Microwave Instrumentation: An Historical Perspective

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I. Introduction

METROLOGY IS THE science of measurements. When one is making a measurement, one is comparing an unknown quantity of some measure with a known (calibrated) quantity of the same measure. The equipment being used in electronics, especially in microwaves, is called instrumentation. When making measurements, using the appropriate instrumentation, the basic rules of metrology have to be observed. It is not enough to gather the data by performing the test; an evaluation of the errors involved also has to be determined. Resolution, readability, repeatability, and absolute calibration accuracy are all important factors in these considerations. It was exactly the evolution of these factors (the need for better accuracy and more data points by systems engineers) which fueled this process. When the measurement techniques fulfilled the requirements of systems designers, better, more sophisticated systems were possible to invent, which in turn posed the need for more improvements in instrumentation.

The biggest push for development of electronics gear for systems, in our lifetime, occurred during World War II. As a result, the 28 volumes of the MIT Radiation Laboratory Series were published. Volume 11, Carol Montgomery's *Microwave Measurements*, became the starting point for many of us dealing with the subject.

To evaluate the history of microwave measurements, i.e., instrumentation, it is prudent to divide metrology into two basic categories: Signal and Network Analysis.

II. Signal Analysis

The most fundamental microwave measurements are power and frequency. Average power measurement during World War II is well described by R. N. Griesheimer [1, ch. 3]. E. L. Ginzton further elaborates this in his book [2, ch. 3]. He describes calorimetric techniques as well as the bolometric power meter systems. The National Bureau of Standards has chosen to use a "microcalorimeter" as the National Power Standard. Early thermistor bridges exhibited dynamic ranges of 15–25 dB in the commonly used microwave ranges of decimeter and centimeter wavelengths. Sensitivities, dynamic ranges, and frequency coverage became targets for evolution to follow. Today, a 50-dB dynamic range is commonplace with thermoelectric and diode power meters, not violating square-law characteristics of devices used in power sensors. Frequency ranges also extend beyond millimeter wavelengths into optical frequencies.

Industry presently uses predominantly thermocouple and diode power meters. Recently, more emphasis was placed on the reduction of measurement error due to multiple mismatch uncertainties. This was achieved through careful design and manufacture of the power sensors, substantially cutting in half the reflection coefficients of power sensors. The use of microcomputers built into power meters and the availability of multiple power head sensing further enhanced applications.

Peak power measurements also have gained substantially from the WW II days, when peak power was calculated from average power measurements and from the assumption of rectangular pulse shapes and assumed duty cycles. Detection and CW comparisons with oscilloscopes followed. Barretter differentiation/ integration and finally sample-and-hold circuits were applied to extend the range of peak power measurements.

In [1, ch. 5], Beringer describes the design procedures of higher order mode cavity wavemeters. Coupling techniques of reaction and transmission types are also explained. Both coaxial and waveguide wavemeters became the workhorses of that technology. In narrow-band applications, such as in early radar applications, echoboxes with extremely high Q's were manufactured with materials exhibiting very small, practically negligible, thermal expansions. These devices were used to calibrate radars to assure their frequency allocations, during and after WW II.

L. B. Young explains frequency measurement in [1, ch. 6]. Early frequency standards, after WW II through transmissions from radio stations WWV of NBS, achieved accuracies of a few parts in 10^7. Seven crystal-controlled oscillators were trimmed to compare with the U.S. Naval Observatory's astronomical observations. The use of harmonic generators through chains of multiplication stages and appropriate filtering gave rise to variable-frequency standards. These techniques, after the application of phase-lock circuits, were predecessors of today's frequency synthesizers.

