NBSIR 75-942

The National Measurement System for Optics

Dennis A. Swyt

Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

Measurements in imaging optics are fundamental to the manufacture of products ranging from spectacles, microscopes, photographic goods and microfilmed documents to aircraft, nuclear reactors and oil pipelines; the measurement quantities of interest are "diffuse visual density" which characterizes the darkness of photographic, radiographic and ink-on-paper images; and numerous measures of optical system performance (refractive power, resolution, optical transfer functions, etc). Diffuse visual density is defined by American National Standards Institute documentary standards; many voluntary standards and federal specifications relate to its application. Measures of optical system performance are in general undefined by documentary standards.

The measurements are most intimately related to the output of the photographic and optical industries. In figures characteristic of years in the early 1970's, these goods included $1.3 billion worth of sensitized photographic goods, $4 billion in photographic products and $485 million in lenses and optical instruments. Typical sales of $5 million in densitometers and $35 million in non-ophthalmic test equipment provide some means of indication.

Some of the measurements are performed by:

*18,000 eye examiners and 20,000 dispensers of lenses supplying 100 million wearers of corrective lenses with ophthalmic lenses costing $190 million in a $2 billion system of eye care

*10,000 medical radiologists, supported by 90,000 technicians, examining an estimated 325 million x-rays of 110 million patients at an estimated cost of $4 billion

*15,000 industrial radiographers performing an estimated 45-90 million measurements in over 6300 plants at an estimated cost of $350 million. Typical data for products affected by these measurements are $7.6 billion in aircraft production, $4.6 billion in missiles and space hardware, the $64 billion in nuclear reactors contracted for in the period 1965-73, and the $600 million of pipelines constracted annually.

NBS contributes to the operation of the measurements system by providing diffuse visual density standards, microcopy resolution charts and an optical system and lens evaluation service. The density standards are used by, among others, the eleven companies which accounted for virtually 100% of photo film sales and 80% of equipment sales in 1970: the standards are required by clear-cut AEC, NASA, and DOD specifications, by an ambiguously worded FAA requirement, with a DOT standard for pipeline inspections that trails off into an oil industry standards. The NBS Microcopy Resolution Chart is a voluntary standard for the $450 million microfilm industry and a mandatory standard for use in DOD microfilming operations; the NBS chart is on the verge of formal acceptance as an international standard. The lens testing services have primarily benefitted federal agencies.

In eighteen month period in which outputs of NBS were evaluated, a program which in 1973 consisted of 3 1/2 man-years of effort with a $319,000 budget (of which $118,000 was from other federal agencies) provided 15,000 microcopy charts, 200 density standards, 10 interferometers for an AEC prime contractor, a handful of lens tests, a number of special studies for federal agencies, a significant amount of testing and consultation on optical systems for security-classified federal agencies, as well as major publications on the theory and operation of advanced optical systems.

The primary result of this study of the measurement system has been to reveal the nature of the users of NBS services and the degree of their dependency on the standards NBS supplies. Incremental analysis, the tracing of the economic effect of NBS services through causal chains to final products and services, has not proven feasible.

Recommendations regarding NBS programs are to upgrade density measurement capabilities, to maintain without further expansionary investment the lens testing services, and to channel the image analysis measurements toward optics-related measurement problems. Discontinuation of NBS services in this field, it is thought, would result in the provision of the same services by one or more other federal agencies. Continuation of the study of the measurement system might involve assessments of the desireability of NBS reference standards of

reflection density and of the interest of optical manufacturers in a round-robin approach to measurement assurance in lens testing.

Documentary data and informed opinion for this study have been acquired by means of a survey questionnaire to 150 users of calibration services; canvassing letters to 30 instrument manufacturers, 25 trade and industrial associations, and 50 optical companies; personal interviews with 30 individuals at organizations throughout the country; innumerable telephone contacts; as well as direct use of documentary and library source materials.

1. INTRODUCTION

From the earliest times man has sought to extend the limited range of his vision and to communicate what he had seen. First with simple magnifiers, later with telescopes and microscopes, he examined the small world within reach and the great world at a distance; but he could convey in words and drawings only a part of what had been observed.

Then in 1839, an artist named Daguerre held an exhibition in the salon of the French Academy. He revealed the results of a process he had developed to permanently record images produced by lenses. The event marked the opening of the era in which men could show others in graphically realistic detail what they had seen.

Separately and in combination, film and lens revolutionized human affairs, science, medicine. Within decades, Europe's populace saw in photographs the carnage of the Crimean war; Madame Curie named radium the element which had fogged some sensitized photographic plates; and physicians based diagnoses on the images of internal organs appearing in x-ray radiographs.

Today the excitement of these events is long in the past but the benefits continue. To illustrate the ways in which lenses and photographic materials affect us, imagine yourself to be a traveller at an air terminal with a long layover. Imagine yourself mentally labelling with red tags the products and services which are based on optical, photographic and radiographic processes.

Start off easily. Tag every lens you see: tourists' cameras, binoculars, passengers' eyeglasses, the security television camera. Mark every photograph: advertising displays, magazine covers, ID badges, the snapshots in your wallet. Put one on everything that has information stored on microfilm: the car rental agency, the insurance desk, the airline company, the New York Times; put a few in your pocket for driver's license, library card, auto registration, and credit cards. Tag the weather report; it's based on satellite photographs of cloud formations. Stick tags on things that had film x-rays taken of them: the chests of pilot, crew and food service workers, all those teeth and arms and legs and things of people around; the aircraft itself gets a handful for airframe, turbines, pumps, landing gear. Paste the tags on anything with integrated circuit devices (they're photofabricated): the radar, tower communications systems, the ordinary radio and television sets. Since nuclear reactors, steam turbines, refinery equipment and transmission pipelines are radiographically inspected, tag just about everything that runs on electricity or oil. Now imagine the number of red tags around you.

Along the complex chain which links a manufacturer to you, all the red-tagged items required measurements on images. These measurements are means to give objective answers to questions such as: Is the image sharp? Is it too dark or light? Are fine details visible? Have the shapes of objects been reproduced faithfully? Is the contrast good? In essence, these measurements seek to tell how well a lens system makes an image or how well a medium records it.

This report in turn is an attempt to answer some questions about the measurements themselves. What are they, who makes them, where, why, at what cost, to whose benefit, what role does the National Bureau of Standards play? The answers are by necessity incomplete but, hopefully, informative nonetheless.

2. STRUCTURE OF THE MEASUREMENT SYSTEM

2.1 Conceptual System

To familiarize oneself with the important measurements of image optics, one might follow in thought the construction and testing of a rudimentary camera.

First, surfaces with the same curvature are ground onto opposite faces of a glass disc. After polishing the surfaces, one measures their *radius of curvature* and the overall lens diameter. Using a textbook formula, measured radii of curvature, and the index of refraction of the lens material, one computes the *focal length*, the distance from the lens at which will be formed the image of small, greatly distant source of light. Focal length is also measured directly by the same prescription. The reciprocal of the focal length is the dioptic power or *refractive power* of this simple lens.

The body of the camera consists of an oilcloth bellows, closed at one end by a ground glass screen and at the other by a plate with a hole into which is mounted the lens. On the wall of the workshop hangs an illuminated target. The device is rested on a tripod, aimed, the bellows length adjusted until a sharp image of the target is focussed on the glass and the bellows locked in place.

The image on the glass is like the *bar test target* on the wall, consisting of patterns of bars, dark on light background, with progressively smaller widths and spacings. However, the focussed image has *distortion*; it is different in shape than the target, due to lens *aberrations*. One may also notice that, in all the patterns smaller than a certain one, the lines are indistinguishable; they may lie below the *resolution limit* of the lens.

Up to this point, measurements have been dimensional. Radius of curvature and focal length are given in millimeters and resolution limit in lines per millimeter. At this point more sophisticated tests begin. The bar test target is replaced by a *sinewave target* in which the variations from dark to light to dark in each pattern are not abrupt but gradual. The reciprocal of the distance between successive dark or light bands is the *spatial frequency* of the pattern (also loosely given in lines per millimeter rather than cycles per millimeter).

The technique is to determine how well the image of the target reproduces for many spatial frequencies the difference in the brightness of the dark and light bands (the *contrast or modulation*); also to determine if the lens causes a band to be in a different position than if the lens were removed and the band projected through the lens-mounting aperture directly onto the ground glass. The difference in these two positions is the *spatial phase* introduced by the lens. The modulation and spatial phase may be determined by measuring the light intensity at different positions in the image or recording the image on film and analyzing that; the latter case will be illustrated.

To the camera is added a bladed shutter which will open to let light enter only for brief periods and the ground glass replaced with film; a series of pictures is taken of the target with the shutter open for progressively longer periods and the film removed and developed. The images on the film reveal much about the lens and the film.

The first picture is completely clear, not enough light has entered the camera for an image to register. The last picture is completely black, so much light has entered that the film is completely exposed. The pictures in between have images in progressively darker shades of grey. The measure of the degree of darkening of the film is the *optical density*. To actually measure the optical density, one would measure the amount of light which strikes the film and the amount which passes through and do a calculation of density, D:

$$D = -\log_{10} \frac{\text{light transmitted}}{\text{light incident}}$$

However, one may assess the optical densities of the images by comparing them, either by eye or machine, to a *photographic step tablet* (also called a grey scale or a

Figure 1. A photograhic density grey scale

density wedge). This is a piece of film with exposed and developed strips of grey for which the optical densities have been measured (Figure 1).

If the density of each image at the same relative position in each picture is determined and this information combined with the times the shutter was open, a graph can be drawn: density versus the logarithm of the relative amount of light reaching the film. This graph is like a *D-log E curve* (or H and D curve, for Hurter and Driffield) except it has relative amounts of light not the absolute amounts. From the D-log E curve come the definitions of the *film speed* (the minimum exposure needed to produce a certain density), the *film contrast* (a measure of how density increases with exposure), and other properties like these which describe *film response* to either light or x-rays.

In order to measure the *lens response*, the test chart was imaged onto the ground glass; photographing the image introduced the film response but information derived from the D-log E curve allows that effect to be subtracted off. Therefore, if the modulation (contrast) on the film is measured for a number of different spatial frequencies and the effects of the contrast of the original target and the film response taken into account, a plot of the modulation introduced by the lens versus spatial frequency (the *modulation transfer function, MTF*) may be made. If the spatial phases are measured and added to this plot, the result is the *optical transfer function* of the lens (Figure 2).

Two more tests which are often performed on lenses and film are: a target essentially consisting of a broad black bar on a white field is photographed and the density of the image in the neighborhood of the sharp boundary between the light and dark areas is measured to get an *edge trace*; and a small point of light is photographed and the density variations along the diameter of the image measured for the *point spread function*.

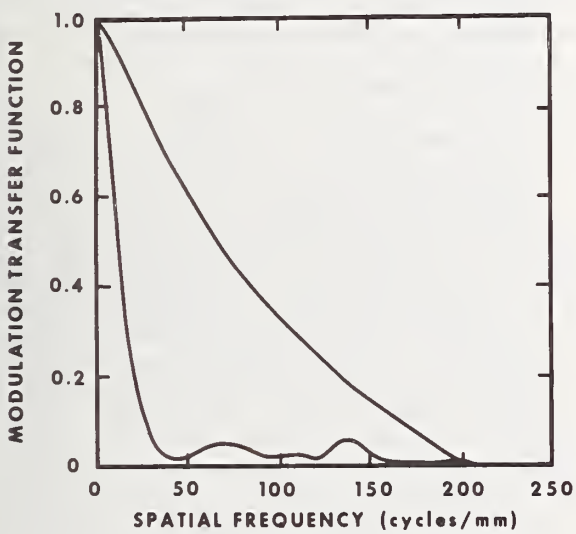


Figure 2. Modulation transfer functions of "good" and "bad" lenses

The conceptual exercise of following the construction and testing of a simple camera has served as a means of introduction to some of the measurements associated with lenses and film. These measurements are a means to answer the questions asked rhetorically in the Introduction. In summary, some of the measurements for a lens are: radius of curvature, focal length, refractive power, resolution limit, aberrations, distortion, modulation transfer function, optical transfer function, edge trace and point spread function; for the film: optical density, speed, contrast, resolution limit, and the same four last items as the lens. These are some of the measurements which are the "what" of imaging optics. In the next two sections will be described some of the "how".

2.2 Basic Technical Infrastructure

2.2.1 Documentary Specification System

2.2.1.1 Standardization Institutions

In the U.S., standardization (that process by which goods are manufactured in uniform size, quality, strengths, etc.) is generally voluntary. Product standards are issued by private groups and serve as guidelines to manufacturers, consumers, and the general public. Except for health and safety regulations and their own procurement specifications, federal, state and local government bodies tend not to exercise enforcement powers in matters of standardization.

The most important private standards organization in the United States is the *American National Standards Institute* (ANSI). This federation of trade, technical, professional, labor, consumer and government organizations approves and coordinates voluntary standards. A documentary standard issued by ANSI "implies a consensus of those substantially concerned with its scope and provisions." Some of the standards are of interest for this report.

In its role as coordinator of U.S. voluntary standards activities, ANSI is the U.S. representative to the *International Organization for Standards (*ISO*)*. This non-governmental group, founded to facilitate trade, promulgates standards which, like American National Standards, are not binding, not even on members which approved the documents.

Two other groups with something to say about lenses or film are the *National Microfilm Association* which is a trade organization in the micrographics industry and the American Society of Mechanical Engineers, a professional organization. A trade group, the *Gravure Technical Association*, supports that particular type of printing industry.

There is a *Department of Agriculture* specification for aerial mapping cameras but nothing on image quality in itself. The *Federal Aviation Agency* (concerned with air safety), *Department of Transportation* (concerned with pipeline safety) and the *Nuclear Regulatory Agency* (concerned with nuclear reactor safety) all have requirements which involve film usage. The *Department of Defense* and the *National Aeronautics* *and Space Agency* have similar requirements in hardware procurement procedures.

The federal *General Services Administration* which handles procurement for the civilian government and the *Military Supply Service* which writes the specifications for the Defense Department have numerous documents more or less relevant to this report.

2.2.1.2 Survey of Documentary Standards

The current catalogue issued by the American National Standards Institute indicates that the group has standards for measuring refractive power of opthalmic lenses; ANSI Z80.1 for spectacle lenses and ANSI Z80.2 for contact lenses. They both say use a "standard" instrument to do the measurement. ANSI has standards for the screw threads of microscope objectives and the barrel markings of photographic lenses; none on testing the lenses. The National Microfilm Association has two standards for determining the resolution of microfilm systems: MS104 for microfilm and MS5 for microfiche. These standards refer to a domestically produced test chart which satisfies the requirements of an international draft standards, ISO DSI 3334, on microfilm resolution.

The standards for film and photographic materials issue from ANSI. PH2.33 gives a method for determining the resolving power of photographic materials. PH2.17 defines optical density for reflection (like prints have) and PH2.19 defines it for transmission (like negatives have). PH2.19 conforms to the international standard for transmission density given in the document ISO5.

Based on the two ANSI standards for optical density are those for determining speed: PH2.2 for photographic paper, PH2.5 for negative materials, PH2.8 for industrial x-ray film, PH2.9 for medical x-ray film and PH6.1 for "intraoral" dental x-ray film. PH2.5 is consistent with the international standard for film speed, ISO6.

A spot survey of the federal specifications issued by the General Services Administration shows, not surprisingly, that this group handles the office supplies and leaves specification of technical systems to the individual agencies which buy them; it has standards on film but not lens sytems. The omnibus Federal Standards No. 170 on photographic film references ANSI PH2.5 for speed, PH2.19 for optical density, and PH2.33 for resolving power. Federal Specification L-F-333A on motion picture film is based on FS No. 170. The specifications for x-ray film, FS L-F-310 on medical and dental and FS L-F-350 on industrial, are both tied to the older ANSI PH2.8.

The military, as one would expect, have standards and specifications on everything. For optical products, from binoculars to gun sights to telescopes to cameras of every kind, there are around 250. In general, the relevant military specifications for film ride along with the federal specifications. The DOD has, however, some significant standards dealing with microfilm. The military specification which gives the basic guidelines for testing microfilm systems is MIL-M-9868D, 'Requirements for Microfilming Engineering Documents'; MIL-M-38748 covers microfiche, MIL-P-9879 covers architectual drawings, and Mil-M-38761 covers microfilm of technical data. The basic standard for resolution testing is consistent with the National Microfilm Association standards; the same test target is called for.

With respect to military standards on optical systems, it should be kept in mind that the Department of Defense procures some rather sophisticated optics with performance specifications that stretch the state of the art of image quality testing. Acceptance standards are of necessity a matter of negotiation.

2.2.2 Instrumentation System

2.2.2.1 Measurement Tools and Techniques

In the mental exercise of following the fabrication and testing of a simple box camera, the details of the principles involved with the measurements, the instruments, and the standards were not given. Before these are covered, some of the relevant properties of light will be reviewed for the convenience of the reader. Light normally travels in straight lines, but when it passes from one transparent medium (such as air) into a different transparent medium (such as glass) it can bend (or refract). Light can be reflected from surfaces such as mirrors or metals. Light may also be bent, or diffracted, as it passes the edge of an object. When light from two different sources, even two points on the same source, reaches some place at the same time, it can add together or cancel out, that is, interfere. The principles of linear propogation, refraction, and reflection form the core of the subdivision of optics called geometrical optics. The principles of diffraction and interference are elements of physical optics. The design of any optical system which uses the focal properties of lenses requires knowledge of geometric optics; the design of especially high performance optical devices requires a further knowledge of physical optics.

For simple optical lenses like ophthalmic spectacles, refractive power measurements are sufficient for the tasks of design and quality control. The imperfections of the images produced by such lenses can be made less than the eye can detect by ascertaining that the lens has the proper focal properties. The refractive power of lenses may be computed from measured values of radii of curvature or focal length, or they may be determined by comparison with lenses of known power. The standards are, therefore, length scales or lenses; the chain of standards is a short one: from a basic unit of length to the length scale to a standard lens or the final lens itself. Precisions along this chain can be of the order of fractions of a millimeter. Lens systems more complicated than spectacles or contact lenses are designed according to the principles of geometrical optics but require testing which extends beyond the measurement of refractive power.

Because the functioning of complex devices cannot be predicted from a simple knowledge of their construction, performance testing is used. One index of performance is the amount of distortion caused by the lens or lenses. The difference in shape of the object and of the image produced by the optical device can be measured by: either comparing the image of a target to the target itself; or by projecting a narrow beam of light through the lens and locating the position of its focus. The first technique involves the use of a standard, the target. Both methods are based on mechanical measurements of position.

A second index of performance for an intermediate-performance lens system is resolution limit. (Resolving power, a measure of the smallest details which can be distinguished, applies to lens and film.) The standard for resolution testing is a bar target, a chart with patterns of lines printed on it; it may be either a transparency or an opaque. Usually, the target is photographed and the image on the film examined with a microscope to determine the smallest pattern in which the lines are unambiguously distinguishable. Resolution limits of optical devices range from perhaps 20 cycles per millimeter for a crude lens and over 1000 c/mm for special photographic films to near 2000 c/mm for a high-quality microscope. Again, the chain of standards proceeds via the unit of length from the manufacturer of the chart to the end user in one step.

For the highest performance optical devices, measurements related to the predictability of function and to actual performance testing are made. At some point in the evolutionary hierarchy of optical systems, the lenses produced are so free of material, manufacturing, and design defects, that the extremely small-scale effects of diffraction and interference serve to limit the ultimate performance of the device. A lens of this quality is called "diffraction-limited." The atmosphere in which these devices are tested is rarefied. There are essentially no documentary standards which offer guidance and no standard test objects. Testing of state-of-the-art optical components is done on ad hoc bases, with reliance placed on the skills and knowledge of people using special measuring instruments.

