June, 1967 Vol. 55 No. 6

Proceedings of the IEEE

Scanning the Issue

Introduction

THIS is the first special issue of the PROCEEDINGS OF THE IEEE to be devoted exclusively to the extensive subject of RF (radio frequency) measurements. Because it attempts to cover the entire field, the issue is rather large.

It consists entirely of invited papers which are grouped in two main sections, the first containing ten editorial and general articles, and the second containing 31 papers on specific technical subjects.

For the purpose of this issue, radio frequencies are considered to begin at approximately 30 kHz (30 000 cycles per second) and go upwards. The upper limit is not as yet clearly defined, but includes frequencies of coherent sources of visible radiation, such as lasers.

Because of the demanding requirements of military and space applications, many important improvements have recently been made in the science and art of RF measurements. Many are not yet covered in today's textbooks and are available here for the first time in one volume. This collection of techniques is designed to bring the engineer and scientist up to date and to serve as a reference issue on the present state-of-the-art of accurate RF measurements.

The Editorial and General Section

The ten editorial and general articles describe activities of professional, semi-governmental, and governmental bodies in furthering research and establishing standards for RF measurements. They also describe international cooperative efforts in standardization and touch upon the potentials of a career in radio metrology.[1]

The Technical Section

The 31 papers on specific technical subjects are grouped under four main headings. The first deals with the extensive subjects of time and frequency, including their interrelationships with RF measurement techniques.

The second group of papers is concerned with standards and measurements of other quantities such as power, noise temperature, voltage, current, impedance, attenuation, phase, and electric field strength at frequencies up to approximately 30 GHz. Also included in this group are papers on coaxial connector standardization and on swept-frequency measurement techniques.

The third group of papers deals with the measurement of some of these same quantities at frequencies from 30 GHz on upwards through the laser region to approximately 800 THz (8×10^{14} cycles per second).

In the fourth group of papers, applications of basic RF measurement techniques to the measurement of various parameters are discussed. These include the determination of the speed of electromagnetic waves, the electrical properties of materials, distance or linear displacement, and parameters affecting electromagnetic compatibility.

The final paper in the issue presents a series of accuracy charts which give an indication of the estimated uncertainty (with respect to NBS or international standards) in calibrations or measurements by the National Bureau of Standards on radio frequency standards or instruments.

Importance of Knowledge of Available Accuracies

In planning ahead for the development of needed facilities and tools, an engineer ordinarily considers the necessary lead time. Unless he is familiar with the accuracies presently available for measurements involved in his planned operations, he will not know whether to plan for corresponding lead times to upgrade his measurement capabilities. In some cases a "measurement pinch" [1] has been felt and appeared critical only because of lack of familiarity with the accuracies currently available and those likely to be soon made available through developments which are under way.

Mass Production Stimulates Precision

In the early days of automobile manufacture, pistons were individually fitted to the bores in the cylinder. With the advent of mass production, parts had to be interchangeable and required higher precision, more accurate measuring methods, and greater confidence in standards. This now holds true for the need to economically mass-produce RF and microwave devices and systems. A realistic knowledge of the limitations of measurements permits the systems engineer to specify and verify with greater confidence the RF properties of the interface for a component or subsystem so that devices produced in separate, specialized facilities operate satisfactorily and cooperate efficiently when assembled. Increased confidence levels in the accuracy of RF measurements are needed to facilitate economical mass production of systems utilizing the specialized skills of many suppliers. Excessive uncertainties result in uneconomical overdesign and often in overweight.

Of course the "gauges" of the many skilled designers,

[1] The term "radio metrology" refers to the field of measurements of electromagnetic quantities at radio frequencies.

manufacturers, and users must all be traceable to the same "standards." While large users and manufacturers can afford to have their own secondary standards laboratories, the small manufacturer and many users must rely upon the availability of Government standards and, in the United States, must depend upon the calibration services of the National Bureau of Standards as well as of privately operated calibration facilities traceable to NBS. The rapid increase in demand for RF calibrations is continuously increasing the work load of the Electronic Calibration Center at the National Bureau of Standards in Boulder, Colo.

RF Metrology Can Accelerate Research and Development

The extension of the art and science of RF measurements permits the exploration of new phenomena, and new phenomena in turn create new measurements. We are therefore observing the interplay between measurements and research in an ascending spiral. Good examples of this are observed in radar technology, microwave spectroscopy, masers, and lasers, as pointed out in Dr. Allen V. Astin's editorial (p. 741). The information in this issue ought to excite the interest of working engineers so that they will use these techniques as tools to increase their professional capabilities. Accurate RF measurement is an important factor in developing technology and advancing science. Because of lack of familiarity with the state-of-the-art of RF measurement, engineers often proceed empirically in lieu of using a judicious mixture of measurement and experiment. One should not proceed blindly by trial and error but by charting the way after analysis of measurement results.

