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New Technology Challenges Metrology

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[2] Some divisions within the center are located at Boulder, CO 80303.

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NEW TECHNOLOGY CHALLENGES METROLOGY

Judson C. French

Abstract

Assurance of measurement quality to meet requirements for regulatory agencies, marketplace equity, and productivity and quality control in manufacturing and research is challenged by unprecedented demands for sensitivity, speed, precision, and accuracy over wide ranges of properties and signal characteristics. New approaches are needed. Examples of NBS response, principally in electrical and electronic engineering, are described.

Key words: Calibration; electrical; electronics; engineering; hazards; measurement; metrology; National Bureau of Standards; power; radiation; semiconductor; technology

1. INTRODUCTION

A new era is in the making in requirements for metrological services.

In broad areas of scientific, industrial, and governmental measurement activities, the traditional metrological services, such as hierarchical calibration laboratory systems that have assured adequacy of precision and accuracy in practical measurements in the past, are no longer sufficient.

There are several reasons for this change.

Practical measurements now require unprecedented sensitivity, precision, and accuracy, over an extremely wide range of material or system properties and signal characteristics. This is true in the research laboratory, on the production line, in the field operations of the military services, or in measurements in support of governmental regulatory efforts concerned with air or water pollution or electromagnetic radiation intensity.

The requirements of these practical measurements may be close to or exceed the state of the measurement art, and yet reproducibility of the measurements between various concerned parties, and accuracy based on accepted national or international standards, are important for the legal requirements of regulatory agencies, for equity in the marketplace, for reliability of the performance of critical products or systems, and for enhanced productivity in the manufacturing and process industries.

In many cases, these measurements must be made at very high speed, either because of the transient nature of the signal itself or because of the necessity for making a large number of repetitive measurements in reasonable times. Often it is impractical for measurements to be made effectively by hand; automation of the process becomes essential where the required speed and quantity of measurements exceed human capabilities, or where the measurement must be performed in places unsafe for, or inaccessible to, a human operator.

In particular, the pervasive application of electrical and electronic systems for control and communication and for energy generation and transmission has both broadened the availability of new measurement methods and extended to new extremes the range of electrical signals and properties to be measured and controlled. The burgeoning field of solid-state electron devices has produced new tools such as the microprocessor to aid in automation of measurement. But it has simultaneously placed new demands on the measurement art for sensitivity and speed in measurements through its routine needs for part-per-billion sensitivity in measurements of the properties of solid-state materials used in the manufacture of these devices, and for speed in measurement of the properties of devices intended for use in information systems operating in the gigabit-per-second range.

Thus, to respond to these new levels of sophistication and complexity, new services are needed from our national measurement laboratories and throughout the measurement chain extending from national laboratories to the place of practical measurement application.

To illustrate how the National Bureau of Standards is responding to this challenge, I will describe in some detail several examples of the new requirements, some new approaches to metrological services, and some responsive activities undertaken at the National Bureau of Standards. In particular, I will emphasize NBS activities in electrical and electronic measurements.

2. NBS RESPONSE TO METROLOGICAL CHALLENGES

Let me address first the National Bureau of Standards (NBS), and some of its responses to this metrological challenge. NBS, with its principal facilities in Gaithersburg, Maryland (figure 1), and in Boulder, Colorado (figure 2), is well known for its traditional activities in maintaining the fundamental standards of measurement for the United States of America; for its activities in disseminating these standards through a hierarchical, cooperative system to governmental and commercial calibration laboratories throughout the country; and for its activities in cooperation with other countries to maintain compatibility of measurements on an international scale. However, the scope of NBS research and services is far broader than is commonly recognized. NBS comprises three principal technical elements (figure 3), the National Engineering Laboratory (NEL), the National Measurement Laboratory (NML), and the Institute for Computer Science and Technology (ICST). At NBS, work is done on a surprising variety of subjects: in NML (figure 4), on the basic measurements of mass, length, time, and so forth, of course, but also on nuclear physics, analyticial chemistry and fundamental material properties, even air and water pollution and dental materials; in NEL (figure 5), on electronics, automation in the mechanical manufacturing industries, building technology, fire research, and safety of consumer products; and, in ICST (figure 6), on computer standards; to name only a few. All this work is required to help provide the measurement methods, data, theory, and associated technology that the scientific community needs for its research; that the manufacturing industries, their suppliers and their customers, including the Government, need either for manufacturing control or for the specifications underlying procurement; and, finally, that governments need for fair and reasonable regulation.

It is a matter of concern to each individual research center in NBS to provide efficient and effective means to deliver needed measurement-related services in its specific field to its customers. It is a matter of concern to NBS management to seek new Bureau-wide means to assure effective services. For example, a central Office of Measurement Services (figure 7) has been established which makes known publicly the measurement services NBS provides, such as its traditional calibration services. This office also plays an important role in developing new measurement dissemination methods such as Measurement Assurance Programs. These Measurement Assurance Programs, or MAPs as they are called because of their acronym, supplement the hierarchical calibration system and provide greater assurance that a measurement is performed with known precision or accuracy. MAPs depend on a particular application of calibrated measurement instruments or artifact standards by the several participating laboratories. Each laboratory retains an artifact which it measures periodically to establish the laboratory's internal precision from charts of its data over time. These measurement results include the effects of errors due to the laboratory's measuring instrument, the operator, the environment, and so on. Periodically an artifact, carefully calibrated by the central laboratory, such as NBS, is circulated among the participating laboratories for measurement. After appropriate treatment of the data from all laboratories by the central laboratory, each laboratory is then able to compare its own mean and standard deviation against those of the central and other participating laboratories, with its own performance maintained private. It is then able to take steps to improve its capabilities if necessary. The most important factor in a MAP program is the evaluation of the complete measurement process as it is actually performed in the laboratory; this evaluation is not available from the usual practice of submission of a standard to the central laboratory for calibration. Incidentally, the central laboratory may also benefit from the MAP through reduced requirements for routine calibrations.

The NBS Office of Measurement Services also conducts studies of new measurement requirements likely to affect the entire Bureau. A recent example is a study of the effect the introduction of the microprocessor will have on, first, the way the Bureau conducts its internal measurement research and, second, the new measurement services that NBS must provide because the microprocessor is expected to change dramatically the way practical measurements are made in science and industry.

Another central office is devoted to standard reference materials (figure 8): to the coordination of the work carried on throughout the Bureau which leads to their development, their production, and their sale. These carefully analyzed materials are made available, along with instructions for their use, as a means of checking the quality of an analytical or other type of measurement at the actual site of performance. Over 1000 different standard reference materials are provided by NBS (figure 9). These cover an amazing range of materials, from spinach, tomato leaves, and pine needles certified for content of over a dozen trace elements such as manganese and lead so that environmental and agricultural scientists can calibrate analytic tools and measurement methods, to highly purified gallium (99.99999% pure) used to provide a temperature reference point (known to 0.0007°C) for control of diagnostic tests in clinical chemistry. Each of these SRMs is of great significance to some industry, research laboratory, or regulating agency.

The metrology-related research at NBS is broad and is increasing in its breadth to meet new requirements. Simultaneously, the services to make its research results available to an ultimate user in the most effective way are of necessity broadening. I have only touched superficially on a few examples of such efforts so far. The subject is far too complex to describe in depth here. So let me pick as an example samples of the work of the Center for Electronics and Electrical Engineering, to give you an impression of the way just one NBS Center is responding to the new challenge in metrology.

3. THE CENTER FOR ELECTRONICS AND ELECTRICAL ENGINEERING

The Center for Electronics and Electrical Engineering provides a focus (figure 10) in NBS for addressing electrical, electronic, and electromagnetic materials, components, instruments, and systems. It provides (figure 11) well-documented and evaluated measurement methods, data, and interpretive theory; physical standards, traceability to these standards or measurement assurance programs; and associated technology and technical services. It provides these to government, industry, and the scientific community, ultimately benefiting the consuming public. These services are essential to equity in domestic and international trade, to control of manufacturing processes, and to the applications of a number of other Federal agencies.

The work of the Center has five principal programmatic thrusts (figure 12), each addressing closely-related technologies, a corresponding market, and technical and societal problems of current significance. These thrusts are in (1) Semiconductor Technology, (2) Fast Signal Acquisition and Processing, (3) Fast Signal Transmission, (4) Electrical Systems, and (5) Electomagnetic Sensing and Hazards. I will treat each of these in turn by describing factors stimulating our work and our responses in measurement research and delivery.

3.1 Semiconductor Technology

Challenge

Semiconductor devices and integrated circuits lie at the heart of the modern electronics revolution (figure 13). Semiconductor technology is therefore central not only to electronics but to the economic and social health of modern industrial societies.

The semiconductor device industry provides extreme challenges for the metrologist. It deals with the purest and most perfect materials known to man and with microscopic and submicroscopic dimensions. It is concerned with trace impurities at concentration levels ranging from parts per trillion to parts per million, with controlled variations in these concentrations which range over several orders of magnitude over a span of less than a micrometer; with dimensional integrity of tenths to hundredths of a micrometer; with circuit element densities of hundreds of thousands of devices per square centimeter; with signals in the gigahertz range; with currents in the picoampere range and less; and with a host of new processing technologies which involve the interaction of radiation with matter, plasma physics, photopolymer chemistry, etc. Despite the great success of this industry in providing new and sophisticated products, it has outstripped available metrology. New and refined techniques are essential for use both in manufacturing control and in the marketplace. In the United States of America, both Federal agencies and industry have called on the National Bureau of Standards to aid in developing this needed measurement technology.

NBS Response

In response, NBS is conducting a broad program in semiconductor measurement technology (figure 14). This program includes research and development on measurement technologies related to mechanical, electrical, and crystallographic properties of finished devices. The program also seeks to develop more effective ways to disseminate this measurement technology. Let me illustrate both this program and the new ways by which NBS must address traditional metrological areas by examples which relate to measurements of length and material properties.

Semiconductor devices are fabricated by changing the concentration of selected impurities in defined regions in a very pure and perfect crystal, usually silicon (figure 15). A photolithographic process is used to define the regions which comprise a device. One of the critical problems in semiconductor device design and manufacturing is the control of dimensions of these regions. Microscopic measurements of features on patterned photomasks and silicon wafers require interpretation of the optical image of a line or a space between lines. The threshold (figure 16) which corresponds to the actual material edge depends on the particular optical system employed in the measurement. For pitch measurements (figure 17), errors in threshold cancel so that accurate measurements on features between edges of the same type (e.g., left-hand or right-hand edges) can be made without accurate knowledge of the threshold. For width measurements, however, errors due to improper selection of threshold add rather than cancel. Until recently, such errors and the resulting inconsistencies between different types of instruments and between laboratories were insignificant. This is no longer so. Apparent differences of 0.25 micrometer or more were observed when measuring lines or spaces with optical instruments using different means for identifying edges such as filar or image-shearing eyepieces. Concern with such errors increased substantially both when process control became more demanding and when it became apparent that feature sizes for future integrated circuits would reach the micrometer and submicrometer range (figure 18). To solve this problem NBS researchers in several cooperating centers extended the existing theory of the optical microscope and developed an automated scanning photometric microscope (figure 19) with a novel laser-controlled stage to make the measurements. With the understanding and techniques developed in this research it was possible to calculate accurate image profiles (figure 20) and threshold levels and to make linewidth measurements accurate to about 50 nm on lines as narrow as 0.5 micrometer. In addition, procedures were worked out to permit accurate measurements of linewidths with the use of suitable instruments available in the field. These techniques are being transferred directly to the industry through the use of workshops (figure 21), which include the opportunity for hands-on measurement of linewidths with the use of a variety of commercially available instruments provided to the workshops through the courtesy of the instrument manufacturers and through a series of new standard reference materials. The first of these, SRM 474 (figure 22), designed for use in measuring opaque photomasks in transmitted illumination, is expected to be available before the end of this year. This standard reference material contains a pattern of lines and spaces in the 0.5- to 10-micrometer range together with other patterns which permit line spacing calibrations and setting of edge-detection thresholds on automatic measuring instruments. Together with the associated measurement procedures (figure 23), this artifact provides the user with the capability of evaluating his own measurement procedure and calibrating his instrument. Artifacts with similar patterns in various layers on silicon wafers and in semitransparent photomasks are planned for the future.

Manufacture of semiconductor devices involves repetitive patterning of the semiconductor wafer by means of photographic processes. Registration of the various layers to submicrometer tolerances is critical. Misregistration can occur because of design errors, photomask fabrication errors, or distortions in the photomasks or in the silicon wafer itself. A microelectronic test structure has been developed which can be used to determine registration errors between selected mask levels (figure 24). The test structure is fabricated on a silicon wafer using manufacturing processes similar to those used for making integrated circuits. The structure is repeated at intervals across an entire wafer. Electrical measurements made with an automatic wafer prober (figure 25) can be used to detect translational, rotational, and distortion errors with a resolution of about 0.1 micrometer. Computer-generated wafer maps of misregistration as a function of position present the information graphically (figure 26). The test structure can be utilized in evaluating photomask generation equipment, photomask aligners and printers, mask aligner operators, and wafer distortion. The range and resolution of the structure itself were determined by means of correlations with specially designed wedge-shaped optical scales which could be measured in a conventional microscope.

Microelectronic test structures (figure 27) have also proven to be very useful in measuring electrical material characteristics. Several years ago a series of test patterns was developed to facilitate determinaton of the relationships between resistivity and dopant intensity, two critically signifcant material parameters in silicon. These patterns (figure 28) contain specially designed microelectronic test structures including a planar square four-probe array for measuring bulk resistivity, a circular junction diode with external field plate for measuring dopant-impurity density, along with other ancillary structures. These patterns also proved to be useful in setting up semiconductor fabrication lines, especially for organizations not previously experienced in this field. More than 60 different organizations in industry, Government, and academia have acquired the mask sets for these patterns. The dopant impurity density distribution controls the electrical activity of a semiconductor device structure. Dopant densities may vary over several orders of magnitude in a region a few micrometers on a side and a micrometer or less deep (figure 29). Numerous complex methods have been developed to measure this variation. A new measurement technique based on the use of a metal-oxide-semiconductor field-effect transisitor (MOSFET) is being investigated (figure 30). This method permits profiles of dopant densities to be measured on a high-speed wafer prober by d-c techniques, and avoids the necessity for preparing special samples, nonstandard surface preparation such as polishing or beveling, insertion of the specimen into a high-vacuum chamber with the use of Auger electron spectroscopy or secondary ion mass spectroscopy, or the use of high-frequency test signals as with capacitance voltage measurements.

A new class of test structures which contain integral electronic circuity to provide signal processing at the point of measurement is being developed for the measurement of very elusive quantities, such as picoampere-level leakage currents. Use of a gated-diode MOSFET structure (figure 31) combined with a throw-away electrometer built into the wafer enables one to measure, by d-c techniques in a short period of time, properties related to defects or impurities in the crystal which control the leakage currents, response time, or storage time of circuits. Use of these integrated test structures makes it possible to map over the surface of a silicon wafer (figure 32) properties such as charge carrier lifetime which can be correlated with crystal defect or impurity densities.

3.2 Fast Signal Acquisition and Processing

Challenge

The development of high-speed signal processing laid the basis for the modern computer and for the information and control revolution that is predicted to be of at least as great significnce to society as the industrial revolution in the nineteenth century (figure 33). The impact of computers, and more recently of microprocessors, in science, in automation of manufacturing and process control, in business and banking, in medicine, in communication, and in defense is too well known to require delineation here.

The advent of digital signal-processing techniques has simultaneously ushered in an important new era for the metrology community. Whereas classical analog standards such as standard (Weston) cells, or Kelvin-Varley dividers, potentiometers, and the like have served well as the basis for calibrating electrical measurement instruments and test equipment, modern electronic instrumentation utilizes fast signal-sampling techniques for which there are few analogous physical standards, adequate characterization methods, and rigorous calibration procedures. The metrology support for important modern instruments and equipment such as digital voltmeters, phase meters, multimeters, oscilloscopes, spectrum analyzers, etc., still often relies on the manual calibration of a few selected parameters and test points based on static laboratory standards. Automation is required (figure 34).

Further, the newest test instruments themselves now have digital signal processing capabilities "built-in" by means of microprocessors and other related data-processing devices. Consequently, the validity of the measurements made by these instruments is dependent on the software algorithms and the integrity of the digital logic, as well as on the data-acquisition hardware. This dependency particularly applies to the evaluation of the performance of complex systems such as automatic test equipment. At present, neither military nor industrial procurement tests of complex automatic test equipment are satisfactory from the point of view of performance assurance.

Nevertheless, there are both national and international requirements for achieving agreement on the performance accuracies of test, measurement, and diagnostic equipments. In the United States of America, for example, there are military contractual agreements with suppliers which require that measuring and test equipment be calibrated using instruments or artifact standards whose calibration in turn is certified as being traceable to national standards at NBS. Similarly, Federal regulatory agencies (such as the Environmental Protection Agency, the Nuclear Regulatory Commission, the Consumer Product Safety Commission, and the Food and Drug Administration) invoke traceability to NBS standards in their regulations and handbooks.

Consequently, a challenge exists in providing the means by which these traceability requirements can be achieved. New physical reference standards which provide for increased ranges for the parameter in question, new test parameters (such as audio-frequency phase angle), dynamic stimulus or measurement capabilities, and the ability to be programmed automatically are required for this purpose. Because in many cases a large number of data points is desired for statistical reasons and because time is often an important factor, automated test and calibration facilities applying these new reference standards must also be developed.

Emerging electronic technologies greatly tax present methods for measuring fast transient phenomena. These new technologies are evolving ultra-fast signal-processing equipment which has been called gigabit electronics. Systems which currently process signals in a strictly analog fashion will become primarily digital in design, and there will be a commensurate revolution in system performance because of the flexibility of digital processing. Whereas narrow-band measurements were satisfactory in the past for characterizing microwave systems, the future emphasis will be on broadband measurements which involve devices such as analog-to-digital converters, samplers, and signal-level discriminators. Signal frequencies will extend into the optical region, with the aid of new optoelectronic devices and circuits and transmission in optical fibers.

Two important new technologies, potential contributors to gigabit systems, are based on gallium arsenide and superconductivity. Gallium arsenide devices are already in wide use. Superconductivity is being applied to experimental computer technology, and the published speeds of operation are impressive (e.g., 13 ps for an "OR" gate operation). These performance levels are beyond current test instrumentation performance. Since the new technology has already moved beyond present test instrumentation capabilities, it is essential that accurate new measurement methods be developed.

Improved methods for dissemination of standards must also be developed in order to provide a more direct traceability link to these new laboratory standards. For complex automatic test equipment, for example, it is not enough to ensure that the built-in secondary reference standards are accurately calibrated at regular intervals. If the adequacy of the software and the interface hardware is not completely verified, the system may be producing inaccurate measurements of the unit being tested. A more direct approach is being considered at NBS for which dynamic transport standards would be developed which are traceable to NBS and can be used in automatic test system calibration verification on site. A system is visualized in which NBS verifies the performance of the highest accuracy transport standards for a relatively small number of key standards laboratories in industry and Government. These organizations would then utilize the high-accuracy transport standards through a minimum of intermediate steps (perhaps employing commercially available standards), to verify automatic test equipment in the field, with the transport standard playing the role of the unit being tested.

NBS Response

The present response at NBS (figure 35) to the support of high-accuracy electronic instrumentation and equipment has as major thrusts the development of new or improved physical reference standards, associated test methods, and calibration techniques; extension of the range of services; and new dissemination means such as transport standards. In many cases the new standards must embody the very technologies which call for their development!

For example, NBS has developed two precision linear digital-to-analog converters to serve as reference standards for completely characterizing the static and dynamic performance of high-accuracy digital-to-analog and analog-to-digital converters such as those used in automatic test equipment systems. One is an 18-bit digital-to-analog converter (figure 36) which has a relatively high current output capability and can, therefore, be used to drive remotely located loads without degrading its output performance. This unit can make 20,000+ conversions per second, has less than one-half least-significant-bit root-mean-square noise, and is intended to be used for testing dynamic performance parameters, such as the settling time of commercially available precision converters.

The second converter standard is a 20-bit unit (figure 37) which consists of a very accurate programmable voltage source having full-scale ranges of ±2.5, ±5, and ±10 V, and less than 1 ppm linearity error relative to the full-scale range.

A test method using this 20-bit instrument has been developed which can accurately measure the output levels of digital-to-analog converters as well as the input transition levels in the transfer characteristics of analog-to-digital converters. A test facility using these techniques (figure 38) is being developed which can scan all possible code states to provide calibration data with 1-ppm resolution on offset, gain, differential and integral linearity errors, and equivalent converter input noise, as well as on monotonicity and missing codes in data converters. A calibration service for data converters using this test facility is planned.

A test method has also been devised for accurately measuring dynamic gain error, signal delay, acquisition time, sample/hold offset, aperture time delay, and related parameters in sample-and-hold amplifiers. A prototype transformer-ratio-arm bridge circuit is being developed which presently can make amplitude measurements on ac signals up to 50 kHz with bridge errors to within 50 ppm and can make time measurements with errors of 4 ns. Extension of this work to provide these measurements on higher frequency signals is planned.

Precision waveform sources using digital synthesis techniques are being developed to serve as standards for calibrating the dynamic performance of instruments and equipment. One source is a programmable audio-frequency phase-angle standard (figure 39). This instrument will provide a pair of precision sinewave output signals whose relative phase difference is accurate to ±0.005° from 20 Hz to 5 kHz. A new calibration service for commercial phase-angle meters is to be provided using this standard. The frequency range coverage will be extended.

An example of precision digital signal acquisition and processing is an ac voltmeter (figure 40) which can take samples from low-frequency ac waveforms over a range of 0.1 to 120 Hz and determine the rms value, period or fundamental frequency, and total harmonic distortion in a time of only two periods of the input signal to an accuracy of 0.1%, or better.

At the other extreme, in support of high-speed time-domain measurements and related instrumentation, NBS is developing systems for the measurement of waveforms of optical and electrical signals that are consistent with one another, are referred to a common set of basic standards, and are capable of a time resolution of 10 ps.

The NBS Automatic Pulse Measurement System (figure 41) is a digital computer-controlled system that acquires time-dependent data from electrical or optical pulses or signals, and processes the acquired waveforms in order to estimate pulse shape or pulse response, signal correlation functions, and complex spectra.

Typical time-domain standards associated with this system include transition duration transfer standards, impulse generators (figure 42), and a time-domain antenna range (figure 43) for the production of standard pulsed electromagnetic fields.

Further, in support of the measurement technology and standards required by the emerging gigabit electronics, NBS is studying the technology of superconductivity and the potential 1-ps switching time of Josephson junctions (figure 44). The objective is to press toward the limits in speed and accuracy of electronic measurements which may best be achieved by superconductor techniques. Circuitry similar to the lower-speed signal sources, converters, and sampling units mentioned earlier will be required. Work on these is underway. For example, a 4-bit analog-to-digital converter (figure 45) based on Josephson junctions and employing 5-micrometer linewidth lithography has been developed. It operates in the range of hundreds of megasamples per second.

Practical superconductor measurement instruments will require practical refrigeration systems to avoid the use of liquid helium or bulky and electrically noisy refrigerators. A Stirling refrigerator (figure 46) has been developed which can reach liquid helium temperatures.

It will be a long time before the superconductor work produces a calibration service! In the meantime, the technolgy developed is promptly made available to other research and development organizations through a variety of means.

3.3 Fast Signal Transmission

Challenge

The emergence of fast signal electronics (figure 47) and of other technological advances, such as satellite systems, lasers, and optical fibers, is having a dramatic impact on signal transmission for telecommunications, navigation, and remote sensing.

Telecommunications is in a period of rapid expansion as markets develop in geographically remote parts of the world and in the business sector of industrialized nations. The technologies of satellite microwave signal transmission, optical fiber signal transmission, and of computers are driving forces. Satellite communication systems, which can employ small low-cost earth terminals, are ideally suited to serve remote locations. The proliferation of computers in all aspects of business is creating a large volume of traffic in digital data. Satellite and optical fiber systems offer broad bandwidth for communication and are well adapted to the growing trend away from direct AM or FM transmission of audio or video signals and towards digitized signals using pulse-code modulation and time-division multiplexing. They are thus excellently suited for business communications.

Both satellite and optical fiber transmission technologies depend for their commercial success on pressing the practical limits of detecting weak signals and of discriminating against noise and interference. Hence they are both very measurement sensitive. The metrology demanded in support of these developments must cover an increasingly wide dynamic range and spectrum of frequencies. Also, it must provide for characterization of components and signals with fine resolution in the time domain.

Developing navigation and remote-sensing applications include collision-avoidance systems and microwave landing systems for aircraft, satellite-based navigation systems, and new radar and laser sensing systems.

The advent of the small computer has made a dramatic improvement in the information that can be obtained from radar reflections. This has led to very complex systems using large, phased-array antennas. There are many advantages for these systems in using shorter wavelengths than hitherto, and after many years of unfulfilled promises serious development work is in progress at frequencies up to 300 GHz. Because of the existence of dense absorption bands in the atmosphere, the natural extension of this trend will be a leap to the other side of the bands in the infrared, where there are powerful laser sources at wavelengths of 10 micrometers and shorter. These are used in many military systems under development for surveillance, the guidance of weapons, and even as destructive weapons.

These advances lead to requirements for an extension of measurement capabilities to cover higher microwave and millimeter wave frequencies, and very high laser power and energy at 10-micrometer and shorter wavelengths. Less obvious but extremely demanding is the need for low-energy measurements. Equipment to evaluate laser guidance systems must be capable of measuring radiation at a level of 10^{-16} J. At 1.06 micrometer, this corresponds to only 500 photons in a pulse.

NBS Response

To support development and trade in signal-transmission technology, NBS is responding (figure 48) in areas which include microwave and millimeter wave components, antennas, satellite ground stations, optical fibers, and lasers. NBS has provided RF and microwave measurement services for many years. The character of these services is now changing dramatically in response to the changing demands of the technology and the markets they support.

Ten years ago, microwave calibrations were performed on accurately made and carefully tuned manual systems (figure 49). Accurate workmanship and patient tuning were at a premium. This mode of measurement became obsolete as microwave measurements covering a wide spectrum of frequency were required to support broadband systems, and the time taken for retuning at each change of frequency became an intolerable disadvantage.

New measurement systems, known as automatic network analyzers (figure 50), have substituted complexity of computation for accuracy of workmanship and operator skill. They operate under the control of a computer and calibrate themselves with the aid of simple check standards at each frequency at which measurements are to be made. Raw measurement data are stored in the computer, which then applies the appropriate corrections to the measurements automatically. The accuracy of each individual measurement is not significantly changed from the manual measurement, but the great speed and efficiency of the new technique provide a great economy in measurement, and enable a much more thorough characterization to be made of the device measured.

An excellent example of the new style of measurement system is the 6-port, which was invented at NBS several years ago and is now in an advanced stage of development. It is based on the general properties of waveguide junctions with six ports (figure 51). Typically, one of the six ports is connected to a signal generator, another defines the plane at which measurements are to be made, and the other four are connected to simple amplitude detectors, such as diodes or bolometers. No phase measurements are made. General microwave scattering theory leads to a set of simultaneous equations that relate the complex description of the wave at the measuring port to the amplitudes observed at the four amplitude-measuring ports.

Probably the most generally useful 6-port system employs two 6-port junctions powered by a common signal source to form an automatic network analyzer (figure 52). The combined calibration routine for the two 6-ports can be particularly elegant, and requires no calibrated standards if measurements of dimensionless ratios (such as attenuation and phase shift) are to be made. Measurement of quantities (such as power and impedance) that have dimensions require a single standard of each. When calibrated, the dual 6-port can measure all the characteristics of any 2-port device, active or passive.