For a type of optical density important to imaging optics, and therefore to this report, the situation is quite different. Associated with this optical density, specified as American National Standards Institute Diffuse Visual Density Type V1-b, is a fully developed measurement system. The ANSI definition of diffuse visual density imposes geometric and spectral conditions on the general definition of optical density:

$$D = -\log_{10} \frac{\text{Light returned from object}}{\text{Light incident on object}} .$$

Diffuse visual transmission density characterizes photographic negatives; diffuse visual reflection density characterizes photographic prints.

Discussions with those familiar with the field, such as standards committee chairmen and instrument producers, have lead to the conclusion, affirmed by these sources, that only three laboratories in the nation have facilities for the fundamental measurement of diffuse transmission densities as defined by the current documentary standards. The basic devices are called "inverse square bars"; the name derives from the principle of operation in which the amount of light which reaches the detector varies as the reciprocal of the square of the distance between the source of light and the detector.

A complete apparatus consists of a track with the light source at one end, the detector which slides along the track, and a length scale. The detector is a hollow sphere with a hole directed at the source of light and another hole which points toward a light meter. The recipe for the determination of the density of a sample of film is: measure the source-to-detector distance, read the meter, cover the first hole in the sphere with the film, move the detector down the track until the meter reads the initial value, and measure the new source-to-detector distance. The optical density of the film sample is computed from the equation:

$$D = -2 \log_{10} \frac{\text{(first distance)}}{\text{(second distance)}}$$

Since the systems are built to conform to the detailed documentary specifications pertaining to geometry and spectral characteristics, they provide fundamental measurements, or primary calibrations, of diffuse visual photographic density.

A primary calibration of a photographic density step tablet is carried out by the measurement of the density of each of its "steps" according to the procedure described. Typically the range of densities which can be measured on an inverse square bar apparatus is from 0 to just above 4. The precision of the measurements will be discussed below in section 2.3.

The concept of optical density may also be applied to reflection. The American National Standards Institute, in its documentary standard ANSI PH2.17, defines diffuse reflection density in a manner analogous to its definition of transmission density. In this case, however, the "primary standard" of reflection density is "freshly prepared magnesium oxide," a white powdery chemical which has been packed into a wafer. The unsatisfactory nature of the documentary standard and the reference material is common knowledge among people who require good measurements of reflection density. A densitometer manufacturer reports that barium sulfate is most often used as a reference. The chairman of the ANSI committee which issued the documentary standard has indicated that the standard is being revised to give a more precise definition of the measurement quantity and to bring it into conformity with the present practice of using the more stable and dependable material, barium sulfate, as a reference.

2.2.2.2 The Instrumentation Industry

Measurements of the various optical quantities being discussed in this report (e.g., refractive power, MTF, resolution limit and specific types of optical density) are made with both commercially manufactured instruments and custom-fabricated devices.

There are three important types of spherometers, instruments for measuring the radius of curvature of spherical lenses or mirror surfaces. The first consists of a ring which rests on the surface and a micrometer plunger in the middle of the ring to measure the sag or bulge of the surface in the plane of the ring. The second one has three feet instead of the ring but works the same way. The manufacturer has put gauges in the devices which read out directly in refractive power and has calibrated them by measuring the distance the plungers move. The third spherometer is a microscope which projects an image onto the surface to be measured. The source image is seen sharply imaged if the microscope is focussed on either the surface itself or on the center of the curvature; the distance between these two positions is equal to the radius of curvature. These devices are calibrated at the factory by measuring the powers of the two lenses they contain. The *Optical Industry and Systems Directory for 1975* lists four companies which make spherometers. People who manufacture and dispense spectacle lenses use them; a representative of an ophthalmic company reports that probably 13,000 spherometers are in use; they cost less than a few hundred dollars each.

A lensometer is also an ophthalmic instrument and is used to measure the magnitude and direction of the maximum and the minimum powers of spherical-and cylindrical-surface spectacle lens. The lens is placed in a parallel beam of light between two other lenses; viewed in an eyepiece, the image of an X-shaped target is brought to a focus by moving the target; the distance moved is proportional to the refractive power of the spectacle lens. A handful of optical companies manufacture lensometers (or focimeters or vertometers, as they are also called). The same company representative estimates that the number of lensometers in use is about 38,000; these are distributed among 8,000 physicians specializing in the eye, 20,000 licensed eye examiners, and the 10,000 or so dispensers or makers of spectacle lenses.

Distortion measurements are often made with non-commercial devices. One such device consists of a bench for mounting a target, the lens to be tested and either a screen with a light measuring device or a camera. A second such apparatus might consist of the same basic set-up with the target replaced by a light source which swings in an arc centered at the lens. The light source is moved to determine where the light which passes through the lens is projected. There are variations on this method but the principle is the same. In any case, a reliable mechanical reference is the basis for distortion measurements.

The most frequently used instrument for optical density measurements in photographic applications is the densitometer. This device has a built in light source, a detector, and a light meter. It measures the amount of light reaching the detector, with and without a sample in place, and electronically computes optical density from the ratio. The newest densitometers may have digital read-out and display densities in the range 0 to 1 to three decimal places and densities from 1 to 4 to two decimal places. Densitometers are adjusted at the factory to read optical densities properly; often photographic step tablets are shipped with instruments to allow periodic readjustment. Instruments may be designed to conform to the ANSI documentary standard PH2.19, "Diffuse Visual Transmission Density." There are also reflection densitometers which conform to the ANSI document PH2.17 on reflection density and operate in a manner analogous to transmission densitometers.

Written responses to requests for data from the manufacturers of densitometers listed in the Optical Industry and Systems Directory and discussions with these sources of information have supplemented the statistics obtainable from governmental agencies. The U.S. Department of Commerce figures for 1972 show sales of densitometers and similar devices of more than $4 million that year and $6 million for 1971 (Current Industrial Reports, MA-38B(72)-1). Although this Department of Commerce report shows only four companies with shipments greater than $100,000, about 30 companies yearly market a total of over 1200 general or special application densitometers or light measuring devices useful in densitometry. Of these 30 firms, four dominate in supplying densitometers for photographic film applications, six supply most devices for clinical uses, a dozen serve the graphic arts, and five or six furnish the instruments for special image-analysis applications called microdensitometers. The simpler densitometers for photographic and graphic arts work cost about $750; for more critical work as in photographic manufacturing and industrial radiography, units range in price from $1000 to $5000. Scanning densitometers used in clinical and chemical analysis run from $5000 to $8000. The basic scanning microdensitometer employed in high precision image analysis might sell for over $20,000; if it were automated by a computer for control and data handling, the total cost might be three to five times as much.

Devices like MTF equipment and interferometers for assessing the performance of high quality optical systems are made up of components: lenses, lamps, lasers, optical benches, mirrors, gratings, prisms, modulators, detectors and related devices. The items, sometimes packaged as modules, are often bought separately. About ten companies sell MTF systems in the U.S. A modular system for measuring the MTF of a sighting device might sell for $15,000; the modules for testing an enlarging lens might cost $20,000. A sales representative reports that his firm has marketed over one hundred of basic systems like these world-wide; four other super-systems had gone for $100,000 each.

Department of Commerce data for 1972 from the Current Industrial Report cited above show sales of optical test equipment to be about $35 million annually.

2.2.3 Reference Data - Not Applicable

2.2.4 Reference Materials

In imaging optics, there are two important types of objects used in measurements which, for want of a better term, can be classified in this report as reference materials; the physical objects are resolution targets and photographic density standards. In turn, there are two major types of resolution targets and two general types of photographic density standards. All are photographic materials which are prepared in careful but conventional ways.

The American National Standards Institute document ANSI PH2.33 describes a resolution target for use in the determination of the resolving power of photographic materials. The basic building block of the overall pattern consists of three bars of equal widths and spacing (Figure 3). A target is fabricated, for example, by laying out on a white background thirty-nine of the basic patterns of different sizes. The size of each one is chosen such that the spatial frequency from one pattern to the next increases by a factor of 1.12. When the complete array of patterns has been laid out, it is photographed at a carefully selected reduction ratio. What had been black patterns on a white background are reversed: clear patterns on a generally black negative. If the reduction ratio is chosen precisely, the spatial frequencies on the transparency will range as the ANSI document specifies from 0.10 cycles per millimeter to 7.94 cycles per millimeter.

The second important resolution target has five bars in the basic pattern rather than three. The design for this target was developed in a government laboratory with the testing of microfilm systems in mind. In this case, 26 patterns of five bars of equal widths and spacings are laid out on a white backgound. Again the ratio of spatial frequencies between successive patterns is 1.12. The same process of reduction photography described above is followed; however, the reduction ratio is chosen to yield patterns on the negative which range from 1 to 18 cycles per millimeter. The negative is contact printed to produce the final chart. Where the ANSI target was a transparency, this microfilm resolution target is on opaque photographic paper (Figure 4).

The third reference material of interest is the photographic density step tablet. The tablet is produced from unexposed negative film; mounted on a mechanical carriage, the strip of film, for example, 25 mm wide and 150 mm long, is advanced 5 mm or so at a time under a slit through which light is projected onto the film. One end of the film strip is started under the slit, exposed for certain length of time, the film advanced, a second section exposed for a longer period, and the procedure repeated with sucessively longer periods until perhaps 21 sections have been exposed. When the film is finally developed, the end product is one photographic density step tablet, each band on the strip being of a greater diffuse density than the preceding. A similar procedure could be followed by printing directly onto photographic paper; in this case, the result would be a reflection density standard rather than one for transmission as was the first. Reflection density standards can also be manufactured by normal ink printing processes although the characteristics of such materials are not precisely those of photographic standards.

Some reference materials of a more specialized nature are: sine wave targets which may be made by recording interference fringes on film; the edge trace target which is simply a film or paper target with a very sharp boundary between the light and dark regions; and a chart originally designed by NBS for application to the testing of photographic lenses (it resembles a television test pattern and is printed from engraved plates).

The ANSI resolution pattern is really a prescription which describes the conventional manner for measuring and specifying the resolving power of photographic materials; as such, targets are made which conform to the specifications of the ANSI document but they apparently are not sold commercially.

The five bar "microcopy resolution chart" was designed for the resolution testing of microfilm systems. The National Microfilm Association, trade and standardization group for the industry, calls for these charts in two documentary standards: NMA MS104 for microfilm systems and NMA MS5 for microfiche. The charts conform to the specifications of ISO DSI 3334, the draft international standard on microfilm resolution (which is nearing adoption as a formal standard). The Department of Defense calls for the microcopy test chart for testing microfilm systems they buy and as part of their record-keeping procedures. The basic document is MIL-M-9868D. The military standard requires that the target be recorded on the first and last frame of every roll of microfilm used by its people; the microfilm group suggests the procedure.

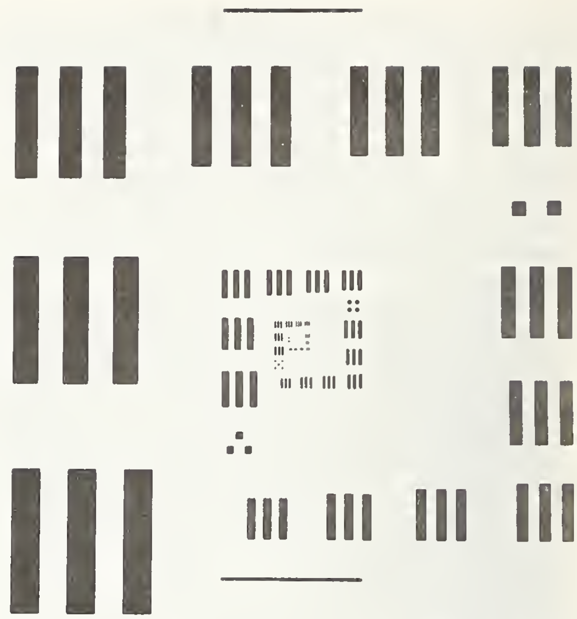


Figure 3. Basic pattern of the ANSI PH2.33 resolving power target

This microcopy resolution chart is manufactured on a competitive contract, for the National Bureau of Standards (NBS), by a major photographic company. The charts bear the logo of the agency, an indication they have been examined by the agency and found to meet rigid quality specifications. The charts may be acquired from the manufacturer or NBS. Since the charts uniquely satisfy the industry standard, the international standard, and military specifications, they find wide usage. One may estimate the number in use by counting the number distributed annually and assuming, probably conservatively, that the charts have a two year lifetime before replacement. That puts the number of microcopy resolution targets which are in circulation at around 20,000.

Photographic density step tablets differ from resolution charts in that their form is not specified; only the basic measureable property, optical density, is specified. Anyone may make a step tablet by a procedure similar to that described earlier and sell it. However, there are reportedly only three places where fundamental measurements of American National Standard diffuse densities are performed: a photographic manufacturing company, an instruments maker, NBS.

Each of the sources of fundamental density measurements distribute step tablets: a great number from the photographic company as products, a proportionately smaller number the instrument maker ships with his densitometers and supplies separately, and the number the NBS offers as basic reference standards. Other photographic suppliers and densitometer manufacturers contribute to the total in circulation.

The tablets are used for direct visual assessment of density, for calibration of densitometers, for the evaluation of light attenuators and as attenuators themselves. As such, there are applications for step tablets in photographic manufacturing and processing, photography, medical radiology, industrial radiography, and graphic arts.

Optical density standards in the form of transparencies and opaques are manufactured and distributed primarily by four domestic firms. There are about a dozen more or less standard types with another dozen or so special configurations. A spokesman for a major photographic company estimates that his firm markets around 150,000 annually and that there may be a total of 500,000 in circulation. The vast majority of these are reflection density grey scales.

2.2.5 Science and People

People concerned with the basic thinking about optical imaging measurements come from a wide variety of backgrounds, carry different credentials, and belong to a spectrum of organizations. Those more or less readily identifiable are described.

People engaged in theoretical and analytical studies of the properties of optical systems usually have degrees in physics, engineering, chemistry or mathematics. A very few have studied at schools with complete programs in optics or optical engineering like the University of Arizona or the University of Rochester's Institute of Optics. Articles on current research appear in the journals of the Optical Society of America, the Society of Photographic Scientists and Engineers, the American Institute of Physics, as well as independent publications like Applied Optics, Optik and Optika Acta. Further removed from the developments in research and theory are the people who use optical systems like ophthalmic test equipment.

There are three ways by which one can acquire custom-prescribed spectacles. One could be examined by any of the 8,000 licensed medical physicians who specialize in the eye. Their professional group is the American Association of Ophthalmology. Second, one can be examined by a licensed non-medical practitioner, an optometrist; there are 15,000 of them. Their groups are the American Academy of Optometry and the American Optometric Association. Both ophthalmologists and optometrists are licensed to examine eyes and prescribe spectacle and contact lenses. With a prescription in hand, one could get the lenses and frames or contact lenses from any of 10,000 dispensing opticians. Their organization is the Guild of Prescription Opticians of America.

In the field of radiography, there are industrial and medical counterparts. When x-ray pictures are taken of persons and animals, the procedure is called radiology. When the x-rays are taken of inanimate objects, like metal parts, the procedure is called radiography. The processes are essentially the same: in medicine, x-rays from a source pass through a person, expose a film and, after processing, the picture on the film is examined for flaws in the person, like cracked bones or tumors or tooth decay; in industry, rays pass through objects like airplane wings and the picture is examined for flaws like cracks and empty spaces inside the metal. About 10,000 physicians specialize in radiology; their association is the American College of Radiology. Dentists who use x-rays (and

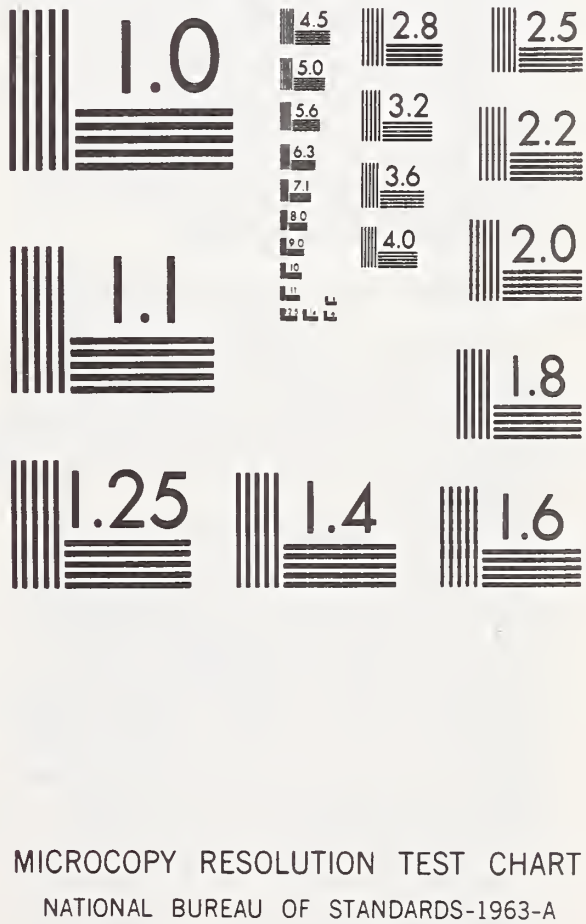


Figure 4. The NBS Microcopy Resolution Chart

those who do not) may belong to the American Dental Association. Over 90,000 medical x-ray technicians are certified by the National Board of X-ray Technologists. Industrial radiographers are not licensed but some are "certified". There are about 15,000 of them and they may belong to the Society for Non-Destructive Evaluation. Medical and industrial people both belong to the American Roentgen Ray Society.

Depending on their commercial status, photographers may join the Professional Photographers of America or the more general Photographic Society of America.

These groups mentioned here provide some of the basic technical expertise for the development of optical and photographic documentary standards. Many others exist. Besides from the technical publications noted, the people involved get measurement information from trade association journals like "Micrographics" of the National Microfilm Association, from special interest magazines like Optical Spectra and Electro-Optical Design, and from the books and sales literature put out by manufacturers of photographic and optical products.

The importance of this last source of information should not be underestimated. In some cases, the technical data sheet, the film box, the instrument instruction manual and the word of the salesman are the major sources of information for the person doing the measurement.

2.3 Realized Measurement Capabilities

Discussions with optical instrument manufacturers, densitometer makers, producers of photographic products, and others competent in the measurement field have led to the following profile of ranges and precisions associated with the measurements:

Resolution targets have patterns of bars; the spatial frequency of a pattern is the reciprocal of the total width of one bar and one space and is expressed in lines or cycles per millimeter (c/mm). The lines on George Washington's face as he appears on a dollar bill have a spatial frequency of about 2 c/mm; the human eye can resolve 10 to 20 c/mm. With these figures in mind, one can outline the measurements associated with different industries. The best engraved plates have resoltuion limits of about 15 c/mm; an inexpensive camera, 25; à blueprint, 50; a decent amateur camera, 100; a professional-grade camera or a microfilm system or a photoreconnaissance camera, 300; the finest quality microscope objective, 2000 c/mm. For photographic film and plates, less than 55 c/mm is low, 80 is medium, 120 high, 225 extremely high and somewhere above 1000 c/mm the highest attained (Figure 5).

One may recall that the spatial frequencies on the resolution chart which is the standard for the microfilm industry range from 1 c/mm to 18 c/mm. The 300 c/mm which is the upper limit of performance of microfilm systems can in principle be obtained by photographing the chart at a reduction ratio of 20:1 or so. This means the spatial frequencies in the reduced image are 20 or more times those on the chart. In the quality control of microfilm records, resolutions better than 144 c/mm are usually satisfactory levels of performance in day-to-day operation.

Diffuse visual density is the measure of how dark the blacks and greys of a negative or print appear to the eye. It is the logarithm of the ratio of the amount of light which passes through the negative (or is reflected from a print) to the amount of light which strikes it. For a perfectly clear negative, all the light gets through, the ratio is 1 so the density is zero; for a black negative, say only 1/10,000th of the light gets through, so the density is 4 (one can barely see the sun through that). Fundamental measurements of density are made on an apparatus which *measures* density. A transmission densitometer is a table-top instrument which *compares* densities. It is calibrated by placing a photographic density step tablet in it and adjusting a knob until a meter reads the value of density written on the tablet. A reflection densitometer is calibrated on the ratio of the amount of light reflected from a sample and the amount reflected from a reference standard like a grey scale. The reference standard is calibrated against something which is arbitrarily defined to have a zero density.

