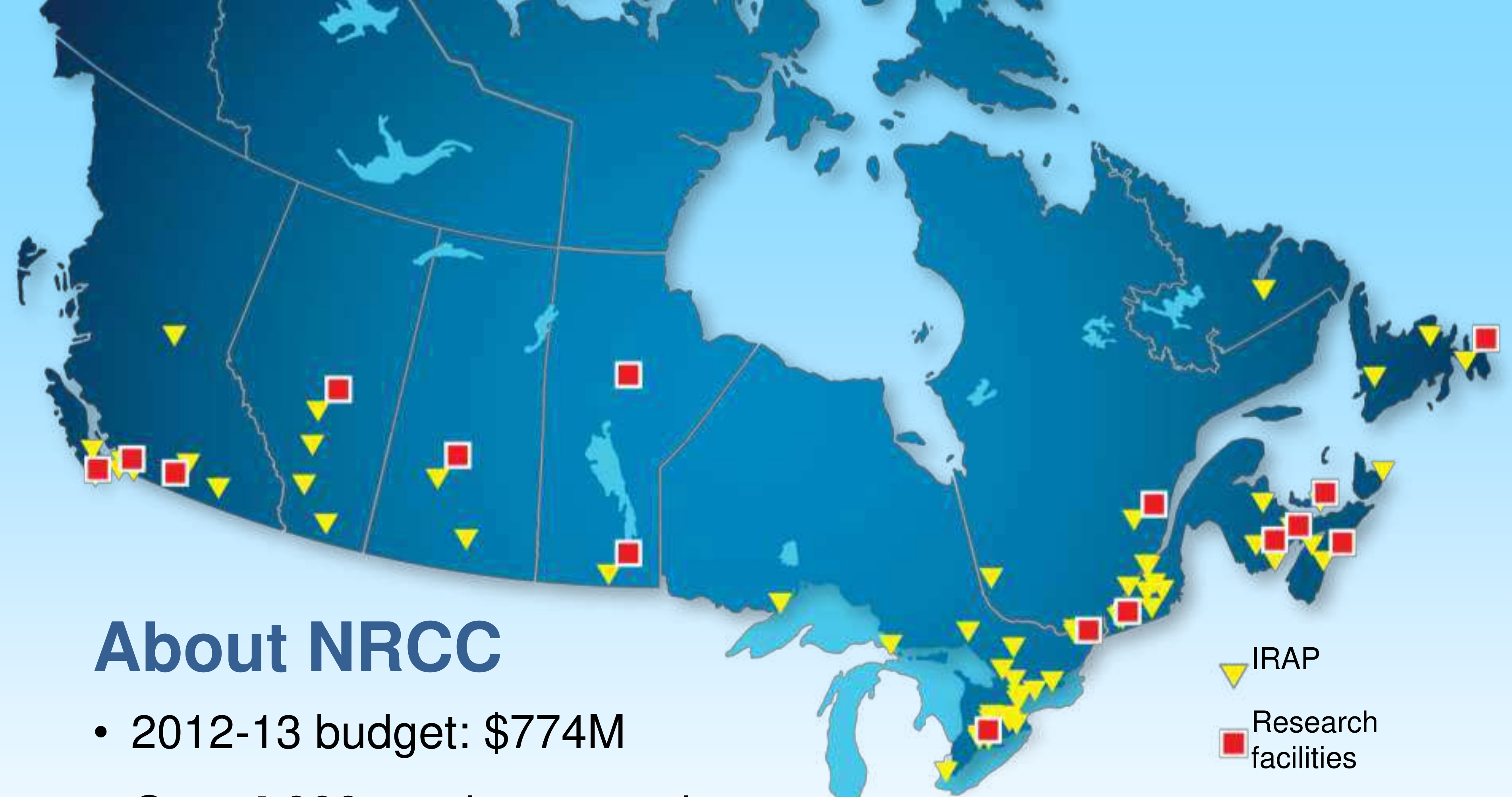
About the Presenter

David MacKinnon

- Research Officer with Measurement Science and Standards at NRC (Canada's National Measurement Institute)
- Ph.D. Systems Engineering, B.Sc. Mathematics, Professional Engineer
- 20+ years experience in statistical analysis and 10+ years experience with 3D imaging systems (development, modelling, metrology)
- Recording Secretary of the ASTM E57 Executive Committee

National Research Council of Canada



About NRCC

- 2012-13 budget: $774M
- Over **4,000** employees and
  650 volunteer and independent visitors
- Wide variety of disciplines and broad array of services and support to industry

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Organizational Structure

DIVISIONS / **PORTFOLIOS**

Emerging Technologies
- Information and Communications Technologies
- Measurement Science and Standards
- National Science Infrastructure
- Security and Disruptive Technologies

