

FINAL REPORT

**ECONOMIC IMPACT ASSESSMENT:
NIST-EEEL
LASER AND FIBEROPTIC POWER AND ENERGY
CALIBRATION SERVICES**

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EXECUTIVE SUMMARY

The National Institute of Standards and Technology (NIST) develops techniques and standards for characterizing the light emitted from lasers. In particular, NIST conducts research and provides metrology services (primary standards and attendant calibration services) for the reliable and accurate measurement of laser beam strength (power and energy). Accurate measurements of laser power and energy are important for research, engineering, industrial processing, quality control, safety, product acceptance, and regulatory compliance. Measurement accuracy is a prerequisite for the design, purchase, and operation of laser-based equipment in diverse fields such as materials processing, medical diagnostics and surgery, computer data storage, barcode scanning, image recording, telecommunications, and entertainment.

This study assesses the economic impact on US industry from NIST's program in laser power and energy measurement. NIST has invested in infratechnologies (infrastructure technologies) that make laser power/energy measurements practical and efficient for a broad base of industry. Case studies are used to examine economic outcomes associated with selected outputs from NIST's program.

ES.1 OVERALL ASSESSMENT OF ANNUAL METROLOGY SERVICES

The provision of primary standards and calibration services affecting all industry sectors is the first output under examination. Laser output power/energy is used to specify the characteristics of lasers and laser systems, and industry has recognized the importance of accurate calibrations of instruments measuring that output with traceability to national (primary) standards established and maintained at NIST. NIST calibrates detectors and instruments containing these detectors to support three types of laser-based measurements:

- (1) The power or energy output of laser light sources used in a broad range of industrial applications,
- (2) The power emerging from the ends of optical fibers used typically in fiberoptic communications, and
- (3) The frequency response of high-speed detectors that enable greater bandwidth (information carrying capacity) in high performance communication systems.

Economic outcomes (benefits) attributable to NIST's primary calibration services were identified through interviews with a sample of firms that obtain calibrations directly from NIST. In the counterfactual absence of NIST's outputs, the survey respondents would have incurred additional costs for: (1) verifying measurement accuracy for their customers, (2) calibrating and maintaining in-house ("golden") measurement standards, and (3) obtaining calibration services from foreign laboratories to enable US exports and support general production.

Lower-bound estimates of the economic impact from NIST's investments in primary standards and calibration services are shown in Table ES-1. The calculated metrics estimate the annual economic impact of the services using the data available for 1999. The metrics are based on an appraisal of net economic benefit and expenditure data attributable to the services associated with the laser metrology infratechnologies provided by NIST in that year. The estimated benefits, based on reports of the survey respondents, are lower-bound estimates because they reflect just a portion of the costs avoided by the private sector because of NIST's services.

Table ES-1. Estimate Range of Lower-bound Economic Impact for Investments in Primary Calibration Services

Metric	Low	Midpoint	High
Benefit-to-Cost Ratio	8.1	11.3	14.9
Net Benefits in 1999	17,100,000	23,800,000	30,300,000

Several factors cause the calculated metrics to be conservative estimates of NIST's economic impact on domestic industry. A major source of downward bias is the unquantified cost to US industry because of the loss in domestic firms' instrument sales that would result from reliance on foreign laboratories as a substitute to NIST for primary calibration services. Domestic firms would likely lose sales and market share to foreign firms in the counterfactual scenario where NIST is not available as a neutral US authority maintaining standards to which measurements could be traced. Unquantified transaction costs avoided in downstream tiers of the affected supply chains are another source of conservatism in the estimates. That is, in addition to the reported benefits for firms working closely with NIST (primarily laser instrument suppliers) and the customers of these firms, NIST's measurement technology diffuses to downstream segments of the industry supply chain, including end-use applications. Additional costs would likely be incurred to verify the accuracy of measurements in these downstream tiers in the absence of NIST, and these avoided costs were not estimated in the calculated metrics.

ES.2 ASSESSMENT OF 248 NM R&D AND METROLOGY SERVICES

A specific measurement technology developed by NIST has benefited the chain of industrial firms in semiconductor manufacturing. That measurement technology is for lasers operating at the 248 nanometer (nm) wavelength used in the current generation of projection photolithography, the key process for the progressive miniaturization of semiconductor integrated circuits (ICs). This trend in miniaturization has increased the functionality of semiconductor ICs, which has been the main reason for the expanded utilization of IC technology in numerous applications affecting daily life.

The particular NIST output under examination is R&D and metrology (standards and calibration services) applied to 248 nm excimer lasers. NIST invested in this measurement technology in synch with "roadmaps" established by the semiconductor industry for innovations in photolithography technology. The NIST measurement technology diffuses through a chain of semiconductor equipment and materials firms, and eventually reaches the end-users—the semiconductor manufacturers. The ability of NIST to accurately measure the power from 248 nm lasers has facilitated the transition to economic fabrication of smaller IC linewidths, which has been a key driver for the continued, rapid development of the electronics industry.

Economic outcomes attributable to NIST's R&D efforts and primary calibration services were identified through structured interviews with the relevant power meter and laser suppliers. In the counterfactual absence of NIST's outputs, the survey respondents would have incurred additional costs as follows:

- Transaction costs to verify measurement accuracy for customers
- Purchase, installation, operation, and maintenance of extra equipment to establish proprietary metrology capabilities
- Extra scientists and engineers to establish in-house proprietary metrology standards
- Technical and administrative costs to work with foreign laboratories rather than NIST

Interviews conducted with experts in semiconductor photolithography revealed limited diffusion of NIST's measurement technology for maintaining process control in high-volume semiconductor production. While the power meters used in a photolithography system typically

are calibrated to absolute standards at NIST as a purchase requirement, semiconductor manufacturers commonly use relative measurements to maintain process control across multiple lithography tools in a fabrication plant as well as across multiple plants within a firm. This common practice of using relative measurements, rather than absolute measurements traceable to primary standards at NIST, shows the potential for improving process control in high volume semiconductor production. The historical experience with experimental, trial-and-error semiconductor fabrication has persisted as a proven method even as advancements in metrology make possible the use of absolute measures to save materials and time. The established way of fabricating semiconductors with trial-and-error applications of laser power has perhaps become a barrier inhibiting movement toward the use of absolute measurements.

Yet, the use of power meters calibrated to absolute standards at NIST is intrinsic to economical semiconductor production. Such traceability to standards ensures integrity and reliability of laser measurement, and the reduced measurement uncertainty lessens the dependence on the experimental method of semiconductor process development and production. Also, a power meter traceable to NIST's primary standards reduces the time spent troubleshooting photolithography problems because engineers have greater confidence in the accuracy of the detector readings. Consequently, when an IC fabrication process goes out of control, the power meter is often the last component investigated among the many potential sources of error in a lithography system. Typically, the problem for process control is found elsewhere and the measurements traceable to NIST reduce the costs of identifying and correcting the problem.

Lower-bound estimates of the economic impact from NIST's investments are shown in Table ES-2. The calculated metrics are based on appraisals of net economic benefit and expenditure data attributable to the infratechnologies provided by NIST.

Table ES-2. Estimate Range of Lower-bound Economic Impact for Investments in 248 nm Metrology (1990-2009)

Metric	Low	Midpoint	High
Real Internal Rate of Return	33.3%	43.1%	52.0%
Benefit-to-Cost Ratio	2.3	3.0	3.8
Net Present Value in 1990	\$1,720,000	\$2,550,000	\$3,380,000
Net Present Value in 1999	\$3,170,000	\$4,690,000	\$6,210,000

Benefits from NIST's measurement technology have been quantified for the suppliers of power/energy meters and lasers. The additional transaction costs avoided for the downstream customers of these suppliers are also estimated. One source of downward bias in the calculated metrics is the unquantified reduction in effort for semiconductor manufacturers to trouble-shoot photolithography process problems because of confidence in the accuracy of detector readings calibrated to NIST's standards as a prerequisite for purchase. The estimate of NIST's expenditures for 248 nm metrology includes joint maintenance costs that also benefit the NIST project in 193 nm metrology. Hence, associated with the costs for the 248 nm project are unmeasured spillover benefits for NIST's project in 193 nm metrology, and those benefits are not measured in the present study.

ES.3 ASSESSMENT OF HIGH-SPEED R&D AND METROLOGY SERVICES

NIST develops and maintains standards as well as provide calibration services for specialized optical sources and detectors used in high performance communications systems. Significant technical progress in the communications industry has been associated with increasing the bandwidth of optical fibers and the associated laser transmitters and receivers (detectors). Systems with greater bandwidth increase the volume of telephone calls, cable television stations, and computer data content (graphics/audio/video) that can be carried over a single fiberoptic communications link. NIST supports industry with methods for characterizing the increasing frequency response of high-speed detectors that are essential to enabling higher bandwidth systems. Advances in high-speed detector measurement technology have contributed to the recent expansion in many areas of the telecommunications industry, including:

- High-speed Internet access despite rapid increases in the number of end users
- Optical fiber replacing copper wire for telephone landline systems (including hybrid fiber-coax trunk lines)
- Cable TV, local area network, and antenna remoting applications with fiberoptic cables (satellite telephone and micro-cellular systems)
- High bandwidth, secure military communications links

Hewlett Packard (HP), a leading supplier of high-speed instrumentation, and other firms have worked cooperatively with NIST since the early 1990s to develop metrology for high-speed detectors. Initially, HP was the major conduit for transferring NIST’s standards for high-speed measurements to the telecommunications industry. A series of interviews with Hewlett Packard’s key expert in metrology for fiberoptic high-speed frequency response provided HP’s perspective about the impact of NIST’s investments. Consultation with other industry experts allowed estimation of industry-wide benefits from NIST’s investments in high-speed metrology.

The detailed interviews with HP revealed that in the absence of NIST’s investments for high-speed metrology, HP would have incurred additional costs in the following categories of economic impact:

- R&D and equipment in the mid-1990s to establish the state-of-the-art metrology
- Engineering effort to establish measurement technology standards; this entails extra technical staff for participation at standards conferences and publication of papers describing the proprietary standards
- Continuous effort to maintain the private investments in high-speed metrology
- Transaction costs to verify the accuracy of measurement traceability because customers would have less trust in calibrations obtained through a private, non-neutral source of primary standards

Table ES-3 shows lower-bound estimates of the economic impact from NIST’s investments by using the information from HP and from other industry experts. The estimated net benefits include R&D costs avoided by HP and other direct users of NIST’s high-speed services as well as transaction cost savings for the direct users and their customers.

Table ES-3. Estimate Range of Lower-bound Economic Impact for Investments in High-speed Metrology (1992-2009)

Metric	Low	Midpoint	High
Real internal rate of return	119%	136%	155%
Benefit-to-cost ratio	7.8	9.1	10.5
Net Present Value in 1992	\$10,900,000	\$12,300,000	\$13,800,000
Net Present Value in 1999	\$17,500,000	\$19,800,000	\$22,100,000

Several factors cause the calculated metrics to be conservative estimates of NIST's economic impact on domestic industry. The key source of downward bias is that additional, counterfactual investments by industry would have been unable to replace completely the measurement technology and services provided by NIST. HP or any other firm attempting to replicate the NIST R&D and metrology would have fallen short of complete substitution because: (1) the neutrality of a US-national standards organization would be lost, and (2) the metrology would be less robust. HP identified instruments that actually embody the NIST measurement technology, and the impact on product sales from less than complete substitution of NIST's investments was not ascertained. Similarly, the degrading effect of any shortfall in the counterfactual proprietary measurement technology on the aforementioned expansions in the telecommunications industry was not quantified.

Additional transaction costs to verify the accuracy of measurements in more downstream tiers of the telecommunications industry in the absence of NIST are not quantified, and therefore are another source of downward bias in the estimate of benefits. Benefits for firms other than HP, which have also worked cooperatively with NIST in developing high-speed measurement technology, have been quantified in part by using the advice of leading industry experts to estimate the benefits based on HP's detailed report. Nonetheless, the estimates are quite conservative for the metrics presented.

ES.4 MEASUREMENT TECHNOLOGY FOR MEDICAL COMMUNITY

Lasers have been used in medicine for a variety of diagnostic and therapeutic applications. The advent in the 1980s of "minimally invasive" laser-based medical procedures have increased the cost effectiveness of many types of surgeries and enabled many new types of procedures.

The output power/energy level of a laser used in a medical laser application often determines the safety and effectiveness of a medical procedure. In particular, severe complications can arise from unintentional damage to non-target tissue if the laser power or dose (amount of radiation received in a time span) is too high. Precise targeting of the power/energy and accurate dosimetry benefits the medical field because they:

- Increase the safety and effectiveness of a laser procedure
- Ensure that complications do not occur for the patient
- Provide precise treatment of delicate tissues, such as arteries and the cornea
- Meet regulatory requirements of the US Food and Drug Administration (FDA) with cost-effective system designs
- Reduce physician liability

The measurement infrastructure provided by NIST (national standards and calibration services) provides a consistent frame of reference for the chain of firms supplying medical laser systems and the users of these systems. Having agreement on this measurement infrastructure reduces disputes and transaction costs among all affected parties, and reduces the cost of regulatory compliance for traceability to absolute standards at NIST. For example, all laser systems used in a clinical trial can be relied upon to provide the same power/energy for a given application, and the subsequent lasers sold commercially can be relied upon to accurately provide the same parameters as those systems used during the clinical trial.

Investments in laser measurement technology by NIST from as early as the 1960s are still applicable to the medical community. In fact, NIST has not conducted any specific research activities toward medical applications of lasers in over 20 years. Until recently, this state of measurement technology at NIST has been sufficient.

Suppliers of power and energy meters believe that new investments in metrology at NIST could support emerging laser technologies that have evolved beyond those served by the capabilities of the current infrastructure. The latest laser applications require doctors to know the laser exposure levels before beginning a medical procedure to within ± 1.5 percent accuracy traceable to NIST's standards, rather than the historical FDA requirement of ± 20 percent measurement accuracy. The latest photodynamic therapy for cancer treatment, for example, uses exposure systems rather than cutting or burning technology. Without tight absolute measurement, permanent damage can be done to the patient.

The more stringent requirement for absolute standards traceability represents a requirement for greater measurement accuracy traceable to NIST standards than the current metrology at NIST allows. Although a quantitative analysis has not been attempted, the qualitative evidence suggests that new investments by NIST and industry could make valuable improvements in the infrastructure for laser metrology that supports the medical supply chain.

ES.5 CONCLUSION

The conservative, lower-bound estimates of economic impact show that NIST's investments have been socially valuable. NIST's development and diffusion of infratechnologies supporting the practical application of laser-based measurements has been a success. Public performance of R&D for laser metrology, maintenance of standards, and the provision of calibration services has been more effective and efficient than performance by the private sector or other national laboratories.

1. INTRODUCTION

1.1 THE ECONOMIC IMPORTANCE OF MEASUREMENT TECHNOLOGY

Measurement is the application of the principles from metrology (the science of measurement) to determine some characteristic or property of products, services, or systems. While the importance of measurement is often overlooked or taken for granted, it is essential to the nation's economy. Effective measurement ensures that, for example, clocks at residences and workplaces display approximately the same time, a pound of coffee purchased from two different stores is approximately of equal weight, and a bolt from Company A fits into a nut made by Company B.

The practice of measurement and the advancement of measurement technology are indispensable for innovation, development, production, marketing, and trade. Industrial researchers and production managers need to measure the performance of devices or systems for a host of reasons, including:

- Controlling manufacturing processes to reliably fabricate products of a desired quality
- Evaluating the design of new or improved products
- Testing the conformance to standards of the interfaces among different implementations or components to ensure system interoperability
- Demonstrating product acceptance with specified performance and assuring the proper amount of output to minimize transaction costs in markets¹

These needs are pervasive, affecting every industrial sector. Thus, the economic impacts of measurement tend to be substantial from the perspective of both individual firms and entire industry supply chains. Robust measurement capability is especially important and challenging in a technology-driven economy.

¹ Transaction costs act as "frictions" in the effective operation of an economic system. Types of transaction costs include the costs of writing contracts, finding parties with whom to trade, policing agreements, bargaining (before and after a sale), assessing the potential and actual performance of purchased goods and services, and haggling to correct *ex post* contractual misalignments.

Measurement technologies can be developed and implemented efficiently through infrastructure technologies (infra-technologies). Infra-technologies are technical “tools” that make the R&D, production, and market penetration stages of product cycles more efficient. These tools enable industry to efficiently develop applications that are based on both generic and proprietary technologies.² Examples of infra-technologies include measurement methods, calibrated artifacts (e.g., standard reference materials) and calibration services that allow efficient use of these methods, reference databases, simulation models for design and process control, technical bases for interface standards, product performance tests, and quality assurance techniques.

Despite the economic benefits from investments in measurement technologies, industries tend to under invest in infra-technologies because the tools and techniques:

- Often derive from a generic technology base that differs from the core technologies that industry develops and draws on to develop its products and processes
- Are used simultaneously by many firms (i.e., as industry protocols or standards)
- Cannot be embodied in products and processes

As a result, the National Institute of Standards and Technology (NIST) develops and transfers infra-technologies as a part of its mission supporting US industry.³ NIST invests in tools commensurate with the commercialization needs of industry, which have become ever more demanding.

² Gregory Tasse, *The Economics of R&D Policy* (Quorum Books: Westport, CT) 1997. The role of infrastructure technology for product development is discussed in Chapter 8.

³ The United States Department of Commerce (DoC) through NIST supports US industry’s efforts to develop and acquire new technologies, accelerate commercialization of new products and processes based on these technologies, and achieve global market penetration to advance the nation’s economic growth and standard of living. NIST’s laboratories provide this support in the form of various types of nonproduct standards, testing, and laboratory accreditation services that are used by industry in meeting the challenge of keeping pace with rapid technological change. NIST is the only federal laboratory with the primary mission of supporting the development and commercial application of technology.

1.2 NIST PROGRAM IN LASER CALIBRATION SERVICES

Over the past few decades, lasers have become increasingly important in industry and the laboratory. Laser applications have been developed in diverse fields such as materials processing, medical diagnostics and surgery, computer data storage, research and development, construction, communications and entertainment. As laser technology expands to meet the needs of new applications, so must the instrumentation that assures the laser works properly to meet the needs of a specific application. In particular, users demand reliable and accurate measurement of laser power and energy as a prerequisite to purchase and operation of their laser system.

NIST's activities in developing techniques to measure the output power and energy of laser light trace back to the early 1960s when the laser itself was being developed. Such activities are organized currently in the Optoelectronics Division of NIST's Electronics and Engineering Laboratory (EEEL). The Division's mission is to provide the optoelectronics industry with advanced measurement technology, standards, and traceability to those standards.⁴ The Sources and Detectors Group is one of four groups within NIST's Optoelectronics Division. Two projects within this Group are Laser Radiometry and High-Speed Measurements.

The Laser Radiometry project develops standards and maintains calibration services for both laser and optical fiber detectors. The goal of the laser calibration service is to enable accurate determination of the power or energy output of laser light sources used in a broad range of applications. The goal of the fiberoptic power calibration services is to enable the accurate determination of the light power emerging from the ends of optical fibers used typically in laser-based fiberoptic communications applications such as telephone, cable television and computer interconnections (e.g., local area networks and the Internet). NIST supports the achievement of both of these calibration services principally by characterizing the performance of both detectors and instruments containing these detectors (mainly, laser power/energy meters and optical fiber power meters) used to measure the power or energy of laser light. NIST first offered laser calibration services in the late-1960s, and fiber power measurement services were added in the mid-1980s.

⁴ The subject of optoelectronics deals with the interaction of light and optical processes with electronic processes. Such interactions are usually accompanied by an energy conversion. Examples of optoelectronic devices include lasers, photodetectors, and light-emitting diodes. The field of optoelectronics has been spurred by the needs of light-wave communications systems, optoelectronic computing, instrumentation, and alternate energy systems.

The High-Speed Measurements project develops standards and maintains calibration services for specialized optical sources and detectors used in high performance communications systems. Technical progress has been made in the communications industry by increasing the bandwidth (information carrying capacity) of optical fibers and the associated laser transmitters and receivers (detectors). Greater bandwidth systems increase the volume of telephone calls, cable television stations, and data content (graphics/audio/video) that can be carried over a single fiberoptic communications link. NIST supports industry with methods for characterizing the increasing frequency response of high-speed detectors that are basic to enabling greater bandwidth systems.

NIST has taken an active role in identifying the laser power/energy and fiberoptic measurement needs of US industry. As the laser field has developed and the range of technical parameters (wavelength, power, pulse length) has expanded, NIST has remained in step by developing technologies and metrologies that expand the envelope of laser measurement capabilities. Figure 1 illustrates the sources of information flowing into NIST and upon which NIST projects have been based to support the growth of the laser industry.

Generally, NIST's outputs (technical contributions) to industry from the Laser Radiometry and High-speed Measurement projects can be categorized as follows:

- Advanced measurement technologies
 - Detector characterization techniques
 - Source characterization techniques
- Services to industry
 - Development and maintenance of primary standards
 - Provision of calibration services
 - Measurements (wavelength, power range, pulsewidth, modulation frequency) at the technological state-of-the-art
- Contributions to commercialized products

Appendix A provides a brief description and history of the above outputs from NIST.

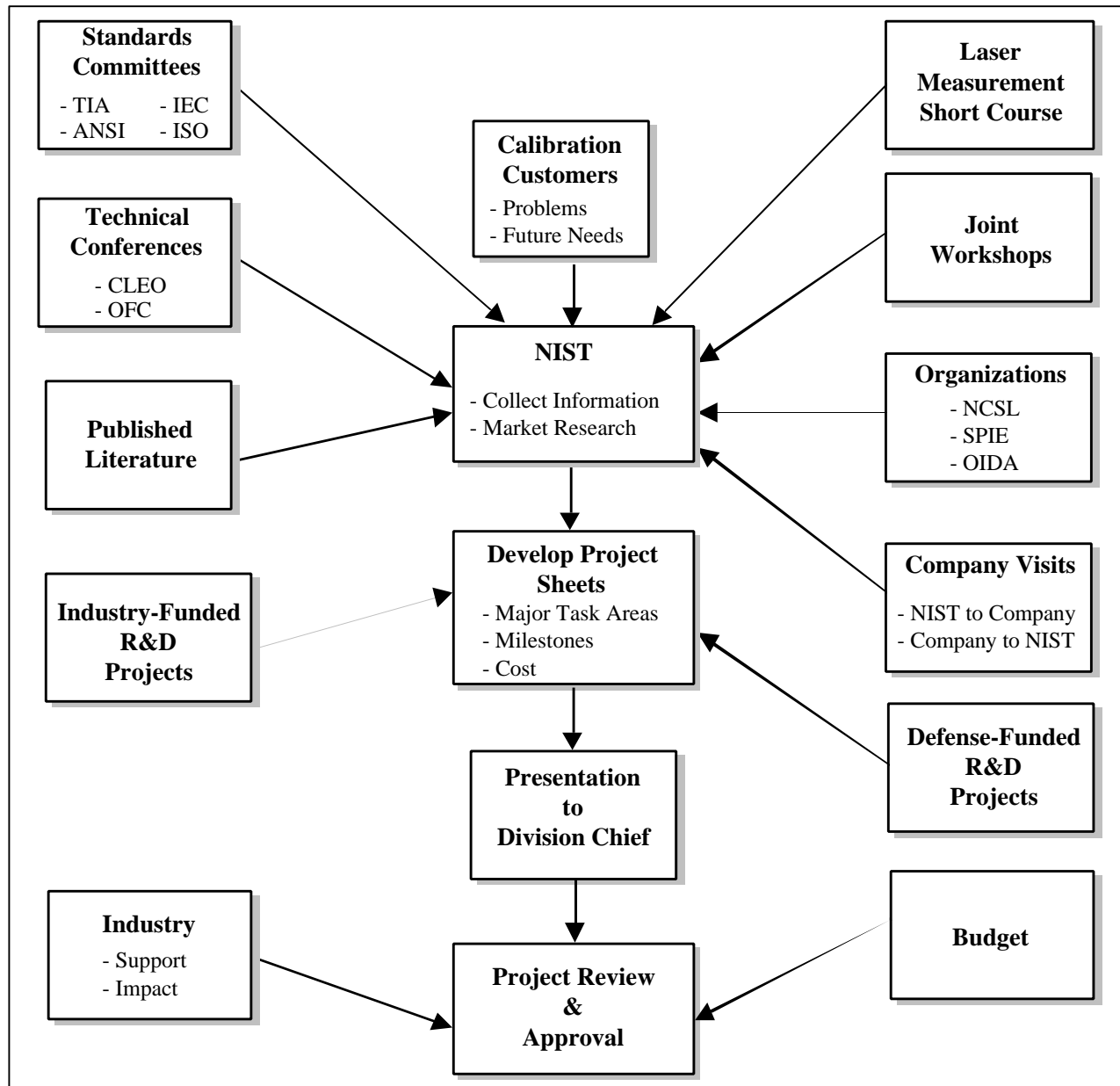


Figure 1. General Approach for Identifying NIST Investments

1.3 ECONOMIC MOTIVATION FOR NIST'S PROGRAM

By developing the technical outputs identified in Section 1.2, NIST-EEEL is providing infra-technology to industry.⁵ As observed in Section 1.1, without public investment in infra-technology, industry left on its own often under invests in such supporting technology infrastructure. This "market failure" occurs for several reasons:

Under investment in supporting technology infrastructures—insufficient infra-technology R&D. Infra-technologies not only have common use characteristics (including their use as standards), but they often derive from a different science and generic technology base than does the core technology being applied by industry through its internally funded R&D. The latter fact argues for a strong role by government laboratories in the conduct and diffusion of infra-technology research. Government labs can realize economies of scale and scope from unique research skills and facilities that can be applied to meet the infra-technology needs of a number of industries. These labs also can provide neutral third party facilitation of the standards process.⁶

Further, such infra-technology is “non-rivalrous”—non-rivalrous goods are consumed collectively:

Critical for R&D policy is the fact that technology infrastructure and other generic technical knowledge fall into the non-rivalous category, but excluding additional consumers of this knowledge is not in the public interest. Thus, these types of public technology goods are funded at least partially by government to compensate for spillovers.⁷

Following this reasoning, markets would fail to provide, in sufficient amounts, the infra-technologies examined in this study. Further, the costs to the private sector of trying to replace NIST’s laser metrology services would exceed NIST’s costs. Therefore, industry benefits from NIST-EEEL's investments in the development of laser measurement technology and in the provision of calibration services for traceability of industry measurements to national standards.