The complete dual 6-port system (figure 53) is quite compact, because its operating principle does not require frequency conversion to measure phase, as other automatic microwave measurement systems do. A programmable desk calculator is used to control the measurement process and to compute the results. This system now operates in the range from 2 to 18 GHz. Its accuracy and stability have been evaluated. For attenuation measurements, for example, systematic error varies from 0.001 dB at 15 dB to 0.15 dB at 60 dB. The dual 6-port needs recalibration only at intervals of several months to maintain this accuracy.

Because it does not rely for its accuracy on the calculable properties of its components, the 6-port principle will be a powerful tool for extending the range of microwave measurements into the millimeter wave part of the spectrum. A 6-port system operating at 95 GHz is already under construction at NBS.

Control of errors made in microwave measurements in the field can be improved by better dissemination of reference standards. To accomplish this, a new measurement assurance program is planned.

In addition to the measurement on microwave circuit components, NBS provides a measurement service for complex antennas (figure 54). In one of the techniques, the near field (figure 55) of the antenna is scanned systematically to measure phase and amplitude over the whole beam. From this information, the far-field radiation pattern (figure 56) is reconstructed automatically by a computer. The accuracy is as great as any that can be obtained on a farfield antenna range, while freedom from environmental effects and from the use of extensive outside ranges offers many advantages.

Another measurement system developed at NBS evaluates the performance of satellite communication ground stations (figure 57), using a radio star for reference.

Optical fiber (figure 58) communication systems will ultimately require measurement services and standards comparable to those presently provided for microwaves. Measurement systems for attenuation, power, and bandwidth are under development (figure 59).

The work at NBS on laser measurements is based on standards of power and energy such as calorimeters (figure 60). They are used to provide measurement services that are heavily used by manufacturers of laser systems, who have to prove their compliance with laser safety regulations.

The range of laser power and energy measurements is wide. At one end, a laser and electro-optic pulse shaper are used to evaluate detectors at 10.6-micrometer wavelength and high power densities. The laser generates pulses of nanosecond duration and peak power densities of 25 MW/cm^2. At the other end of the scale, a system to measure laser energy at the 10^{-15} J level has already been developed and evaluated.

3.4 Electrical Systems

Measurements at low frequency and very high voltage and power are important to researchers in high-energy atomic and molecular phenomena, manufacturers and users of medical x-ray equipment, and in the defense industry, but clearly the primary application is in the electrical power industry.

The world's energy crisis has drawn attention to all energy-producing and distributing activities, including those that relate to the distribution of electrical energy (figure 61). As petroleum-based resources become depleted, the emphasis will have to be on greater utilization of other resources such as coal and nuclear energy. Electricity is often the only form for end use. Thus the growth of electric energy consumption is expected to continue at nearly the historic rate, doubling in the United States of America in ten to fifteen years in spite of reduced growth in total energy consumption.

New technology is needed to transmit electrical energy in an acceptable manner. Specifically, the power energy density of available rights-of-way must be increased. One way to achieve this increase is to transmit power at higher voltages.

Overhead transmission at extra high voltage levels (EHV), from 345 kV to 765 kV, has already been introduced. Experimental transmission lines are being tested at ultra high voltages (UHV), above 1 MV. There are objections to overhead lines on environmental grounds. They are considered to be unsightly, and there are concerns about potentially adverse biological effects resulting from high electric fields under such lines.

Underground transmission overcomes environmental objections, but is perhaps 10 to 20 times more costly to install and operate. Underground lines also have higher losses and are to date less reliable. Hence, underground lines are presently used for very short distances only in locations where overhead lines would be unacceptable, e.g., in densely populated urban areas.

There are great challenges to develop less costly, higher capacity, and more reliable underground transmission systems. Alternatives being explored are SF_6-insulated lines, cryogenic lines, and lines with synthetic liquid and solid insulators. In each case, new material property data and test methods for line performance are required.

Advances in electronic and computer technologies are affecting the control and monitoring of the electrical power systems and the consequent need for new metrology. In high-capacity power systems, decisions about faults and their clearances must be accomplished within a fraction of a cycle. Electrical quantities in power networks must be sensed and measured with increasing accuracy. Efforts are being made to reduce generating peaks and to implement rate structures which will take into consideration varying costs of supplying electricity during a day or season; load management and variable-rate metering are emerging; new instrumentation will call for new calibration and measurement services.

NBS Response

In the past, NBS has been responsible for providing primary standards upon which electrical energy metering in the United States of America is based, ranging from watthour meters for individual users to instrument transformers used in intersystem metering, and encompassing numerous other related measurement services for power systems (for example, for high-voltage and power-factor correction capacitors, and dividers to measure high AC, DC, and transient voltages) with the emphasis on measurements under very controlled laboratory conditions.

The trends in electrical power transmission technology are placing new demands on NBS services (figure 62). The necessity is arising to provide higher voltage measurements on the user's site. New measurements are required for environmental investigations. New measurements are required to aid the industry to develop new underground transmission technology. And improvements in accuracy are required to support advances in modern instrumentation and data processing.

Extensions of voltage ranges and calibrations in the field are necessary in connection with voltage measurements, both steady state and transient, in the EHV and UHV ranges. Power-line voltages in these ranges are measured by first reducing them by means of a capacitative voltage transformer (figure 63) as opposed to the more conventional inductive divider used at lower voltages. Capacitive transformers do not have the intrinsic stability of their inductive counterparts. Hence periodic rechecks after initial installation are desirable, and are becoming even more important as metering errors become more costly. It is impractical to dismantle capacitive transformers and bring them back to the laboratory for calibration. NBS, in collaboration with the Electric Power Research Institute, has developed a transportable system for on-site calibrations (figure 64).

Similarly, since the ratio of an impulse divider is very much affected by the laboratory environment due to stray capacitances, unique grounding systems, and electromagnetic coupling with other equipment, NBS performs impulse calibrations in the customers' laboratories (figure 65).

Measurements related to power-line environmental impacts -- potential hazards -- have been undertaken; they will be treated later in connection with electromagnetic hazards work.

Measurement support is provided by NBS for industrial development of new transmission technologies, particularly for underground transmission. These are measurements to aid in the understanding of the processes of insulation failures. For example, we are developing measurement methodology, based on both electrical and chemical techniques, to assess the deterioration of insulating gases in the presence of low-level corona. Analysis of the frequency and the energy distribution of corona pulses is performed; simultaneously, minute chemical changes in the gases are monitored with a mass spectrometer and gas chromatograph (figure 66).

In related work, the electro-optic Kerr-effect and high-speed photographic techniques are employed to diagnose submicrosecond electrical prebreakdown events ("trees" in liquid insulators and at liquid-solid interfaces; figure 67).

Recently, electronic power-metering instruments (figure 68) have appeared on the commercial market having stabilities in the field of the order of ±0.1%, an order of magnitude better than traditional electrodynamic meters. The appropriate NBS services have been improved to provide better than 0.01% accuracy. For dissemination of standards to this accuracy, the conventional method of the customer sending his standard to NBS has proved to be inadequate. A measurement assurance program for this service has been implemented.

3.5 Electromagnetic Sensing and Hazards

Challenge

We are witnessing in the United States of America a rapid proliferation of sources of electromagnetic radiation for industrial, safety, law enforcement, broad-casting, citizens band, and defense applications (figure 69). Examples include over nine million commercial transmitters and 30 million citizens band radios; the 40,000 circuit miles of overhead EHV electrical transmission lines; an estimated four million microwave ovens; as well as arc welders, combustion engine ignitions, electric motors, and so on.

On the other hand, we are also witnessing an explosion of applications of electronics: for control of household appliances, transportation systems, business machines, industrial manufacturing and processing, medical diagnostics, and patient care. All of these electronic controls are susceptible to interference from stray electromagnetic radiation whose effects may range from a temporary disruption of function, to subtle alteration of commands in a microprocessor, to complete failure.

Another aspect of the problem is the effect of electromagnetic radiation on living organisms. While the research results on hazardous effects of electromagnetic radiation on biological systems are still the subject of much disagreement, it is becoming increasingly accepted that this radiation can cause changes, for example, to the nervous sytem and immunological defense systems, at levels below that associated with thermal heating of tissue.

Electromagnetic radiation is also employed for beneficial uses. There is increasing recognition that electromagnetic radiation can provide a tool for the nondestructive evaluation of materials and structures, both manmade and natural, to determine structural integrity and consequent safety. Potential applications of this technique include determining coal seam thickness in coal mine ceilings and the curing rate of concrete, detection of flaws in earthen dams, and sensing of water content of soils and snow.

Common to both the applications of electromagnetic radiation and the problems resulting from such application is the need for suitable measurement methods and instrumentation to characterize the electromagnetic environment, to assess the susceptibility and emission characteristics of electric components and systems, and to apply electromagnetic radiation for public benefit. In addition, mechanisms for the delivery of measurement services must be developed for potential users in governments and in the private sector to ensure proper application of measurement techniques and instrumentation and to facilitate compliance with regulations for public health and safety.

NBS Response

The response to the measurement requirements associated with the effects of electromagnetic radiation on biological systems and electronic equipment is a growing effort at NBS (figure 70). The heart of the problem is that there is an inadequate measurement base for determining either the electromagnetic environment at any point in time or the susceptibility of electronic systems to the electromagnetic environment. The problem is complicated by the fact that measurement of amplitude, phase, frequency, polarization, and spatial coordinates as a function of time is required in order to obtain an accurate picture of the radiation environment. Typically, measurements are made of signal amplitude as a function only of frequency. However, significant information can be lost unless one also measures frequency response as a function of time (figure 71). Another aspect of the measurement problem is the need for isotropically sensitive probes.

Instrumentation to make such measurements must be capable of dealing with complex fields, such as those with reactive near-field components, multipath reflections, arbitrary polarization, multiple frequency components, complicated modulations, and large field gradients. No instrument is available that can actually measure power density in the near field, although this is the quantity on which most radiation exposure limits are based; no single probe has been developed that can cover the frequency range of concern (dc to 3000 GHz); nor is there a calibration technique available for present measurement instrumentation.

NBS is currently developing such calibration and measurement techniques, and associated instrumentation, including appropriate probes. For example, NBS has developed an apparatus, the transverse electromagnetic (TEM) cell (figure 72), for testing both electromagnetic emissions and susceptibility to electromagnetic interference of equipment placed inside. The cell's frequency range is from dc to a wavelength which is proportional to the cell's size. The cell can accommodate a test electronic package as large as one-third the volume of the upper-half space without varying the electric field strength by more than one percent from predictable empty-cell values. This development has already found wide application in industry. It is also beginning to find applications in bioeffects research.

To measure electromagnetic fields, NBS has developed several sensitive electric and magnetic probes in response to the requirements of Federal regulatory agencies concerned with health and safety, and of military agencies concerned with weapons reliability. Examples include the following: for the National Institute for Occupational Safety and Health, electric- and magnetic-field probes for the frequency ranges 10 MHz to 500 MHz and 10 MHz to 40 MHz, respectively; for the Bureau of Radiological Health, an isotropic hazard meter with a frequency range of 300 MHz to 3GHz; and for the military, and electromagnetic monitoring system, covering the range 10 KHz to 18 GHz, to protect sensitive electronics in weapons. This monitoring system has been engineered for easy adaptation to commercial manufacture. It may also serve as a hazards monitor for safety in the industrial workplace. Most recently, NBS has incorporated three tiny dipole-diode field sensors, in an orthogonal array (figures 73 and 74), to provide an electric-field probe designed to operate from 500 kHz to 1 GHz. It is 100 times more sensitive than commercially available units. This probe (figure 75) was specifically designed and engineered for commercial manufacture to encourage its use.

In related efforts, mentioned earlier, we are working with the Department of Energy to ensure accuracy of measurements of electric and magnetic fields and ion currents in the vicinity of actual high-voltage transmission lines (figure 76) and in simulated environments where studies are conducted on the bioeffects of these 60-Hz fields; and for the Bureau of Radiological Health, we provide the measurement services and calibrations underlying the enforcement of Federal safety regulations covering lasers.

NBS is concerned with the correlation of electromagnetic scattering properties with material and structural properties such as moisture content, stratification, and porosity so that electromagnetic scattering measurements can be better applied to testing of materials and structures.

An example is the application of electromagnetic measurements to requirements in the mining of coal (figure 77), underlying both mine safety and energy production. NBS has developed a radar-like technique (figure 78) based on the relationship of the physical properties of the various strata and structures found in mines to changes in phase and amplitude between the propagating and reflected radiation. This technique can be used to determine the structural integrity of the coal mine shaft or tunnel. NBS is working directly with other Federal agencies to assure transfer of this technology to application in automated coal-mining equipment.

4. CONCLUSION

Let me conclude by expressing the hope that I have made my message clear: While the provision of traditional metrological standards and services is the foundation of national and international measurement systems, new demands and opportunities face those responsible for the success of such measurement systems. Rapidly advancing technology, and its impact on science, industry, and governmental functions, bring with them demands on measurements for research, manufacture, procurement, and regulation which go beyond traditional concerns of metrological organizations. Yet these organizations, I believe, have a responsibility, a knowledge, and a dedication with respect to the science and technology of measurement, that transcend those of the organizations which desperately need new practical measurement capabilities beyond those now available to them. Thus it is that metrologists should look to the emerging needs and provide the exciting new methods, standards, and services required. My examples from the work at NBS give just a flavor of the way one national laboratory dedicated to metrology is addressing these challenging measurement problems.

Acknowledgment

The assistance of members of the Center for Electronics and Electrical Engineering in the preparation of this review is gratefully acknowledged. The aid of W.M. Bullis, R.A. Kamper, C.K.S. Miller, O. Petersons, J.F. Mayo-Wells, and C.E. Hood is particularly appreciated.

NEW TECHNOLOGY CHALLENGES METROLOGY

Figures 1 - 78

Fig. 1 Aerial View of Gaithersburg, Maryland NBS site.

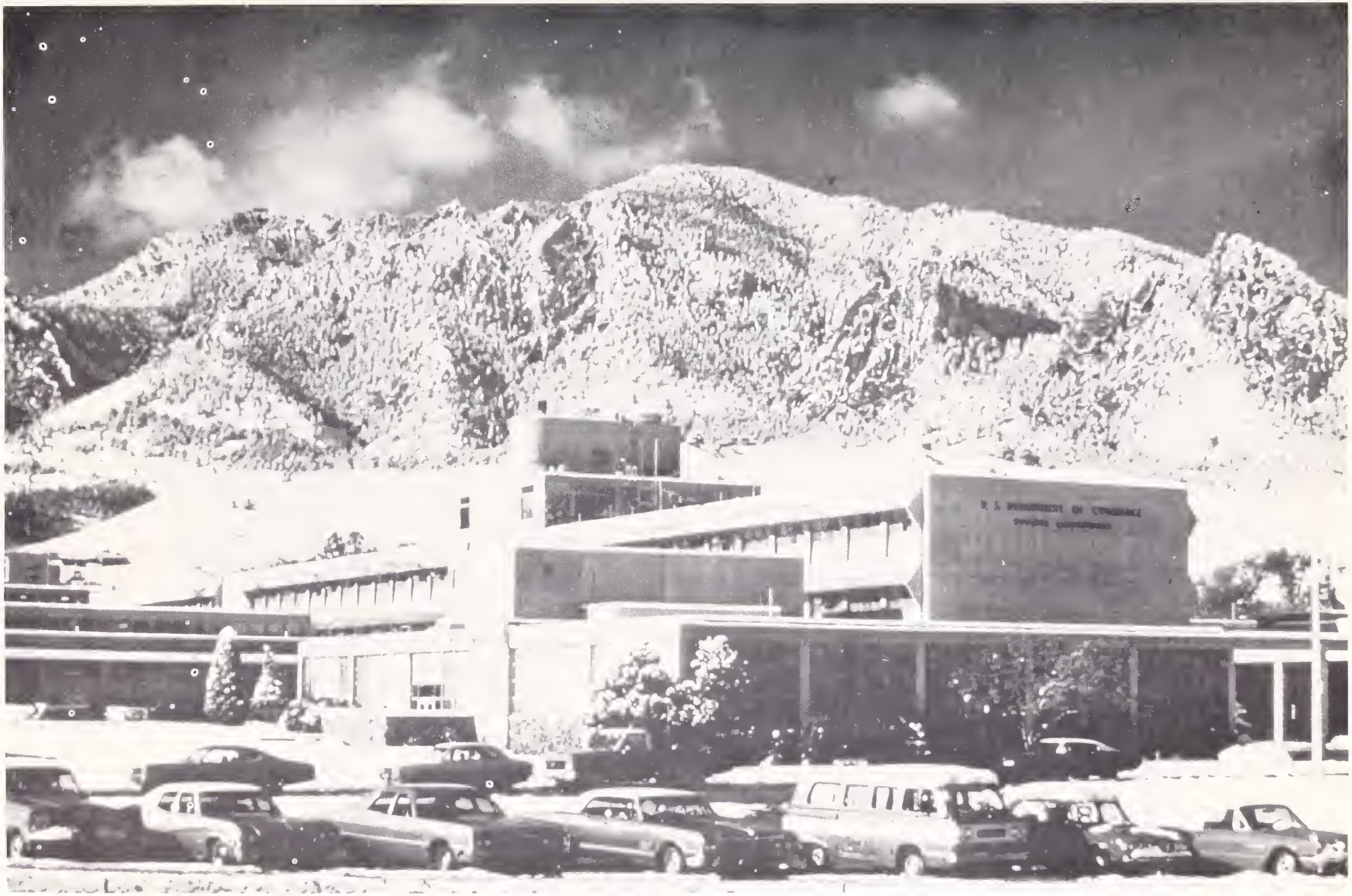
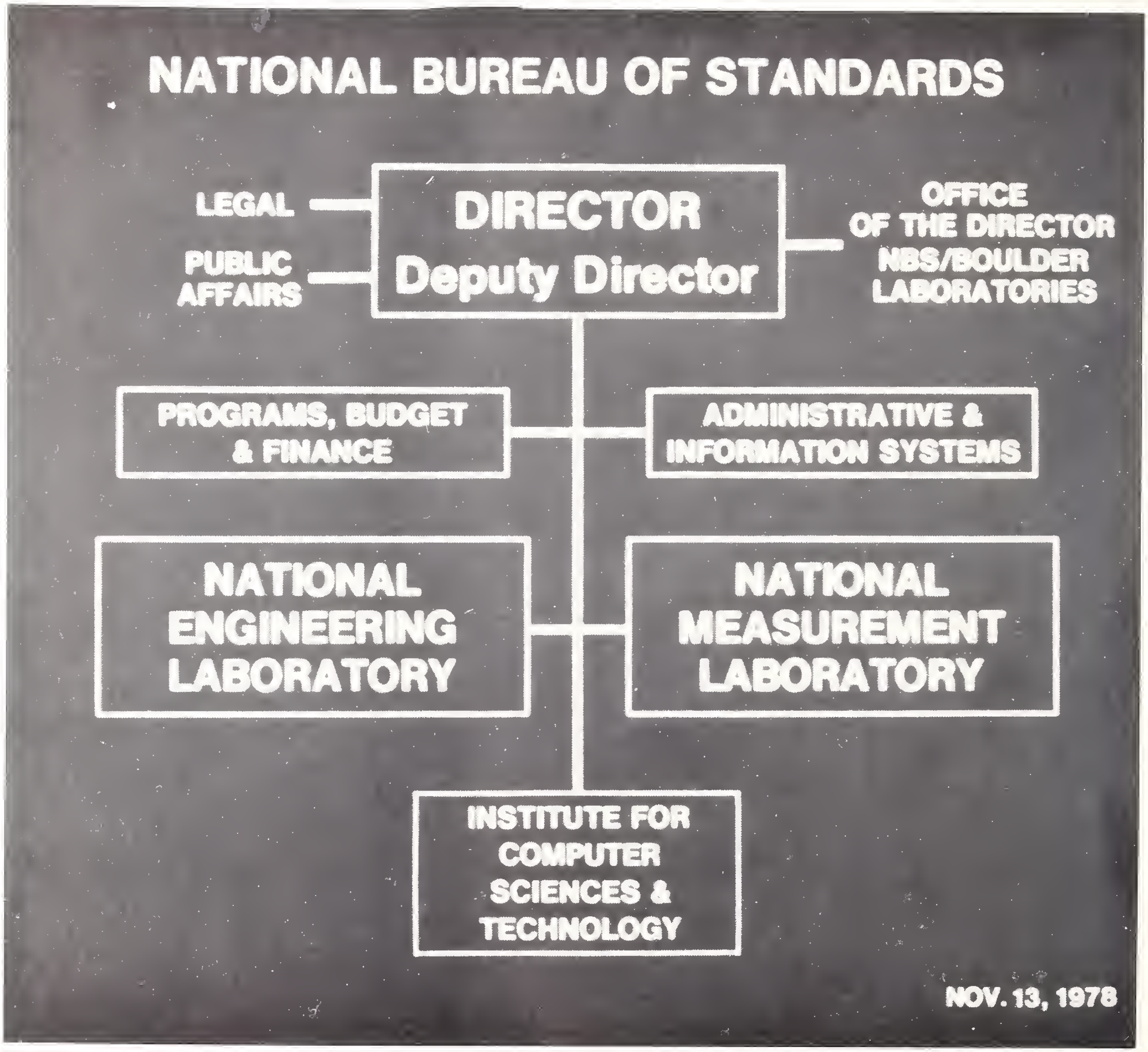


Fig. 2 Principal building at Boulder, Colorado NBS site.



NATIONAL BUREAU OF STANDARDS

LEGAL

PUBLIC AFFAIRS

DIRECTOR
Deputy Director

OFFICE OF THE DIRECTOR NBS/BOULDER LABORATORIES

PROGRAMS, BUDGET & FINANCE

ADMINISTRATIVE & INFORMATION SYSTEMS

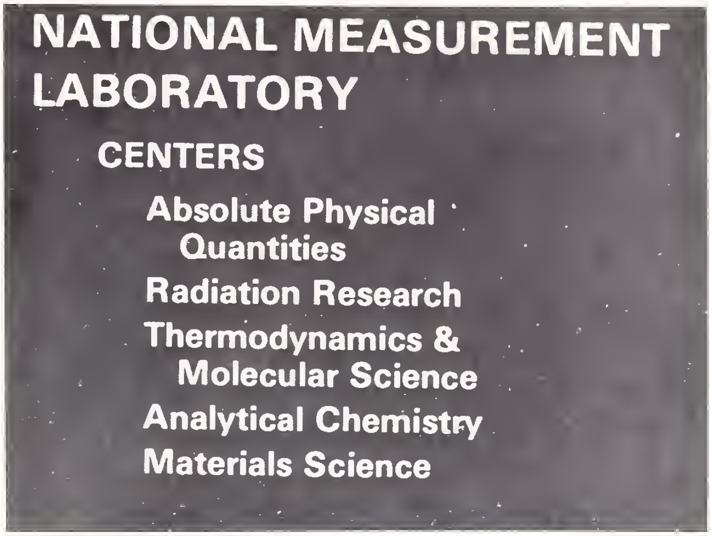
NATIONAL ENGINEERING LABORATORY

NATIONAL MEASUREMENT LABORATORY

INSTITUTE FOR COMPUTER SCIENCES & TECHNOLOGY

NOV. 13, 1978

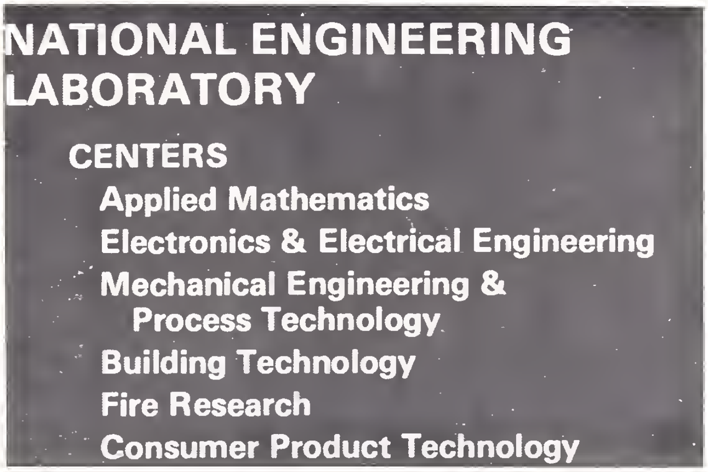
Fig. 3 NBS Organization chart.



NATIONAL MEASUREMENT LABORATORY

CENTERS

- Absolute Physical Quantities
- Radiation Research
- Thermodynamics & Molecular Science
- Analytical Chemistry
- Materials Science



NATIONAL ENGINEERING LABORATORY

CENTERS

- Applied Mathematics
- Electronics & Electrical Engineering
- Mechanical Engineering & Process Technology
- Building Technology
- Fire Research
- Consumer Product Technology

INSTITUTE FOR COMPUTER SCIENCES AND TECHNOLOGY

CENTERS

- Programming Science & Technology
- Computer Systems Engineering

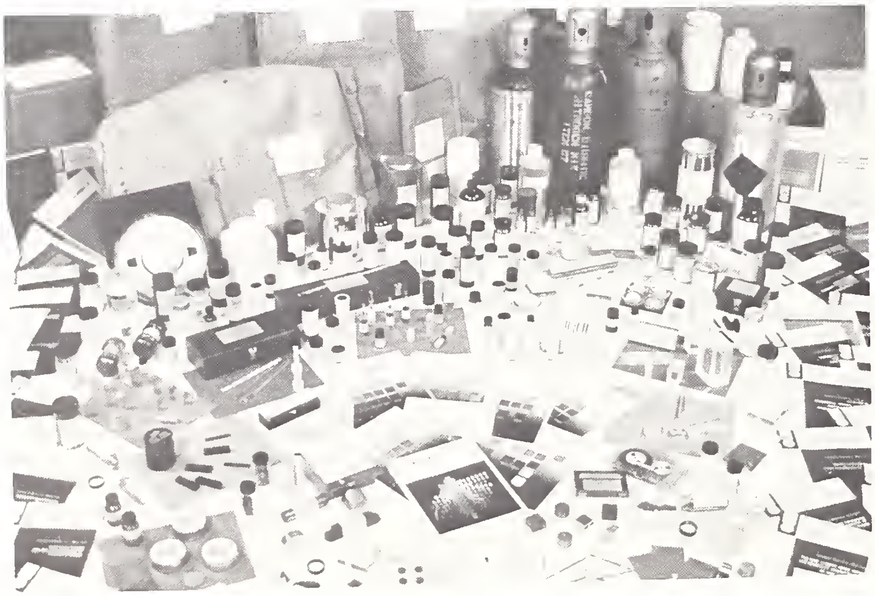
Figs. 4,5,6 Major organizational constituents (centers) of NBS National Measurements Laboratory, National Engineering Laboratory, and Institute for Computer Sciences and Technology.

Office of Measurement Services

- Calibration Services
- Measurement Assurance Programs
- New Measurement Requirements

Office of Standard Reference Materials

- Coordination of research and production of Standard Reference Materials
- Sale of Standard Reference Materials



Figs. 7,8,9 Activities of NBS Office of Measurement Services and Office of Standard Reference Materials, with photograph illustrating diversity of standard reference materials provided by NBS.

CENTER FOR ELECTRONICS AND ELECTRICAL ENGINEERING

Provides focus in NBS

- Research, development and applications
- Electronic and electrical materials and engineering

CENTER FOR ELECTRONICS AND ELECTRICAL ENGINEERING

Provides	To	For
Measurement methods	Government	Trade
Data	Industry	Manufacture
Standards and traceability	Scientific community	Application
Technology		
Technical services		

CEEE Programs

- Semiconductor Technology
- Fast Signal Acquisition and Processing
- Fast Signal Transmission
- Electrical Systems
- Electromagnetic Sensing and Hazards

Figs. 10,11,12 The Center for Electronics and Electrical Engineering's focus, services, clientele, and technical program areas.