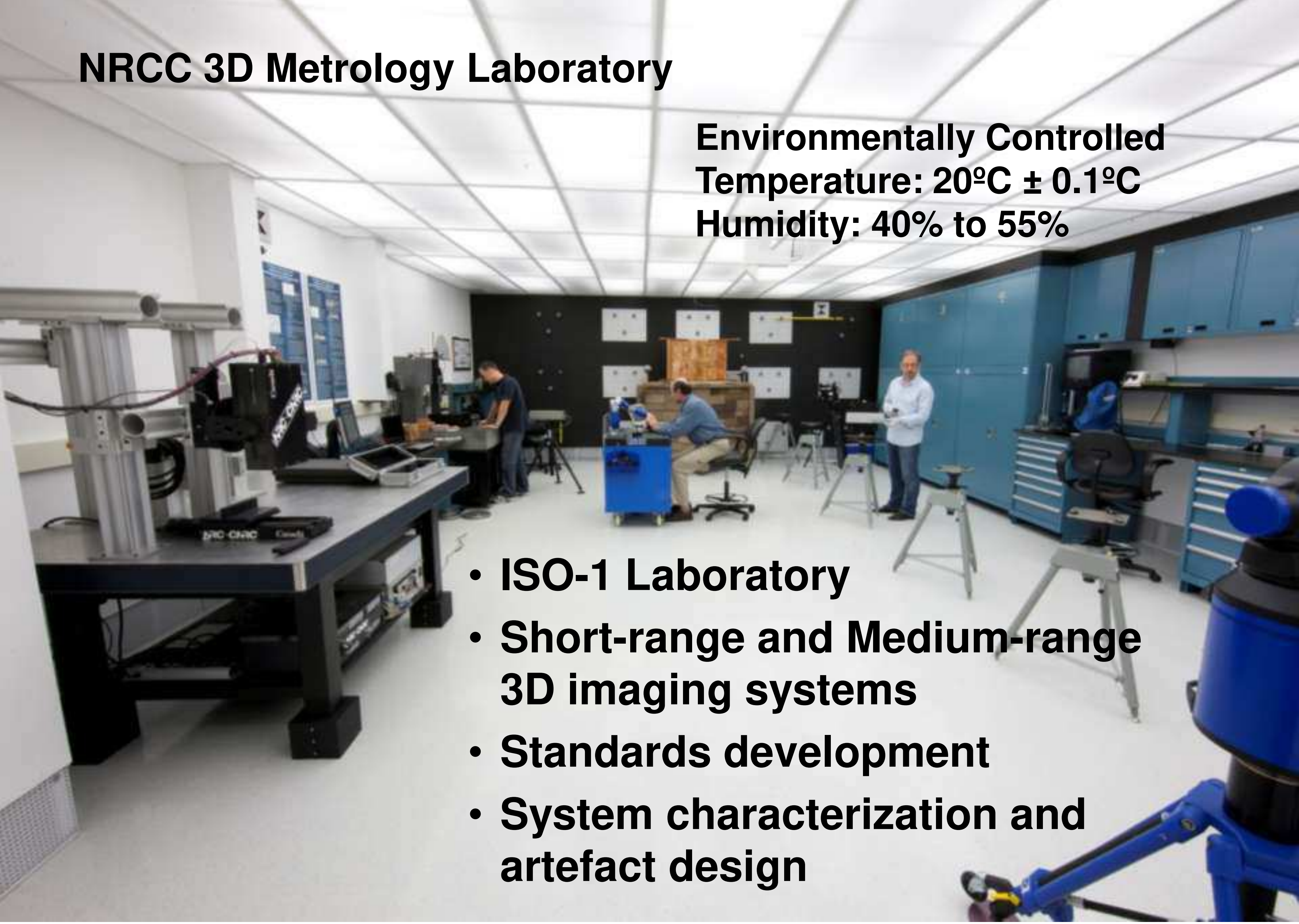
Engineering
- Aerospace
- Automotive and Surface Transportation
- Construction
- Energy, Mining and Environment
- Ocean, Coastal and River Engineering

Life Sciences
- Aquatic and Crop Resource Development
- Human Health Therapeutics
- Medical Devices

Industrial Research Assistance Program
- Pacific Region
- West Region
- Ontario Region
- Quebec Region
- Atlantic & Nunavut
- National Office

Common Services to support portfolios and IRAP

Measurement Science and Standards is Canada National Measurement Institute



NRCC 3D Metrology Laboratory

Environmentally Controlled
Temperature: 20ºC ± 0.1ºC
Humidity: 40% to 55%

- **ISO-1 Laboratory**
- **Short-range and Medium-range 3D imaging systems**
- **Standards development**
- **System characterization and artefact design**

ASTM E57 Committee on 3D Imaging Systems

ASTM International

- Founded in 1898
  - Initially to develop standards for railroads
- Formerly American Society for Testing and Materials, became ASTM International in 2001
- Voluntary consensus standards
  - More than 12,000 standards currently in use around the world
  - Currently 143 active technical committees
- More than 30,000 contributors from over 150 countries
- Key operating principles:
  - coherence, consensus, effectiveness, impartiality, relevance, transparency

ASTM E57 (3D Imaging Systems)

- Formed in 2006
  - NRC Canada was one of the founding committee members
- Initial focus - 3D imaging system specification and performance evaluation for applications
- Current focus – medium-range systems and data interoperability
- 4 standards have been completed with 2 under development
- Challenges
  - Much more work to be done due to the lack of standards
  - Need proactive support of industry

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ASTM E57 Standards Development

Completed

- **E2544**: Standard Terminology for 3D Imaging Systems
- **E2611**: Standard Practice for Best Practices for Safe Application of 3D Imaging Technology
- **E2807**: Standard Specification for 3D Imaging Data Exchange
- **E2919**: Evaluating the Performance of Systems that Measure Static, Six Degrees of Freedom (6DOF), Pose

Under Development

- **WK12373**: Evaluation of Relative Range Error for Medium-Range 3D Imaging Systems
- **WK43218**: Evaluating the Point-to-point Distance Measurement Error for a 3D Imaging System

Why are non-contact 3D imaging systems standards important?

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Problems with Contact 3D Imaging Systems