⁵ Gregory Tasse, "R&D Trends in the U.S. Economy: Strategies and Policy Implications," Planning Report 99-2, Program Office, Strategic Planning and Economic Analysis Group, National Institute of Standards & Technology, US Department of Commerce, pp. 24-26, April 1999.

⁶ Ibid, p.40.

⁷ Ibid, p.23, footnote 25.

1.4 CASE STUDY OVERVIEW

This study assesses ex post the economic impacts on US industry from selected NIST outputs in laser radiometry and high-speed optical measurement. Case study analyses were conducted to better understand the prevailing mechanisms of market failure, and to characterize the benefits from NIST's infra-technology investments. NIST's infra-structural outputs are examined in terms of the affected industrial activities, the technical innovation strategy of the affected industries, and the competitive performance of these industries.

The economic impacts are assessed from several perspectives. The first assessment is across numerous supply chains that benefit from laser metrology services provided by the entire NIST EEEL Sources and Detectors Group. This overall assessment is followed by in-depth studies of services for two industry supply chains, semiconductor manufacturing and telecommunications. These two studies examine some of the recent R&D efforts of EEEL in laser metrology. Such recent NIST R&D in laser metrology helps industry establish new process technology that makes possible new products and services, thereby opening new markets. New semiconductor lithography techniques and new telecommunications technologies have been enabled by NIST's recent R&D investments in laser measurement technology. In addition to new R&D efforts, simply having NIST as the repository for national standards and as the provider of primary calibration services—allowing traceability of industrial laser measurements to those national standards—provides infra-technology that supports numerous applications of laser technology throughout the economy. To illustrate NIST's role in such applications, and to explain the importance of ongoing investments in new laser metrology, the report also assesses the economic importance of laser measurements traceable to NIST's standards in medical services.

The economic impacts of NIST's investments as revealed by the case studies are discussed in the ensuing chapters as follows:

- Chapter 2 assesses the overall economic impact of NIST's role in providing primary calibration services to a broad range of industries
- Chapter 3 analyzes the economic impact on the semiconductor industry from NIST's investments in R&D and calibration services for 248 nanometer (nm) measurement technology
- Chapter 4 analyzes the economic impact on the telecommunications industry from NIST's investments in R&D and calibration services for high-speed measurement technology

- Chapter 5 uses the applications of lasers in medical services to illustrate the usefulness of having NIST as the repository of national standards for laser metrology and to explain the importance of ongoing investments at NIST

Additionally, the report contains the following appendices:

- Appendix A provides a brief description and history of the technical contributions from NIST in laser metrology
- Appendix B provides a technical overview of lasers as well as the techniques and equipment used in laser and fiberoptic power measurement
- Appendix C describes the metrics used for calculating economic impact
- Appendix D describes the technical importance of high-speed frequency response measurements in communications systems

2. ASSESSMENT OF PRIMARY CALIBRATION SERVICES

As described in Section 1.2, the provision of primary standards and calibration services is a major technical output of the entire NIST EEEL Sources and Detectors Group. In this chapter, the economic outcomes associated with this output are assessed across all affected industry sectors.

This chapter begins with a brief discussion of the economic importance of lasers and the attendant role of accurate measurement technology. The next section characterizes the general tiers that form the relevant industry supply chain. The next section presents the methodology used for the economic analysis and the industry survey. Subsequent sections provide results of the survey and an analysis of the economic impact.

2.1 ECONOMIC IMPORTANCE TO INDUSTRY

2.1.1 Technological Advancement and Application of Lasers

Ted Maiman implemented the first laser at the Hughes Research Laboratories in 1960. Throughout the 1960s, lasers were developed primarily for military applications such as laser rangefinders and laser gyroscopes. By the 1970s, lasers were used in a broad array of commercial applications, from alignment tools used for surveying and saw mill operations to barcode readers used for supermarket checkout. Medical applications of lasers were developed at this time, including their use in ophthalmology (for retinal photocoagulation), surgical cutting, and coagulation.

In the 1980s, military applications of lasers included rangefinders, designators, communications links, missile fusing, and countermeasures as well as research on laser weapons. Medical applications of lasers expanded greatly in this decade, with growing acceptance of surgical and ophthalmic lasers as well as the development of new applications such as laser angioplasty (clearing plaque from blood vessels) and refractive surgery (cutting or shaping the cornea to correct vision). During this same timeframe, materials processing applications became firmly established (e.g., cutting and welding auto bodies and ships as well as heat-treating gears and turbines) using very high power (multi-kilowatt) lasers. Image recording applications (laser printing and copying) also expanded rapidly during the 1980s, with higher laser output power levels and shorter wavelengths being demanded later in the period to enable faster and higher

resolution printing. Laser technology developed rapidly in several directions during the 1980s as more efficient manufacturing techniques made lasers a cost-effective system component for enabling compact disk (CD) and digital video disk (DVD) players in the consumer market. Meanwhile, higher-power lasers were developed for more specialized applications such as high-end laser printing, optical storage, and vision correction (corneal shaping).

Through the 1990s, laser technology has been accepted in a dozen major application areas as shown in Table 1. In 1999, the size of the worldwide laser market was estimated at \$4.9 billion, with the US accounting for approximately 60 percent of these total revenues.⁸

Table 1. Worldwide Laser Sales, 1999

	Revenues (\$M)	Units (thousands)
Telecommunications	2,179	2,060
Materials Processing	1,113	32
Optical Storage	709	302,500
Medical Therapeutics	461	18
Research	125	5,025
Image Recording	110	14
Other	77	10,646
Instrumentation	60	36,004
Sensing	33	40
Entertainment	15	66
Inspection, Measurement and Control	11	1
Barcode Scanning	8	1,325
Total	4,900	357,731

In terms of total sales, the top four markets in descending order are:

- (1) Telecommunications, accounting for about 45 percent of 1999 revenues. This market is being driven by worldwide growth in fiberoptic telecommunications to handle increasing rates of voice and data traffic in developed countries as well as the needs for new communications infrastructures in developing countries.

⁸ As reported in the January and February 2000 issues of *Laser Focus World*.

- (2) Materials processing, which includes lasers for metal processing (e.g., cutting and welding auto bodies, and heat-treating turbine blades), marking, semiconductor and microelectronic fabrication, rapid prototyping, and micromachining. About 24 percent of the \$1.1 billion in the materials processing sector went toward excimer lasers, which are being used primarily for manufacturing the most recent generation of semiconductor devices.
- (3) Optical memory, with large numbers of relatively inexpensive diode lasers being used for audio and video CD players as well as computer CD-ROMs and DVD-ROMs.
- (4) Medical field, with lasers being used for both therapeutic and diagnostic purposes, and products span virtually every medical specialty—in many cases allowing the accomplishment of procedures that could never have been performed previously. Much of the current growth is coming from office-based cosmetic laser applications.

2.1.2 Laser Power/energy Measurement

Generally, laser power and fiberoptic power meters are used to measure the radiation emitted from lasers used in a wide range of applications. These two families of instrumentation are similar technologically, both having a detector that converts optical power or energy into an electrical signal for measuring the optical parameter of interest. Laser power meters are used in a variety of applications, while fiberoptic power meters are used primarily in telecommunications applications to measure optical power transmitted through an optical fiber system. Technical concepts of lasers and the general procedure for laser and fiberoptic power measurements are described briefly in Appendix B.

Importance of Accurate Laser Power Measurements. As laser technology has developed over the past two decades, the needs for measurement of laser output power and energy have expanded in several technical directions:

- Increased power range, from picowatts to kilowatts for continuous wave lasers
- Increased wavelength range, from 193 nm in the ultraviolet part of the electromagnetic spectrum to 10.6 microns (μm) in the infrared

- Increased modulation frequency and decreased laser pulsewidth
- Increased accuracy

The relative importance of these expanded power/energy measurement capabilities varies by application of the laser technology.

Measurements of laser beam strength (power and energy) are fundamental to nearly all applications of lasers, and thus are a high priority across the entire US laser industry.⁹ Accurate laser power and energy measurements are important for research, engineering, industrial processing, quality control, safety, product acceptance and compliance. Further, laser measurements attain an increasing importance as laser systems are integrated into high-value applications.

In many cases, the accuracy of the laser output measurement plays a critical role in the safe and effective use of the laser system. For example:

- The technical progression for smaller transistors and denser circuitry has forced the semiconductor manufacturing industry to use excimer laser (deep ultraviolet) lithography, thereby requiring accurate measurements of laser pulse energy to ensure high-yield, low-cost chip manufacturing
- The quality of a weld on an auto body may depend on the optical power being supplied by a CO₂ laser
- In laser surgery, if the laser power is too high, severe complications can arise from unintentional damage to target or non-target tissue
- In the telecommunications field, measuring the optical loss of fiberoptic components at microwatt levels is necessary to ensure proper transmission of voice and data signals across long-distance landlines

Ultimately, the success or failure for many of these applications depends on the accuracy of the laser power/energy measurement. Many factors can affect the accuracy of laser and fiberoptic power/energy measurements as described in Appendix B.

⁹ "Measurements for Competitiveness in Electronics," NISTIR 4583, April, 1993.

Calibration to National Standards. As laser output power/energy is used to specify lasers and laser system characteristics, industry has recognized the importance of maintaining accurate calibration of laser power/energy meters based on national standards. A traceable calibration to a national (primary) standard through an unbroken chain of comparisons or transfers allows purchasers of laser products to utilize a common frame of reference when designing lasers into commercial systems. Purchasers of lasers, whether for research or integration into original equipment manufactured (OEM) systems, generally have a minimum output power requirement to ensure success for their laser applications. Laser manufacturers must specify the output power/energy of their products, and product pricing is related closely to these output specifications. Therefore, calibrating laser power/energy outputs to national standards provides an efficient means for ensuring accurate measurements among detector manufacturers, laser manufacturers, laser system integrators, and laser users.

NIST has offered calibration services since the late 1960s to assist the laser community in obtaining accurate measurements of laser sources which are traceable to primary standards. Generally, calibration involves a two-step process. First, the power/energy output of a laser is measured using both the detector under test (DUT) and a NIST standard detector. Second, the results of these measurements are compared to determine a correction factor for the DUT according to the NIST standard. Appendix A provides additional details on the process of calibrating laser power/energy meters between NIST and its customers.

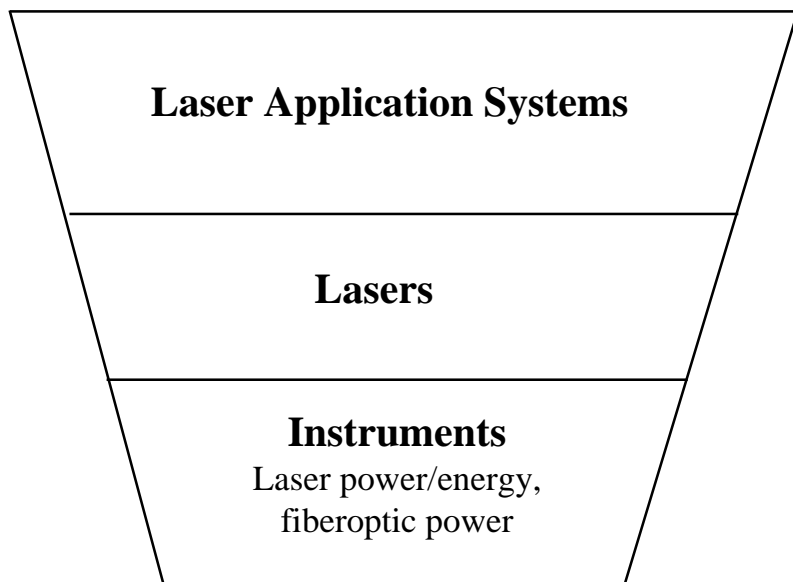
Regulatory Requirements. Since the 1970s, the Center for Devices and Radiological Health (CDRH), which is now a part of the Food and Drug Administration (FDA), has been regulating the sale of all laser products by ensuring that certain safety features are provided. These features include a keyswitch, pilot light, and time delay before the laser operates, and various labels showing the laser output location, maximum power, wavelength, and safety class. Various safety classes have been defined according to the hazard type (eye safety, skin safety, fire hazard, etc.), which are dependent on the laser wavelength and output power/energy.

As a result of CDRH regulations, laser and laser system manufacturers have been required to monitor their laser power and report these measurements and other parameters to the CDRH in order to maintain approval for the sale of these lasers and systems. Annual submissions are required, and traceability to primary standards at NIST is a requirement.

2.2 INDUSTRIAL SUPPLY CHAIN

The generalized industrial supply chain for the diffusion of NIST's radiometric measurement technology is shown in Figure 2. A similar supply chain for high-speed frequency response measurement technology is shown in Section 4.2.

Figure 2. Flow of Measurement Technology for NIST's Radiometry Outputs



2.2.1 Laser Power/ Energy Meter Instrumentation Suppliers

In 1998, over 30 companies (7 are non-domestic) manufactured and sold laser power and energy meters.¹⁰ Many firms focus exclusively on laser power/energy meters, and some of these companies also sell fiberoptic measurement instrumentation. Based on discussions with industry representatives, the top producers in the US laser power/energy meter market and their approximate market shares include:

¹⁰ *Laser Focus World Buyers Guide 98*, Pennwell Publications, December 15, 1997.

- Molelectron (20 percent market share)
- Coherent (20 percent share)
- Ophir (20 percent share)
- Scientech (10 percent share)¹¹

Other producers in this field include Gentech (Canada), Fotec, Laser Precision, and OAI. Additionally, the optical accessories companies (e.g., Newport Corporation, Ealing Electro-Optics, Edmund Scientific, and Jodon) and the laser suppliers (e.g., Coherent with its subsidiary Lambda Physik, Lexel Laser, and Spectra Physics) market OEM power meters from the top producers. All the power/energy meter suppliers benefit directly from NIST calibration services, and some have incorporated NIST-developed technology into their products.

Approximately 15,000 laser power meters are sold annually in the US. In addition, about 20,000 laser energy meters (joulemeters) are sold. Assuming an average selling price of \$1000, the total laser power/energy meter market is approximately \$35 million. The lifetime of a laser power meter is approximately 6 years (range of 4-10), implying that about 200,000 power/energy meters are in use.

Most products in a laser system supply chain require traceability to NIST as a purchase specification. The power meter companies utilize “working” standards to calibrate their customers’ meters, while an in-house “gold” standard calibrates the working standards. The gold standard is the transfer standard calibrated against the NIST primary standard. Due to the large number of different lasers and wavelengths required, power meter companies cannot duplicate the metrology systems maintained at NIST. Therefore, typical power meter companies spend \$30,000 or more per year for NIST calibration fees to maintain their in-house gold standards. A portion of the acquisition cost for each power meter usually is ascribed to the calibration costs. For the largest customers, NIST calibration can represent 20 percent of the cost of the power meter.

Power meters sold to the industrial market typically are calibrated annually, but power meters used in research applications may not be calibrated as often. On average, industry sources estimate that 60 percent of the installed base of power/energy meters are calibrated annually, for

¹¹ The share figures reflect a consensus opinion of industry experts interviewed in this study. Some respondents provided somewhat different figures for market shares, but the basic results are not sensitive to those differences.

a total of 120,000 calibrations per year in the US. Typically, a calibration performed by the power/energy meter company costs \$200 (range of \$100-400), which equates to a total calibration market of about \$2.4 million annually. Very few firms provide detector calibration services other than the firms that supply power/energy meters and laser systems.

2.2.2 Fiberoptic and High-speed Instrumentation Suppliers

More than 30 companies (10 are non-domestic) manufacture and sell fiberoptic power meters. Nearly half of these companies also sell laser power/energy meters, as noted above. Other fiberoptic instrumentation incorporating detectors include:

- Attenuation meters: 16 firms (7 non-domestic)
- Bit error rate testers: 5 firms (1 non-domestic)
- Dispersion testers: 8 firms (3 non-domestic)
- Index profilers: 1 firm (non-domestic)
- Numeric aperture testers: 6 firms (2 non-domestic)

Many firms other than the meter suppliers provide calibration services for fiberoptic power meters. These firms support the multitude of telephone, cable television (CATV), and local area network (LAN) system installers that perform fiber power measurements on a daily basis. Calibration service providers for fiber power meters include Noyes, Photecs, and EXFO (Canada). Both the meter suppliers and commercial calibration service providers maintain transfer standards from NIST, and a large part of the value these companies provide for recalibration is NIST traceability.

Suppliers of high-speed instrumentation are described in Chapter 4, which provides a more focused assessment of NIST's impact on these suppliers and the telecommunications industry.

2.2.3 Laser Suppliers

Over 120 firms (over 50 are non-domestic) supply lasers in 12 categories of use. As noted in Section 2.2.1, many laser manufacturers (Coherent with its subsidiary Lambda Physik, Jodon, Lexcel, Spectra Physics) also sell laser power/energy meters, many of which are manufactured by one of the top power meter manufacturers (Molelectron, Coherent, Scientech, and Ophir). All laser

manufacturers utilize power meters to characterize the output of their systems for: (1) commercial purposes since the price of the laser typically is dependent on the power output, and (2) certain regulatory purposes (e.g., requirements of the CDRH, and the FDA in the medical laser arena).

2.2.4 Laser Application Systems Suppliers

Over 150 firms (45 are non-domestic) supply laser application systems just for materials processing.¹² Many other firms supply laser systems in 15 other product categories. Many of these firms are also listed as suppliers of lasers.

The market for laser application systems is in the tens of billions of dollars. Suppliers often base their system designs on the laser output power since the laser is often the most costly and least controllable of system components. All suppliers of laser systems utilize laser power meters to:

- Conduct incoming inspection of lasers
- Perform R&D and engineering development of new system designs
- Test laser systems

Each of the above uses of power meters requires accurate measurements traceable to NIST's primary standards. Incoming lasers must meet minimum power specifications to be useful in the intended system. System design and testing of prototypes in R&D are based on the laser powers measured at various points within the system, and laser systems must be tested to ensure proper operation for end users.

¹² *Laser Focus World Buyers Guide 98.*

2.3 ECONOMIC ANALYSIS FRAMEWORK

Table 2 summarizes the framework for assessing the economic impact on US industry of NIST's primary calibration services.

Table 2. Economic Framework for Overall Assessment of NIST's Calibration Services

NIST Outputs	Hypothesized Outcomes	Affected Industrial Organizations	Outcome Measure and Affected Stage of Economic Activity	Comparison Scenario (counterfactual replacement of NIST outputs)	Time Series of NIST Costs (C) and Industry Net Benefits (B)
Primary calibration services for – Radiometry – High-speed measurements	Avoidance of: – Extra equipment and personnel costs for in-house metrology – Extra transaction costs incurred in the absence of industry agreement on NIST as a primary reference for calibrated standards in all laser wavelengths and high-speed measurements	All laser-based markets, firms that supply: – power/energy meters – fiberoptic power meters – lasers – high-speed instrumentation	Increased personnel and equipment to validate accuracy of laser measurements for obtaining: – transfer standards from foreign labs or proprietary firms – product acceptance with customers	Use of foreign laboratories, or Establishment of proprietary standards	(C) 1999 NIST's costs to maintain and provide calibration services (B) 1999 net costs avoided by industry because of NIST's calibration services

Most of NIST's customers for primary calibration services are suppliers of laser power/energy meters, fiberoptic power meters, and high-speed instrumentation. NIST calibrates annually about 50 laser power meters, 40 optical fiber power meters, and 20-25 high-speed detectors. Customers use these calibrated artifacts as a basis for internal measurement, known as “gold standards,” to establish traceability with NIST’s national reference standards. The gold standards are used, in turn, as a basis for calibrating downstream instruments to NIST's standards. Thus, the relatively few primary calibrations performed at NIST are transfer standards that form the basis for consistent measurements among the hundreds of thousands of instruments used in industry.

This overall assessment poses a counterfactual hypothesis whereby NIST's calibration services would be unavailable in 1999. For the overall assessment, the annual costs of operating and maintaining NIST's laser calibrations services are compared with the net 1999 costs that industry would have incurred to cope without NIST's calibration services. Those counterfactual costs to industry are avoided because of NIST's laser calibration services, and hence those costs avoided are one measure of the benefits from NIST's laser calibration services.

Just the single 1999 annual benefits-to-costs metric is provided for the overall assessment because the time series showing the history of all of the relevant costs and benefits associated with NIST EEEL laser calibration services is not available. In the absence of such a comprehensive time series, one hypothetical question is posed: Had NIST not provided the laser calibration services in 1999, what would industry have spent to provide quality laser calibrations without those services? This scenario assumes that all of the measurement technology has been developed and is publicly available, and the change is that NIST ceases to provide its laser calibration services.

For the overall assessment, the benefits for industry are the 1999 costs avoided because NIST provides laser calibration services. Those benefits for 1999 include any additional costs for new equipment and personnel as well as the annual ongoing costs of replacing NIST's services. These initial additional costs do not entail R&D because the state of metrology development is assumed. However, absent NIST, some companies would invest in equipment to allow more in-house metrology work to replace the use of NIST's services.

The benefits-to-costs ratio developed for the overall assessment of NIST's laser calibration services does not measure the broad set of all benefits from the products supported by the traceable laser calibrations. Rather, the benefits measured are just the net costs that industry would incur without NIST's laser calibration services.¹³ The assumption is that absent NIST's laser calibration services, the affected domestic industry would find or establish substitute means for obtaining laser calibrations traceable to standards. The net costs of the effort to establish the substitute means (the costs avoided because of NIST's services) are the measure of industrial benefits for this study.

2.4 SURVEY FINDINGS

For the overall assessment, the population of beneficiaries from NIST's laser calibration services includes the laser power and energy meter suppliers, fiber-optics power meter suppliers, the suppliers of high-speed frequency-response fiber-optic measurements, and the suppliers of lasers and laser systems. The sample, from which information about the benefits of NIST's laser calibrations services were obtained through telephone interviews, covered suppliers of laser

¹³ The net costs are the additional costs; namely, new costs incurred minus any old costs that would no longer be incurred in the counterfactual scenario.

power and energy meters representing over 70 percent of the market for those meters. Also interviewed were two of the leading suppliers of fiber-optics calibrations services and fiber-optic power meters, the key supplier of high-speed frequency-response fiber-optic measurements, and two of the leading suppliers of lasers and laser systems.

The interviews show clearly that the provision by NIST of those laser calibration services is of great importance to industry. Industry values the calibration services because they are grounded in NIST's laser measurement technology and in NIST's role as the repository of national standards. Respondents were asked to rank the relative importance of NIST's outputs to their company. The NIST outputs to be ranked were:

- The provision by NIST of the measurement technology for laser strength at different wavelengths
- The provision of standards
- The provision of calibration services
- The provision of state-of-the-art measurements for special needs
- Direct contributions to commercialization and production

The respondents typically ranked the package, or combination, of the measurement technology, the standards, and the calibration services as most important, although some respondents would emphasize one aspect of the package over others. Further, certainly there are cases where a special measurement to meet a particular need has been important, and respondents mentioned such cases, but ranked that particular output behind the package of measurement technology, standards, and calibration services. Direct contributions to commercialization and production ranked last.

The traceability of laser measurements to standards at NIST is generally seen as a key part of the successful use of laser technology in industry. Respondents indicated that they would face substantial additional costs for laser metrology if the services of NIST were not available in 1999.

2.4.1 Suppliers of Laser Power/Energy Meters and Fiberoptic Power Meters

The largest US laser power/energy meter suppliers were interviewed: Molelectron, Ophir, Coherent, and Scientech. OAI, a company that dominates the market for portable power/energy meters used in the semiconductor industry's supply chain, was also interviewed. Coverage of fiber-optic power meters included interviews with Hewlett Packard (now Agilent—Hewlett Packard's spin-off of its test and measurement businesses), and EXFO Electro Optical Engineering, one of the leading suppliers of fiber-optic power calibration services (including the fiber-optic power meters) worldwide.

Respondents spoke authoritatively about the additional costs that industry would incur if NIST's laser calibration services were not available. Those additional costs would result, in part, because of the need for extra effort to resolve disputes about measurements with customers. Customers would need to be convinced of the validity of measurements in the absence of traceability to NIST's standards. Further, additional equipment costs as well as additional costs for scientists and engineers to deal with proprietary metrology standards would be required. Likewise, obtaining primary calibrations from foreign laboratories would entail extra costs for technical and administrative reasons. Respondents did not break out any differences in calibration services fees for dealing with foreign labs, but instead gave overall estimates of the increase in costs and then listed the sources for the cost increases. Working with foreign labs would take more time and resources because of technical issues about ensuring traceability to standards for US customers, shipping problems (including dealing with US customs), language problems, and problems of dealing with different time zones. As one respondent observed, NIST is better for its US customers because they are familiar with NIST, and because some customers have contracts that specify traceability to NIST.

The responding companies identified a mixture of approaches in the absence of NIST. Some would build more in-house metrology capability, some would use foreign labs, and some would do both. Most firms reported extra costs of dealing with customers absent traceability to NIST. The loss of the US standards organization would entail additional transaction costs of dealing with customers, even given the use of more in-house metrology and the use of foreign labs. Clearly, in 1999 a mixture of approaches would have been used to deal with a loss of calibration services from NIST. Respondents did not provide an assessment of what the ultimate approach for working without NIST would be, but in the short term they reported that both the neutral services of foreign labs and the proprietary services of leading firms would be the sources for primary calibrations.

The additional costs identified reflect the costs for just the fractions of the US laser power/energy meter market and of the fiber-optic power meter market represented by the companies of the respondents. For each market, the product of the reciprocal of that fraction and the additional costs identified was used to estimate the total industry-wide addition to costs for the meter suppliers in 1999 in the absence of NIST's laser calibrations services.