In medical radiology, the maximum transmission density of interest may be 1, while a great deal of information the physician is looking for is at densities less than about 0.2. In this range, he visually detects density differences of the order of 0.01. In industrial radiography, densities on the x-ray picture of metal parts generally lie between 1.5 and 3. In this range, an industrial radiographer can visually detect density differences of 0.02 to 0.03. With a decent densitometer he can get down to 0.01. In general photographic work like film processing, the range of densities is 0 to 4. Densitometers which read to $\pm$ 0.01 are sufficient. The manufacturers of photographic film generally work in the range 0 to 4 but some special tasks require

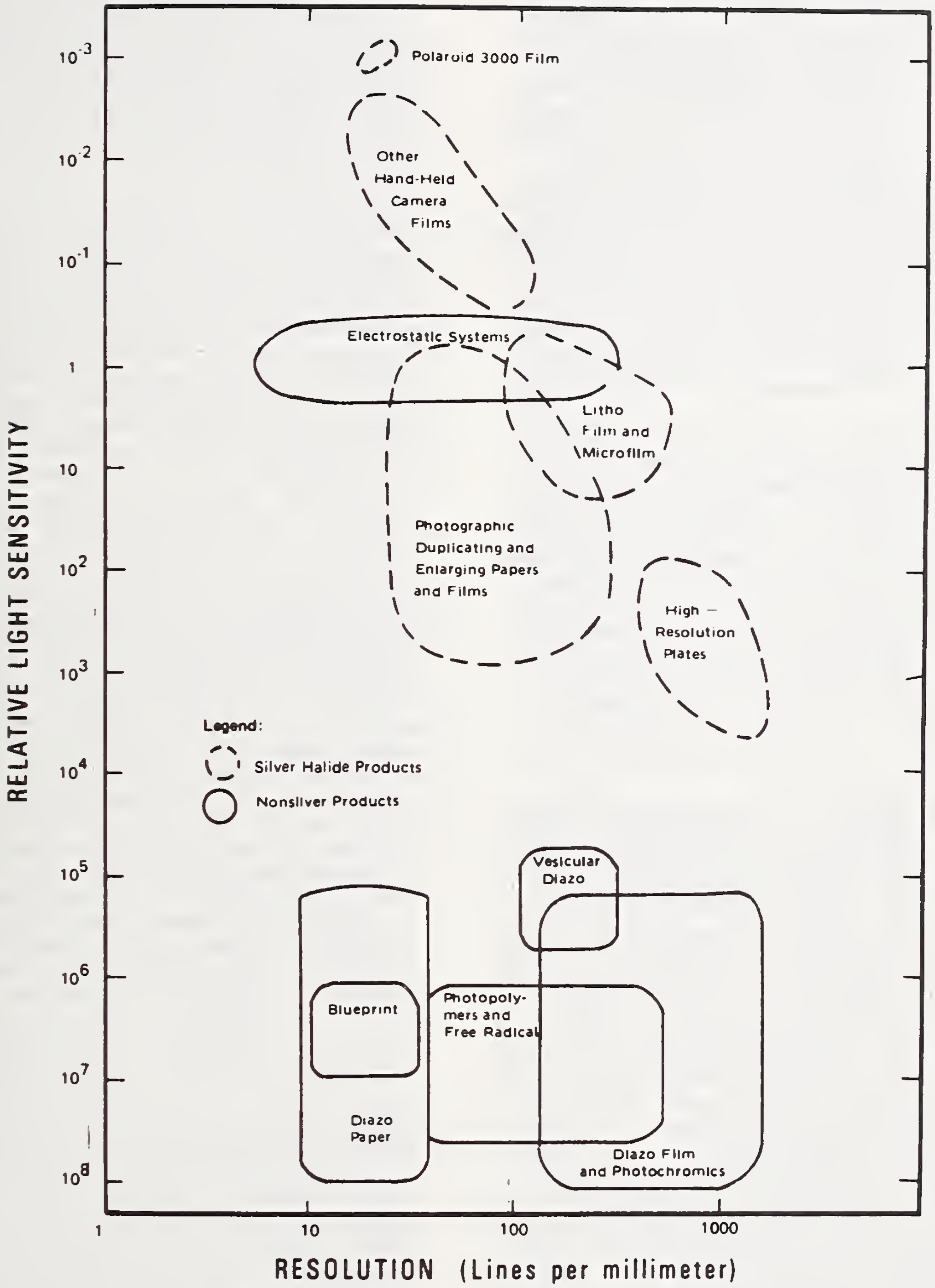


Figure 5. Spatial frequency ranges of some sensitized photographic materials

densities between 4 and 6 (which is outside the range of ordinary densitometers). Some applications like film speed measurements involve densities below about 0.2 and require precisions greater than ± 0.01; the newest top-of-the-line transmission densitometers have precisions of ± 0.001 and find use in these and similar critical situations.

Transmission densitometers are calibrated with photographic density tablets; the tablet with which the user of the densitometer calibrates his instrument may be far removed from the original source of densities. The values of density on the tablet may derive from a number of intermediate comparisons or they may be the result of fundamental measurements at the source.

The present range of original density measurements, primary calibrations, is 0 to 4; accuracies are generally 1/2%, corresponding to ± 0.005 at a density of 1 and ± 0.02 at 4. NBS distributes calibrated reference standards for which the stated uncertainty of densities below 1 is ± 0.005; at times, uncertainties of ± 0.002 have been attained on that lab's present apparatus. One densitometer manufacturer reports fundamental measurements with observed deviations of ± 0.0005. He markets a densitometer which has a repeatability of ± 0.001 for densities less than 1.

By comparing the data in the paragraph above with the user requirements outlined two paragraphs back, we can deduce that present fundamental measurements of transmission density meet the needs of major users except those doing critical photographic work or manufacturing photographic film and paper. These people need standards with densities ranging from 0 to 6 and accuracies of 1/2% or ± 0.001 whichever is larger. Current density standards offered by NBS have densities from 0 to 4 with accuracies of 1.0% or ± 0.005 whichever is greater.

In reflection measurements, printers (the ink on paper kind) generally work with densities between 0.04 and 1.65. The precisions they need can be obtained by obtained by the good commercial densitometers which read to ± 0.01. Reflection density measurements performed by NBS (on samples supplied by customers) have these accuracies, ± 0.01 or 1/2%. Photo manufacturers make measurements from 0 to 2.5 or higher. Since visible variations in the white area of a photograph correspond to density differences of about 0.01, these manufacturers need standards with accuracies of ± 0.001 or 1/2%. Such standards are not currently available.

One index of the effectiveness of a spectacle lens is its refractive power; this property of the lens provides compensation for the eye's inability to focus properly. Refractive power is expressed in diopters and is the reciprocal of focal length expressed in meters.

One of the basic tools of eye examination is a set of test lenses which range from -16 to +16 diopters in power. The examiner places different lenses before the eye until the patient judges he can best see the letters on the chart. The lenses are graduated in steps of 1/4 diopters in power; a single lens of 1/8 diopter may be added to obtain values of power between the 1/4 diopter values of the primary lenses. A typical value of overall correction is 4 to 5 diopters; in rare cases, 14 or 15 diopters of correction are required. The examiner usually prescribes lens powers that are multiples of the 1/4 diopter unit; occasionally the power is specified as a multiple of 1/8 diopter.

Lensometers (also called vertometers or focimeters) and spherometers are used in the offices of ophthalmologists and optometrists, in the laboratories of dispensing opticians, and by the optical companies which manufacture finished spectacles and unfinished blanks. The range of a lensometer is -20 to +20 diopters; by comparing the spectacle with a lens of known power, the device determines the refractive power of the spectacle to a precision of ± 1/8 diopter (where 1/16 D is the tolerance on a finished lens specified by the ANSI documents on first quality prescription spectacle lenses). Spherometers measure the radii of curvature of spherical lenses; the scale on a spherometer may be calibrated in dioptic power by assuming the lens being measured is made of a specific type of glass. The typical precision of spherometer measurement is ± 1/16 diopter; under carefully controlled conditions, ± 1/32 diopter precisions are attainable with the device. Lensometers and spherometers are comparison instruments. The master standards are sets of lenses. Test lenses have been calibrated for the major manufacturers of ophthalmic instruments and lenses by a NBS to accuracies of 1/500 diopter.

For some simple lenses like spectacles, refractive power is an adequate measure of effectiveness. For some lens systems like microfilm readers, resolution is practical gage of performance. But for high quality lenses and advanced optical systems, no single number can adequately characterize image quality. Required are measurement techniques which assess the combined effects of system parameters: lens material, focal length, aperture, aberrations, configuration and illumination. Modulation transfer function is commonly accepted as one means of lens performance testing. Commercial systems measure MTF over a range of spatial frequencies up to about 100 c/mm. An interferometric technique developed at NBS yields MTF measurements for spatial frequencies up to 250 c/mm and is in principle capable of measurements out to 1000 c/mm; the method also gives maximum values of aberrations. The field of advanced lens testing has not matured to the point of having documentary standards, standard test objects and instrumentation, or readily discernable patterns of measurement.

2.4 Dissemination and Enforcement Network

2.4.1 Central Standards Authorities

Put to an informed and detached observer, the question of which measurement quantities in imaging optics must derive from a central standards authority no matter how remote, such question would likely be answered with a qualified: none. None of the measurement quantities are based on quasi-legal definitions or chains of transfer from unique master standards. As a result, the role of a central authority is to act as the source of authoritative, objective, and competent measurements and information; by doing so, such a source would serve to unify, not determine the measurement system. The National Bureau of Standards of the U.S. Department of Commerce provides measurement services to this end.

2.4.2 State and Local Offices of Weights Measures

Not surprisingly, measurements in imaging optics do not fall within the present sphere of measurement activities of state and local offices of weights and measures or related agencies. In the field of imaging optics, no analogue exists to the system of mass measurements linking the international kilogram to the grocer's scale.

2.4.3 Standards and Testing Laboratories

Some organizations perform functions similar to standards and test labs; they are not part of an "enforcement and dissemination network".

Some optical companies will perform lens testing since they have the facilities for testing their own products. A handful of companies advertise under "optical instrument calibrations" in the Optical Industry and Systems Directory. Some general testing firms will test anything, including optics, if they are hired to do so. None of these organizations are part of any network of standards.

Two firms, a photographic products company and a densitometer manufacturer, can perform fundamental measurements of optical density; they supply density standards as products or along with instruments. Both firms compare the measurements they make with fundamental measurements by buying and using standards from NBS. The standards these two firms distribute are *referred* to the national standards rather mechanically *derived* from them.

A group of testing laboratories measure film densities as part of their testing of other products; they don't test or measure the film itself. They are the commercial testing laboratories which do radiographic non-destructive testing (NDT). Radiographic inspections done for the military, either in commercial labs or manufacturers' quality control departments, must be based on density standards obtained directly from NBS. Some regulatory agencies have similar requirements.

2.4.4 Regulatory Agencies

Regulatory agencies and bodies which have procurement specifications that tend to have pseudo-regulatory effects do not in general control measurements; some have "rules" which generally relate to optical imaging systems. Information from standards committee chairmen and agency officials have led to the following conclusions:

Spectacle lenses. All the states license eye doctors, about half license optometrists, about one third do opticians. The states don't put performance specifications on the manufactured lenses or police the delivery system. A federal regulation governs the mechanical but not the optical properties of impact-resistant spectacle lenses. While a 1974 bill pased by the Senate (S2368 on Medical Devices) was mentioned in the popular press as potentially dealing with the effectiveness of prescription lenses, the Senate report (Calendar No. 646) doesn't explicitly deal with the ophthalmic lenses.

Safety eyewear. The Department of Health, Education and Welfare's National Institute for Occupational Health and Safety (NIOSH) which provides technical support to the Department of Labor's Occupational Safety and Health (OSHA) actually measures the refractive power of safety eyewear to determine conformity to ANSI Z87.1, "Practice for Occupational and Educational Eye and Face Protection." As a part of its test procedure, NIOSH uses a test target obtained from the National Bureau of Standards.

Aerial mapping cameras. The Department of Interior's United States Geological Survey (USGS) calibrates aerial cameras according to Department of Agriculture (DOA) specifications. The DOA, the United States Forestry Service, the Bureau of Land Management, other federal agencies, and many state departments of highways and transportation have specifications which either require or conform to the DOA calibration requirements. The relevant camera calibration facility, originally part of NBS in the Department of Commerce, was transferred to Interior in 1972.

Medical x-ray. The states license radiologists who are the doctors that generally oversee hospital x-ray rooms and who interpret the pictures for diagnostic purposes. The Food and Drug Administration's Bureau of Radiological Health (BRH) is charged with enforcement of Public Law 90-602, the Radiation for Health and Safety Act of 1968, which has provisions dealing with the components of diagnostic x-ray systems including film and intensifier screens. BRH enforces the provisions of documentary standards developed in conjunction with industry; they apply at the manufacturer's level. BRH bases its measurements of the response of films and intensifying screens on optical density standards obtained from NBS.

Microfilm systems. The Department of Defense (DOD) requires performance testing of microfilm and microfilm equipment in its procurement and in its use. A series of documents, the most basic of which is MIL-M-9868D, describes resolution testing and specifies a microcopy resolution chart obtainable from NBS; it also calls for photographic density standards from the same source. The General Services Administration (GSA) relies on the industry standards which specify the same chart.

Industrial radiography and civilian aviation. Responsibility for the airworthiness of all domestic civilian aircraft rests with the Department of Transportation's Frederal Aviation Agency. The FAA basically has two procedural means for insuring the structural integrity of aircraft. To provide for the reliability of new aircraft before marketing, the FAA requires that a complete system of nondestructive testing (NDT) inspection be developed during construction and made available to buyers and users of aircraft. NDT procedures, especially radiography, are emphasized. To provide for continued airworthiness, the FAA oversees the operation of a system of certified inspection and repair stations. Mechanics and inspectors are certified (rather than licensed by the FAA); the inspectors are employees of aircraft manufacturers, airlines, repair services and independent NDT test labs.

When an unsafe condition is found in an aircraft after delivery, the FAA notifies the operators of similar aircraft of the potential problem and specifies the conditions, including NDT inspections, under which the aircraft may continue in use; as a last resort, the FAA can ground the aircraft. During 1972, the FAA issued 147 reports of possible unsafe conditions in the form of Administrative Directives (AD's as they are called in the industry). Of these 147, 66% requires NDT inspections. Formal compliance with AD's is mandatory; records of inspections and radiographs become a matter of record.

Industrial radiography in military and space applications. The Department of Defense (DOD) operates by the book. One document (MIL-I-45208A) outlines general quality control standards and practices; a second document (MIL-C-45662A) requires that the densitometers used for the evaluation of radiographs be calibrated with photographic step tablets obtained directly from NBS. Other specifications describe the procedures for the radiographic inspection of castings, welds, and forgings. As a result, everyone who radiographically inspects military hardware - including contractors who assemble systems, subcontractors who supply components, or independent test labs - is required to base his measurements of photographic densities directly on standards obtained from the National Bureau of Standards. In procurement of space vehicles and launch systems, the National Aeronautics and Space Agency (NASA) imposes similar requirements on its suppliers.

Radiography of pipelines and nuclear reactors. Responsibility for the safety of oil and gas transmission pipelines rests with the department of Transportation's Hazardous Materials Regulation Board (HMRB). Pipelines are constructed from short sections of pipe that are welded into a continuous line; the weld seams are x-rayed. HMRB specifications (Title 49, Chapter 1, Section 195.234) tell how many welded seams must be inspected. The required number is given in terms of a percentage of a day's production of welded seams.

Where the pipe is laid within populated areas, within any incorporated subdivision of a state, where the threat of water pollution from spillage exists, etc., 100% of the welds must be radiographically inspected; outside these areas, 10%. The HMRB document states that the acceptability of welds should be judged according to the American Petroleum Institute's document on NDT testing, API Standard 1104, section 6, current edition. The industry's standard specifies a density on the film but does not refer to the ANSI document which defines density nor does it refer to any density standards. It leaves the final judgement on acceptablity of welds to the company for which the pipeline is built. DOT does not license or certify radiographic inspectors of pipelines, tank cars, or other equipment used in the transport of dangerous substances.

Until recently the former Atomic Energy Commission was responsible for the structural integrity of *nuclear reactors*. The present Nuclear Regulatory Commission discharges this responsbility in part by the enforcement of mandatory NDT inspections of nuclear pressure vessels and components. The basic procedures for inspections are given in the American Society of Mechanical Engineer's Boiler and Pressure Vessel Code (ASME BPVC, 1971). Fulfillment of the sections of the code dealing with radiographic inspection of nuclear reactors (ASME BPVC III, IV, and VIII) is achieved either in plant or in independent test laboratories. These manufacturing and testing facilities are tied by photographic step tablets to NBS.

2.5 Direct Measurement Transaction Matrix

2.5.1 Analysis of Suppliers and Users

To add structure to the presentation of the information acquired on the measurement system, organizations and entities which generate and use measurement information (Table 2) have been grouped according to their functions. To the commercial categories have been added others such as the governmental as well as the general public. These categories have been arranged in a 16 x 16 grid (Table 1). The groups will be defined; their measurement capabilities, and the measurement information, standards, and the products they deliver will be given. The reader is cautioned that statistical data on the value of products and services often involves multiple-counting; the total sum of the dollar figures quoted may exceed the gross national product.

Photographic Industry. These are manufacturers of photographic equipment and supplies who appear in the Standard Industrial Classification category, SIC 3861. They produce cameras, lenses for cameras, sensitized paper, processing chemicals and the assorted materials and equipment that go with picture making. Besides amateur still and movie equipment and film, there are non-amateur products in various categories; microfilm (including cameras, readers, printers and processors), graphics arts (which along with the appropriate camera and film items includes photocopiers and phototypesetting products), professional motion picture, aerial photography and prepared photochemicals. According to a private study of the industry ("Photographic Equipment and Supplies", Predicasts, Cleveland, 1972), the markets are highly concentrated. Nine companies represent 97% of domestic film sales and 80% of all photographic products. Three firms produce 82% of the film and two 50% of all goods. The photo industry, as a class, uses the complete line of commercial and prototype instruments for measuring every conceivable property of lenses and film. One company has an apparatus for doing fundamental measurement of photographic density.

Some of the information they acquire in research is fed into the system via scientific literature; much of it is proprietary; the industry provides general information in books and articles on photography, radiography and related topics. The industry is represented on all the important trade associations, professional and technical societies, and standards bodies related to the field. They maintain close but for the most part informal ties to the instrumentation manufacturers; in some cases, they make or have made densitometers. They contribute to the development of federal procurement specifications and to the mandatory standards which apply to them, e.g. the FDA requirements on specifying x-ray film-intensifying screen performance.

The private market survey quoted above (based in part on DOC data) shows $4.4 billion in product shipment for 1970 and projects sharply increased sales. Products delivered into our Metal Product and Health Establishment sectors are primarily radiographic film and equipment; into the Commercial --Institutional go the gamut of still and motion picture, microfilm, x-ray, graphic arts and photocopying products; into the General Public, primarily amateur still and motion picture cameras and film.