SEMICONDUCTOR TECHNOLOGY

Significance

- **Underlies the electronics revolution; central to success of industrial societies**
- **Metrology required for manufacturing control and the marketplace exceeds the state of the art**

SEMICONDUCTOR TECHNOLOGY

NBS Response

- **Measurement methods for:**
  - **Semiconductor material properties**
  - **Process and assembly control**
  - **Device testing**
- **More effective means to disseminate the methods**

Figs. 13,14 Semiconductor Technology Program - metrological significance and challenge and NBS response.

Fig. 15 The starting material for integrated circuits: a single-crystal ingot of high-purity silicon, and slices.

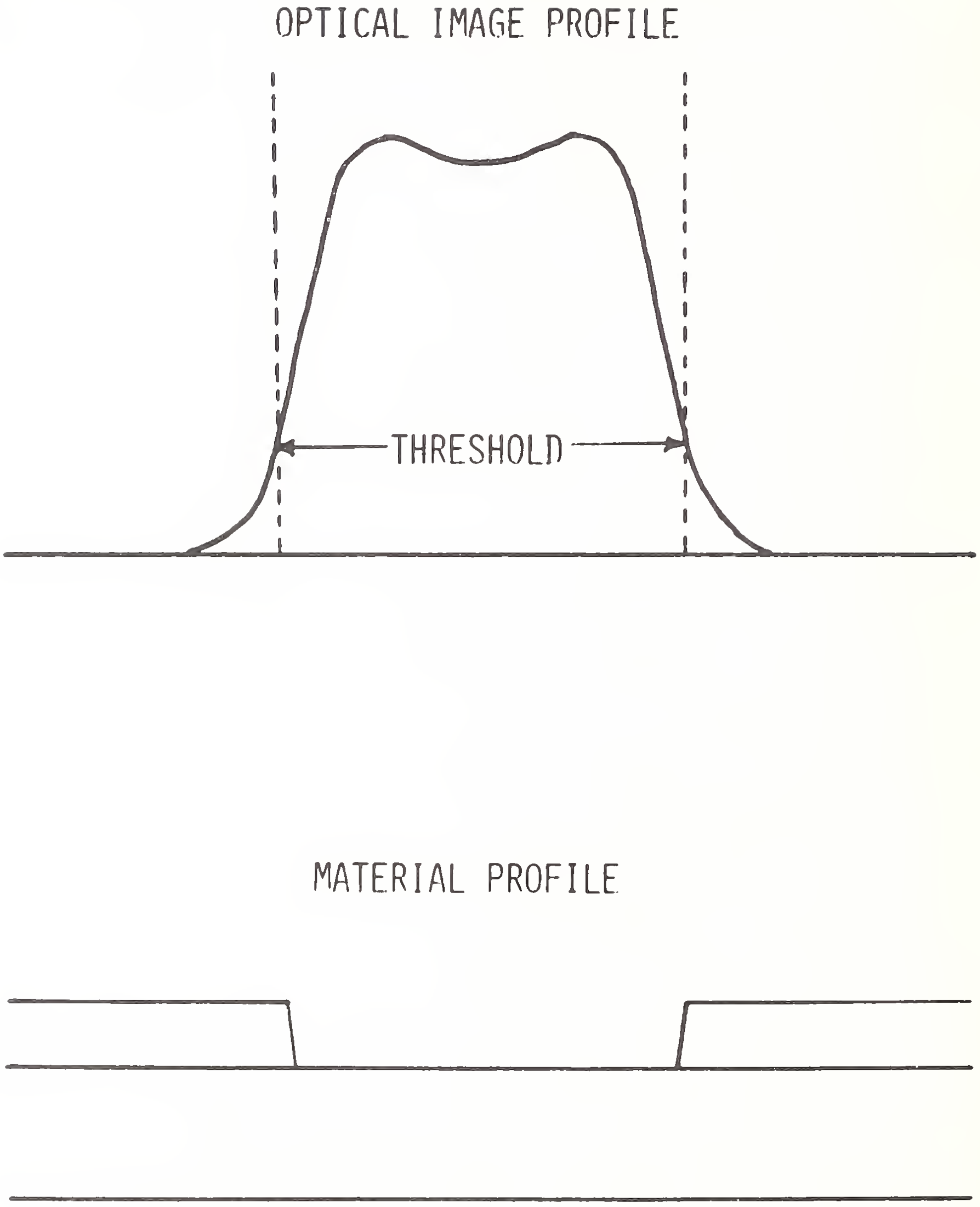


Fig. 16 Uncertainty in the definition of edges in the optical image profile of material steps.

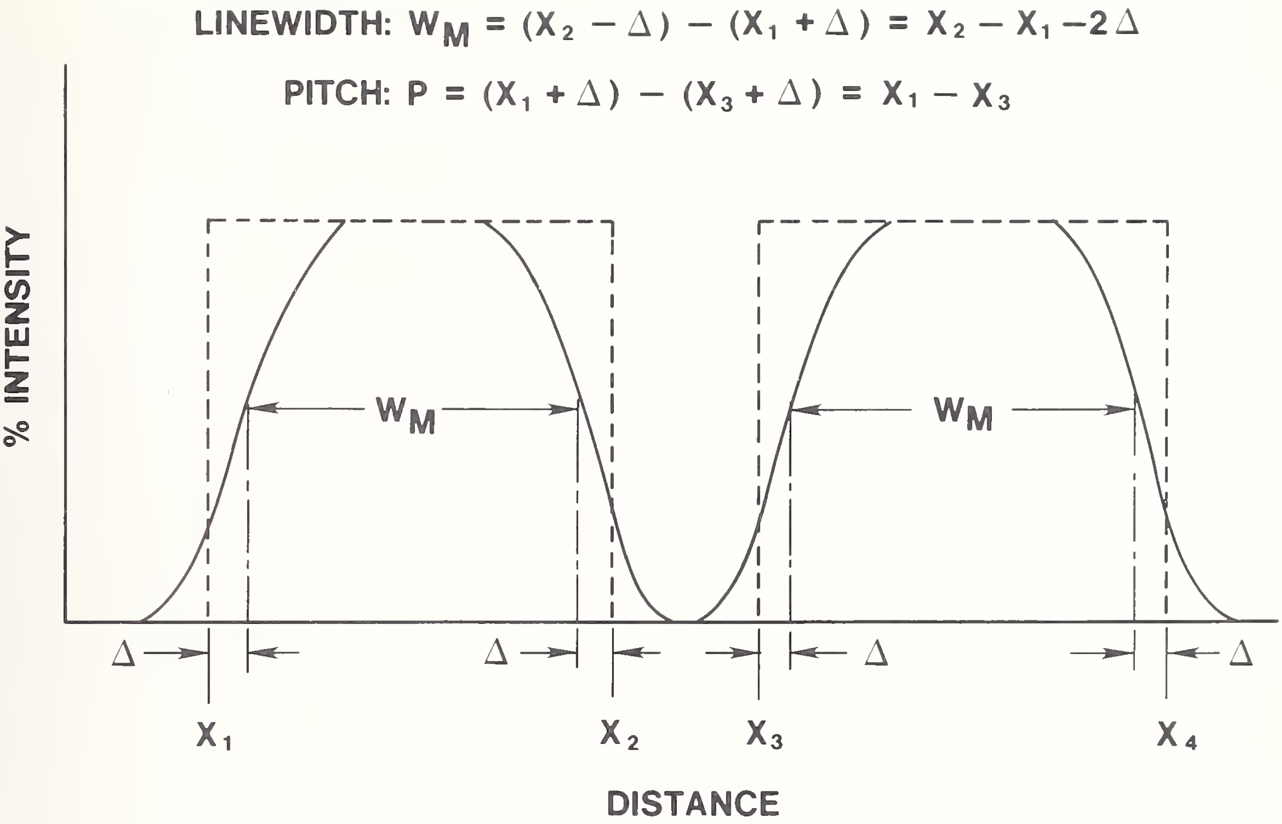


Fig. 17 Measurements of linewidths are subject to edge uncertainty Δ, whereas measurements of pitch are not.

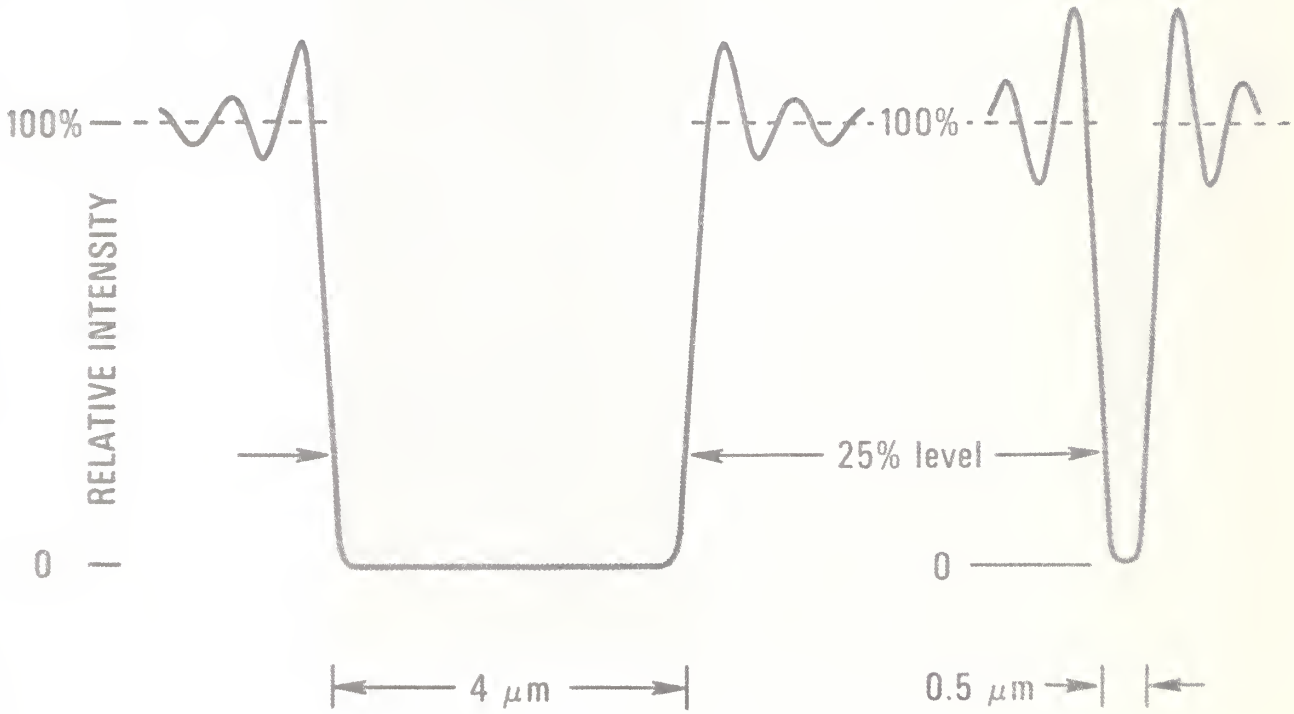


Fig. 18 Problems with edge definition become more acute proportionally as feature size becomes smaller.

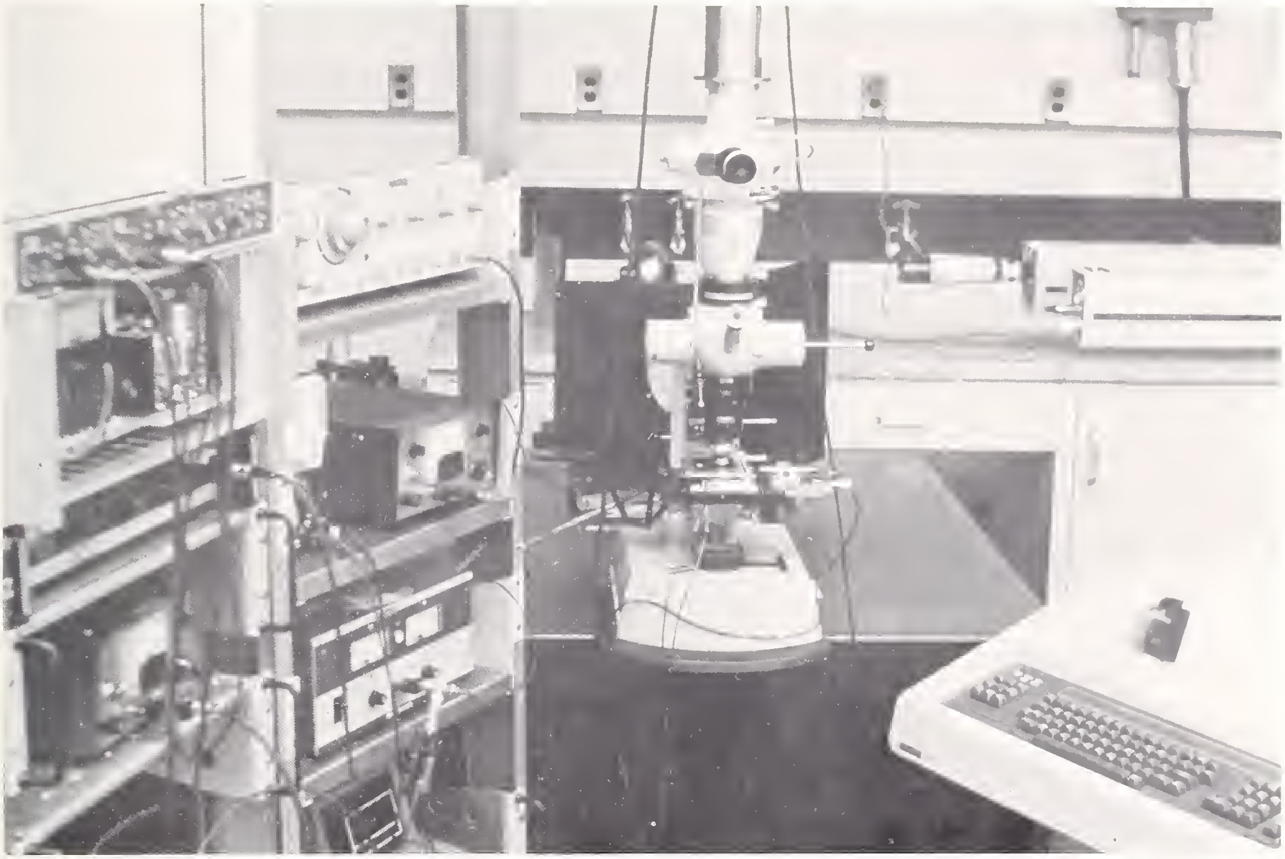


Fig. 19 NBS-developed automatic scanning photometric microscope for linewidth measurement.

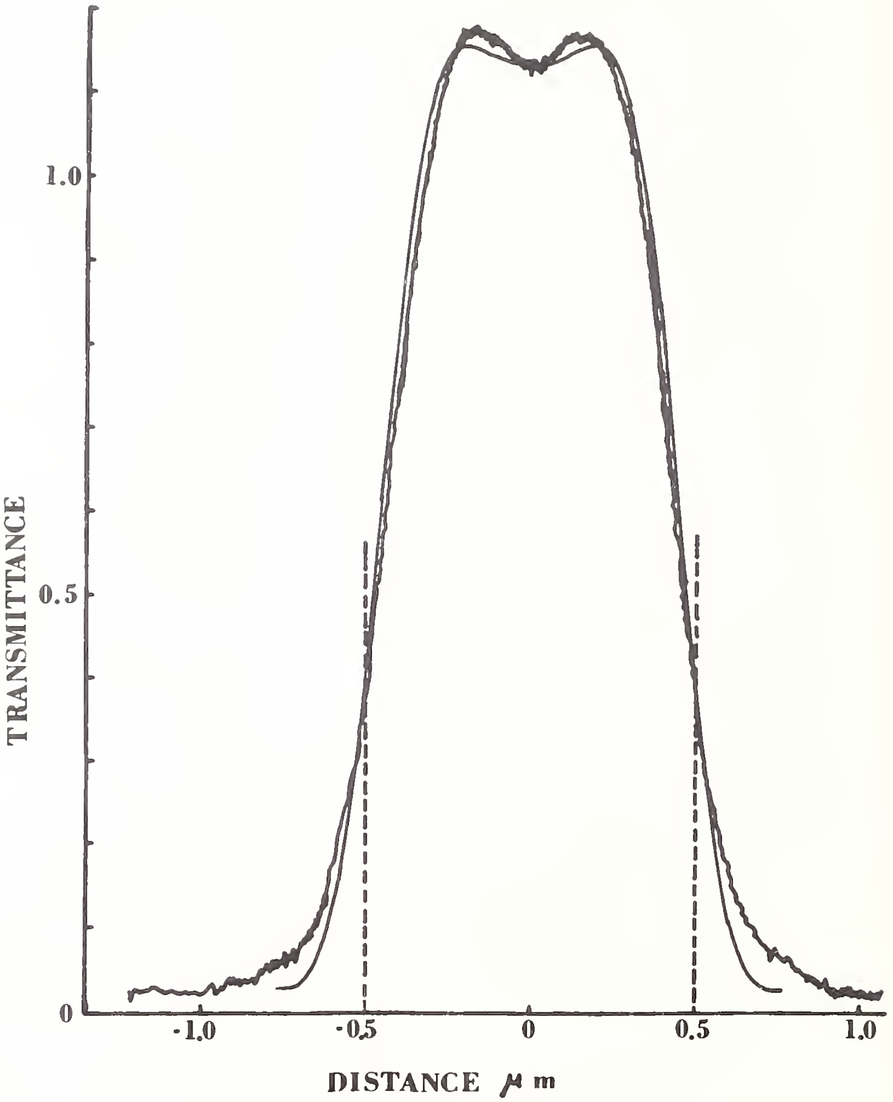


Fig. 20 Comparison of theoretically predicted profile (smooth line) with profile obtained with the photometric microscope.

Fig. 21 Dissemination is an important part of CEEE programs. This photograph was taken during a special training seminar on linewidth measurement attended by industrial representatives who need to be able to make the measurement in their daily work.

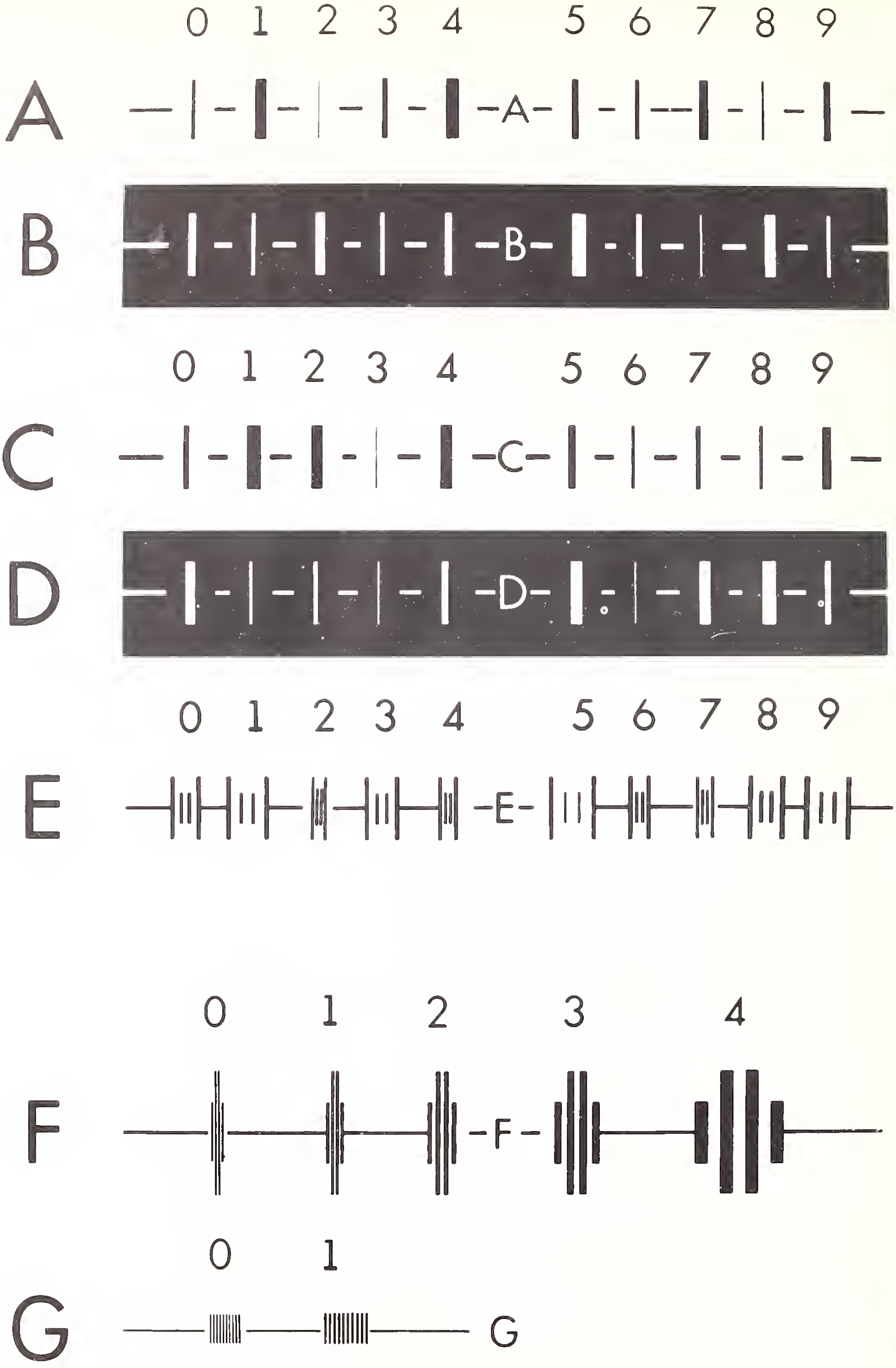
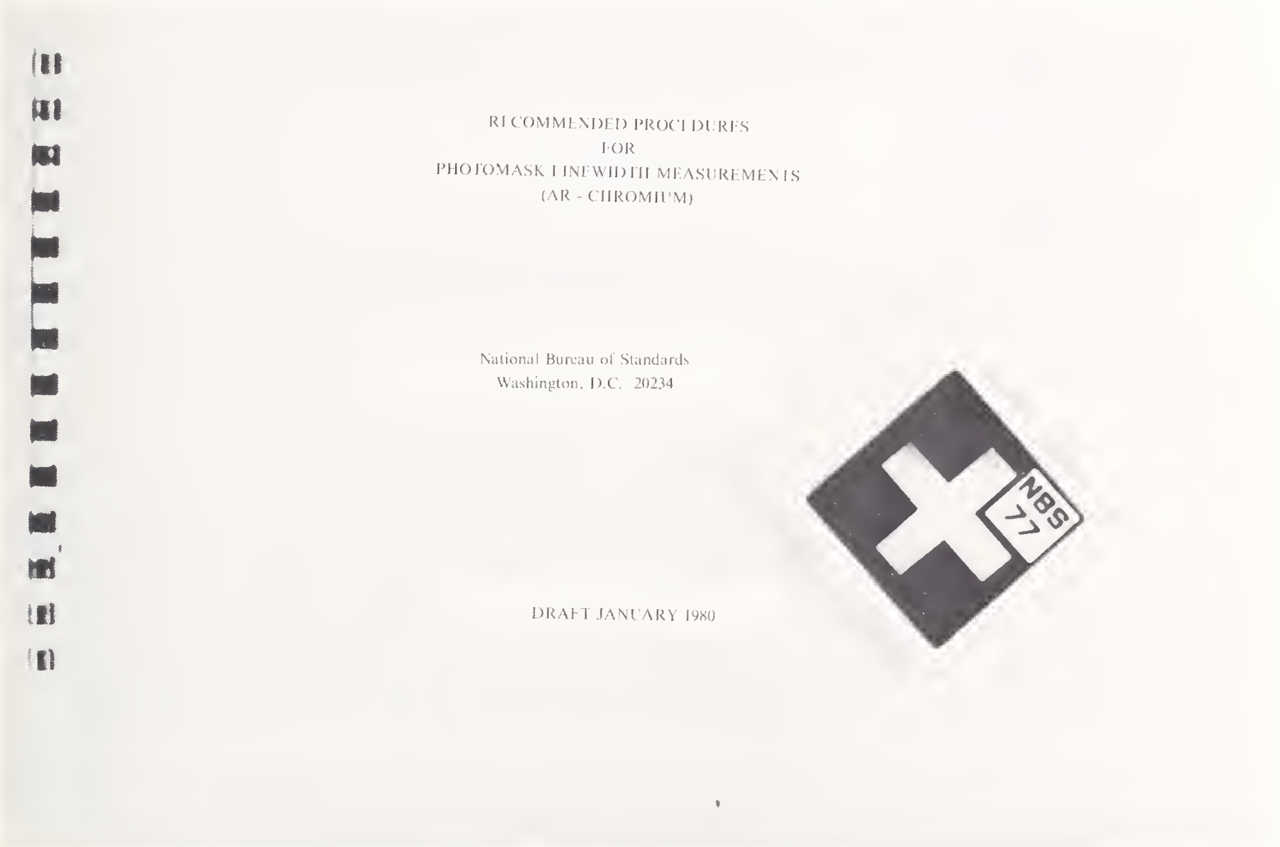


Fig. 22 One of the measured and calibrated linewidth patterns forming part of standard reference material 474.



RECOMMENDED PROCEDURES
FOR
PHOTOMASK LINEWIDTH MEASUREMENTS
(AR - CHROMIUM)

National Bureau of Standards
Washington, D.C. 20234

DRAFT JANUARY 1980

Fig. 23 Measurement procedures are part of the documentation furnished as part of standard reference material 474.

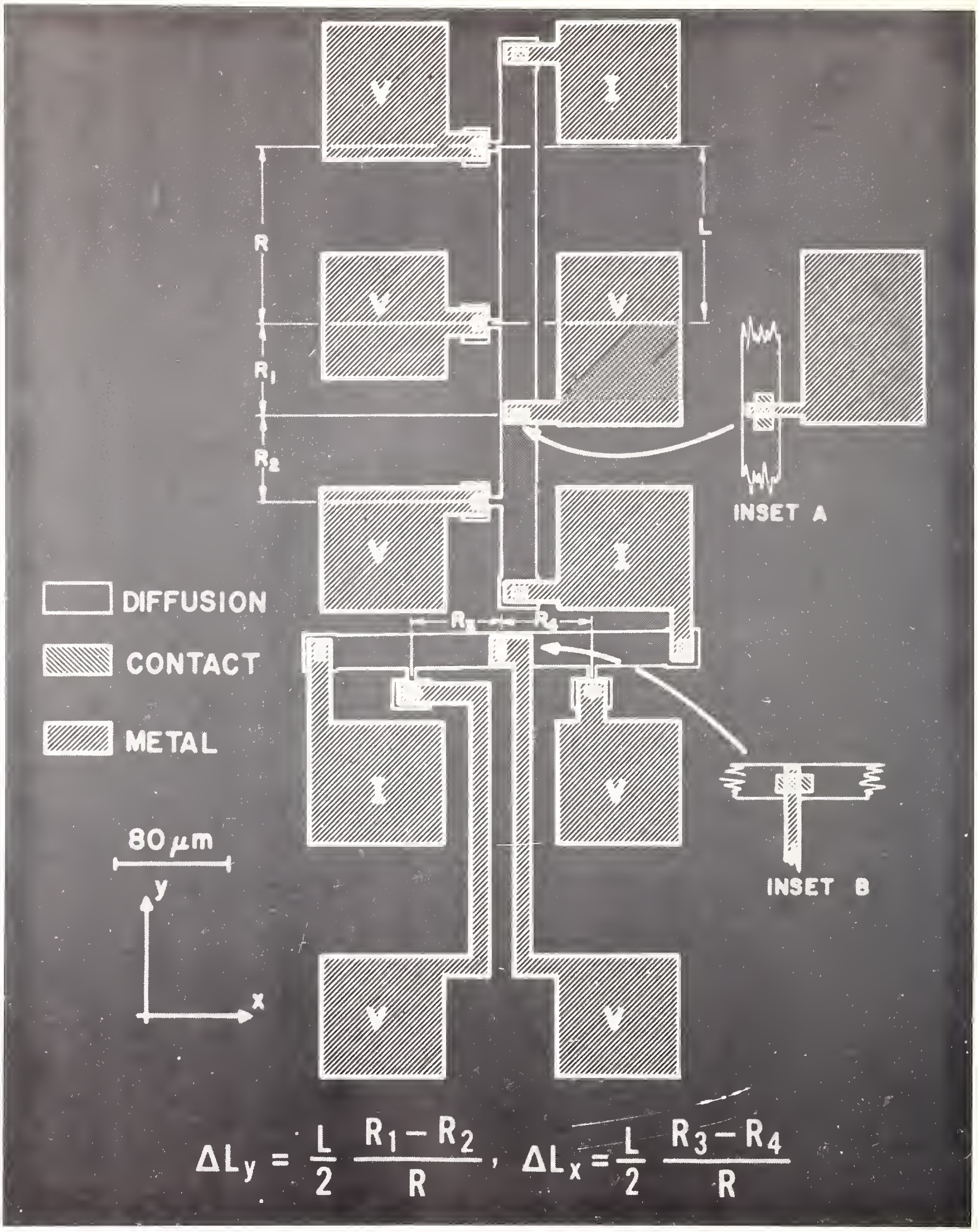


Fig. 24 A test structure for determining registration errors between selected mask levels in a semiconductor device fabrication process. Electrical measurements are used to determine mechanical parameters.