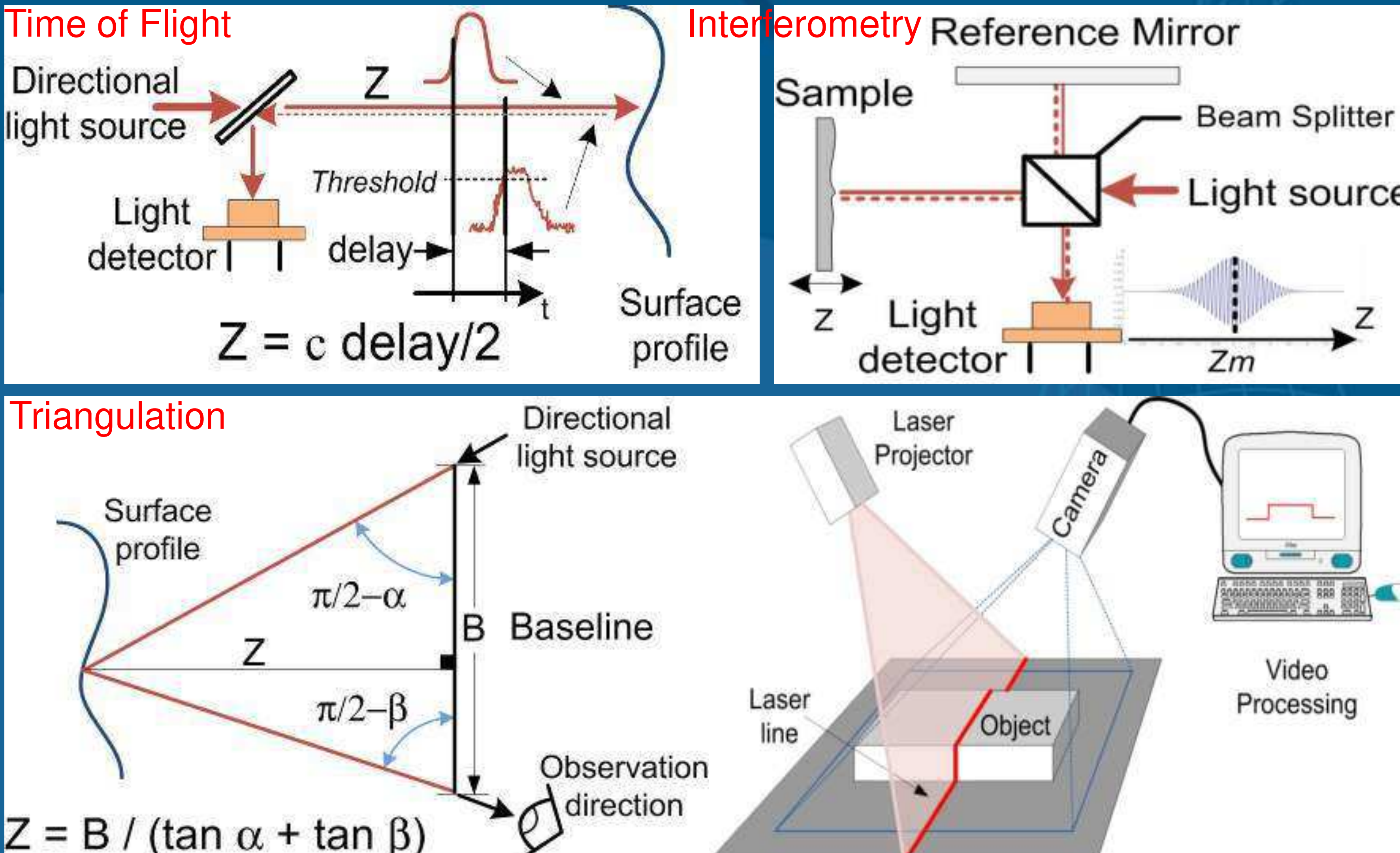
CMM (Coordinate measuring machines) and Articulated Arm systems typically use a stylus in contact with the surface

- Problems:
  - Slow (no more than several hundred hertz)
  - Can cause damage to surface
  - Limited volume

Non-contact 3D Imaging systems provide

- Faster scan times
- No surface contact so no damage
- Wide range of imaging volumes from sub-millimetre to kilometres

Classification of Optical 3D Imaging Systems



Investing in 3D Imaging Systems

3D Imaging Systems can represent a significant investment

- Initial purchase
  - **CMM-based scanners**: $20,000 to $50,000+
  - **Arm-mounted portable laser scanners**: $15,000 to $65,000+
  - **Stand-alone laser scanners**: $20,000 to $70,000+
  - **White-light scanners**: $50,000 to $130,000+
  - **Laser Trackers**: $75,000 to $150,000+
- Certification/Calibration
- Maintenance (~10% a year)/replacement (full cost with no exchange)
- Training (**No certification for 3D imaging systems yet**)
- Software (Enterprise-level solutions, single-solution for programming and reporting, user-friendly)
- …plus time investment