The photographic industry produces reference materials: photographic step tablets for transmission density measurements, grey scale charts for reflection density, and the microcopy resolution chart (for NBS). One manufacturer in a private communication with NBS estimates that 500,000 density standards are in use by people in appli-

Table 1: Direct Measurement Transaction Matrix

DIRECT MEASUREMENTS TRANSACTIONS MATRIX FOR OPTICS / USERS / SUPPLIERS	KNOWLEDGE COMMUNITY 1	DOCUMENTARY SPECIFICATIONS 2	INSTRUMENTATION MANUFACTURERS 3	NBS 4	U.S. GEOLOGICAL SURVEY 5	STATE AND LOCAL AGENCIES 6	DOD 7	REGULATORY AGENCIES 8	FEDERAL AGENCIES 9	PHOTO INDUSTRY 10	OPTICAL INDUSTRY 11	METAL PRODUCTS 12	STANDARDS AND TEST LABS 13	COMMERCIAL INSTITUTIONAL 14	HEALTH ESTABLISHMENT 15	GENERAL PUBLIC 16
1 KNOWLEDGE COMMUNITY	3	2	3	4 4 1	2		3	3	2	4	4	2	2	2		
2 DOCUMENTARY SPECIFICATIONS	2	4	4 3	3 4 1	3		2	4	2	3	0	3	3	2	1	
3 INSTRUMENTATION MANUFACTURERS	3	4 3	4	2 3 1	0		2	1	1	2	3	2	2	3	4	
4 NBS	2 1 3 0	2 2 1	3 1 2 0	3 1 2 0	0 1 N	1 1	4 3	3 1 1 0	4 1 2 0	3 1 4 0	1 3	4 0 4	4 0 4	2 1 3 0	1 0 1	1 0 1
5 U.S. GEOLOGICAL SURVEY	1	2		2 1	4	3			3					4		1 0 1
6 STATE AND LOCAL AGENCIES				0	3						3 1 0				1	
7 DOD	1	2	1	1 3			4			2	3	4	1			
8 REGULATORY AGENCIES	1	1	0	1 0				2	3		2 0	1 1	1	2	0	
9 FEDERAL AGENCIES	1	1		2	3							4 2				
10 PHOTO INDUSTRY	2 4	4	3	4 0 4 0			4	2	4	4		3	3	4	4 1 4 2	2 0 4 0
11 OPTICAL INDUSTRY	4	4	2	3 1 3 1		3	4	2	4	2	3			4	3 2 4	4 1 4 2
12 METAL PRODUCTS	3		1	2 1 1			4	3	2			4 4	4 4	4 1 4 2		4 4
13 STANDARDS AND TEST LABS	1	2	1	2 2 1								4 0 4	2	3		1
14 COMMERCIAL INSTITUTIONAL	3	3	3	3 3 1	4		2	2	2	4	4	3	3	4		4
15 HEALTH ESTABLISHMENT	1	2	0	0		3		3	1	3	1				3	4 1 4 2
16 GENERAL PUBLIC				0 1	1	1		2	2	3					3	

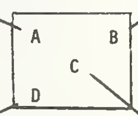
KEY TO ENTRIES

A IMPORTANCE OR CRITICALITY OF TRANSACTION

1 Purely a matter of convenience
2 Economically compelling; strongly desirable
3 Legally required; alternate sources unsatisfactory
4 Matters of life and death; sole source; essential

B ADEQUACY OF TRANSACTION SERVICE

1 Under control
2 Marginally OK
3 Seriously deficient
4 Out of control



D RATE OF CHANGE

N Declining
0 Stable
2 Growing
4 Explosive growth

C MAGNITUDE OF TRANSACTION

0 Trivial
2 Moderate
4 Major

cations ranging from photography, radiography, gravure printing, phototypesetting, and television broadcasting to consummer product package labelling (machine readable labels). The microcopy resolution charts which are the microfilm industry standard are produced on a competitive contract by a photo manufacturer for NBS; he distributes about half of them directly to users, about half go to NBS. Judging by the number distributed anually and estimating serviceable lifetime, one would put the number in use at any given time as around 20,000; apart from their primary use in the evaluation of microfilm systems, they are general purpose tools in optical testing. Users appear in the photo, optical, and commercial-institutional sectors.

Optical Industry. A survey of industry (Institute of Graphics Communication, 1973) shows over 1500 companies making equipment related to optics, this includes everything from lenses to lasers. A Department of Commerce source, writing in Optical Industry News, July 1973, counted 303 firms which manufacture lenses or instruments that use lenses (excluding photographic equipment). Many of the 303 companies are small. Statistics compiled by the Bureau of Census (Current Industrial Reports, MA-38B(73)-1) show just the manufacturers with sales over $100,000: for example, only four producers of ophthalmic lenses and five of optical test equipment (including microscopes) had reported sales above that level in 1972 (see Table 3).

The optical industry is diverse, with the high-technology companies often overlapping into the photo industry. One company might manufacture space telescopes, reconnaissance cameras, microfilm systems, and ophthalmic goods; as such it would possess the entire range of test equipment from interferometers to spherometers. Another company might produce inexpensive general-purpose lenses, sunglasses and ophthalmic goods; its measurement facilities might run to the simpler forms of refractive power and distortion testing. Between these two extremes is an entire spectrum

In terms of its relation with standards committees and regulatory agencies, this industry follows the pattern described for the photo industry. Except for ophthalmic lenses, test sets and the ANSI documents on prescription lenses, there are apparently no other physical or documentary standards related directly to the industry. Into the general public sector, the industry delivers spectacles, contact lenses, binoculars and amateur telescopes. To the health establishment go research microscopes, ophthalmic equipment like test

Table 2. Interaction Matrix Suppliers and Users: SIC Codes of Non-Governmental Entries

SIC	Transaction Matrix Category and Members
	Instrumentation Manufacturers
3611	Measurement and test equipment
3811	Scientific instruments
3693	Radiographic apparatus
	Photographic Industry
3861	Photographic equipment and supplies
	Optical Industry
3831	Optical lenses and equipment
3851	Ophthalmic goods
3861	Photoreconnaissance systems
3861	Microcopying systems
3861	Photocopying machines
	Metal Products Manufacturers
1925	Guided missiles and space vehicles
3360	Castings
3390	Forgings
3440	Fabricated structural steel
3490	Pipes, valves and fittings
3511	Turbines and generator sets
3533	Oilfield machinery and equipment
3711	Motor vehicles
3721	Aircraft
3731	Shipbuilding and repair
	Standards and Testing Laboratories
7397	Commercial Testing Laboratories
7397	Non-profit research institutions
	Commercial-Institutional Services
1799	Welding contractors
2751	Commercial printing
4511	Certified scheduled aircarriers
4521	Non-scheduled aircarriers
4582	Aircraft service and repair
5300	Retail trade
6000	Banking
6100	Credit agencies
6300	Insurance companies
7333	Aerial photographic services
7395	Photofinishing
7399	Mapmaking and aerial surveying
7692	Weld shops
7813	Motion picture production services
7815	Still and slide picture production
8200	Educational services
	Health Establishment
8011	Offices of physicians
8021	Offices of dentists
8042	Offices of optometrists and opticians
8061	Hospitals
8071	Clinical medical laboratories
8922	Medical research institutions

lenses, refractometers, retinoscopes and others, plus a whole series of special devices for peering into the various orifices of the human body. Besides these ordinary devices, federal agencies or their contractors are supplied special products; e.g., to the FBI went a lens for a finger print analyzer and to the AEC similarly costly lenses for a laser-induced hydrogen fusion experiment. The industry supplies to the DOD the optical products to carry out its mission, like binoculars, telescopes, sighting-fire control-tracking devices, and to support its personnel, like the ophthalmic and medical devices. The Bureau of Census report quoted above shows 1972 sales of ophthalmic lenses of $190 million and non-ophthalmic lenses and instruments of $300 million, for a total in non-photographic lenses and instruments of $490 million.

Metal Products. This is a broad category which crosses industry lines; it includes the major industries which use radiography to non-destructively test their own metal products. Such products are formed by casting, forging, rolling, and other shaping processes; finished assemblies may be precision welded. A survey of industry (Hitchcock Publishing Company, Fall 1971) found 6,300 plants that use radiographic inspection of metal products. Those of primary interest manufacture castings, forgings, fabricated metal structures, pipes, valves, and fittings; produce turbines, generator sets, oilfield machinery and equipment, motor vehicles, aircraft and ships (see Table 1 for SIC categories).

The information transfer from this group of industries in primarily into those firms which buy the products that are radiographically inspected; the measurement capabilities consist of densitometers for the measurement of photographic densities on radiographs. The companies in this category supply the Commercial-Institutional sector with manufactured goods; aircraft, pipelines, nuclear reactor pressure vessels and components, ships, and the like. To DOD they supply ordnance: missiles, aircraft, tanks, small arms, and the rest. To the general public, in the main, go automobiles. The volume of product generated by this sector is large. It is practical to cite only some examples of metal products subjected to criticial radiographic inspection; Department of Commerce data (Current Industrial Reports, MA-38B(1)-1, 1973) show completed aircraft sales for one year of $7.6 billion and guided missile and space vehicles sales of $4.6 billion; AEC data from that source indicates $64 billion awarded in contracts between 1965 and 1973; for the construction of nuclear reactors; an American Petroleum Institute report

Table 3: 1972 Shipments of Non-Ophthalmic and Non-Photographic Lenses and Lens Instruments

Instruments	No. Firms[1]	Shipments ($ millions)
Binoculars	2	5.0
Alignment and Display[2]	3	
Test Equipment[3]	5	35.8
Lenses and Components[4]	27	51.0
General[5]	14	92.3
Sighting and Tracking[6]	33	95.8

1. Companies with reported shipments over $100,000 in the year.
2. Except photographic.
3. Including standard sources, modulators, microscopes, comparators, interferometers.
4. Including mirrors, filters, gratings, reflectors, coatings, light amplifiers, etc.
5. Excluding analytical instruments.
6. Made from lenses produced in plant and purchased.
(Source: U.S.Department of Commerce, "Current Industrial Reports, MA-38B(72)-1.)

("Petroleum Facts and Figures", API, 1971) points to $600 million in new pipeline constructed annually.

The Testing and Standards Laboratories category is an adjunct to the Metals Product group. These are independent companies which perform radiographic inspection as a service. either in their own facilities or, as in the case of aircraft inspection, on site. They appear is SIC 7397. Their measurement capabilities are like those of the Metal Product entries. No dollar value has been attributed to them since these same companies very often perform NDT which does not involve radiography.

Commercial and Industrial. This category includes those organizations which use the products of the photographic, optical and metal industries in order to supply services and goods to people. Those specifically mentioned have been identified as measuring optical image properties either in the course of a service they provide or in testing what they procure:

*Photofinishing labs, motion picture production facilities, still and slide picture producers, commercial photographers, and television broadcasters;

*Graphic art and design companies, lithographic and gravure printers, phototypetypesetters, photocopying and blueprinting establishments;

*Microfilm recording and developing services and a host of microfilm users, some important ones being in retail trade, banking, credit, insurance, and educational services;

*X-ray radiography users outside manufacturing, including scheduled and non-scheduled aircarriers, aircraft service and repair facilities, pipeline operators, and natural gas and electric utilities.

The measurement capabilities of these establishments fall into three categories: users of commercial transmission densitometers such as the photofinishers, photographers, and radiographic inspectors; users of commereial reflection densitometers such as the graphics arts group; and users of test standards with specific instrumentation such as the microfilm users for resolution charts and the television broodcasters for reflection density grey scales.

The output of this sector is product and service, not measurement information, and an estimate of the total cost of these services has not been made. Just to hint at the magnitude, some data for photo services:

A private market study (The Photographic Industry, Arthur D. Little Inc., 1971) estimated that amateur photofinishing, 40% of which was handled through drugstores, cost $400 million; microfilm services $250 million; professional still photography like wedding pictures, portraits and industrial applications, $145 million.

Health Establishment. This category is primarily based on those portions of the health care service devoted to either supplying prescription spectacles and contact lenses or to x-ray examination. By SIC grouping, it includes; physicians (either ophthalmologists or radiologists), dentists, optometrists and opticians, hospitals, clinical laboratories and medical research facilities, and the general group of medical people who use optical instruments. The category also includes the professional associations like the American Medical and Dental Associations, the College of Radiology, etc.

The measurement capabilities of eye examiners have been described in section 2.3; those of medical radiology vary from the research installation which extracts quantitative data from radiographs by densitometry to the ordinary hospital x-ray lab in which subjective judgments of density are apparently the norm. Information flow from the medical community to the film manufacturers and standards bodies like ANSI is primarily via their professional organizations like the medical and dental associations. The product delivered into the public sector is eye care and diagnosis of abnormal conditions like tooth decay, bone fractures, and pathological conditions. The dollar value of product is large. A private corporation compiled data from a 1970 U.S. Public Health Survey, from the American College of Radiology and from the Bureau of Public Health Insurance; they reported in a confidential proposal to the National Science Foundation that the cost of non-dental medical x-rays was between $2 and $4 billion. An undocumented reference in the popular press (Parade Magazine, Dec. 13, 1973) gives the cost of eye care at $2 billion. For perspective, the Department of Commerce estimate of the total cost of health care for 1973 was $97 billion (Current Industrial Reports, MA-38B (73)-1).

The Instrumentation Industry has been described above. In summary, the instruments range from densitometers (reflection and transmission), microdensitometers, interferometers, lensometers, spherometers, and MTF devices to all the loose lenses, light sources and components from which to build a test apparatus.

The industry has high input into the scientific literature and standards committees. It overlaps with the photo and optical industries; its measurement capabilities are the same. One densitometer manufacturer (like one photographic) has an apparatus for fundamental measurement of optical density. Standards and densitometers are supplied to radiographic people in the metal products sector. The entire range of people who do photographic processing, and to the commercial printers; special densitometers used in chemical analysis go to the health and commercial sectors. Optical equipment including test lenses and lensometers go to the health establishment; a great deal finds its way to the photo and optical industries. Product shipments annually amount to $4 to $6 million in densitometers and $35 million in optical test equipment Table 7.

Central Standards Authorities. The National Bureau of Standards contributes to the system by calibrating the master test lenses of ophthalmic goods manufacturers, providing optical density standards to photographic manufacturers and others, issuing the test charts which are the microfilm industry's standard, performing high accuracy lens tests, and supplying density standards to vendors who need to meet certain military and/or health and safety regulations. The U.S. Geological Survey calibrates aerial cameras for people doing business with the state highway departments, the Department of Agriculture and other federal agencies; these are basically distortion measurements.

The General Public has input to the system through consumer groups on standards committees, through public hearings on federal agency operations, and as customers of commercial, industrial and health facilities.

2.5.2 Highlights of Major Users

The measurement system in imaging optics is a complex one. Different people measure different things for different reasons with different people looking over their shoulders. Only a few examples can be cited.

Refractive power; spectacles. If you are not one of the 100 million people who already wear glasses or contact lenses (HEW Report No. (HRS) 75-1520), you may eventually need them. For an eye examination you go to a medical ophthalmologist or a non-medical optometrist. The former is always licensed by the state because he's an MD; the latter only in some states. While you're looking at an eye chart, the examiner places lenses from a test set before your eyes until you can read the little letters. The test lenses are calibrated by the manufacturer of ophthalmic goods who supplied them. The examiner can measure the refractive power of the lenses on a lensometer or spherometer in his office. The devices are factory-calibrated. The examiner writes a prescription for lenses equivalent to the ones that worked best for you. The prescription is filled by a dispenser, either through the examiner or a non-licensed dispensing optician. The lenses can be fabricated by either a large optical company or by a small laboratory which obtains the unfinished lenses from a large company. In either case, the same basic equipment is used to measure refractive power (see section 2.2.2.2 for instruments and 2.3 for accuracies). The lensometer is very likely from a company which has master test lenses calibrated by the National Bureau of Standards. The dispensing optician, the laboratory which ground the lenses (either the small lab or the large optical company) and the examiner use basically the same instruments. There is a voluntary industry standard for first-quality prescription lenses. The federal government only requires that safety glasses be resistant to shatter. So you get your glasses and wear them. They may be fine; they may not. By means of a private communication to NBS, an Associate Director of the Optometric Center of New York reported that of 2270 patients' ophthalmic materials examined in 1973-4, 50% were of unsatisfactory performance due to fabrication: lenses either ground or set into frames improperly.

Transmission density; photography. When you use a camera that has different shutter speeds and lens openings, you must take into account the speed of the film to set the exposure. On the film package is an "ASA number" which tells the film speed: like 25 or 64 or 3000. ASA stands for American Standards Association, the former name of the American National Standards Institute (ANSI); this organization has written standards which describe the conventional ways to determine how much light is required to produce a certain density on the film (see section 2.1). All the photographic companies which manufacture or market film in the U.S. use the convention. (see Photographic Industry in section 2.5.1).

You set the camera, shoot a roll of film, and take it to the drugstore which sends it out to a photofinishing laboratory for processing. The processor develops the negatives and makes prints. In monitoring the development process he measures the photographic density of the negative with a densitometer. To calibrate the densitometer he uses a photographic step tablet; one had come with the instrument and he bought more from a photo company.

The company which manufactured the film and those which produced the step tablets use densitometers and step tablets in the same way as the processor. In addition, the manufacturers use them as tools in research, production, quality control and the basis for the assignment of ASA speed ratings of film. All major domestic producers of film and the two dominant foreign firms which sell in the U.S. have photographic density step tablets from the National Bureau of Standards. Voluntary use of the standards provides a basis for uniformity of measurements and may lend credence to product information; it also aids the U.S. firms in their marketing to any foreign consumers who prefer that measurements be traceable to a governmental authority.

So you got your prints back from the drugstore and maybe they're not too good. It's probably your fault.

Transmission density: aircraft. The commercial airliner in which you travel has had non-destructive testing (NDT) quite a few times. The plane itself probably gets a thorough inspection after every 6000 hours of flight; specific parts more often. If aircraft of the model you're in have been involved in accidents due to structural failure (that's rare), the FAA might have issued an Administrative Directive requiring frequent radiographic inspection. The inspection takes place in the airline's facilities or at an independent service and repair station. The inspector is certified by the FAA. He may be an employee of the airline, the repair service or NDT test laboratory. The x-ray film comes from the manufacturer marked with a general speed classification.

The aircraft was also inspected during assembly by the manufacturer. The FAA requires that an NDT procedure be developed during the plane's construction and manuals describing it go to the purchaser of the plane. The castings and forgings of parts like turbines, airframe, landing gear, etc., were inspected during their manufacture, either at the plant or in a NDT test lab.

The same companies which manufacture the passenger transport aircraft for the airlines also manufacture the aircraft for the military. Radiographic inspection processes are the same in each case; the density on a radiograph is checked on a densitometer calibrated with a photographic density step tablet. The DOD formally requires that densitometers be calibrated with step tablets from the National Bureau of Standards; the FAA has similar requirements.

The effectiveness of federal safety standards regarding the structural integrity of aircraft is evident in statistics complied by the National Transportation Safety Board, and independent federal agency responsible for the investigation of aircraft accidents. According to NTSB data for the years 1960 to 1969, fatal crashes of commercial airliners occurred at an average rate of two per million departures. In the period 1970 to 1974, only two fatal crashes of commerical aircraft resulted from structural failure due to any cause; in the same period, an average of about 40 private planes per year were involved in fatal crashes due to structural failured.

An NTSB report on one particular private-plane crash shows the importance of careful radiographic inspection, including densitometric measurements of radiographs. According to the NTSB Accident Report (Air Iowa, Inc., Beech E183, N3IOWA, Davenport, Iowa, April 19, 1973, adopted October 3, 1973):

> "Air Iowa, Inc., Flight 333, a Beech Aircraft Model E18S, operating as a scheduled air taxi passenger flight, crashed into an open, plowed field about 1704 central standard time. April 19, 1973, while approaching the Municipal Airport at Davenport, Iowa, for a landing. The accident occurred approximately 3 miles southwest of the Davenport Airport. The pilot and five passengers were fatally injured. There were no injuries to persons on the ground. The aircraft was destroyed by impact forces; there was no fire".
>
> "The National Transportation Safety Board determines that the probable cause of this accident was the inflight failure of the right wing, which resulted from a preexisting fatigue crack in the lower spar cap of the wing at Wing Station 81. Although the fatigue crack existed and was discernible during inspections conducted over the 6-year period prior to this accident, it was not detected."
>
> "The procedures for detection of cracks in the elliptical front spar cap of the wing center section are outlined in FAA Amendment 39-1526 to Airworthiness Directive 72-20-5, effective September 29, 1972. The radiograph exposure of the X-ray film, also specified in this amendment, should be from 1.5 to 2.8 on the densitometer of the National Bureau of Standards density scale. The radiograph exposures of several of the X-ray films examined were found to be outside the allowable tolerances. The densities of this film ranged from 0.5 to 5.0. The procedures and densities specified in Amendment 39-1526 were also specified in the amendments issued before September 1972."
>
> "The Safety Board concludes that the concerned repair stations did not comply with the wing spar inspection procedures prescribed in the applicable airworthiness directives and that quality control of their inspection programs was practically nonexistent. As a result, the aircraft was flown with a detectable crack in the elliptical tube of the lower main spar at Right WS 81 until the crack became large enough to cause complete failure. Furthermore, there are no well-defined standards for certifying a repair station as a radiographic facility or for qualitying a technician for non-destructive testing."