The survey findings include benefits for the customers of the instrument suppliers that were interviewed. Respondents indicate that a portion of the cost of doing without NIST's calibration services is transaction costs incurred between instrument suppliers and their customers. Time is spent in negotiations between the sellers of laser measurement instruments and their customers about the accuracy of measurements. The interviews have established an estimate of those transaction costs for the firms supplying the US market. The negotiations about measurement accuracy are, of course, two-sided. If a power meter company reports spending an extra hour discussing or negotiating with customers to resolve measurement disputes, then those customers are assumed to spend an hour on the additional discussions. Hence, the estimate of transaction costs found for the instrument suppliers has been doubled to estimate a small portion of the total transaction costs avoided by industry.

2.4.2 High-speed, Frequency Response Detector Instruments

In-depth interviews were conducted with Hewlett Packard, the major company that obtains high-speed, frequency response detector measurement standards directly from NIST. Hewlett Packard and other companies that are direct customers of NIST's high-speed services then transfer the calibrated technology to the rest of the telecommunications industry. Hewlett Packard has provided information about the counterfactual costs of replacing the investments that NIST made in developing high-speed measurement technology, and the benefits from those investments are analyzed separately in Chapter 4. For the purpose of the evaluation in this chapter, the benefits from NIST's calibration services are estimated given the current state of measurement technology. The additional costs that would have been incurred by industry absent NIST's high-speed frequency response investments are addressed in Chapter 4.¹⁴

¹⁴ Counterfactual investments would have been made in 1999 by some of the power meter firms to attain the necessary in-house capability. In those cases, if NIST quit providing services, then the companies would invest in the requisite equipment. With the high-speed measurements, the recent R&D investments established the metrology that HP now has at hand.

Without NIST and the traceability it provides, Hewlett Packard and other direct customers of NIST's services would incur additional transaction costs of becoming primary standards providers. The switch from a neutral standard provided by NIST to a proprietary standard provided by HP and others would entail costs. Interviews identified the costs for HP to become a proprietary source of primary standards. Those costs entail additional staffing to resolve disputes with customers, additional participation at standards conferences, and additional efforts for writing papers establishing measurement technology standards. Additional engineers, specializing in fiber-optics measurement technology, would be needed.

Under the counterfactual scenario, during the initial years of high-speed metrology development HP becomes the primary standards organization and all subsequent measurements become traceable to HP's standard. However, beginning in 1997, NIST developed a heterodyne system operating at 850 nm to address the needs of the computer interconnect market, and after that, HP, previously the main customer for NIST's high-speed calibrations services, accounted for only about 50 percent of NIST's calibration work load. Therefore, from 1998 onward, the counterfactual scenario assumes that other current direct customers of NIST would provide some of the proprietary primary standards. Since HP and other direct customers of NIST are working with the same R&D base as NIST, the quality of the replacement measurement technology is theoretically equivalent. However, Hewlett Packard emphasized that, realistically, industry could not be completely replace NIST's services for high-speed frequency response detector measurements because there would be no neutral US authority to provide a standard to which all calibrations could be traced. Industry values the neutrality of NIST as a non-proprietary agency. That neutrality is what cannot be replaced or substituted for even the very best proprietary primary standards, and it forms the basis for the additional transaction costs that would be incurred.

2.4.3 Laser Suppliers

Occasionally, a laser supplier will obtain calibration services directly from NIST to ensure the highest possible accuracy of measurements taken on their lasers and laser systems. One special case involved the laser suppliers Cymer and Coherent (with its laser supplier Lambda Physik as a subsidiary) working cooperatively on a calibration project with NIST. Cymer interacted directly with NIST, while Coherent provided some of the project's funding and some sensors used in the project. More generally, laser suppliers need to validate the quality of their metrology for the laser power at wavelengths of interest for their lasers and laser systems. For that reason, traceability of measurements to NIST is important to laser suppliers.

Cymer, the dominant supplier of 248 nm lasers for the semiconductor industry, was interviewed primarily for the in-depth study of the semiconductor chain in Chapter 3. Coherent was also interviewed regarding its subsidiary, the laser supplier Lamda Physik. From these interviews were obtained estimates of benefits that resulted because NIST's services address special calibrations needs for the laser supplier Cymer. Such benefits were not projected industry-wide, but simply counted as benefits for the Cymer alone. The more general benefits identified by Cymer and Coherent (for its laser-supplier subsidiary) of traceable measurements, including reduced transaction costs with customers and reduced costs for in-house metrology, were projected industry-wide using estimates of the respondents' market shares.

2.5 QUANTITATIVE ANALYSIS

2.5.1 NIST's Costs

The NIST-EEEL Sources and Detectors Group is composed of two projects: (1) Laser Radiometry, and (2) High-speed Source and Detector Measurement. The Laser Radiometry project includes calibration services for laser power and energy as well as for fiber-optic power. NIST's estimated costs of the projects for calendar year 1999 are shown in Table 3.

Table 3. NIST's 1999 Costs for Laser Calibration Services

NIST Project	Expenditures 1999 (\$K)	Expenditure Mix (percentage)		
		Measurement Capability	Technology Development	Fundamental Research
Laser Radiometry	1,703	80	20	0
High-speed	1,036	90	10	0

NIST's managers observe that the distinction between measurement capability and technology development is quite unclear. The estimates are accurate to ± 5 percent, but the band of uncertainty could be much larger if the evaluator used different assumptions for the definitions of the categories than those used by NIST's managers.

Thus, NIST's estimated 1999 annual cost for providing calibrations services for laser power and energy meters, fiber-optic power meters, and high-speed frequency response measurements is approximately \$2.3 million:

$$(0.80) * (\$1,703,000) + (0.90) * (\$1,036,000) = \$2,294,800$$

Some of NIST's costs are reimbursed by industry in the form of fees for calibration services. However, for the analysis of social economic impact of a NIST program, such reimbursed costs are not "negative costs." When calculating the social rate of return to the public provision of the infra-technology, all of the costs of the policy should be considered. The social cost of a program equals the resource costs for making available the program's services. Then, against those social costs are weighed the benefits of the program. Some of those benefits are the reason that the private sector is willing to pay for NIST's services. Subtracting the private sector payments for these services would incorrectly subtract some of the costs of maintaining the program. Those costs exist whether the government pays for them entirely with public funds or whether some of the cost is reimbursed by the private sector. Further, such reimbursed costs

should not be subtracted from the industry payments for NIST services as "pull costs" in the context of the social rate of return analysis.¹⁵ Rather, the reimbursed costs are "pecuniary costs" that simply redistribute the costs of providing NIST's services. The total social benefits and costs of the program are the same, regardless of who pays for the costs.

2.5.2 Industry Benefits

To weigh against NIST's 1999 costs of \$2.3 million are the social benefits in the form of costs avoided in 1999 by industry because of NIST's laser calibrations services. The benefits of NIST's services would have been lost, and industry would have had to incur costs to replace NIST's lost services. The costs that industry avoided in 1999 are the social benefits from NIST's calibration services, which become the numerator of the benefit-to-cost ratio.

The computed estimate of the social benefits to industry is conservative. Many of the respondents emphasized that even incurring the additional costs to cope with the loss of NIST's services, those services could not be replaced completely. Many respondents said it would be impossible for industry to replace completely the essential service of traceability to a US national standard provided by the neutral US authority. One respondent with a dominant market position in a particular type of meter even quantified the loss of traceability to NIST for his company's power and energy meters. He stated that without traceability to NIST, half of his company's sales would be lost to foreign competitors. Hence, the benefit-to-cost ratio is an underestimate because the industrial costs avoided that are measured do not include all of the costs from the loss of traceability to a national US standard provided by a neutral authority. Only partial benefits from NIST EEEL laser calibration services are measured. The benefits measured are only the additional costs for US industry of trying to replace NIST's calibration services with additional:

¹⁵ "Pull costs" should indeed be considered in an economic impact evaluation. If a company employs a scientist full-time on an annual basis in order to use the services of NIST, then the fully burdened cost of the scientist is considered—usually in the analysis of the benefits of NIST's program for industry. Typically, such costs are (usually implicitly) netted out from the benefit stream. For example, an industrial representative who is asked to identify the additional expenditures to replace NIST's services may reply: "we currently have to employ one scientist full time to make use of (pull in) NIST's services. Without NIST, we would employ that scientist and two others full time to have the same capabilities that we have now." Then, for the benefits accruing to NIST's investments in the program, the fully burdened costs of two (not three) scientists are avoided because of NIST's program being available.

- Time spent verifying meter calibrations with customers (transaction costs)
- Equipment and labor to calibrate gold standards
- Effort of dealing with foreign laboratories

The benefits from NIST's services that cannot be replaced by industry's extra efforts are not measured. Industry benefits measured are just the additional direct costs that industry would incur in attempting to replace NIST's services, and do not include the indirect effects on sales that would result according to the respondents. Thus, NIST's role as a neutral US provider of traceable standards could never be completely replaced.

Total benefits are estimated as \$26,100,000. The benefits are the costs that industry avoided in 1999 because NIST did, in fact, provide the services. When the respondents estimated benefits for their companies and analogous benefits would accrue to all companies in the industry, the reported benefits were multiplied by the reciprocal of the sum of the respondents' market shares to estimate the industry-wide benefits.¹⁶

As recounted above, companies differed in the ways they would adjust to a situation without NIST's laser calibration services. Various mixtures of expanded in-house metrology and proprietary standards, extra negotiations with customers about measurement accuracy, and use of foreign labs would be used. The total benefit figure reflects the mix of counterfactual approaches that would occur as reported by the respondents. Companies also differed in the extent to which they disaggregated the additional costs that they would face when pursuing those alternatives. For example, some respondents broke out additional equipment costs from personnel costs associated with new in-house metrology efforts. Other respondents would make a single estimate covering both sources of additional costs. Further, the transaction costs from the additional negotiations with customers often cannot be separated from additional costs of dealing with foreign laboratories. Some of those costs, such as dealing with customs or extra fees or time zones or various technical issues could be seen as a separate category of additional costs associated with using foreign laboratories for US customers who would prefer traceability to NIST. There are

¹⁶ Thus, if respondents with two-thirds of a market estimate benefits totaling \$y, the estimate of the industry-wide benefits would be $$(1.5)*y$.

associated transaction costs of dealing with those customers, however, which respondents typically are unable to separate, instead giving an overall assessment of extra costs from dealing with foreign labs from all of the various sources. To the extent possible, given the foregoing difficulties when disaggregating costs, the makeup of the additional costs is given in Table 4.

Table 4. Disaggregated 1999 Benefits (costs avoided) for Calibration Services

Expanded in-house metrology —additional costs for equipment and personnel	Transaction costs —additional costs of dealing with customers, suppliers, and/or foreign laboratories
\$13,100,000	\$13,000,000

2.5.3 Metrics

Dividing the 1999 annual benefits from NIST EEEL laser calibration services by the 1999 annual costs for the NIST program (\$26,100,000/ \$2,300,000) provides a point estimate of the lower bound for the benefit-to-cost ratio of 11.3. Using the same figures, the 1999 net benefit is \$23,800,000.

2.5.4 Uncertainty

If respondents gave a range for an answer, the midpoint of the range was used as the estimate. Such ranges can vary from one respondent to another, even for the same cost (such as additional time, and hence cost, of dealing with customers, or additional equipment costs, or additional needs for scientists and engineers). Uncertainty about market shares can vary for different products. At times respondents gave an expected value, but did not attempt to provide a range of estimates for uncertainty. Studying the various sources of uncertainty, an approximate range for the uncertainty was determined based on the stated responses and judgements of those close to the technology and the markets. Taken together, the benefits measured are believed to have a range of uncertainty of approximately ± 25 percent based on the respondents' judgements. Thus, an estimate of 100 would correspond to a possible range from 75 to 125. NIST has estimated its costs with a range of uncertainty of ± 5 percent. Incorporating the uncertainty ranges into the calculations, the range of uncertainty for the metrics is shown in Table 5.

Table 5. Estimate Range of Lower-bound Economic Impact for Investments in Primary Calibration Services

Metric	Low	Midpoint	High
Benefit-to-cost ratio	8.1	11.3	14.9
Net Benefits in 1999	17,100,000	23,800,000	30,300,000

3. ASSESSMENT OF 248 NM R&D AND CALIBRATION SERVICES

This chapter assesses a specific R&D effort and primary calibration services for measurement technology applied to 248 nm lasers used in semiconductor manufacturing. The first section briefly describes the economic importance of projection lithography within the semiconductor manufacturing process and the attendant role of laser measurement technology. The second section describes the industry supply chain affected by NIST's 248 nm measurement technology. The third section describes the framework for economic analysis of NIST's 248 nm investments. This is followed by the findings from an industry survey and an analysis of the economic impact.

3.1 ECONOMIC IMPORTANCE TO SEMICONDUCTOR INDUSTRY

3.1.1 Semiconductor Manufacturing

Significant progress in the functionality of semiconductor integrated circuits (ICs) achieved over the past three decades has been the key reason for the expanded utilization of this technology in numerous computer applications affecting daily life. The impetus for this growth in functionality has been the continued shrinkage of transistors, device spacing, and interconnect paths formed in the semiconductor manufacturing process.¹⁷ Such miniaturization has enabled an increase in the transistor density (number of transistors that can fit onto a single chip), which is the key driver of product complexity and price in integrated circuits. Making transistors smaller is desirable since:

- The microcircuits operate faster
- Interconnections are smaller
- System reliability increases because more functions are integrated into a single space
- Less power is consumed
- Manufacturing yields increase, thus reducing production costs

¹⁷ Transistors are the basic building blocks of integrated circuits. Transistors are gates that open and close at high-speeds to direct electrons around electronic circuitry. Making transistors and the attendant circuitry smaller gives electrons less distance to travel, which makes them faster. Transistor devices are microscopic in scale, allowing millions of these devices to be packed onto individual chips.

In other words, all performance and cost metrics improve, and no engineering tradeoffs are required.

Making transistors smaller depends on the minimum printable linewidth (the feature size of the thinnest circuit line or transistor element) that can be fabricated cost effectively. Table 6 illustrates the trend toward reduction in linewidth and increased functionality for the Dynamic Random Access Memory (DRAM), the largest category of memory chips. For example, in 1980 DRAM devices containing 64,000 bits-per-device (64Kb) were produced using “design rules” having 2.5 μm (2.5 microns) feature sizes.¹⁸ By 1996, 256Mb DRAMS—a 4,000-fold increase in capacity—were being produced using 0.25 μm feature sizes. This trend, largely unprecedented in industrial history, is fundamental in the semiconductor business. The technical progression has been described as “Moore’s Law”: the power and complexity of the silicon chip doubles every 18 months with a proportionate decrease in costs.¹⁹

Table 6. Measures of DRAM Process Improvements

	1975	1980	1985	1990	1992	1995	1998
Minimum line widths (microns)	6	2.5	1.5	0.5	.035	0.25	0.18
DRAM (# bits)	4K	64K	1M	16M	64M	256M	1G
Defect Density/cm ²	8	6	2	1	<1	<1	<1
DRAM Yield (%)	25	40	60	80	85	90	90+
Wafer Size (mm)	75	100	125	150	200	200	300
Asset Utilization (%)		30	40	45	55	80	>90
Fab Cost (20K wafer starts/month)	100M	150M	250M	500M	750M	1B	2B
Cost of good die (\$/cm ²)	8	7.5	6	5.5	4	3.9	3.8

Source: James Freedman, Semiconductor Research Corporation

¹⁸ The semiconductor industry has been organized around design rules that specify the minimum feature size of each device generation.

¹⁹ Gordon Moore, currently chairman emeritus and founder of Intel, observed in 1965 that transistor logic density of silicon integrated circuits closely followed the following relationship: bits per square inch = 2^{t-1962}, where t is time in years. In other words, the amount of information storable on a given amount of silicon had doubled roughly every year since the year (1962) that planar IC technology was invented. Moore posited that this trend would continue into the future, and computing power would rise exponentially over a relatively brief period of time. The relation held until the late 1970s when the technical pace slowed to the point where the doubling period occurred every 18 months, the current definition of Moore’s Law which Moore himself accepts. This trend continues and is the basis for the planning forecasts of many firms in the semiconductor industry.

3.1.2 Projection Lithography

Producing semiconductors on pace with the rapid technological continuum of Moore's Law over the past twenty years has required advances in projection photolithography. Lithography is the dominant cost element in wafer processing, representing about 35 percent of the total cost of a processed wafer. Conceptually, imaging a circuit pattern with photolithography is analogous to the process used in traditional photography:

- The “flashbulb” illumination source is either a high-power arc lamp or, more recently, a laser
- The camera “lens” is near-perfect projection optics
- The “scenery” to be imaged is a set of carefully designed circuit patterns on a mask or reticle
- The photographic “emulsion” is a high-resolution photoresist
- The “film” is a wafer, usually made of silicon
- The film “advance mechanism” is a step-and-repeat stage for imaging numerous chips on a single silicon wafer

However, this conceptual simplicity belies the great complexity involved with photolithography. In particular, the lithography tool must provide a sharp aerial image of a minute feature size while maintaining a comfortable margin for process repeatability.²⁰

Following the laws of optics, the most practical way to reduce the smallest elements on the chip while maintaining acceptable levels of process margin has been to reduce the wavelength of the illumination source.²¹ Mercury arc lamps have been the primary lithographic illumination sources for integrated circuit (IC) manufacturing for more than 30 years. The

²⁰ Mordechi Rothschild, et. al., “Photolithography at 193 nm,” MIT Lincoln Laboratory Journal, Volume 10, Number 1, 1997.

²¹ Depth of focus (DOF) is the most critical parameter in determining the process margin for photolithography. Generally, DOF represents the range of focus errors that a process can tolerate while giving acceptable lithographic results. The DOF must be larger than any variation in the flatness of the photoresist surface. Such variations in flatness are unavoidable due to: (1) surface deviations of the wafer, and (2) the topography added to the wafer through the deposition and etching of various thin films in the course of fabricating the semiconductor device.

semiconductor industry has made the transition from a wavelength of 436 nm (the so-called "G-line" of mercury arc lamps) to 365 nm (the "I-line" of mercury arc lamps), and is now in the transition to 248 nm using the krypton-fluoride (KrF) excimer laser. A future transition is being planned to a wavelength of 193 nm using the argon-fluoride (ArF) excimer laser. Both the 248 nm and 193 nm excimer lasers are referred to as deep ultraviolet (DUV) sources.²²

The 1997 technology roadmap of the Semiconductor Industry Association (SIA), as shown in Table 7, forecasts that DUV laser technology will be used to fabricate the smallest elements in semiconductor production for the next 10 years (through the 130 nm IC device generation). As the table shows, the useful life of the DUV lithography tools extends beyond leading-edge fabrications. These tools can continue to be used for patterning the majority of non-critical level wafer levels in succeeding IC generations.

Table 7. DUV Life Cycle for Semiconductor Lithography

98-0127.a

	1997	1999	2001	2003	2006	2009
1997 SIA Roadmap						
Device Generation (nm)	250	180	150	130	100	70
DRAM (bits)	256M	1G	---	4G	16G	64G
DUV Life Cycle						
KrF (248 nm)	Leading edge					
ArF (193 nm)			Leading edge			

²² Excimer lasers provide powerful pulses of ultraviolet light. Their high brightness (energy density) makes them capable of exposing 10 wafers per hour, versus 1 wafer per hour using a 248 nm incoherent light source (lamp). This energy-intensive procedure is repeated 1000 times a second or nearly five to 10 million times a day for months at a time in synchronization with the stepper.

3.1.3 Optical Power Measurement

The exposure of photoresist to DUV laser light is based on the total energy deposited in the photoresist. The standardization of the photoresist and the accurate measurement of excimer laser pulse energy—process tolerances of about 1 percent are common—have been required to obtain consistency in wafer results. Accurate power/energy meters for excimer lasers have been required to make these lasers practical in a high-yield, high-volume manufacturing environments as the energy level must be adjusted to achieve the proper exposure time for the corresponding photoresist and circuit pattern.

The optical path for a generic excimer laser lithography tool is shown in Figure 3. The figure shows two built-in power meters for process control. One power meter is internal to the laser system for gauging the laser power supply voltage to ensure a constant pulse intensity output. The other, more critical power meter is the exposure power meter. This power meter is used for measurement and control of the laser pulse energy. A third power meter is used to transfer power meter measurements portably from one lithography tool to multiple tools in a semiconductor fabrication plant

The lithography process requires a precise amount of laser dose when exposing the photoresist.²³ Delivering the correct amount of dose depends highly on the ability to accurately measure each pulse of energy. A simple power meter that averages or samples the pulses is insufficient since the energy in a typical pulsed laser varies from pulse-to-pulse. Every pulse has to be accounted for, or the process is not repeatable. Reproducing the exact dose continuously is a key challenge facing lithography companies. Thus, two key parameters of the laser are the pulse repetition rate and the pulse-to-pulse energy stability. These parameters have an important effect on the energy dose accuracy. Such accuracy can translate into:

²³ Dose is a set of laser pulses, where the energy in consecutive pulses accumulates to produce a total amount of energy in a given area. Power meters infer dose by measuring the total pulse energy in millijoules per square centimeter.

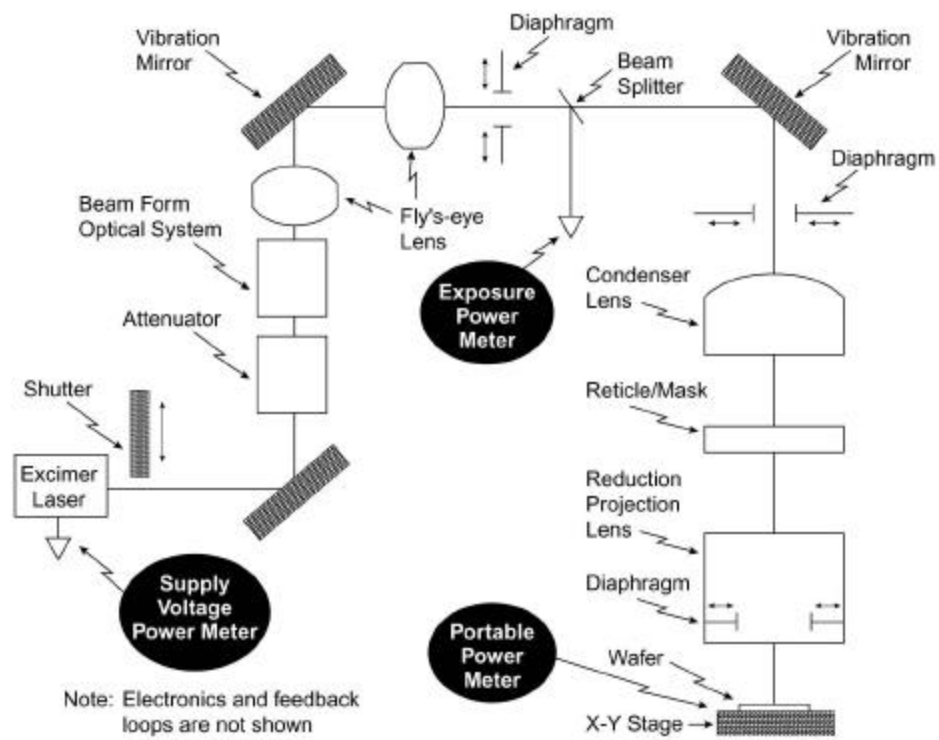


Figure 3. Schematic of an Excimer Laser Photolithography System

- Higher wafer throughput
- Reduced numbers of test wafers²⁴
- Extended lifetime of the optics on the lithography tool

Laser power at the wafer level (i.e., exposing the photoresist) is only one of many parameters that affect chip manufacturing. Resist consistency, laser wavelength, wavelength stability, spectral width, and the optical system utilized all have an impact on the resolution (minimum linewidth) and the manufacturing yield that can be achieved. Taking these other factors into account, laser power at the wafer level must be measured to ± 1 percent accuracy with respect to a primary standard to satisfy the needs of semiconductor manufacturers.

3.2 INDUSTRY SUPPLY CHAIN

The general supply chain for semiconductor manufacturing is shown in Figure 4. Moletron has been the largest supplier of wafer plane power meters for 248 nm power meters, and other key domestic suppliers include OAI, Scientech, and Ophir. Power meters are used with laser illumination sources, which are produced by only a few companies:

- Cymer, Inc., based in the US
- Lambda-Physik R&D, a German-based subsidiary of Coherent, Inc., a US firm
- Komatsu, based in Japan

²⁴ In-process metrology in semiconductor manufacturing requires test wafers that are processed together with production wafers. The test wafers are removed from the fab line at selected steps in the process for measuring conformance to the process. If deviations or defects are observed during this routine inspection, then detailed inspections are undertaken to determine the source and occurrence of the problems. Both routine and detailed inspections frequently include measurements of key parameters. Thus, test wafers are essential to produce good products consistently.