It is critical to evaluate **Fitness-for-Purpose**

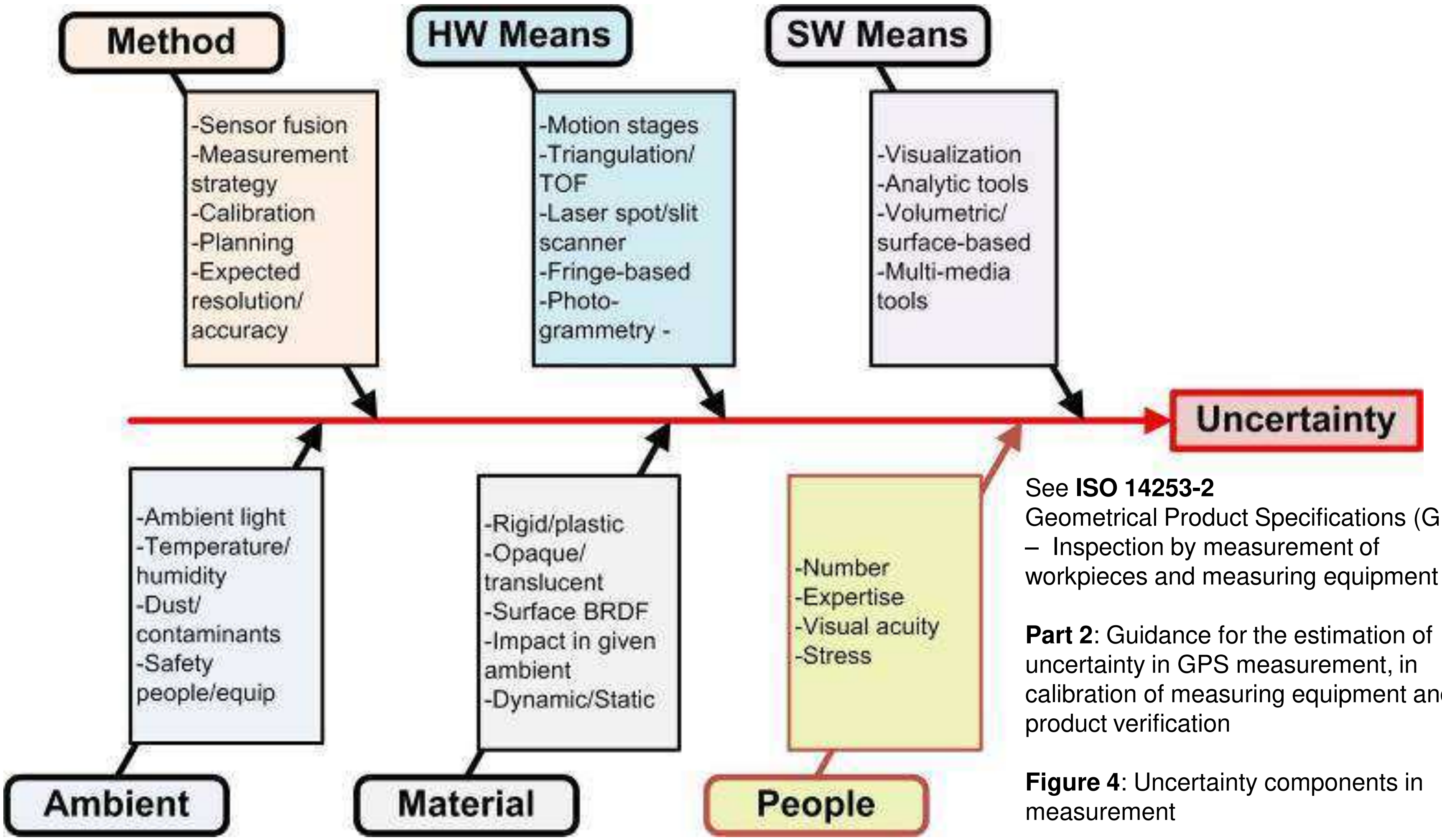
- Right tools
- Right measurements

Best Practices

- The Right People: Measurement staff should be competent, properly qualified and well informed,
- The Right Tools: Measurements should be made using equipment and methods that have been demonstrated to be fit for purpose,
- The Right Procedures: Well-defined procedures consistent with national or international standards should be in place for all measurements.
- The Right Measurements: Measurements should only be made to satisfy agreed and well-specified requirements,
- Demonstrable Consistency: Measurements made in one location should be consistent with those made elsewhere
- Regular Review: There should be both internal and independent assessment of the technical performance of all measurement facilities and procedures,

NPL Good Practice Guide (2005)

Sources of Measurement Uncertainty



See **ISO 14253-2**
Geometrical Product Specifications (GPS) – Inspection by measurement of workpieces and measuring equipment

Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification

Figure 4: Uncertainty components in measurement

What is Metrology?

- *Metrology is the science of measurement, embracing all measurements, made at a known level of uncertainty, in any field of human activity.* (BIPM)

- **Measurand:** Know what you're measuring?
- **Calibration:** Know how much you can trust the measurement result?
- **Traceability:** How do you know measurements are equivalent?

"Metrology is not just a process of measurement that is applied to an end product…. it is often considerably more expensive to re-engineer a product at a later stage when it is found that it is difficult to measure, compared to designing at the start with the needs of metrology in mind."

- Dr Richard K Leach 2003 (National Physical Laboratory, UK)

What are Standards

Definitions

- "A document, established by consensus and approved by a recognized body, that provides, **for common and repeated use**, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context"
- "NOTE: Standards should be based on the consolidated results of science, technology and experience, and aimed at the promotion of optimum community benefits." ISO/IEC Guide 2:2004

"A standard is a document that contains technical specifications or other precise criteria to be used consistently as a rule, guideline, or definition of characteristics, to ensure that materials, products, processes, personnel or services are competent and/or fit for their intended purpose(s)."

- *NIST web site*

Standards for Non-contact 3D Imaging Systems

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Standards for non-contact 3D Imaging Systems

ASTM E57: 3D Imaging Systems

NRC has been a key member of the E57 committee since its inception

ISO

NRC contributes to ISO standards development through membership in the SCC (Statistical Council of Canada)

- **ISO/TC 213**: Dimensional and geometrical product specifications and verifications
- **ISO/TC 172/SC 6**: Geodetic and surveying instruments

VDI/VDE 2634 (Germany)

NOT a standard, only a guideline

- Part 1: Point-to-point probing
- Part 2: Surface probing using area scanning
- Part 3: Combine different views

ISO/TC 213 - GPS

Dimensional and geometrical product specifications and verifications

ISO 10360: Geometrical product specifications (GPS) - Acceptance and reverification tests for coordinate measuring machines (CMM)

- **Part 7:2011** – Cartesian CMMs with imaging probing systems
- **Part 8:2013** – Cartesian CMMs with optical distance sensors
- **Part 11** – Computed Tomography **(under discussion)**
- **Part 12** – Articulated Arm CMM **(working document)**

ISO 25178: Geometrical product specifications (GPS) - Surface texture: Areal

- **Part 602:2013** – confocal chromatic probe
- **Part 604:2013** – coherence scanning interferometry
- **Part 605:2014** – point autofocus probe
- **Part 606** – focus variation (under development)

No ISO standards exist for non-CMM-based 3D imaging systems.

ISO/TC 172/SC 6 – Surveying

Geodetic and surveying instruments

ISO 17123: Optics and optical instruments – Field procedures for testing geodetic and surveying instruments

- **Part 9** – Terrestrial laser scanners **(on hold)**

ISO 16331: Optics and optical instruments -- Laboratory procedures for testing surveying and construction instruments

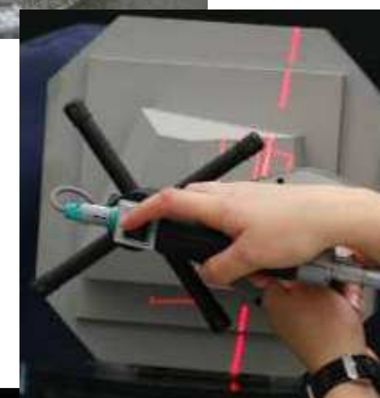
- **Part 2** – Terrestrial laser scanners **(on hold)**

Terrestrial laser scanning systems standards development on hold due to lack of participation.

3D Imaging Systems NOT covered by ISO standards

TOF laser scanners (Lidar)

- Pulse-based
- Phase-based
- Flash



Triangulation-based laser scanners (spot, line, cross patterns)

