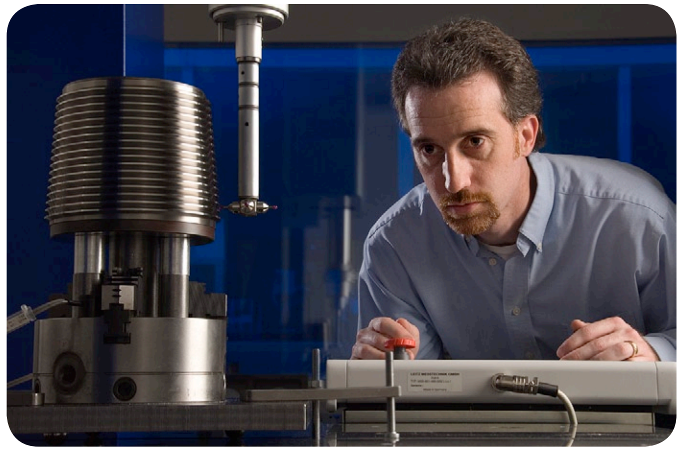
Precision Engineering Division Program

Dimensional Metrology Program

Annual FTEs:	17.5 NIST staff
	4.5 Guest Researchers/Contractors
	22 total FTEs



Measurement of API Rotary Master Gauge on CMM

Challenge:

Technological leadership in high accuracy dimensional metrology is critical to maintaining U.S. competitiveness. The challenge is to sustain MEL's core dimensional metrology capability while developing new metrological infrastructure for high value or innovative technologies that improve U.S. competitiveness.

Overview / DMP Strategic Objectives

The Dimensional Metrology Program (DMP) addresses selected needs of the U.S. industrial and standards community for dimensional metrology over a length scale of kilometers to micrometers. This includes calibrations of measuring instruments such as laser interferometers and laser trackers, a wide array of engineering gauges, standard reference materials, and specialized, e.g., high accuracy measurements by coordinated measurement machines (CMM). The program also seeks to provide expertise and representation of U.S. interests in national and international standards.

The long term external objective of the DMP is to improve US competitiveness by: (1) providing infrastructure for core metrological traceability through deep penetration of the DMP's measurements into the US metrology chain; (2) creating measurement capability for high value components; and (3) focusing new metrological activities on enabling technologies where the U.S. has a significant industrial presence.

DMP is developing unique measurement capabilities – typically a combination of extremely low uncertainty or difficult to measure measurands that differentiate MEL from other top-tier laboratories. These capabilities seek to exploit strategic fit within MEL and to take advantage of economies of experience and scope. Particular emphasis is placed on the formation of capital equipment and facilities. To implement these objectives the DMP is increasing its use of flexible CMM-based measurement systems. For example, several dedicated calibration systems are now replaced by the M-48 CMM, which provides higher accuracy and throughput. The M-48 was in measurement service for 320 days in FY-07.

Some gauge calibrations with low penetration into industry and diminishing technological value are being eliminated. Additionally, the DMP is developing calibration techniques and standards for laser trackers using absolute distance and laser radar sensors (the United States is home to two of the top three manufacturers of this rapidly growing technology). The program is also advancing fundamental metrology such as the realization of the unit of length through refractometry and the optical comb.

Program projects can be roughly categorized as either:

- Research and development (R&D) activities
- Ongoing measurement services
- National or international standardization efforts.

This categorization is somewhat artificial as all three areas strongly interact. For example, R&D activities frequently yield new measurement services and a corresponding industrial need for standardization.

Key Accomplishments and Impacts:

- Development of the world's most accurate CMM probe, capable of inspecting microfeatures.
- Development of world class 60 meter laser test range for laser tracker calibrations
- Completion of a comprehensive five part series of national standards on measurement uncertainty for industrial users.

Future Directions and Plans:

The program anticipates further culling of low penetration or low value added calibrations from our services. We will continue developing unique high accuracy equipment and facilities. For example, we are developing a second Moore M-48 CMM that will incorporate the DMP's microfeature probe. This CMM will be dedicated to high value components and reference materials with sub-millimeter features and will free up time on our existing M-48 for additional calibration volume. Continuing emphasis will be placed on enabling technology that supports U.S. industrial interests, notably optical coordinate metrology instrumentation that improves productivity.