Trends

There are challenging frontiers and undeveloped areas which exist in RF metrology and its application to mass production. There is always the challenge of extending present measurement capabilities to higher and higher frequencies as well as of reducing uncertainties in measurements at any frequency or extending the range of the measurement. There are also gaps and unsolved problems at the lower frequencies, where either some standards need to be developed or ranges and accuracies need to be extended and improved. For example, accurate field strength measurements need to be extended above 1 GHz and accurate measurements of most quantities are needed at frequencies from 30 GHz through 800 THz. At the lower frequencies, there is a present lack of NBS standards of pulsed voltage to 12 GHz, phase shift below 30 MHz, noise below 1 GHz, CW and pulsed current, balanced voltage and current, and impulse spectral density.

Accurate RF measurements containing more information over greater bandwidths are required. Ely (p. 991) describes advances in swept-frequency techniques. The economy of mass production and shortage of skilled test technicians result in marriage of fixed or swept-frequency RF measurements with programmable semi-automatic test sets producing a high volume of recorded data. Highly repeatable connections are made with automated jigs. These test systems are usually custom-designed. A computer has been combined with such a system to solve explicitly for a term in the scattering matrix or to correct for systematic errors such as finite directivity vs. frequency [2]. The field of RF metrology is in a rapid state of flux, marrying new and old technologies, and creating new test systems and design tools.

Robert W. Beatty *(S'43–A'45–M'50–SM'53–F'67) was born in York, Pa., on May 31, 1917. He received the B.S. degree in electrical engineering from George Washington University, Washington, D. C., in 1939, and the S.M. degree in electrical communication from the Massachusetts Institute of Technology, Cambridge, in 1943.*

From 1940 to 1942 he was associated with the Naval Research Laboratory, Washington, D. C., in work on underwater sound- and radio-direction finding. He was a Staff Aide at the M.I.T. Radar School in 1943 and served in the U. S. Naval Reserve from 1943 to 1946. He has had several years' experience in the field of consulting radio engineering for the radio broadcast industry. Since 1948 he has been associated with the National Bureau of Standards, working in the field of microwave standards, and was Chief of the Microwave Circuit Standards Section at NBS, Boulder, Colo., from 1955 to 1962. He is at present a Consultant in the Radio Standards Laboratories Engineering Division.

Mr. Beatty received the Department of Commerce Silver Medal in 1963. He is a member of Sigma Tau, Theta Tau, Sigma Xi, the Instrument Society of America (ISA), and the International Scientific Radio Union (URSI). He was chairman of U. S. Commission I of URSI from 1957 to 1960, and was editor of the IEEE Transactions on Microwave Theory and Techniques *during 1963–1965. He was Scientific Editor of Commission I for the 14th and 15th General Assemblies of URSI, and is a member of the Administrative Committee of the IEEE Group on Microwave Theory and Techniques.*

Information Sources on the State-of-the-Art

As previously stated, rapid advances of very accurate RF measurement techniques were propelled mainly by the demands of the military and space programs. This made it difficult for textbooks to keep abreast of the field. This issue of the PROCEEDINGS has attempted to collate these techniques and make them available in one volume.

Other important supplements to the standard textbooks have been IRE and IEEE publications, especially the issues reporting on the biennial Conferences on Precision Electromagnetic Measurements [3]–[8].

Another important source of RF measurement information is "Section C, Engineering and Instrumentation" of the *Journal of Research of the National Bureau of Standards*, which frequently publishes on current advances in the field. Technical review papers similar in type to those in this issue have recently appeared, somewhat scattered and more limited in scope. For example, the triennial survey reports [9], [10] of Commission I, URSI (International Scientific Radio Union) cover progress at three-year intervals throughout the world in radio standards and measurement techniques. The journal *Metrologia*, first published in 1965, has contained three invited review papers [11]–[13], concerned with time and frequency standards and the system of electromagnetic quantities. In February of 1966, a special issue of the PROCEEDINGS OF THE IEEE on "Frequency Stability" contained some papers concerned with frequency standards.