- Stand-alone
- Tracked

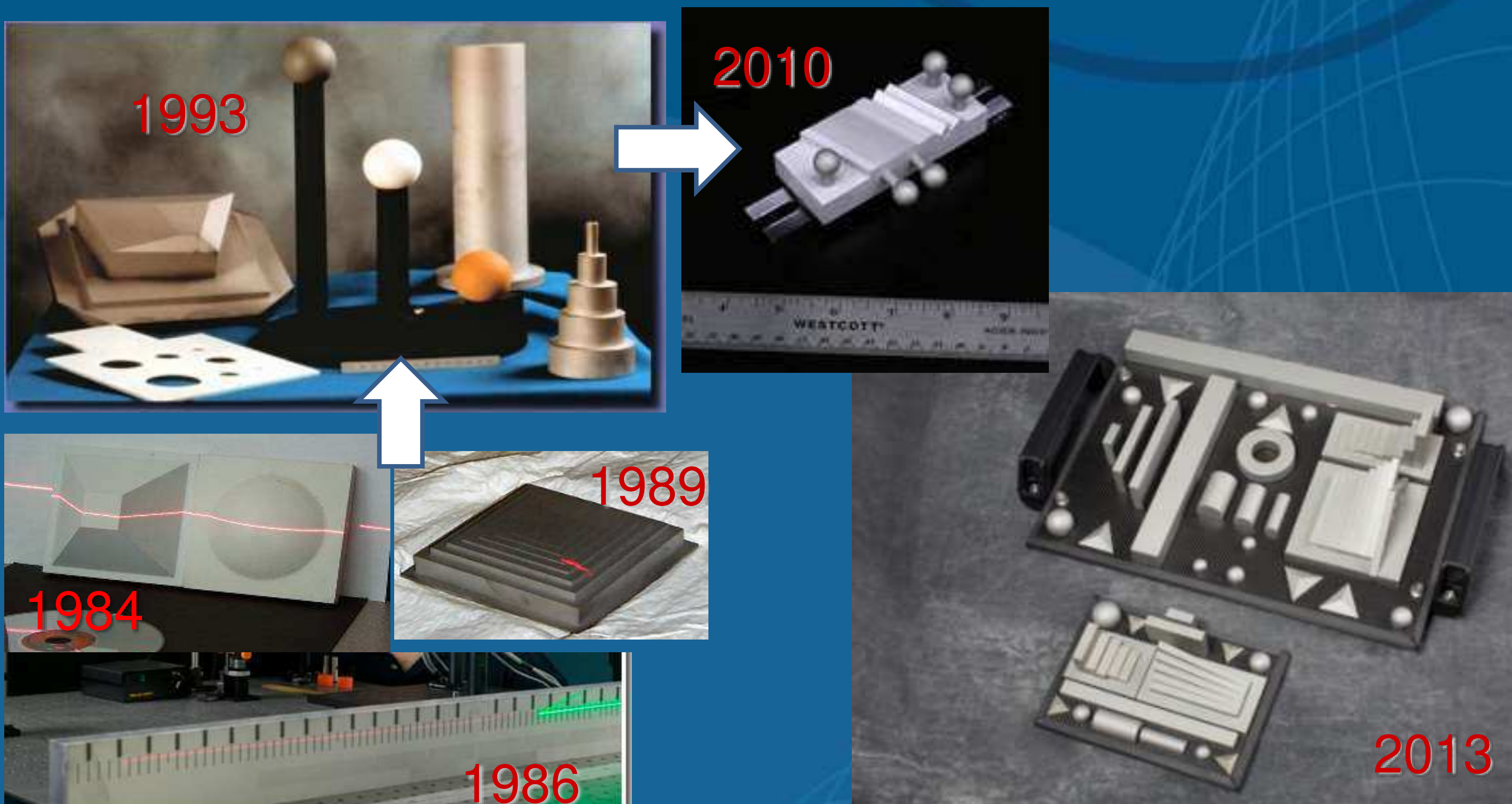
Photogrammetry

- Stereophotogrammetry
- Photometric stereo
- Pattern projection/structured light

NRCC 3D Imaging System Characterization Research

Artefact-based Characterization

NRC has 25+ years of artefact development experience



What do we mean by Characterization?

How "good" are these systems? That depends on….

- …what is being scanned? (surface material, volume, etc.)
- …what are the requirements? (resolution, precision, accuracy, etc.)
- …where is it being used? (workspace, temperature, lighting, etc.)
- …who is using it? (novice, skilled, expert)

To evaluate "fitness-for-purpose", we need a way to characterize each system so that they can be compared…

- …to the project or client specifications (Can it do the job?)
- …to other similar 3D imaging systems (Which is the best fit?)
- …to better understand costs: equipment, training, software, maintenance

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Portable Characterization Toolkit (PCT)

- Designed for short-range (5 cm to 2 m) triangulation-based laser systems
- System-independent GD&T-based characterization
- Can characterize system performance for 12 different GD&T parameters
- Lightweight and portable
- Two designs:
  - PCT-G-120: Small (120 mm) volume
  - PCT-G-240: Medium (240 mm) volume

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ASTM E57 Working Groups

- Two ASTM working groups currently active
  - WK12373: Evaluation of Relative Range Error for Medium-Range 3D Imaging Systems
  - WK 43218: Evaluating the Point-to-Point Distance Measurement Error for a 3D Imaging System
- Both working groups are focused strictly on medium-range (2 m to 150 m range) 3D imaging systems
  - Pulse Lidar
  - Amplitude-modulated continuous-wave (AM-CW)
  - Frequency-modulated continuous-wave (FM-CW)
- NRCC and NIST are actively involved in laboratory testing to support development of these standards

Derived versus Measured points

- Introduces a complicating factor into development of both proposed standards.

Measured point: Obtained directly by the instrument

Derived point: Obtained through mathematical manipulation of multiple measured points

- Examples:
  - Geometric center of a plane
  - Geometric center of a sphere

- The mathematical manipulation might introduce bias and/or error into the derived point

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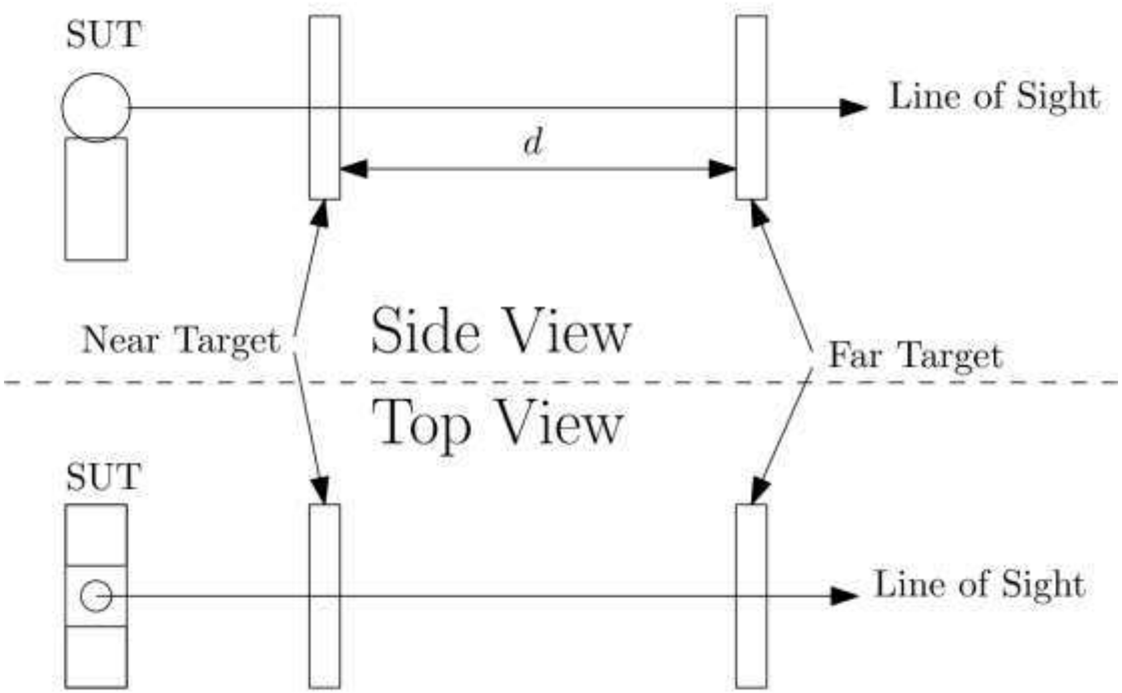
WK12373: Relative Range Error