Excellence & Leadership Recognition

Staff	Excellence & Leadership Demonstrated
Blackburn, Chris Borchardt, Bruce Estler, Tyler Phillips, Steven Sawyer, Daniel	• 2007 NIST J.D. French Award for Measurement Service Excellence for significant improvements in accuracy and extensions of range in the calibration of long length standards. Their efforts resulted in a reduction in uncertainty by more than 600% over prior capability.
Stone, Jack	• 2007 Department of Commerce Silver Medal Award for development of a unique high-accuracy optical probe for the measurement of sub-millimeter features and deep holes allowing NIST to open a new, unprecedented, realm of dimensional measurements 100 times smaller than previously available.
Doiron, Ted	• 2006 Best Paper Award, Measurement Science Conference
Estler, Tyler	• Elected Fellow of CIRP – The International Academy for Production Engineering, 2005

Projects

Dimensional Metrology Program

Research and Development Project

Challenge/Problem Addressed:

Industrial measurements continue to need increasing accuracy and component extent (both larger and smaller workpieces). The challenge is to identify new measurement areas that promote technological growth, are within the reach of the program, and deliver a significant social return on investment (SROI).

Objective(s):

Develop new dimensional measurement services that support industrial innovation, advance measurement science, and create new and unique measurement capabilities at NIST.

Accomplishments:

- 60 Meter Measurement & Test Range (Status: R&D Completed in FY-07):

  The large scale metrology industry is rapidly moving to optical measurement systems. Unlike large fixed placement CMMs, these new systems can be easily transported to different measurement sites, have significantly lower capital equipment costs, and allow factory floor space to be rapidly reconfigured.

  New optical technologies that provide absolute distance measurement (ADM) capability eliminate the need to transport retroreflectors from the system to the workpiece and the associated problems of beam breakage. For that reason, measurement technology using ADMs has exploded in recent years and numerous firms are developing new products and measurement services. The United States leads the world in this technology, particularly in the development of ADM laser trackers.

  The DMP is supporting this crucial technology through development of a high accuracy 60 meter test range that can calibrate ADM ranging systems. Direct assessment of the errors in these (often highly proprietary) ADM systems helps manufacturers of this technology to improve the accuracy of their equipment and gives users confidence in the measurements. Using our existing tape calibration facility, augmented with a newly developed high accuracy long range interferometer system, represents a unique national resource. Current test range calibration uncertainties are $U(k = 2) = 2$ µm + $3 \times 10^{-7} L$ for cooperative targets (specially made to be ADM friendly) and $U(k = 2) = 10$ µm + $1 \times 10^{-6} L$ for noncooperative targets.

  QuantaPoint Inc., a manufacturer and service provider of laser ranging metrology, was one of our first industrial collaborators to use the test range in FY-06. Darin Ingimarson, Director of Hardware Development, wrote in a letter to NIST:

  "The data we acquired at NIST on our four prototype Mark VI systems has helped us find several issues that would have remained unnoticed. With this information we are able to devise specific tests and procedures that will improve the accuracy and reliability of the ranging system. We have shaved weeks from our development schedule and are better prepared to place our systems into commercial service sooner. Furthermore, the competitive advantage gained from our testing will translate to direct financial benefits to Quantapoint and will help us keep the US laser-scanning industry one step ahead of our offshore competition."

- Microfeature CMM Probe: (Status: R&D Completed in FY-07):

  New fabrication technologies are creating an ever-expanding array of microfeature (10 µm to 1000 µm) size products. Microfeature technology can both create novel functions and enhance product value. For example, experimental fuel injectors with sub-100 µm holes have reduced emissions and improved the mileage of diesel engines. Microfeatures are increasingly common in optical fibers and their connectors, medical devices, DNA processing chips, drug delivery systems, and a myriad of other applications. These components are both too small and too delicate to inspect with conventional contact probing techniques.

  The DMP is addressing this need by developing new CMM probing technology. This new probe adapts to our M48 CMM and extends our 3D coordinate metrology capability to feature sizes below 100 µm. The probe can access bores with aspect ratios of over 50:1. We have recently extended use of the probe to measurements of knife-edge apertures that would be too fragile to measure with a traditional CMM probe. (These apertures are used as radiometry standards by the Optical Technology Division.) The aperture measurements achieve state-of-art uncertainty and provide a clear pathway toward better basic radiometry standards. We have started using the probe in conjunction with a precision spindle to do precision roundness measurements of small bores.

  The probe is better characterized than any other system in the world for microfeature measurement. We have demonstrated hole diameter measurements with expanded uncertainties below 100 nm. The probe also exerts exceptionally low measurement force (on the order of 100 nanonewtons) giving it unique measurement capability on small external features and delicate surfaces.

