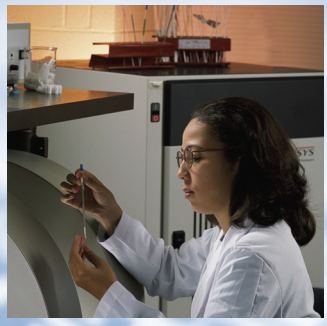
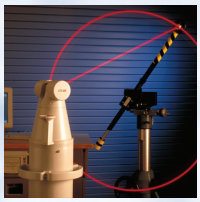
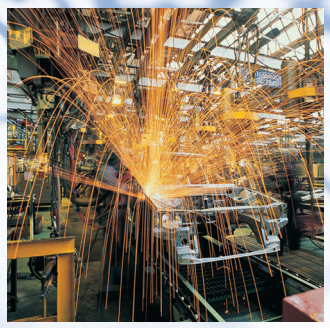
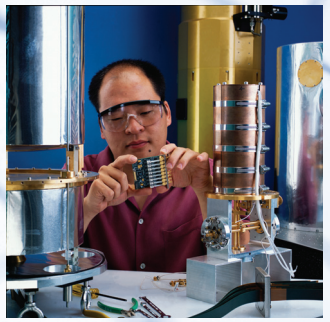
An Assessment of the United States Measurement System:

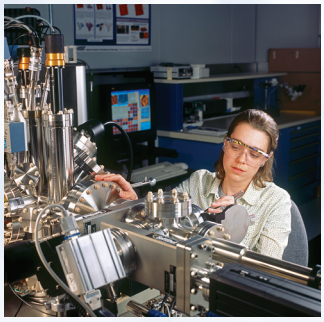
Addressing Measurement Barriers to Accelerate Innovation

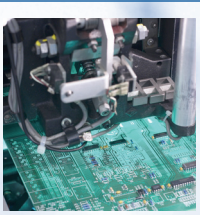












NIST Special Publication 1048

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

Dr. Dennis A. Swyt, Director
NIST USMS Program

NIST USMS Report Editorial Committee

Mark Bello
Jacqueline Calhoun
Kari Harper
Mary Saunders
James Whetstone

NIST USMS Task Group

James Adams
Thelma Allen
Clare Allocca
Frank Barros
Herbert Bennett
Jacqueline Calhoun
Leslie Collica
Hunter Fanney
Barbara Goldstein
Prasad Gupte
Kari Harper
Cameron Miller
Thomas Rhodes
Mary Saunders
John Slotwinski
James Whetstone

http://usms.nist.gov

NIST Special Publication 1048

An Assessment of the United States Measurement System:

Addressing Measurement Barriers to Accelerate Innovation

Dr. Dennis A. Swyt
Office of the Director
National Institute of Standards and Technology
Gaithersburg, MD 20899

February 2007

U.S. Department of Commerce
Carlos M. Gutierrez, Secretary

Technology Administration
Robert Cresanti, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
William Jeffrey, Director

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

National Institute of Standards and Technology Special Publication 1048

Natl. Inst. Stand. Technol. Spec. Publ. 1048, 64 pages (August 2006) (Released February 2007)

CODEN: NSPUE2

UNITED STATES DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
Gaithersburg, Maryland 20899
OFFICE OF THE DIRECTOR

"To measure is to know."† And knowledge – whether aimed at unraveling a fundamental law of nature or ensuring that a manufactured part will fit into its assembly – is critical to continued technical progress, to innovation, and ultimately to the economic security of our nation.

The requirement to measure things more accurately, faster, and at smaller dimensions is now pervasive throughout U.S. science and industry. Whether designing complex nanostructures, exploiting fundamental quantum properties of matter, or probing the chemical pathways inside a cell – the demand for more and better measurements is unrelenting.

Progress to date has been phenomenal. We can now measure time with an accuracy of better than 1 second in 60 million years, measure force to a nanonewton (roughly equal to the force required to sever a single chemical bond between two atoms), and count single electrons and photons.

But as the magnitude and quality of global competition has increased, there is a greater urgency in ensuring that the measurement capabilities required by science and industry are addressed or are in development.

This report documents the breadth of the U.S. Measurement System (USMS). It also documents current unmet measurement needs that pose immediate barriers to technological innovation across a number of industry and technology sectors.

The measurement needs identified in this initial assessment are compelling evidence that new or improved measurement capabilities are required. Meeting this requirement is necessary if we are to continue "*to generate and harness the latest in scientific and technological developments and to apply these developments to real world applications*," as called for in President Bush's American Competitiveness Initiative.

This report should be viewed as a beginning, not as an end product. At NIST, we will use this assessment as a means to focus our own work in support of U.S. innovation and competitiveness. We also will partner with other stakeholders in both the public and private sectors to focus organizational, sectoral, and cross-sectoral attention on overcoming the most significant measurement-related barriers to innovation.

I want to extend my sincere thanks to the hundreds of participants from industry, universities, and government who contributed to the development and authentication of these measurement needs. Your contributions were invaluable.

Ensuring that the nation's measurement infrastructure is robust and forward-looking is a job for all of us. Your continued participation is important as we establish and implement a shared measurement innovation agenda.

William Jeffrey

William Jeffrey
Director

†William Thomson (Lord Kelvin) 1824-1907

NIST

Table of Contents

Foreword iii

Executive Summary v

I. Introduction 1

II. Purpose and Elements of the USMS 4

III. Focus on Innovation: The Importance of Measurement 11

IV. Methodology of the Assessment 15

V. Results of the Inferential Analysis 20

VI. Summary of the Assessment of the USMS 36

VII. Next Steps 44

Glossary of Terms and Abbreviations 48

Endnotes 50

References 51

Appendices

A . . . . . .Descriptions of NIST USMS Workshops

B . . . . . .Case-Study Measurement Needs: A Compilation

C . . . . . .Technology Roadmap Review: Summary Report

D . . . . . .Contributors to the 2006 Assessment of the USMS by NIST

E . . . . . .NIST's Realization and Dissemination of the Units of the SI

F . . . . . .The Methodology of the Inferential Analysis

G . . . . . .Descriptions of Selected Broad Technologies

H . . . . . .Analysis of Case-Study Measurement Needs: Summary Report

I . . . . . .Summary Results of Inferential Analysis of Measurement Needs

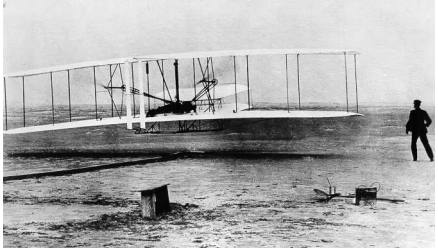
All Appendices are contained on the accompanying CD, along with an electronic copy of this document.

Guidelines for users on searching and navigating the appendices are included in the main directory of the CD.

Foreword

The creation of the Wright Flyer of 1903, the world's first airplane, is a story of *a measurement barrier to technological innovation* overcome.

The Wright Brothers had been vexed by the under-performance of a wing they had designed based on data published by Otto Lilienthal, the foremost glider expert of the day. The lift generated by the wing was but one-third of that expected, and, to their consternation, they were forced to conclude that the measurement data were wrong.



To solve the problem of the inaccurate measurement data impeding their innovation, they built a balance for the precise measurement of the aerodynamic lift of wings of different profiles. Based on the accurate measurement data they produced, they designed the wings and propeller of what came to be recognized as the world's first powered, controlled, heavier-than-air flying machine.

This report is about measurement barriers to potential technological innovations that are pending today. Some of these innovations, for example, those of nanotechnology, bio-medicine, and intelligent machines, have the allure and promise that flying machines had a century ago. The measurement barriers impeding these innovations are as vexing as those encountered by the Wright Brothers. The science and technology enabling these innovations are more complex. The dependence of would-be innovators on the technical infrastructure of the nation, including its measurement system, is, as a result, greater.

The technological innovation that the flying machine was in its day benefited this nation immensely. Other innovations pending today could benefit it as well.

This report is an assessment of the nation's measurement system, aimed at addressing measurement barriers with the goal to accelerate U.S. innovations. NIST hopes through this assessment to contribute to the realization of that goal. I hope that your reading of this report will lead in some way to your contributing to the realization of this goal as well.