- Completed one round of balloting
- Relative (not absolute) range measurement error
- Measured between flat plates



Relative Range Error Procedure

1. Align target plate with front face normal along line-of-sight
   a) Derive the geometric centre (**R_1**) using reference instrument (RI)
   b) Derive the geometric centre (**M_1**) using system under test (SUT)
2. Repeat at different distance from SUT to obtain **R_2** and **M_2**
3. Calculate reference distance $d_{ref}=||\mathbf{R_2} - \mathbf{R_1}||$
4. Calculate test distance $d_{meas}=||\mathbf{M_2} - \mathbf{M_1}||$
5. Calculate the relative range error $E_{range}=d_{meas} - d_{ref}$

Geometric Centre Estimation

1. Segmentation
   a) Visually eliminate all points not associated with the surface
   b) Resulting data set $\mathbf{S}_{\mathbf{full}}$ contains only points from the target plate
2. Plane Fitting
   a) Select all points $\mathbf{S}_{\mathbf{TLS}}$ from $\mathbf{S}_{\mathbf{full}}$ far enough from the edges to be unaffected by them
   b) Perform total least-squares (TLS) fit of an infinite plane P_{TLS} to $\mathbf{S}_{\mathbf{TLS}}$
3. Boundary Estimation
   a) Use best available method on $\mathbf{S}_{\mathbf{full}}$ to estimate the target plate face edges
   b) Use those edges to place bounds on P_{TLS}
4. Geometric Centre Estimation
   a) Use the bounds on P_{TLS} to estimate the geometric centre $\mathbf{M}_{\mathbf{i}}$ of the target plate face.

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WK43218: Point-to-Point Measurement Error

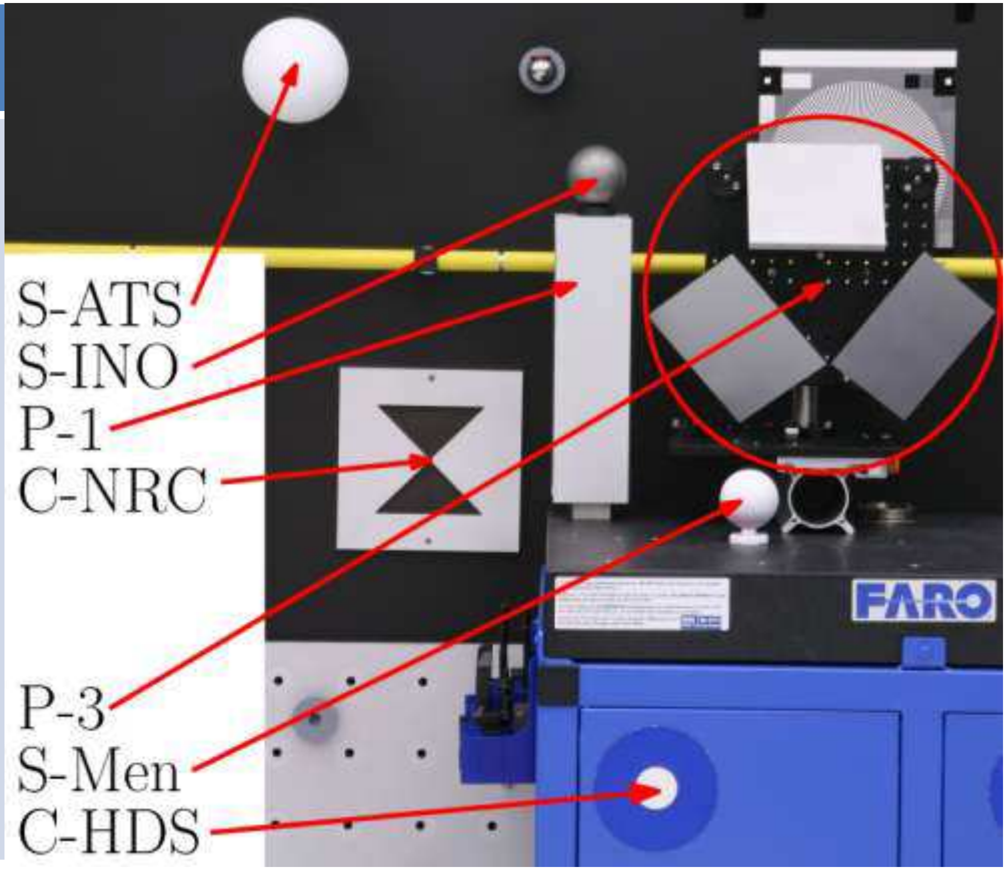
- Measures error in estimating the distance between two points in the environments
- Development process
  1. Select target types
  2. Correlating RI and SUT measurement results
  3. Identify complicating issues for point-to-point measurement error evaluation
  4. Development of test strategy
- Spheres were favoured as the preferred target type
  - Visible from a variety of angles
  - How well do RI sphere centers correlate to SUT sphere centres?