Fig. 25 View through a microscope of a wafer prober in operation.

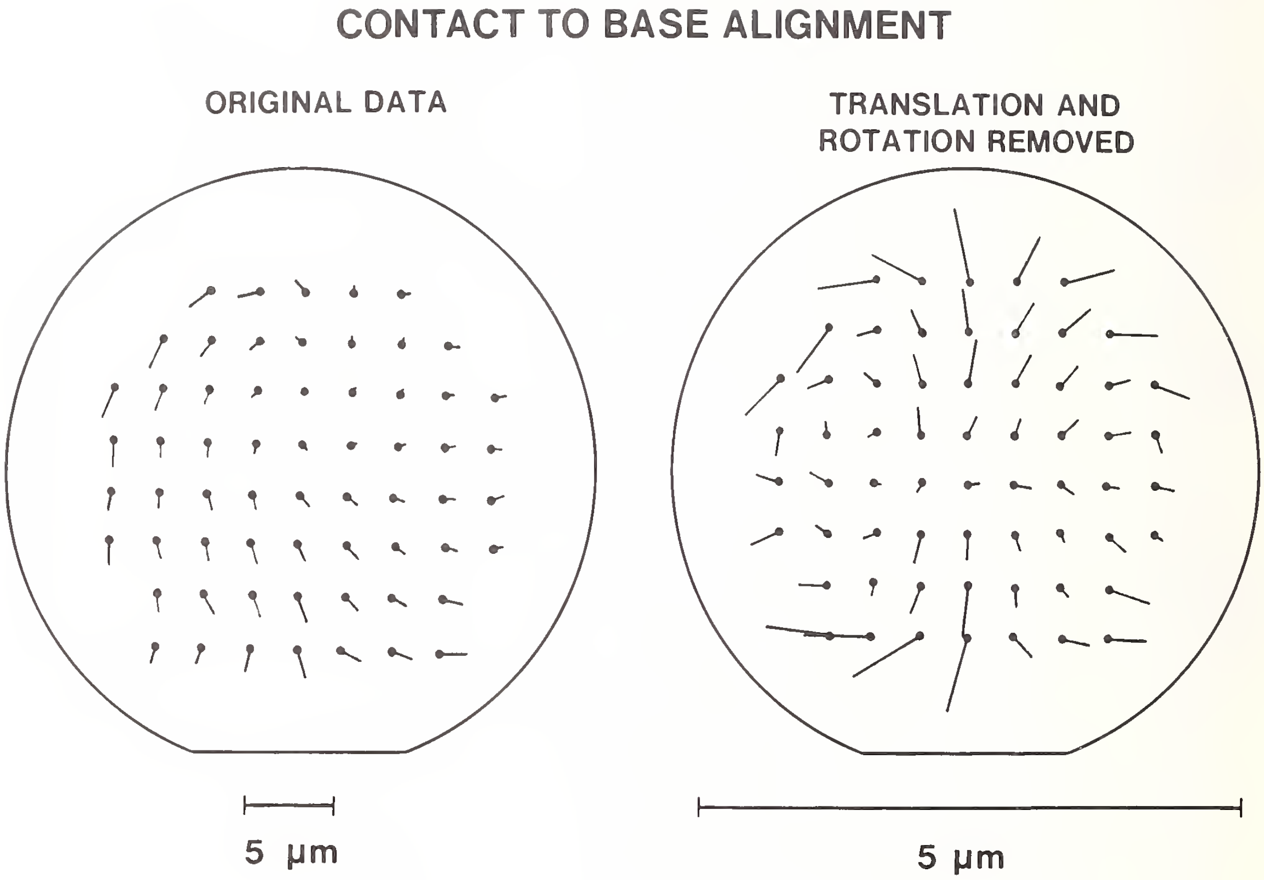


Fig. 26 A computer-generated map of registration or alignment errors demonstrates the existence of significant distortions (on the order of 1 µm) in wafer or mask, or both, when translation and rotation errors are computationally removed.

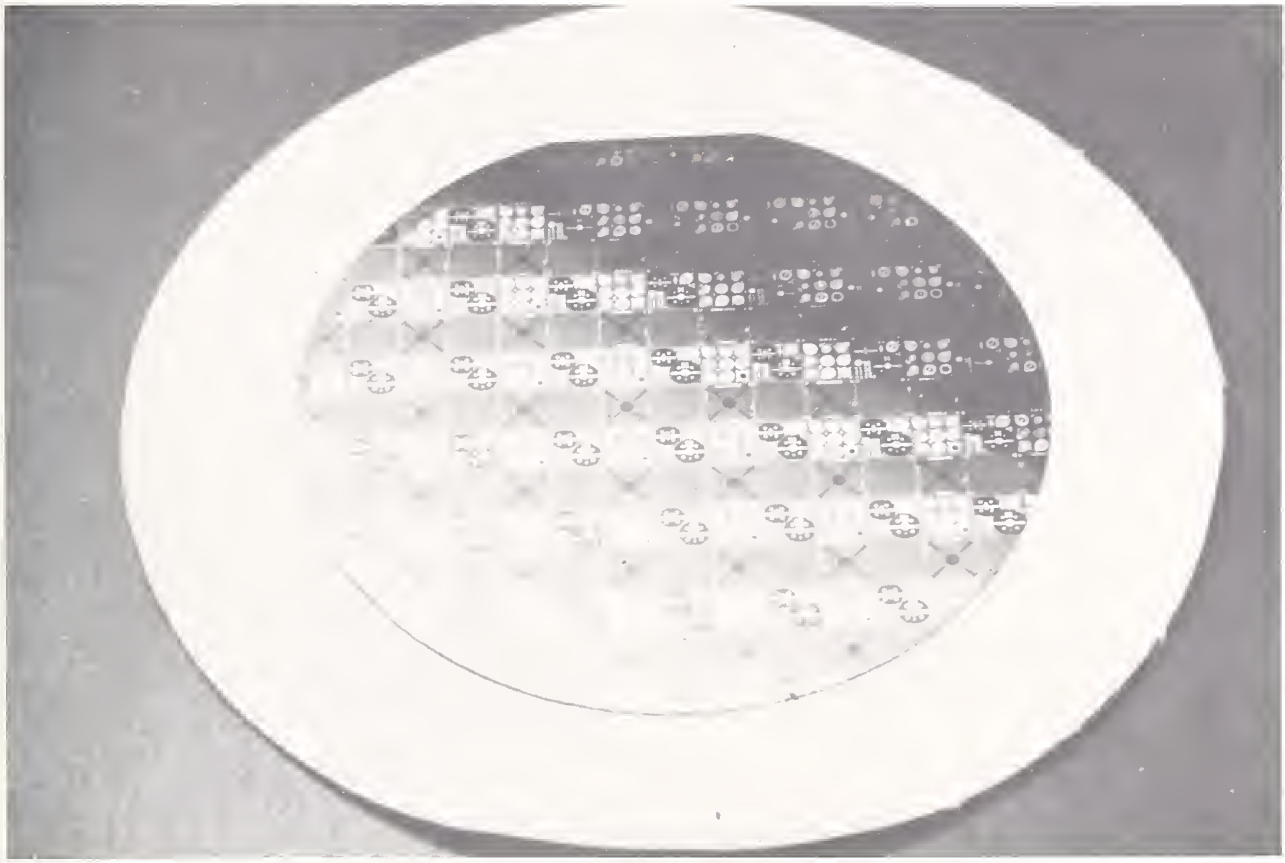


Fig. 27 Photograph of wafer covered with test patterns.

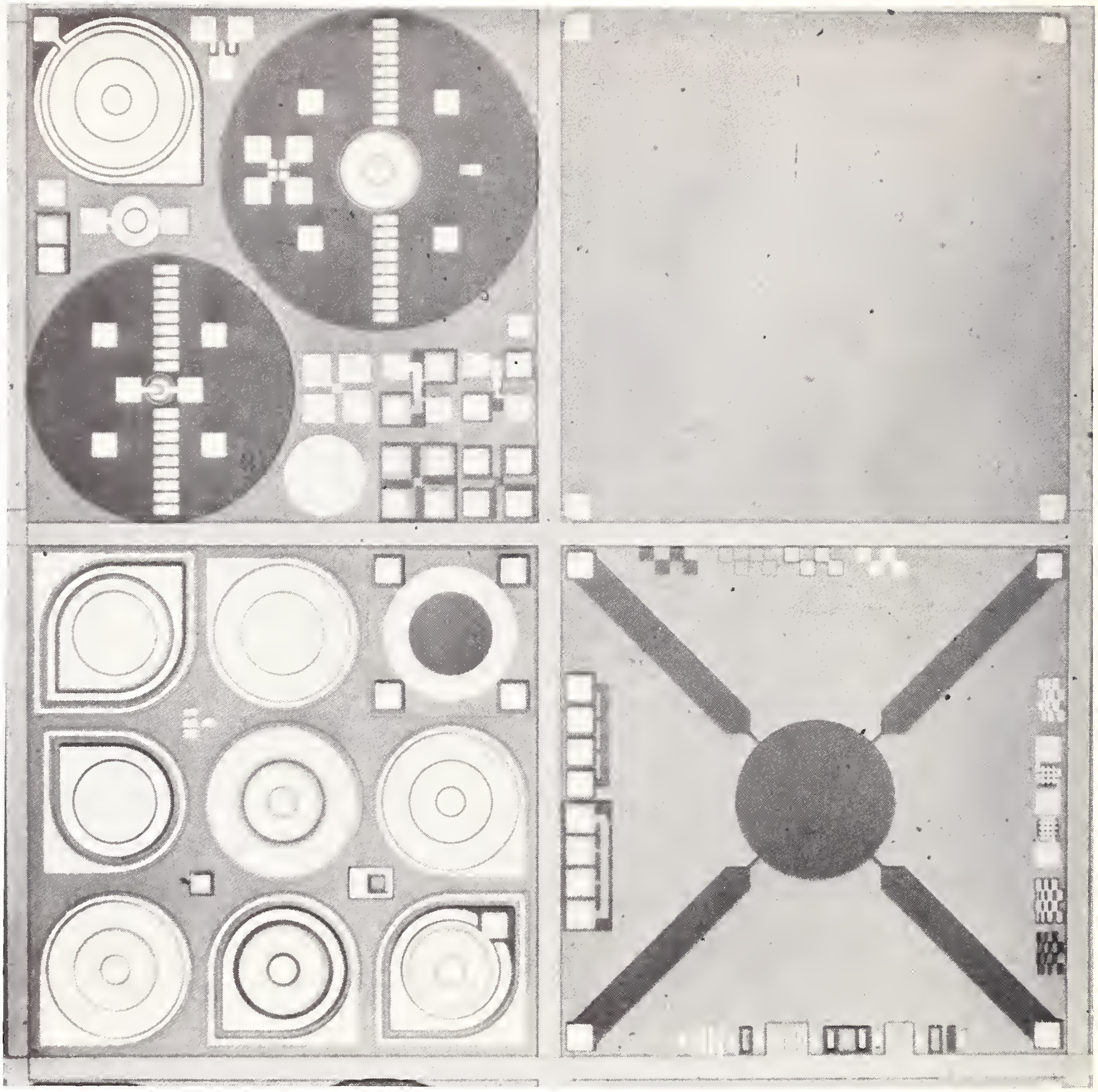


Fig. 28 A single test pattern from the wafer of figure 27. The pattern is made up of a number of individual test structures for measuring various parameters, including bulk resistivity and dopant-impurity density.

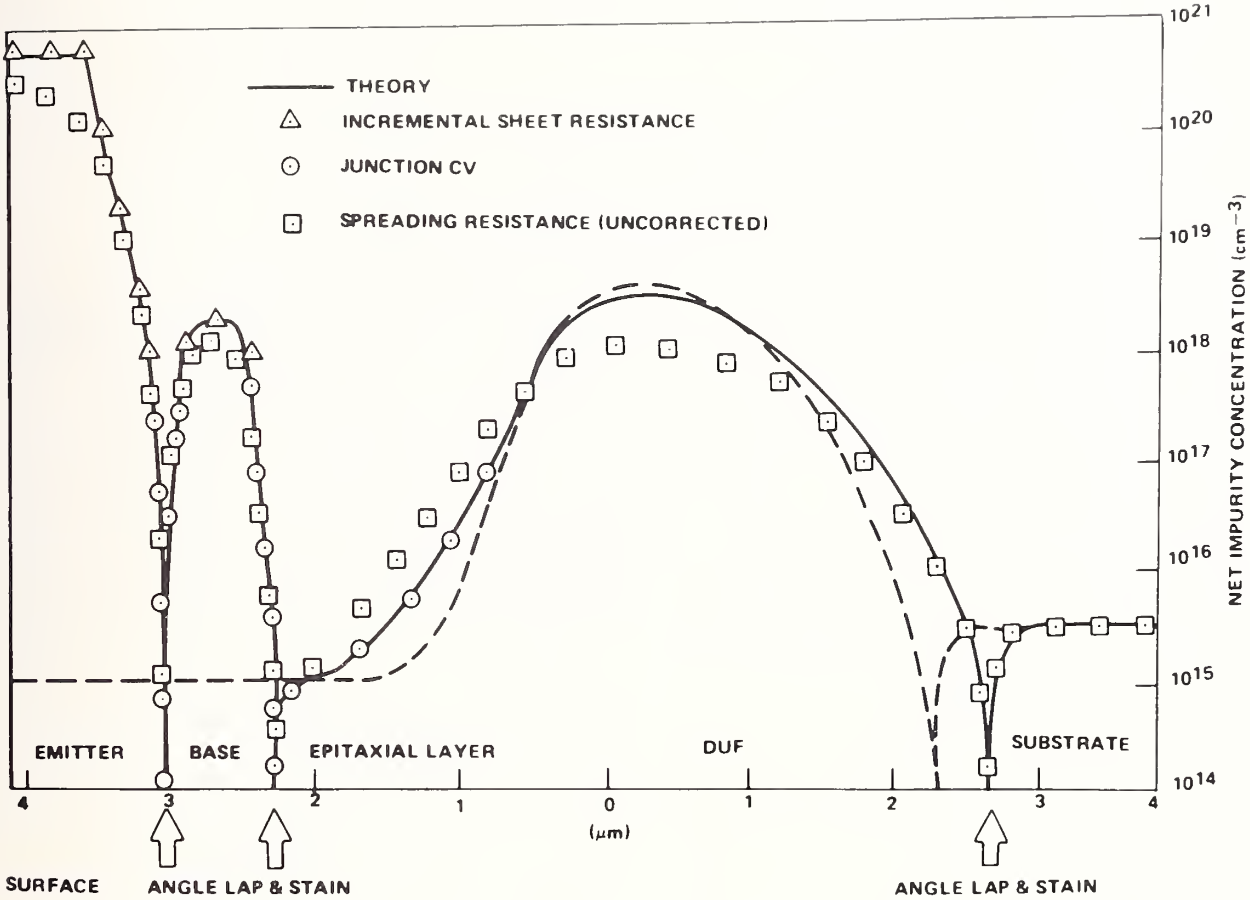
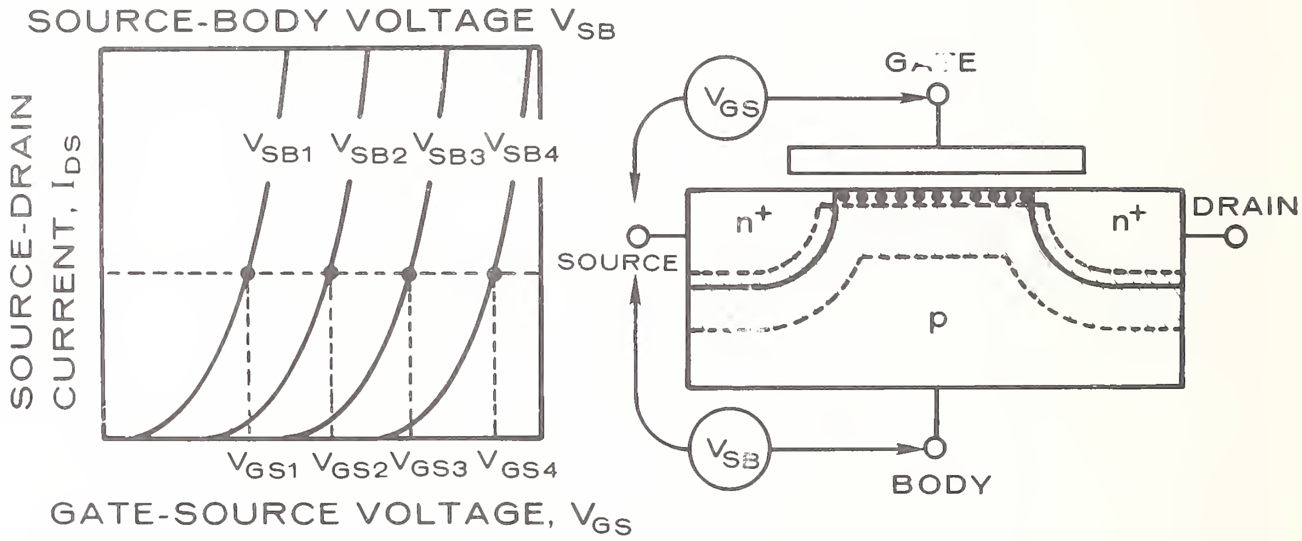


Fig. 29 In actual devices, very large changes in dopant impurity concentration occur over very small dimensions.

MOSFET D-C DOPANT PROFILES



$$W_m = \frac{\epsilon_s X_0}{\epsilon_0} \frac{dV_{SB}}{dV_{GS}} \qquad N_m(W_m) = \frac{\epsilon_0^2}{q\epsilon_s X_0^2}\left(\frac{d^2V_{SB}}{dV_{GS}^2}\right)^{-1}$$

Fig. 30 A metal oxide-semiconductor (MOS) structure (on right) for measuring dopant-impurity concentration profiles.

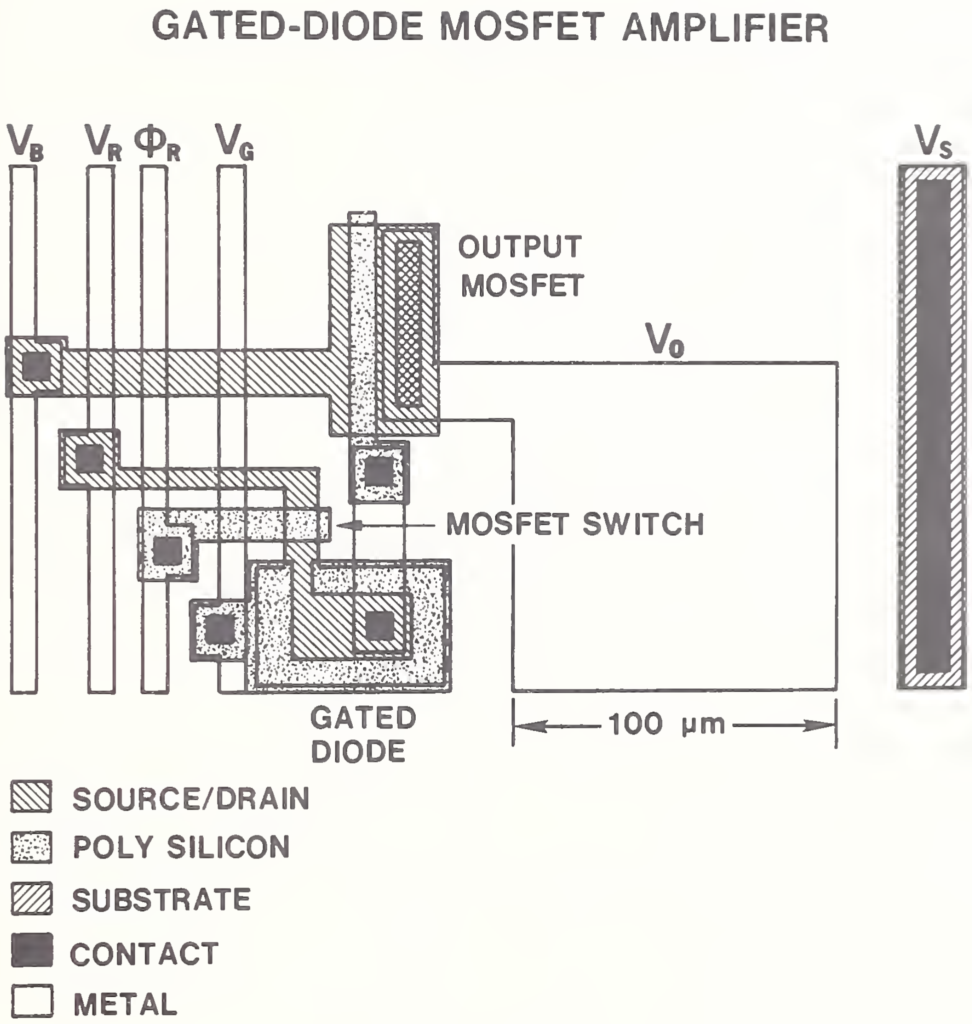


Fig. 31 An MOS structure incorporating a "throw-away" electrometer for measurements of charge carrier lifetime, a parameter that relates to the number of defects or impurities present in the crystal.

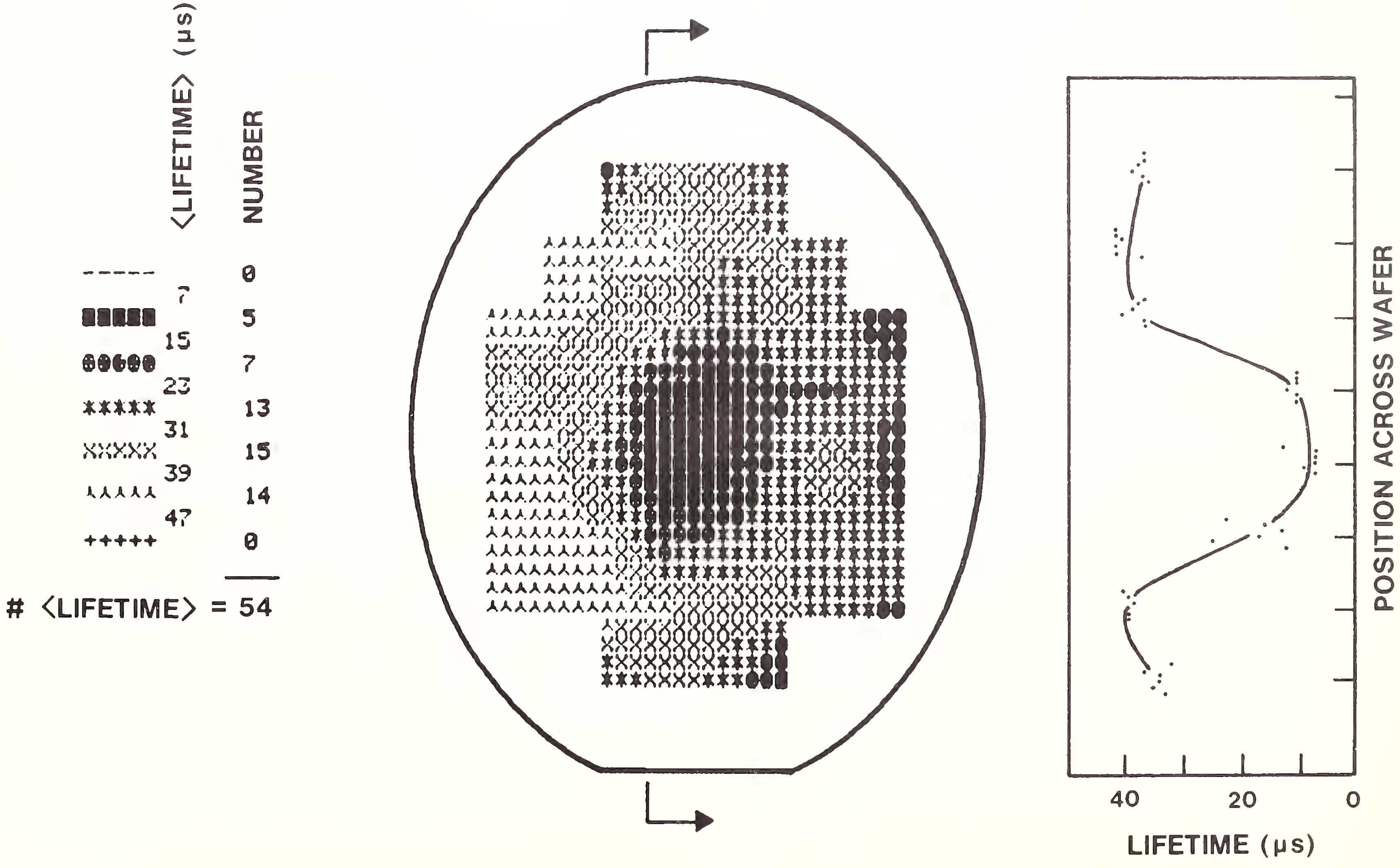


Fig. 32 A computer-generated map of lifetime measurements on a test wafer. These measurements were made using the structure shown in figure 31.

FAST SIGNAL ACQUISITION AND PROCESSING

Significance

- Digital signals underlie the electronic information and control revolution, with impact akin to the industrial revolution
- Traditional metrology is inadequate to assure in-situ accuracy of high speed instruments, automatic test equipment, and "gigabit electronics".

FAST SIGNAL ACQUISITION AND PROCESSING

Key Factors

- Automation of calibration
- Software
- Traceability
- New physical standards
- Broadening range of key parameters
- Emerging technologies
- Improved dissemination of standards

FAST SIGNAL ACQUISITION AND PROCESSING

NBS Response

- New physical reference standards (For analog/digital equipment, waveform sources, etc.)
- Extension of frequency and time-domain coverage (0.1 Hz sinewaves, picosecond pulses, etc.)
- New dissemination methods (Transport standards, etc.)

Fig. 33,34,35 Fast Signal Acquisition and Processing Program - metrological significance and challenge, key factors, and NBS response.