Dr. Dennis A. Swyt
Director, NIST USMS Program

Cover clockwise from the top: © Robert Rathe, © Robert Rathe, © Geoffrey Wheeler, stock photo, Beamie Young/NIST, stock photo, stock photo; center: © Corbis. Page 1 large photo: NIST; upper left: © Robert Rathe; middle left: Barry Gardner; lower left: Courtesy HDR Architecture, Inc./Steve Hall © Hedrich Blessing. Page 4 large photo: Lorelle Mansfield/NIST; upper right: stock photo; middle right: © Corbis; lower right: stock photo. Page 7 upper: Barry Gardner; lower: NIST. Page 11 large photo: © Robert Rathe; top left: stock photo; middle left: stock photo; lower left: stock photo. Page 13 upper: stock photo; lower: stock photo. Page 15 large: © Robert Rathe; upper left: Gail Porter/NIST; middle left: stock photo; lower left: Gail Porter/NIST. Page 20 large: © Robert Rathe; upper right: NIST; middle right: stock photo; lower right: NIST. Page 26 © Corbis. Page 32 NIST. Page 36 large: N. Miller and A. Clark/NIST; upper left: © Robert Rathe; middle left: © Robert Rathe; lower left: © Robert Rathe. Page 44 large: © Robert Rathe; upper left: Barry Gardner; middle left: Barry Gardner; lower left: Signe Seidelin and John Chiaverini/NIST. Photos on pages not listed above are stock photos.

Executive Summary

Introduction

The National Institute of Standards and Technology (NIST) has teamed with the private sector and others to undertake an assessment of the United States Measurement System (USMS), with a focus on technological innovation. The 2005 Council on Competitiveness report, *Innovate America*, notes that, "Innovation will be the single most important factor in determining America's success through the 21st century," and further asserts that the acceleration of innovation is critical for the United States to maintain its competitive edge in the world economy. Technological innovation is taken to be that part of the innovation process relating to the introduction into the marketplace of new technology. Fundamental and potentially transformative technological innovations in nanotechnology, bio-medicine, and intelligent machines hold great promise. Advanced measurement capabilities are essential to innovation in every major economic area and at every stage of the innovation process. Advanced tools and measurements are required to innovate—to design and incorporate new or better features into the kind of next-generation products and processes necessary for the United States to compete effectively and stay ahead in the global marketplace.

The United States Measurement System

The USMS is the complex network of all private and public organizations that develop, supply, use, or ensure the validity of measurements. It is an essential infrastructure, woven into the fabric of our market economy, supporting industry, commerce, government, research, and trade as well as homeland security, defense, health, safety, consumer protection, and other national interests. Encompassing the methods, standards, instruments, and private- and public-sector organizations involved in measurements of products and processes, the USMS is vital to the production and service sectors of the U.S. economy.

In the United States, measurement matters to technology and innovation:

- This year the U.S. semiconductor industry will spend $9 billion on measurement equipment, citing measurement challenges as a major barrier to continued miniaturization of circuits.
- The electric power grid that links the 10,000 generating stations in the United States must be synchronized to within one millionth of one second per day and the Global Positioning System (GPS) to one billionth.
- The U.S. Army requires calibrations traceable to national standards for 58,000 different types of equipment in order to maintain the operational readiness of its weapons systems.
- Improved accuracy of reference measurements for emissions of sulfur in oil refining and steel production has been estimated to have produced $440 million in cost savings and other benefits.
- Software errors due to ineffective testing cost the U.S. economy $60 billion annually.
- The United States spends more than $100 billion per year on measurements in health care, incurring increased costs due to errors in measurement. For example, in a cancer screening trial participants spent an extra $1,000 a year in medical expenses due to false-positive results.

The Assessment Process

This assessment seeks to determine the capability of the USMS to sustain the nation's ever-present need to enhance its performance as a world leader in innovation. NIST undertook several activities from October 2005 to June 2006 to accomplish this goal:

- conducted 15 NIST-industry workshops
- interviewed industry representatives about innovation-impeding measurement problems facing U.S. industry, which were documented as case studies
- reviewed 164 industry technology roadmaps and extracted measurement needs
- contacted executives, in an outreach effort, at more than 100 businesses and trade organizations

In total, more than 1,000 people contributed to this unique assessment of the USMS.

The assessment resulted in the documentation of 723 innovation-impeding measurement problems authenticated by industry. This sample of U.S. industry's unresolved measurement problems is considered to be sufficient to represent measurement barriers impeding technological innovation confronting the USMS. The assessment process consisted of the following:

- content analysis of measurement needs abstracted from industry technology roadmaps
- characterization into various categories of the measurement needs identified in workshops and documented by NIST and industry in authenticated case studies
- application of an inferential analysis methodology to the collected measurement needs, whether derived from roadmaps or case studies
- authentication of the findings from the inferential analysis
- interpretation of the authenticated findings to arrive at judgments about the USMS

Findings from the Assessment Process

Outputs of the inferential analysis process form the basis for findings regarding measurement barriers to technological innovation. Findings were obtained for 11 individual sector/technology areas defined by this assessment and for all the sector/technology areas taken together. These findings were authenticated by representatives of industry to verify their validity, relevance, and significance. This also was done for case-study measurement needs. The findings for all sector/technology areas taken together are the following:

- Fundamentally new measurement technologies are required to overcome limitations of accuracy, which are the most prevalent type of measurement barrier to technological innovation across all sector/technology areas.
- The absence of accurate sensors for real-time monitoring and control of manufacturing processes and environmental conditions poses a significant barrier to innovation that spans multiple sector/technology areas.
- A lack of standards, benchmarks, metrics, and protocols for assessing system-level performance of new technologies, including the compatibility and interoperability of hardware and software systems, is a substantial measurement barrier in a number of sector/technology areas.

Conclusions of the Assessment

Distilled from the full set of 723 measurement needs documented for this study, the conclusions reported here provide a system-wide perspective. They are high-level judgments: about the overall structure of the USMS; about challenges to the system posed by the economic imperative for continuing technological innovation; and about possible responses to those challenges.

The following conclusions, while high level and relatively general in nature, represent a first step toward understanding and addressing system-level weaknesses that diminish the ability of the USMS to support innovation in a rapidly changing technology environment and an increasingly competitive global economy.

Structure and Function of the USMS

- The USMS must provide a national measurement infrastructure for the nation to keep pace with the measurement needs of a growing, rapidly changing, technologically sophisticated economy.
- Novel, multidisciplinary approaches often will be required to meet new types of measurement needs, significantly extending the established USMS structure and paradigm.
- The USMS must evolve in concert with the international measurement system to enable U.S. companies, including technology innovators, to meet the growing number of measurement-based standards that influence access to and transactional efficiency in the global marketplace.

Challenges to the USMS Posed by Technological Innovation

- Measurement innovation (breakthroughs in measurement capabilities) often will be a critical determinant of successful technological innovation in nearly all sectors of the economy.
- The USMS must anticipate and deliver innovations required to meet measurement needs of producers and users of new technology in the manufacturing sector, as well as users of new technology in the service sector.
- To achieve the promise of nanotechnology—an area that may yield the most important technological innovations of the first quarter of the 21st century—major innovations in measurement science and measurement technology are required.
- Successful technological innovation ultimately hinges on the timely availability of production-ready, advanced measurement capabilities.
- The inability to adequately measure system performance (especially the performance of software and information technology hardware) limits the effectiveness and application of new technologies in important service industries.
- New measurement capabilities are required to support emerging technologies for sensing and controlling a wide array of properties and parameters in applications critical to industrial competitiveness as well as to national security and human health and safety.
- Technological innovation has in some cases been stalled due to the lack of measurement technology to assure and verify compliance or to resolve questions regarding potential risks and hazards that emerging technologies may pose.

Responding to USMS Challenges

- Pre-competitive, collaborative R&D is an effective vehicle for addressing needs for new measurement technologies, many of which will have broad utility.
- Federal research organizations and other public-sector organizations that are a part of the USMS will be challenged to prioritize needs within a growing inventory of measurement-related obstacles to technological innovation.
- USMS stakeholders, particularly supporters of fundamental research, need to strengthen the two-way link between advanced measurement capability and the scientific discoveries that become the basis for future technologies.
- The measurement barriers to technological innovation identified in this assessment of the USMS are clear and compelling and call for concerted efforts by the private and public sectors to achieve timely resolution.