Test 1: Target Type Repeatability Comparison

- Compare repeatability performance of different target types
  - **C:** Contrast (not easily measured by the RI)
  - **S:** Sphere (visible from a wide range of angles)
  - **P:** Plane (consistent noise profile)
- Repeatability based on 10 scans of all targets
- Compare software options
  - **Bundled:** Software that was sold with the system
  - **Embedded:** Software on the SUT
  - **Common:** non-vendor-specific software
- Spheres are preferred, but how well do other targets compare?
- Selected target must be measurable by both RI and SUT
- Must be highly repeatable for all scanning systems
  - Each test to be performed on a different scanning system

Target Repeatability Evaluation Scanner #1

Rank	Target + Software
1	C-HDS + Bundled
2	S-ATS + Common
3	C-NRC + Bundled
4	S-Men + Common
5	S-INO + Common
6	P-1 + Common
8	P-3 + Common
8	S-ATS + Bundled



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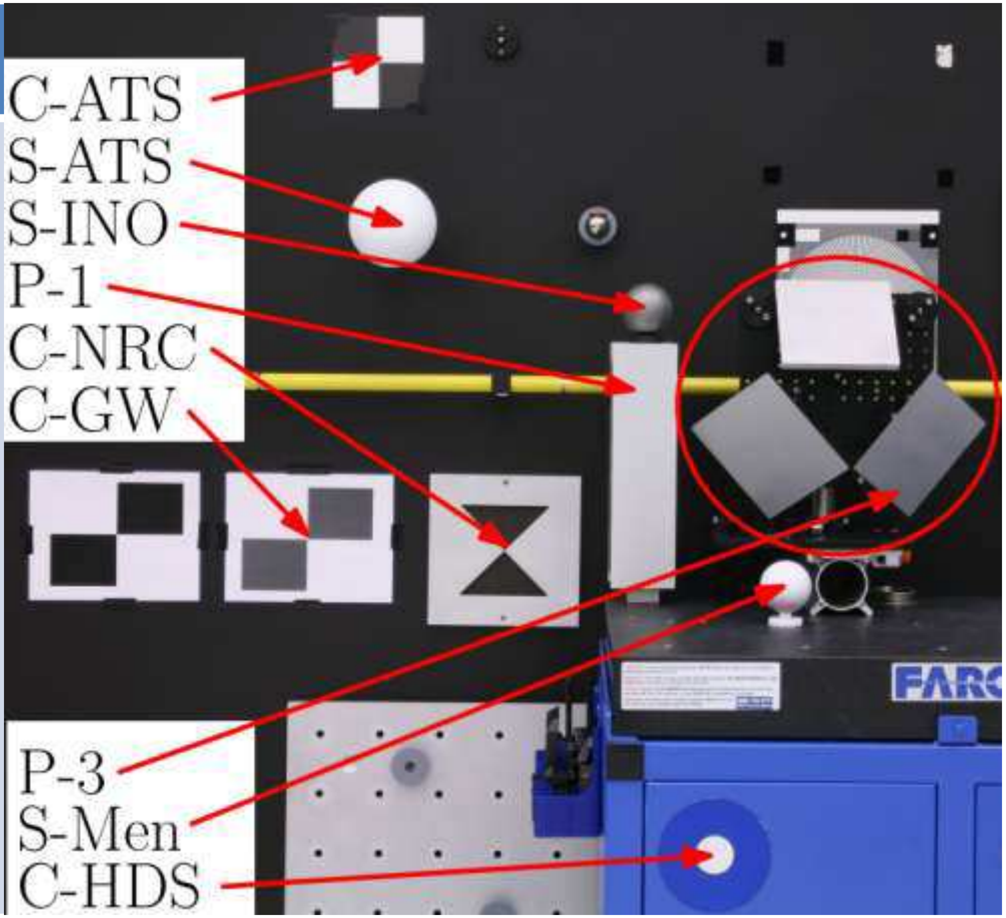
Target Repeatability Evaluation Scanner #2

Rank	Target + Software
1	C-NRC + Bundled
2	C-GW + Bundled
3	S-ATS + Common
4	C-ATS + Bundled
5	S-ATS + Bundled
6	S-INO + Common
8	P-1 + Common
8	P-3 + Common
9	S-INO + Bundled



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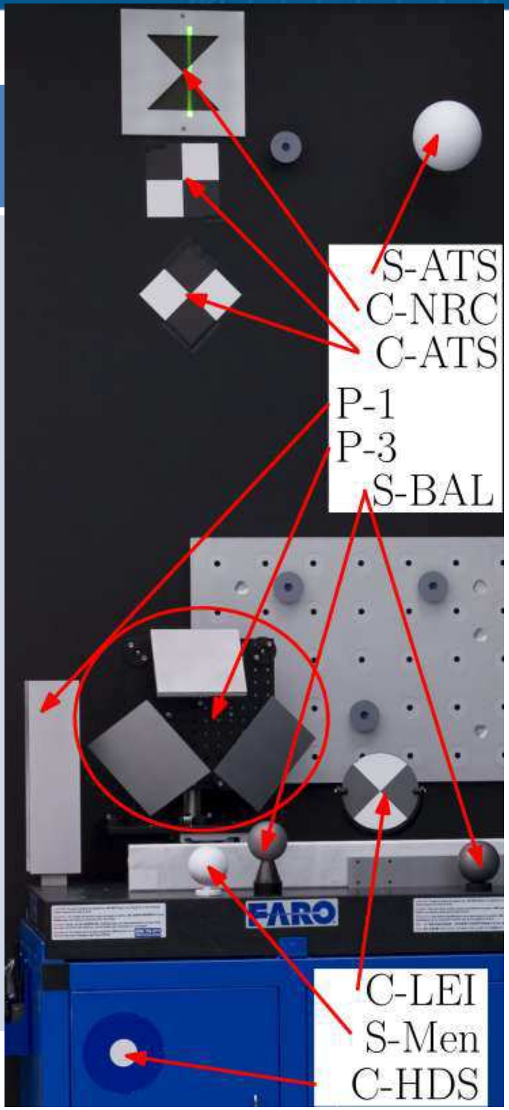
Target Repeatability Evaluation Scanner #3

Rank	Target(Angle) + Software
1	C-HDS + Embedded
2	S-ATS + Common
3	S-Bal + Common
5	P-1 + Common
5	S-ATS + Embedded
6	C-Lei(45º) + Embedded
8	C-ATS(45º) + Embedded
8	C-NRC + Embedded
9	C-ATS(0º) + Embedded



Target Repeatability Conclusions

- Spheres considered to be a good choice of target
- Continue testing using a combination of large white (S-ATS or similar) and small metallic (S-Bal or similar) spherical targets
- Planes no longer considered for this proposed standard
- 45 degree orientation showed some improvement for contrast targets