Resolution: microfilm. Although anything from a credit rating to a birth certificate may be stored on microfilm, the average person has probably never seen any.

Microfilm is used in amny forms: 16 and 35 mm strips in reel, cartridge, and cassetts; sheets called fiche (like feesh), aperture cards (which are punched computer cards with microfilm windows) and micropaques (micro-images recorded on paper). Use falls into four major categories:

1) engineering documentation - graphs, drawings, and the like. Major industries in this category include transportation, construction, manufacturing, utilities and government.
2) security microfilming - for material that doesn't need updating but must be retained for "security" and historical purposes.
3) micropublishing - the placement of original documents on mircofilm for sale or the microfilming of published documents for resale (magazines, newspapers, catalogues, etc.). The Government Printing Office has begun a program to offer its publications on microfilm.

4) recordkeeping - the daily handling and processing of business information involving generation, storage, retrieval, dissemination and updating.

The users of microfilm are numerous and what they record defies categorization: legal records, birth and death certificates, auto registrations, manuscripts, books, doctoral theses, periodicals, medical records, x-ray radiographs, parts lists, catalogues, engineering drawings, the records of health and life insurance companies, banks, airlines, and manufacturers of all types. Many government agencies use microfilm, including the Library of Congress, Patent Office, HEW, AEC, NASA, DOD, as well as the National Technical Information Service.

The National Microfilm Association (NMA) is the trade association and standards body for the industry. This organization has adopted the National Bureau of Standards microcopy resolution chart for their recommended practice to evaluate cameras, readers, and processes; the NMA recommends that the resolution chart be photographed onto the first and last frame of each roll of microfilm.

Reflection density: gravure printing. The supplement to your Sunday newspaper is gravure printed as are hundreds of other things from catalogues to gift wrap. There are different kinds of gravure-printing but they're all photomechanical. Printing is done from a recessed image etched into a plate or cylinder; tiny wells of variable depth and size deposit ink onto a surface like paper or cloth. In their most recent survey (1971), the Gravure Technical Association questioned gravure press manufacturers, engravers, ink manufacturers and others; the consensus was that there were about 15,000 gravure press units in the U.S., not including textile printers. The same organization estimated that the dollar value of gravure printing in 1971 was $2.8 billion.

Reflection densitometers are used to measure the optical density of ink on paper; the language of densitometry is used to communicate between the photographer, the engraver, the printer, the ink maker, and the advertising agencies.

Reflection densitometers are calibrated using standards similar to photographic step tablets, that is, they have a range of tones. However, this tonal range may be in shades of grey or shades of color. The reflection standards are produced photographically or by ink printing; they originate from photographic manufacturers, densitometer manufacturers and other sources.

The grey standards are calibrated by applying the prescription outlined in an ANSI standard; the measurement is basically a comparison to something defined as white, like magnesium oxide as specified by an ANSI document or barium sulfate as endorsed by common industry practice.

3. IMPACT, STATUS, AND TRENDS OF THE MEASUREMENT SYSTEM

3.1 Impacts of Measurements

3.1.1 Functional, Technological and Scientific Impacts

To avoid a tedious enumeration of the many industrial, scientific, and medical applications of optical and photographic devices, a few of the more esoteric and unfamiliar examples in which quantitative data is extracted from film or lens devices and a few in which the higher grades of film or lens are used will be given.

Density variations are the information carriers in a film image. In the fields of astronomy, spectroscopy, chemical chromatography and photoreconnaissance, the variations are measured and information like star magnitudes, physical composition, chemical concentrations, and subject content derived. In medicine, a radiograph might be scanned with a densitometer to study bone decalcification. In holography, high grade film may be required, for example, to record finely detailed three dimensional pictures of biological structures; similarly, for holographic computer data storage devices.

Outside photography, precision lenses and non-plane mirrors (which are tested in similar fashions) are used in astronomy, in the manufacture of lasers, in holographic applications, in laser-induced fusion research, and in applications like photosensitive semiconductor memory devices. In semiconductor fabrication, both photographic techniques and the use of optical devices as measurement tools are routine and essential.

3.1.2 Economic Impacts - Cost and Benefits

Measurements of refractive power are essential to the manufacture of optical systems which use the focal properties of lenses. Spectacles cannot be prescribed or fabricated, a camera cannot be designed or built, without them. The DOC Office of Business Analysis reports (Optical Industry News, Aug. 1973) that total shipments of lenses and optical instruments in all industries amounted to $485 million. Cost of the measurements involved in this production have not been determined.

Similarly, measurements of optical density are fundamental to the design, manufacture and use of photographic materials. Total shipments of sensitized goods in 1970, $1.7

Table 4. Author's Composite of the Industrial and Medical Radiographic Measurement Systems of 1970.[1]

Facilities	Industrial	Medical[2]
Installations	6300	-
X-ray units	25,000	115,000
Radiographers	15,000	10,000
Technicians	-	90,000
Annual use		
Film	$29 million	$210 million
Equipment	$37 million	$96 million
Radiographs	70 million[3]	625 million
Cost	$350 million[3]	$4.2 billion

1. Sources of data for each entry cited in text.
2. Excludes dental personnel and x-ray units.
3. In-house estimate based on a comparison of film and equipment usage, personnel, and operating costs in the two fields.

billion; photographic equipment, $1.1 billion; cost of photofinishing services, $0.9 billion; total product involved, $4 billion. (Private market surveys by Arthur D. Little, Inc. and Predicasts, Inc.). Cost of measurement also is undetermined.

These two categories, lens and film, are most intimately connected with measurements of imaging properties; they are the basic manufactured goods. Some of the users of these products also do measurements.

An eye examination is a measurement of the refractive properties of the eye. The bill from the examiner who writes the prescription is the cost of his measurement, maybe $15. Since 100 million people wear prescription spectacles, it's a large overall cost for those measurements. Data on the cost of measurement in the manufacture of the $190 million worth of ophthalmic lenses sold in 1972 (see section 2.5.1) is unavailable.

In the field of industrial radiography direct measurement of the photographic density are made of x-ray radiographs in order to insure good image visibility. The Society of Non-Destructive Evaluation in a private communication to NBS estimated there are 15,000 industrial radiographers. A survey by the Hitchcock Publishing Company found 6,300 plants with 25,000 x-ray units using

Table 5. Profile of a Hypothetical Steel Foundry.

Company name:	The Hypothetical Steel Foundry*	
Annual sales:	$1 million	
Products:	Steel valves, flanges, pumps	
Customers:	Nuclear reactor, refinery, and power plant builders.	
Inspec. Code:	ASME BPVC, Sections III, VIII.	
Equipment:	Xray sources-300kv tube	$10k
	-Iridium 192	$4k
	-Cobalt 60	$5k
	Manual darkroom	$5k
	Accessories	$2k
	Shielded room	$10k
	Densitometer	$1k
Personnel:	Acceptance judge	$15k
	Interpreter	$10k
	Technician	$6k
Radiographs:		10,000
Film Cost:		$15k
Equipment:		$37k
Film:		$15k
Salaries:		$30k

*Formulated by a manager of a radiographic training center.

the technique. The survey of the photographic industry shows $65 million dollars worth of film and equipment were bought in 1970. An in-house estimate (based on film consumption) is that between 45 and 90 million industrial radiographs were made in that year at a cost of $350 million (Table 4).

Some of the products directly affected by these measurements in years for which we can give data are: the 9,000 miles of natural gas pipeline costing $600 million built in 1970 (API Petroleum Facts and Figures, 1971) the 16,000 aircraft costing $7.61 billion completed in 1973 as well as $4.6 billion worth of guided missiles, launch and space vehicles and the 180 central station nuclear reactors for which $64 billion in contracts were let between 1965 and 1973 (Current Industrial Reports cited above).

To see what the cost benefit of a single densitometer measurement of a radiograph is, we asked the manager of a radiographic training center to sketch a "Hypothetical Steel Foundry" which makes cast components

Table 6. Cost of a Single "Traceable" Measurement at a Hypothetical Steel Foundry.

NBS Step Tablet	
Initial	$72.00
Annual (depreciated over 2 yrs)	$36.00
Per radiograph (10% of 10,000)	$ 0.04
Densitometer	
Initial	$1,500.00
Annual (depreciated over 5 yrs)	$300.00
Per radiograph (10% of 10,000)	$ 0.30
Calibration of Densitometer	
Annual (salary & overhead)	$300.00
Per radiograph (10% of 10,000)	$ 0.30
Film	
Annual	$15,000.00
Per radiograph (10,000)	$1.50
Salaries	
Annual	$30,000.00
Per radiograph	$3.00
Overhead	
Annual	$45,000.00
Per radiograph	$4.50
Total per "traceable radiograph"	$9.64

for nuclear reactors. The company has radiographic equipment costing $35,000, including a $1,000 densitometer. With an acceptance judge, an interpreter/technique formulator and a technician, its salary costs in 1973 were $30,000. It does $1 million in business and makes 10,000 radiographs a year. The cost of the radiographic measurement is $10, including salaries, overhead, the film and the densitometers; not the big x-ray equipment. One densitometer measurement is on the radiograph of a flange (see Tables 5 and 6).

An article on NDT (Materials Evaluation, May 1973) describes the intent of that measurement. A central station nuclear reactor of 1000 Megawatt capacity is described as having a down-time cost of non-operation of between $100,000 and $200,000 per day. For a simple part breakdown, like a broken flange, time and materials for part replacement *per se* may be $10,000. But where the repair work is hindered by residual radiation as well as loss of primary coolant, cost of clean-up, shielding and additional personnel must be counted. Total cost of replacement of one faulty flange would be about $250,000.

To avoid this cost (flange failure) the facility owner may follow a code which prescribes the use of licensed welders and radiographic inspection. For this avoidance procedure to be worth its cost the probability of flange failue should be reduced by the procedure to the point where the return on expected avoidance just equals the marginal cost of preventions. One of these latter costs is the $10 one estimated in Table 6 for traceability of film density measurement to NBS. Presumably this cost "pays its way" in avoidance, but by exactly how much is not known.

In the field of medical radiology, subjective measurements of photographic density are made by physicians and dentists. Market surveys identified above show 1970 sales of medical x-ray film of $210 million and equipment of $96 million. There are about 115,000 diagnostic x-ray units in place. A confidential proposal to the National Science Foundation analyzed the cost of measurement for the year 1970. In a medical system consisting of 10,000 radiologists supported by 90,000 technicians, 325 million medical x-rays were taken of 110 million patients at a cost (fees, supplies, depreciated equipment, and overhead) of $3.9 billion; another 300 million x-rays were taken by dentists at a cost of $0.3 billion. That comes out to $12 for a measurement on a leg (Table 7) and $1 for a measurement on a mouth.

The same surveys of the photographic industry quoted above show primary equipment and film sales in the microfilm industry of $280 million. Equipment sales and rentals totalled $78 million in 1970; the 1972 report predicted this would rise to $450 million in 1975. Astronomical growth was projected for the whole industry (see Table 7). The cost of measurement includes the price of the resolution chart and the cost of recording its image on the film; at $14 for test charts with a lifetime of say 2 years, the standard costs 2 cents a day. The cost of measurement is in the processing. Microfilm systems are the end of the line of product and the beginning of the line of information service; the value of those services is considerable.

3.1.3 Societal, Human, Person-on-the-street

Measurement makes possible the design of optical systems with predicable behavior and measurement provides for efficiency in manufacture, interchangeability of parts, product reliability and consumer confidence.

In the prescribing and manufacture of spectacle lenses, good measurement of refractive power leads to a product which improves an individuals vision. The benefits are the comfort, happiness and productivity of the wearer.

In the manufacture of photographic goods, precision measurement of photographic density leads to innovation and reliability. The benefit is a consumer more confident in the film than in his camera technique.

In industrial radiography, measurement of transmission density yields radiographic

Table 7. Estimated Cost of Medical X-rays for 1970.

Cost Component	Cost[1] $ millions	Cost/x-ray[2] $
Radiologists' fees	858	2.64
Technicians' wages	702	2.16
Film & development	390	1.20
Supplies & equipment	624	1.82
Overhead	1170	3.60
Amortization	156	0.48
Total	$3900	$11.80

1. Estimate based on Public Health Service, American Medical Association, and Bureau of Medical Insurance data, as reported by a private organization.
2. For an estimated 325 million medical (non-dental) x-rays.

images that tell something about the structural soundness of parts. The economic benefits are reduced processing of inherently faulty materials, improved workmanship, and product reliability. The societal benefit of structurally sound civilian and military aircraft is lives saved. Similarly, in medical radiology, a benefit is the early detection of a faint shadow on a lung.

Finally, advanced measurement techniques in lens testing and image analysis contribute to innovations in the design of optical systems and improved control in their manufacture. The benefits are an earth resources satellite camera which gives information on crop conditions, weather forecasting, ocean currents, mineral deposit formations; and photoreconnaissance systems, which give intelligence data on strategic weapons deployment and tactical troop activity.

3.2 Status and Trends of the System

Were it possible to convene a session of standards committee chairmen and members, employees of the regulatory agencies involved, manufacturers of photographic goods, instrument makers, workers in the field of imaging optics, and market analysis, a synopsis of their judgments and opinions might sound like this:

Photography: In terms of ordinary film processors, current ranges of density on photographic tablets are fine. They have, however, problem with low photograph densities; commercial densitometers use opal glass in the light collection system instead of integrating spheres. This results in small discrepancies between what the instrument reads and what standards calibrated with the other method say. A draft ANSI standard to update PH2.19 gives equal status to both methods. New primary calibrated standards are required. The photographic manufacturers need an extension of the range of standards to higher densities with better precisions at the lower. Projections for industry growth as given in a private market survey (Predicasts, Cleveland, 1972) show total industry sales growing from $4.4 billion in 1970 to $16 billion by 1985.

Radiography. The present range and precision of photographic densities meets the current and expected needs of radiographers in general: A Standard Research Institute report predicts that the resolution and sensitivity levels now demanded in critical industrial radiography will become industry-wide practice by 1980. The use of radiographic NDT is expected to grow rapidly; the photographic market survey mentioned above projects industrial x-ray equipment and film sales to rise from the 1970 level of $65 million to $150 million in 1980. In medical radiography innovative practices are being introduced. Microfilming of radiographs for record keeping has begun; it is not thought that the microfilm images are being used for original diagnosis or reevaluation. Were this to be done, it would facilitate "packaged" medical histories, including radiographs, which follow a patient as he moves geographically. Advances in digital and optical (Fourier transform) computer technology, combined with techniques derived from aerial reconnaissance optics, has led to a system for machine reading of medical radiographs. It has been asserted that if preliminary evaluation of x-rays be machine could reduce by 50% the time required for a physican to scan a chest x-ray, a savings to society of $75 to $200 million could result (see Table 9 for calculation and source). The 1970 sales of medical x-ray film and equipment amounted to $305 million with $585 million anticipated for 1980 (Table 8).

Graphic Arts. People in this industry are getting by on what reflection density standards are available. Their needs are mixed; some need a true grey scale (black and white), some need color tone scales. A study of reflection densitometers as used in the gravure printing industry (Miles Southworth, Gravure Technical Association, 1972) showed they performed well; he pointed out that reflection standards were not available from NBS. A recent development in the industry is the introduction of the Universal Product Code which allows machine-readable package labels for use with automated point-of-sale equipment. At least one photographic company sells reflection chart standards for UPC printing control. The retail associations are mixed in their feelings about the need for technical support from the federal government. Graphic arts photographic equipment (process cameras and phototypesetters) are expected to rise from $67 million in 1970 to $335 million by 1980; in the same period, photocopying equipment revenues (purchases, rental, lenses) have been predicted to go from $1.1 billion to $2.6 billion (Table 8).

Microfilm. Industry people are happy with the Microcopy Resolution Chart itself, but not too happy about its price. The range of spatial frequencies is more than adequate. If the medical people start microfilming radiographs in any numbers, the volume of users could increase. A recent development: the draft ISO standard which gives coequal status to the NBS Resolution Chart and the French Mire Target is nearing adoption. At present, only the French Chart has official status. The Mire chart has been touted as a superior test of legibility but a British Standards Institute worker has given substantial technical evidence to the contrary. (The British Standard, BS4310-2.1-1970, specifies the NBS Microcopy Chart as a standard).

A new development in automation of microfilm systems is the Computer Output Microfilm (COM) system. COM system consist of a cathode ray tube display and a high speed microfilm camera. They can transfer data from magnetic computer type onto microfilm at a rate of 90,000 characters per second. The Navy Printing and Publications Service has a COM system worth $250,000 that handles 5 million pages of data per year. COM equipment sales were 30% of microfilm equipment sales 1970 and are expected to approach 70% by 1985. Primary microfilm equipment and film sales were $280 million in 1970 with a projected increase to $1.3 billion by 1980 (Table 8).

Lens Testing. Two documentary standards, ANSI Z80.1 and Z80.2, apply to prescription lenses. Manufacturers and dispensers have available to them the means to execute the provisions of these standards. The formation in 1971 of a committee under the auspices of ANSI PH3.2 on Photographic Apparatus has not resulted in a written standard on lens testing. One producer of medical and industrial x-ray units describes the effect of this situation of his operations; 80% of the units he manufactures have CRT displays with lens systems and image intensifiers; he buys the lenses from two foreign firms and tests them with MTF equipment from a third; he adds that the MTF device has become his standard. A somewhat bewildered physician reports that he can find no documentary standard or test standard for evaluating the microscopes he procures for a medical research lab. Since the resolution limit of a microscope may be as high as 2000 c/mm and non-silver halide photographic materials with resolution limits above 1000 c/mm are available, there is room for progress in this region of testing and standardization. Sales of passive optics (lenses, spectacles, binoculars, etc.) have hovered around the $500 million mark for a few years. Optical microscopes advanced in sales from $10 million in 1969 to $15 million at the present.

Table 8. Approximate Values of Shipments of Some Optical & Photographic Equipment.[1]

Products	Shipments ($millions) 1970	1980
Densitometers & allied devices	6	-
Optical test equipment	35	-
Industrial x-ray	66	150
Graphic arts	67	335
Ophthalmic lenses	190	-
Microfilm	280	1275
Medical x-ray	305	585
Optical lenses & instruments	500	-
Motion picture	548	1224
Still picture	1072	2860
Photocopy equipment[2]	1090	2610

1. Data for optical equipment based on Department of Commerce figures cited in the text; no 1980 projections included. Photographic film and equipment data based on market survey by Predicasts, Inc., Cleveland, 1972.
2. Includes sales, leases, and rentals.

The growth part of the industry is involved with active devices in which the image is observed not by a human eye but an electronic detector: such systems as optical character readers used at present in sorting mail, read-heads for point-of-sale computer systems now in use in supermarkets, and "optical computers" which analyze images such as in the automatic chest x-ray scanner described above and in devices like a finger print scanner the Federal Bureau of Investigation has acquired. Economic data on these systems is inseparable from the overall optoelectronics market which includes light sources and detectors. A private survey of this field found shipments of $106 million in 1972 and projects growth to $265 million by 1978 (Frost and Sullivan, Inc., New York, 1973).

Table 9. Effect of the Semi-Automation of the Examination of Chest X-rays.[1]

Number of x-rays	150 million per year
Rate of inspection	15-30 per hour
Time consumed	5-10 million hours
Increase in rate by semi-automation[1]	50%
Time saved	2.5-5 million hours
Cost of radiologists' time	$30-$40 per hour
Value of time saved	$75-$200 million

1. Computation reported by a private organization to the National Science Foundation.
2. Preliminary selection of radiographs which have signs of pathology; final judgment by radiologist.