The first serious effort in the United States to use some kind of molecular resonance was made by the National Bureau of Standards as early as 1948. H. Lyons [56] and J. C. Helmer [57] first suggested such structures as frequency standards. Atomic frequency standards using molecular

Manuscript received January 10, 1984.
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0018-9480/84/0900-1157$01.00 ©1984 IEEE

resonances were developed in the early 1960's. A. S. Bagley and L. S. Cutler described their "flying clock experiments" using a pair of cesium-beam frequency standards. They compared European (Swiss) and U.S. atomic clocks within 1 μs, and other comparisons were made, never attained before. Today, hydrogen masers are keeping national frequency standards to better than a few parts in 10^{15}. With heterodyning now from visible lights, the National Bureau of Standards has been able to improve their distance standard by some margin.

G. N. Kamm [1, ch. 7] describes the efforts made by the Laboratory during WW II to develop the various spectrum analyzers used with wartime radars. Since RF oscilloscopes did not have fast enough circuits to show the correct values of risetime and pulse width of radar pulses, through a Fourier transform, that time-domain signal was converted to the frequency domain. The development of frequency discriminating circuitry, using heterodyning, and further filtering at IF frequencies, gave rise to spectrum analysis. Early analyzers were the TSK-3RL (a 1-cm), the TS-148/UP (a 3-cm), and the TSS-4SE (a 10-cm) spectrum analyzer, all Radiation Laboratory designs. The first harmonically mixed spectrum analyzer, the TSK-2SE using a 3-cm klystron, was also designed by the Laboratory. General Electric Co. Research Laboratory designed the RP-347 dual conversion analyzer. The G.E.-designed RP-392-K corrected several problems of the earlier design and provided the first "wide-range" analyzer (10–3000 MHz) with bandwidths of 10–60 MHz.

From the first appearance of the spectrum analyzer, it became apparent that it was a very versatile measurement tool. After WW II, such companies as Polarad, Lavoy, Panoramic, etc., marketed these swept-tuned microwave and RF spectrum analyzers. The first fully calibrated, wide-range spectrum analyzer equipped with signal identifier, also capable of sweeping broad frequency ranges, were introduced by Hewlett-Packard in the early 1960's. During the last two decades, many levels of improvement have been made to achieve present-day automatic spectrum analyzer techniques with on-board computational and error correction capabilities. Applications of these instruments range from simple distortion measurements through sophisticated phase-noise measuring schemes, to preprogrammed, modular electromagnetic interference test procedures.

III. Network Analysis

Network analysis is the measurement of scattering parameters. Montgomery discusses the measurement of impedance and standing waves [1, pt. III] and attenuators and radiation measurements [1, pt. IV]. Since microwave circuits were always considered as parts of transmission lines, considerations in line with transmission-line theory were fulfilled. In other words, all measurements of impedance and attenuation/gain were made terminated with their characteristic impedances. This coincides with the requirements known today as scattering parameter measurements.

E. Weber in [1, ch. 13] discusses microwave attenuation measurements. Different substitution methods of power ratio measurements and their accuracies are well dealt with. All the measurements described used impedance/admittance tuning devices to achieve as perfect a match as possible, and shows the single-frequency measurement techniques applied in those days. Dynamic ranges were limited to 20–30 dB due to the square-law and noise limitations of early bolometers and detectors. Calibration of those early attenuators was, even in WW II, very well thought out, and great efforts were expended to keep good standards. These techniques were further developed during the following decades, and used for the magnitude of both attenuation and gain measurements.

R. W. Beatty defined, in 1964, the different ways of understanding insertion loss [3]. He further defined attenuation as the decrease in power level (at the load) caused by inserting a device between a well-matched source and load.

Transmission phase measurement described by R. M. Redheffer in [1, ch. 10] shows the first efforts made in microwaves using a bridge method with calibrated phase shifters. R. A. Sparks has written a good review [4] on methods of phase measurements up until the early 1960's. Techniques described are: the slotted-line technique by Blattner and Beam [5]; Schafer's modulated subcarrier method [6]; standard phase shifter method, after Magid [7]; methods of Robertson [8], Finnila, Roberts, and Susskind [9], Mittra [10], and Stevens [11].