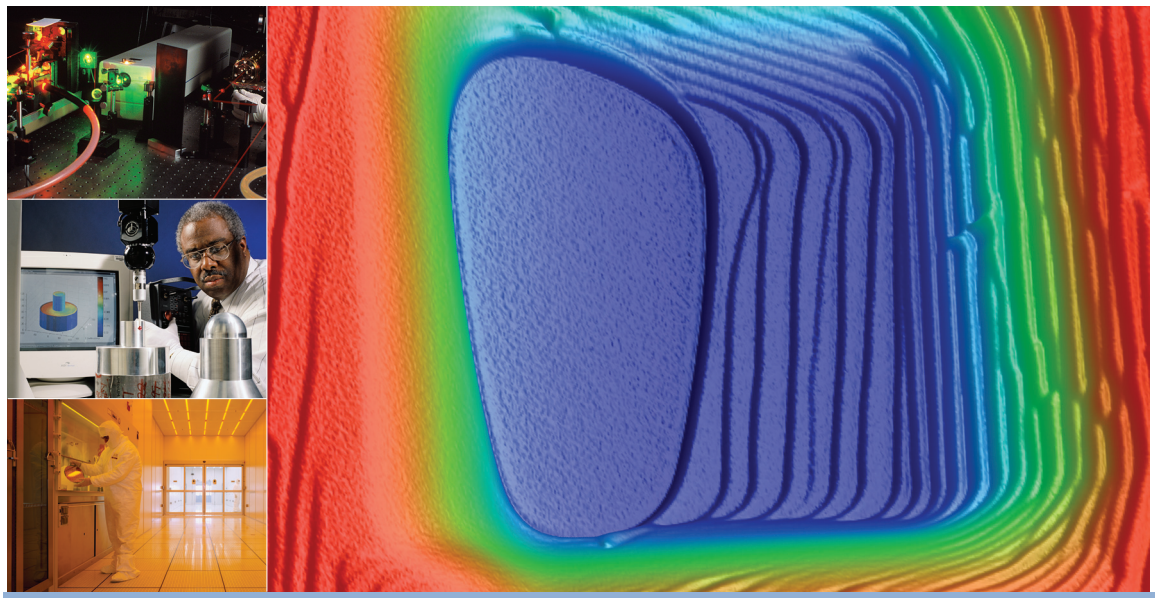
Next Steps

This report makes recommendations for action by all USMS stakeholders, acting individually and in collaboration, to enhance USMS capabilities and, in turn, to accelerate technological innovation. Participation from across the USMS is essential, given the breadth and diversity of the USMS and the challenges it faces. This assessment has identified seven specific actions to be taken as next steps.

NIST, in its unique role as the nation's national measurement institute, has committed to participate in each of the seven recommended actions:

- promoting awareness of critical measurement needs identified in this assessment throughout the measurement research community
- identifying strategies to bolster the effectiveness of USMS solution providers and accelerating development and delivery of measurement technologies that respond to measurement problems impeding innovation
- fostering collaboration to accelerate measurement breakthroughs
- encouraging industrial sectors to identify and prioritize measurement needs
- facilitating pursuit of solutions to specific industry measurement problems documented in this assessment
- identifying shared measurement needs and opportunities for synergy across industries and research areas
- fostering strategic public-sector investments in measurement R&D to accelerate technological innovation by:
  - keeping end users and solution providers informed of federal measurement capabilities
  - incorporating insights from this assessment into strategic and program plans
  - establishing an explicit agenda for measurement innovation

NIST will use this assessment as a means to focus its own work in support of U.S. innovation and competitiveness. It also will partner with other stakeholders in both the private and public sectors to focus organizational, sectoral, and cross-sectoral attention on overcoming the most significant measurement-related barriers to innovation. Feedback on this assessment from stakeholders in industry and government will be solicited and used to improve and guide the next steps described above.



I. Introduction

The ability to innovate and apply new technology is central to our nation's future. In fact, the fiercely competitive global economy demands that innovation become a core competency, not only for businesses and industries, but also for the nation as a whole.

Recent studies have highlighted the critical role played by innovation in science and technology to the continued success of the U.S. economy. The Council on Competitiveness report, *Innovate America*, notes that, "Innovation will be the single most important factor in determining America's success through the 21st century," and further asserts that the acceleration of innovation is critical for the United States to maintain its competitive edge in the world economy.[1]

A recent report published by the National Academies, *Rising Above the Gathering Storm*, notes that, "Although many people assume that the United States will always be a world leader in science and technology, this may not continue to be the case inasmuch as great minds and ideas exist throughout the world. We fear the abruptness with which a lead in science and technology can be lost—and the difficulty of recovering a lead once lost, if indeed it can be regained at all."[2]

In February 2006, President Bush said, "One of the great engines of our growing economy is our nation's capacity to innovate." The situation facing the U.S. economy is summed up in the President's *American Competitiveness Initiative*, which states that, "America's economic strength and global leadership depend in large measure on our nation's ability to generate and harness the latest in scientific and technological developments and to apply these developments to real world applications."[3]

Advanced measurement capabilities are essential to innovation—in every major economic area and at every stage of the innovation process. Research represents the inception of revolutionary technologies of the future; progress in such research depends on advanced measurement capabilities that are fundamental to the exchange of the resulting new knowledge and its refinement into experimental applications.

"One of the great engines of our growing economy is our nation's capacity to innovate."

–President George W. Bush

Ultimately, new, factory-ready measurement tools are essential for cost-effective manufacturing and efficient marketing of leading-edge products and for the integration of these products with other advanced technologies. Advanced tools will be required to design and incorporate new or better features into the next-generation products that will be necessary for the United States to stay ahead in the global marketplace.

To help ensure that these capabilities will be ready when needed, the National Institute of Standards and Technology (NIST) has teamed with the private sector and others to undertake an assessment of the United States Measurement System (USMS) with a focus on technological innovation.

This assessment concentrates on that part of the innovation process that relates to the introduction into the marketplace of new technology. The aim of the assessment is to determine whether the USMS, a vital component of our underpinning technology infrastructure, is adequate to sustain the nation's ever-present need to improve its performance as a world leader in innovation.

The ability to measure new things in new ways is critical to U.S. industry.

Staying ahead in the race to innovate is critical if the United States is to maintain a key competitive advantage, foster productive investment, and create new jobs.

A Defining Moment

This assessment was initiated at an important stage in the evolution of the global economy. Competition in markets for high-value-added products and services is intensifying in two ways—first, as more foreign nations and companies increase their investment in R&D to generate innovative products, and second, as more nations promote their domestic measurements and standards in the global marketplace. Japan has singled out enhancement of its measurement infrastructure as a strategic priority in its science and technology plan for the years 2006–2010. China is proffering its nanotechnology measurement standards for international adoption. The European Union is instituting demanding requirements for assuring the accuracy of measurements used to manufacture certain types of medical equipment and other high-technology products.

Measurements Matter

- This year the U.S. semiconductor industry will spend $9 billion on measurement equipment, citing measurement challenges as a major barrier to continued miniaturization of circuits.
- The electric power grid that links the 10,000 generating stations in the United States must be synchronized to within one millionth of one second per day and the Global Positioning System (GPS) to one billionth.
- The U.S. Army requires calibrations traceable to national standards for 58,000 different types of equipment in order to maintain the operational readiness of its weapons systems.
- Improved accuracy of reference measurements for emissions of sulphur in oil refining and steel production has been estimated to have produced $440 million in cost savings and other benefits.
- Software errors due to ineffective testing cost the U.S. economy $60 billion annually.
- The United States spends more than $100 billion per year on measurements in health care, incurring increased costs due to errors in measurement. For example, in a cancer screening trial participants spent an extra $1,000 a year in medical expenses due to false-positive results.

Nanotechnology exemplifies the challenge of the new landscape of global competition on emerging technologies. It is a measurement-intensive and still largely experimental domain. As industries, universities, and government agencies work to master this and other emerging technologies, many organizations are calling for more focused and cooperative efforts to surmount new types of measurement barriers. As interacting technologies and the linkages among organizations grow and diversify, the demand for accurate, reliable measurements will experience proportionate growth. Such measurements will become an integral part of consumer expectations for product performance evaluation in the marketplace. These measurements also will be required to support efficient transactions in markets for future advanced technology products.

The USMS, NIST, and This Assessment

The USMS is the complex of all of the private and public organizations that develop, supply, use, or ensure the validity of measurements. These measurements are vital to the production and service sectors of the U.S. economy. The USMS functions to deliver measurements that meet the nation's measurement needs.