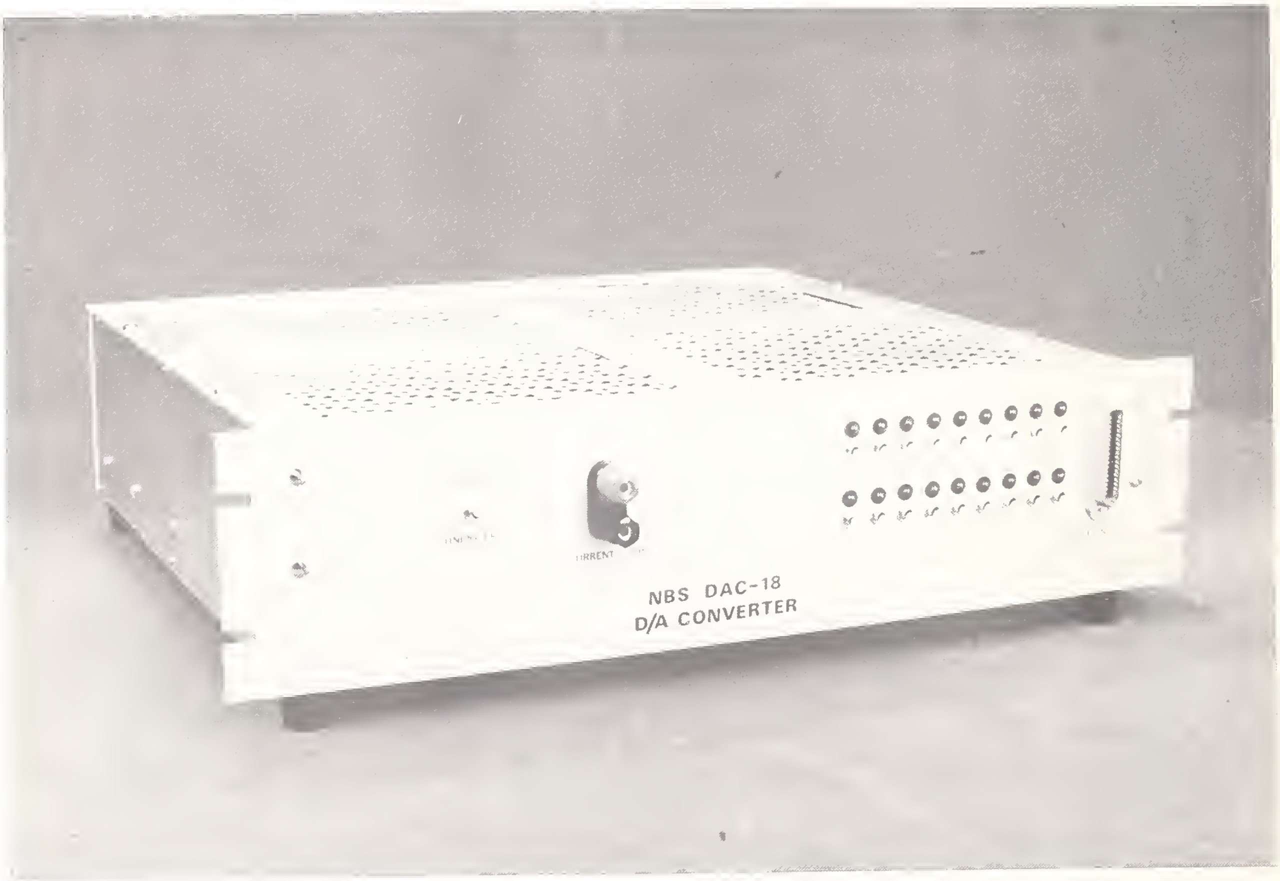


Fig. 36 An 18-bit reference digital-to-analog converter.

Fig. 37 The NBS Super DAC: a 20-bit reference digital-to-analog converter. This instrument is used in the characterization of static performance parameters of analog-to-digital converters.

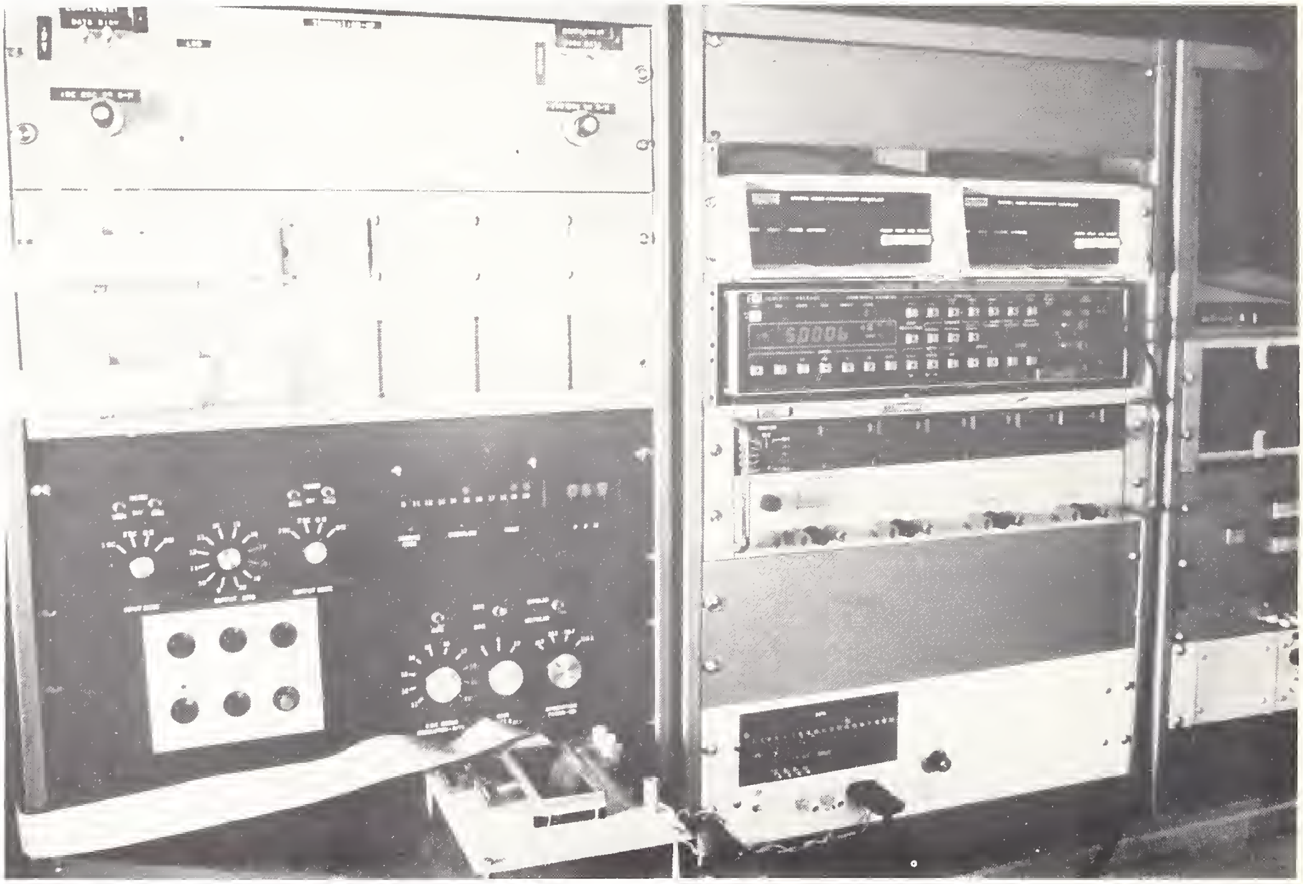


Fig. 38 A developmental test facility for calibrating static performance parameters of analog-to-digital converters. The reference Super DAC is at the bottom of the right-hand equipment rack.

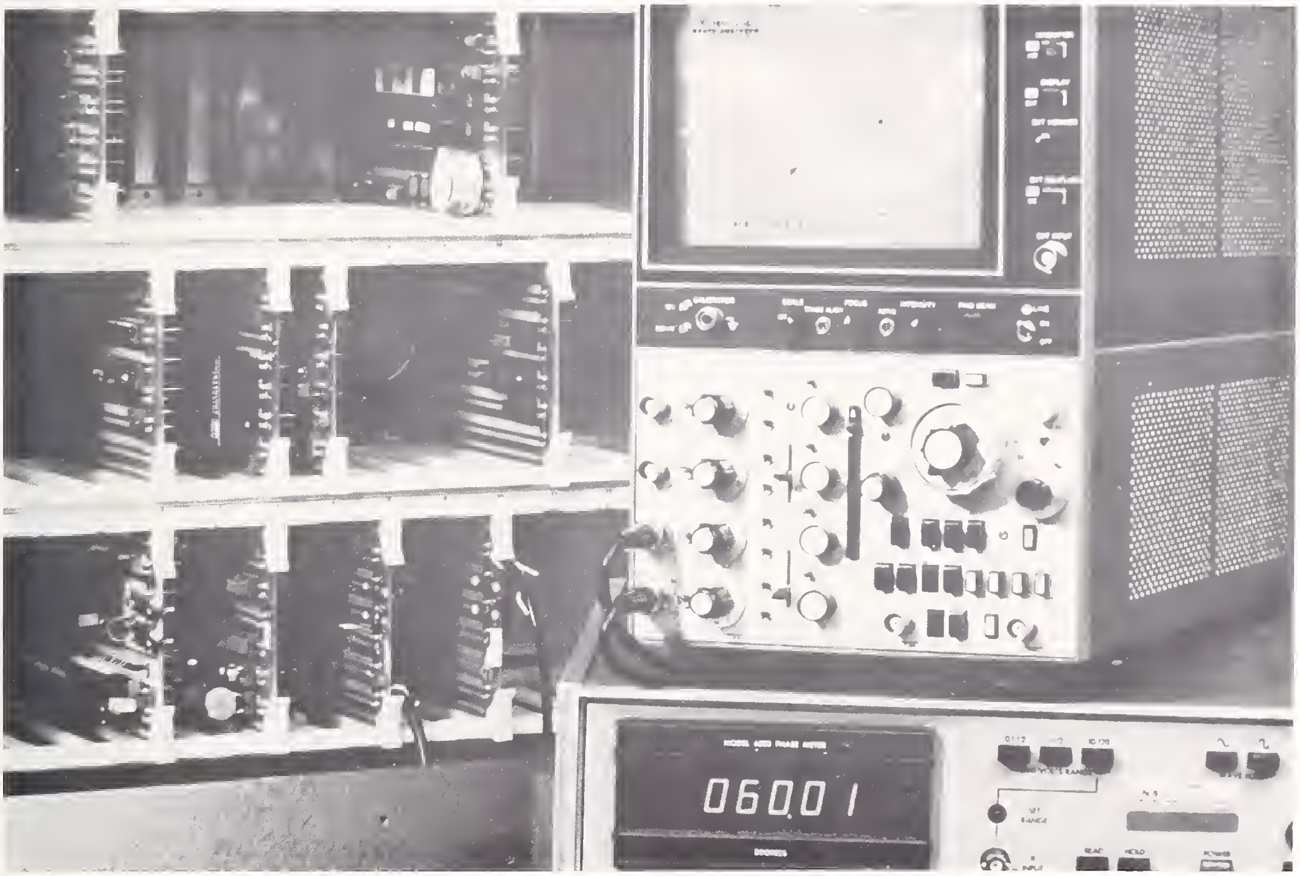


Fig. 39 Implementation of programmable audio-frequency phase-angle standard. Component circuit boards are visible at the left; the oscilloscope displays the output sinewaves displaced in phase.

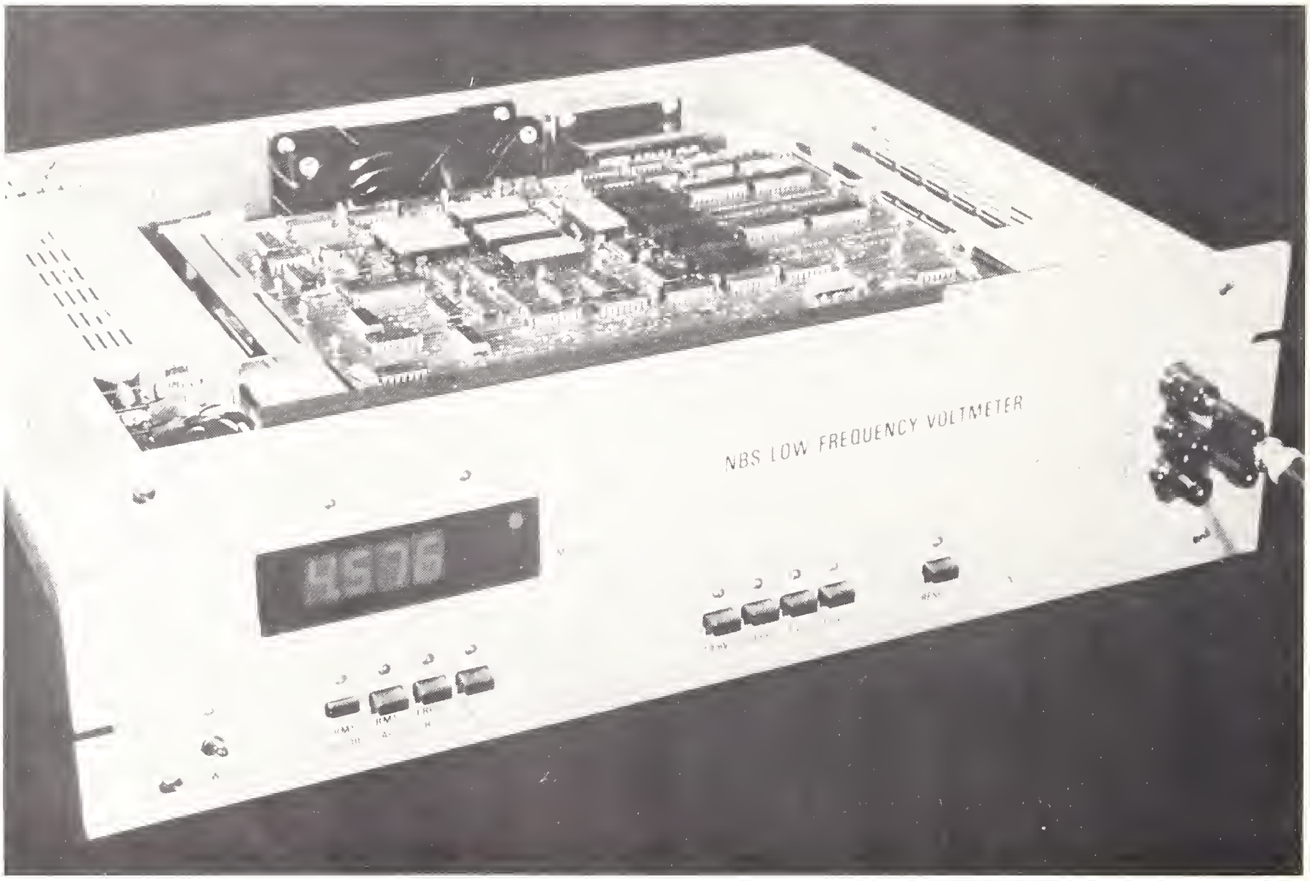


Fig. 40 Digital technology makes possible this NBS low-frequency (0.1-Hz) voltmeter. One application is the measurement of seismic response of structures.

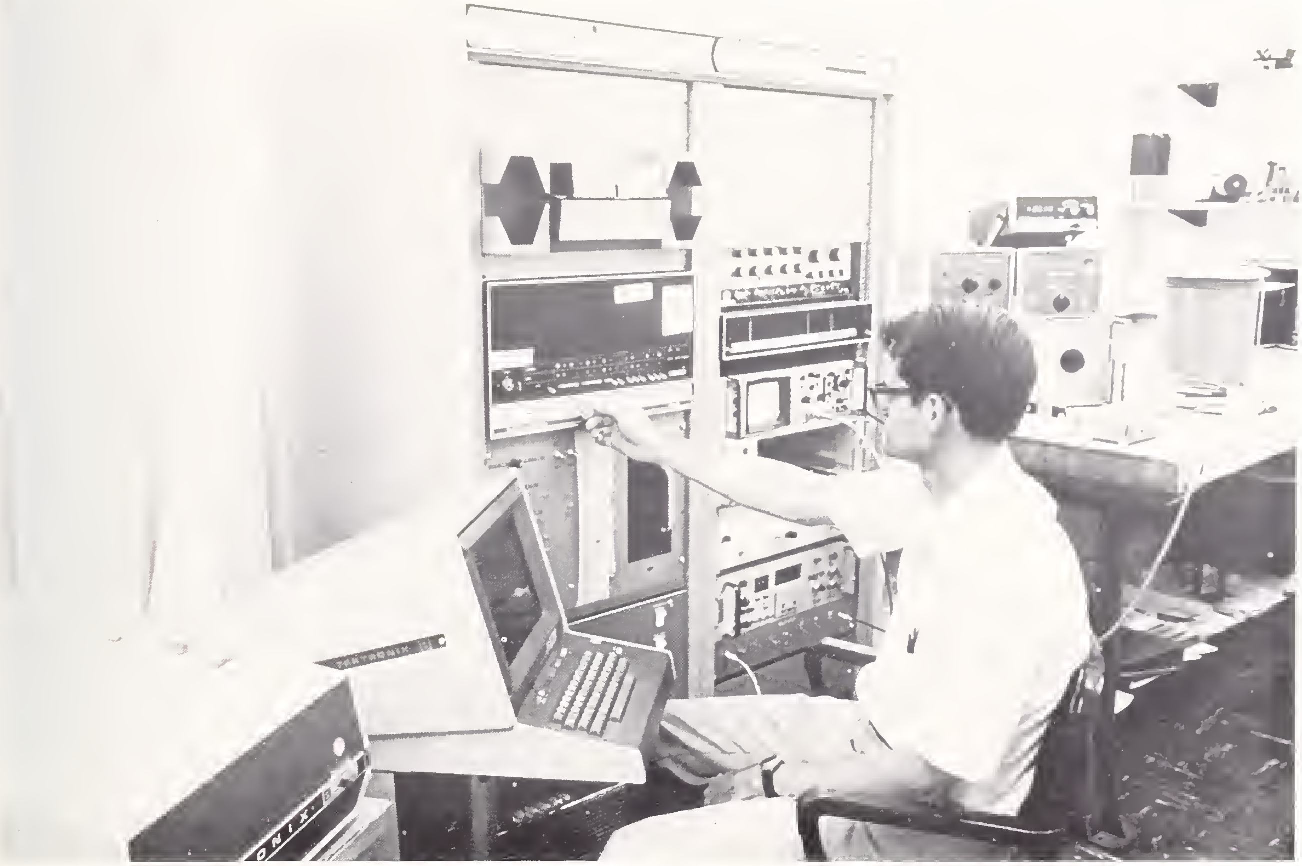


Fig. 41 One version of the NBS Automatic Pulse Measurement System for determining waveshape of signals from nanosecond-duration events.

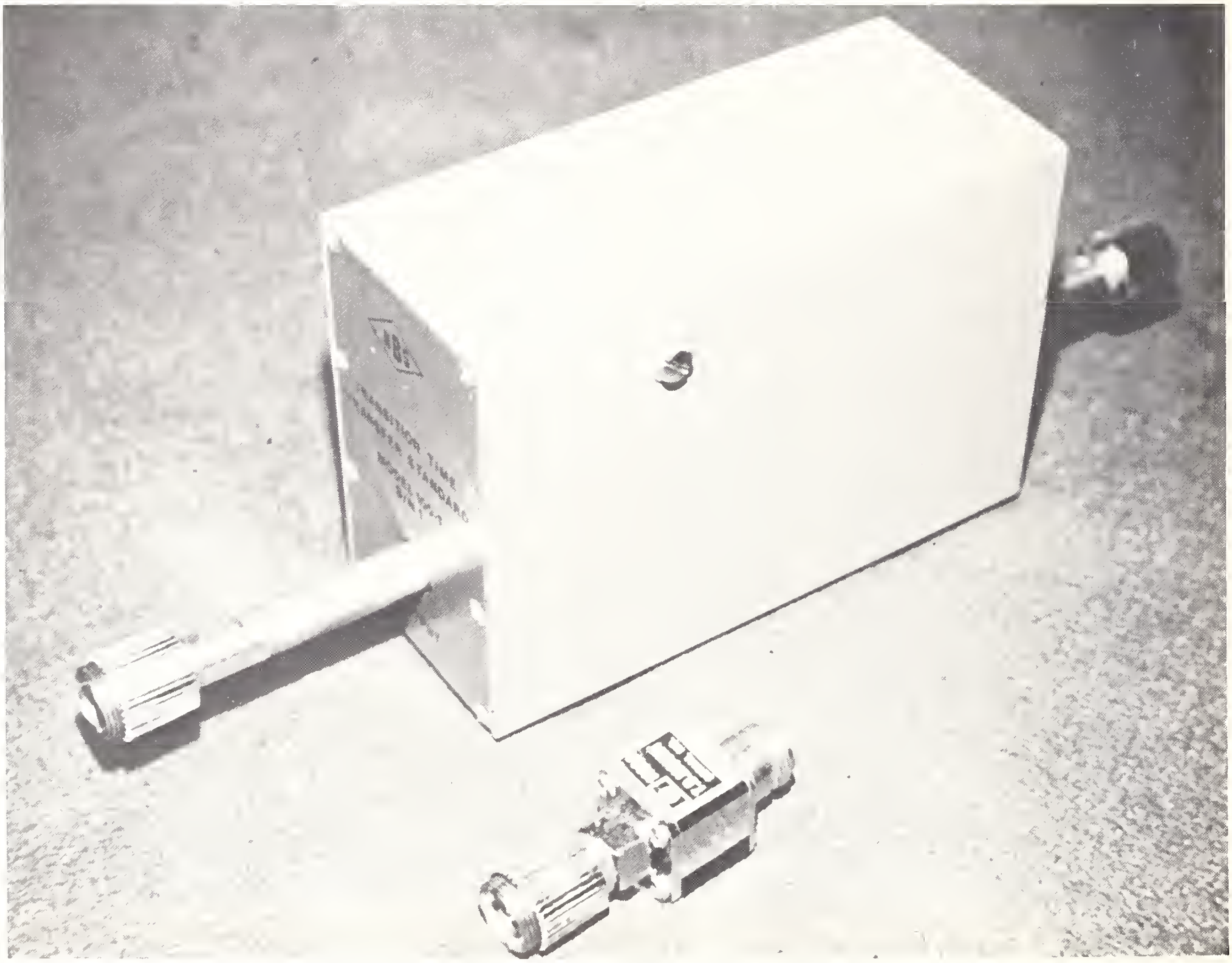


Fig. 42 NBS-developed impulse generator based on a tunnel diode and a Debye-liquid delay line.

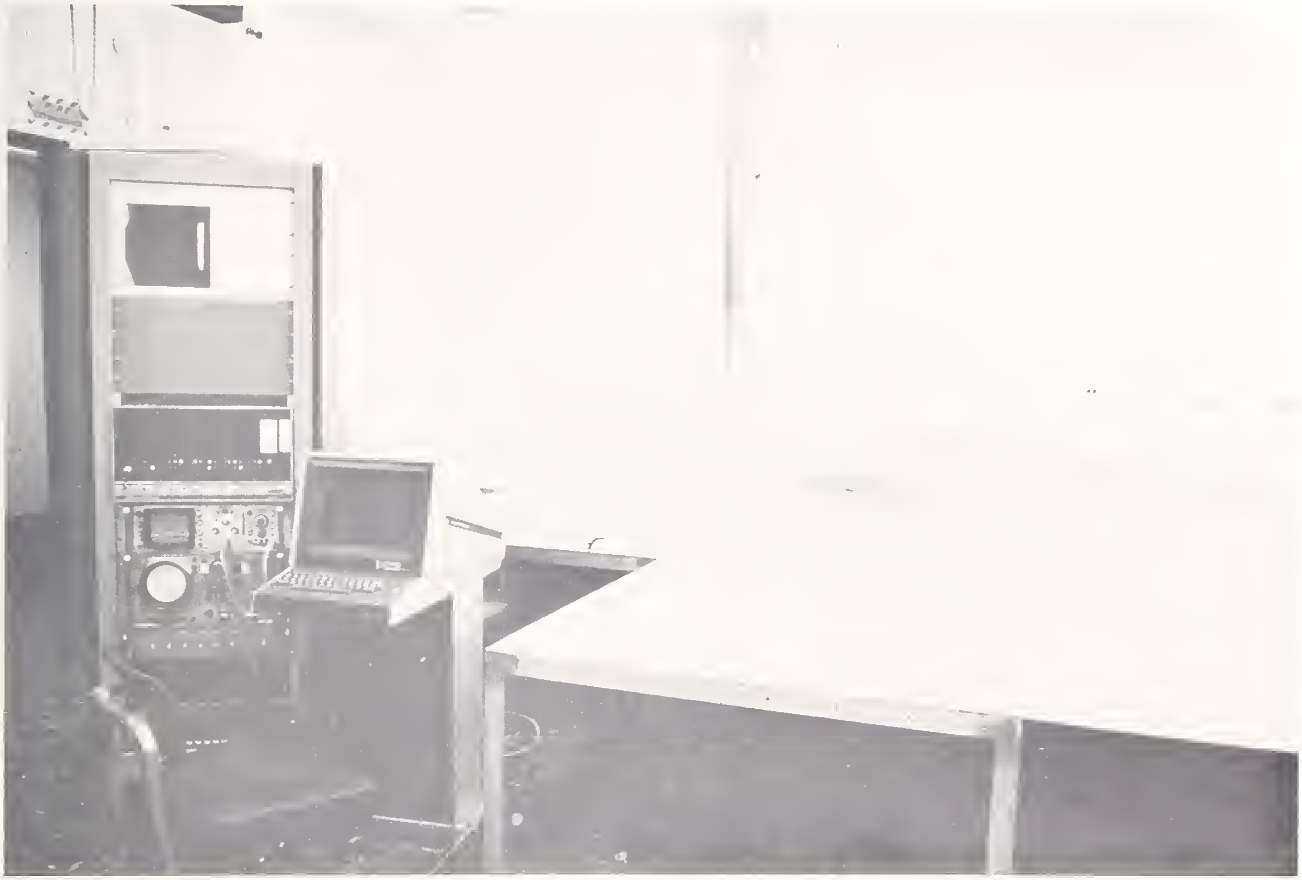


Fig. 43 NBS time-domain antenna range and Automatic Pulse Measurement System (at the left). The half-conical launching antenna can be seen near the center of the photograph. The test antenna is mounted on wooden blocks just above the ground plane.