E. M. Purcell in [1, ch. 8] describes the art of standing wave measurement. Of course, P. H. Smith in his publication [12] on the Smith chart already alludes to impedance measurements. Impedance meters, bridges, and several designs of tunable and untuned detector designs showed up after WW II. Modulated signals were employed as signal sources to slotted lines. A narrow-band selective amplifier, better known as the standing wave indicator, was used for data gathering. Altar, Marshall, and Hunter [13] give a very good evaluation of errors in slotted lines, especially relating to pick-up probe errors. General Radio Co. has introduced, in the post-WW II years, their 14-mm slotted-line system. In 1950, the Hewlett-Packard Co. introduced the first "slab-line" slotted line to reduce probe-related errors [14]–[16].

Weinschel, Sorger, Raff, and Ebert [17] introduced the coupled sliding-load technique with a slotted line to cancel the sliding-load's mismatch. Sorger and Weinschel [18] and Adam [19] have discussed swept slotted-line measuring techniques, although the latter method does not provide phase information.

L B. Young [1, ch. 9] described early impedance bridge designs. He deals with the Magic-tee, waveguide and coaxial ring networks, and their use in making impedance measurements. During the war, pulse power applications preceded all other impedance bridge developments. The TBX-1BR is the first known impedance bridge design which was built during the war.

R. L. Kyhl [1, ch. 14] explained the operation and design of directional couplers. Bethe [20] explained how a single hole in a waveguide transmission line exhibits directivity. Lippmann [21] and Julian [22] further explained different directional couplers as signal separation devices. Myers and Charles [23] and Julian [24] were among the first to describe the reflectometer as a reflection coefficient measuring test setup. Hunton and Pappas [25] explained the operation of waveguide reflectometers. Ginzton also showed the operation of a reflectometer with two probes for magnitude-only reflection coefficient measurements and a three-probe method for vectorial phase measurement [2, p. 301]. Other multiple-probe methods were cited by Ginzton [2] in an unpublished Naval Research Laboratory memorandum by C. H. Taylor, September 1945. Peterson, Kreer, and Ware had shown a low-frequency automatic oscilloscope display of complex transfer factors of amplifiers as early as 1934 [26]. Samuel discussed an early version of the "six-port" technique in 1947 [27]. Ely analyzed the errors in swept-frequency measurements [28].

Packard [29], Gabriel [30], Bachman [31], and Watts and Alford [31] made early efforts designing and producing vector impedance measuring equipment. Cohn and Oltman [32] and Lacy [33], then Leed and Kummer [34], all in 1961, discussed phase measurements with newer sophistication, applying some kind of heterodyning scheme. Lacy [35] in 1963 and, a year later, Cohn and Weinhouse [36] described their approach to some automation applied to vectorial measurements. Anderson and Dennison reported only in 1967 about the design of the harmonic conversion-based network analyzer. Hackborn [37] and Adam [38] showed computer-controlled and error-corrected versions of the network analyzers. As the much-improved network measurement capability of automatic network analyzers became commonplace, the next level of sophistication was introduced by Hines and Stinehelfer [39], converting the frequency-domain data to the time-domain providing "TDR" types of information, as well as giving rise to de-embedding techniques.

In the mid 1970's, Hoer and Roe [40], Hoer [41], Engen [42], and Komarek [43] reintroduced the "six-port" technique. At this time, the availability of digital computation to correct vectorial errors and enable one to store and manipulate large numbers of data gave a new life to the technique. It became the most accurate way of calibrating power sensors.

The latest improvement in network analysis has just recently been announced by the Hewlett-Packard Co. The new HP 8510 Network Analyzer System has all the functions of an automatic network analyzer provided with an on-board computer. It performs error correction of all parameters in real time. It has extended frequency range with a single-sweep capability of 45 MHz to 26.5 GHz. It has available an optional transformation program where data between frequency and time-domain is possible at speeds permitting real-time adjustments. Also, the on-board computer can act as controller, providing control functions to peripheral equipment [44].