Despite its broad utility and diverse composition, the USMS is usually unseen but is deeply embedded in the nation's commercial technology infrastructure.

Unmet measurement needs—or ineffectively delivered measurement-based services—can slow the progress of research and impede innovation, consequences that undermine the competitiveness of U.S. industry and jeopardize the nation's economic future.

Resolution of measurement needs can speed the progress of research, accelerate innovation, and contribute to supporting the competitiveness of U.S. industry and the nation's economic well-being.

NIST, an agency in the U.S. Department of Commerce, plays a central role in the USMS. By law, NIST is responsible for maintaining U.S. national standards of measurement, a job that the agency and its predecessor (the National Bureau of Standards) have carried out since 1901. As the nation's measurement laboratory, NIST chose to initiate an examination of the USMS, specifically focusing on measurement-related barriers to technological innovation. NIST recognizes that a healthy, effectively performing measurement system is a responsibility shared across the USMS. At the same time, NIST believes that this assessment is clearly needed as an essential step toward ensuring that the USMS remains a valuable contributor to the innovation efforts of organizations and the nation as a whole.

Unmet measurement needs can slow the progress of research and impede innovation.

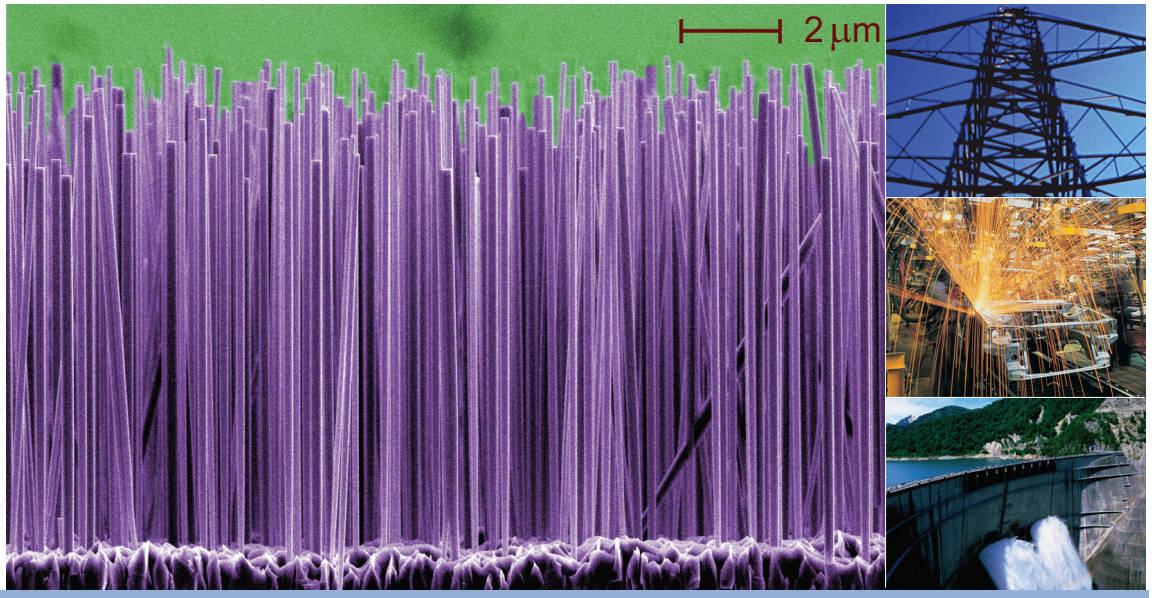
Resolution of measurement needs can accelerate innovation.

For its assessment, conducted from October 2005 to June 2006, NIST solicited broad input on measurement needs that pose barriers to innovation. For this effort NIST undertook the following activities:

- conducted 15 NIST-industry workshops that engaged more than 500 participants in identifying measurement barriers to innovation (Appendix A)
- interviewed industry representatives about innovation-impeding measurement problems facing U.S. industry which were documented as case studies (Appendix B)
- reviewed 164 industry technology roadmaps and extracted measurement needs (Appendix C)
- contacted executives, in an outreach effort, at more than 100 businesses and trade organizations

In total, more than 1,000 people contributed to this unique undertaking (Appendix D).

The remainder of this report provides an overview of the USMS, describes the methodology of the assessment, presents the results of the assessment, and details the follow-up actions that NIST intends to take in response to the assessment. The full report is available on the NIST Web site at http://usms.nist.gov.



II. Purpose and Elements of the USMS

The USMS is an essential infrastructure, woven into the fabric of our market economy and society. It supports industry, commerce, government, research, and trade as well as homeland security, defense, health, safety, consumer protection, and other national interests.

The USMS is essential to the function and performance of the national economy.

In terms of technological innovation and economic growth, the USMS provides, or enables, measurement capabilities, tools, and services that are employed throughout the process of innovation. This process ranges from research (the source of new knowledge) to the diffusion of new ideas and nascent technologies and, ultimately, to the production and sale of new products and services that embody the results of the innovation process.

In this assessment, the USMS is taken to include the methods, standards, instruments, and private and public organizations involved in measurements of products and processes or in other measurement-related activities relevant to the function and performance of the national economy. It includes both measurement suppliers and users, two broad categories with many divisions notable for both their variety and their vastly different requirements. Measurement and related terms are defined in Figure 2.1.

For clarity, it is important to distinguish between the USMS and a necessary core element common to all industrialized economies: the National Measurement System (NMS). Previous studies of the economics of measurement, undertaken in the United States and several other nations,[4] focused almost exclusively on the NMS within these countries.

As depicted in Figure 2.2, the NMS is situated within—and operates in support of—the broader USMS. In the United States, as elsewhere, key functions of the NMS are 1) to ensure the reliability and uniformity of measurement results, as is required for orderly markets and technological innovation; and 2) to enable comparability of

measurements through linkages to the international measurement system, as is required to integrate the United States with the global economy.

Key elements of the NMS and several other components of the USMS, as shown in Figure 2.2, are discussed in the remainder of this chapter. In the context of technological innovation, the scientific research enterprise plays an especially critical underpinning role within the USMS. Also as indicated in the figure, the ultimate effectiveness of the USMS depends on private- and public-sector inputs and participation, as well as on cross-sector collaboration.

International System of Units

Most measurements made for economic purposes quantify properties of "things." Such measurements are primarily rooted in physical mechanisms and processes described by the laws of physics.

The International System of Units (SI) is globally accepted. Its goal is to define a system of measurement units directly based on quantities of nature that do not vary with time or circumstance (e.g., the meter—the unit of length—is defined in terms of the speed of light). Basing the SI on the laws of physics provides an unambiguous reference for comparison, and it facilitates the dissemination of accurate measurements in commerce, industry, and science.

The SI is the modern descendant of the 1875 Convention of the Meter, a treaty that included the United States as the second of 17 original signatory nations. The modern SI dates back to the early 1960s. Both metric and customary units are presently legal and in use in the United States.

The Convention of the Meter also established the International Committee for Weights and Measures (CIPM) and the International Bureau of Weights and Measures (BIPM), which are charged with ensuring worldwide uniformity of measurements and traceability to SI units, and with improving the SI. The CIPM fulfills these responsibilities through a series of Consultative Committees. Committee members are representatives of national measurement institutions from the signatory nations of the Convention. In addition, the BIPM, headquartered near Paris, France, performs its own laboratory work. As the fields of science and technology advance, values of existing units are refined and new derived units may be established, all by international agreement through the General Conference on Weights and Measures.