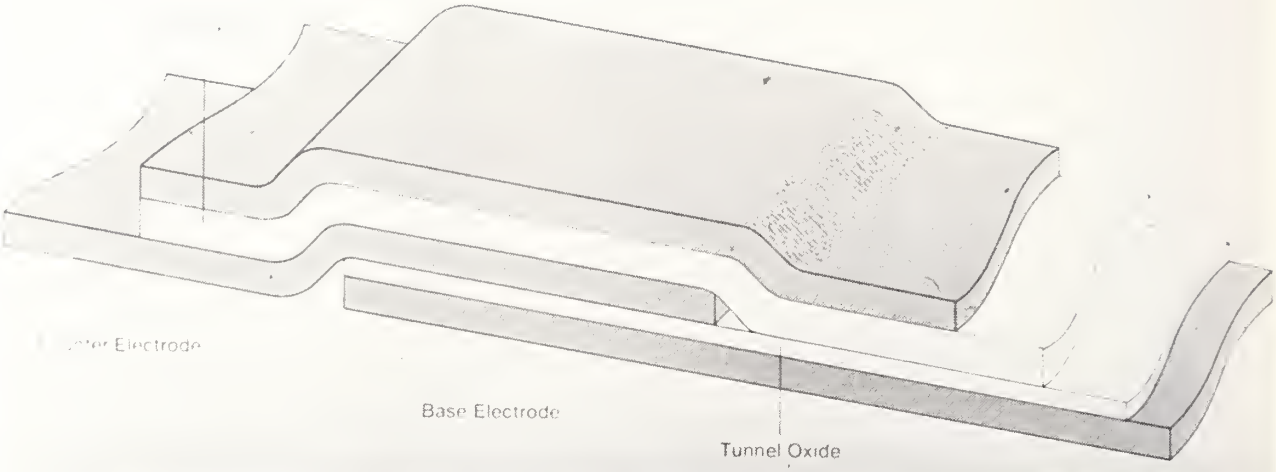


Fig. 44 Schematic of Josephson Junction

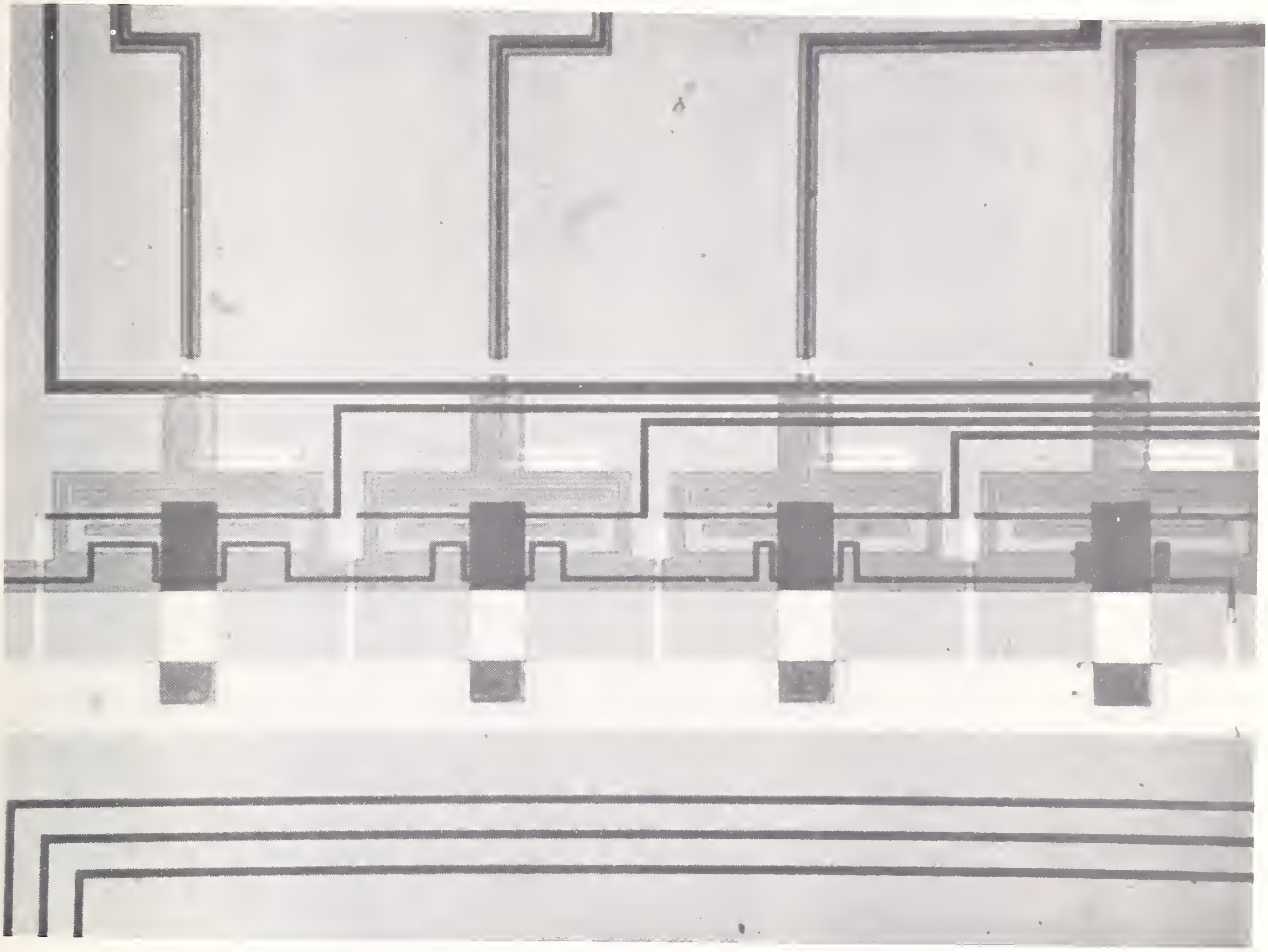


Fig. 45 Photograph of four-bit, very-high-speed, superconducting analog-to-digital converter. Three Josephson junction interferometers are used to encode each bit.

Fig. 46 Developmental model of Stirling-cycle mechanical refrigerator. Two units in cascade are capable of reaching liquid-helium temperatures.

FAST SIGNAL TRANSMISSION

Significance

- Digital and optical electronics, satellites, optical fibers and lasers are radically changing telecommunications, navigation, and remote sensing
- Metrology is challenged by demands for
  - Increasing dynamic range, spectrum, and time-domain resolution of signals
  - Test methods to characterize new components of transmission systems

FAST SIGNAL TRANSMISSION

NBS Response

- Automation, extended ranges, new methods and dissemination services for measurements of
  - Microwave and millimeter-wave components
  - Antennas
  - Satellite ground stations
  - Optical fibers
  - Lasers

Figs. 47,48 Fast Signal Transmission Program - metrological significance and challenge and NBS response.

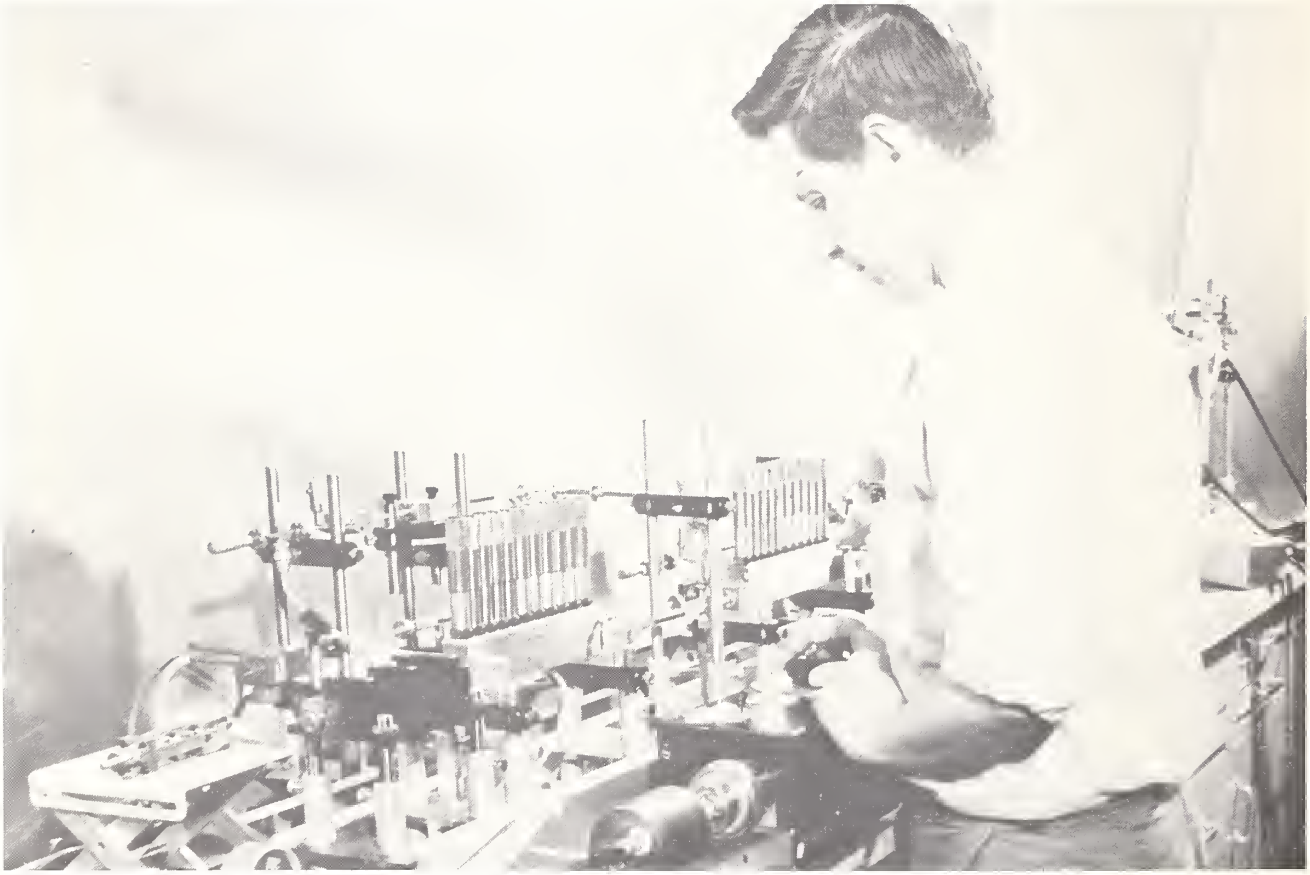


Fig. 49 Manually tuned microwave calibration rig for two-port linear devices.

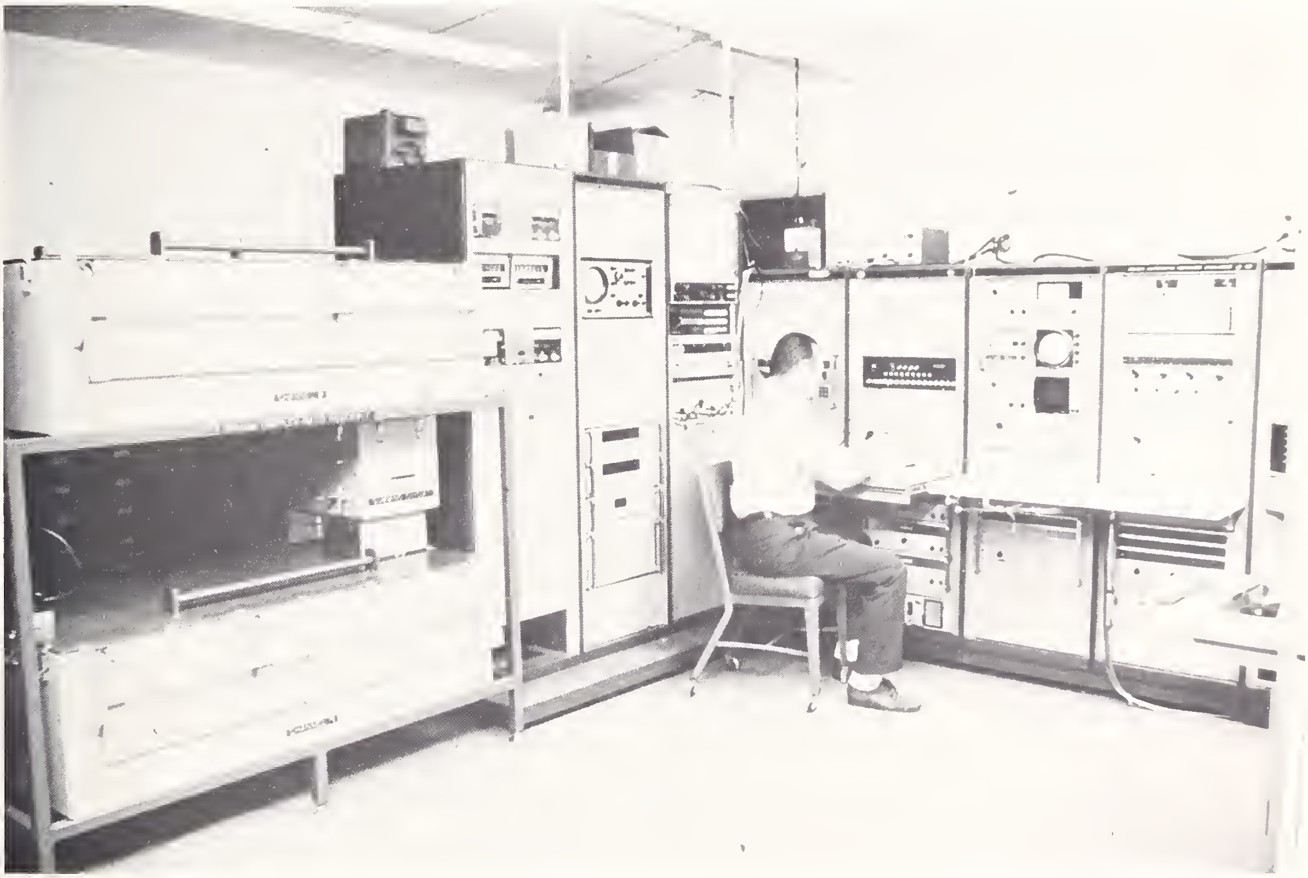
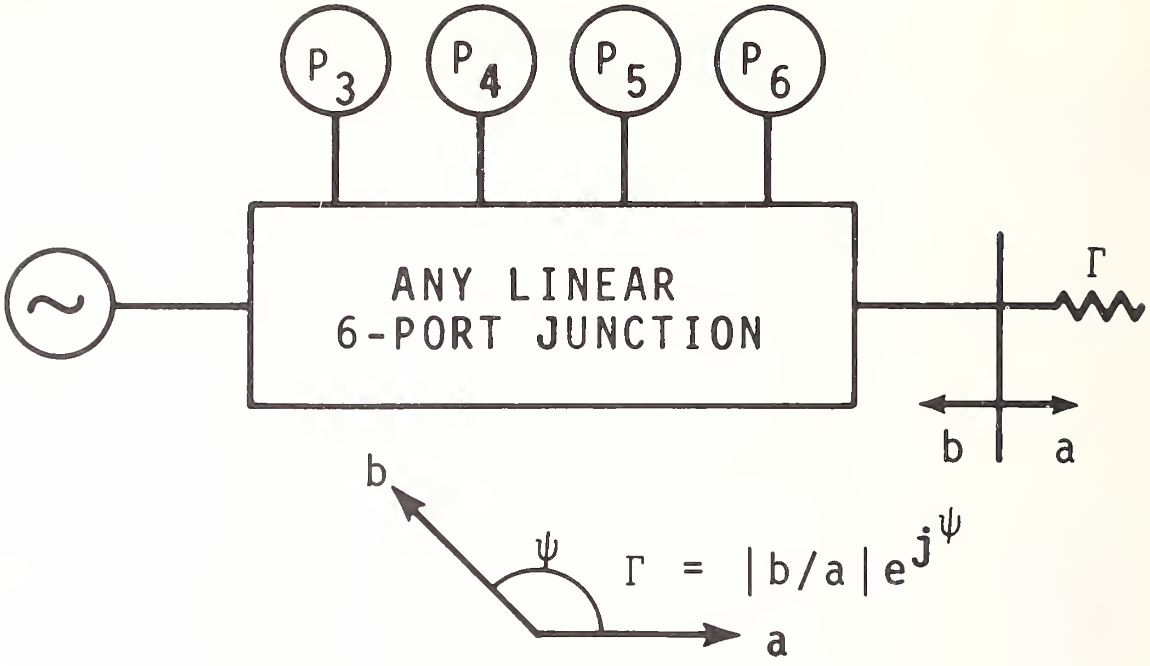


Fig. 50 Automatic Network Analyzer (ANA) for making the same measurement depicted in figure 49, but at a rate that makes practical complete mapping of specimen device performance over its specified frequency range.



$$\Gamma = |b/a| e^{j\psi}$$

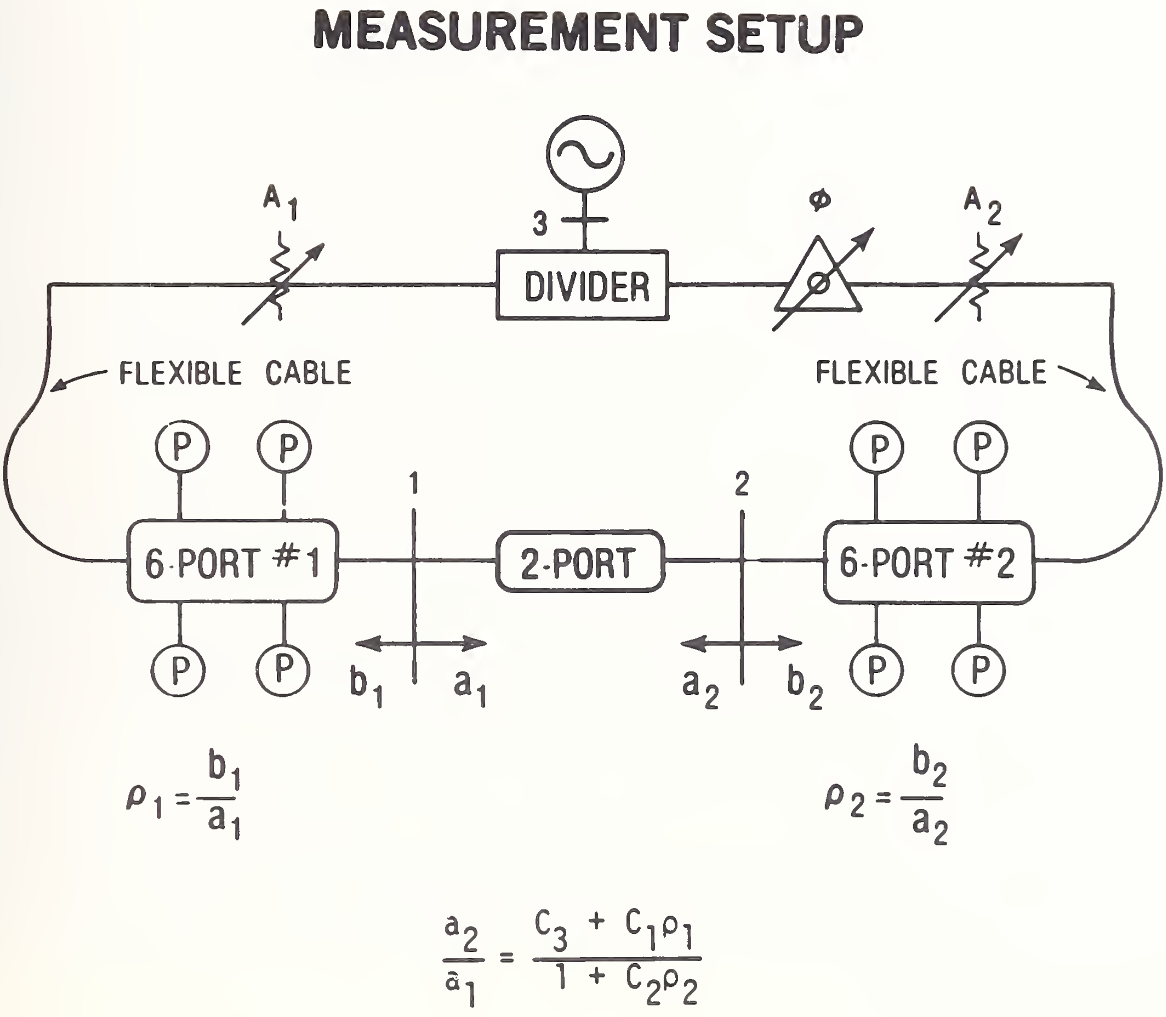
$$|a|^2 = \sum_{i=3}^{6} \alpha_i P_i$$

$$|b|^2 = \Sigma \beta_i P_i$$

$$|ab| \cos \psi = \Sigma c_i P_i$$

$$|ab| \cos \psi = \Sigma s_i P_i$$

Fig. 51 6-port principle: only simple power measurement - not phase - are required to determine the reflection characteristics at the unknown port.



$$\rho_1 = \frac{b_1}{a_1} \qquad \rho_2 = \frac{b_2}{a_2}$$

$$\frac{a_2}{a_1} = \frac{C_3 + C_1\rho_1}{1 + C_2\rho_2}$$

Fig. 52 Schematic of the dual 6-port ANA, an NBS development. The unknown is the device marked "2-port".

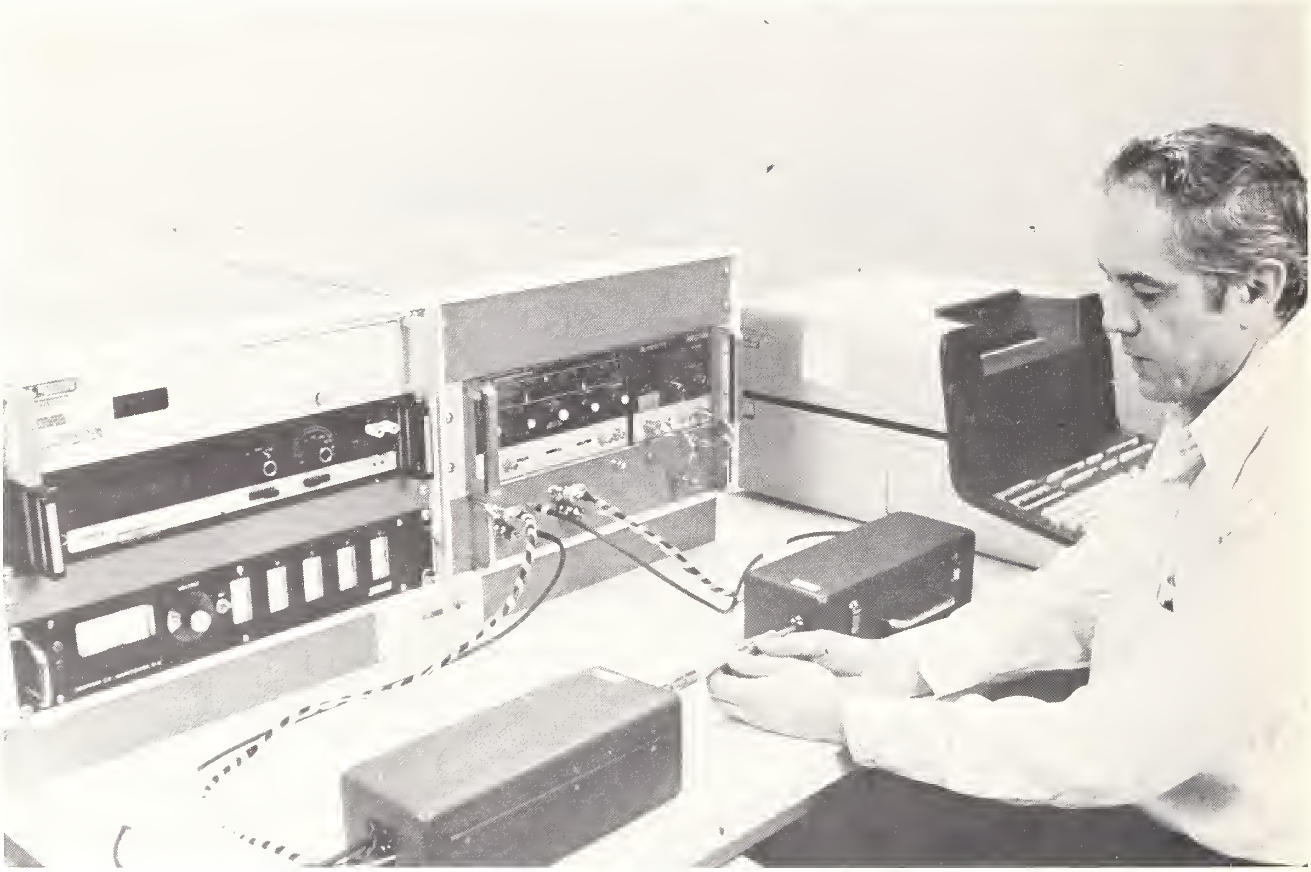


Fig. 53 Implementation of the dual 6-port ANA as a practical, stable, and accurate calibration tool. Scattering parameters, quantities of great interest to microwave design engineers, are directly measured.

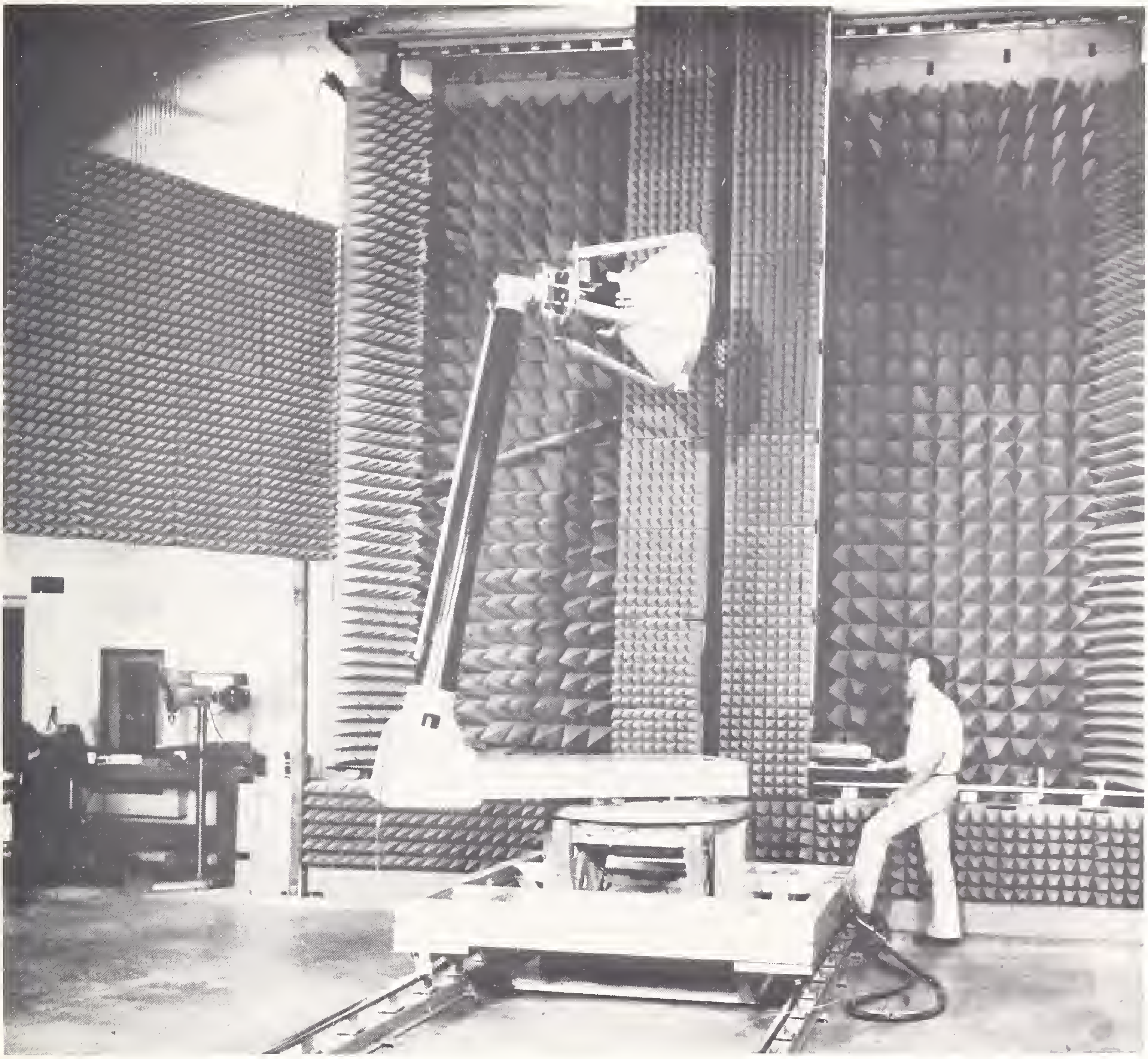


Fig. 54 NBS calibration facility for near-field scanning of antenna pattern.