  We are also characterizing other microfeature capable CMMs such as the Mitutoyo Corporation for the UMAP Ultra CMM, currently on long term loan to NIST. This system, while not as accurate as the NIST probe, has greater throughput. The UMAP is currently being used in evaluating microchannels associated with fuel cell manufacturing.

- Large Scale Metrology Research and Artifacts (Status: R&D ongoing, to be completed FY-10):

  Performance testing of large scale coordinate metrology systems poses a significant challenge. Large testing volumes are needed to adequately evaluate the 3D performance of laser trackers, “indoor GPS” systems (actually an optically based technology), and laser scanners. The DMP is currently developing a facility capable of testing a wide assortment of these optically based systems.

  This facility can rapidly conduct the volumetric tests specified for laser trackers in the ASME B89.4.19 laser tracker standard. We have also collaborated with the Boeing Company and MetricVision (a U.S. manufacturer of large scale metrology equipment, now owned by Metris) to evaluate laser radar technology, an emerging technology for high accuracy noncooperative target scanning. Research also includes work on large (e.g. 3 meter) artifacts typical of industrial environments and we are developing instruments to provide high accuracy calibrations of these artifacts.

- Fundamental Length Metrology (Status: R&D ongoing, to be completed FY-10):

The DMP is actively engaged on improving the fundamental realization of the meter. Conventionally, the meter is tied to the unit of time (the second) through a complex chain of frequency doublings that provides a few selected calibrated laser frequencies, most notably the iodine stabilized HeNe laser. The recent development of the optical comb provides ultraprecise measurements of vacuum wavelength directly tied to the definition of the second. In addition to providing tremendous accuracy, the comb can be used to calibrate a laser operating at essentially any wavelength. It may therefore help to stimulate innovative new approaches to length metrology. For example, if an application needs multiwavelength interferometry based on telecom lasers, we would have no problem providing the required wavelength calibrations at any desired level of uncertainty.

Thus far, we have demonstrated better performance than had previously been reported for combs employing a GPS reference frequency. We have also established a complete set of internal consistency checks to guarantee that measurement results are correct. This set of checks could in principle be employed by anyone to verify performance of a comb+GPS system without the need for NMI calibrations, and hence goes a long way toward fulfilling a goal of delivering reliable "length by satellite". During the next two years, we expect to demonstrate competence for frequency measurements over much of the visible spectrum, from 540 nm (green lasers for multicolor interferometry) up to 700 nm. We also will have capability at telecom wavelengths from about 1200 nm to 1600 nm.

The comb measurements must be supplemented by refractive index measurements to determine laser wavelength *in air*, which is the basic metric for almost all interferometer-based measurements. However, uncertainty in the value of air's refractive index sets the fundamental limitation for practical measurements, preventing us from fully utilizing the inherent high accuracy associated with the laser frequency. Using new optical materials and recent improvements in optical coating and contacting technology, we are building refractometers that should allow for refractive index measurements—and thus length measurements—with a relative uncertainty below 1 part in 10^8. Ultimately, this will lower the uncertainties in NIST calibrations and hence improve the program's competitive position by enhancing our unique measurement capability.

Planned Future Accomplishments:

- Contact Profilometer Development (Status: new project, to be completed FY-09):

This project will deliver contact profilometry measurements with world class performance. Contact profilometry is the gold standard of microform measurements. The DMP uses contact profilometry in a wide array of measurements including surface roughness calibrations, microindentor characterization for hardness instruments (maintaining the national hardness scale), and in reference measurements for the optical metrology techniques used for standard bullets (used in law enforcement). Standard reference materials (SRMs) 2071 – 2075 are calibrated as surface roughness standards using contact profilometry and are used throughout the industry.

A new contact profilometer to replace the current obsolete system will offer significantly better resolution and accuracy. The new instrument will be metrologically characterized with a detailed uncertainty budget and cross checked against previously calibrated artifacts to ensure continuity of this measurement service. The instrument will be in use by the end of FY-09.

- CMM Metrology Capability (Status: new project, to be completed FY-10):

  This project will deliver another Moore M48 CMM as a calibration instrument with world-class performance by FY-10. The DMP's current M48 CMM is running at full capacity, providing a unique measurement capability for features ranging from 0.5 mm to 1000 mm. The new M48 CMM, acquired from Sandia National Laboratories, will be dedicated to microfeatures measurements using the new NIST probe and a vision (CCD) system. This new capability will significantly improve the DMP's capacity to calibrate this high value class of products. We will exploit our deep learning curve about M48 operations to achieve world class performance within three years.