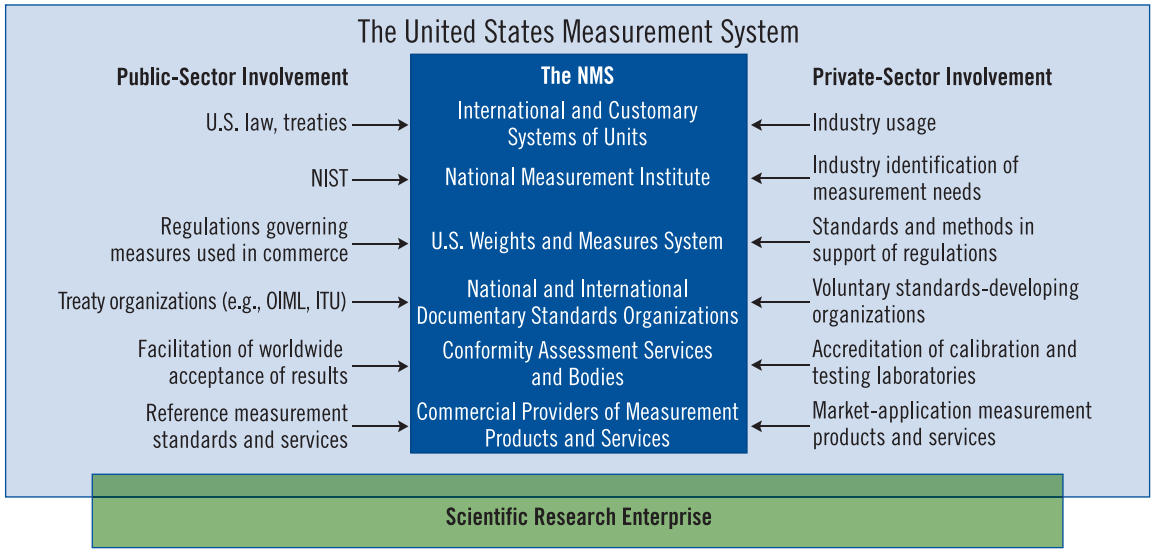
Figure 2.1. Useful Terms

Measurement: The process of quantitatively comparing a variable characteristic, property, or attribute of a substance, object, or system to some norm.

Measurement result: The quantitative result of the measurement process, achieved to a level of certainty influenced by a combination of technical and human elements that include measurement methods, instruments, information, standards, and institutions.

Measurement system: The entire set of technical and human elements involved in producing measurements for an intended purpose.

Figure 2.2. The USMS and the NMS Within It



Measurement traceability and comparability across nations also is facilitated through bilateral and multilateral agreements and through Regional Metrology Organizations (RMOs), such as the Inter-American Metrology System (SIM) and the Asia Pacific Metrology Program (APMP). NIST serves as the U.S. representative in SIM.

National and International Documentary Standards Organizations

An estimated 80 percent of world trade is influenced by standards for products, processes, and systems, as well as by regulations embodying these standards. In turn, measurement-related requirements (and specified tests or inspections for demonstrating compliance with those requirements) are significant components of most standards and regulations.

The SI is the globally accepted system of units of measurement.

Documentary standards development in the United States is led by the private sector, aligned with industry sectors, and largely demand driven. Individual standards are typically developed in response to specific concerns and constituent issues expressed by both industry and government. Government agencies are major users of standards, in both regulation and procurement. Agency representatives also participate in the development of all kinds of voluntary standards, including test methods, specifications, and other measurement-related standards.

While there are more than 450 standards-developing organizations (SDOs) in the United States, about 20 of these develop 80 percent of the standards in use by both the private sector and government. Many of these documents have a substantial measurement component.

Some U.S.-domiciled organizations develop standards that are used globally to meet specific sector needs, including electronics and materials standards, boiler and pressure vessel codes, and specifications for piping and fuels. These organizations include the Institute for Electrical and Electronics Engineers (IEEE), ASTM International, the Society of Automotive Engineers, ASME International, the Aerospace Industries Association, and American Petroleum Institute, among others. Membership in these organizations is on an individual or organizational basis.

International measurement-related documentary standards also are developed by treaty organizations (with governments as members); private, voluntary organizations with memberships composed of national entities; and consortia and forums, whose memberships are typically company and industry based. These include the following organizations:

- The International Organization of Legal Metrology (OIML) is a treaty organization that develops model international standards pertaining to measurements used for regulatory purposes, such as commodity exchange and environmental monitoring.
- The International Telecommunications Union (ITU) is a treaty organization that focuses on standards for information and communications technologies.
- The International Organization for Standardization includes the national standards bodies of 149 countries and develops standards for nearly every industrial sector.
- The International Electrotechnical Commission (IEC) focuses on electronics standards.

The United States is prominently involved in standards activities conducted in each of these organizations. NIST is the technical representative to OIML, on behalf of the Department of State. The State Department represents U.S. interests directly in ITU. U.S. interests in ISO and IEC are represented by the American National Standards Institute (ANSI), a federation of SDOs, companies, trade associations, government agencies, and consumer groups.

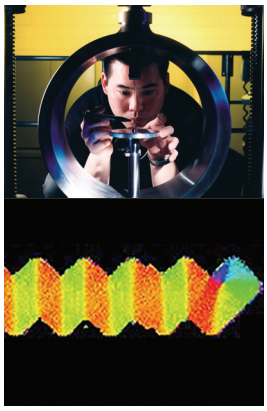
National Measurement Institute

By federal statute, NIST is the National Measurement Institute (NMI) of the United States, responsible for national standards of measurement and, within the SI framework, for their compatibility with the standards of other nations. To achieve international compatibility in measurement, NIST works with its counterpart NMIs. These government-established entities exist in nearly every nation.

The role of NIST as an NMI is multifaceted:

- representing the United States in the Consultative Committees of CIPM and in SIM
- establishing, maintaining, and disseminating national standards of measurement, basing them on its realizations of SI units and linking them globally through international comparisons conducted with other NMIs
- collaborating with BIPM and other NMIs to ensure that realizations of the definitions of the base SI units—and those units derived from these base units—have accuracies that stay ahead of industrial needs
- providing U.S. industry, the scientific community, and federal, state, and local governments with access to national standards of measurement, often at the highest level of accuracy in the world. This is accomplished through research and the resulting measurement services:
  - calibration of customers' precision measuring instruments and physical standards
  - provision of reference materials of the highest metrological quality
  - provision of evaluated reference data
  - provision of measurement science results that enable new measurements and the development of new measuring instruments

NIST's maintenance of base SI units (length, mass, time, electric current, temperature, amount of substance, and luminous intensity) and a growing number of derived units underpins private-sector investments in measurement technology and standards. Realizations of these units provide the necessary means for assessing the quality of the myriad measurements made daily during the design, production, inspection, and sale of goods and services. They provide benchmark references for so-called second- and third-tier suppliers of measurement services, instruments, and related products, as well as for the users of these measurement solutions. Examples of these suppliers and users include private-sector test and calibration laboratories, manufacturers of measurement tools and control systems, and the businesses that rely on these services and tools. Additional details of NIST's realization and dissemination of the units of the SI are provided in Appendix E.



In 1999 NIST was one of the original signatories to the CIPM Mutual Recognition Arrangement. This agreement set a framework for establishing the degree of equivalence of measurement standards maintained by NMIs worldwide. A key objective was to assure that measurement results traceable to different NMIs could be accepted across international borders, thereby improving transactional efficiency and eliminating potential regulatory burdens and technical barriers to international trade.

U. S. Weights and Measures System

The U.S. Weights and Measures System, a subset of the USMS, is stipulated in the U.S. Constitution. It is composed of organizations that make, use, and ensure the validity of measurements involved in the buying and selling of products and services on the basis of weight, measure, or count. These commercial transactions account for about half of the U.S. economy. The U.S. Weights and Measures System facilitates fairness in the marketplace. It enables accurate weighing and measuring devices, from truck scales and parking meters to gasoline pumps and price scanners.

Commercial transactions based on weight, measure, or count, make up about half of the U.S. economy.

The system includes the following key elements:

- scale and meter manufacturers, consumer product manufacturers, retailers, consumer agencies, and government agencies
- an extensive network of local and state weights-and-measures programs
- the National Conference on Weights and Measures (NCWM), a private, nonprofit organization with representatives from industry, the states, and the federal government, develops standards, test procedures, and model laws and regulations on weights and measures
- NIST, which provides technical assistance to the NCWM as it develops standards, regulations, and methods of practice

Except for the following federal responsibilities, laws and regulations governing weights and measures used in commerce are generally created—and enforced—at state and local levels. However, the NCWM works to achieve uniformity across jurisdictions to reduce barriers to interstate commerce.

At the federal level, Congress has assigned weights-and-measures regulatory authority to three organizations:

- U.S. Department of Agriculture, for the export of meat and poultry products and grains
- Food and Drug Administration, for pharmaceutical safety and labeling
- Federal Trade Commission, for product labeling and advertising

At the international level, OIML oversees efforts to promote harmonization of performance requirements for measuring instruments that are subject to laws or regulations.