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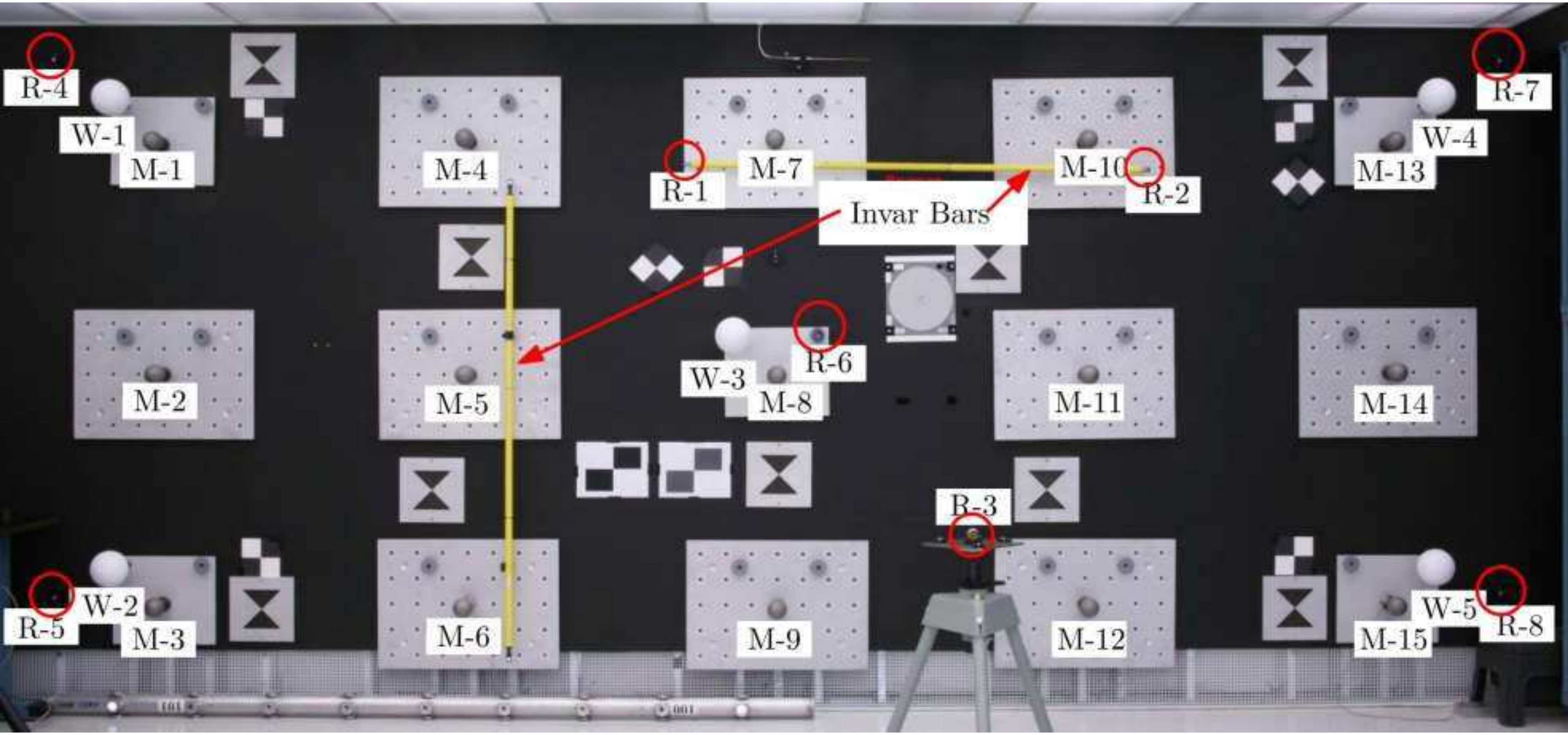
Test 2: Long-term Stability of Sphere Constellation

- Three target elements
  - **R:** Reference SMRs
  - **M:** Small (76.2 mm diameter) grey metallic (titanium) spheres (Bal-tec™)
  - **W:** Large (145 mm diameter) white spheres (ATS)
- R-SMR constellation
  - X-configuration across wall (wall corners and center)
  - Horizontal and vertical Invar bars
  - Single SMR on tripod (off-wall reference)
- M-sphere constellation
  - 15 spheres in a 5 (horizontal) by 3 (vertical) grid with 1.2 meter horizontal and 0.9 meter vertical separation between spheres
- W-sphere constellation
  - X-configuration across wall

Wall-mounted Sphere Constellation



R: Reference SMRs (circled in red)
M: Small grey metallic spheres
W: Large white spheres

Wall Stability Test Results

Wall stability

1. Distance between middle SMR (R-6) and corner SMRs (R-4 to R-8) calculated on Day 0
2. Distance between middle SMR (R-6) and corner SMRs (R-4 to R-8) calculated on Day 5
3. Deviation between Day 0 and Day 5 distances computed

Results:

- Maximum observed deviation was 0.02 mm

Distance between SMRs on Invar bar (R-1 to R-2) computed for comparison

- Invar ("invariable") has a low coefficient of thermal expansion (1.2 ppm/ºC) so is relatively invariant to the ±0.1ºC thermal fluctuation of the lab
- The bar was mounted so that any changes in wall dimensions would not affect the bar length

Results:

- Maximum observed deviation was 0.02 mm

Sphere Constellation Stability Test Results

- 38.1 mm (1.5 inch) diameter SMR used to probe spheres to derive centers
- Sphere fits using constrained (known radius) fit method
- 105 distances between all sphere pairs computed
- Process repeated after 0, 1, 2, 3, 6, and 13 days
- Results:
  - Maximum average deviation was 0.01 ± 0.02 mm

Concluding Remarks

Concluding Remarks

- The ASTM is developing two proposed standards for medium-range systems
  - WK12373 relative range error evaluation
  - WK43218 point-to-point error evaluation
- These standards fill a standards development gap not currently covered by either ISO or ASME
- NRCC is actively involved in research to support the development of these standards
- Results were presented for point-to-point protocol development research
  - Measurement repeatability of possible targets for test method
  - Measurement repeatability and stability of the sphere constellation

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Thank you

David MacKinnon, Ph.D., P.Eng.
Research Officer
Tel: 613-993-0114
david.mackinnon@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca

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