4. SURVEY OF NBS SERVICES

4.1 The Past

The National Bureau of Standards, an agency of the U.S. Department of Commerce, was founded shortly after the turn of the centory by an act of Congress. Its mission, to provide technical support to industry and the federal government, is spelled out in that act. NBS became active in optics around that time when a worker at NBS did basic studies of the commercially available photographic materials. Shortly after World War I, NBS began calibrations of "airplane cameras" for the U.S. Army. Filters to reproduce sunlight and daylight in the laboratory, the so-called Davis-Gilson filters still in use today, were developed at NBS and adopted by the International Congress of Photography in 1928 and the International Commission on Illumination in 1931. An NBS worker in the 1930's introduced the "gamma-bar" bar" method for film speed classification. The NBS Microcopy Resolution Chart, initially intended in the 1940's for the specification of federal contract work, became an industry standard. Work on photoresists and high resolution microphotography drew scientists and engineers from every segment of the electronics industry in the late '50s and early '60s to discuss the photoetching which revolutionized the industry and to see the extremely high resolution camera NBS developed for testing the resolving powers of photographic materials. The concepts, terminology and notation for photographic densities to be incorporated fully in a new ANSI standard were proposed by an NBS worker in the late '60s.

Since that time, photographic sciences have been discontinued, aerial camera calibrations have been transferred to another agency, and program in optics have been directed toward the application of optics to problems outside the field. The changes reflect a general trend at national laboratories, at home and abroad, away from "optics" in the classical sense.

4.2 The Present - Scope of NBS Services

4.2.1 Description of NBS Services

Traced on an NBS organizational chart, a pointer following lines of management would move down from the Institute of Basic Standards, through the Mechanics Division, and come to rest on the Optics and Micrometrology Section, the present home of the work in imaging optics.

Parts of six people, that currently add up to 3 1/3 full-timers, work in the field. One is a voting delegate to ANSI Committee PH2 which deals with sensitometry in general the same person is a technical representative on PH2.19 which developed the new standard on photographic diffuse density now under consideration by PH2. Another person is on the ANSI PH2 Work Group on Microdensitometry and a third on a PH3 Task Force on Optical Transfer Function; these latter groups are doing the spadework on the development of standards in their respective fields of optical system testing.

The important measurement instruments at at their disposal include:

*an inverse square bar (see section 2.2.2) for the fundamental measurement of photographic density and the primary calibration of transmission density standards; the device operates over the range of densities 0 to 4.25 with accuracies of 0.005 or 1/2 percent which ever is greater.

*two commercial transmission densitometers for the transfer of densities to secondary standards. One model uses an integrating sphere for light collection; the second, which digitally displays densities in the range 0 to 1 to 0.001, uses opal glass. The range of both instruments compares with the range of basic measurements; they transfer measurement with a resulting accuracy of 1%.

*a commercial reflection densitometer used to compare secondary standards to ceramic plaques which require calibration outside the section. The range of the densities on the plaques is 0 to 2.33, with accuracies or ± 0.01 or 2%.

*a wavefront shearing interferometer (WSI) developed in the section, for testing lenses and lens systems; the WSI currently yields on-axis monochromatic pupil function, MTF, OTF, and maximum aberration measurement for optical devices with f numbers above f/2; in spatial frequencies, its range of measurements for the first three quantities is 0 to 2000 c/mm. Aberrations are measured with repeatabilities of 0.03 of the wavelength of light.

*four commercially produced scanning microdensitometers for the evaluation of photo images; one has automatic scanning and is interfaced with a computer and magnetic tape system. It has the capability to resolve density differences of the order of 0.001, to record data derived at intervals on the film of 1 micrometer, and to resolve up to 200 c/mm.

*plus measurement microscopes for the examination of microcopy resolution charts, the usual light sources, collimators and optical benches used for refractive power measurements, and MTF instrument and a Twyman-Green interferometer (both noncommercial) for general lens testing, and the assorted hardware and optical components associated with interferometry and optics in general.

The devices are the basis for the calibration of the standards which NBS distributes:

*SRM 1001 - a double emulsion blue-based x-ray film tablet with transmission densities from 0 to 3 in 21 steps.

*SRM 1008 - a single emulsion neutral grey photographic tablet with densities from 0 to 4 in 21 steps.

*SRM 1009 - a tablet similar to the 1008 with densities from 0 to 3.

*SRM 1010a - the NBS Microscopy Resolution Chart, with 21 patterns with spatial frequencies ranging from 1 to 18 cycles/mm.

Density standards, both reflection and transmission, submitted by users are also calibrated. Similarly, lenses sent to NBS are calibrated for focal length and refractive power or tested for wave-front properties as requested. Density measurements conform with the basic definitions given in ANSI PH2.19 and, through these, with ISO specifications; the microcopy resolution chart, designed by and manufactured for NBS, is the domestic industry standard and is in the process of becoming an ISO standard; no documentary standards define lens properties or specify the means of their measurement.

Besides routine calibrations, the people and the equipment are involved with activties directed toward improved standards and standard measurement techniques:

*A new primary calibration facility, based on a novel approach to the measurement of photographic density, is being developed which will extend the range and increase the accuracies of the transmission density standards NBS provides.

*The WSI with its proven capabilities for easy and precise lens testing is being tailored for use on a variety of optical systems and its computer system for data acquisition is being implemented.

*Physical standards for testing the dimensional - measurement properties of optical and electron microscopes are being developed; a supportive study of the effects of eyepieces and stage illumination of light microscopes on these properties is being made.

*Special prototype artifacts for the evaluation of high performance photographic and optical systems are being produced; along with the production of the artifacts, the theory related to their use and to optical performance testing in general is being analyzed and applied.

The purposes of these projects are dual in nature. In a limited sense, they are to provide physical standards and measurement services and to maintain the requisite competence. In a broader sense, they are to fulfill parts of the overall NBS mission; namely, to aid industry in general and to satisfy the measurement needs of federal agencies.

In the field of imaging optics, NBS provides physical standards directly to individuals and private organizations who have one or both of two reasons for acquiring them; first, to satisfy a desire to refer their measurements to an objective, competent and authoritative source; second, to satisfy the requirements of federal agencies with whom they do business or which regulate them: specifically, DOD, NASA, AEC, FAA or DOT. (See section 2.4.4). NBS measurement services outside the provision of standards are used by private organizations which act from the first motivation.

The standards, testing and consultation which NBS provides to federal civilian and military organizations similarly falls into two categories; that which is needed in matters of procurement and that which is needed in matters of mission. Specific details of the relationship of private and governmental organizations to NBS standards and measurements will be analyzed in section 4.2.2, where users are identified.

The output of NBS in imaging optics is varied. In round numbers, 10,000 microcopy charts are distributed annually and 200 photographic density step tablets; 40 or so density standards submitted by users are calibrated; 2 or 3 primary calibrations of transmission density are performed for users as well as 2 or 3 reflection density calibrations.

Conventional lens testing declined sharply with the transfer of camera and photographic lens testing facilities to the U.S. Geological Survey. A series of papers consisting of 12 or so journal articles and 10 NBS technical notes on interferometric lens testing, the theory of diffraction and interference effects in optical systems, and microdensitometry (leading to a recent article on state-of-the-art measurement and theory), laid the groundwork for the interferometric lens testing service introduced in fall of 1974.

The benefit of this activity in optical testing has gone primarily to civilian and military agencies. Ten interferometers were fabricated for an AEC prime contractor, extended consulting and in-house testing of optical systems have been done for others. A handful of lenses and sets of lenses from private companies have been received. Information transfer to and from NBS, independent of this study, has been via the standard committee activities, the scientific journals and meetings, and in-depth study of the optical measurement requirements of the semiconductor industry (part of a larger Advanced Research Projects Agency study of their overall needs), attendance at three concentrated academic courses in optics, a training course provided by NBS to users on the theory and practice of microdensitometry, interaction with the Council on Radiation Measurement (an NBS sponsored users group) as well as the usual give-and-take between NBS and the users of its services.

4.2.2 Users of NBS Services

NBS records show that in one eighteen month period, 300 photographic density standards were distributed: 39 to manufacturers and service companies in photographic and graphic arts production, 189 to firms doing industrial NDT, 21 to government agencies, and 51 to users in assorted fields as shown in Table 10. Three received primary calibrated standards: a photographic manufacturer, a maker of densitometers and a defense agency.

In a period of the same duration, nearly 15,000 microcopy resolution charts went to about 200 organizations: 13,200 to private commercial and institutional users and 1800 to government agencies. In 1973, 30 domestic suppliers of microfilm, microfilm equipment and photocopiers received 60% of the charts; one of these companies also distributes charts it receives.

For a similar 18 month period, 10 WSI interferometers, designed and fabricated by NBS, were shipped to an AEC prime contractor: a set of 100 or so master test lenses were calibrated for an ophthalmic goods manufacturer; a set of four for another; a $20,000 lens was tested for a federal law enforcement agency; a similar lens for a semiconductor manufacturer; special sine wave and edge targets were supplied to 15 companies and a number of special studies were performed for federal agencies. In the period 1971-4, these included:

*the evaluation of a $2 million microfilm system the Patent Office was in the process of procuring; the testing resulted in the settlement of a dispute between that agency and the manufacturer of the system over the performance specified by the contract; happily,the system was show to perform properly

*testing for the Postal Service of binoculars sold by mail to determine the possibility of fraudulent advertising of the binoculars' performance capabilities

*provision of test materials and consultation in a law enforcement program study of the correlation of the 'identifiability' of persons in photographs with machine-measured characteristics of the photographs (NBS Report LESP-RRT 0303.00)

*the evaluation of the optical system which NIOSH (see section 2.4.4) uses to monitor the output of manufacturers of safety goggles and eyewear

*consultation on the specification of telescopes and image intensifiers for a system of remote visual observation of Postal Service trucks during loading and unloading (NBS Report 10-967)

*the redesign and testing of a commercial terrestial telescope for a civilian intelligence agency

*extensive analysis of the operation of a microdensitometer being procured by the Department of the Air Force, including development of performance specifications, supply of test materials and the overseeing of testing

*confidential design work and testing of a special photographic printer which was in the process of being developed by a vendor for a government security agency *extended consultation on some security-classified programs of the defense department which involve high performance optical systems, their design, specification, evaluation and use

*the provision of standards and consultation to the FDA's Bureau of Radiological Health for their program of monitoring the performance of medical x-ray image intensifiers

The manufacturers of photographic goods (See in section 2.5.1, "Photo Industry") are major users of NBS standards. Table 11 shows the nine domestic companies which represent 97% of film sales and 80% of all equipment sales in 1970, (Predicasts, Inc., Cleveland, 1971); also shown are the two foreign film companies which picked up the bulk of the 3% remaining of film sales. All eleven companies (save one photocopier manufacturer) procured NBS density standards in the 18 month period; all eleven procured microcopy resolution charts; seven of the nine domestic companies have been supplied with edge and/or sine wave targets. In general, the standards are used on a voluntary basis: the density standards relate to the evaluation of film performance and the designation of film speeds on the basis of revelant ANSI standards; the microcopy resolution charts find use in testing resolution in general.

Table 10. Users of NBS Photographic Density Standards.

Product or Service	SIC	Share[1]
Photographic products	3861	12.4%
Printing & graphic arts	2751	5.8
Aerospace systems	3721	11.8
X-ray & radiation equipment	3693	10.6
Castings & forgings	3300	8.9
Turbine, boiler, reactor	3511	6.2
Precision welding	7692	3.7
NDT test labs	7397	6.5
General research	-	3.5
Other	-	16.5
Government agencies	-	11.3
Foreign consumers	-	2.7
		100%

Organizations which purchased NBS photograhic density standards in the period 6/71 to 12/72, grouped according to their product lines as described in the Thomas Index of Manufacturers.

1. Share of the NBS standards delivered in the base period.

The second major class of density standard users are those involved in radiographic NDT. (see "Metal Products" in section 2.5.1).

Table 11. NBS Standards by Kind Supplied to the Major Manufacturers of Basic Photographic Products.

Major U.S. Photographic Product Manufacturers				Calibration Items Received from NBS[3]		
Co.	Sales ($mllns)	Products Film	Equip.	Den. Stds.	Resol. Chrts.	Spec. Trgts.
A	1200	*	*	*	*	*
B	1000		*		*	*
C	350	*	*	*	*	*
D	350	*	*	*	*	
E	190	*	*	*	*	*
F	150		*	*	*	
G	150	*	*	*	*	*
H	75		*	*	*	*
I	70	*	*	*	*	*
J[2]	-	*	*	*	*	
K[2]	-	*	*	*	*	

1. According to the market survey from which the economic data is taken (Predicasts, Inc., Cleveland, 1972), the first nine companies represented 97% of film sales and 80% of overall photographic equipment sales.
2. These companies are the major foreign suppliers to the U.S. film market.
3. Based on NBS internal records.

This group included, among others, for the 18 month period:

*the "big five" manufacturers of nuclear reactors

*5 of 6 manufacturers of commerical passenger and cargo transport aircraft

*all 8 aircraft turbine engine manufacturers

*all of the makers of airframes and rocket engines for the 62 missile systems produced in 1973 (Table 12)

*all of the makers of the military and civilian space vehicles and launchcraft

*two prime contractors of nuclear ordnance

*a major shipbuilding installation

*plus a distribution of NDT test labs, casting and forging producers, and related firms.

The relation of these industries (except the security-bound ordnance people) to regulatory agencies has been described in section 2.4.4. In general, they work to AEC, DOD, FAA, and NASA specifications and require NBS photographic density standards.

The third major group of users of NBS measurement services includes the vast array of companies and institutions which require evaluation of microfilm systems. These are end-users, not manufacturers (see section 2.5.1 for details). The Microcopy Resolution Chart is an important standard; it is recommended for use by the National Microfilm Association (NMA) and required by the military in its applications. These charts go into circulation at the rate of about 10,000 per year and are used by the whole spectrum of people who record things on microfilm; from libraries, retailers, insurance companies, and banks to a religious group which records the genealogical histories of its members. (For the applications of microfilm and the major users, see section 2.5.1; for documentary standards, 2.2.1.2).

Since the needs of the photo companies with respect to measurements was known to NBS (via an NBS-sponsored users group) and since the needs of the microfilm users are voiced by NMA, a survey was made of a limited group of users of NBS measurement services: the domestic industrial manufacturers which appeared on NBS customer lists for photographic density standards in the 18 month base period, 145 firms in all. Over 25% of the firms replied to a questionnaire dealing with their operations (see Appendix A). The percentages of the 37 respondees involved in NDT and in graphic arts and printing is comparable to the percentages for the entire group as already shown in Table 9, roughly 86% to 14%.

Those surveyed were asked how many densitometers they owned, how many people used them for how many hours per week, what their investment in measuring equipment was, and how much product was effected by the standards NBS supplied. Profiles of nine companies which answered these questions more or less fully appear in Table 13. Generalization is impossible: anywhere from 1 to 5 densitometers in a company control "dollar volumes of product affected by the calibration service" ranging from $120,000 through $25 million to "many" millions.

One question that all 37 companies answered dealt with why they bought items from NBS: all the NDT people said they were required to, all the graphic arts, printing and photo people said they wanted them for their own production control. On the adequancy of the standards, the NDT people said fine (except for three who need a different kind of x-ray standard now available from NBS): the graphic arts people have trouble with vesicular film (for which standards are not now available.

Table 12. Users of NBS Photographic Density Standards Involved in the Production of Strategic and Tactical Missile Systems.

Some representative combinations of the program contributors and manufacturers of the airframes and engines of the U.S. missiles listed in the Aviation Week and Space Technology, Forecast and Inventory Issue of March 1973. All the companies listed but two procured NBS density standards in the 18 month period for which NBS records were examined; the two were explicitly mentioned as customers of testing laboratories which use NBS standards.

Prime Contractor /Program Manager	Subcontractor/Contributor	
Beech	AMF	Hercules
Bell Labs	Martin-Marietta	Bendix
Bendix	Altamil	
Boeing	Lockheed	
Emerson	Honeywell	Hercules
Gen Dynamics	Aerojet	
Goodyear Aero	Thiokol	
Honeywell		
Hughes	Thiokol	
Lockheed	Thiokol	Hercules
LTV Aerospace	North American	
Martin-Marietta	Hughes	
McDonnell	Thiokol	GE
Maxson Electron	Thiokol	
North American	Pratt & Whitney	
Philco Ford		
Raytheon		
Sperry Rand	Thiokol	
TRW	Boeing	Aerojet
Western Electric	McDonnell	Hercules

The best answer to the question of how NBS services related to the end products came from a self-described "small printer" doing $250,000 a year in business, with $175,000 in valued-added that is related directly to measurements. He buys NBS standards because he wants to and says "we sleep better at night, just knowing you are there."

The direct and indirect effects of NBS measurement services have been illustrated in section 2.5.3 on "Major Users" in the measurement system and section 3.1.2, "Impact of Measurements." In general, photo companies have an objective third-party for density and resolution standards, manufacturing and service organizations can get the standards they

Table 13: Profiles of the Measurement Operations of Some NBS Density Standards Users

Company Pseudonym	Densito-meters (units)	Measurement Personnel	Instrument use (hrs/wk)	Capital Investment ($1000)	Product Affected ($1000)
NDT Test Laboratory	3	3	4	1.3	120
Small Printing Company	1	3	-	low	250
NDT Test Company	1	4	-	5.0	300
Instrument Company	3	-	3	2.1	480
AEC Prime Contractor	4	6	6	5.0	1000
Casting Manufacturer	2	2	5	.75	1500
Metal Fabricator	1	3	3	-	4000
Turbine Part Maker	3	15	10	2.0	25000
Microfilm Product Firm	5	-	6	720	many

need for dealings with the federal government, spectacle lens manufacturers have a source of measurements which has technical status, and almost everybody comes out ahead on the deal.

4.2.3 Alternate Sources

A photographic company (SIC 3861) and a densitometer manufacturer (SIC 3861) are known to have facilities for fundamental measurements of photographic density; they both provide standards to customers. A photographic company makes the Microcopy Resolution Charts for NBS who checks them for comformity to design specifications. A few high technology optical companies (SIC 3831) have somewhat similar lens test capabilities. The photographic company and the densitometer manufacturer refer their measurements to NBS; the optical companies speak to NBS. Where users need measurements, these alternate sources either provide or are attempting to provide for their needs.

4.2.4 Funding Sources for NBS Services

The costs to the users of NBS services are based by Congressional mandate (Title 31, U.S. Code, annotated, section 483(a)) on the full cost of the performance of those services. As implemented by Department of Commerce guidelines (DOC Administrative Order No. 203-5, revised) that cost includes:

*direct costs (supplies, labor, accrued leave factor, personnel benefits, etc.),
*direct supervisory costs
*overheads (including depreciation, maintenance, etc.)
*and cost of space.

As a result, prices are not based on what an economist might call "price-quantity relationship in the market structure"; that is, *not* on what the market will bear but what it costs NBS to supply the services (Tables 14 and 15).

Prices do not include the cost of development of the measurement capabilities; the tax payer handles that. Money flows by Congressional appropriation from the Treasury, through the Bureau of the Budget, through Commerce, down the NBS organization to the imaging optics program where it appears as equipment and salaries - Governmental agencies pay for the services they get from NBS on a contractual basis (for extended projects) or an any other user would for short jobs or standards.

In fiscal year 1973, $27,000 worth of microcopy resolutions charts were sold, $11,500 worth of photographic step tablets, and $4,000 worth of density calibrations were performed on samples submitted by users. Of this $42,000, $12,000 returned to the section in STRS money. Total STRS money; $197,000; other agency money, $118,000; direct calibration fees, $4,000; total operating budget in 1973, $319,000.