Requirements of an RF Metrologist

In scanning the issue and in actually reading the papers, a number of general conclusions regarding radio metrology may be drawn. For instance, the pursuit of accuracy in RF measurements requires the analysis of errors and the evaluation of limits of uncertainty. This is usually the most challenging aspect of this type of research since the measurement techniques themselves often are relatively straightforward. The solution of problems in radio metrology requires great skill, ingenuity, analytical ability, and perseverance on the part of the metrologist. Solid-state and atomic physics, circuit theory, electromagnetic theory, and advanced mathematics are used, and some problems require exceptional experimental ability. It is not enough to make ingenious use of the best measurement techniques in order to reduce errors—one must investigate the errors and determine the limits of uncertainty if measurement is to be a science rather than an art. However, RF metrology needs both its artists and its scientists to produce excellent measuring instruments and the means to calibrate and evaluate them.

Limited Exposure to Accurate RF Measurements in Engineering Schools

Today's engineering education poses the problem of where to strike the balance between science and art, where art includes the action which applies science [14]. Dean Mason in his editorial (p. 774) indicates that most electrical engineering schools teach only basic RF measurements in the laboratory section of a course, leaving the teaching of the most accurate measurement techniques to the employer. Brooks [14] recommends that engineering schools bring in the outside specialist as an adjunct professor to teach such advanced subjects. Only a few engineering schools, among them the George Washington University School of Engineering and Applied Science which contains the Center for Measurements Science, offer formal courses in state-of-the-art RF measurements which include rigorous error analysis and employ modern mathematical techniques including scattering matrices and flow graphs. Kerns' article (p. 892) defines scattering matrices, while Ely (p. 991) employs flow graph analysis for determining the error of a reflectometer. Also trying to fill this gap is the Radio Frequency Standards Laboratory of the National Bureau of Standards in its precision measurement seminars.

It is hoped that this special issue will introduce RF measurements to newcomers to the field through tutorial reviews, and will, through its bibliographies, serve as a reference source for those who wish more detail. The greatest hope, however, is that it will call attention to the challenges facing the radio metrologists of the future and kindle the interest of young engineers and physicists in this basic, all-important, wide-open field of scientific investigation.

R. W. BEATTY
B. O. WEINSCHEL
Guest Editors

Bruno O. Weinschel (*A'45–M'47–SM'53–F'66*) *was born in Germany on May 26, 1919. He studied physics at the Technische Hochschule, Stuttgart, Germany, and received the Doctor's degree in engineering from the Technische Hochschule, Munich, Germany, in 1966.*

Prior to founding his own company he was Chief Engineer of the Industrial Instruments Company, Senior Engineer in the Electrical Test Planning Department of Western Electric, and a Research Worker at the National Bureau of Standards. Since 1952 he has been President of Weinschel Engineering Company, Inc., Gaithersburg, Md. He has contributed to the state-of-the-art of insertion loss microwave measurement.

Dr. Weinschel is Chairman of U. S. Commission I of the International Scientific Radio Union (URSI) for 1967–1970 and Liaison Representative for the Group on Instrumentation and Measurement to the IEEE Standards Committee.

Acknowledgment

In preparing this issue, the editors gratefully acknowledge the liberal and wholehearted support of the organizations by whom authors and reviewers are employed. They are recognized in the credits given to authors and in the following list of persons who helped in the editorial process.