Noise limits the detection or reception of weak signals. As the signal is processed and amplified, more noise is added to the signal. Thus, the signal-to-noise ratio is further reduced. Noise figure is the measure of this degradation. Noise figure is a unique figure of merit, because it characterizes not only the receiver, but devices and subassemblies, as well. Usually, we find two kinds of noise: thermal and shot noise generated in the process of amplification. Thermal noise is generated by the random motion of electrons thermally agitated, according to Nyquist [45] and Johnson [46]. Shot noise is due to the corpuscular flow of carriers in transistors or electron tubes. The current arriving at the collecting electrode of a transistor or electron tube is a series of small pulses randomly distributed in time, having a charge of one electron. This is a noisy process, and the noise generated is called shot noise. Thus, there are many possible sources of random noise in electrical devices and systems. Noise characterization usually refers to the combined effect of all causes, that is, to a system as having all noises caused by thermal noise.

In [1, ch. 4], Beringer, Montgomery, Howard, and Katz give credit to Roberts [47] and Friis [48] for the definition of noise figure. The discovery of the usefulness of gas discharge tubes, according to Ginzton [2], is due to Mumford [49]. Kompfner, Hatton, Schneider, and Dresel [50] are considered first in working with diodes as noise generators. Further advances were reported by Haitz and Voltmer [51], [52] and Haitz [53] in the 1960's. A good article on the measurement of noise figure was written by Oliver [54]. Modern noise-figure measurements with on-board computational capability are described by Swain and Cox [55]. The equipment is capable of making simultaneous measurements of noise figure and associated gain, while the "second stage" noise-figure contribution is corrected for at any stage previously defined, among other modern capabilities.

IV. Conclusion

Microwave measurement instrumentation has made great strides during the last few decades. It is true, however, that the basic concepts of electromagnetism were founded by Maxwell, Hertz, and other numerous forefathers of ours. The need for better and more communications systems with the ever increasing sophistication of electronic warfare are the driving forces behind this evolution. Automation of measuring equipment dates back to pre-WW II, when attempts using analog techniques provided improvements in speed and accuracy. The largest improvements in instrumentation occured in the 1960's, when the digital computer was combined with analog instrumentation. This yielded orders of magnitude improvement in accuracy and speed.

These new systems brought new capabilities in data gathering and data manipulation. Many more improvements are expected to follow in the near future to fulfill the needs of systems designers with measurement capabilities not yet dreamed of.

REFERENCES

[1] C. C. Montgomery, Ed. *Technique of Microwave Measurements* (MIT Radiation Laboratory Series, vol. 11). New York:McGraw-Hill, 1947.

[2] Edward L. Ginzton, *Microwave Measurements*. New York: McGraw-Hill, 1957.

[3] R. W. Beatty, "Insertion loss concepts," *Proc. IEEE*, vol. 52, p. 663, June 1964.

[4] R. A. Sparks, "A comparative review of phase measurements at microwave frequencies," Appl. Phys. Lab., Johns Hopkins Univ., Silver Springs, MD. A Presentation at the Fifth National Convention on Military Electronics, June 26–28, 1961.

[5] W. R. Beam and D. J. Blattner, "Phase angle distortion in TWT's," *RCA Rev.*, vol. 17, pp. 86–99, Mar. 1956.

[6] G. E. Schafer, "A modulated subcarrier technique of measuring microwave phase shifts," *IRE Trans. Instrum.*, vol. 9, pp. 217–219, Sept. 1960.

[7] M. Magid, "Precision microwave phase shift measurements," *IRE Trans. Instrum.*, vol. 7, pp. 321–331, Dec. 1958.

[8] S. D. Robertson, "A method of measuring phase at microwave frequencies," *Bell Syst. Tech. J.*, vol. 28, pp. 99–103, Jan. 1949.

[9] C. A. Finnila, L. A. Roberts, and C. Susskind, "Measurement of relative phase shift at microwave frequencies," *IRE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 143–147, Mar. 1960.