Conformity Assessment Services and Bodies

Sampling and testing, inspection, product certification, and other conformity assessment procedures provide a means of ensuring that products, services, or systems meet customer or regulatory requirements. These procedures also provide assurance of consistency from product to product, service to service, or system to system. Other examples of conformity assessment include quality and environmental system assessments and registrations as well as formal programs for accrediting the competence of organizations that provide conformity assessment services. Evaluation and recognition of the capabilities of accreditation programs comprise another aspect of conformity assessment.

Each of these activities is a distinct operation, but they are closely interrelated. Conformity assessment activities form a vital link between standards and products. These standards typically define necessary characteristics or requirements for products and specify tests and measurements for achieving and demonstrating compliance.

Conformity assessment in the United States is complex, multifaceted, and decentralized, with more than 100 organizations accrediting calibration, measurement, and testing laboratories. Unfortunately, businesses that use the services of accredited laboratories often find that the results are not universally recognized. Consequently, one customer may require a business to demonstrate conformity with requirements through testing done by a laboratory accredited by a specific organization, while another customer may stipulate a testing laboratory with a different accreditation.

Three U.S.-based organizations—the International Accreditation Service, National Voluntary Laboratory Accreditation Program, and American Association for Laboratory Accreditation—along with 49 other laboratory accreditation bodies from 42 economies around the world, are signatories to the International Laboratory Accreditation Cooperation (ILAC) Mutual Recognition Arrangement (MRA). Signatories accept, on the basis of a peer evaluation process, that the accreditations granted by other signatories are accomplished through a process that is in conformance with internationally accepted standards and practices. Further, signatories promote the acceptance of calibration, testing, and/or inspection results within the respective scopes of accreditation for laboratories accredited by any of the MRA signatories.

The aim of the ILAC MRA is to develop a global network of accredited testing, calibration, and inspection facilities that can be relied on to provide accurate data. To that end, ILAC and the CIPM signed a memorandum of understanding in March 2005, recognizing the important link between accreditation and traceability to national standards. ILAC's ultimate aim is increased use and acceptance by industry as well as government of the results from accredited laboratories, including results from laboratories in other countries so that a product tested once can be accepted everywhere.

Commercial Providers of Measurement Products and Services

Given the scale and diversity of the U.S. economy, the number of businesses that provide measurement products and services is proportionately large. The composition of this hybrid sector is commensurately diverse and includes the following:

- commercial suppliers of measurement standards
- measurement, calibration, and testing laboratories and services
- suppliers of measurement instruments and devices
- measurement consulting and training services

Because of the tremendous variety of test and measurement tools and services required to support the U.S. economy, no single industrial classification encompasses all the businesses that supply these tools and services. Specific segments within the "measurement sector" range from manufacturers of process control equipment to makers of meters for measuring consumption of water, gas, or electricity, and from suppliers of laboratory analytical equipment to makers of tools for inspecting semiconductor wafers and measuring the thickness and quality of thin films. Figure 2.3 provides examples of selected measurement instrument industries and their characteristics.

The measurement-intensive nature of processes and the required levels of measurement accuracy vary considerably across industries. Generally speaking, the more advanced and complex the technologies incorporated into a commercial product, the greater the need for measurement support.

For example, a NIST study found that the semiconductor industry spent about $5 billion on measurement (not including labor and overhead) in 2001. This investment has been growing at a rate of about 15 percent per year, raising this expenditure to an estimated $9 billion in 2006.

Assuming that the nation's entire high-technology sector invests about the same percentage on measurement as does the semiconductor industry, it would have spent about $70 billion on measurement in 2004.

The semiconductor industry alone will spend an estimated $9 billion on measurement in 2006.

Scientific Research Enterprise

The scientific research enterprise forms the foundation of the USMS, while also serving as an element of the USMS. Science is, to a large extent, the quantitative, predictive description of the observable behavior of the things of the physical world. Science rests on measurement. Measurement rests on science. The discoveries of science enable and propel advances in measurement technology. Advances in measurement technology enable and propel advances in science. Research and advances in the most basic sciences—physics, biology, chemistry—and in measurement science proceed in tandem. And, most importantly, technological innovation rests on the availability of and access to new knowledge that is produced primarily by scientific research.

Several principal elements of the U.S. scientific research enterprise are foundational elements of the USMS:

- mission-directed fundamental research in measurement science conducted by NIST and other parts of the research enterprise
- curiosity-driven basic research in science conducted by universities
- mission-directed applied research conducted by government agencies
- business-directed applied research conducted by industry that they report publicly
- measurement-technology R&D conducted by government agencies, including NIST
- measurement-technology R&D conducted by industry that it reports publicly

The USMS has been described here as a complex system of independently operating entities. Given this description, how should an assessment of the USMS be conducted? What should it include? Chapters 3 and 4 provide the parameters of this assessment of the USMS, along with the methodology used to conduct it.

Figure 2.3. Examples of Measurement Instrument Industries, 2004*

Industry	No. of Companies	Value of Shipments
Aeronautical, Nautical, & Navigational Instruments	86	$2.4 billion
Analytical & Scientific Instruments (except optical)	296	$8.8 billion
Automatic Valves	154	$2.2 billion
Equipment for Testing Elec., Radio & Comm. Circuits, & Motors	310	$9 billion
Process Control Instruments	481	$6.5 billion

* Economic and Statistics Administration, U.S. Census Bureau, *Selected Instruments and Related Products: 2004; Current Industrial Reports*, August 2005.

III. Focus on Innovation: The Importance of Measurement

"The United States achieved global leadership in innovation in the 20th century. And the capacity to innovate is the foundation for bringing our competitiveness into fruition."

National Summit on Competitiveness 2005

Technological innovation drives the nation's economic growth and sustains U.S. competitiveness in world markets. In nearly all industrialized nations, progress in developing and applying technology drives growth in economic output (gross domestic product). According to economic studies—beginning with those of Nobel Laureate Robert Solow—technology accounts for more than half of U.S. economic growth in the last 60 years. Statistics within the United States mirror this fact. Growth and productivity represent the primary means of increasing national prosperity, and new technology has fueled about 75 percent of growth in U.S. productivity. And since the mid-1990s, technology has been credited with driving an even larger share of productivity gains.

As international competition increases, technological innovation has become the chief differentiator for U.S. industry, a source of comparative advantage to counter low-cost manufacturing or labor. However, more and more developed and developing nations recognize that improving their technological performance is key to future economic growth. Many of these countries are rapidly ascending from the ranks of imitators to become innovators.

Recognizing the strategic importance of technological innovation, NIST's assessment of the USMS looks at unmet measurement needs that impede our ability to develop and commercialize new technology. The pivotal role that innovation will play in the nation's economic future is underscored by the President's American Competitiveness Initiative and in a growing collection of evaluations of U.S. prospects for sustaining technology-driven economic growth. Nearly all have concluded that innovation will be vital to the nation's economic success.

Innovation will be the single most important factor in determining America's success through the 21st century.

A focus on innovation, however, does not fully capture other vital functions and contributions of the USMS. For example, measurement needs tangential to innovation may be key to furthering the mission-related goals of federal agencies or to improving safety, health, and other determinants of the nation's well-being.

Unmet measurement needs impede our ability to develop and commercialize new technology.

U.S. industrial competitiveness is necessary to sustain long-term economic growth. Technological innovation, in turn, is critical to industrial competitiveness and to the degree of productivity growth necessary for U.S. citizens to improve their standard of living. Both benefits serve the national interest and warrant the focus on innovation of this initial USMS assessment.

The Role of Measurement in Innovation

Technological innovation is critical to U.S. industrial competitiveness and long-term economic growth.

The underpinning or infrastructural role of advanced measurement capabilities is multifaceted. Every phase of research and development (basic and applied research and exploratory development) and the subsequent manufacturing and commercialization stages of innovation require measurement tools and related standards. During the discovery stage, accepted measurement methods are necessary for interpreting, communicating, replicating, and extending the results of research. At the commercialization end of the spectrum, the role is just as significant. Market acceptance of new high-technology products may be contingent upon the availability and acceptance of test and measurement methods necessary to verify product performance claims.

For example, a communications services company requires a range of testing standards to determine whether the thousands of kilometers of ultra-thin optical fiber it purchases will meet specifications for an assortment of performance attributes, such as bandwidth, signal-loss rates, and core-diameter consistency. Without such measurement capabilities, which are essential to sellers and buyers alike, growth of emerging high-tech industries would be hampered. Lack of measurement capabilities results in transactional inefficiencies that delay market acceptance and eliminate the "first-mover" advantage of innovating firms.