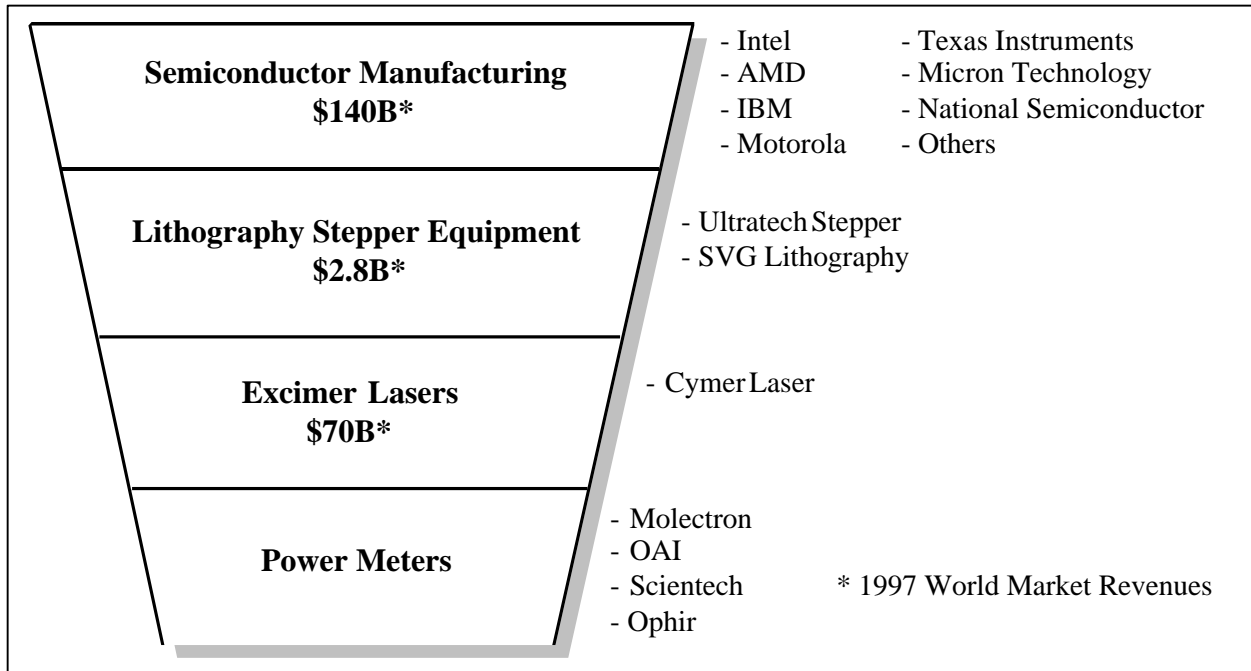


Figure 4. Measurement Technology Flow for Semiconductor Industry

Cymer has controlled about 80 percent of the world-wide market for DUV laser sources since 1995, when the market for 248 nm production systems began to develop. Through December 1997, Cymer has sold over 600 lasers systems that have been incorporated into the photolithography tools manufactured by the following five firms:²⁵

- ASM Lithography
- Canon
- Nikon
- SVG Lithography
- Ultratech Stepper

Sales to the three foreign lithography suppliers (ASM Lithography, Netherlands; Canon and Nikon, Japan) accounted for 69, 81 and 89 percent, respectively, of Cymer's total product sales in 1995 (\$15.6M), 1996 (\$62.5M) and 1997 (\$201M). Cymer spent seven years developing its

²⁵ Cymer, Inc. 1997 Annual Report on Securities and Exchange Commission form 10-K.

248 nm laser before the product design and performance were acceptable to wafer fab managers.²⁶ Their laser systems sell for about \$500K each, including the power meter monitoring subsystem. Altogether, Cymer's lasers have been incorporated into the lithography tools used by the 15 largest semiconductor manufacturers worldwide and by 17 US entities.

In 1997, the world market for lithography systems, in which average selling prices are about \$10 million apiece, was approximately \$2.8 billion. According to Dataquest, about 100 total DUV lithography systems were sold worldwide from 1992-1996.²⁷ The DUV market began to take off in 1997 with about 300 units shipped. Sales are expected to rise steadily and reach 800 units per year by 2000.

3.3 ECONOMIC ANALYSIS FRAMEWORK

Table 8 summarizes the framework for assessing the economic impact on the US industrial supply chain from NIST's investments in 248 nm measurement technology.

SEMATECH, the industrial consortium whose members work together in precompetitive technology areas of semiconductor manufacturing, initiated a joint project with NIST in 1990 to study metrology requirements of light intensity measurements for 248 nm excimer and I-line photolithography systems. The joint SEMATECH/NIST project addressed these needs by developing hardware, standards, and the implementation of calibration procedures for the metrology. This project was motivated by earlier studies at SEMATECH which revealed that I-line power meters supplied from the primary domestic source, Optical Associates Incorporated (OAI), and OAI's primary competitor (Ushio, a Japanese firm) read 20 percent below and above, respectively, from a NIST test reference. This significant difference in power meter readings created difficulty for SEMATECH member companies in making accurate comparisons of lithography tool performance among alternative suppliers of the tools. In fact, an unexpected benefit of the joint NIST-SEMATECH project was that the I-line stepper tool produced at the time by GCA, then the leading domestic supplier for such tools, compared better in terms of dose energy performance against its foreign competition than had been thought previously.

²⁶ Design issues included narrowing the bandwidth of the laser output, shaping the output beam, and controlling the pulse-repetition rates through a feedback loop. A significant part of the development time involved ramping up Cymer's manufacturing capabilities to a level that could meet volume demands.

²⁷ As reported in "Lithography Market Challenges Manufacturers," *Laser Focus World*, October 1997.

Table 8. Economic Framework for Assessing 248 nm R&D and Calibration Services

NIST Outputs	Hypothesized Outcomes	Affected Industrial Organizations	Outcome Measures and Affected Stage of Economic Activity Absent NIST	Comparison Scenarios (counterfactual replacement of NIST outputs)	Time Series of NIST Costs and Industry Net Benefits
<p>R&D to establish 248nm metrology</p> <p>Primary calibration services for 248nm excimer lasers</p>	<p>More efficient R&D or reduced R&D replication to establish metrology services</p> <p>Avoidance of extra transaction costs due to industry agreement on NIST as a primary reference for calibrated standards at 248nm excimer wavelength</p> <p>Improved laser-based products and processes from more accurate standards)</p>	<p>Affected semiconductor supply chain:</p> <ul style="list-style-type: none"> – power/energy meters – lasers – lithography tools – semiconductor manufacturers 	<p>Increased personnel and equipment to establish metrology services prior to industry adoption of 248nm lithography systems</p> <p>Increased personnel and equipment to validate accuracy of laser measurements for obtaining:</p> <ul style="list-style-type: none"> – transfer standards from foreign labs or proprietary firms – product acceptance with customers <p>Lower product/ process quality and performance leading to decreased sales</p> <p>Reduced fab IC yield for semiconductor manufacturers</p>	<p>Use of foreign laboratories</p> <p>Establishment of proprietary standards</p>	<p>(C) research, develop, maintain, and provide calibration services from 1990-2009</p> <p>(B) 1994-2009</p>

As a part of the SEMATECH-NIST project, NIST built and delivered two 248 nm calorimeters for GCA. GCA closed its semiconductor lithography division in 1993 and returned the two calorimeters to NIST, which has been using them as a basis for primary standards since 1994. One of the early NIST contributions was the development of suitable materials within the cavity of the calorimeter and power meters to absorb the 248 nm wavelength and withstand the high peak power of excimer laser pulses.²⁸ Prior commercial work by Questec and Scientech had relied on using conventional laser power meters and correcting for the absorption of the cavity at ultraviolet versus visible wavelengths.²⁹ Since the completion of the joint NIST/SEMATECH

²⁸ NIST developed and characterized highly absorptive materials for use at the ultraviolet wavelengths of these lasers. Calorimeters depend on the absorptivity of the cavity at the optical wavelengths being measured. In the visible and at infrared wavelengths, very high absorption can be obtained (i.e., the cavity can be made to look very “black”). However, absorption becomes more difficult at ultraviolet wavelengths.

²⁹ Originally, the approach to power measurement at 248 nm (the initial excimer laser wavelength used in these systems) involved indirect methods of calibration. These methods were based on reflectivity or absorption measurements of the 248 nm energy by a conventional (visible wavelength) power meter. The measurements were then corrected to ultraviolet wavelengths based on the presumed absorption/reflection curve of the power meter detector surface.

project, NIST has developed technology and procedures for improving the power measurement accuracy at 248 nm from 2 percent to 1 percent for the standard against which transfer meters (and then field meters) are calibrated.

As the technical push for denser and faster circuits shrinks linewidths to 0.15 μm and below, the semiconductor industry has shifted to 193 nm excimer laser technology. Lincoln Laboratory requested measurement support from NIST at this wavelength in 1996, and SEMATECH has been funding NIST for the development of an absolute standard at 193 nm. The 193 nm excimer laser output characteristics require improved calorimeter technology to establish 193 nm metrology.³⁰ Due to the nascent nature of this infra-technology at the time of evaluation, the NIST investments in 193 nm technology are not included in the scope of this assessment.

NIST has provided calibration services for the suppliers and users of optical power meters for 248 nm excimer lasers. NIST has developed the calibration system, including both hardware and software. Since the mid-1990s, NIST has provided numerous calibrations of excimer laser power and energy meters at 248 nm. Until recently, power meters used in the field (primarily for research) were only able to measure excimer laser pulse energy to about 10-15 percent accuracy, a range that is insufficient to controlling wafer plane exposure for high yield chip manufacturing. Through research at NIST, accuracy of 1 percent can now be achieved at 248 nm.

In summary, NIST has developed improved excimer laser calorimeter designs to establish DUV metrology. This measurement technology diffuses through a chain of semiconductor equipment and materials firms, and eventually leads to the end-users, semiconductor manufacturers. The ability to measure laser power, and thus photoresist exposure, made possible by NIST has facilitated the transition to fabricate smaller IC linewidths—0.25 μm in the case of the 248 nm excimer systems, and 0.15 μm with 193 nm systems. The ability to reduce linewidth makes possible denser circuits, faster circuits, cooler-running circuits, more reliable manufacturing and higher yield, and lower cost chips. This, in turn, has fueled the continued rapid development of the electronics industry.

³⁰ For example, new volume absorbing materials and detector surface materials have to be developed. Additionally, the cavity of the calorimeter has to be evacuated to prevent absorption by air and creation of ozone by the high beam energy, and the optics material has been changed from quartz to calcium fluoride, which is more transmissive in the 193 nm region of the spectrum.

3.4 SURVEY FINDINGS

To assess the economic outcomes from NIST's technical outputs, interviews were held with industrial representatives from different tiers of the semiconductor supply chain.

3.4.1 Semiconductor Lithography

The first set of interviews involved experts in semiconductor lithography from the following organizations: SEMATECH, Ultratech Stepper, Dominion Semiconductor (a collaboration of IBM, Siemens, and Toshiba for fabricating memory ICs), and MIT Lincoln Laboratory (leading developer of 193 nm photolithography process technology). These interviews were intended to understand economic benefits of NIST's measurement program primarily from the view of the semiconductor manufacturer.

The allocation of SEMATECH funding through NIST to develop the outputs is widely believed to have been more efficient and effective than alternative investment strategies. That is, likely counterfactual investments in the absence of NIST would have had higher R&D expenditures and not carried the imprimatur of a neutral organization. Additionally, the timely availability of NIST's outputs reduced collectively the private and public expenditures of various domestic semiconductor organizations involved with developing 248 nm manufacturing process technology.

The diffusion of a common measurement technology through NIST calibration services has decreased transaction costs among all firms in the affected supply chain (suppliers of detectors, power meters, laser systems, lithography tools, and photoresist, as well as semiconductor manufacturers). Since the availability of absolute radiometric standards at NIST for I-line and KrF lasers, semiconductor manufacturers typically have been specifying calibration of the power meters to NIST standards in acquisitions of lithography tools. Such traceability provides semiconductor manufacturers with: (1) a common basis for evaluating competing lithography systems with respect to the performance of dose control, and (2) assurance that the power meters in the lithography tool function within acceptable limits (i.e., to ensure "no surprises" such as a power meter reading 10 watts when the laser is actually emitting 20 watts by NIST standards). Generally, a semiconductor manufacturer relies on the lithography tool supplier to warrant the technical characteristics of the power meter. Additionally, the set-up and maintenance of precision calorimeters for excimer laser metrology is quite expensive, precluding most commercial suppliers from developing and maintaining their own standards.

A particular area of investigation for the study team was to understand the extent of the economic impact from the NIST measurement technology for maintaining process control in high-volume semiconductor production. According to all the organizations interviewed, conventional process control of dose settings for multiple lithography tools in a semiconductor manufacturing plant relies on an open-loop system of “send-ahead” wafers. The objective of this procedure is to obtain a relative measurement that matches the settings to an empirically optimized dose. The procedure begins by exposing various field areas of a send-ahead wafer on a single lithography tool to graduated dose levels, and measuring these dose levels with the internal power meter, which is compared periodically to a portable power meter. The dose level and detector reading corresponding to the appropriate image quality (processing of the photoresist) is selected for the production setting. The detector's measurement is then used to calibrate the dose levels of other lithography tools used in parallel with the first tool. Thus, while the power meters on lithography tools are typically calibrated to absolute standards at NIST as a purchase requirement of the tool, semiconductor manufacturers commonly use relative radiometric measurements to maintain process control across multiple lithography tools. As a result, the measurement technology developed at NIST is not a factor in cost-of-ownership modeling used by semiconductor manufacturers.³¹ The common practice for calibrating the laser output of the lithography process on a relative basis using the “send-ahead” system of wafers, rather than on an absolute basis traceable to primary standards at NIST, shows that there is even more, as yet untapped, potential for use of NIST’s 248 nm outputs for dose energy control in high-volume semiconductor production.

Theoretically, process control based on absolute radiometric standards at NIST could yield several productivity advantages:

- Obviate the “dose knob” to reduce the need (and the expense) of send-ahead wafers
- Facilitate an automated, closed-loop system to reduce the overall complexity of process control

³¹ Cost-of-ownership (COO) models have been used by semiconductor manufacturers for making investment decisions in lithography tools and other equipment. COO modeling considers acquisition and operational costs, and particularly focuses on the scrap value of work in progress due to the yield-intensive nature of IC manufacturing.

- Provide a more efficient linkage between lithography computer modeling and manufacturing R&D³²

However, absolute radiometry has been impractical generally in today's semiconductor fabrication plants because of the experimental ("recipe") nature of semiconductor manufacturing. Moreover, dose control is only one of about 10 other key process variables, most of which do not have NIST standards or result from contributing processes.

This does not imply that semiconductor manufacturers currently obtain no economic value beyond transaction cost savings from purchasing power meters calibrated to absolute standards at NIST. In fact, all respondents stated that the use of instruments traceable to NIST standards is intrinsic to economical semiconductor production. Such traceability imparts integrity and reliability of laser measurements which economizes the experimental method of semiconductor process development and the send-ahead wafer calibration method for semiconductor production. Utilizing a power meter traceable to NIST's primary standards reduces the time to trouble-shoot lithography process problems because lithography engineers have confidence that the detector readings are accurate. When the IC fabrication process goes out of control, the power meter is often the last source of error investigated among the other lithography system components to determine the error source.

3.4.2 Power Meter and Laser Suppliers

Firms in the stages of the domestic semiconductor supply chain that are closest to NIST were surveyed. The firms interviewed in the survey were the power meter and detector suppliers Moletron, OAI, Coherent, and Ophir, as well as the excimer laser supplier, Cymer. Additionally, a separate interview was held with Coherent regarding its foreign subsidiary, Lambda Physik, which also is an excimer laser supplier. These firms represent the main suppliers of excimer laser technology to the semiconductor supply chain.

For the metrics to be presented, the benefits measured are a well-defined set of costs avoided because of NIST's 248 nm investments and services. Namely, the benefits are the costs that the semiconductor industry would incur from replacing NIST's excimer laser metrology investments and services. The working assumption is that absent NIST's investments and

³² Christopher Cromer, et al, "Improved Dose Metrology in Optical Lithography," *Solid State Technology*, April 1998.

services, the semiconductor industry would find other means for establishing the excimer laser metrology that NIST has provided. Based on the interviews, the most likely counterfactual scenario entails a mixture of additional investments in equipment as well as scientific and engineering personnel for expanded in-house metrology for proprietary standards, along with increased use of foreign laboratories and the extra costs they would cause. Additionally, there would be new transaction costs in resolving measurement disputes with customers and suppliers without a US standards organization to which measurements could be traced.

Traceability of measurements to NIST standards is important for businesses using 248 nm measurements as described in the paraphrased comments of several respondents:

"Our customers audit our measurements, and traceability of our measurements to NIST's standards reduces transaction costs incurred in the audits. Customers are satisfied when they see the comparisons to NIST's standards, and having those standards at the wavelengths of interest to the customers is valuable. NIST's measurement service at particular wavelengths allows validation of our company's in-house metrology and reduces the time spent with customers resolving measurement issues. The availability of NIST's services also reduces the need for specialized measurement equipment."

"NIST's calibration services and standards offer a comfort level to all involved in the use of laser metrology in the semiconductor supply chain. Having reliable standards month after month is important so that we can get on with the business at hand. Traceability to NIST is important to the semiconductor equipment integrators because it removes one of many elements of uncertainty."

"Our company's relationship with NIST is extremely important. There has to be a neutral authority to judge our company's work. NIST's services are an indispensable part of the calibration and traceability effort. The key role of NIST is to ensure the correctness of our company's measurements. We maintain two gold standards for rotation every six months to give NIST enough time to turn them around for recalibration. I reiterate that NIST is indispensable for our company, because without NIST it would be our word against our customers in measurement disputes, and such a situation would be very difficult if there were no standard to follow. If that final link of traceability is taken away, who is to say my standard is better than my competitors' standards? There would be extra costs of dealing with measurement disputes and extra costs of trying to use foreign labs for traceable standards. We're dead in the water without NIST."

"The relationship between our company and NIST is important because it helps us [the company] provide our customers with the most accurate, repeatable measurement possible. Traceability is important for the sale of products, and it is a tough sell without NIST. Without NIST, our company would need to make substantial investments in additional equipment and additional personnel to develop in-house standards."

"Having NIST's services has been very important for both costs and sales. Without NIST, our company would incur higher costs for in-house metrology efforts to maintain our gold standard. Even with that extra effort, extra costs would be incurred in explaining to customers that the measurements of our instruments would not shift. With NIST providing calibration services and standards, our company does not need to prove to our customers that the measurement values from the power meters would not shift over time. All we have to do now is show that our calibrations are traceable to NIST. Even with the extra efforts, NIST could not be replaced. NIST is very important to us. Without NIST, the accuracy of our meters would not be as good and our sales would suffer. I expect we would likely lose half of our sales to foreign competitors."

3.5 QUANTITATIVE ANALYSIS

3.5.1 NIST's Costs

Expenditures by NIST and SEMATECH for developing the 248 nm excimer laser measurement technologies at NIST are shown in Table 9. The table shows that some joint costs exist for developing both the 248 and the 193 nm measurement technologies. For the purpose of evaluation, the total joint costs for 248 nm and 193 nm maintenance are included in the estimate of 248 nm investments. That imparts a downward bias in the metrics because those costs have generated unmeasured benefits for 193 nm metrology as well as the measured benefits for 248 nm metrology.

In addition to the development costs, NIST incurred the costs of maintaining 248 nm calibration services. NIST estimates conservatively that the useful lifetime of this measurement technology should extend for a decade beyond 1999. The annual EEEL costs to provide and maintain calibration services from calendar year 1994 through 2009 is estimated to be \$46.5K per year in 1999 dollars. The figure includes \$36.5K for salary and \$10K for equipment. Converting the total costs to constant 1999 dollars using the Gross Domestic Product Price Index (chain-

type), Table 10 presents the time series for the total costs of NIST's 248 nm measurement technology program through 1999.

Table 9. Development costs for NIST's program (current-year dollars) for 248 nm Laser Measurement Technology

Year	NIST			SEMATECH	
	248 nm Development	Equipment	Joint maintenance (248,193 nm)	248 nm Development	Equipment
1990	26,000	0	0	100,000	0
1991	81,000	0	0	100,000	0
1992	0	0	0	0	0
1993	211,000	60,000	0	0	80,000
1994	0	0	42,000	0	0
1995	0	0	44,000	0	0
1996	0	0	50,000	0	0
1997	0	0	0	0	0
1998	0	0	0	0	140,000
1999	0	0	0	0	100,000

3.5.2 Industry Benefits

The survey respondents (power meter and laser suppliers) have described the additional costs that they would have incurred if NIST had not invested in 248 nm measurement technology and if NIST did not provide 248 nm calibration services. The reasons for those additional costs include:

- Transaction costs of dealing with customers without having traceability to standards at NIST
- Costs of additional equipment and its maintenance to provide additional in-house proprietary metrology capabilities
- Costs of additional scientists and engineers to establish de facto standards in the absence of NIST
- Technical and administrative costs of dealing with foreign laboratories rather than NIST

Table 10. Costs for NIST's 248 nm Program (Current and Constant 1999 Dollars)

Year	Development Costs (current \$)	Services Costs (1999 \$)	Price Index (chain type, base year 1999)	Total Cost (constant 1999 \$)
1990	126,000	-----	0.819	154,000
1991	181,000	-----	0.851	213,000
1992	0	-----	0.874	0
1993	351,000	-----	0.897	391,000
1994	42,000	46,500	0.919	92,000
1995	44,000	46,500	0.940	93,000
1996	50,000	46,500	0.958	99,000
1997	0	46,500	0.975	46,500
1998	140,000	46,500	0.985	189,000
1999	100,000	46,500	1.000	146,500

The benefits here are just partial benefits because, despite the best efforts of industry to establish or find substitutes for NIST's services, according to the respondents, problems would remain because there would be no neutral US national standards organization to which measurements could be traced.

The benefits of the respondents are simply summed to have the total benefits for primary beneficiaries. No attempt has been made to quantify additional benefits for the downstream users of the power meters and laser systems—the domestic suppliers of lithography systems (Ultratech and SVGL) and semiconductor manufacturers (Intel, AMD, IBM, TI Motorola, National Semiconductor, Micron Technology, and others).

The respondents report that a conservative estimate of the remaining life of the 248 nm technology in the semiconductor supply chain is 10 years. Therefore, whenever the respondents provided annual benefits that they said would last in perpetuity, the benefits were conservatively truncated after ten years. During the initial years of the technology some of the leading firms reported that without NIST's investments there would have been combined equipment and personnel costs to develop in-house metrology. After those initial investments, respondents reported additional transaction costs in the absence of NIST for dealing with customers or suppliers or with foreign laboratories. Table 11 shows the estimates of the costs avoided by industry.

Table 11. Semiconductor Supply Chain Benefits (constant 1999 \$) from Investments in NIST's 248 nm measurement technology

Year	Expanded In-house Metrology (equipment and personnel costs avoided)	Transaction Cost Avoidance	Total Benefits
1994	780,000	-----	780,000
1995	590,000	-----	590,000
1996	590,000	-----	590,000
1997	610,000	210,000	820,000
1998	595,000	210,000	805,000
1999	95,000	210,000	305,000
2000	210,000	217,000	427,000
2001	100,000	217,000	317,000
2002	100,000	217,000	317,000
2003	100,000	217,000	317,000
2004	100,000	217,000	317,000
2005	100,000	217,000	317,000
2006	100,000	217,000	317,000
2007	100,000	217,000	317,000
2008	100,000	217,000	317,000
2009	100,000	217,000	317,000

3.5.3 Metrics

Bringing together the costs of developing the 248 nm measurement technology and providing calibrations services with the industrial benefits, Table 12 presents the time series for costs and benefits.

Appendix C provides a detailed explanation of the metrics that are used to evaluate the economic impact of NIST's investments in infratechnology. Using the time series above yields the following metrics for the NIST investments in 248 nm metrology:

- **Real internal rate of return = 43.1%** (using constant 1999 dollars)
- **Present value in 1990 of costs = \$1,271,000** (discounting, at the real discount rate of 7%, the stream of costs in constant 1999 dollars)

- **Present value in 1990 of benefits = \$3,821,000** (discounting, at the real discount rate of 7%, the stream of benefits in constant 1999 dollars)
- **Benefit-to-cost ratio = 3.0**
- **Net Present Value in 1990 = \$2,550,000**
- **Net Present Value in 1999 = \$4,688,000** [investing the NPV in 1990 at the real rate of 7%, and growing it for nine years ($NPV_{1990} * 1.07^{1999-1990}$)]

3.5.4 Uncertainty

The range of uncertainty for the 248 nm benefits series is estimated to be ± 20 percent, and the range for the costs is ± 5 percent. Calculating the metrics using the lower estimate for the costs and the upper estimate for the benefits yields high estimates for the metrics describing the lower bound returns to NIST's investments. Using the upper estimate for the costs and the lower estimate for the benefits yields a set of low estimates for the metrics. This technique yields the ranges for the metrics as shown in Table 13.

Table 12. Total Costs and Benefits (constant 1999 dollars) for Investments in NIST's 248 nm Measurement Technology

Year	Costs for NIST's 248 nm Program	Benefits for Semiconductor Supply Chain
1990	154,000	-----
1991	213,000	-----
1992	0	-----
1993	391,000	-----
1994	92,000	780,000
1995	93,000	590,000
1996	99,000	590,000
1997	46,500	820,000
1998	189,000	805,000
1999	146,500	305,000
2000	46,500	427,000
2001	46,500	317,000
2002	46,500	317,000
2003	46,500	317,000
2004	46,500	317,000
2005	46,500	317,000
2006	46,500	317,000
2007	46,500	317,000
2008	46,500	317,000
2009	46,500	317,000

Table 13. Estimate Range of Lower-bound Economic Impact for Investments in NIST's 248 nm Metrology

Metric	Low	Midpoint	High
Real internal rate of return	33.3%	43.1%	52.0%
Benefit-to-cost ratio	2.3	3.0	3.8
Net Present Value in 1990	\$1,720,000	\$2,550,000	\$3,380,000
Net Present Value in 1999	\$3,170,000	\$4,688,000	\$6,210,000

4. ASSESSMENT OF HIGH-SPEED MEASUREMENT R&D AND CALIBRATION SERVICES

This chapter assesses a specific R&D effort and primary calibration services for measurement technology applied to high-speed detectors used in fiberoptic communication systems. The first section describes fiberoptic communications and the economic importance of accuracy in both laser power and high-speed measurement technologies. The second section identifies the industry supply chain affected by NIST's measurement technologies. The third section describes the framework for economic analysis of NIST's investments only in high-speed measurement technology. This is followed by the findings from an industrial survey and an analysis of the economic impact.

4.1 ECONOMIC IMPORTANCE TO TELECOMMUNICATIONS INDUSTRY

4.1.1 Fiberoptic Communications

The use of silica-based (glass) optical fibers to transmit data was proposed in 1966. Although optical fiber bundles had been used earlier to transmit light and images, with the development of low-loss optical fibers from high-purity glass materials during the 1970s, optical fiber communication rapidly became an important form of telecommunications. “Low-loss” refers to a minimal loss of light as signals pass through the glass material.