[10] R. Mittra, "An automatic phase measuring circuit at microwaves," *IRE Trans. Instrum.*, vol. 6, pp. 238–240, Dec. 1957.

[11] R. T. Stevens, "Precision phase meter for CW or pulsed UHF," *Electronics*, vol. 33, pp. 54–57, Mar. 4, 1960.

[12] Phillip H. Smith, "Transmission line calculator," *Electronics*, vol. 12, pp. 29–31, Jan. 1939.

[13] W. Altar, F. B. Marshall, and L. P. Hunter, "Probe error in standing wave detectors," *Proc. IRE*, vol. 34, pp. 33–44, Jan. 1946.

[14] J. R. Woodyard, "Ultra-high frequency apparatus," U.S. Patent 2 496 837, 1950.

[15] E. L. Ginzton, "Ultra-high transmission line system," U.S. Patent 2 534 437, 1950.

[16] W. B. Wholey and W. N. Eldred, "A new type of slotted line section," *Proc. IRE*, vol. 38, p. 244, Mar. 1950.

[17] B. O. Weinschel, G. U. Sorger, S. J. Raff, and J. E. Ebert, "Precision coaxial VSWR measurements by coupled sliding-load technique," *IEEE Trans. Instrum. Meas.*, vol. IM-13, no. 4, Dec. 1964.

[18] G. U. Sorger and B. O. Weinschel, " Swept frequency high resolution VSWR measuring system," Weinschel Engineering Co., Internal Rep. 90-117, 723-3/66, Mar. 1966.

[19] S. F. Adam, "Swept frequency VSWR measurement in coax," *Hewlett-Packard J.*, vol. 18, no. 4, Dec. 1966.

[20] H. A. Bethe, "Lumped constant for small holes," RL Rep. 194, Mar. 24, 1943; and "Theory of side windows in waveguide," RL Rep. 199, Apr. 4, 1943.

[21] B. A. Lippmann, "Theory of directional couplers," RL Rep. 860, Dec. 28, 1945.

[22] R. S. Julian, "Directional transmission line taps," BTL MM-44-170-6, Jan. 26, 1944.

[23] G. B. Meyers and B. P. Charles, "The reflectometer," Navy Rep. 521, Aug. 25, 1944.

[24] R. S. Julian, "A precision impedance comparator," BTL MM-44-170-18, Mar. 10, 1944.

[25] J. K. Hunton and N. L. Pappas, "The H-P microwave reflectometers," *Hewlett-Packard J.*, vol. 6, nos. 1–2, Sept.–Oct. 1954.

[26] E. Peterson, J. G. Kreer, and L. A. Ware, "Automatic display on oscilloscope of complex transfer factor of amplifiers, 0.5–30 kHz," *Proc. IRE*, p. 1191, 1934.

[27] A. L. Samuel, "An oscillographic method of presenting impedances on the reflection coefficient plane," *Proc. IRE*, vol. 35, pp. 1279–1283, Nov. 1947.

[28] P. C. Ely, "Swept-frequency techniques," *Proc. IEEE*, vol. 55, pp. 991–1002, June 1967.

[29] D. S. Packard, "Automatic Smith Chart plotter," *Tele-Tech*, 65-67 and 181-183, Apr. 1953.

[30] W. F. Gabriel, "An automatic impedance recorder for *X*-band," *Proc. IRE*, vol. 42, pp. 1410–1421, Sept. 1954.

[31] H. L. Bachman, "A waveguide impedance meter for the automatic display of complex reflection coefficient," *Trans. IRE Microwave Theory Tech.*, vol. MTT-3, pp. 22–30, Jan. 1955.

[31] G. B. Watts and A. Alford, "An automatic impedance plotter based on a hybrid-like network with a very wide frequency range," in *IRE Conv. Rec.*, no. 5, 1957, pp. 146–150.