R. T. Adair, National Bureau of Standards
J. W. Adams, National Bureau of Standards
C. M. Allred, National Bureau of Standards
H. M. Altschuler, National Bureau of Standards
D. H. Andrews, National Bureau of Standards
E. Z. Bahar, University of Colorado
Y. Beers, National Bureau of Standards
L. M. Branscomb, National Bureau of Standards
K. S. Champlin, University of Minnesota
E. W. Chapin, Federal Communications Commission Laboratories
A. R. Chi, National Aeronautics and Space Administration
F. R. Clague, National Bureau of Standards
P. D. Coleman, University of Illinois
R. E. Collin, Case Institute of Technology
S. B. Cohn, Rantec Corporation
S. I. Cohn, U. S. Naval Marine Engineering Laboratory
C. C. Cook, National Bureau of Standards
D. D. Crombie, Environmental Science Services Administration
E. L. Crow, Environmental Science Services Administration
W. Culshaw, Lockheed Missiles and Space Company
C. A. Douglas, National Bureau of Standards
J. D. Dyson, University of Illinois
A. J. Estin, National Bureau of Standards
J. E. Ferris, University of Michigan
R. W. Frank, General Radio Company
G. J. Frye, Tektronix, Inc.
O. L. Gaddy, University of Illinois
R. D. Goodwin, National Bureau of Standards
W. M. Grove, Hewlett-Packard Company
M. B. Hall, National Bureau of Standards
B. P. Hand, Hewlett-Packard Company
G. Hefley, Environmental Science Services Administration
F. L. Hermach, National Bureau of Standards
A. E. Hess, National Bureau of Standards
R. D. Huntoon, National Bureau of Standards
H. Jaffe, Clevite Corporation
D. A. Jennings, National Bureau of Standards
E. M. T. Jones, TRG-West
W. K. Kahn, Polytechnic Institute of Brooklyn
R. A. Kamper, National Bureau of Standards
P. Lacy, Wiltron Company
H. W. Lance, National Bureau of Standards
N. T. Larsen, National Bureau of Standards
R. E. Larson, National Bureau of Standards
R. S. Lawrence, Environmental Science Services Administration
C. H. Looney, National Aeronautics and Space Administration
T. E. MacKenzie, General Radio Company
W. Markowitz, Marquette University
W. P. Mason, Columbia University
D. G. McDonald, National Bureau of Standards
A. G. McNish, National Bureau of Standards
D. A. McSparron, National Bureau of Standards
D. G. Melquist, National Bureau of Standards
J. H. Mennie, Boonton Electronics Corporation
K. D. Mielenz, National Bureau of Standards
R. C. Mockler, University of Colorado
K. B. Persson, National Bureau of Standards
R. L. Peterson, National Bureau of Standards
R. C. Powell, National Bureau of Standards
R. S. Powers, National Bureau of Standards
F. X. Ries, National Bureau of Standards
W. K. Roberts, Federal Communications Commission Laboratories
R. B. Schulz, The Boeing Company
A. H. Shapley, Environmental Science Services Administration
P. A. Simpson, National Bureau of Standards
J. K. Skilling, General Radio Company
G. U. Sorger, Weinschel Engineering Company
G. W. Stroke, Massachusetts Institute of Technology
C. T. Tai, University of Michigan
J. J. Taub, Airborne Instruments Laboratory
K. R. Wendt, National Bureau of Standards
F. Wenninger, Hewlett-Packard Company
A. C. Wilson, National Bureau of Standards
G. M. R. Winkler, U. S. Army Electronics Command
B. C. Yates, National Bureau of Standards
J. Zorzy, General Radio Company

Editorial Secretaries

Grace McClure, Weinschel Engineering Company
Judy Thompson, National Bureau of Standards
Ellie Campbell, National Bureau of Standards

References

[1] A. V. Astin, "Our measurement system and national needs," *Sperryscope*, vol. 19, pp. 16–19, 3rd quarter 1960.
[2] P. C. Ely, Jr., "The engineer, automated network analysis and the computer—signs of things to come," *Hewlett-Packard J.*, pp. 11–12, February 1967.
[3] 4th Conference on High Frequency Measurements, *IRE Trans. Instrumentation*, vol. PGI-4, October 1955.
[4] August 1958 Boulder Conference on Electronic Standards and Measurements, *IRE Trans. Instrumentation*, vol. I-7, December 1958.
[5] June 1960 Boulder Conference on Standards and Electromagnetic Measurements, *IRE Trans. Instrumentation*, vol. I-9, September 1960.
[6] August 1962 International Conference on Precision Electromagnetic Measurements at Boulder, *IRE Trans. Instrumentation*, vol. I-11, December 1962.
[7] June 1964 Conference on Precision Electromagnetic Measurements, *IEEE Trans. Instrumentation and Measurement*, vol. IM-13, December 1964.
[8] June 1966 Conference on Precision Electromagnetic Measurements, *IEEE Trans. Instrumentation and Measurement*, vol. IM-15, December 1966.
[9] USNC/URSI, "Progress in Scientific Radio, 1963–1966," NAS-NRC, 2101 Constitution Ave., Washington, D. C. 20418, Publ. 1468, 1966.
[10] URSI, "Progress in Radio Science," Space Sciences Lab. (Prof. S. Silver), University of California, Berkeley, Calif. 94720, 1967.
[11] R. E. Beehler, R. C. Mockler, and J. M. Richardson, "Cesium beam atomic time and frequency standards," *Metrologia*, vol. 1, pp. 114–131, July 1965.
[12] M. C. Selby, "The system of electromagnetic quantities at 30 kHz to 1 GHz," *Metrologia*, vol. 2, pp. 37–45, January 1966.
[13] R. W. Beatty, "The system of electromagnetic quantities at frequencies above 1 GHz," *Metrologia*, vol. 2, pp. 46–54, January 1966.
[14] H. Brooks, "Dilemmas of engineering education," *IEEE Spectrum*, vol. 4, pp. 89–91, February 1967.