By the 1980s, applications for optical fiber communication systems began to expand. A major application was the installation of fiberoptics for new telephone system landlines as a replacement for copper wire cables. Other applications included undersea transcontinental communications, cable television distribution systems, telephone wide area networks (WANs), computer local area networks (LANs), and secure military communications systems.

In the past decade, fiberoptic communications has grown into one of the two major media for long distance voice and data communications. Generally, fiberoptics competes with wire and communications satellites, although these technologies can be complementary.

Light-wave communications via optical fibers has the advantage of high bandwidth (information carrying capacity). A single fiber has the potential to carry hundreds of television channels or thousands of telephone conversations simultaneously. Bandwidth is often expressed in terms of signal (modulation) frequency, which is related to data rates, the number of transmitted bits per second. If a very high data rate is desired, then a very high signal frequency is required.

Increasing the bandwidth of fiberoptic cables has been a major technical trend in the telecommunications industry. From 1985 to 1995, bandwidth for fiberoptic communication increased from 50 MHz to 20 GHz.³³ Today, some systems have bandwidths approaching 60 GHz. As the bandwidth of the transmitted signal increases, the requirements on the fiberoptic link become more stringent. The demands are especially stringent for the detectors in this linkage, which typically have a lower response as the frequency of modulation on the laser light source increases.

Technical progress for increasing system bandwidth has been made along two paths: (1) expanding the limits of signal frequency, and (2) new techniques for multiplexing multiple carrier wavelengths into a single fiber. This economic impact assessment focuses on NIST's contributions to expanding the signal frequency of a single beam by accurately testing the detectors used in fiberoptic receivers. The scope of this assessment does not include NIST measurement technologies associated with multiple wavelength systems, such as Wavelength Division Multiplexing.

The concept of a fiberoptic communications link is shown in Figure 5. Generally, a fiberoptic link involves a transmitter (modulator and laser diode), the fiber itself, and a receiver (optical detector and/or demodulator). In a long-distance link where optical losses occur through attenuation within the fiber core material, many "repeaters" may be required to regenerate the light power. Repeaters comprise receivers and transmitters that are spliced into the fiber at specified intervals to boost the signal strength back to nominal values. Repeaters are complex and expensive components that, ideally, are minimized in a communications system design.

³³ The trend for increased bandwidth necessitated the utilization of "single-mode" fibers, where the core diameter was reduced to support a single optical path to decrease dispersion. Dispersion is the separation of a beam into its various wavelength components. In an optical fiber, dispersion occurs because the differing wavelengths propagate at differing speeds. The use of single-mode fibers necessitated smaller fiber connectors, which made power measurement more difficult due to problems with aligning the fiber to the detector.

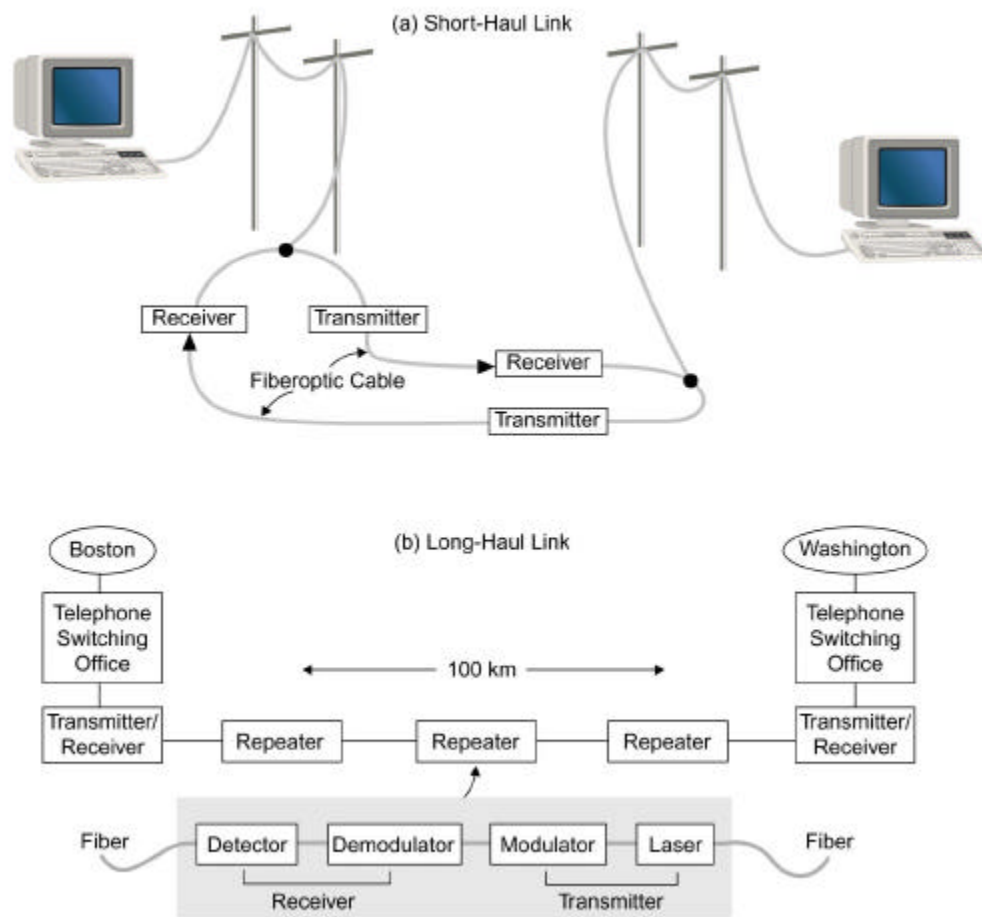


Figure 5. General Concept of (a) Short-, (b) Long-Haul Fiberoptic Communications Links

The key parameters in the design of a fiberoptic telecommunications system are bandwidth and the spacing of repeaters or amplifiers. Attenuation (optical loss) and dispersion are the main determinants for these parameters.³⁴ Additional key determinants of system performance are the power of the laser and the bandwidth of the detector. For this report, two different types of detector measurements are important in fiberoptic communication systems: optical fiber power and high-speed detector measurements. The next two subsections provide a brief overview of these two types of detector measurements to explain the role of NIST's laser calibration services for the telecommunications industry. The economic benefits of NIST's fiberoptic power measurement technology have been included in the overall assessment of NIST's primary calibration services in Chapter 2, while this chapter assesses the benefits from NIST's high-speed frequency response measurement technology.

4.1.2 Optical Fiber Power Measurements

Designers of communications systems must measure the optical loss of the fiber to determine whether the signal strength at the receiver is sufficiently high. In lengthy fiber runs, the light gets absorbed and/or scattered by the fiber along its length, and the light intensity decreases continuously. To ensure enough light intensity for the detector (receiver) to pick up the signal with a high signal-to-noise ratio along a given length of fiber, the fiber is measured for its optical loss (attenuation). This is done by measuring the power going both into and out from the fiber with a fiberoptic power meter, and the loss is characterized in decibels per kilometer (dB/km). This ensures low "bit error rates" or the possibility that a "0" or "1" will be mistaken for the other in a digital system. When the optical loss of the fiber exceeds a certain specification, then a repeater (receiver/transmitter) may have to be placed midway in the fiber link.

Fiberoptic power meters are used to measure optical losses in the development and production of communications systems. Each fiber, connector, laser, and receiver may introduce losses that must be taken into account when a fiberoptic communications network is assembled. Thus, fiberoptic power meters are used routinely to determine optical losses. Power measurements of both long and short lengths of fiber are compared to determine the optical loss of the fiber per unit length.

³⁴ Attenuation refers to the loss of average optical power (optical loss). Dispersion refers to the natural tendency of a light beam to lose intensity as distance increases, similar to the way a beam of light emitted from a flashlight widens with distance.

The telecommunications field provides a challenge for power measurement. Detectors must be capable of measuring minute amounts of light emitted from a long optical fiber at precise wavelengths. Some receivers can detect a signal with only 1 percent received of the power going into the fiber. Although no significant technical breakthroughs have been required for these measurements, the reduction of fiber loss to a small fraction of a dB/km has required great accuracy in the power measurements.

NIST began addressing the calibration needs of the telecommunications industry in laser power measurement during the mid-1980s. NIST had established optical fiber power measurement services for the primary carrier wavelengths (850 nm, 1300 nm, and 1550 nm) by FY 1989, and added other wavelengths (670 nm and 780 nm) by FY 1992. NIST is now developing an all-wavelength fiber power measurement system that will be applicable to the variety of laser diodes and wavelengths used in systems from telephone and television transmission to local area networks. Therefore, NIST has established these measurement systems and services as new laser wavelengths and lower-loss fibers have been developed by the telecommunications industry.

NIST's calibration services are used to calibrate virtually all in-house gold standards used by suppliers of fiberoptic power meters and commercial calibration service providers. These firms, in turn, provide NIST-traceable standards to the broader set of communications service providers (e.g., the telephone companies and data service providers) that use fiberoptic power meters. This system of transfer standards provides an economical means for downstream firms to obtain measurement traceability to NIST standards. A representative from a commercial fiberoptic calibration service provider noted that a fiber calibration from his company costs \$100-150 versus about \$2,500 for a fiber calibration from NIST.

4.1.3 High-speed Detector Measurements

Measurements of high-speed detectors are necessary to support high-performance systems that take advantage of the potential bandwidth of optical fibers. High-speed detectors are general-purpose laboratory devices that are useful in a wide variety of high bandwidth applications. The most well known application is in the fiberoptic receiver portion of a communications system, where a high-speed detector used to receive the high bandwidth data signal must be characterized in terms of important technical parameters such as modulation frequency response, relative noise intensity, and “eye diagrams.”³⁵

AT&T, IBM, Hewlett Packard, and others became interested in characterizing high-speed detectors in the 1988-1990 timeframe as advances in short-pulse lasers and other communications technologies began to dramatically increase the bandwidth of fiberoptic communications systems. Since the early 1990s, measurement technology to characterize the bandwidth of high frequency optical detectors has been important for the telecommunications industry, and a major developmental focus for NIST.

In telecommunication systems, product performance is often measured in bandwidth (which should be maximized) and bit error rate (which should be minimized). As bandwidth increased progressively from 50 MHz to 50 GHz over a decade of time, the accurate measurement of fiber power at high modulation frequencies became more difficult. Determining the bandwidth of detectors accurately in the early-1990s required the telecommunications industry to over-specify the components of a system, which increased the cost of the communication system. Therefore, if a test receiver does not have sufficient accuracy to ensure confidence in testing with a low bit error rate, then too many transmitters (laser diodes) would be rejected, thereby decreasing the yield and increasing the cost of the communication system. Since bandwidth is a key determinant of communications system cost, accurate high-speed detector measurement results in reduced cost of the system.

³⁵ Andrew Davidson and Kathy LiDessau, “High-Speed Detectors: Faster Measurements for Today’s Laboratory,” *Photonics Spectra*, September 1998.

Although not regulated by a governmental entity, telecommunications equipment manufacturers must meet SONET/SDH worldwide standards for market acceptance.³⁶ As the accuracy of fiber measurements improves to meet SONET/SDH standards, component and system suppliers can reduce the design margin for uncertainty in their products. Minimizing this margin translates into improved system performance factors, including additional bandwidth, lower bit error rate, and reduced system cost.

4.2 INDUSTRY SUPPLY CHAIN

Figure 6 shows the ripple effect of measurement technologies in the telecommunications supply chain. Several major companies are listed in each industry tier. NIST's outputs in laser fiber power measurement directly affect the fiberoptic instrumentation suppliers, which were described in Section 2.2.2. Other parties affected more indirectly include the suppliers of fiberoptic components, such as:

- Fiberoptic cables/fibers: 84 firms (20 are non-domestic)
- Digital transmitters: 17 firms (7 are non-domestic)
- Digital receivers: 21 firms (4 are non-domestic)

The worldwide fiberoptics industry purchased \$6.3 billion of fiberoptic cabling for communications applications in 1996, according to the Fiber Optic Cable Global Market Forecast (1996-2006) produced by ElectroniCast Corp. (San Mateo, CA). The study predicts that global use of fiberoptic cabling will increase at about 19% per year over the next five years, to \$14.9 billion in 2001 (in current dollars). The general distribution of cabling consumption by specific applications is telecommunications (76 percent), private data local- and wide-area networks (11 percent), and cable TV (9 percent).

³⁶ Synchronous Optical Network (SONET) is a high-speed fiber-optic transmission standard originally used on backbone networks, which is now making its way onto local links. SONET was proposed by Bellcore in the middle 1980s and is now an ANSI/ISO standard. The SONET standard defines a hierarchy of interface rates that allow data streams at different rates to be multiplexed. Prior rate standards used by different countries specified rates that were not compatible for multiplexing. With the implementation of SONET, communication carriers throughout the world can interconnect their existing digital carrier and fiber optic systems.

The international equivalent of SONET, standardized by the ITU (International Telecommunication Union), is called SDH (Synchronous Digital Hierarchy).

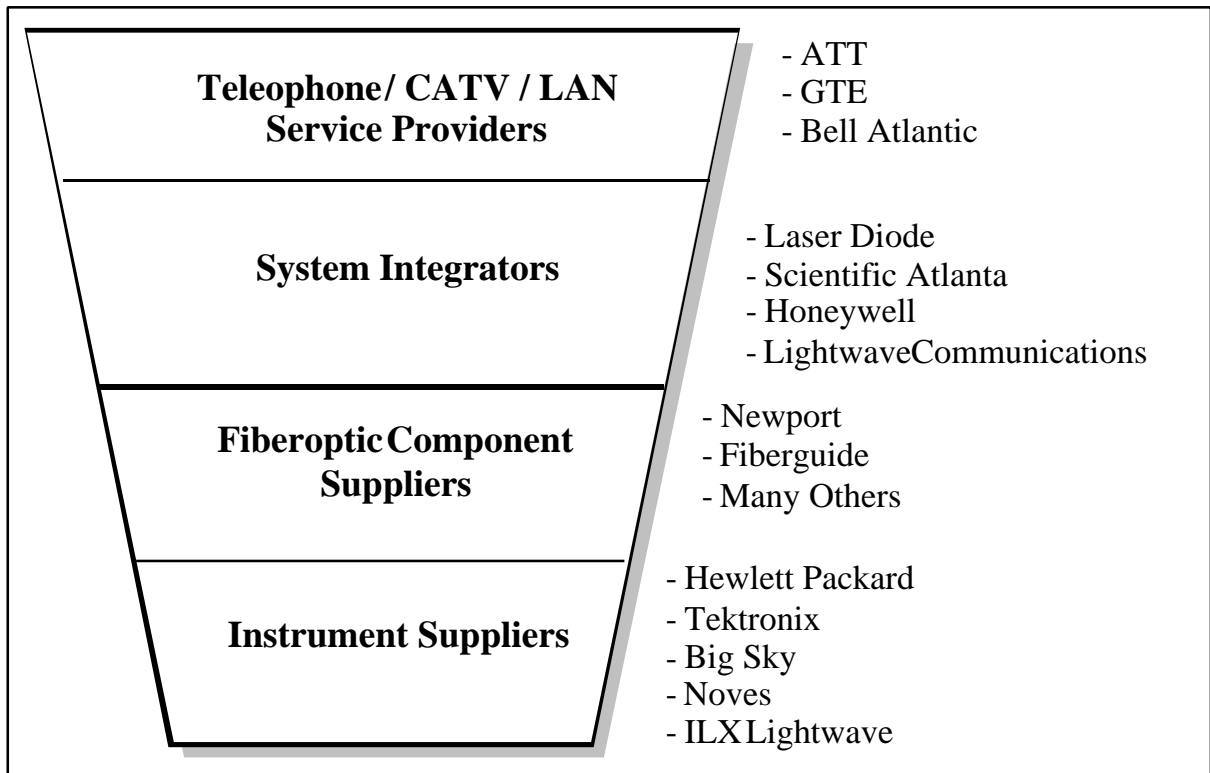


Figure 6. Measurement Technology Flow for Telecommunications Industry

NIST's infrastructure outputs for high-speed detector measurements directly affect the instrument companies (e.g., Hewlett Packard and Tektronix) that supply the test equipment for measuring detector (or receiver) speed. These instruments are used, in turn, by the downstream tiers of the telecommunications supply chain.

4.3 ECONOMIC ANALYSIS FRAMEWORK

Table 14 summarizes the framework for assessing the economic impact on the US industrial supply chain from NIST's investments in high-speed frequency response measurement technology. The economic impact for NIST's investments supporting optical fiber power measurements was included in the overall assessment of NIST's calibration services in Chapter 2.

Table 14. Economic Framework for Assessing High-speed R&D and Calibration Services

NIST Outputs	Hypothesized Outcomes	Affected Industrial Organizations	Outcome Measures and Affected Stage of Economic Activity, Absent NIST	Comparison Scenario (counterfactual replacement of NIST outputs)	Time Series of NIST Costs and Industry Net Benefits
R&D to establish high-speed metrology	Enabling of high-bandwidth communications systems	Affected telecommunications supply chain : – Hewlett Packard	Lag in technical innovation for enabling higher bandwidth communications systems Lag in enabling of new information-based applications in a wide variety of end-use markets	R&D conducted by HP Establishment of proprietary standards at HP	(C) research, develop, maintain, and provide calibration services from 1992-2009 (B) 1994-2009
Primary calibration services for high-speed measurements	More efficient R&D or reduced R&D replication to establish metrology services Avoidance of extra transaction costs because of industry agreement on NIST as a primary reference for calibrated standards for high-speed measurements Improved laser-based telecommunications products and services from better technical accuracy	– HP's customers and competitors	Lag in achieving reduced capital costs for telecommunications service providers to establish information system capacity since NIST investments enabled more data, voice and video can be carried in each optical fiber Increased personnel and equipment to establish metrology services prior to industry need for high bandwidth communications systems Increased personnel and equipment to validate accuracy of laser measurements for obtaining: – transfer standards from foreign labs or proprietary firms – product acceptance with customers Lower product /process quality and performance leading to decreased sales		

In 1990, NIST participated with various international laboratories in a "round-robin" of high-speed detector measurements at the 1300 nm (1.3 μm) wavelength. The measurements among the participating laboratories exhibited a spread (uncertainty) of 3.3 dB at 20 GHz, such that "the 3-dB cut-off point" varied from 15.1 to 19.8 GHz. As a result, the "3-dB point" in a telecommunications system could not be determined with suitable accuracy. (The technical significance of the 3-dB cut-off point is explained in Appendix D.)

The 3-dB point is an important parameter for determining the bandwidth of a detector. Measuring the laser power accurately allows a more accurate determination of the cut-off frequency that partially characterizes the bandwidth of fiberoptic communication system. If a power measurement shows a high frequency cut-off, then the detector can be used in a communications system with high bandwidth. Otherwise, if the power measurement shows a lower frequency cut-off, then the device must be used in a lower-bandwidth system to maintain low error rates (i.e., the chance of a “0” or “1” being confused in a digital communication system). A high error rate in a communication system produces static in telephone conversations, “snow” in television reception, or digital errors in computer communications (e.g., over a local area network or through the Internet). Although error correction methods are used in data transmission, a large number of errors will slow the data rate. In a computer application, a single error could be disastrous.

Resulting measurements from the 1990 round-robin would require the system bandwidth be limited to about 15 GHz. If the system was specified at a higher frequency, the detector could produce a low output resulting in a single bit error (e.g., a digital system erroneously receiving a “0” instead of a “1”). The more often this bit error occurs, the higher the “bit error rate” of the communication system.

Measurements of both the 3-dB point and the smoothness of the detector "roll-off" at frequencies higher than the 3-dB point using “eye diagrams” are required to fully characterize the bandwidth of a telecommunications system. Both types of measurements depend on accurate optical power measurement techniques at high modulation frequencies, which are the techniques that NIST has been developing.

The 1990 round robin highlighted the need to improve detector response measurements. From 1992-1994, NIST received funding from the US Navy for advancing measurement technology for high-speed detectors. After improvements attributable to NIST research, another round-robin was conducted in 1994 between NIST and the UK National Physical Laboratory (NPL) for measurements at 20 GHz. This intercomparison demonstrated a 0.12 dB spread; that is, the interlab comparison difference was reduced from 10-15 percent down to 1-1.5 percent. NIST now has the capability of measuring detector output at 20 GHz with an accuracy of 0.06 dB. This high accuracy in power measurement translates into very accurate measurement of the 3-dB point of the detector, and allows the detector to be utilized safely at its full bandwidth—20 GHz in this case. NIST extended the range of high-speed measurements up to 50 GHz by 1995, and most recently, the range is being extended still further, up to 100 GHz.

Since 1994, NIST has offered Special Tests for frequency response measurements at high accuracy at modulation frequencies from 300 kHz to 50 GHz. NIST has calibrated about 50 detectors using its current capabilities. About a dozen of these detectors were calibrated for Hewlett Packard for use in its service centers. An additional 15 – 20 detectors have been calibrated for Hewlett-Packard and resold to Philips (US and Netherlands), Scientific Atlanta, and Lucent Technologies.

NIST began developing technology for high-speed optical measurements in a program with Hewlett Packard and other instrument companies (e.g., Tektronix) in the early 1990s to develop optical analyzers that are calibrated using NIST-developed transfer standards for detectors used in fiberoptic receivers. In order to test the frequency response of a detector accurately, two single-frequency laser outputs can be combined to form a “beat” frequency with a known modulation depth. NIST developed such a system in parallel with similar developments at Hewlett Packard.³⁷ These systems have now been commercialized as communications analyzers (detector and oscilloscope), component analyzers (network analyzers), and signal analyzers (detector and spectrum analyzer). An example of direct use for the NIST technology was an instrument built by Lightwave for Hewlett Packard, based on the NIST approach to detector frequency response measurement. NIST capabilities in measuring detector bandwidth now extend up to 58 GHz, and developmental activities are approaching 100 GHz frequencies.

NIST’s technology developments and services have provided the telecommunications industry with improved measurement accuracy of detectors based on SONET/SDH standards. A detailed account of the history of these developments from NIST/ITL is provided in Appendix E.

The improved accuracy based on SONET/SDH standards accelerated the development of higher system performance (in terms of lower bit error rates and higher speed) at lower cost for a given specification. These developments form the basis for the current expansion in the telecommunications industry, including:

- High-speed Internet access despite rapid increases in number of users
- Optical fiber replacing copper wire for telephone landline systems (including hybrid fiber-coax trunk lines)

³⁷ The NIST system uses two lasers and a phase-locked loop, based on an acousto-optic modulator, while the Hewlett Packard system is based on three lasers and two phase-locked loops.

- Cable TV, LAN, and antenna remoting with fiberoptic cables (satellite telephone and micro-cellular systems)
- High bandwidth, secure military communications links

4.4 SURVEY FINDINGS

Hewlett Packard (now Agilent, Hewlett Packard's subsidiary for test and measurement businesses) has been a major conduit for transferring NIST's high-speed frequency-response fiber-optics metrology to the telecommunications industry. In addition to its key role in the process of technology transfer, Hewlett Packard was a key firm that worked closely with NIST to develop the measurement technology. The Hewlett Packard experience provides a window on the evolution of NIST's laser metrology from the perspective of industry. The counterfactual adjustments that industry would have made to replace NIST's investments and services for high-speed metrology were identified in a series of interviews with Hewlett Packard's key expert in fiber-optic high-speed frequency-response metrology and in discussions with other industry experts.

HP and several other firms have worked with NIST at Boulder on high-speed photoreceiver measurements for the telecommunications industry. The flow of technology transfer is from NIST as the source of agreed upon national standards, through instrument manufacturers such as HP, and then to the companies that use those products needing high-speed measurement technology. Among the downstream customers are companies providing cable TV services, companies providing data communications services, and telecommunications hardware and service providers.

In the case of HP, high-speed measurement technology is not licensed to other firms. Instead the other firms buy HP's instruments. The other firms specify measurement technology for particular bandwidths, and then ask HP to verify the measurements of the instruments. In response, HP provides their traceability path to NIST.

To illustrate NIST's interaction with industry, HP's perspective, as developed in interviews with TASC, is instructive. NIST's broader perspective of its interaction with several firms is provided in Appendix E. The development of high-speed measurement technology was an interactive process between HP and NIST. HP would have a need for technology, and then it would explain that need to NIST. HP would develop some initial capability in the needed measurement technology, and then HP would show the technology to NIST, discussing and

explaining it. NIST would then develop its own capability in the measurement technology to support industry's needs. HP and NIST worked together as measurement needs evolved, and with the interaction the measurement capability has evolved over time as well.

HP reports that in the early 1990s it needed high-speed measurement standards that were unavailable anywhere; even NIST did not have the capability for the measurement technology needed for the frequencies used with high-speed fiber optic receivers. At the time, existing measurement technology went up to 20 GHz at the high end. There was not much concern about the low end, and there was little concern about resolution. Thus, the first generation of technology was at a high end of 20 GHz. By the mid-1990s, the bandwidths were up to 50 GHz, and that required new equipment and new technological knowledge. Earlier generations of equipment simply would not work. Initial measurement technology was developed in-house by HP, but the technology lacked the credibility that would be provided by traceability to national standards. In the technology where it focused effort, HP was the industry leader, developing a temporary solution, doing the necessary measurement technology in-house at HP. The most commercially viable solution, however, required the validity of a national standard and a process for traceability to that standard. HP began an interactive development process with NIST at Boulder, and that interaction helped bring about the current high-speed measurement technology at NIST.

Once NIST's system was in place, HP relied on NIST for primary standards. HP reports that NIST's measurements are very accurate with low uncertainty. The new measurement technology, at 50 GHz at the high end, that has been developed in NIST's interaction with industry and transferred to industry through companies like HP is used heavily to this day and will continue to be used.