  The new CMM will also serve as a testbed for new enhancements, including integration of glass scales for nanometer-level interpolation of the machine scales. For larger displacements, advancements made in our refractometry project should yield length-proportional uncertainty of less than five parts in 10^8.

Collaborators:

- The Boeing Company; laser trackers and laser radar performance evaluation
- Metris Inc.; Laser radar research and performance evaluation.
- QantaPoint; LIDAR development
- Faro Technologies; laser tracker research
- Inora Technologies; large scale artifact development
- Brunson Instrument Company; large scale artifact development
- Automated Precision Inc.; large scale artifact development
- Drexel University; surface roughness instrumentation
- Process Specialties Inc.; surface roughness research
- Bethesda Naval Medical Center, CMM measurements
- MSP Corporation, microfeatures

Dimensional Metrology Program

Measurement Services Project

Challenge/Problem Addressed:

The DMP's fundamental role is to provide industry with accurate and timely measurement services, including calibrations, special tests, and standard reference materials and data. Measurement services link the SI unit into almost all dimensional traceability paths in the United States. This role differentiates NIST from other calibration laboratories and from universities that also perform R&D and standardization activities.

Some measurement services focus on deep penetration into the U.S. traceability chain. For example, each gauge block calibrated at NIST explicitly provides metrological traceability to over 1000 blocks in industrial use. Other services focus on high value components which typically involve complex geometry and measurands. These complex measurands require the flexibility of coordinate measuring machines (CMMs). Calibration activity involving CMMs now represents nearly 40% of total measurement services revenue, up from less than 10% a decade ago. This increase is attributed both to our increased CMM measurement capability and the increasingly sophisticated mix of customer components.

As technology rapidly expands, so does the need for additional calibration services. However, the program's capacity to address these needs is diminishing (with respect to purchasing power) so measurement service activities must be carefully selected.

Objective(s):

To provide an optimal mix of measurement services that address both current and future dimensional measurement needs.

Accomplishments:

- Measurement services in technologically declining areas are being eliminated. For example, level rod calibrations (used in civil engineering) have been eliminated since GPS offers higher accuracy over large distances. Mechanical sieve calibrations are also being eliminated as they have relatively low value and can be performed by secondary calibration laboratories.
- We have halved the uncertainty of our long calibrations (e.g., survey tapes), and added new capability for long cables particularly for the optical fiber telecommunications industry. This new capability was highly synergistic with the improved accuracy developed for the 60 meter laser ranging facility.
- Quality assurance metrics have continuously improved over the past three years. On time delivery is now at 98%. However, turnaround time remains fixed at roughly 65 days; additional emphasis is being focused on reducing this value.
- Calibration income has steadily increased with gross revenues now at $1M / year and net revenues at $0.75M /year.
- Results from international laboratory Key Comparison (CCL-K6) for diameter show the NIST results well centered with respect to results from other major laboratories.

- The DMP is currently the pilot lab for a Key Comparison on hardness testing that aims to establish a worldwide unified Rockwell hardness scale with metrological traceability.
- The radiometric physics Key Comparison CCPR-S2 was released by the NIST Physics Laboratory, incorporating the apertures measurements made on the M48 CMM; all of the results were consistent with the reference values to within our uncertainty.

Planned Future Accomplishments:

Successful DMP R&D projects are leading to implementation of new measurement services. Laser range calibrations are now (FY-08) a listed measurement service. Similarly, microfeature measurement capability will be listed by the end of FY-08.

Customers and Collaborators:

The identities of our measurement service customers are protected by our privacy policy. From FY-05 to FY-07, DMP provided dimensional measurement services to 360 different industrial customers and 25 government entities. DMP calibrates over 5,000 master gauges, instruments, and artifacts per year, accruing gross annual revenues of approximately $1M.

National and International Standards Project

Challenge/Problem Addressed:

Documentary standards are the metrologically deepest penetrating activity of the DMP. Standards can dictate how an entire industry specifies its products and thus how those products are tested and subsequently accepted or rejected. Well written standards provide significant positive externalities to industry. Through standardized specifications and testing, manufacturers can avoid the costs of idiosyncratic individualized testing for different customers. Users of standardized technology can readily compare products from different manufacturers to common specifications and so purchase products best suited to their needs. Standards written with unbiased expert input also protect inexperienced users by providing appropriate specifications and testing. Standardization benefits industry as whole by focusing on metrologically meaningful metrics that drive innovation.

International standards are now becoming *de facto* national standards worldwide. However, many nations strongly assert their own interests at meetings that establish standards, and discrepancies among nations can result in nontariff trade barriers that put the United States at an economic disadvantage. Identifying high value technologies with a significant U.S. industrial base is critical to prioritizing standardization topics.