4.2.5 Mechanism for Supplying Services

The bulk of measurements are dispersed via Standard Reference Materials as described in the Special Publication, NBS SP-260. The Office of Standard Reference Materials (OSRM) contracts for the manufacture of photographic density tablets and microcopy resolution charts, receives them, gives them over to the Optics and Micrometrology Section for calibration and, on their return, puts them up for sale as:

SRM 1001 Double-emulsion, blue-based x-ray photographic step tablet, 0 to 3 density
SRM 1008 Single emulsion, neutral grey tablet, 0 to 4 density
SRM 1009 Similar to 1008 but 0 to 3 density
SRM 1010a The NBS Microcopy Resolution Chart (known to industry as NBS 1010a).

The original manufacturer of the SRM 1010a happens to buy back about 60% of them and distributes them as a "service to customers."

Primary calibrations of transmission density standards, secondary calibrations of reflection and transmission density standards, measurements or testing of lenses, and similar conventional measurement services are described in NBS Special Publication, SP-250. All prices are based on cost-recovery as described in section 4.2.4.1. On the basis of what appears in SP-250, NBS does not do conventional lens testing; it gave that facility over to the Geological Survey. However, manufacturers of ophthalmic goods and measuring instruments have requested NBS "certification" of their master lenses; the lenses are, therefore, tested and reports issued.

Besides the general communication activity described in section 4.2.2, the measurement services in optical imaging have recently included an announcement of the new lens test service before its inauguration by a 300 letter mailing to potentially interested parties, the publication of an NBS report (NBSIR 10970) on densitometer calibration which outlines a useful computer program, a course at NBS on microdensitometery for users of the devices, a series of guest lectures at graduate and undergraduate levels for a university with an optics program, a description of services regarding reflection microdensitometry to a retailers' symposium on the use of the Universal Product Code (UPC), and, unrelated to the study upon which this report is based, direct contact with densitometer manufacturers, optical companies, defense agencies and general users. An attempt to schematically represent how NBS fits into the system is shown in Figure 6. The sources of information flow into NBS and the measurement services flow out of NBS is given in Figure 7.

4.3.1 Economic Impact of Major User Classes

Some of the more obviously interesting and practically unanswerable questions about measurements in imaging optics deal with their ultimate value in dollars and cents. The best answers require some form of "incremental analysis" by which the economic effects of a change in some aspect of measurements (e.g., frequency, precision or accuracy) are traced through the manufacturing process to the end product, the marketplace and the consumer.

Such analyses have proven to be beyond the scope of this work. Rather, the "economic impact" of measurements will be discussed in terms of the economic dimensions of some of the industries involved, and the relationships of measurements and NBS services to the output of these industries.

In 1970, eleven firms manufactured virtually 100% of the photographic film marketed in the U.S. that year. An essential part of the manufacturing process and the performance rating of the film is the measurement of photographic densities. The common bases of measurement among the eleven firms were the NBS standards each procured. The total value of the film marketed by these companies in 1970: $1.3 billion; the size of the overall

Table 14. NBS Revenues in FY-1973 from Fixed-Fee Services.

Measurement Service	Items	Sales
Microcopy Resolution Charts	10,650	$27,000
Photographic Step Tables	182	$11,500
User-submitted Tablets	40	$2,475
Inverse Square Calibrations	2	$1,400
Reflection Calibrations	2	$125

Table 15. Cost-to-NBS Basis for Sales Price of Photographic Standards in FY-1973.

SRM 1008	Materials & handling	$44.00
	Calibration	28.00
	Sales price	72.00
SRM 1009	Materials & handling	$39.10
	Calibration	18.90
	Sales price	58.00
NBS 1010a	Materials & handling	$2.02
	Calibration	0.72
	Sales price	2.80

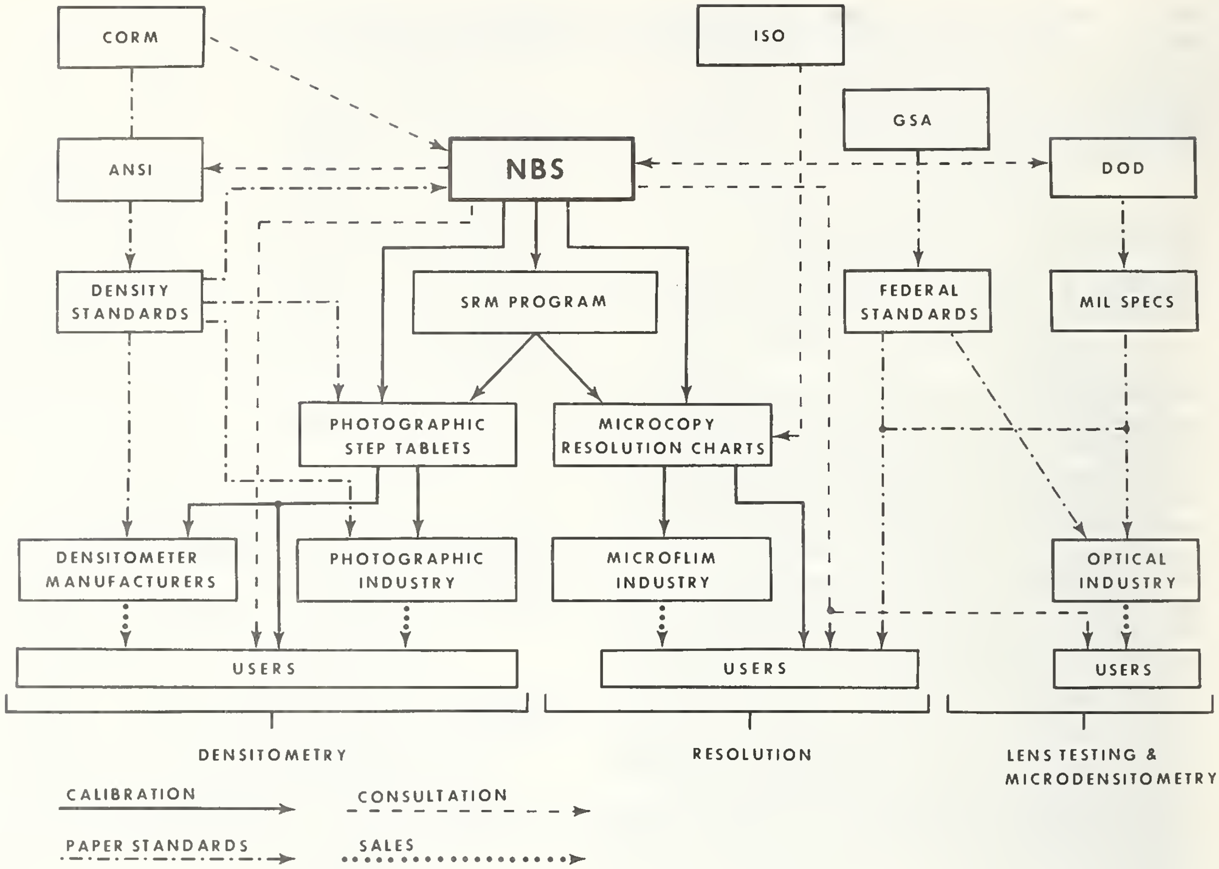


Figure 6: NBS and the Measurement System

photographic market the film supported: $4 billion.

In 1973, five firms were the major producers of nuclear reactors for electric power generation, research and defense. The Nuclear Regulatory Agency (formerly the Atomic Energy Commission) enforces mandatory radiographic inspection of critical reactor components during their manufacture. In the course of a radiographic inspection of a reactor part, a photographic density standard is used to calibrate the instrument which monitors the density of the film image. All five manufacturers of reactors in 1973 procured and used NBS density standard. For the period 1965 to 1973, contracts for construction of new reactors averaged about $8 billion per year.

In 1973, the aerospace industry produced over 16,000 aircraft as well as an unspecified number of military and civilian spacecraft and launch vehicles. The Federal Aviation Agency, the Department of Defense, and the National Aeronautic and Space Agency have mandatory procedures for the radiographic inspection of aircraft and spacecraft. Again, radiographic inspection involves the use of photographic density standards, In 1973, five of the six manufacturers of commercial passenger and cargo transport aircraft, as well as all of the manufacturers of aircraft turbine engines, missile system airframes and engines, and military and civilian spaces vehicles and launchcraft, procured and used NBS photographic density standards. The value of the air and space hardware produced by the aerospace industry that year was $12.2 billion.

In 1970, medical radiologists performed an estimated 325 million diagnostic x-rays on 110 million patients. The FDA's Bureau of Radiological Health monitors performance of medical x-ray receptors by evaluating film-screen combinations. A well-characterized receptor allows a doctor to obtain a good x-ray picture at a lower level of potentially dangerous radiation to the patient. The BRH uses an NBS-constructed instrument to expose films and an NBS density standard to evaluate them. The market value of the medical x-ray film consumed in 1970 was over $200

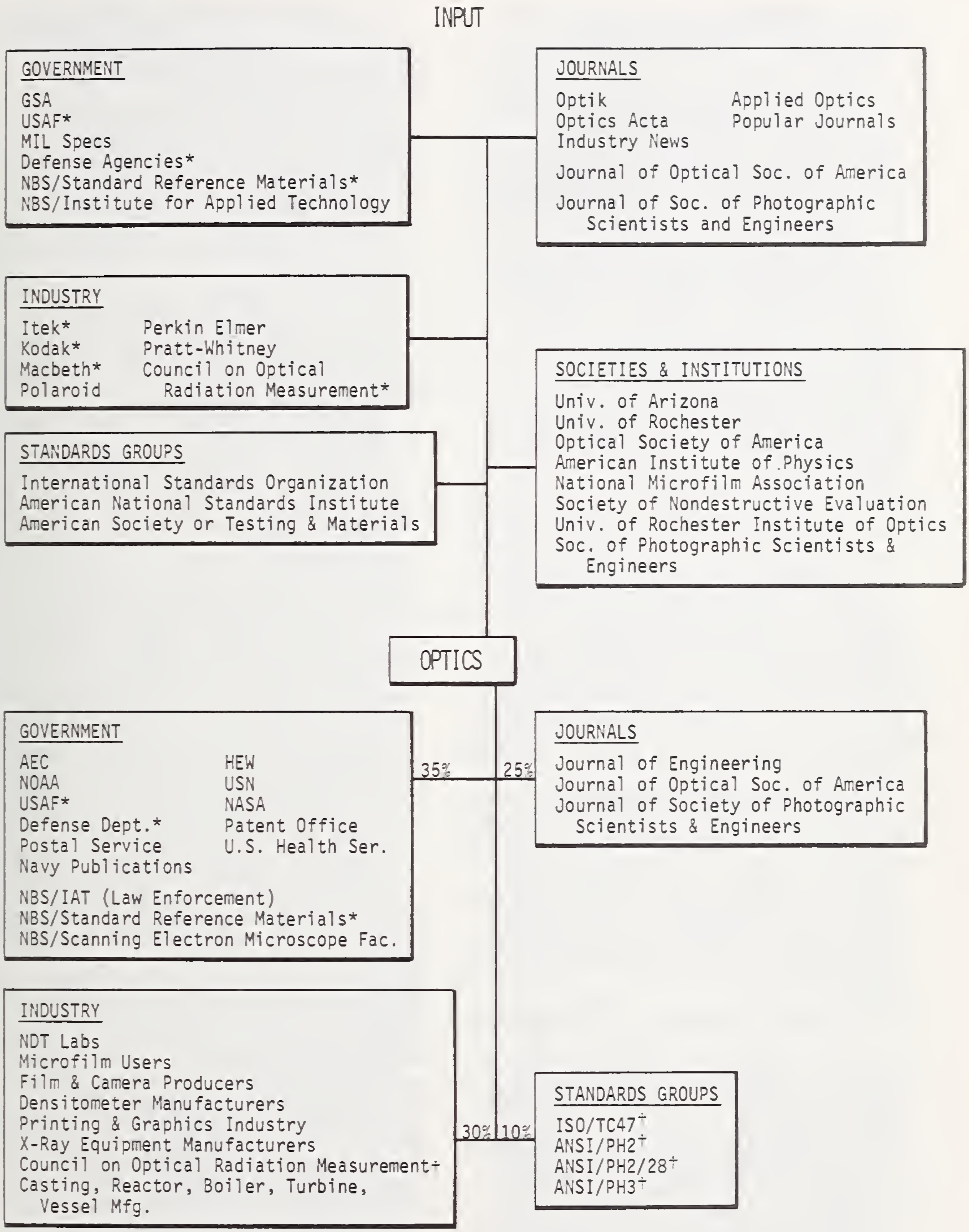


Figure 7: Input-Output Chart for NBS Programs in Optics

million; the portion of the health care delivery system devoted to medical radiology has been estimated at over $4 billion.

In 1970, over 100 million square feet of microfilm, the equivalent of over 10 billion frames in 35 mm format, were used in the U.S. for recordkeeping purposes. The standard means of evaluating the reproduction quality of micrographic film, cameras and readers involves the measurement of resolution by means of a microcopy resolution chart. NBS, the sole source of the industry-recommended resolution charts, supplies over 10,000 to users annually. The value of the microfilm sold in 1970 was over $100 million; the microfilm market as a whole amounted to over $600 million.

Other statistics for industries using NBS imaging optics standards in the areas of radiography, graphic arts, and ophthalmic lenses are given in section 3.1.2.

4.3.2 Technological Impacts of NBS Services

The technologies supported by the standards which NBS provide are mature. The development of new photographic products are basically matters of photographic chemistry; the density and resolution measurements are tools to evaluate them. The development of new lens and lens systems is a matter, it seems, of refining the old ideas. The standards, therefore, keep the photographic and optical industries tuned.

The moving technology supported is that of high performance optical systems; it may take a while but the principles of physical optics embodied in the theoretical and analytical studies of these systems now being done will feed down from the production of high technology devices into consumer optical productes and instruments, like automatic x-ray image analyzers, which effect the consumer.

4.3.3 Pay-off from Changes in NBS Services

In the distant past, changes in NBS services related to the inauguration of a program in camera testing and photographic sciences produced:

*a camera testing capability which led to the development of federal and state specifications on land survey aerial cameras
*the daylight filters which became international standards and are still is use
*the "gamma-bar" technique which became an industry practice for the assessment of film speed
*the microscopy resolution chart which was adopted as the industry standard.

In the past decade, modifications in NBS calibration services have produced the following results:

*In 1963, the old microcopy chart was redesigned with spatial frequencies based on an ISO preferred number series and, in 1967, five more spatial frequencies added. The combined effect was the NBS 1010a which is becoming a formal ISO standard. The result is a domestic standard by which microfilm manufacturers can satisfy the needs of foreign and domestic customers.
*In 1974, a new photographic density standard, the SRM 1001, was introduced. Consisting of a blue based, double emulsion film, the SRM 1001 satisfied the needs of radiographers for a complement to the neutral gray, single emulsion standards already available. The result for NBS was a reduction in the number of special calibrations required of it.
*In 1971, the aerial camera calibration facility of NBS was transferred to the U.S. Geological Survey. The development of such testing had reached a zenith a decade ago and measurements had become routine. Transfer of the operation to the Geological Survey resulted in no loss of benefit to the users of the service. While conventional lens testing went with the camera calibration, some companies like ophthalmic goods manufacturers request that NBS perform this service for them; they receive such service. In fall of 1974, NBS supplemented the lens evaluation services available through federal laboratories with an interferometric lens testing service described in Special Publication, SP-250.

For about a decade, NBS facilities for the measurement of photographic densities have been maintained on a status quo. Reflection density reference standards and densitometers have not been upgraded recently and calibrations for users have dwindled to a scant two or three per year. While in regular use, the transmission density calibration facility has not kept pace with industry practice in fields outside radiography. Commercial transmission and reflection densitometers which exceed in range and precision those of NBS calibrations are on the market. Densitometer manufacturers and their more measurement-intensive customers are seeking better calibrations from NBS. Improvement of NBS capabilities would result in benefits to manufacturers of photographic film and equipment, photocopiers, densitometers, and, indirectly, to the consumers of these products.

It is possible that continuation of the status quo at NBS would result in a decline in the number of standards calibrated. The order in which users would find NBS standards insufficient to their needs depends on the nature of the need: whether the requirement is for hard measurement information, a pro forma reference to an authoritative source, or a talisman to fulfill government procurement specifications.

4.4 Evaluation of NBS Program

Basic capabilities. In transmission densitometry, the primary calibration device, the inverse-square bar, yields precisions and operates over a range of transmission densities which do not compare with measurements currently being done in the photographic industry or which can be measured with commercial densitometers. Further, the light collection system is capable of measuring only one of the two types of transmission density to be given equal status in the ANSI standard, PH2.19, now in the final stages of adoption; the type of density measured by NBS is not the type which is measured by prevelant commercial densitometers. A new densitometer, recently procured by NBS, measures this 'opal density' and has a precision at low densities which is greater than the accuracy to which NBS can calibrate its own standards. Because of the relation of the precision of these instruments to the accuracy of NBS standard, users have reported that they believe they cannot exploit the instruments full capabilities.

In reflection densitometry, the basic reference standard is a set of plaques which were calibrated by the old Colorimetry Section of NBS; the reference standards need replacement. The reflection densitometer is antiquated.

In lens testing, the wave-front shearing interferometer, WSI, which was developed at NBS, is capable of operation with precisions that fulfill the requirements of the most demanding users of optical testing and over a range of spatial frequencies which surpasses commercial testing devices, most prototype devices, and the resolution limit of every optical system except the finest quality microscopes.

In microdensitometry, the equipment is first class; the supporting theoretical and analytical studies of the performance of microdensitometers, of their applications in image analysis and the testing of optical systems, and of high performance optical systems in general, are state-of-the-art and unsurpassed.

Current Standards and Measurements. A survey of users of NBS photographic density step tablets (section 4.2.2) showed that these standards meet the current needs of radiographers and, along with this survey, discussions with many active in the field of industrial radiography have led to the conclusion that the standards will meet the needs for at least a decade. The standards are not adequate to fulfill the needs of the manufacturers of photographic equipment, photocopiers, and related products.

A cogent statement of these needs has been given by a special users group founded under the auspices of NBS. After a series of meetings at NBS between October, 1971 and May, 1972, representatives of the optical radiation measurement community, scientists and engineers seriously concerned with the present lack of adequate standards in this field, were organized into the Council for Optical Radiation Measurements (CORM) as an activity of the Technical Committee 1.2 on Photometry of the U.S. National Committee of the CIE (Commission Internationale de L' Eclairage). The report of CORM (Pressing Problems and Projected National Needs in Optical Radiation Measurements: A Consensus of Services Desired of NBS) presents the consensus of CORM on the most urgent problems in the areas of sources, detectors and techniques and their relative priorities. The specific details of CORM recommendations with regard to diffuse visual transmission and reflection density standards and measurement techniques represent an extension of the range, an increase in the accuracies, and changes in the techniques of NBS measurements.

The recommendations concerning transmission density standards are:

*an extension of the density range of standards provided by NBS from a maxmium density of 4 to 6.

*an increase in the calibration accuracy from ± .005 or 1/2% over the entire range to ± .001 or 1/2% in the range 0 to 3 and ± .02 or 1/2% in the range 3 to 6.

*the introduction of the use of opal glass in calibration measurements.

*a study of the effects of sample geometry and composition and of measurement techniques on measurement results, including the relations of opal glass and integrating sphere techniques, densitometer and inverse-square techniques, and general tablet parameters and measurement results.

The CORM recommendations for diffuse reflection density standards include:

*the introduction of a new NBS master artifact standard consisting of neutral, non-fluorescent ceramic tiles.

*an increase in the basic accuracy of reflection density measurements from ± .01 or 2% to ± .001 or 1/2%.

The NBS Microcopy Resolution Chart, NBS 1010a, meets the needs of industry and users, reports an official of the National Microfilm Association. A controversy over the relative merits of the NBS-type chart and the French Mire chart has prompted a member of the British Standards Institute (who is also on the ISO working Group on microcopy quality) to evaluate the relative performance of each; he concludes that the Mire chart is "not more of a test for legibility than the NBS is, and is inferior in testing resolution" (NMA Journal of Micrographics, Vol. 7, No. 6, July 1974). A draft ISO proposal now in committee would designate the NBS-type chart "ISO Test Chart No. 2" and put it on co-equal status with the presently recommended Mire Chart which would become "ISO Test Chart No. 1". The NBS chart will not be formally referred to in the standard but the specifications cited are those of the 1010a. Anyone may manufacture a chart patterned after the NBS 1010a and consumers will not be required to use NBS as a source of an ISO standard target.