NIST and HP have cooperated on three generations of R&D and technology. The first generation was the technology at HP at 20 GHz, and the second generation is the technology at NIST with the 50 GHz system. The latest work, now that high-speed measurement needs are well covered, is the third generation, and is at HP again with 50 GHz plus new measurement technology with high resolution at low frequencies.³⁸ Just as with the high-speed measurements,

³⁸ Resolution refers to the spacing of the measurement points that are made. Thus, in measuring from 1 GHz to 10 GHz, the resolution is how fine of a step that you can take between these measurements. For example, if measuring from 1 GHz to 3 GHz, with a resolution of 500 MHz, then the steps are 1 GHz, 1.5 GHz, 2 GHz, 2.5 GHz, 3 GHz. Resolution is the finest of the steps that can be taken when measuring in a given range. So, the third

there has been an interactive process with NIST's Boulder facilities. In 1997 HP needed the new measurement technology for high resolution at low frequencies. The high-speed measurement needs were well covered. HP needed new measurement technology at lower speed, but with higher resolution. So, again HP built a new system. And again, in the interactive manner used to develop the high-speed measurement technology, NIST built a system. The interactive work here continues with hand-in-hand development of measurement technology and traceability to a national standard in response to industry's needs.

In a few years HP expects that once again there will be pressure for new measurement technology at the high end—up to 80 to 100 GHz. Looking now at the research papers, only a few are currently developing high-speed capability in that high frequency range. Only a few are exploring technology that looks promising in that frequency range. HP expects the development there will come in the next two to five years.

HP believes that the improved measurement technology has a positive impact on the business dynamics among the players in the telecommunications supply chain. Since HP is a key fulcrum for the development and the technology transfer to industry, the new measurement technology allows greater performance throughout the supply chain. Instruments are better, and so products and services are better. As NIST, together with companies like HP, improve the measurement technology, the accuracy is better and the uncertainty is lower for the measurements. By reducing measurement uncertainty, companies can adjust their instruments to allow a fiber optics system to perform closer to the maximum performance capability because the confidence factor for its measurements is higher. A wide "guardband" is then not needed.

Using HP as an example, there are many different HP instruments that incorporate the high-speed measurement technology. All have in common the fact that they are photoreceivers. That is, they are instruments that take the modulated light beam and then produce an electronic signal as output. A laser beam travels along a fiber optic line; the light beam has superimposed on it the information (TV, telephone voice, computer data). Photoreceivers take away the light beam and leave the information. The process is analogous to a big truck coming to a loading dock. The truck (the light beam) delivers a box (the information for TV, for telephone voice, or for computer data). The box (the information) is taken away from the truck (the light beam). The photoreceivers leave the information with the least distortion possible. The users of HP

generation technology has an impressive low end capability that HP had not anticipated, plus it has high resolution. If resolution is too coarse, then fine features are not seen with the photoreceivers.

photoreceivers want to send information faster. They want to send more telephone calls, more data for financial transactions, and so forth over the same line in the same time. The photoreceivers have the capability to recover the information traveling along the light wave carrier and pass it along as electronic communications information without distortion. If a photoreceiver does not have enough bandwidth, it distorts the digital electronic representation of the information—the ones and zeros that describe the information. If the bandwidth is too low, the photoreceivers worsen the bit errors. The errors would be reflected in garbled streams of data (for financial transactions for example), or for cable TV, the picture would not be crisp if the bandwidth were too low.

The TASC team posed the following two hypotheses about the effects of NIST's high-speed measurement investments and services:

- High-speed measurement technology transferred to domestic instrument firms has resulted in new product technologies, enhanced competitiveness, and increased sales for these firms
- The allocation of US Navy resources through NIST to develop the high-speed measurement outputs has been more efficient and effective than alternative investment strategies. That is, it is likely that had NIST not been present, the investments that would have occurred to replace NIST technology and services would have fallen short of complete replacement, would have been more costly, and would not have carried the imprimatur of a neutral organization.

The foregoing hypotheses are correct and clearly true from the perspective of HP.

The HP83440D DC-30 GHz Lightwave Converter, which is an optical to electric converter, is an example of a product enabled by the NIST measurement technology. Information carried via laser light enters a fiberoptic port of the converter, which then strips off the light and extracts the electrical signal. Doing this at so high a frequency as 30 GHz is a real challenge, and the NIST technology made this product possible. This product, in turn, is an essential part of a fiberoptics communications system for transmitting a telephone conversation, computer data, or a video. The customer base for HP's instruments is global, so the users of the measurement technology are not isolated in the US. There is a great deal of world-wide interaction, and NIST is, therefore, contributing to world-wide standards and enabling world-wide commerce. HP cannot obtain the quality of measurement technology that NIST provides for high-speed frequency response measurements from any of the other national standards laboratories.

One reason HP approached NIST for research on improved measurement technology was for traceability to a national standard, but that is just the obvious reason. With NIST, industry can trace measurements back to a world-recognized national laboratory. Also very important as a reason for HP to approach NIST about measurement technology was that HP wanted to share with NIST its technology and allow an interaction that was mutually helpful for developing the measurement technology. The technology development and transfer side of the process is a key reason for the interactive work that HP has undertaken with NIST.

The alternative to collaborative effort by HP with NIST would have been for HP to develop its own in-house metrology and standards alone. Before NIST developed its capabilities, HP did use its own resources for high-speed metrology. HP would have continued with its in-house methods in the counterfactual absence of NIST. “But there would have been limitations to what we could do. We did not have a traceable path to an agreed upon standards association. Our customers know that NIST can be trusted; they know that NIST will be unbiased. A company manufacturing and marketing the instruments of course could not be perceived as unbiased or neutral in its evaluations.” Without NIST, the development and transfer of the technology would have taken longer and the resulting technology would probably not have been as robust.

4.5 QUANTITATIVE ANALYSIS

For the metrics here, the benefits do not measure the frequency response metrology benefits in the broad sense of all benefits from the products supported by the metrology. Rather, the benefits measured are just the costs that industry would have had to incur if it had not had the benefit of NIST’s frequency response metrology investments and services. The assumption is that absent NIST’s investments and services, industry would find or establish other means for obtaining the frequency response metrology that NIST has provided.

4.5.1 NIST's Costs

NIST has provided the development costs for the program in high-speed metrology used in telecommunications. Table 15 reports those costs in current dollars.³⁹

³⁹ “Current dollars” here show expenditures in the dollars of the year in which the expenditure occurred.

Table 15. Development Costs (current dollars) of NIST's High-speed, Frequency-response Measurement Technology

Year	NIST Development Costs	Equipment	DoD Development Costs
1992	97,000	0	50,000
1993	165,000	0	0
1994	183,000	0	0
1995	193,000	0	0
1996	217,000	0	0
1997	120,000	20,000	50,000
1998	109,000	40,000	75,000
1999	30,000	40,000	71,000
2000	30,000	0	50,000

The current cost data in Table 15 are converted to constant 1999 dollars using the Gross Domestic Product Price Index (chain type), as shown in Table 16.

The foregoing costs provided by NIST are the development costs and equipment costs only. NIST also provided estimates of the annual costs of providing calibration services using the technology. NIST estimates that the annual EEEL costs in constant 1999 dollars to provide and maintain calibration services for frequency response measurements for calendar years 1994 through 2009 are \$27.7K/year. The total includes \$22.7K for salary and \$5K for equipment.

Table 16. Current and Constant (1999 base year) Development Costs of NIST's Program for High-speed, Frequency-response Measurement Technology

Year	Costs (current-year dollars)	Price Index (chain type, base year 1999)	Costs (constant 1999 dollars)
1992	147,000	0.874	168,000
1993	165,000	0.897	184,000
1994	183,000	0.919	199,000
1995	193,000	0.940	205,000
1996	217,000	0.958	227,000
1997	190,000	0.975	195,000
1998	224,000	0.985	227,000
1999	141,000	1.000	141,000
2000	80,000	1.021	78,000

4.5.2 Industry Benefits

HP initially had a unique position as the major conduit for technology transfer from NIST to the telecommunications industry. The interviews with HP have, therefore, provided key information about the additional costs that industry would have had to incur, and would continue to incur, in the counterfactual absence of NIST's presence in high-speed measurements. However, NIST estimates that since the development of its 850 nm heterodyne system, HP accounts for about 50 percent of NIST's calibration work load. The development of the heterodyne system began in March 1997, and from 1998 onward, industry benefits the direct users of NIST's high-speed calibration services are estimated as twice the benefits estimated for HP. NIST's experts believe that each of the direct customers would have benefits similar to those estimated for HP.

Hewlett Packard identified several sorts of additional cost that it would have incurred in the absence of NIST's investments in high-speed measurement technology. Those costs include additional research costs and additional equipment costs in the mid-1990s along with continuing annual costs to maintain the investment in measurement technology. Also, Hewlett Packard identified additional transaction costs that it would have incurred when dealing with its customers if NIST's services and traceability to NIST standards as a neutral authority had not been available. Those costs would entail additional staffing, plus additional participation at TIA standards conferences, and additional effort writing papers establishing measurement technology standards. Additional engineers specializing in fiber optics measurement technology would be needed. Following the procedure described above when discussing the transaction costs for power/energy meter suppliers, the transaction costs identified by a company acting as an intermediary that transfers instruments traceable to NIST standards into the supply chain are doubled. Each extra hour that Hewlett Packard must spend resolving measurement issues with customers will presumably entail about an hour of customers' time as well.

Based on discussions with experts in industry and at NIST, the useful life of the high-speed measurement technology as it now exists would conservatively be another ten years. Table 17 shows the total benefits and the breakdown of these benefits between additional in-house metrology costs for personnel and equipment and the transaction costs avoided in dealing with customers or suppliers.

Table 17. Telecommunications Supply Chain Benefits from NIST's Investments in High-Speed Measurement Technology (constant 1999 dollars)

Year	Expanded In-house Metrology Costs Avoided	Transaction Costs Avoided	Total Benefits
1994	200,000	800,000	1,000,000
1995	200,000	800,000	1,000,000
1996	150,000	800,000	950,000
1997	150,000	800,000	950,000
1998	300,000	1,600,000	1,900,000
1999	300,000	1,600,000	1,900,000
2000	300,000	1,600,000	1,900,000
2001	300,000	1,600,000	1,900,000
2002	300,000	1,600,000	1,900,000
2003	300,000	1,600,000	1,900,000
2004	300,000	1,600,000	1,900,000
2005	300,000	1,600,000	1,900,000
2006	300,000	1,600,000	1,900,000
2007	300,000	1,600,000	1,900,000
2008	300,000	1,600,000	1,900,000
2009	300,000	1,600,000	1,900,000

The benefits quantified by the TASC team represent a subset of the benefits attributable to NIST's investments in high-speed measurement technology. Based on the interviews, NIST's investments have enabled new products such as the HP 30 GHz lightwave converter, which, in turn, are essential to enabling high bandwidth fiberoptic communication systems. No information was available from the interviews to quantify how the economic impacts of such products would have changed if industry had needed to provide the necessary measurement technology without NIST's help and also had operated without traceability to NIST.

4.5.3 Metrics

Table 18 brings together the costs and benefits necessary to present evaluation metrics.

Table 18. NIST's Costs and Telecommunications Industry Benefits for Investments in High-speed Measurement Technology (constant 1999 dollars)

Year	Total Costs of NIST's Program in High-speed Measurement (development and calibration services)	Benefits for the Telecommunications Industry
1992	168,000	-----
1993	184,000	-----
1994	226,700	1,000,000
1995	232,700	1,000,000
1996	254,700	950,000
1997	222,700	950,000
1998	254,700	1,900,000
1999	168,700	1,900,000
2000	105,700	1,900,000
2001	27,700	1,900,000
2002	27,700	1,900,000
2003	27,700	1,900,000
2004	27,700	1,900,000
2005	27,700	1,900,000
2006	27,700	1,900,000
2007	27,700	1,900,000
2008	27,700	1,900,000
2009	27,700	1,900,000

Appendix C provides a detailed explanation of the metrics that are used to evaluate the economic impact of NIST’s investments in infratechnology. Using the time series of costs and benefits yields the following metrics for the NIST investments in high-speed measurement technology:

- **Real internal rate of return = 136.2%** (using constant 1999 dollars)
- **Present value in 1992 of costs = \$1,522,000** (discounting, at the real discount rate of 7%, the stream of costs in constant 1999 dollars)
- **Present value in 1992 of benefits = \$13,850,000** (discounting, at the real discount rate of 7%, the stream of benefits in constant 1999 dollars)
- **Benefit-to-cost ratio = 9.1**
- **NPV in 1992 = \$12,300,000**
- **NPV1999 = \$19,800,000** [investing the NPV in 1992 at the real rate of 7%, and letting it grow for seven years ($NPV_{1992} * 1.07^{1999-1992}$)]

4.5.4 Uncertainty

The range of uncertainty for the high-speed frequency-response benefits series is estimated to be ± 10 percent, while the range for the costs is ± 5 percent. Calculating the metrics using the lower estimate for the costs and the upper estimate for the benefits yields high estimates for the metrics describing the lower bound returns to NIST’s investments. Using the upper estimate for the costs and the lower estimate for the benefits yields a set of low estimates for the metrics. This technique yields the ranges for the metrics as shown in Table 19.

Table 19. Estimate Range of Lower-bound Economic Impact for NIST's Investments in High-speed Metrology

Metric	Low	Midpoint	High
Real internal rate of return	119%	136%	155%
Benefit-to-cost ratio	7.8	9.1	10.5
NPV in 1992	\$10,900,000	\$12,300,000	\$13,800,000
NPV in 1999	\$17,500,000	\$19,800,000	\$22,100,000

5. ASSESSMENT OF MEASUREMENT TECHNOLOGY FOR THE MEDICAL INDUSTRY

The two preceding chapters provided quantitative studies of NIST's laser metrology used in the manufacturing technology of the semiconductor industry and in the provision of fiber-optic telecommunications services. In this chapter, the evolving applications of lasers in medical services are used to provide another illustration of the economic importance of having NIST as the repository of national standards for laser metrology.

The TASC team reviewed the economic importance of lasers and accurate measurements in medical applications, identified NIST's technical contributions, identified the relevant industry structure, and developed hypothesized outcomes for economic impact. The scope of the study did not permit a formal survey of the medical supply chain's downstream users of laser metrology, so an analysis of outcomes was not undertaken. However, interviews with the suppliers of power meter firms to the laser medical community yielded the identification of future investment opportunities for NIST.

5.1 ECONOMIC IMPORTANCE TO THE MEDICAL COMMUNITY

5.1.1 Laser-based Medical Services

Lasers have been used in medicine for a variety of diagnostic and therapeutic applications. Diagnostic applications include cell counting (e.g., for blood tests) and laser induced fluorescence for detection of various types of tissues. Therapeutic applications include ophthalmic laser treatments and surgical procedures to cut or vaporize tissue.⁴⁰

During the 1960s, a few medical applications were explored, such as the use of the ruby laser for retinal welding. As new types of lasers were developed and refined through the 1970s, successful medical applications of these newer lasers followed. Examples include the use of argon lasers in ophthalmology (for retinal photocoagulation), the CO₂ laser for surgical cutting, and the Nd-YAG laser for coagulation.

⁴⁰ Examples of ophthalmic laser treatments include photocoagulation of the retina for age-related macular degeneration, the leading cause of blindness, and diabetic retinopathy. Examples of surgical procedures include: removal of a cancerous or pre-cancerous lesion using a CO₂ laser, tissue coagulation such as Nd-YAG laser treatment of bladder cancer, selective interaction with tissue such as using a dye laser for port wine stains, or tissue disruption such as using a pulsed dye laser for fracturing kidney and ureteral stones.

Medical applications of lasers exploded in the 1980s. Surgical and ophthalmic lasers became widely accepted, and new applications were developed, such as laser angioplasty (removal of plaque from coronary arteries via a fiberoptic catheter), laser lithotripsy (breaking kidney and ureteral stones), laser tissue welding and refractive eye surgery (cutting/lathing of the cornea to correct vision). These new applications utilize lasers to remove tissue very precisely (e.g., removing a 0.5 mm layer of plaque inside a 3 mm diameter artery; or a 0.3 mm layer of cornea to correct vision). Further, these “minimally invasive” laser-based procedures began to replace traditional, more invasive, surgical applications.

A major trend in medicine has been the reduction in cost of patient outcomes. A key cost driver in medical economics is the length-of-stay in the hospital for the patient. The less invasive procedures enabled through laser technology have been a significant factor in reducing the average patient length-of-stay in comparison to traditional, more invasive procedures. Laser-based procedures have also contributed to recent reductions in the rate of medical inflation that was running rampant during the early 1990s.

5.1.2 Optical Power Measurement

The power monitoring equipment used in surgical laser systems must ensure the delivery of accurate and consistent laser power to the patient. Generally, accurate laser power measurements in the medical field provide the following benefits:

- Increased safety and effectiveness of a laser procedure
- Ability to provide precise treatment of delicate tissues, such as arteries and the cornea
- Ability to meet regulatory requirements with cost-effective system designs
- Reduced physician liability

In medical laser applications, the laser output power often determines the safety and effectiveness of a procedure. Precise targeting of the power (or energy, in the case of pulsed lasers) and accurate dosimetry are required to ensure that complications do not occur for the patient. In particular, severe complications can arise from unintentional damage to non-target tissue if the laser power or dose is too high. For example, excessive power applied during angioplasty can lead to a punctured artery (possibly requiring correction by open-heart surgery), or cause blindness in a patient undergoing refractive eye surgery by cutting through the entire

cornea. Excessive power delivered from a Nd-YAG laser while coagulating a tumor in the esophagus can potentially lead to a rupture of the aorta—and death of the patient—several days after the surgery.

Laser power levels for medical applications range from very low (milliwatts for tissue welding) to quite high (kilowatt pulses for drilling holes in the heart for laser transmyocardial revascularization, a potentially less invasive alternative to coronary artery bypass surgery). Laser wavelengths run the gamut from ultraviolet (193 nm) to far infrared (10.6 μm), and both continuous wave and pulsed systems are utilized.

Correct dosimetry for laser procedures requires an accurate measurement of the power/energy of the laser output. Manufacturers of medical laser systems usually incorporate power meters as a means to measure the power/energy. These power meters may be purchased as OEM subsystems or commercially available detectors used in a custom designed power monitoring system. In either case, calibration of the system power meter to national standards is crucial for both system performance and regulatory purposes.

In addition to the CDRH requirements for all laser and laser systems manufacturers, medical laser companies must obtain clearance or approval from the FDA prior to marketing new products in the US. Clearance may be granted for new systems that are substantially equivalent to systems already marketed in the US, while full approval based on clinical trials may be required for new types of medical laser systems (new wavelengths, power levels, applications, etc.). All of these systems must incorporate a power monitoring capability that measures the laser power/energy that the physician applies to the patient. Further, the power meters must be calibrated to national standards to help ensure that patients are treated as safely and effectively with “production” systems as those involved in the clinical trials (testing) of the system.

A hierarchy of standards traceability is used to meet regulatory requirements efficiently. The FDA requires that the physician know the laser output power delivered to tissue at the start of a procedure to within ± 20 percent of absolute standards at NIST, including all possible errors and variations. Most lasers have a drift (CW) or pulse-to-pulse variation (pulsed) on the order of 10 percent, so the measurement system must be accurate to within ± 10 percent. Since the measurement system includes optical elements as well as the calibrated detector, the detector must be calibrated typically to better than ± 5 percent. And since each calibration (national standard, to transfer/gold standard, to working standard, to meter in the equipment) results in a loss of about 1 percent accuracy, the traceable standard must be accurate to 1-2 percent. In

submitting laser products for FDA approval or clearance, suppliers are required to provide not only power measurements, but also an analysis showing how the accuracy of their measurements fits within the error budget allowed by the FDA.

The power meter built into a medical laser system is often calibrated not to the actual laser output, but to the output of the beam delivery system (i.e., the power that will impinge on the patient's tissue). The power measurement presented to the physician must take into account losses in optical systems, articulated arms (for delivering CO₂ laser energy flexibly to the surgical site) and fiberoptic catheters. Therefore, medical laser manufacturers often use uncalibrated detectors, and then calibrate their system using an external power meter that measures the light emitted from the delivery system. These external power meters must be calibrated accurately, and are usually traceable to the NIST standard.

Laser power is often monitored and recorded during a medical procedure as a policy of the medical service provider. If the results of a procedure are not favorable, this documentation could be instrumental in litigation between the patient and physician or hospital, as well as their insurance companies. Such liability concerns may also apply to biomedical engineers who are responsible for regular service and calibration of the laser system.

For decades, measurement accuracy down to 0.01 percent (relative to standards) has been attainable for lasers operating with visible and near-infrared wavelengths. Attainment of better than 2 percent accuracy has not always been possible for laser power measurement in the far infrared and ultraviolet wavelengths as well as for pulsed lasers. Historically, obtaining accurate measurements over these ranges of power and wavelength has not been a great technical challenge for the medical equipment industry. That is, neither industry nor NIST has had to make significant investments in measurement technology to obtain the required accuracy pertinent to medical applications. However, a representative of a power meter supplier who works with the new medical applications reports that picture is changing. New challenges for measurement technology in the medical applications of lasers are now emerging. This chapter concludes with a description of those challenges.

5.2 INDUSTRY SUPPLY CHAIN

Figure 7 shows the ripple effect of measurement technology in the supply chain for medical therapeutics. In 1998, at least 70 companies that supplied lasers for medical therapeutic laser systems.

- Biomedical instrumentation: 11 firms (1 is non-domestic)
- Biostimulation: 8 firms (4 are nondomestic)
- Dental: 9 firms (2 are nondomestic)
- Dermatology: 19 firms (4 are nondomestic)
- Ophthalmology: 14 firms (3 are nondomestic)
- Other: 9 firms (3 nondomestic)⁴¹

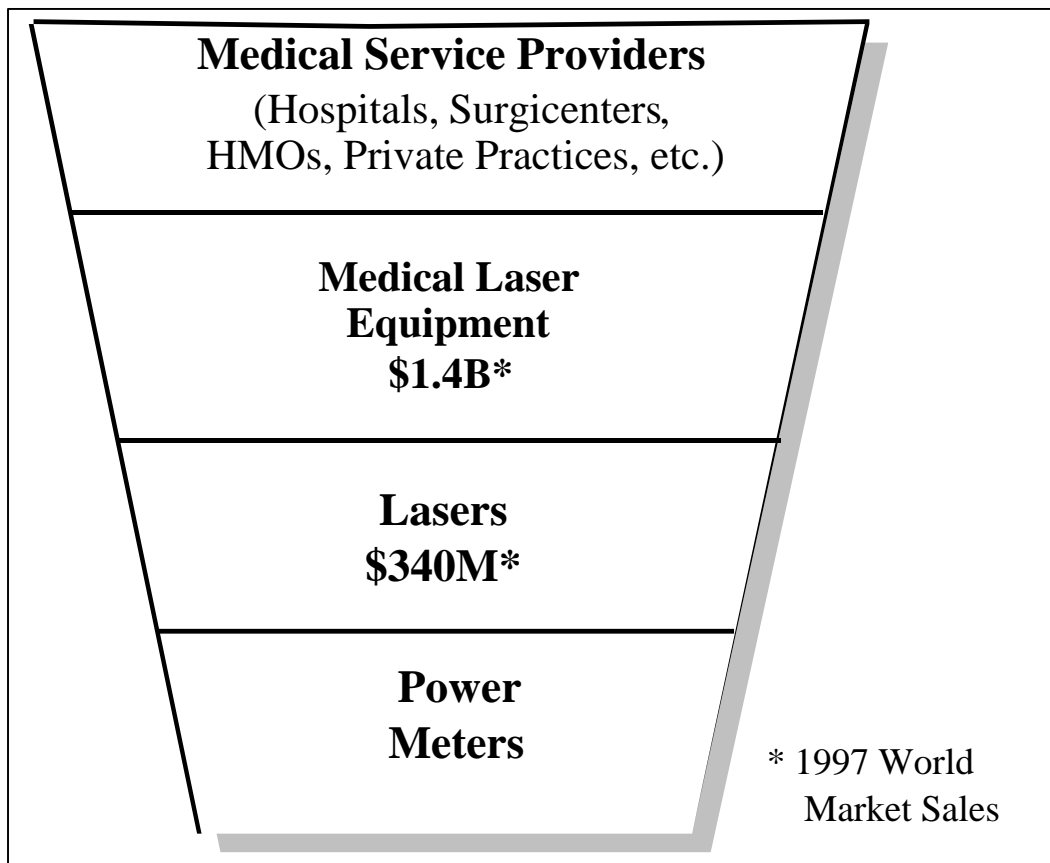


Figure 7. Measurement Technology Flow for Medical Therapeutics

⁴¹ *Laser Focus World Buyers Guide 98.*

Sales of lasers to medical laser systems manufacturers totaled \$340 million in 1997.⁴² The worldwide market for medical laser systems approached \$1.2 billion, a small segment of the \$140 billion market for all medical systems. The medical laser systems market consists of several key segments:

- Surgical laser systems, \$500 million
- Ophthalmic systems, \$350 million
- Accessories and services, \$350 million; this segment includes revenues for power meters purchased by end users and power meter calibration services

Table 20 lists many of the medical laser systems companies (i.e., those supplying medical laser systems to hospitals or physicians) and key market areas on which each company is focusing. This list is not complete, but most of the important companies are included. Also, many of these companies address several market segments (e.g., surgical, aesthetic, ophthalmic), and some may be leaders in one segment, and minor players in another. Some companies are in the development phase only, and have essentially no sales, yet.

The US has about 6,000 hospitals and 1,000 surgicenters. Most, if not all, of the hospitals use medical lasers in one or another specialty (e.g., ophthalmology, urology, neurosurgery). Many of the surgicenters also use lasers. In addition, a large number of private practices use lasers—primarily in ophthalmology and in dermatology. The US has about 12,000 ophthalmologists (many of whom practice at hospitals), roughly 3,000 ophthalmic practices, and another 3,000 dermatology practices.

⁴² Spectrum Consulting, *Medical & Healthcare Marketplace Guide*, 13th ed., (Dorland), 1997-98.