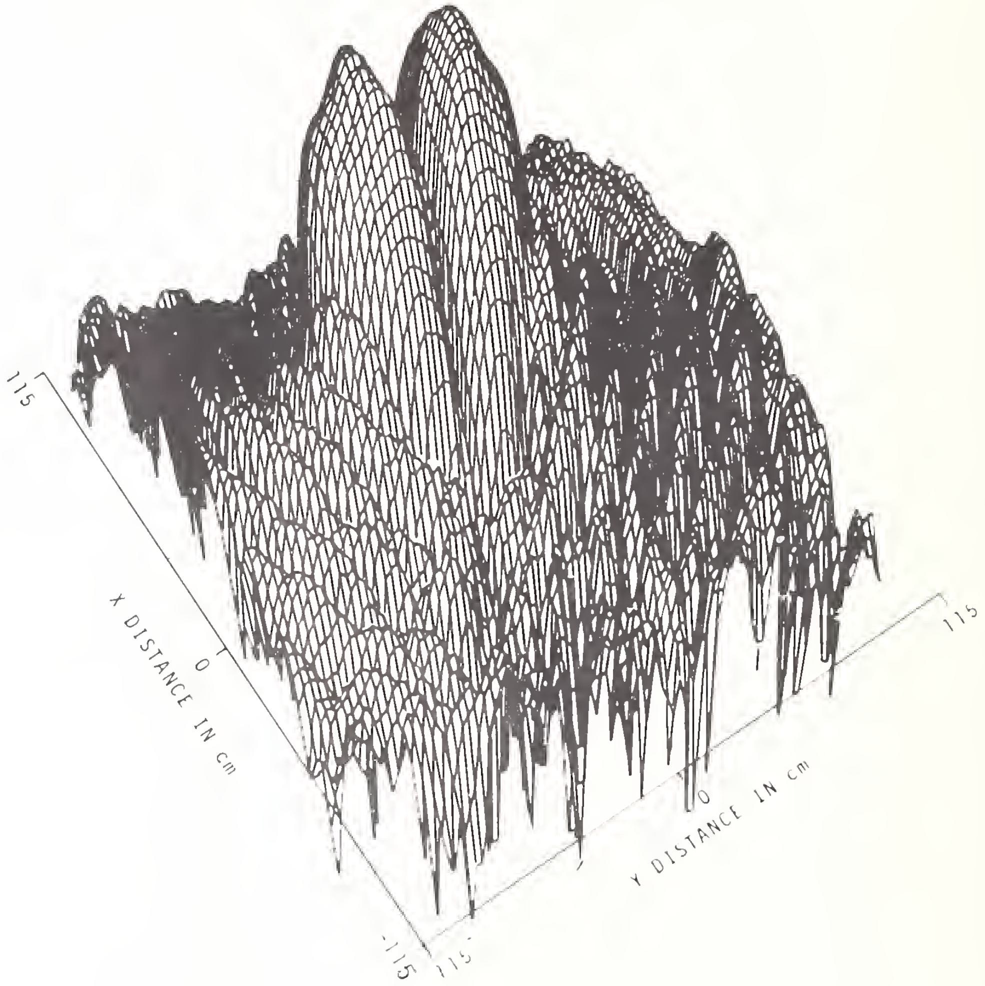


Fig. 55 Computer-generated plot of measured near-field data for a specimen antenna.

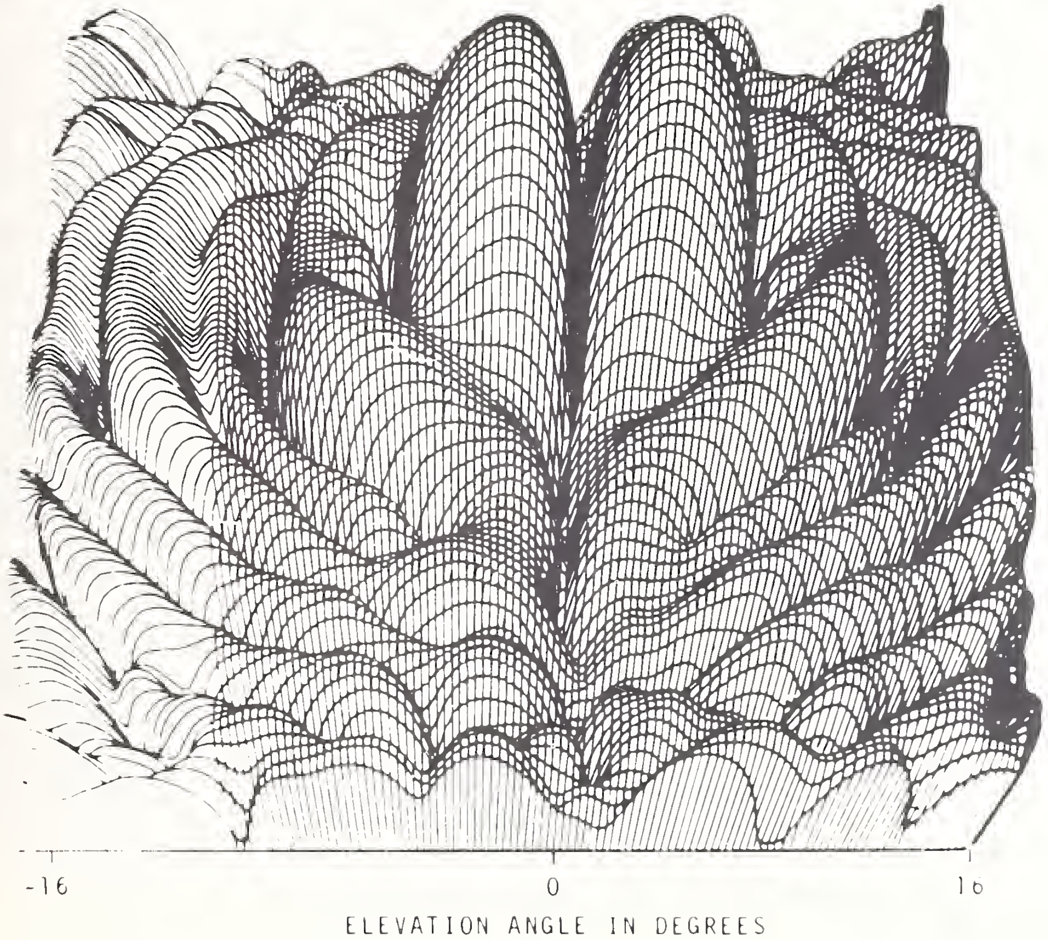


Fig. 56 Computer-generated plot of calculated far-field pattern for antenna measured in the near field. A major NBS contribution has been the development of the theory required to transform near-field measurements to far-field pattern.

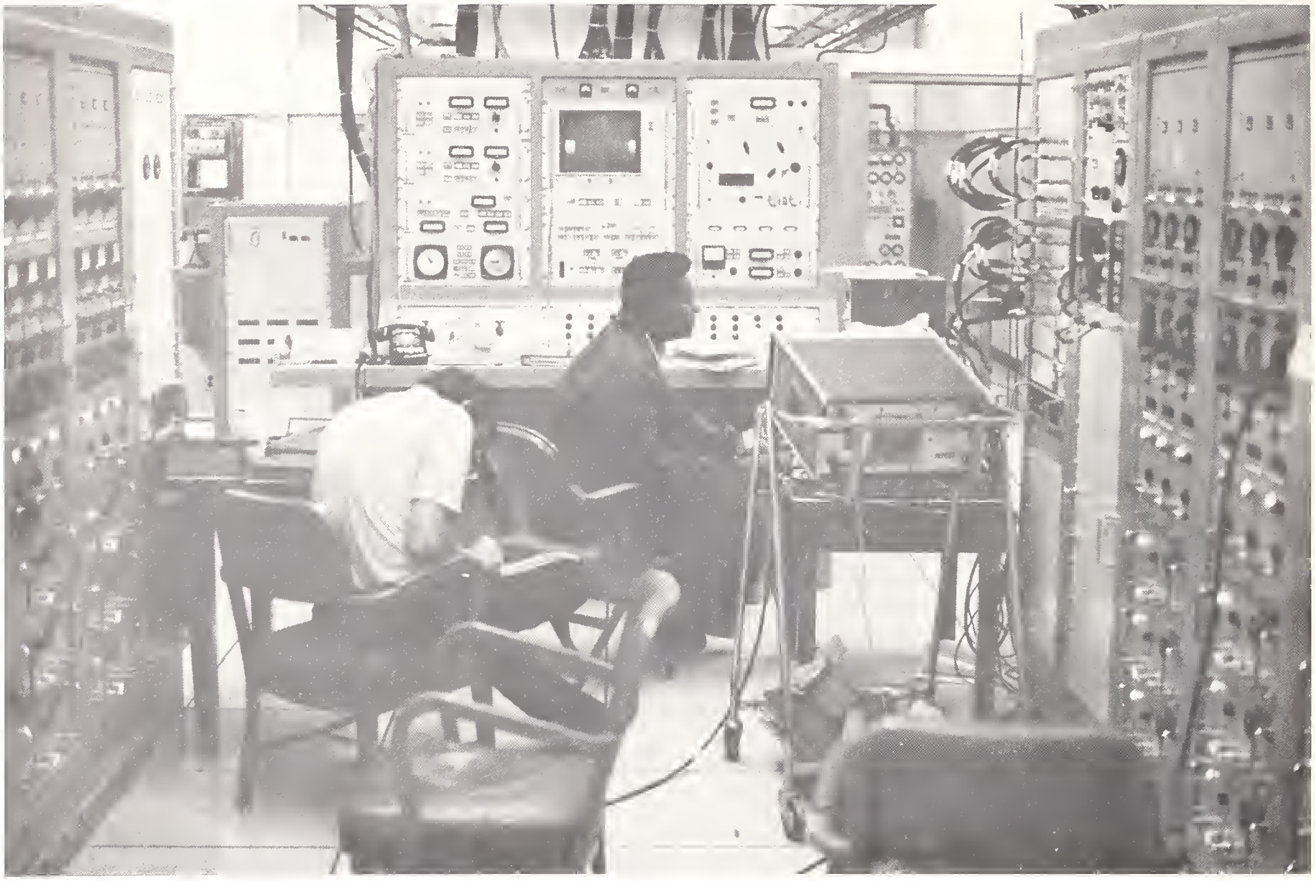


Fig. 57 Interior of satellite communication ground station, the noise performance of which is being checked with a radio star as reference.

Fig. 58 An illuminated spool of optical fiber.

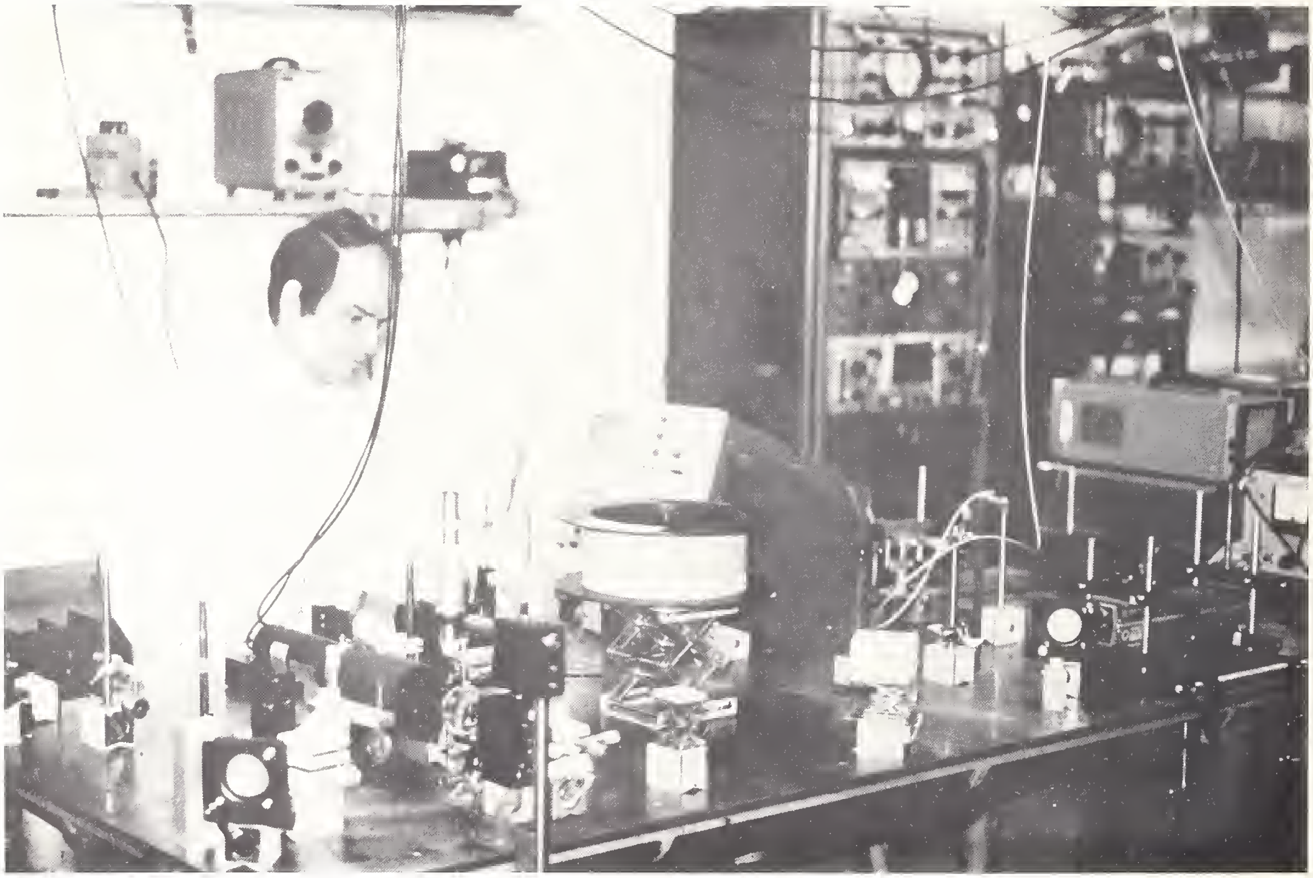


Fig. 59 Apparatus for measuring attenuation in optical fibers. The specimen fiber spool is visible near the center of the picture.

Fig. 60 NBS calorimeter system for calibrating measurements of laser power.

ELECTRICAL SYSTEMS

Significance

- Energy crisis and environmental concerns force new developments in electrical distribution systems
- Improved metrology is essential for
  - Higher voltages
  - Environmental effects
  - New transmission line technologies
  - Network transients
  - Variable-rate low power metering

ELECTRICAL SYSTEMS

NBS Response

- Increased range, in-situ calibration services for high power metering
- New test methods for electromagnetic fields near transmission lines
- Test methods and data for new underground transmission systems
- Improved accuracy, new measurement assurance program for low power metering

Fig. 61,62 Electrical Systems Program - metrological significance and challenge and NBS response.

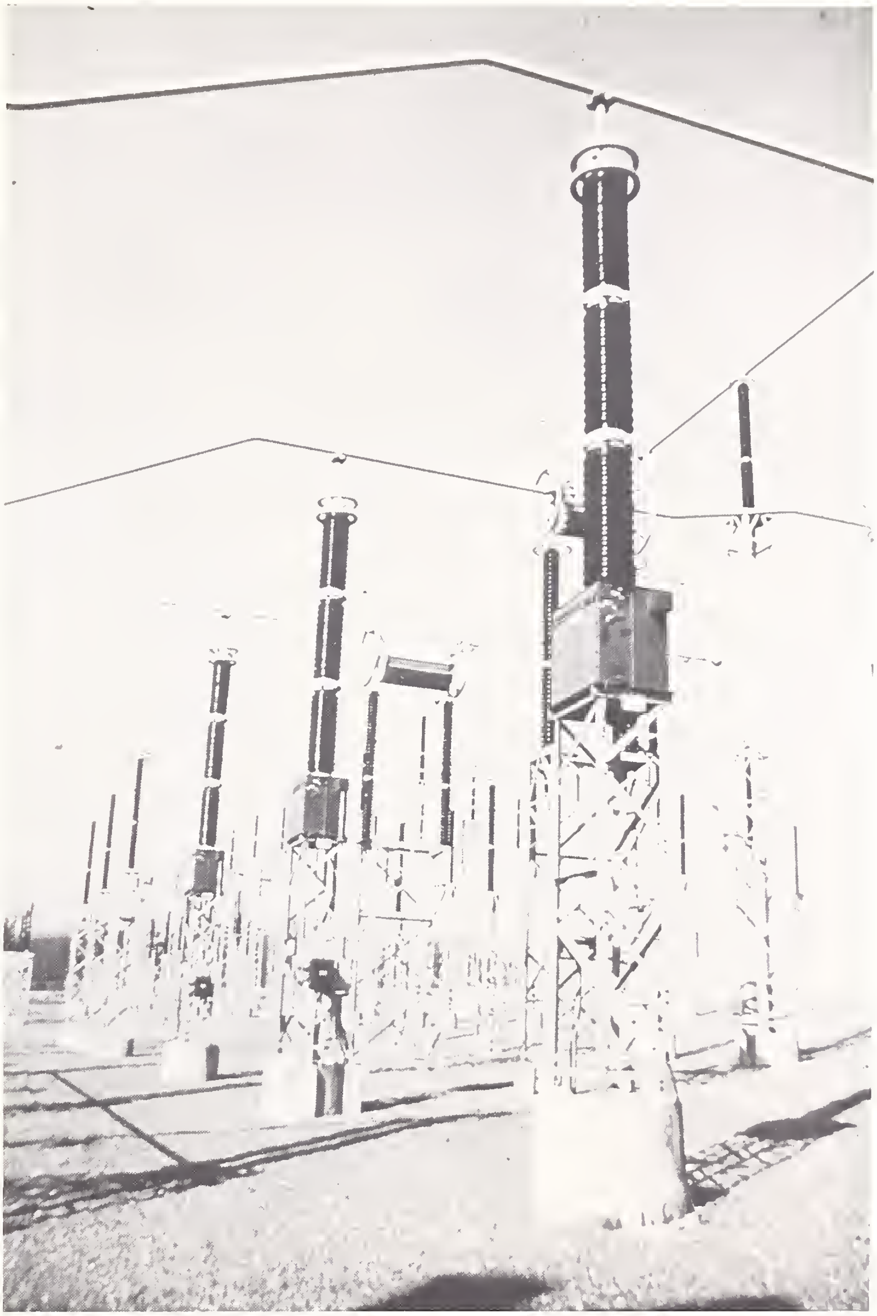


Fig. 63 Capacitive coupling voltage transformers on site at electric utility substation.

Fig. 64 NBS-developed voltage divider and test van for calibrating CCVTs as shown in figure 63.

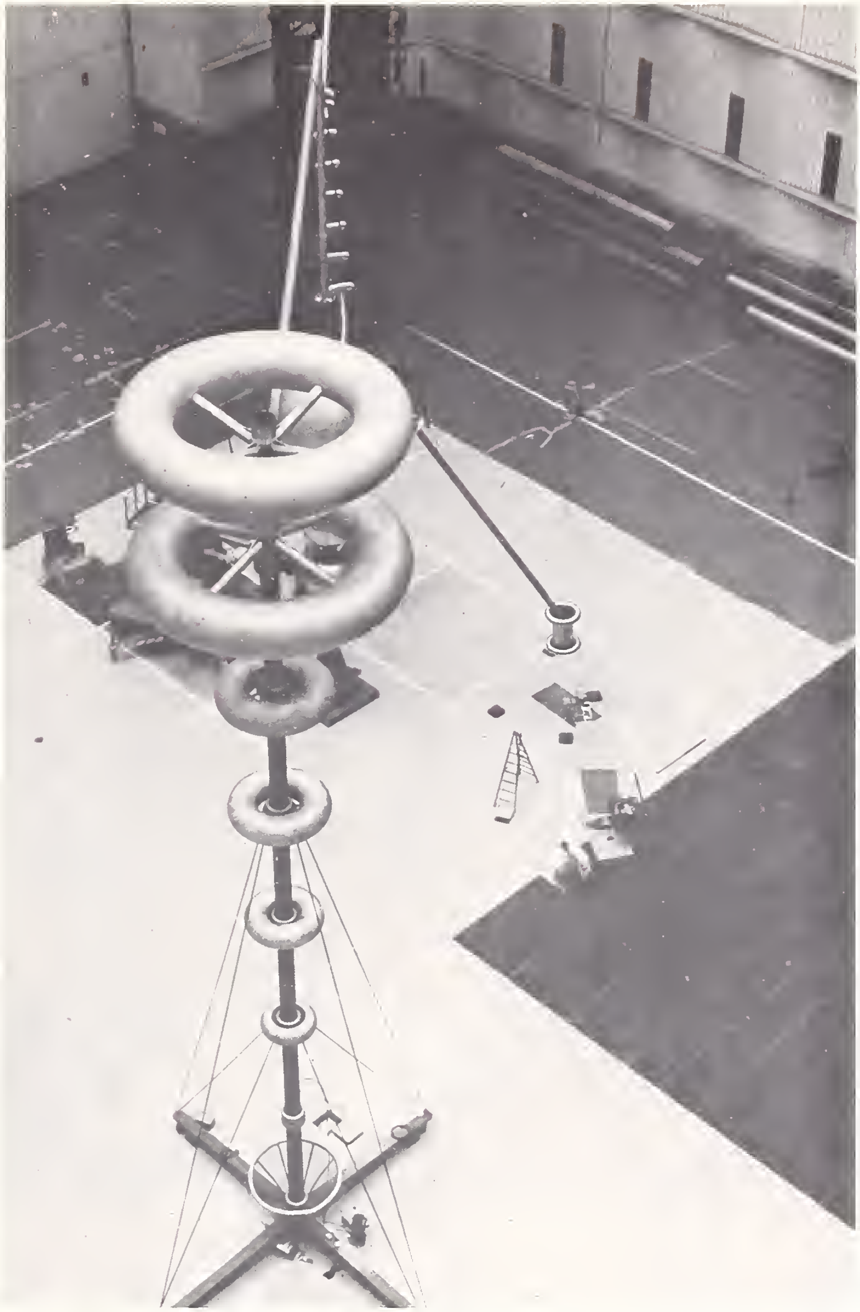


Fig. 65 NBS measurement of a very-high-voltage device in a French laboratory. The NBS apparatus appears as a small spool-shaped object at the center right of the photograph. Note the size of the stepladder and the person at the equipment rack.

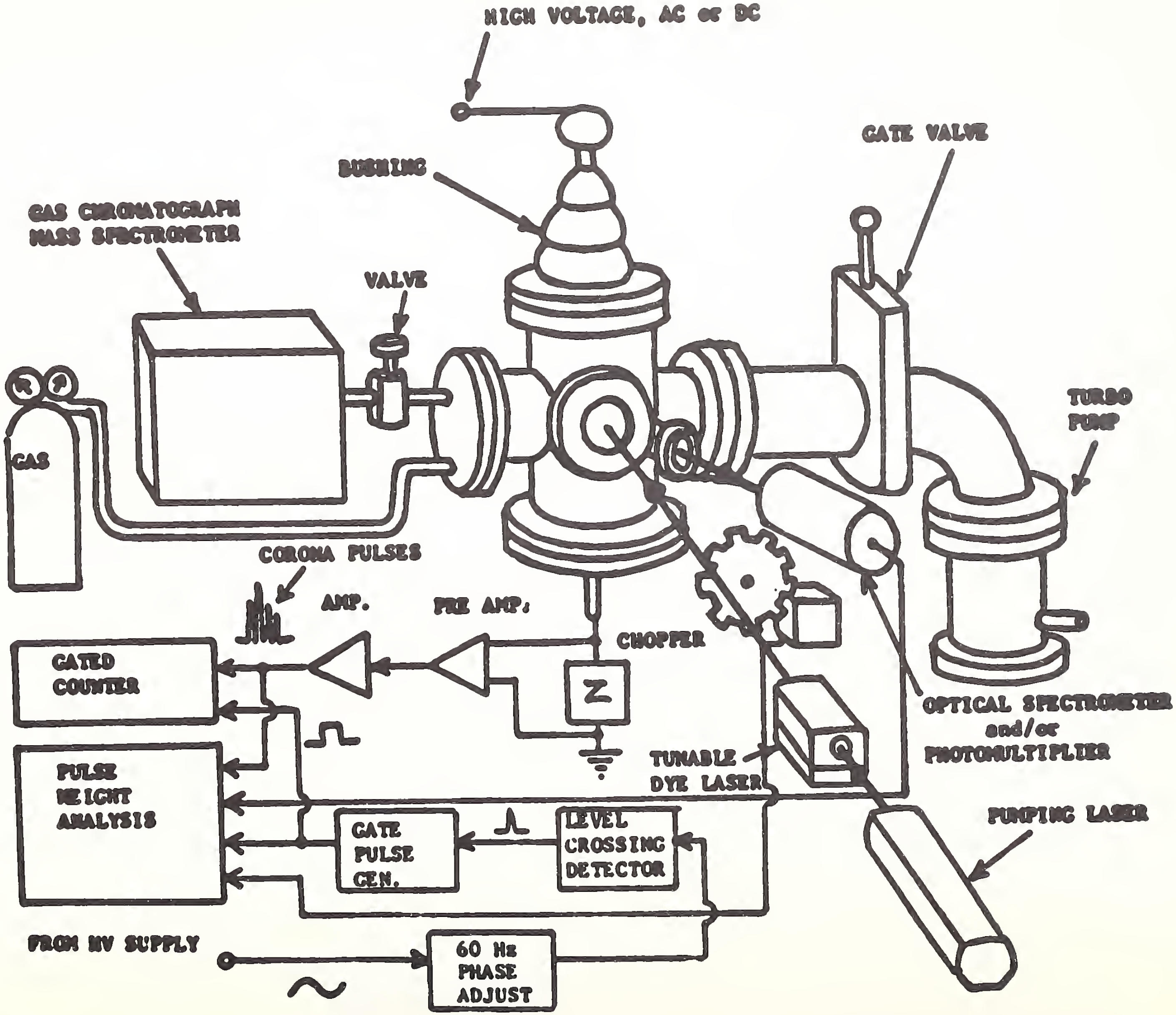


Fig. 66 Schematic of apparatus for measuring the breakdown products in an insulating gas subject to electrical stress (such as arcing).