The lens testing service derived from research supported by agencies outside NBS and became part of NBS measurement services in fall of 1974. Advance notice in the form of letters to potential users has not resulted in utilization of the service. The most recent Optical Physics Division Advisory Panel has just suggested that, except in extreme cases, industry may be unwilling to pay the cost of measurement; they suggest that NBS might initiate the formation of a committee from the optical industry in order that, by means of the testing of sample lenses, some level of quality certification might result.

Programs in-progress. A new primary calibration facility which will extend the range and increase the accuracies of transimission density standards is under development; based on a novel idea to "cascade" inverse-square measurements, the system is designed to conform with ANSI documentary standards and to fulfill the industry needs as described by CORM. The applicability of the system to the general problem of detector linearity characterization will be determined.

A project to develop a physical standard for use in the evaluation of the dimensional measurement capabilities of optical and electron microscopes as used in industry is under way; a supportive study on the effects of eyepieces and substage illumination on measurements made with optical microscopes is also being done. The physical standard and the results of study are important since optical microscopes are basic measurement tools in the semiconductor industry and electron microscopes are daily becoming more widely used as dimensional-measurement devices.

A microdensitometry facility is being developed which will have general utility in the quantitative analysis of photographic images and of interferograms which derive from dimensional-measurement interferometers. This capability will support NBS measurement services in and out of imaging optics and may become available to users outside NBS.

Rationale and Effect of Services. The rationale of NBS services and the effect, if they are successful, is the same: supplying the measurements which facilitate commerce and fulfill the needs of government agencies. As presently constituted, photographic density standards provide non-demanding industrial users with a reference to NBS which they desire for their own purposes or require because of their dealings with federal agencies. Likewise for microscopy standards. The lens evaluation and microdensitometry capabilities fulfill the needs of defense agencies for an impartial arbiter in procurement matters and a source of state-of-the-art expertise.

4.5 The Future

To the extent that it depends on the evolution of presently nascent trends, the "foreseeable future" of imaging optics will bring the following developments:

Standardization: There will be within the next few years documentary standards which: place on co-equal status integrating sphere and opal transmission densities; establish magnesium oxide as the preferred reference standard for the zero value of diffuse reflection density; define the methods for measuring the densities of non-silver halide photographic materials; make the NBS microcopy resolution chart a formal international standard; and, possibly, treat lens testing, microdensitometry and gravure printing reflection density.

Federal specifications: There may be regulations governing the performance rating of medical x-ray film screen combinations, the licensing of radiographic inspectors or commercial transport aircraft, and the effectiveness of medical devices such as ophthalmic lenses.

Measurement practices and new technologies: In photography, factors such as the relative scarcity of mineral resources will promote the ascendancy of non-silver halide photographic materials. Because the light-modulation properties of these materials are different from those of conventional film, applicable measuring instruments and calibration standards for density measurements will be necessary.

In radiography, the quest for more quantitative and detailed image information from radiographs will make the use of visual microscopy, microdensitometry and automated image analysis industrial and medical radiographs common.

In micrographics, computer-output microfilm will play a major role in the manipulation and mass-storage of recorded data and will likely be interfaced with optical character recognition to provide complete data storage and retrieval systems.

In optical microscopy, emphasis upon quantitative dimensional measurements rather than qualitative observations will push the optical microscope's present limits of utility and generate pressure for new optical designs which would extend the range of application. Better test procedures and calibration standards for optical microscopes will be sought.

In Fourier-transform and diffraction optics, the advent of optical-lens instruments which operate in non-imaging modes will call for revised lens evaluation produces, including new measures of proper lens function as well as reinterpretations of currently measureable parameters.

* * *

In the light of some of the current and anticipated needs for calibration standards in imaging optics, it is recommended that NBS:

*continue the development of the primary calibration facility with its intended purpose of satisfying users needs in transmission density measurements.

*acquire a new reflection densitometer, develop suitable primary reference standards and have them calibrated by the appropriate NBS group.

*maintain the present lens test measurement service without further direct investment in it.

*continue the program of expanding the application of microdensitometry into allied fields, such as the general evaluation of photographic images and interferograms.

*continue efforts to develop a physical standard applicable to optical and electron microscope dimensional measurements.

Recommendations for actions when time and resources become available are:

*determine the appropriateness of and industry interest in an active users group in the optical industry.

*investigate the feasibility and desireability of NBS standard reference materials for reflection density applicable to graphic arts and related fields.

The means for implementation of these two recommendations are effectively a continuation of the study of users needs. The results of this present study have been:

*the definition of the relationship of NBS to the users of its measurement services. Little had been known by NBS of the composition, nature, and dependency on NBS of its customers.

*the discovery by NBS, in the graphics arts industry of a group which are potential users of NBS services in reflection densitometry. Since there is no mandatory dependency on this group at NBS, its use of density standards was unknown.

*the knowledge of its users which allows NBS to place in content the services asked of it by the Council on Radiation Measurement.

*the redirection of NBS programs toward measurement applications of optics rather than optical testing *per se*.

5. SUMMARY AND CONCLUSIONS

Generalizations that may be made about the state of the measurement system in imaging optics of necessity depend on the perspective of the viewer. From the lower echelons of the National Bureau of Standards organization, the view has resulted in the following conclusions.

In transmission density measurements, specifically those based on American National Standards Institute documentary standards, there is a fairly well-defined structure to the measurement system; basic parameters are well-defined, the methods for the performance of fundamental measurements clearly given, the requisite appparatus and instruments available, physical standards commercially marketed and obtainable from the National Bureau of Standards. The accuracies of these standards are generally suitable to user's needs. There are two classes of dependency on the NBS standards: some organizations in the photographic and allied industries acquire the standards voluntarilly in order to maintain control of their production processes; some organizations engaged in industrial radiographic non-destructive testing obtain the standards to meet the requirements of federal agencies with which they do business. The first class of users have called upon the National Bureau of Standards to improve the accuracies and extend the range of the standards it provides; an apparatus is under development which will allow these conditions to be fulfilled as well as to allow a type of detector linearity evaluation not possible on the present device.

In reflection density measurements, documentary standards are currently under revision to place measurements on a more firm technical footing and to bring them more in line with current industry practice. Commercial devices for reflection density measurements are marketed and physical standards are available from private organizations. The National Bureau of Standards does not provide reflection density standards and the quality of its reflection density calibrations is not considered satisfactory to the groups of users which would normally use the service. Since there are apparently no federal specifications which require traceability to NBS reflection density standards or calibrations, the question of the responsibility of NBS to supply these services to users is a matter of management philosophy. There is a need within the photographic industry, the microfilm industry, the gravure and lithographic industries, and other users of reflection density measurements for improved physical standards to allow better production control.

In the field of optical testing, the measurement system is even less well-defined. Specific groups such as the manufacturers of ophthalmic goods have documentary standards which govern the measurements appropriate to their operations; testing instruments and techniques are standardized. The optical industry in general lacks documentary standards and agreed upon testing procedures. NBS, in gauging the developments in the industry, made the judgment that the existence of a documentary standard defining measureable indices of optical system performance was a prerequisite to the development of a structured measurement system. NBS workers became active on the appropriate standards committees working on such standards. A system for the testing of lenses and optical systems was developed in the course of work being done for federal agencies and, based on the anticipated issuance of documentary standards by the voluntary standards organizations, introduced as a testing service. Difficulties encountered by the standards bodies in arriving at satisfactory definitions of testing methods has slowed the progress of those committees and at this time documentary standards are still in the draft stages. Based on analogous occurrences in unrelated fields of measurements, it is thought that regular use of NBS lens test services will commence with the formalization of the testing methods as signalled by the adoption of such standards. In the field of microfilm resolution testing, the industry has documentary and physical standards and gives evidence of smooth functioning. The role of the National Bureau of Standards in the operation of this subsystem of optical testing is well-established and its contributions desired by voluntary users of its services and required by others.

Market projections made by private firms in the second year of this decade projected 1980 levels of consumption of amateur and professional, microfilm, medical and industrial x-ray, and graphics arts supplies and equipment which are multiples of consumption in the present period. These projections imply similar increases in demand for photographic density standards and microcopy resolution charts while the development of new photographic materials points to the need in the near future for similarly new types of density standards. What may occur in the optical industry is conjectural. Domestic sales of passive optics (lenses, lens instruments, binoculars, etc.) have been relatively stable for a few years, rapid growth being seen in the electro-optical industry in which lens devices are coupled to electronic sensors. The evolution of the measurement system in lens testing and evaluation will likely be accelerated by the awaited documentary standards.

Appendix A. THE METHODOLGY OF THE STUDY

The starting point for the preparation of this report was NBS records of its calibration services. Computer lists of the companies, organizations, and individuals which had purchased NBS standards were compiled and, where practical, the entries grouped according to the products or services they supply as described in the Thomas Register of Manufacturers.

Letters soliciting information were sent to 50 optical companies, 30 instrument manufacturers, and 25 trade and professional organizations. Those not represented in NBS records were located in directories such as The Optical Industry and Systems Directory. The letters stated the nature of the study, its purpose, the use to which information would be put, and a statement of deference to the requirements of proprietary operations.

A survey questionnaire was prepared with the advice of the Bureau of the Census and sent to over 150 domestic industrial establishments which procured NBS photographic density standards in the period for which records were examined, specifically, June 1971 to December 1972. Survey questions were directed at the nature of the products or services related to the standards, the reason for acquiring NBS standards, the number and kind of measuring instruments used, the personnel and time devoted to measurement, the product volume effected, and the adequacy of the services NBS provides. A sample questionnaire and a compilation of the quantitative results follow this text.

For information on the role of regulatory agencies, personal visits were made to the Federal Aviation Agency, the Department of Transportation, the Hazardous Materials Regulation Board, and the National Transportation Safety Board; telephone conversations were held with appropriate level personnel of the former Atomic Energy Commission, now the Nuclear Regulatory Commission, the Bureau of Radiological Health, and the National Institute of Occupational Health and Safety. Information on the system of eye care was derived from confirming the salient facts reported in the popular press article mentioned in the body of the report with the standards committee chairman and medical personnel referred to in that article.

Data compiled on documentary standards derived from interviews with the chairmen of the American National Standards Institute committees on photographic sensitometry, the subcommittee on medical densitometry, the technical director of the National Microfilm Association, a representative to the International Standards Organization, the director of the Gravure Technical Association, and NBS representatives to the subcommittees on lens testing and microdensitometry. Copies of the documents were procured from the NBS library of standards and specifications.

Economic data per se were obtained from a number of sources, two being market research fimrs which graciously provided reports on the photographic industry: Predicasts, Inc., of Cleveland, Ohio and the Arthur D. Little firm of New York. The Department of Commerce Office of Business Analysis submitted the documents cited in the text.

General overviews of the operations of the measurement system were provided by: the manager of a radiographic training center (industrial radiography); the chairman of a American National Standards committee (medical radiology); the author of a comprehensive text-book chapter on ophthalmic measurements (eye care); a pipeline specialist of the Hazardous Materials Regulation Board (radiography and pipelines); an FAA official and an investigator for the National Transportation Safety Board (radiography and aerospace systems); a densitometer manufacturer and a photographic goods producer (densitometery in general); an official of the Gravure Technical Association (densitometry and printing); the technical director of the National Microfilm Association (commercial microfilming); and a number of workers in the field of optical testing in general. The requirements of the defense agencies in advanced optical testing were documented in letters from the officials of selected organizations within those agencies.

Further bits and pieces of information derived from numerous telephone conversattions, plant visits, standards committee meetings, and discussions with workers in the field. The more important source persons and documents are listed in Appendix B.

Appendix B. SUMMARY OF BACKGROUND DOCUMENTS

The information upon which this report is based derived from a number of sources, many of which were published books and documents, some of which were written communications to the author. The following is a list of approximately 100 persons who graciously answered questionnaires, provided substantial letters outlining their measurement programs, submitted technical literature, documentary standards, economic data or general background information. Their names, titles, and affiliations are given, as well as the nature of the contact which led to the data transfer. Also included are the published documents cited in the text and those which were sources of more general data.

OMB No. 41-S73042
APPROVAL EXPIRES 12-31-73

NBS-746
(7-73)

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

EVALUATION OF PHOTOGRAPHIC STEP TABLETS

COMPANY *(Name and Address)*	RESPONDENT *(Name)* ADDRESS *(Business)* TITLE PHONE
ADMINISTRATIVE CONTACT *(Name)* ADDRESS *(Business)* TITLE PHONE	TECHNICAL CONTACT *(Name)* ADDRESS *(Business)* TITLE PHONE

1. TYPE OF CALIBRATION SERVICE EMPLOYED

- ☐ PURCHASE OF STANDARD REFERENCE MATERIAL
  - ☐ PHOTOGRAPHIC STEP TABLET #1008
  - ☐ PHOTOGRAPHIC STEP TABLET #1009
- ☐ STANDARD SUBMITTED FOR ORDINARY CALIBRATION
  - ☐ NEUTRAL DENSITY PHOTO TABLET
  - ☐ DOUBLE EMULSION X-RAY TABLET
- ☐ SPECIAL INVERSE SQUARE BAR CALIBRATION
  - ☐ NEUTRAL DENSITY PHOTO TABLET
  - ☐ DOUBLE EMULSION X-RAY TABLET

2. REASONS FOR CALIBRATION REQUIREMENTS

- ☐ SELF-IMPOSED PRODUCTION STANDARD
- ☐ CONSUMER'S PROCUREMENT REQUIREMENT
  - ☐ GOVERNMENT (GSA)
  - ☐ MILITARY SPEC. (DSA)
  - ☐ OTHER *(Specify)*
- ☐ RESEARCH OR PRODUCT DEVELOPMENT TOOL
- ☐ OTHER *(Specify)*

CONTINUED NEXT PAGE

3. PRODUCTS

A. PLEASE ENUMERATE THE PRODUCTS OR SERVICES OF YOUR COMPANY WHICH ARE DEPENDENT UPON THE CALIBRATION SERVICE.

B. PLEASE ENUMERATE THE CONSUMERS *(BY NAME OR TYPE)* WHOM YOU SERVE.

4. COMPANY STANDARDS CONTROL

A. PLEASE INDICATE THE USES OF THE STEP TABLETS.

- ☐ DIRECT INSTRUMENT CALIBRATION
- ☐ COMPARISON STANDARD
- ☐ CALIBRATION OF SECONDARY STANDARDS
  - ☐ FOR INTERNAL COMPANY USE
  - ☐ FOR DISTRIBUTION TO CUSTOMERS
- ☐ OTHER *(Specify)*

5. COMPANY MEASUREMENT SYSTEM

A. HOW MANY DENSITOMETERS ARE IN USE?

RESEARCH LABORATORY ____________

METROLOGY LABORATORY ____________

PRODUCTION CONTROL ____________

OTHER *(Specify)* ____________

B. WHAT TYPES OF DENSITOMETERS ARE IN USE?

C. WHAT IS THE CAPITAL INVESTMENT IN THE MEASUREMENT SYSTEM?

D. HOW MANY PERSONNEL *(And/or man-hours per week)* ARE INVOLVED IN MEASUREMENT?

CONTINUED NEXT PAGE

6. CALIBRATION SERVICES SUPPLIED BY NBS

A. PRESENT ACCURACIES OF STEP TABLET CALIBRATIONS (☐ MEET, ☐ FALL SHORT OF, ☐ EXCEED) PRESENT COMPANY REQUIREMENTS. COMMENT.

B. PRESENT ACCURACIES OF STEP TABLET CALIBRATIONS (☐ MEET, ☐ FALL SHORT OF, ☐ EXCEED) ANTICIPATED COMPANY REQUIREMENTS.

C. WOULD CHANGES IN THE SERVICES SUPPLIED BY NBS CONCERNING DENSITY STANDARDS (FORM, ACCURACY, TYPE, SUPPORTIVE INFORMATION) AID YOUR COMPANY IN IMPROVING YOUR PRODUCTS, INCREASING RELIABILITY, OR REDUCING COST? COMMENT.

D. HOW ARE PRESENT SERVICES RELATED TO PRODUCT DEVELOPMENT, PRODUCTION, RELIABILITY OR COST?

E. IS THERE A RELATION BETWEEN THE CALIBRATION SERVICES AND INFORMATION WE COULD PROVIDE TO YOU AND CONSUMER HEALTH AND SAFETY? THE DEVELOPMENT OF NEW TECHNOLOGIES? YOUR COMPETITIVE POSITION IN WORLD MARKETS?

F. COULD THIS RELATION BE ALTERED OR IMPROVED BY ANY CHANGES ON THE PART OF NBS IN ITS PHOTOGRAPHIC DENSITY CALIBRATION SERVICE?

CONTINUED NEXT PAGE

7. MEASUREMENT PROCESS AND PRODUCT VALUE

A. WHAT DOLLAR-VOLUME OF PRODUCT IS EFFECTED BY THE CALIBRATION SERVICE?

B. WHAT IS THE DOLLAR VALUE-ADDED TO THE PRODUCT EFFECTED BY THE SERVICE?

8. REMARKS

USCOMM-NBS-DC

QUANTITATIVE RESULTS OF SURVEY OF NBS SRM 1008

AND 1009 STEP TABLET USERS

Population polled: One hundred and forty seven domestic industrial consumers of SRM Materials 1008 and 1009 (photographic Transmission Density Step Tablets) for the period April 1971 - January 1973.

Primary Field of Application:

Total population polled, as inferred from industry index information of company products.

Industrial NDT	124	(86%)
Graphics and Printing	21	(14%)
Total	145	(100%)

Total respondents, as indicated by response.

Industrial NDT	31	(84%)
Graphics and Printing	6	(16%)
Total	37	(100%)

Respondents Specification of Reason For Calibration By NBS Standard

Federal requirement (MIL-STD, AEC, etc.)	31
Self-imposed production standard	6
Total	37

Type of Calibration

SRM 1008 and/or 1009	17
SRM 1008, 1009 plus double emulsion Xray film (PW XRM1)	3
Double emulsion film only	13
SRM 1008, 1009 plus special neutral density tablet	2
Neutral density tablet only	2
	37

Number of Densitometers in Respondents Facility

	Companies	#Densitometers	Subtotals
	14	1	14
	6	2	12
	7	3	21
	2	4	8
	1	5	5
	3	8	24
	1	18	18
	4	NR	-
Totals	37		102

(Average per company for 33 responses, 3)

Densitometer Investment and Supplies

Companies	Investment
9	$1 K or less
10	$1-5 K
5	$5 K or greater
11	NR
37	

Companies	Brand
18	MacBeth
12	Photovolt
5	Kodak
2	Sargent Welch
1	Joyce Loebl
1	GE
3	NR

Personnel Involved in Densitometric Measurement

Companies	Persons
10	4 or less
5	5-10
3	10-20
19	NR
37	

Companies	Manhours/Week
10	5 or less
8	6-10
6	Greater than 10
3	NR
37	

Selected List of Individuals Responding to Contacts

Response Code

- P: personal interview
- T: telephone contact
- R: survey respondent
- V: plant visit
- L: simple letter
- S: substantive letter
- C: literature/cover letter

Code	Alphabetical List by Individual
L	Robert A. Abbott Technical Director American Society for Quality Control 761 West Wisconsin Avenue Milwaukee, Wisconsin 53203 414-272-8575
L	Dr. Eugene Allen National Printing Ink Research Institute F. M. Sinclair Memorial Library Lehigh University Bethlehem, Pennsylvania 18015 215-691-7000 Ext. 220 or 560
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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

NBS has conducted a study of the National Measurement System for Optics. The proposed system model is discussed including the role of standards committees, instrument manufacturers and measurement users. The economic dimensions of the measurements impact areas and the technological base from which new measurement technology springs are described.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
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