Table 20. Key Medical Laser System Suppliers and Markets⁴³

Company	Market Area	Market Leader	Largest Suppliers	Niche Market Leader	Niche Market, Secondary
Aesculap/Meditec	Ophthalmic/Surgical				X
Allergan Medical Optics	Ophthalmic	X			
American Dental Laser	Dental			X	
Biolase	Dental				X
Candela	Surgical	X			
Coherent Medical	Ophthalmic/Surgical		X		
Continuum Biomedical	Aesthetic				
Cynosure	Aesthetic				X
Eclipse Surgical Technologies	Surgical/Cardiovascular	X			
ESC/Laser Industries	Surgical/Aesthetic		X		
HGM	Ophthalmic/Surgical	X			
LaserLite	Aesthetic				
Laserscope/Heraeus Surgical	Surgical	X			
LaserSight	Ophthalmic				X
Laser Vision	Ophthalmic				
Mehl/Biophile	Aesthetic				
Palomar	Surgical/Aesthetic				X
PLC Systems	Cardiovascular (TMR)			X	
Premier Laser	Surgical/Aesthetic	X			
Spectranetics	Cardiovascular			X	
Summit Technologies	Ophthalmic	X			
Surgical Laser Technologies	Surgical	X			
Thermolase	Aesthetic				
Trimedyne	Surgical	X			
VISX	Ophthalmic				X

⁴³ Ophthalmic: Retinal photocoagulation (argon/krypton dye lasers); refractive surgery (excimer laser); capsulotomy (Nd-YAG pulsed laser)

Surgical: Cutting/vaporizing tissue in general surgery, gynecology, neurosurgery, ENT, urology, gastroenterology, etc. (CO₂ laser, Nd-YAG laser, KTP laser, Holmium laser)

Aesthetic: Skin resurfacing, hair removal (CO₂ laser, Er-YAG laser, Nd-YAG laser, Holmium laser, Alexandrite laser, pulsed dye laser, ruby laser, diode laser)

Cardiovascular: Laser angioplasty, transmyocardial revascularization (Excimer laser, high power pulsed CO₂ laser, Holmium laser)

5.3 ECONOMIC ANALYSIS FRAMEWORK

Several of NIST's early advancements in measurement technology have been incorporated in commercialized medical laser products. Early calorimeter designs developed at NIST were spun-off by a new startup company, Scientech, in 1973. Scientech's power meters were used in a large percentage of early medical laser applications, particularly those using the early CO₂ and Nd-YAG surgical lasers. Additionally, as the surgical laser field was developing in the 1970s, NIST developed the electrically-calibrated pyroelectric radiometer. In this system, the pyroelectric element is alternately heated using optical and electrical energies that are then matched. The electrical energy can then be measured accurately using conventional technology (e.g., voltmeters, and ammeters) for an absolute calibration to electrical standards—without optical calibration. Some medical laser systems suppliers have incorporated this power meter technology into their surgical laser products.

Work on calorimeters developed more recently by NIST for the semiconductor lithography area has also played a role in characterizing excimer lasers used for refractive eye surgery and angioplasty. These medical applications of excimer lasers utilize 308 nm and 193 nm wavelengths, not the 248 nm wavelength targeted by NIST and SEMATECH. Yet, the accuracy of pulse energy measurements for the 308 nm excimer laser benefited from research derived from the 248 nm work at NIST.

The measurement infrastructure provided by NIST (national standards and calibration services) provides a consistent frame of reference for both the chain of firms supplying medical laser systems and the users of these systems. Having agreement on this measurement infrastructure reduces disputes and transaction costs among all affected parties, and reduces the cost of regulatory compliance for traceability to absolute standards. For example, all of the laser systems used in a clinical trial can be relied upon to provide the same power/energy for a given application, and the subsequent lasers sold commercially can be relied upon to accurately provide the same parameters as those systems used during the clinical trial.

As newer surgical laser applications develop and proliferate, industry will continue to obtain measurement support from NIST. NIST provides the measurement foundation for developing these less-traumatic and more cost-effective medical procedures through its development and maintenance of primary standards and the assistance provided to power meter companies and laser companies in calibrating their transfer standards.

Hypotheses regarding the types of economic outcomes and the affected parties include the following:

- High measurement accuracy and standards traceability through NIST ensures that consistent and safe laser power/energy levels are used at the start of laser surgery to maximize procedure effectiveness and reduce patient complications.

NIST's measurement technology effects patient (end-user) outcomes of laser surgical procedures since the FDA requires the physician's choice of starting power for the beam delivery system be guided by a power meter that is calibrated to within 20 percent of absolute standards at NIST. Yet, analogous to the situation with semiconductor lithography, NIST's measurement technology historically did not extend directly to the actual operating procedure because the physician adjusts the output power of the beam delivery system based on observation of laser effects on particular tissue for each patient. However, as noted in the concluding section of this chapter, the need for direct use of absolute measurement is now emerging in the latest medical applications of "exposure" lasers.

- The diffusion of the measurement technology through NIST's calibration services has decreased transaction costs among firms in the affected supply chain (laser manufacturers and medical laser equipment suppliers) as well as physician staffs (hospitals, surgicenters, private practices, etc.).
- The diffusion of the measurement technology through calibration services provides an efficient vehicle for medical equipment suppliers and physician staffs to meet FDA regulatory requirements for power meter accuracy to absolute standards.
- NIST's measurement infrastructure has provided a common reference for calibration and a foundation for incremental advancements in medical laser technology that has benefited the entire medical community.

5.4 SURVEY FINDINGS⁴⁴

Suppliers of power and energy meters believe that with the latest medical applications of lasers, new investments in metrology at NIST could support emerging laser technologies that have evolved beyond those served by the capabilities of the current infrastructure. The latest medical lasers are less forgiving to the doctor applying the laser procedure. These are exposure lasers, and require doctors to know the exposure level before using them. The historical FDA requirement of ± 20 percent measurement accuracy is often no longer sufficient. Now, the doctors need measurement accuracy within ± 1.5 percent, which represents a requirement for greater measurement accuracy traceable to NIST standards than the current metrology infratechnology allows. The latest PDT (photo-dynamic therapy) for cancer treatment, for example, uses exposure systems rather than cutting or burning technology. Without tight absolute measurement, permanent damage can be done to the patient. For skin resurfacing as well, physicians now need to know absolute power. In the past, physicians could experiment with power levels because they were just cutting and increase the laser power until they obtained the desired effect. But they now need to know the absolute power before exposing the skin. Although a quantitative analysis has not been attempted, the qualitative evidence suggests that new investments by NIST and industry could make valuable improvements in the infrastructure for laser metrology that supports the medical supply chain.

The new lasers being used in medicine are in great demand. Customers are on waiting lists to get them. NIST typically needs to get the lasers to be able to provide a measurement assurance program or standard. One knowledgeable expert stated that demand is so great in medical applications, that NIST is not able to get the newly developed lasers; the customers are waiting for them and the doctors cannot wait for NIST to develop calibration metrology using the particular new laser that is in great demand. Further, the same expert believes that industry would benefit if NIST could undertake investments to develop measurement standards independent of measurement parameters. Such standards could be shipped to the power meter manufacturers for calibrating the rapidly evolving new lasers. The power meter suppliers provide the calibrations, and work together with the medical laser system manufacturers to establish a de facto agreement on a particular measurement. NIST could help a great deal by renting a suitable standard that could be carried by the power meter supplier to the laser manufacturer. But the

⁴⁴ A formal survey of the affected medical supply chain was not conducted for this study. Qualitative results from in-depth interviews are reported.

current standards are not general enough, and NIST actually needs the new laser to develop the appropriate standard. One approach would be to have NIST certify an industry laser calibration laboratory as a nationally recognized standards lab. Some envision a network of national certified standards labs in industry where NIST does the certification and recertifies annually with an auditing process. Such an approach might be useful for many applications of laser metrology throughout the economy.

Appendix A

NIST's TECHNICAL CONTRIBUTIONS

A.1 ADVANCED MEASUREMENT TECHNOLOGY

As the laser industry developed during the 1960s, NIST (then NBS) became involved in laser power measurement and established a measurement infrastructure to serve this emerging industry. In the early-mid 1960s, NIST invented a liquid-cell calorimeter that could measure the energy of high peak power laser pulses. By the late 1960s, NIST was providing laser power calibration services to the public and the military. In the early 1970s, Dale West and other researchers at NIST designed and constructed laser calorimeters for the measurement of low power, high power, and pulse energy. At the time, the use of calorimeters to relate optical power and energy to electrical power and energy was a novel concept.

As the laser markets expanded, power meter suppliers began to emerge. Two of these suppliers, Scientech and Calorimetrics, were founded by former NIST employees in the early 1970s. During the 1970s and 1980s, several large optics companies (Newport Corporation, Ealing Electro-Optics, and Edmund Scientific) provided laser power meters as did many of the laser manufacturers (Spectra Physics, Coherent, Jodon, Lambda Physik, and Lexel).

In the mid-1970s, NIST researchers developed the concept of the electrically-calibrated pyroelectric detector. Here, the optical signal is applied to the detector alternately with an electrical signal. When the response from these two signals is matched, the power of the electrical input can be measured and related directly to the optical power. These detectors were commercialized during the 1970s for application with CW lasers by Laser Precision, now called Laser Probe.

During the mid-1980s, NIST developed a laser power measurement capability for high power lasers (e.g., up to 1 kilowatt for 10.6 μm lasers). In the late 1980s, NIST developed a parallel beam measurement capability for fiber power measurements with diode laser sources (850, 1300, 1550 nm wavelengths) that could provide measurements down to the 100 μW power level. A "connectorized fiber" capability was soon added to meet customer demand.

In the early 1990s, NIST initiated a project to develop spectral response measurements for optical power meters. NIST now provides specialized tests to industrial and research customers using a spectral response measurement system, and is currently developing a tunable laser system for spectral response measurements. In the mid-1990s, NIST developed a detector linearity measurement system and a tunable laser system for fiber power meter measurements.

A cryogenic radiometer was added to NIST's suite of primary standards during the mid-1990s. NIST also developed prototype secondary (transfer) standards that are traceable to the cryogenic radiometer. Currently, NIST is developing improved cryogenic radiometer designs, with faster response time and improved dynamic range.

Also during the 1990s, NIST developed an impulse response measurement capability for characterizing detectors used to measure ultrashort (100 femtosecond) pulses; developed techniques for measuring optoelectronic noise in laser diodes; and developed low-level radiometers for measurements of pulsed lasers used in target designators, rangefinders, lidar, and remote sensing applications. The low-level pulsed laser radiometer work has been conducted by NIST primarily to support the military in the use of laser target designators and laser rangefinders, devices that operate typically at 1.06 μm and 1.55 μm wavelengths.

NIST conducted other important work in the 1990s to support the product development strategies of U.S. industry. NIST's efforts on excimer laser energy measurements to support the domestic semiconductor industry are described in Section 4.3. NIST's work on high-speed detector measurement technology to meet the needs of the telecommunications industry is described in Section 5.2.

A-2 SERVICES TO INDUSTRY

NIST has developed and maintained primary standards for optical power and energy measurements. Generally, the metrology (hardware, software, techniques, etc.) associated with these standards has been based on the advancements described in the previous section. NIST has also developed measurement and calibration procedures to ensure traceability of other power/energy meter systems to the primary standards.

Once a laser power/energy measurement instrument is purchased or built, the accuracy of measurements made with the instrument has to be documented as a part of the standards traceability process. NIST has developed a laser Measurement Assurance Program (MAP) that

assists those calibrating power meters in establishing the calibration relative to primary standards and in documenting the precision and accuracy of the measurement process. A participant goes through a MAP process as shown schematically in Figure A-1.

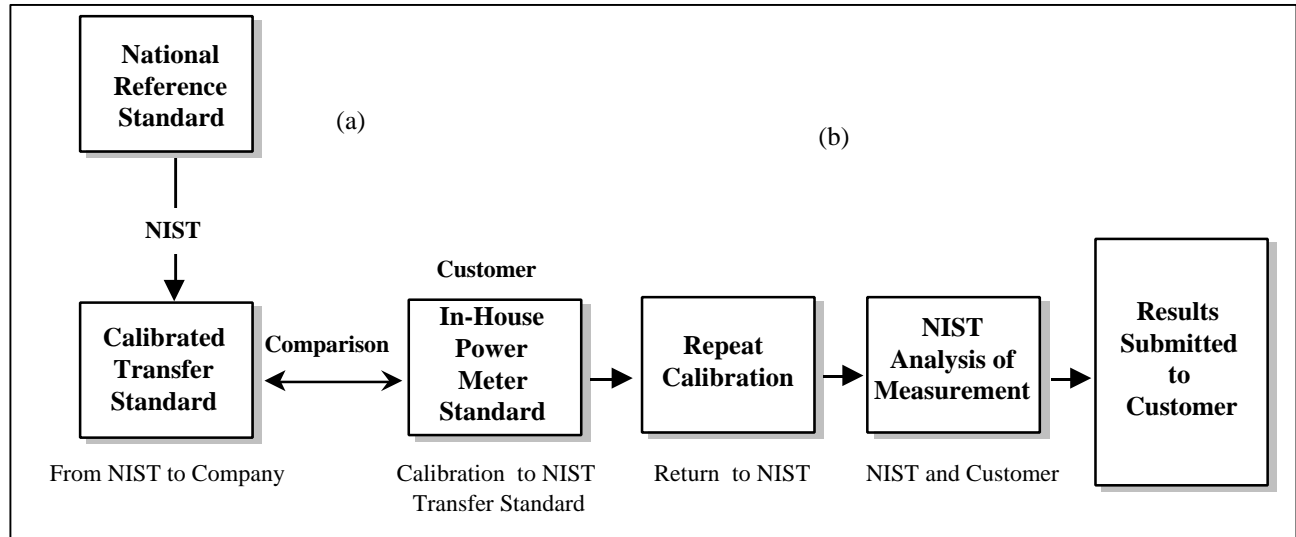


Figure A-1. NIST Calibration Process: (a) Initial calibration, and (b) Six-month recalibration

The MAP is based on transfer standard power meters calibrated by NIST. These power meters compare measurements made in industry against national standards maintained at NIST. When a participant joins the NIST laser MAP program, a transfer standard is forwarded for comparison with the participant’s power meters. The participant calibrates its in-house standard against the transfer standard. The participant then sends the measured artifact back to NIST, which then repeats the calibration and analyzes data from the calibrations. NIST then forwards to the participant documented results showing how the participant’s calibration constant compares with standards maintained at NIST. These results provide the participant with a new calibration constant for accurate calibration of internal power meters relative to NIST. NIST’s documentation becomes a record of the participant’s measurement capability and traceability to the NIST primary standard.

As shown on Figure A-2, standards traceability is achieved through a hierarchy of calibration levels. Traceability begins with the NIST primary standard, then to the transfer standards, and down the chain from the laser and power meter companies to the OEM manufacturers that incorporate this equipment, and ultimately to the end users of the systems.



Figure A-2. Hierarchy of Standards Traceability

The NIST measurement services provide about 50 laser power meter calibrations per year, 40 optical fiber power meter calibrations per year, and about 20-25 high-speed detector measurements per year. While this represents a small fraction of the tens of thousands of power meters used in the field, it accounts for most of the transfer standards used to provide NIST traceability. MAP participants mainly include power meter suppliers, laser suppliers, and commercial calibration service providers—all of which provide calibrations of their customer’s instrumentation to the transfer standard, and therefore ultimately to the NIST primary standard.

NIST’s calibration services are relevant to virtually 100 percent of all laser power instrumentation. Typically, end-users of laser equipment purchase power meters that are calibrated by the power meter supplier. Most end-users perform calibrations in-house, and send their meters back to the power meter supplier once every 6-12 months for recalibration. The supplier, in turn, will check its in-house meters regularly with NIST to ensure traceability. Power meter suppliers, laser suppliers, and large organizations with metrology departments seek NIST’s calibration services most often. Thus, the market for NIST’s calibration services is substantially smaller than the unit market for laser power meters. Virtually every power meter sold is ultimately traceable to NIST, at least when purchased, although some end-users may elect not to maintain traceability through regular calibrations depending on the criticality of their specific application.

NIST’s calibration services are also relevant to virtually 100 percent of the fiberoptic power calibration instrumentation. Users of optical fiber (e.g., telephone companies, cable television companies, and LAN system installers) often utilize commercial calibration service providers that base their transfer standards on calibrations by NIST. As an example of the difference in cost between a commercial fiberoptic calibration service and the NIST calibration service, a secondary fiberoptic calibration from Bell Technologies costs \$100-150 while a primary calibration from NIST’s fiber measurement services costs approximately \$2,500.

NIST's services also target high accuracy measurements (i.e., better accuracy than transfer standard instrumentation) and measurements that are at the leading edge of the technological envelope. These include measurements at short wavelengths (excimer laser), measurements at the extremes of power ranges, measurements of extremely short pulsewidths, and measurements involving high modulation frequencies. In each of these areas, NIST has "pushed the envelope" for measurement capabilities as industry and the military have developed laser and fiberoptic technologies having output parameters at the edge of the envelope.

A service that NIST provides when appropriate is a "round robin" of measurements among various national laboratories and research laboratories. A round robin demonstrates the level of accuracy that can be attained among the best laboratories, and these intercomparisons highlight the need for improved measurement systems and techniques in specific areas. During the mid-1990s, NIST conducted a round robin for beam width and other beam property measurements which led to the development of an improved beam profile standard. The new standard was used in another round robin with industry in 1998.

A.2.1. Contributions to Commercialized Products

Measurement technology developed at NIST has been transferred to industry as in the aforementioned cases of Scientech and Calorimetrics. Additionally, the electrically-calibrated pyroelectric radiometer developed by NIST staff was produced as a commercial product in the early 1970s by Laser Precision, a company later purchased by Laser Probe. More recently, high-speed measurement technology developed at NIST has been spun-off to companies such as Hewlett-Packard as described in Section 5.2.

Appendix B

LASER TECHNOLOGY

B-1 BASIC CONCEPTS

The word *laser* is an acronym that stands for “Light Amplification by Stimulated Emission of Radiation.” Generally, laser energy is distinguished from other forms of light by three characteristics: narrowness of the beam (directionality), single color (monochromaticity), and phase consistency (coherence). Directionality is the key property for creating intense light levels in a particular direction. For example, this property allows lasers to:

- Read minute, encoded information on a stereo CD
- Create the precise patterns of a laser printer
- Send electrical signals over long distances
- Focus for the cutting or welding of metal with relatively little power

The monochromatic property of the beam provides the spectral purity required for certain chemical and physical reactions. For example:

- In medical applications, certain wavelengths of laser light are used to interact with blood (green light from Argon lasers), water in tissue (such as infrared light from the CO₂ laser), or tissue colors (such as birthmarks and tattoos)
- In the telecommunications field, lasers are designed to have wavelengths that match the transmission window (spectral region of lowest loss) of glass optical fibers
- For integrated circuit fabrication, the short wavelengths (ultraviolet) from lasers provide better resolution than the longer wavelengths (visible light) from mercury lamps

Finally, the phase consistency, or coherence, of laser light allows the fabrication of three-dimensional holograms and creation of ultra-short pulses of light.

Laser calibration relates to the branch of science known as radiometry, which deals with the measurement and detection of radiant energy and power. The radiant energy is the quantity of photons transported in an electromagnetic wave. The radiant power is the intensity of the light, and is proportional to the number of photons propagated in the laser beam each second. The

fundamental units of measure for energy and power are the joule (J) and watt (W), respectively. One watt is equal to one joule per second. Consequently, the energy of a laser beam equals the power of the beam times the duration (exposure time) on a detector. Further, radiance (power density) and fluence (energy density) represent the power and energy, respectively, impinging on a unit area. Radiance and fluence are measured in watts/cm^2 and joules/cm^2 , respectively.

Lasers are capable of generating light in the form of either a continuous delivery of energy, referred to as continuous wave (CW) lasers, or discrete pulses, referred to as pulsed lasers. Generally, the range of peak power obtained from CW lasers is much lower (0.001 to 1,000 watts) than for pulsed lasers (10^6 to 10^{10} watts). Also, the typical exposure time for CW lasers is about 0.01 - 10 seconds depending on the field of application, while the pulse duration for a pulsed laser is much lower—typically 10^{-11} to 10^{-6} seconds.

Unique effects (e.g., biophysical effect of laser light on tissue) can be achieved through careful selection of the power and energy characteristics of the light source as well as the exposure time. The laser power is the most important parameter for some applications, while the laser energy is the key parameter for other applications.

B.2 LASER POWER AND ENERGY MEASUREMENTS

The measurement of laser output power is important to all laser manufacturers and users, but is especially critical for specific applications requiring precise power levels. Examples include medical applications (due to both the optimization of procedure efficacy and the regulatory requirements imposed by the FDA), materials processing (where precise powers are required to weld or heat-treat metallic structures) and telecommunications applications.

B.2.1 Laser Power Instruments

Laser power meters generally are of two types: those with thermal detectors, and those with solid-state (e.g., silicon) detectors, also known as photodiodes. Thermal detectors have the advantage of a flat response over a broad spectral range,⁴⁵ but are more difficult to use because of

⁴⁵ Radiometric detectors filter the incoming light to even out the responsivity, producing a “flat response.” This is important for accurate radiometric measurements, because the spectrum of a light source may be unknown or dependent on operating conditions such as input voltage. The frequency range of spectral flatness is important since this specification indicates the area of predictable performance.

their low sensitivity. Laser power meters are available that measure from 10^{-9} - 10^2 watts. Figure B-1 shows several examples of commercially-available laser power meters. These systems range from calorimeters that incorporate large heat-sinks, to miniature meters that provide sophisticated functions in a pocket size. For laser energy measurement, integrating radiometers are available with response times in the nanosecond range. High-speed radiometers, however, have problems with detector current saturation caused by high peak power at low energies.

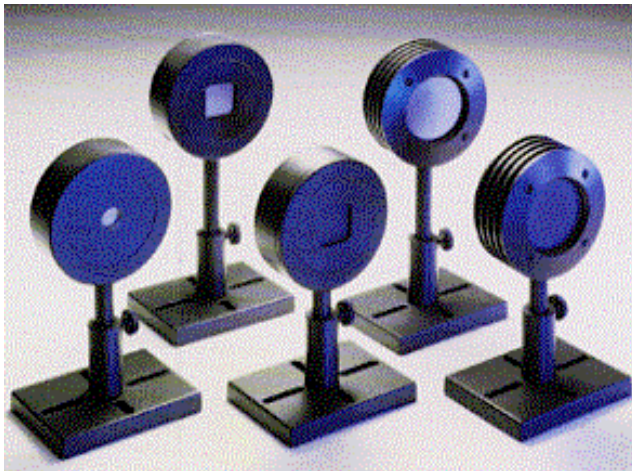


Figure B-1. Examples of Laser Power Meters

Generally, power/energy measurements of laser sources are accomplished using calorimeters or photodiodes. The concept of a calorimeter—developed by NIST in the 1960s—is shown on Figure B-2. A calorimeter absorbs the optical energy inside a meter cavity for conversion to thermal energy, which is measured using a thermopile (an array of thermocouples connected in series) or other temperature-electrical conversion device. Thermopiles detect heat differences to allow electrical calibration (i.e., difference between heat input from optical signal

Most sources are continuums, emitting over a broad band of the spectrum. Incandescent lamps are a good example. The color temperature and output of these lamps vary significantly with input voltage. Flat response detectors measure only output power in watts, taking into consideration light at every wavelength.

vs. heat input from known electrical parameters). Photodiodes are solid-state detectors that produce a direct electrical response to an optical input.

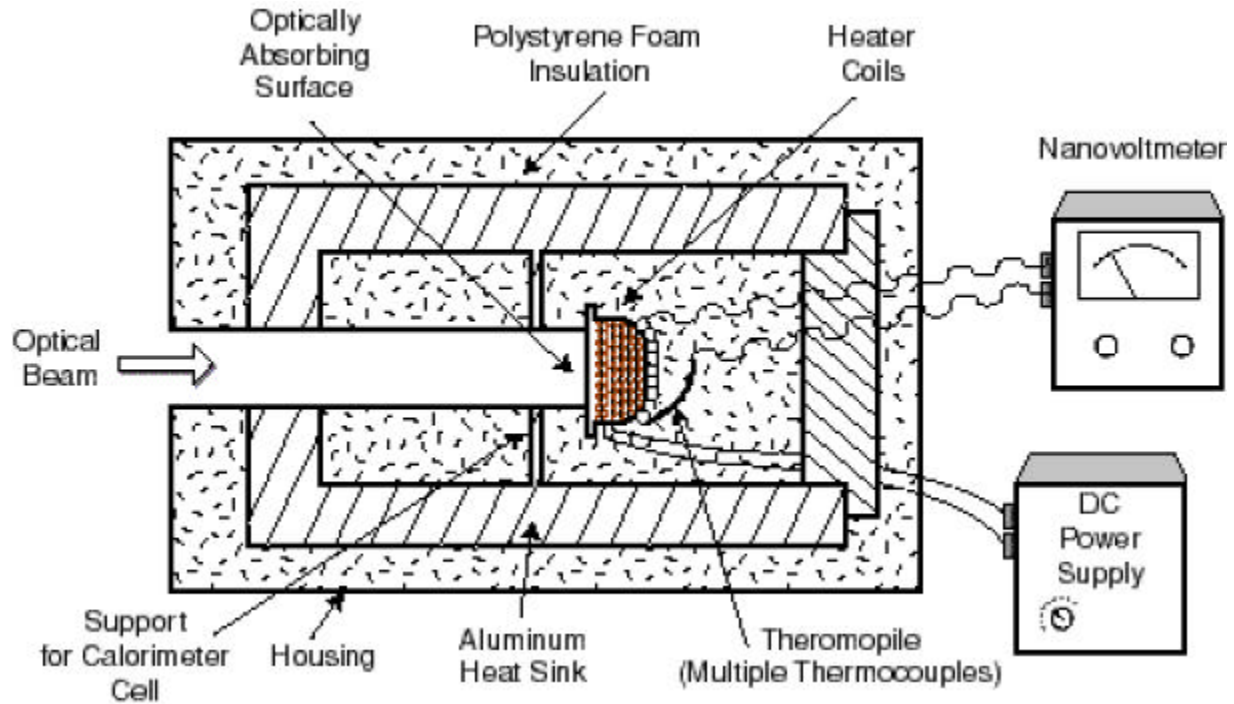


Figure B-2. Cross Section of a Generic Calorimeter

Another method of measuring laser light with a thermal detector is to use a pyroelectric material. This material changes electrical properties in proportion to optical power input, but is only useful when the optical beam is chopped (gated or shuttered repeatedly) to produce alternating light and no-light conditions. Many internal power meters of medical laser equipment (e.g., CO₂ surgical lasers) utilize pyroelectric detectors.