Methods of measurement, analysis, testing, and evaluation, along with relevant standards and related databases, function as "general-purpose technologies," valuable for their impact on the effectiveness, efficiency, and productivity of the innovation process. Like electricity and information technology, two of the most widely recognized general-purpose technologies, measurement tools have broad utility but can be leveraged in different ways. For example, new measurement capabilities enable the following:

- making it easier to invent and produce new products and processes
- working across functions to be adapted, enhanced, or extended, serving multiple uses, such as research and production, and they can be applied to a wide variety of commercial products and services
- enabling communication across stages of the innovation process and among collaborators
- increasing in value and utility as they diffuse more broadly within industries and across sectors
- complementing existing and emerging technologies

Although less apparent than electricity and information technology, measurement tools are just as ubiquitous. The capabilities that these tools enable may mean the difference between success and failure in realizing the promise of emerging technologies. That is, the ability to measure accurately, reliably, and cost effectively can set the

limits on what can be accomplished in the laboratory, on what can be realized on the factory floor, and on which products can be marketed at affordable prices. In short, what gets measured is often what gets done.

The most recent International Technology Roadmap for Semiconductors (2005) helps to illustrate this increasingly vital link between measurement and successful innovation. According to this roadmap, "As the industry moves further into the world of nanoelectronics, metrology,[5] including materials characterization, will take on greater challenges and become even more critical."[6] Examples of these challenges include measuring materials properties at sub-atomic dimensions and achieving control of atomic dimensions while maintaining profitable high-volume manufacturing.

Similar challenges confront many industries, many companies, and many laboratories—not just those aiming to control, manufacture, and assemble at the scale of atoms and molecules. The more than 700 measurement needs identified in this initial assessment of the USMS serve as compelling evidence that new or improved measurement capabilities are a collective requirement for leadership in innovation.

Technological Innovation and Measurement Innovation

In this assessment technological innovation is considered to be either a process or a physical entity. As a process, technological innovation is that part of the overall innovation process relating to the introduction into the marketplace of new technology. As a physical entity, technological innovation is the new technology itself.

Technological innovation is considered to occur in four stages. This conceptualization is consistent with that of a consensus of economists and is akin to others used to characterize product development. It shares with them limitations in representing the non-sequential, iterative, and conceptually messy processes of the real world. The four stages of technological innovation are:

- *applied research* specifically directed at realization of a particular new technology and encompassing invention and development of a prototype, if appropriate
- *production* to implement the processes for producing market quantities of the new technology as future product
- *market placement* of the new technology as product
- *end use* of the new technology product for its intended purpose

These stages of technological innovation are considered to be informed by what this report calls a technology developer's vision. This vision is the conceptual view of what the new technology will functionally do, who the user of the new technology will be, and what benefit to the user that new technology will yield. Central to the story of the Wright Brothers' encounter with a measurement barrier to technological innovation, cited in the foreword of this report, is their technology developer's vision—a machine for powered, controlled, heavier-than-air human flight.

Figure 3.1 illustrates the process of measurement innovation for addressing measurement barriers to technological innovation. Shown are the process of technological innovation, the

process of measurement innovation, and the relationship between the two when a measurement barrier occurs at a particular stage of technological innovation. If the measurement technology necessary to solve that problem does not exist, a measurement innovation is needed. Because a measurement innovation is itself a technological innovation, the measurement innovation process is the same as that for the technological innovation. It involves successively, applied research, production, market, and end use of the new measurement technology.

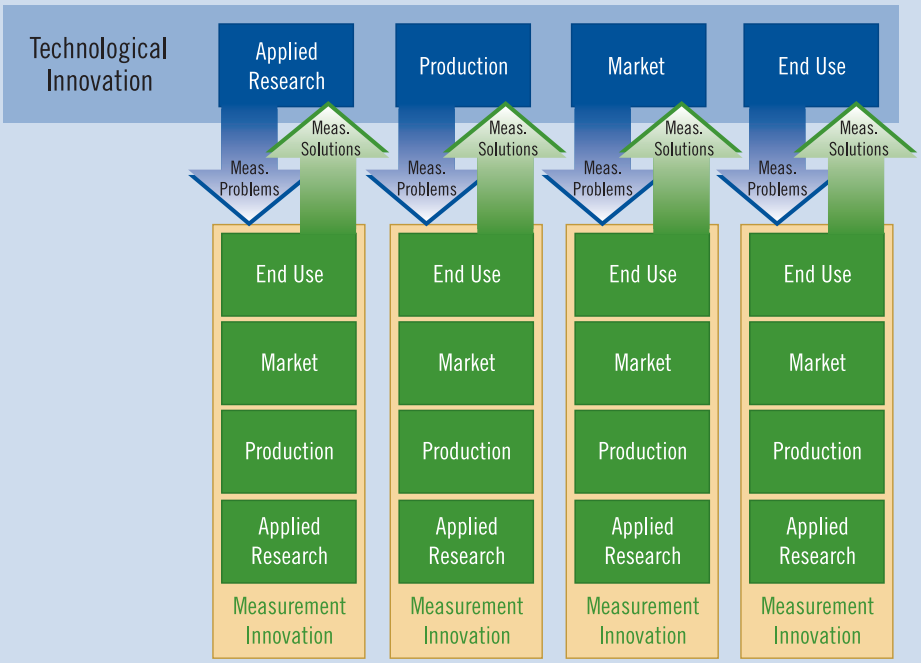
Roles of the Public and Private Sectors

In the United States, the public and private sectors play different, yet complementary, roles in the process of technological innovation:

- The public sector (government) supports basic research, which generates the new knowledge and scientific discoveries upon which new technologies ultimately are based.
- The private sector (industry) develops and commercializes technology.
- The public and private sectors jointly contribute to enhancing the technical infrastructure, including the USMS, that supports technological innovation.

The U.S. government seeks to create an environment that encourages investment in the pursuit of new technologies and helps to reduce shared barriers to innovation. Unaddressed measurement needs can impede the nation's innovation performance. Through this assessment, NIST aims not only to identify measurement problems that pose barriers to innovation, but also to identify steps toward effective solutions.

Figure 3.1. The process of measurement innovation for addressing measurement problems that pose barriers to the process of technological innovation



IV. Methodology of the Assessment

Information Gathering

This assessment of the USMS is based on the identification and analysis of measurement problems that confront U.S. industry and pose barriers to technological innovation. Each measurement problem represents a current, unmet industry measurement need.

The set of measurement needs identified for this assessment, while a sampling, nevertheless is sufficiently representative to yield good indicators of the USMS as a whole.

NIST identified hundreds of industry measurement needs across selected industries (sectors) and technology areas considered to be significant to the U.S. economy—either today or in the future.

This chapter summarizes the methodology that was used to identify, characterize, and analyze these measurement needs within and across sectors and technology areas. A detailed description of the methodology is contained in Appendix F.

Identification of Measurement Needs

The information used to document each measurement need was gathered from one or more of the following sources:

- published industry technology roadmaps
- USMS-affiliated industry workshops convened by NIST and other organizations to identify measurement problems in specific sectors or technology areas
- various combinations of industry reports, technical publications, and interviews, as documented by NIST staff
- submissions by individuals or organizations within specific industries

Submissions were solicited by NIST through outreach efforts to senior executives in 120 measurement-related industry, trade, standards, and professional organizations. NIST informed these executives of the USMS effort and invited participation to indicate industry measurement needs or authenticate measurement needs or findings. NIST also solicited input through news announcements, its USMS Web site, and briefings to various industry audiences.

Because technological innovation spans a broad range of activities—from basic research to product and process development and beyond—and often draws on the efforts of many individuals and organizations, measurement needs were pursued from four points of view, described below. The objective of this multiple-view sampling was to achieve a wide-angle snapshot of measurement barriers to technological innovation across a breadth of industries and technologies.