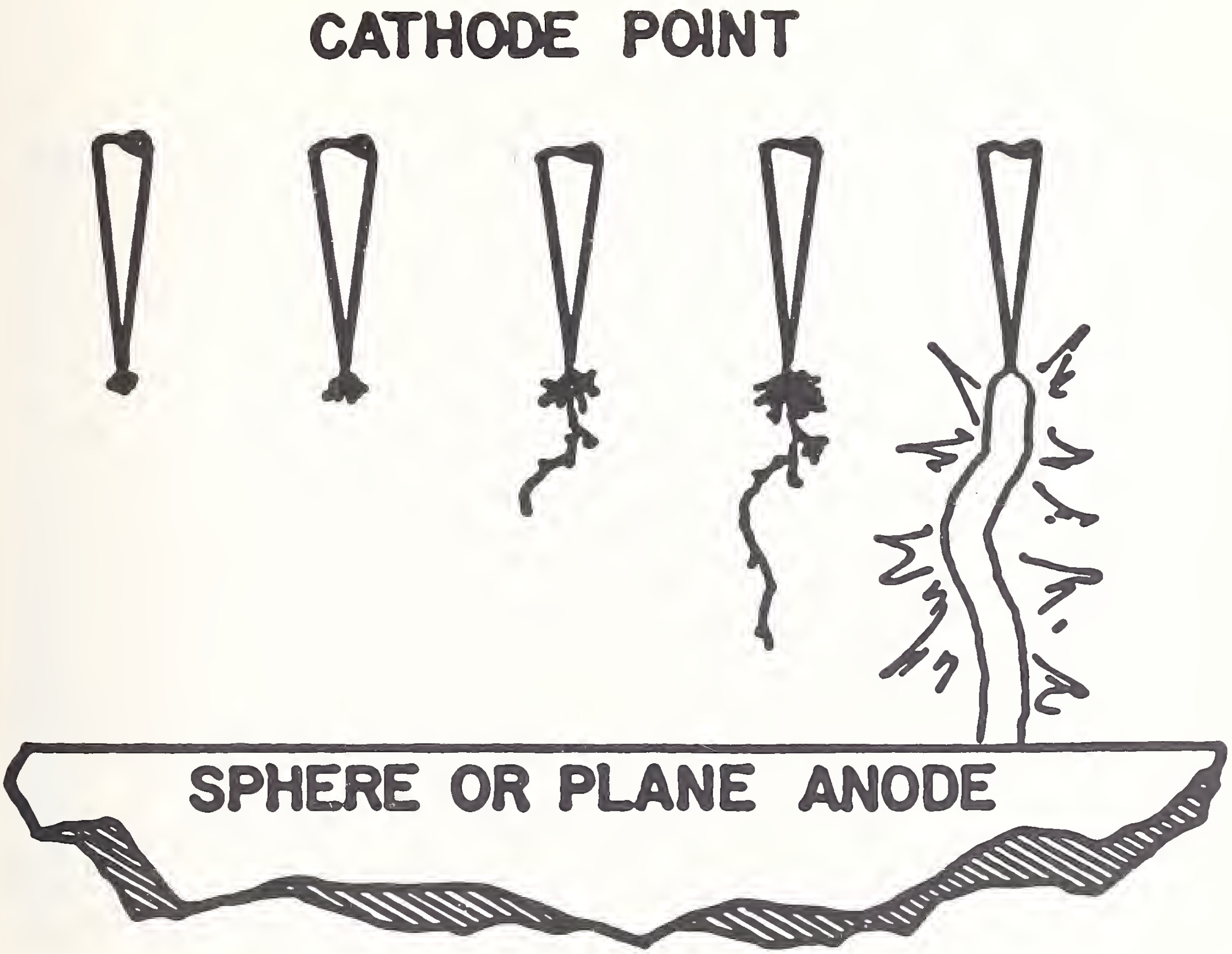


Fig. 67 Diagram showing a breakdown event in a liquid insulating material between a point and a plane.

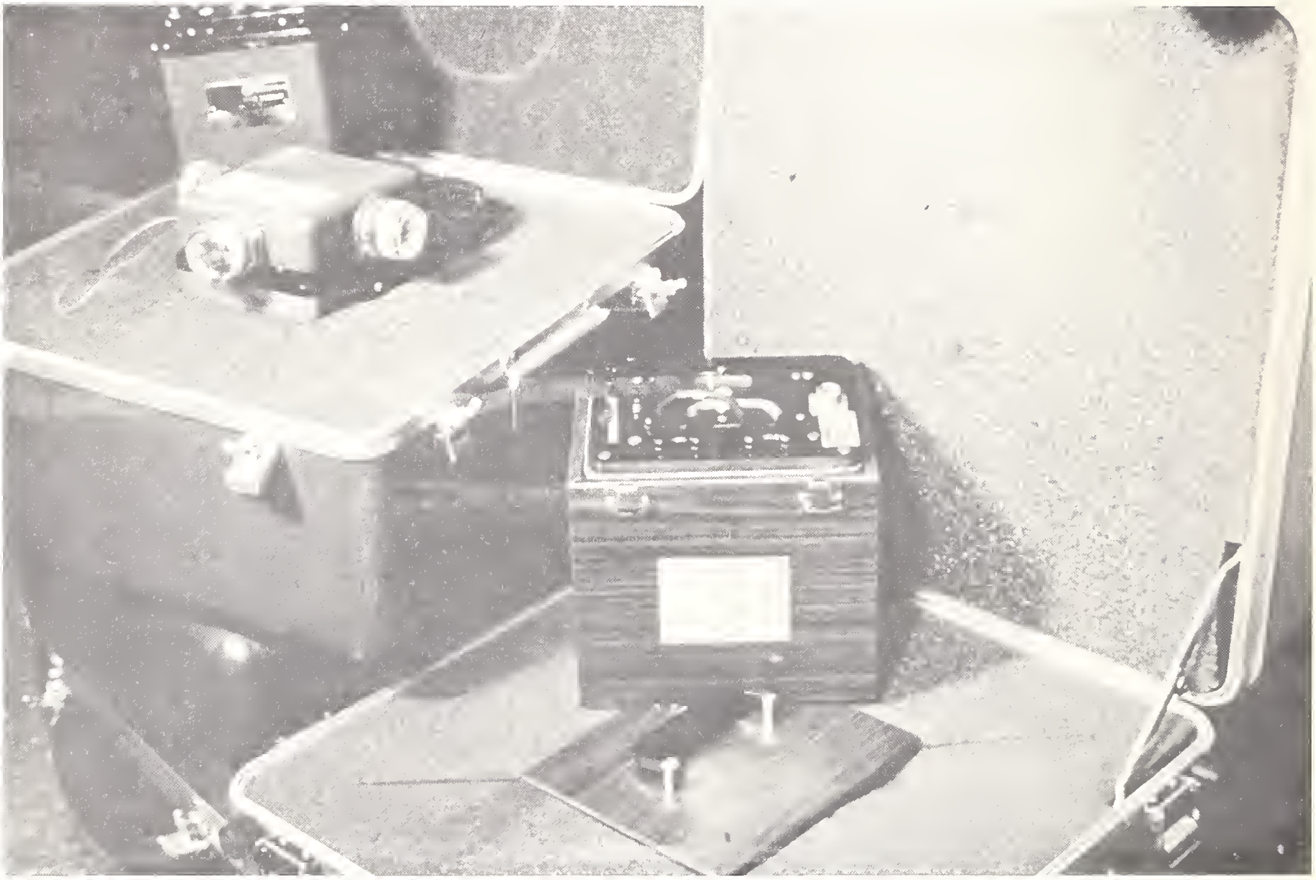


Fig. 68 An electronic watthour meter. This instrument requires a ten-fold improvement in accuracy of calibration compared to the requirements of previous electrodynamic designs.

ELECTRO-MAGNETIC SENSING AND HAZARDS

Significance

- Proliferation of electromagnetic (EM) radiation sources has created concern for interference with key electronic systems and for hazards to humans
- EM radiation can serve as a non-destructive probe for structural integrity and safety, and water resource management
- Metrology is now inadequate to
  - Characterize the EM environment
  - Assess EM susceptibility and emission of electronic components and systems
  - Apply EM radiation for non-destructive evaluation of structures and materials

ELECTRO-MAGNETIC SENSING AND HAZARDS

NBS Response

- Provision to industry and regulatory agencies of measurement techniques covering critical frequency and power density ranges to characterize EM interference and hazards
- Correlation of EM properties of selected natural and structural materials with their physical properties as bases for non-destructive evaluation of integrity and safety and water resource management

Figs. 69,70 Electromagnetic Sensing and Hazards Program - metrological significance and challenge and NBS response.

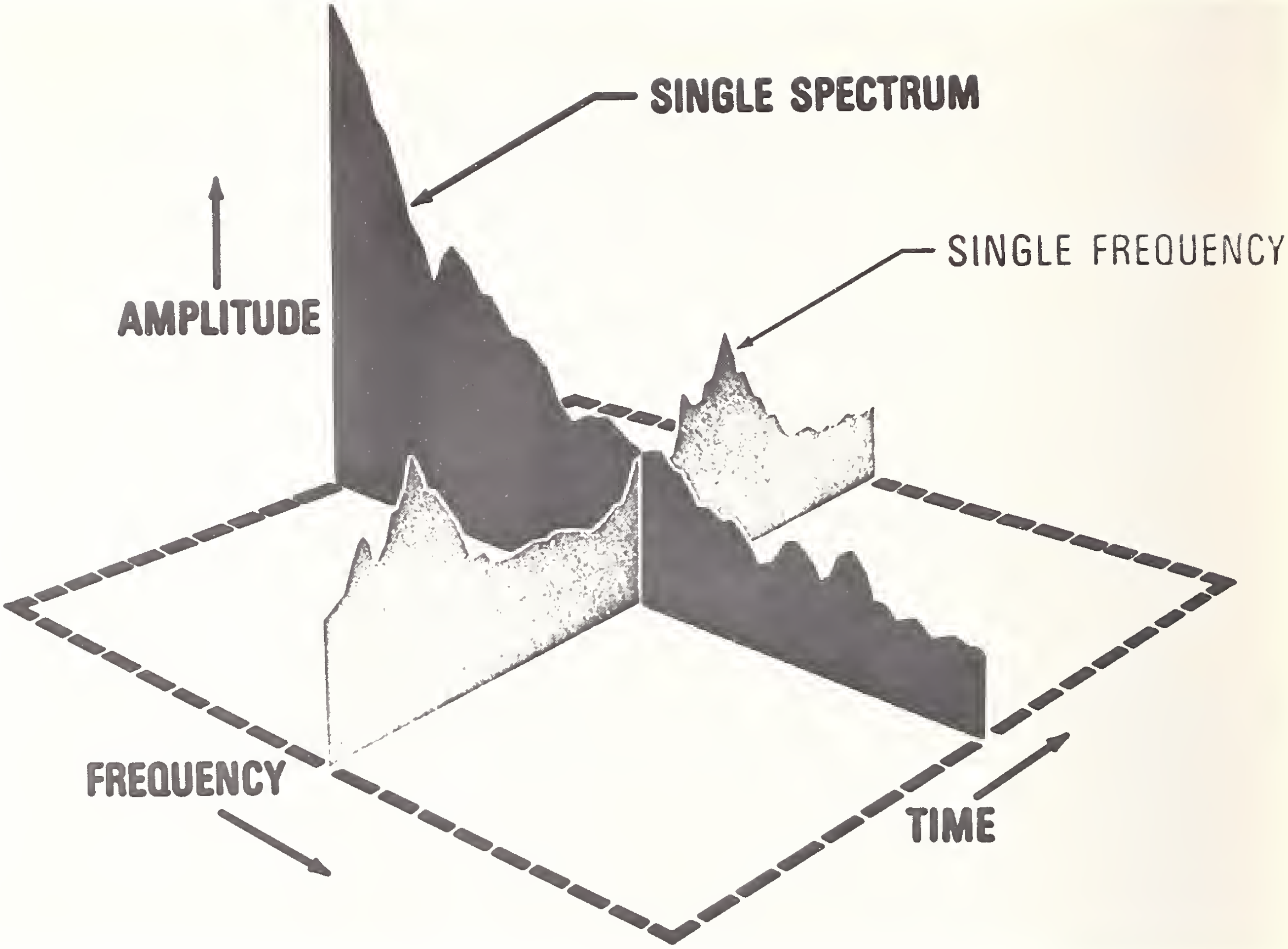


Fig. 71 Adequate characterization of the electromagnetic fields present in real situations of practical interest (e.g., in cities) requires multispectral measurements over time and frequency.

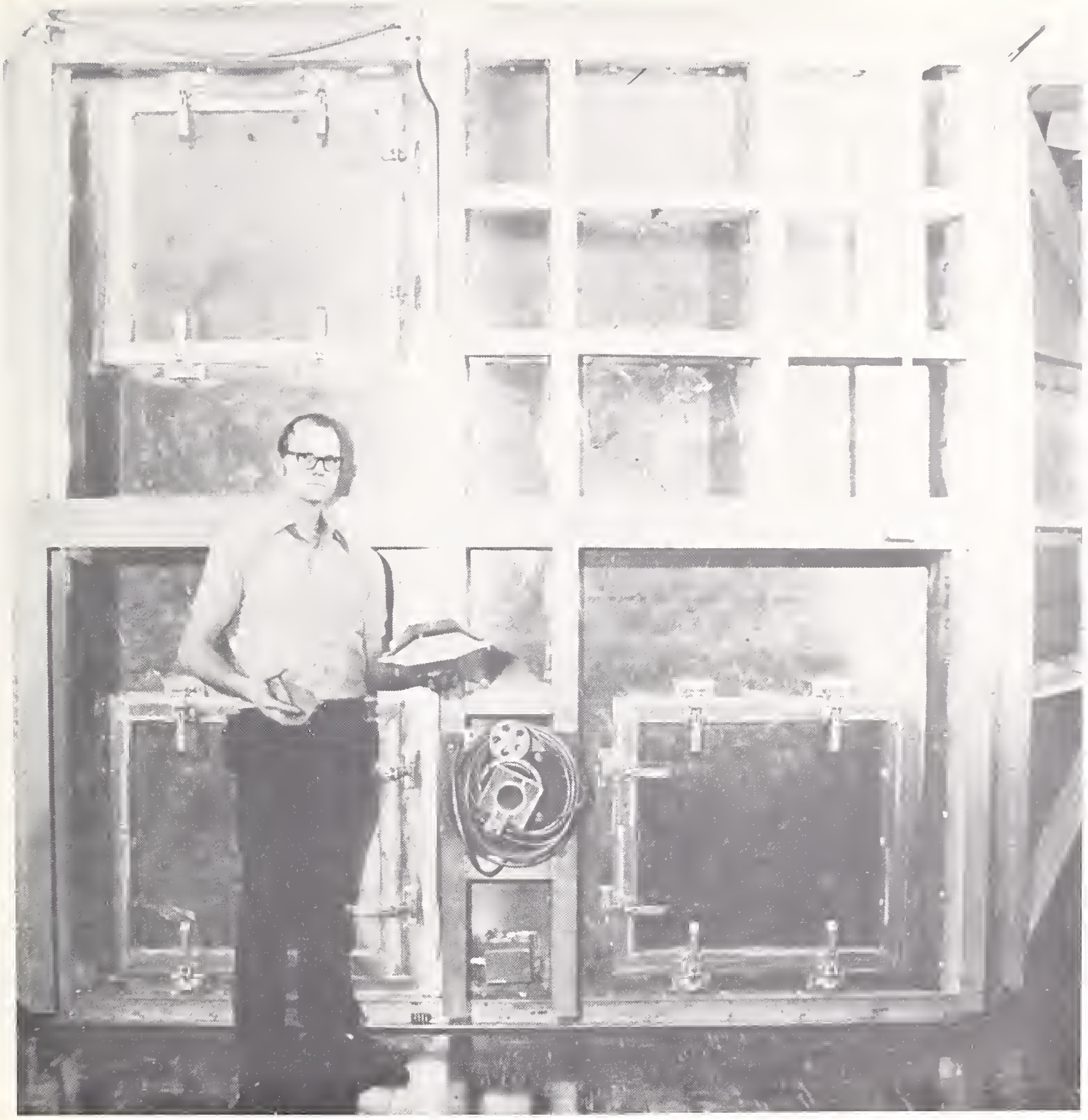


Fig. 72 Three transverse electromagnetic (TEM) cells. TEM cells provide a well-characterized field over a useful volume and are used for both susceptibility and emission measurements. The cells operate over a frequency range from dc to an upper limit proportional to cell size.

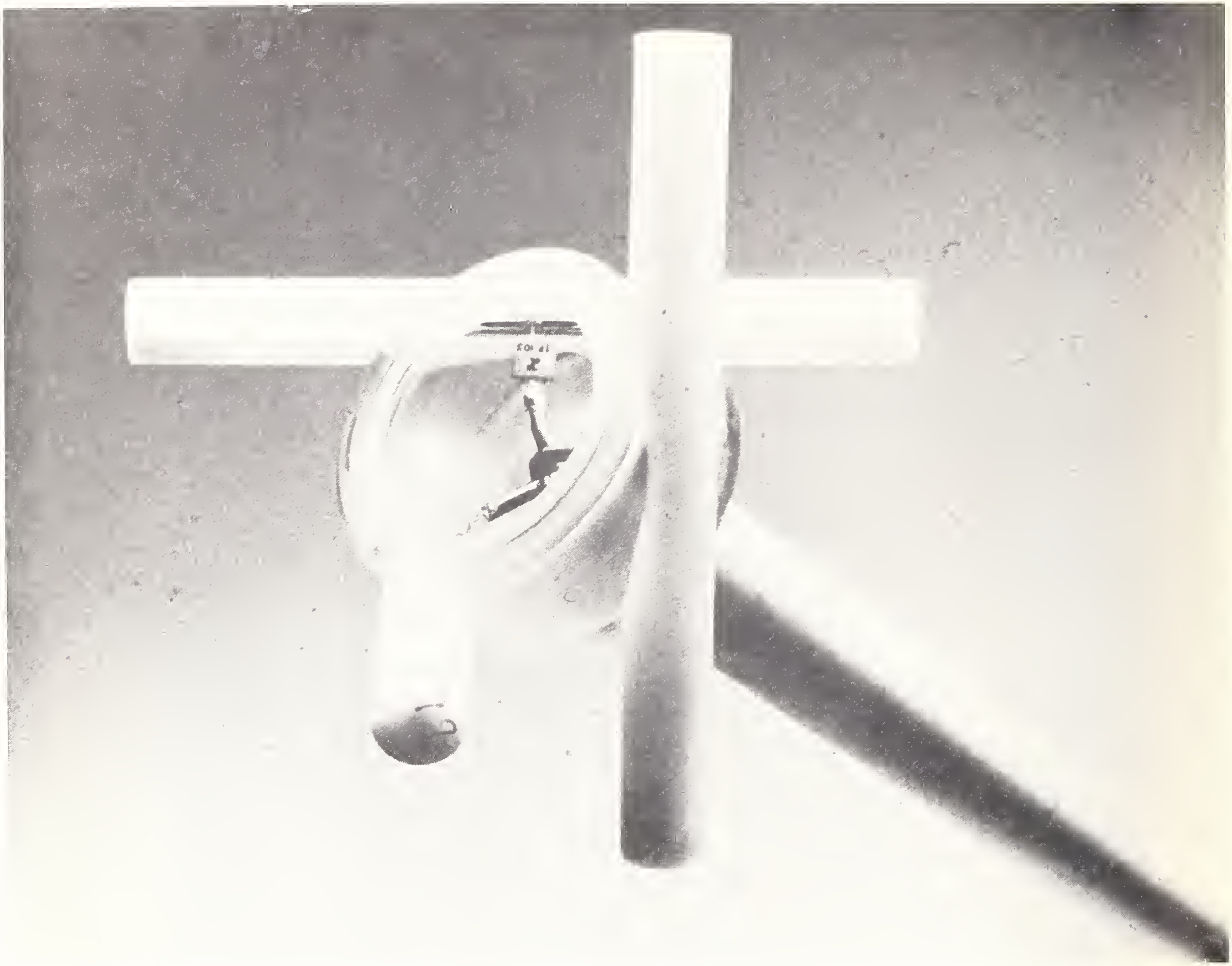


Fig. 73 Photograph of dipole-diode array for isotropic measurement of electric field strength. This antenna and an associated electronics package constitute the NBS EFM-5 probe, now available commercially.

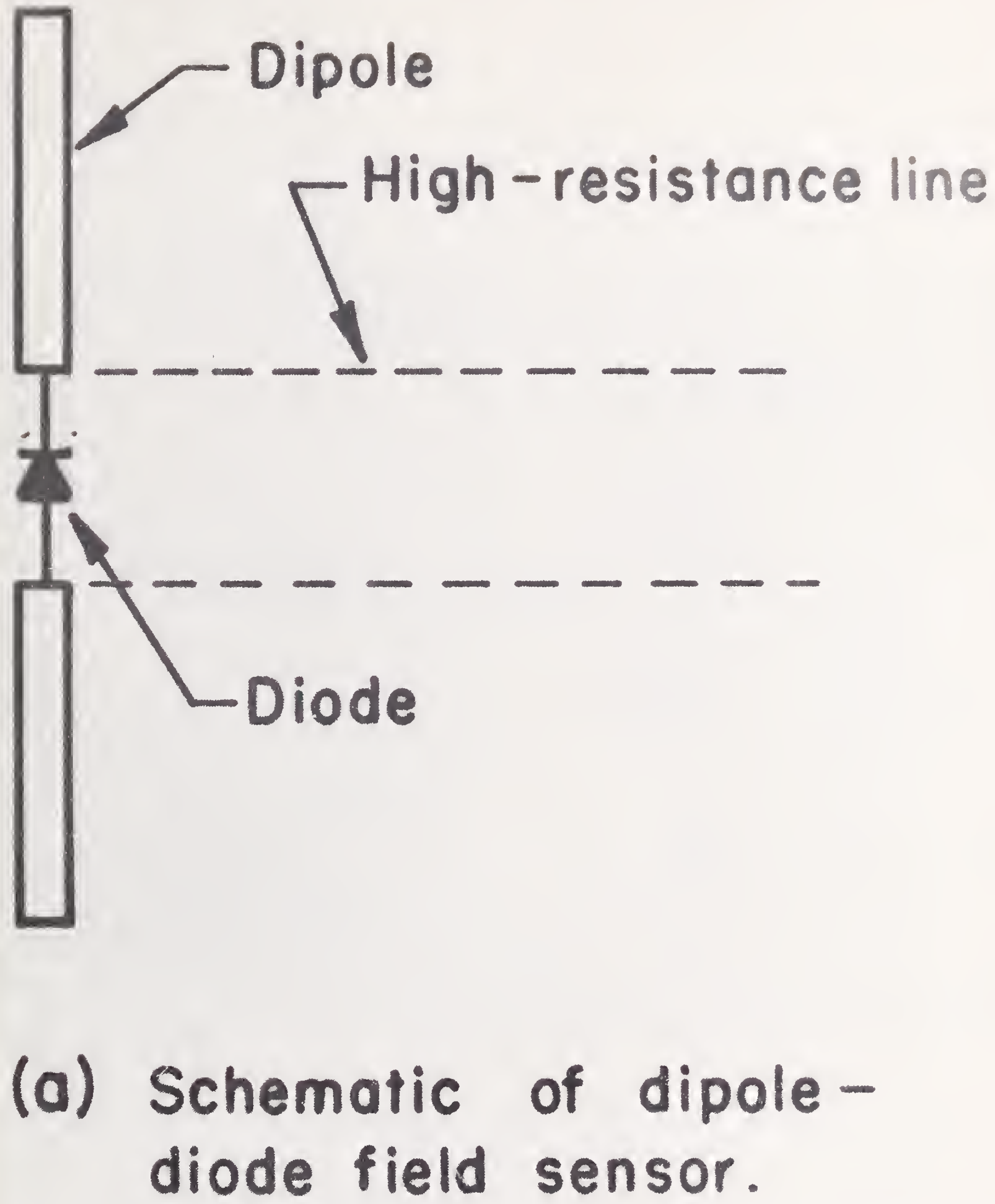


Fig. 74 Dipole-diode electric field sensor.

Fig. 75 The NBS EFM-5 probe package. A significant feature of this instrument is that is provide coverage of the radio and television broadcast bands.

Fig. 76 Measurement of electric fields resulting from high-voltage transmission lines. this measurement is sensitive to the presence of the operator, hence the long handle.

Fig. 77 An NBS-developed instrument for measuring the roof thickness of a mined coal seam. The mine operator desires to remove as much coal as possible, but to leave a thick enough roof layer to support the overlying slate and to protect it from weathering. Common practice is to leave more coal than is required to safety, on the basis of both experience and the use of small test bores in which a direct measurement may be made.

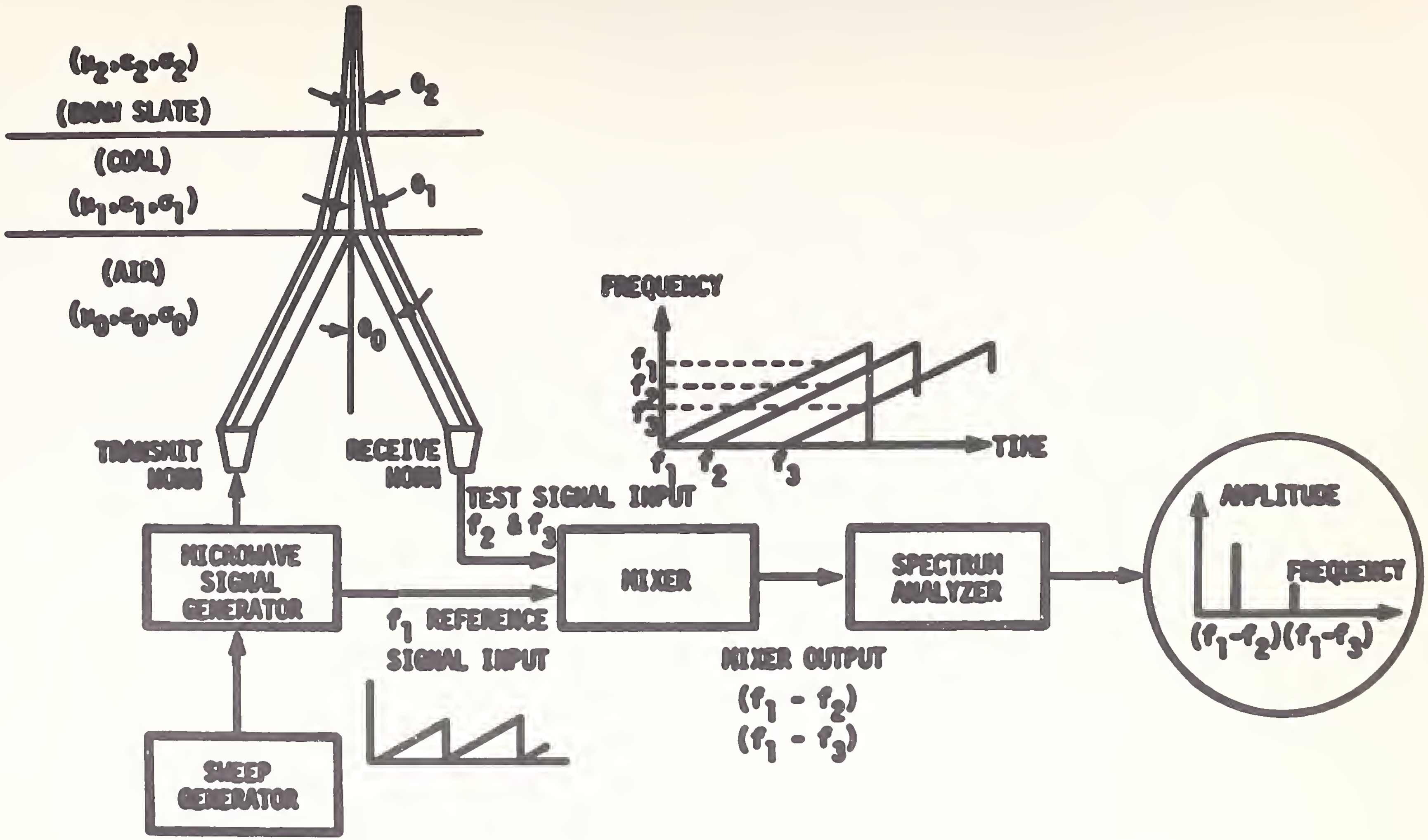


Fig. 78 Schematic diagram illustrating the principle of operation of the instrument shown in figure 77. Electromagnetic radiation is used to probe the coal and slate layers in a radar-like system. Continuous mapping of the coal seam thickness is possible.

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Assurance of measurement quality to meet requirements for regulatory agencies, marketplace equity, and productivity and quality control in manufacturing and research is challenged by unprecedented demands for sensitivity, speed, precision, and accuracy over wide ranges of properties and signal characteristics. New approaches are needed. Examples of NBS response, principally in electrical and electronic engineering, are described.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

calibration; electrical; electronics; engineering; hazards; measurement; metrology; National Bureau of Standards; power; radiation; semiconductor; technology

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