The techniques for measuring pulsed laser energy are basically the same as those for measuring the power of CW sources. However, instead of relatively slow thermal calorimeters, photodiode detectors are utilized which have very fast response times (light input to electrical output, or “risetimes”) of nanoseconds or less. The electrical signal from the photodiode can be integrated to determine the laser output energy (i.e., the area under the pulse power vs. time curve).

B.2.2 Fiberoptic Measurements

Fiberoptic power meters are used primarily for telecommunications applications to measure optical power transmitted through an optical fiber system. Although power is measured in these tests—often in the microwatt range—the output parameter is typically expressed in decibels (dBs).⁴⁶ For example, AT&T may check a fiber in the telephone system to ensure that the optical loss of the fiber is less than 1 dB per kilometer. Most fiberoptic power meters use silicon, germanium, and indium-gallium-arsenide photodetectors, and are equipped with adapters that connect to the fiber terminations (connectors) to measure all the light that exits the fiber. While the instruments for laser power and fiberoptic power are similar, the two types of instrumentation differ in terms of:

- The use of relative dB measurement parameters
- Fiber/connector input
- Beam shape
- Dynamic range
- Wavelengths

As the use of optical fibers in telecommunications has grown, so has the need for fiberoptic power measurements. Fiberoptic power meters (radiometers) differ from the typical laser power meter in both wavelength range and measurement units. Spectrally, such radiometers operate in two ranges: from 800-900 nm using silicon detectors, and 1300-1600 nm with germanium or indium gallium arsenide (InGaAs) detectors. These ranges are utilized most frequently in fiberoptic communication since they are the “windows” where the fiberoptic material absorbs the least amount of light. Semiconductor diode lasers have been developed at specific wavelengths in these ranges, and measurements can be standardized in terms of the wavelength range of interest.

⁴⁶ The unit of fiberoptic transmission measurement is the decibel (dB), defined as: $\text{dB} = 10 * \log (\text{power out} / \text{power in})$. Decibel units are useful in compressing power measurement data that has a wide dynamic range. Fiberoptic radiometers can measure up to 80 dB of loss, using an input power in the range of microwatts to milliwatts.

B.2.3 Measurement Set-up and Procedure

A typical set-up for laser power measurement is shown in Figure B-3. The laser beam is directed onto the detector surface of the power meter either directly or with focusing optics. The power meter is attached to an electronic readout that provides appropriate units (e.g., W, mW or μW).

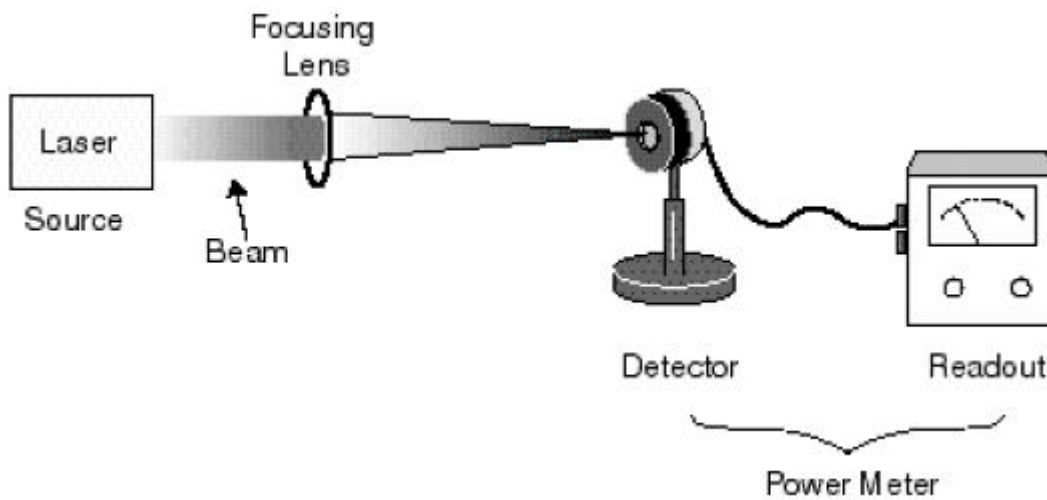


Figure B-3. Laser Power Measurement Set-Up

The measurement procedure is quite simple. First, the laser beam is blocked. The meter is turned on, adjusted to the appropriate power scale, and then zeroed—perhaps with the room lighting off, if that is a factor. The laser is then unblocked. The detector comes to an equilibrium temperature in a short time period (typically less than one second), and the readout shows the calibrated reading in optical power. Measurement of average power can be attained with the same procedure. Also, measurement of peak power is dependent on using a silicon (or other solid-state) photodiode with appropriate instrumentation. Sources of error in laser power measurement include:

- Geometric variations in detector sensitivity
- Alignment errors
- Environmental influences (e.g., temperature, air currents)
- Procedures

B.3 CALIBRATION

Laser power meters are calibrated routinely to ensure accurate power measurements. Typically, calibration involves a comparison of the subject power meter to a transfer standard, another power meter that has been referenced to national standards at NIST. Two basic techniques include:

- (1) Reading the power of a calibrated source (e.g., mercury lamp) sequentially using the two meters and correcting the subject meter to correspond with the transfer standard meter.
5. Using a beamsplitter to input the same laser power to the two power meters, which make the readings simultaneously as shown in Figure B-4.

In the sequential case, the calibrated source provides a reference that is assumed not to change between measurements. In the simultaneous case, the beamsplitter creates two equal beams that are directed into the separate detectors.

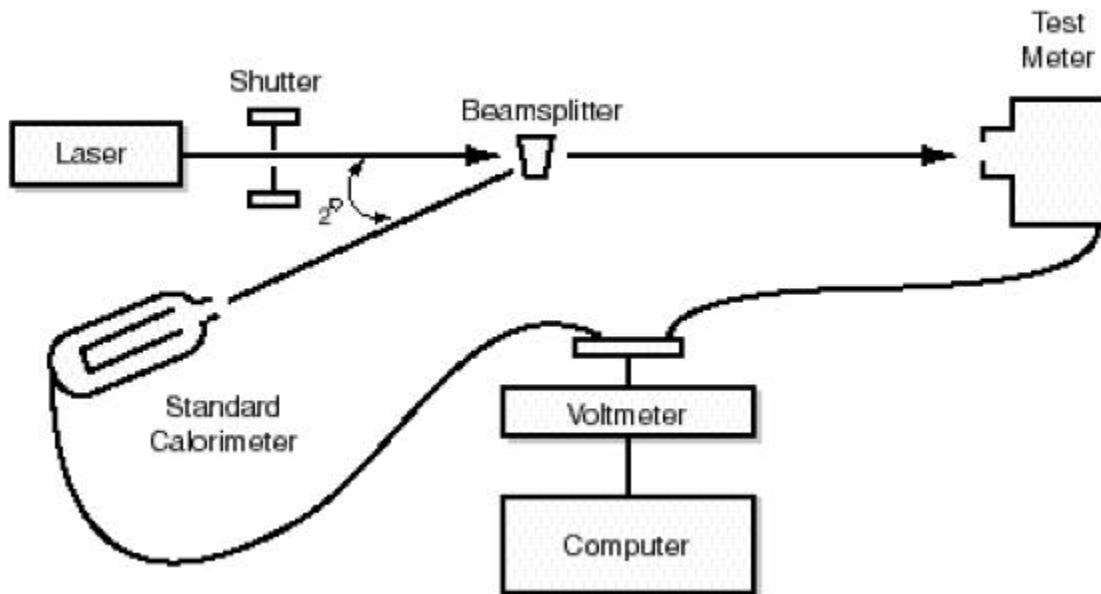


Figure B-4. Laser Power Calibration Set-up

Laser power meters must be calibrated regularly to ensure the desired level of accuracy. Some of the factors that determine the frequency of calibration include:

- The amount of use the meter endures
- The amount of abuse the meter endures (e.g., on a manufacturing line or in harsh environmental conditions in the field)
- The level of accuracy required for the application

For traceability to standards at NIST, two general levels of calibration that must be considered: field instrumentation and transfer standards.

B.3.1 Field Instrumentation

The manufacturer calibrates all power meters that are sold commercially. The manufacturer measures a source using both the test meter and a transfer standard meter, and adjusts the test meter (or provides a calibration curve or correction factors) to match the transfer standard.

Most manufacturers recommend an annual calibration of the power meters used by their end users (e.g., the physician or biomedical engineer in the case of a medical laser application, or a fiberoptic local area network (LAN) installer). In practice, the average time between calibrations for many power meters in use may be closer to 2-3 years. In extremely critical applications, the power meter may be calibrated biannually.

Most often, the power meter manufacturers recalibrate their customers' laser power meters. This process typically costs \$100-400. In the case of power meters internal to specialized equipment, such as semiconductor processing equipment or surgical lasers, the manufacturer of the equipment generally calibrates the power meter on-site. For on-site calibrations, the power meter manufacturers uses the same calibration techniques as described above.

B.3.2 Transfer Standards

A calibration is considered traceable to a primary standard when it can be related to an unbroken chain of transfer standards. NIST maintains absolute primary standards at a national laboratory. The use of transfer standards calibrated regularly by NIST enables power meter

manufacturers and users to achieve high measurement accuracy that can be transferred to the field instrumentation.

Manufacturers, research labs, and other organizations usually have their transfer standard power meters calibrated through calibration services provided by NIST. NIST provides a reference meter to the customer to which his power meter under test is compared. The comparison is sent to NIST, which calculates the appropriate correction factors for the customer to apply to its transfer standard meter. The reference meter sent by NIST is decalibrated so that the customer has no knowledge of whether the transfer standard meter is reading low or high relative to NIST's primary standard. In this way, the calibration is "blinded." The cost of a NIST power meter calibration is approximately \$1,600. While many power meter manufacturers have used "self-declared traceability," more recently companies are utilizing calibration laboratories or the services of NIST directly, to ensure compliance with the ISO/ANSI guidelines for quality assurance.

B.4 FACTORS AFFECTING MEASUREMENT ACCURACY

B.4.1 Wavelength

Generally, optical detectors are sensitive over a relatively narrow range of wavelengths. Some detectors are sensitive over the entire visible wavelength range, but their sensitivity varies dramatically over this range.

Calorimeters are used over a wider range of wavelengths, including the infrared (e.g., from 2-12 μm , that covers the CO₂ laser, the CO laser, the Erbium laser, and the Holmium laser as well as other lasers used in military and research applications, such as hydrogen fluoride.

Specialized applications that require great accuracy may utilize detectors calibrated to precise wavelengths. For example, the fiberoptic transmission loss measurement in telecommunications is performed at "carrier" frequencies of 1300 and 1550 nm. Other power meters and detectors, however, may cover a wide spectral range. In this latter case, some method must be used to compensate for the wavelength dependence of the detector sensitivity.

B.4.2 Detector Characteristics

In addition to the spectral response curve, detectors have other characteristics that may affect the accuracy of power measurements. For example, large diameter detectors often have variability of response across the detector surface. Therefore, if a small diameter laser beam (e.g., 2 mm HeNe beam) illuminates a portion of a large diameter (e.g., 1 cm) detector surface, a movement of the beam to a different position on the detector surface might cause a change in the power reading. Detectors can be characterized by scanning a laser beam across them and plotting the output, but this variability can usually be minimized by filling the detector entirely (e.g., defocusing the beam, if necessary).

Another important parameter for pulsed laser energy meters is the speed of the detector. If the response time of the detector (light input to electrical output) is not a very small fraction of the laser pulsewidth, then the peak signal from the detector will be less than if the detector were ideal (i.e., have an infinitely fast risetime), whereby the energy will read inaccurately. Detector speed has been increasing, but errors are still caused by the laser energy reading being a function of the response time of the detector.

Detector linearity relates to the electrical output of the detector being linearly proportional to the optical power on the detector surface. However, detectors can saturate at high power levels. For example, photodiodes saturate at powers of a few milliwatts. By using attenuators (e.g., filters) or integrating spheres, which provide an average attenuated signal to the detector, the detector saturation problem can be minimized.

Temperature can affect the response time of a detector. For example, with germanium detectors, the variation in responsivity with temperature becomes important near 1500 nm, which is the band edge for the detector. Therefore, temperature control equipment is required to stabilize the photodetector temperature in order to make accurate power readings at this important wavelength for telecommunications.

B.4.3 Beamsplitter

In the case of the simultaneous measurement of power from a single source by two meters to allow calibration of one meter by the other, a beamsplitter is commonly used to direct power into each of the meters. The beamsplitter does not have to produce exactly 50 percent power in each beam; however, the percentage reflected and transmitted must be known accurately. Should

the beamsplitter ratio be in error, a systematic error in calibrating power meters from a single transfer standard will occur.

A laser power measurement set-up must be used to measure the beamsplitter ratio. Therefore, a close connection exists between the measurement system used to test the beamsplitter and the measurement system that uses the beamsplitter. In both cases (beamsplitter manufacturer and beamsplitter customer), calibration to a transfer standard is possible.

B.4.4 Fiberoptic Connector

The insertion loss of fiber optic interconnecting devices, such as connectors, couplers, and splices, is an important system design parameter. Special techniques for measuring connectors and interconnect loss have been developed; these techniques are described in the EIA Fiber Optic Test Procedures (FOTP).

Significant variations in transmission losses can occur through differing fiberoptic connectors, splices and couplers. The telecommunications industry has standardized on several specific types of connectors for fiberoptic cables. Not only can the transmission loss differ between connector types, but also among connectors of the same type due to the variability in the process of assembling the fiber and connector. Moreover, if the connector used during calibration is different than the connector actually used, then an error will occur in determining the transmission loss of the system.

B.4.5 Other

Other factors include accuracy of detector/meter electronics, test procedures, environmental influences, and operator differences.

Appendix C METRICS

Two evaluation metrics used customarily by NIST's Program Office are the internal (social) rate of return and the ratio of benefits-to-costs. A third metric, net present value, is readily derived from the information developed for the benefit-to-cost ratio.

The metrics in this report are calculated from a time series of costs and benefits in constant dollars. Therefore, "real" rates of return are presented based on this time series of constant dollars. In contrast, previous economic impact assessments conducted by TASC for NIST's Program Office presented "nominal" rates of return that were based on time series of current dollars (the dollars of the year in which the benefits were realized or the costs were incurred).

C.1 INTERNAL RATE OF RETURN (IRR)⁴⁷

The IRR is the value of the discount rate, i , that equates the net present value (NPV) of a stream of net benefits associated with a research project to zero. The time series runs from the beginning of the research project, $t = 0$, to a milestone terminal point, $t = n$. Net benefits refer to total benefits (B) less total costs (C) in each time period. Mathematically,

$$(1) \text{ NPV} = [(B_0 - C_0) / (1 + i)^0] + \dots + [(B_n - C_n) / (1 + i)^n] = 0$$

where $(B_t - C_t)$ represents the net benefits associated with the project in year t , and n represents the number of time periods (years in most cases) being considered in the evaluation. For unique solutions of i , from equation (1), the IRR can be compared to a value, r , that represents the opportunity cost of funds invested by the technology-based public institution. Thus, if the opportunity cost of funds is less than the internal rate of return, the project was worthwhile from an *ex post* social perspective.

⁴⁷ The characterization of the three metrics follows Chapter 4 of Albert N. Link and John T. Scott, *Public Accountability: Evaluating Technology-Based Institutions* (Boston: Kluwer Academic Publishers) 1998.

C.2 BENEFIT-TO-COST RATIO

The ratio of benefits-to-costs is precisely that, the ratio of the present value of all measured benefits to the present value of all costs. Both benefits and costs are referenced to the initial time period, $t = 0$, as:

$$B / C = [\sum_{t=0 \text{ to } t=n} B_t / (1 + r)^t] / [\sum_{t=0 \text{ to } t=n} C_t / (1 + r)^t]$$

A benefit-to-cost ratio of 1 implies a break-even project. Any project with $B / C > 1$ is a relatively successful project.

Fundamental to implementing the ratio of benefits-to-costs is a value for the discount rate, r . While the discount rate representing the opportunity cost for public funds could differ across a portfolio of public investments, the calculated metrics in this report follow the guidelines set forth by the Office of Management and Budget:

Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent.⁴⁸

C.3 NET PRESENT VALUE (NPV)

The information developed to determine the benefit-to-cost ratio can be used to determine net present value as:

$$NPV = B - C$$

Note that NPV allows in principle one means of prioritizing among several projects *ex post*.

⁴⁸ “Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs,” Office of Management and Budget (OMB), Circular No. A-94, 29 October 1992.

APPENDIX D

HIGH-SPEED MEASUREMENT TECHNOLOGY

Frequency response is an important figure of merit for high-speed detectors used in a fiberoptic receiver (detector and associated electronics). Frequency response is determined by measuring the optical power at a precise wavelength.⁴⁹ A “perfect” frequency response extending to infinite frequency is portrayed in Figure D-1(a). In Figure D-1(b), a finite frequency response is shown for an idealized detector. The amplitude (detector electrical response to the optical signal shown on a logarithmic scale) “rolls off” as the modulation frequency is increased. The bandwidth at which a detector can reliably be used is determined by the modulation frequency at which the detector output is reduced by one half. This frequency is commonly referred to as the “half-power” point, the “3-dB point,” or the “cut-off frequency.” To determine the 3-dB point, a modulated optical signal is applied to the input of the detector, and the electrical output is observed. As the modulation frequency is increased, the electrical signal amplitude from the detector will decrease; when the detector output is down by a factor of two, the frequency is noted, and this is the 3-dB point.

In actual practice, due to mismatches in impedance between the optical detector and the electrical circuitry, reflections of the signal occur which lead to a multitude of phase-shifted, attenuated signals. The resulting measured frequency response is shown on Figure D-1(c). The ripples seen on this frequency response curve result in “ringing” in the time domain; that is, a single optical pulse input to the system will result in several electronic pulses at the output (at various levels of attenuation). These additional pulses may be detected in a digital system as a “one” where the input signal was a “zero,” thus leading to intersymbol interference, which increases the bit error rate of the system. Thus, measurement of both the 3-dB point and the smoothness of the detector roll-off at frequencies higher than the 3-dB point using “eye diagrams” are required to fully characterize the bandwidth of a telecommunications system. Both of these measurements depend on accurate optical power measurement techniques at high modulation frequencies, which are the techniques that NIST has been developing.

⁴⁹ In practice, fiberoptic communication requires the laser (carrier) wavelength to be within one of the transmission “windows” (typically wavelengths around 800 nm, 1300 nm, or 1550 nm) where the fiberoptic core material absorbs the least amount of light.

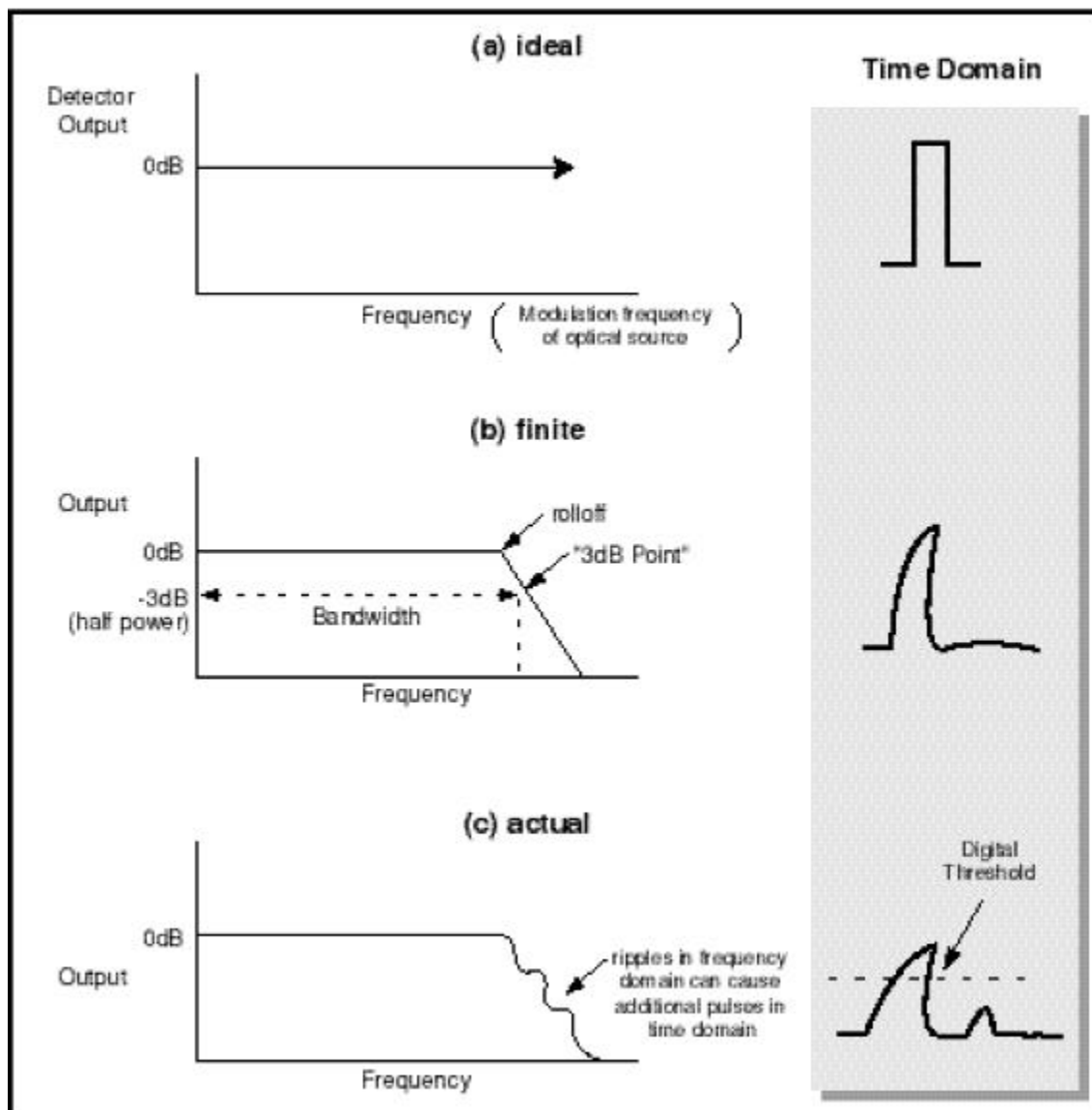


Figure D-1. Frequency Response of Optical Detectors

Appendix E

History of NIST's High-Speed Measurement Program

NIST frequency response Calibration Services were developed as a result of the NPL round robin, Navy interest, and general industry interests. HP was not the sole requesting entity. Later work developing certain transfer standards to specifically address the manufacturability of certain SONET/SDH reference receivers was in close collaboration with HP

Development of the heterodyne method used at NIST was done by first conducting a careful review of pertinent literature and industry experience, including work at NTT (Japan), NPL (UK), Tektronix, New Focus, and HP. We had direct conversations with personnel from Tektronix, NPL, New Focus, and HP. From this review, NIST found several things which could be improved over previous implementations, including those at HP. These improvements and innovations include:

- A novel and previously undiscovered method for normalization. The new NIST developed method make measurements insensitive to fluctuations in laser power, simplifies the measurement setup, reduces measurement time by as much as a factor of 10, and eliminates arbitrary normalization factors commonly used elsewhere. The NIST normalization method has never been implemented anywhere else, although a similar version was implemented at HP in their second generation system (see below).
- The use of open beams for combining the lasers, followed by a single polarized and normal single-mode fiber. This modification simplifies alignment and makes errors due to power and polarization matching negligible.
- Use of an electrical power sensor for power measurement rather than an electrical spectrum analyzer. Correction for mismatch error has only been implemented at HP in the past year, if at all. Mismatch errors have been corrected at NIST for several years.
- Use of a frequency counter for measuring frequency, instead of an electrical spectrum analyzer, giving greatly improved frequency accuracy.
- Use of Kernel smoothing to interpolate swept heterodyne data.

In about 1995 the HP heterodyne system was failing and could not provide the accuracy that the NIST system had achieved, so it was scrapped. Soon after this NIST was furloughed and could not provide calibrations for a short period of time. The combination of these occurrences made HP realize that they needed to build a new heterodyne system for in house measurements, using NIST only for “Golden Standards”. They decided that they required higher resolution (about 0.1 MHz) than their old system could achieve. NIST could already achieve about 0.5 MHz resolution. From a manufacturing point of view, it would be advantageous for the higher resolution measurement to be made with a phase-locked loop. For various technical reasons they decided to build a system that used 3 lasers to achieve phase-locked loop operation over the range of about 0.3 MHz to 1 GHz.

Because of the new requirements that HP supplied, NIST upgraded its system to provide phase-locked loop operation from 0.3 MHz to beyond 1 GHz. However, the NIST solution used NIST developed phase-locked loop circuitry, used only two lasers, and achieved the same performance at significantly less cost. Hence, the NIST system was improved because of customer demand, and was done without help from HP or other customers.

The open beam design of the new HP heterodyne system was a direct result of seeing the ease of operation that the NIST design offered. The previous HP design used awkward polarization maintaining fibers to maintain polarization alignment, making the old system very difficult to align.

Because of anticipated customer demand, and requests for HP and the Navy, NIST built a heterodyne system operating at 850 nm to address the needs of the computer interconnect market. The only other 850 nm heterodyne system publicly documented as being specifically for measuring detector frequency is at New Focus. The new NIST 850 nm system far outperforms the New Focus system in terms of accuracy and frequency resolution. It was built with Navy and NIST funding and without help from HP or other commercial customers.

HP is not the only customer of NIST frequency response measurement services. HP was the main customer of 1319 nm calibrations, with occasional calibration requests from component vendors. However, with the addition of the 850 nm systems, HP only accounts for about 50% of NISTs calibration work load.

Development of the 850 nm heterodyne system was started in March 1997, and now accounts for the majority of NISTs measurements.