Objective(s):

To gain first mover advantage in new technological fields by developing new U.S. national standards that will entrench commercial specifications and lead to international standardization along U.S. guidelines.

Accomplishments:

- National Standards on Measurement Uncertainty and Traceability (status: completed FY-07).

  Over the past eight years the DMP has led the effort to develop a complete suite of five standards to address the entire measurement uncertainty issue. The suite has a strong industrial orientation. It describes not only how to compute measurement uncertainty, but its implication in specifications, testing (accept/reject decisions), product conformance, and metrological traceability. During the past three years we have completed three of these documents (B89.7.3.2, B89.7.4.1, and B89.7.5); the entire series is described below. These standards are already being cited in industry and incorporated into other metrology standards and documents.

  ASME B89.7.3.1-2001, *Guidelines to Decision Rules in Determining Conformance to Specifications*, addresses the role of measurement uncertainty when accepting or rejecting products based on a measurement result and a product specification.

  ASME B89.7.3.2-2007, *Guidelines for the Evaluation of Dimensional Measurement Uncertainty*, provides a simplified approach (relative to the GUM) to the evaluation of dimensional measurement uncertainty.

  ASME B89.7.3.3, *Guidelines For Assessing the Reliability of Dimensional Measurement Uncertainty Statements*, examines how to resolve disagreements over the magnitude of the measurement uncertainty statement.

  ASME B89.7.4-2005, *Measurement Uncertainty And Conformance Testing: Risk Analysis*, provides guidance on the risks involved in any product accept/reject decision.

  ASME B89.7.5-2006 *Metrological Traceability of Dimensional Measurements to the SI Unit of Length*, specifies a practical interpretation of traceability and details the requirements necessary to provide evidence that traceability is satisfied.

- National & International Standards on Cartesian CMMs. (Status: ongoing, to be completed in FY-11):

  Over the past eight years the DMP has led a major effort to extensively revise both the international standard (ISO 10360 parts 2, 3, 4 and 5) and the US national standard (B89.4.1) governing the specification and testing of Cartesian CMMs. In particular, the effort will include US tests in the ISO standard and also harmonize the United States with the rest of the world. In addition to the usual benefits of standardization, this will reduce U.S. industry's costs by establishing a common set of testing procedures and artifacts. This project also returns the United States to the forefront of international standards, because the U.S. version of the ISO standard includes numerous additional topics, such as how to derate CMM specifications when the customer's facility does not comply with the CMM manufacturer's thermal environment requirements.

- National & International Standards on Surface Roughness. (Status: ongoing, to be completed in FY-10)

  Recent advancements in instrumentation to evaluate surface roughness is driving a new set of national (B89.46.1) and international (ISO TC213/WG16) standards. DMP staff chair taskforces on committees to address 3D topology measurement techniques and new algorithms that extract roughness parameters. The U.S. standard is expected to be completed in FY-09. This effort will harmonize the U.S. and ISO approaches to 3D surface texture characterization.

Planned Future Accomplishments:

- National Standard on Laser Scanning Probes. (Status: new project, to be completed in FY-11)

  Laser scanning probes are increasingly used in conjunction with Cartesian CMMs, laser trackers, and articulating arm CMMs, and as stand-alone coordinate metrology systems. These probes use a variety of technologies (including triangulation, structured light, and time of flight) to densely scan workpieces in a non-contact manner. Recently, the ASTM E57 committee initiated a standardization project for this class of optical probes. DMP is leading this taskforce along with industrial and manufacturing partners. As an entry point into this project, DMP has joined a USCAR (domestic automobile manufacturers) project to characterize flexible hoses as a function of their boundary conditions.

Customers and Collaborators:

- Brown and Sharpe Corporation (now part of Hexagon Metrology): B89.7.3 series, B89.7.4
- Hutchinson Technology Inc; B89.7.3 series, B89.7.4, B89.7.5
- The Boeing Company; B89.7.3 series
- Mitutoyo of America; B89.7.3 series, B89.7.4, B89.7.5
- US Air Force; B89.7.5
- Physikalisch-Technische Bundesanstalt: B89.7.5
- Caterpillar Corporation: B89.7.3 series B89.7.5
- University of North Carolina Charlotte: B89.4.19
- Mc Donnell Douglas Co.: B89.4.19
- Arc Second Inc.: B89.4.19
- Leica Geosystems Inc.: B89.4.19
- Faro Technologies: B89.4.19