- **Industrial Sectors:** Three sectors—automotive, semiconductors, and IT software—were selected to generate a sample of industry-specific measurement needs. The industries that make up this sampling are economically and socially important as they depend heavily on technological innovation and are known to have measurement barriers to innovation.
- **Technologies:** Four broad technologies—nanotechnology, disaster first responder technology, biomedical imaging, and magnetic data storage[7]—were selected for the sample of technology areas. (See Appendix G.) These areas were selected because of their dependence on innovation, potential to yield numerous commercial applications, or relevance to important national needs.
- **Scientific and Engineering Disciplines:** Seven disciplines were selected—physics, chemistry, materials science, electrical and electronic engineering, mechanical and civil engineering, manufacturing engineering, and computer science and engineering—on the basis of their foundational relationships to new product and process technologies.
- **International System of Units (SI):** The units of the SI—both base units (length, mass, time, electric current, temperature, amount of substance, and luminous intensity) and derived units—were selected because of their centrality to the spectrum of measurements performed in industry, commerce, and science. (See Appendix E.)

Regardless of the sector, technology, discipline, or SI unit taken as the vantage point for identifying measurement problems that pose barriers to technological innovation, all participating scientists, industry representatives, and technology experts were presented with the same challenge whether they participated in workshops, abstracted technology roadmaps, or otherwise represented a measurement need. All were asked to respond to the following question: "From your position in this sector (be it an industry, technology area, scientific-engineering discipline, or field of measurement), what industry measurement problems do you see that pose barriers to technological innovation?"

Documentation of Measurement Needs

Basic units of input to this report are measurement needs, defined as unresolved industry measurement problems that pose technical barriers to economically important technological innovations. As mentioned previously, these measurement needs were identified in industry technology roadmaps; in workshops; in NIST staff syntheses from various combinations of industry reports, technical publications, and interviews; or in submissions by individuals outside NIST. Measurement needs from the latter three sources were documented following a standardized reporting format. The data fields of this format are listed in Figure 4.1.

Within this report, these one-page, stand-alone measurement need summaries are referred to as case studies. These case-study measurement needs appear in Appendix B.

Measurement needs abstracted from published technology roadmaps could be summarized in general terms only, as they were documented prior to this assessment, not documented explicitly for this purpose, and, in many cases, not detailed in information for all the fields in the case-study format.

Authentication of Measurement Needs

Measurement needs reported and analyzed in this assessment have undergone authentication. That is, they were independently verified as valid, relevant, and significant.

For measurement needs distilled by NIST technical staff, the facts asserted were authenticated by multiple sources external to NIST. These sources included the following:

- industry representatives and/or technology experts selected for their knowledge of the specific industry or technology in question
- public domain documentary references, including technology roadmaps
- reports from workshops having broad industrial representation

Measurement needs abstracted from industry technology roadmaps were considered to be self-authenticated. Each roadmap was produced by a group representative of that particular community and knowledgeable about the specific industry or technology area in question.

Measurement needs derived from USMS-affiliated, industry-needs workshops were considered to be self-authenticated. As a group, participants in each workshop met the criteria for authenticators. By design and mix of interests, the workshop groups were knowledgeable and representative.

Analysis of Gathered Information

The principal results of this assessment are based on several types of analyses of identified industry measurement needs:

- content analysis of measurement needs abstracted from industry technology roadmaps
- characterization into various categories of the case-study measurement needs identified in workshops, documented by NIST staff, or submitted by individuals outside of NIST
- inferential analysis of all the collected measurement needs, whether derived from roadmaps or case studies and whether derived from the perspectives of sectors, technologies, disciplines, or SI units
- authentication of the findings from the inferential analysis
- interpretation of the authenticated findings to arrive at judgments about the USMS

Content Analysis of Measurement Needs Abstracted from Industry Technology Roadmaps

An industry technology roadmap analysis was conducted. (See Appendix C.) Through the analysis process, the set of measurement needs derived from industry technology roadmaps was examined, trends in measurement needs within sectors were evaluated, and a review probing for key themes, synergies, and commonalities across sectors was performed.

Figure 4.1. Data Fields for the Case-Study Measurement Needs

- Technology at Issue
- Submitters
- Technological Innovation at Stake
- Economic Significance of Innovation
- Technical Barrier to the Innovation
- Stage of Innovation Where Barrier Appears
- Measurement-Problem Part of Technical Barrier
- Potential Solutions to Measurement Problem

Figure 4.2. Sector/Technology Areas

- Building and Construction
- Chemicals
- Defense and Homeland Security
- Discrete-Parts Manufacturing Including Automotive
- Electronics and Information Technology (IT) Hardware
- Energy, Power, and Environment
- Health Care Including Bioimaging
- IT Software
- Materials
- Nanotechnology
- Semiconductor Electronics

Characterization Analysis of Case-Study Measurement Needs

The measurement needs documented as case studies were analyzed according to various characteristics within seven major categories. (See Appendix B.)

- **Economic Sector/Technology Area:** In what part of the economy does the vision exist for the development of the particular technological innovation?
- **Stage of Technological Innovation:** Where along the spectrum, from applied research on a concept to end use of the product, is the technological innovation planned?
- **Is the Technological Innovation at Stake a Measurement Technology?** Is a new measurement technology the planned technological innovation?
- **Measurand:** What type of quantity is being measured?
- **Measurement Problem Posing Technical Barrier:** What is the measurement-related portion of the technical barrier that is inhibiting the technological innovation?
- **Potential Measurement Solution(s):** What possible routes can be followed to solve the measurement-problem part of the technical barrier?
- **Potential Solution Provider(s):** What private or public organizations, groups of organizations, and individuals might contribute to solutions to the measurement-problem part of the technical barrier?

Case-study measurement needs were first categorized according to *sector/technology area*, which encompasses the combination of the economic sector or the technology area with which a particular technological innovation is associated, as shown in Figure 4.2.

Next, the measurement needs within each sector/technology area were categorized according to specific characteristics of the data fields—*Measurement Problem, Solution to the Measurement Problem*, and *Potential Solution Providers*. These specific characteristics are listed in Exhibit 3 of Appendix F.

The categorized set of all case-study measurement needs was sorted, tabulated, and correlated according to the data fields mentioned above. The resulting statistical data and the content analysis of the industry technology roadmaps were used as the basis for making inferences about measurement barriers to technological innovations and the USMS.

Inferential Analysis Process

As the basis of its assessment of the USMS, NIST developed an inferential analysis process consisting of these steps:

- examining the case-study and roadmap measurement needs and the results of statistical and content analyses to identify significant features and patterns within and among those measurement needs
- extracting facts from and making factual statements about those features and patterns
- using informed judgment to interpret the meaning and significance of those factual statements

- making declarative statements based on the factual statements as so interpreted
- identifying some declarative statements as being based on a sufficient number of documented measurement needs and supported by sufficient fact and logic to qualify as potential ***findings*** and submitting them for authentication by industry representatives
- identifying other declarative statements as not meeting the standard of a potential finding but representing a potentially significant measurement issue and submitting it for review by industry representatives as ***other observations***

This process for generation of potential findings was applied to each of the 11 sector/technology areas, as well as to the aggregated group of all the measurement needs from each sector/technology area. In each case, a small group of NIST technical staff knowledgeable about that area was convened to participate in the inferential analysis process.

The process was applied in rounds, focusing in turn on the following areas:

- barriers, providers, and solutions
- measurands (i.e., the quantities measured) and cases where the technological innovation was a measurement technology
- stage of technological innovation
- technology developer's vision and cross-sector aspects

There was neither an upper nor a lower limit to the number of findings in each round. Rather, the number of findings, and the rounds in which they were noted, varied across the sector/technology areas, as the data supported them. The final round asked the participants in the inferential analysis to list challenges to measurement innovation and the operation of the USMS that were noted during the analysis.

Authentication of Findings

The findings of this assessment report are those findings that resulted from the inferential analysis process that were subsequently authenticated. As with the case-study measurement needs, the findings were vetted with individuals outside NIST who were considered to be knowledgeable and representative of a particular sector/technology area. Authenticators, working in a web-based environment, reviewed and commented on each of the findings within a specific sector/technology area. Findings based on the entire set of measurement needs were similarly authenticated.

Interpretation of Findings

The outputs of the inferential analysis form the basis for the principal results of this assessment, which are, first, authenticated findings on measurement barriers to technological innovation and, second, conclusions about the USMS as it relates to those barriers. These ***conclusions*** are judgments about the capacity of the USMS to address the identified measurement barriers to technological innovation. They are based on an examination of the findings, the measurement needs, the analysis of them on which the findings are based, and the overall context of technological innovation within the United States.