[32] S. B. Cohn and H. G. Oltman, "A precision microwave phase-measurement system with swept presentation," in *IRE Conv. Rec.*, pt. 3, Mar. 1961, pp. 147–150.

[33] P. Lacy, "Analysis and measurement of phase characteristics in microwave systems," in *Proc. WESCON*, Aug. 1961, paper 23/3.

[34] D. Leed and O. Kummer, "A loss and phase set for measuring transistor parameters and two-port networks between 5 and 250 mc," *Bell Syst. Tech. J.*, vol. 40, no. 3, pp. 841–884, May 1961.

[35] P. Lacy, "Automated measurement of phase and transmission characteristics of microwave amplifiers," in *IEEE Int. Conv. Rec.*, pt. 3, Mar. 1963, pp. 119–125.

[36] S. B. Cohn and N. P. Weinhouse, An automatic microwave phase-measurement system," *Microwave J.*, vol. 7, no. 2, pp. 49–56, Feb. 1964.

[37] R. A. Hackborn, "An automatic network analyzer system," *Microwave J.*, vol. 11, no. 5, pp. 45–52, May 1968.

[38] S. F. Adam, "A new precision automatic microwave measurement system," *IEEE Trans. Instrum. Meas.*, vol. IM-17, no. 4, pp. 308–313, Dec. 1968.

[39] M. E. Hines and H. E. Stinehelfer, Sr., "Time-domain oscillographic microwave-network analysis using frequency-domain data," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 276–282, Mar. 1974.

[40] C. A. Hoer and K. C. Roe, "Using an arbitrary six-port junction to measure complex voltage ratios," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 978–984, Dec. 1975.

[41] C. A. Hoer, "Using six-port and eight-port junctions to measure active and passive circuit parameters," *Nat. Bur. Stand. Tech. Note* 673, Sept. 1975.

[42] G. F. Engen, "The six-port reflectometer: An alternative network analyzer," in *1977 IEEE MTT-S Int. Microwave Symp. Dig.*, June 1977, pp. 44–45, 53–55.

[43] E. L. Komarek, "An application of the six-port reflectometer to precision measurement of microwave one-port parameters,"in *1977 IEEE MTT-S Int. Microwave Symp. Dig.*, June 1977, pp. 56–57.

[44] Hewlett-Packard Press-release; "Wideband microwave network analyzer makes real-time, error-corrected measurments," Jan. 16, 1984.

[45] H. Nyquist," Thermal agitation of electron charge in conductors," *Phys. Rev.*, pp. 110–113, July 1928.

[46] J. B. Johnson, "Thermal agitation of electricity in conductors," *Phys. Rev.*, pp. 97–109, July 1928.

[47] S. Roberts, RL Rep. 293, Jan. 30, 1943.

[48] H. T. Friis, "Noise figures of radio receivers," *Proc. IRE*, pp. 419–422, July 1944.

[49] W. W. Mumford, "A broadband microwave noise source," *Bell Syst. Tech. J.*, vol. 28, no. 4, pp. 608–618, Oct. 1949.

[50] R. Kompfner, J. Hatton, E. E. Schneider, and L. A. G. Dresel, "The transmission line diode as a noise source at centimeter wavelengths," *J. Inst. Elec. Eng.*, vol. 93, pt. IIIA, no. 9, pp. 1436–1442, Mar.–May 1946.

[51] R. H. Haitz and F. W. Voltmer, "Noise studies in uniform avalanche diodes," *Appl. Phys. Lett.*, vol. 15, pp. 381–383, Nov. 1966.

[52] R. H. Haitz and F. W. Voltmer, "Noise of a self-sustaining avalanche discharge in silicon: Studies at microwave frequencies," *J. Appl. Phys.*, pp. 3379–3384, June 1968.

[53] R. H. Haitz, "Noise in self-sustaining avalanche discharge in silicon: Low-frequency noise studies," *J. Appl. Phys.*, pp. 2935–2946, June 1967.

[54] B. M. Oliver, "Noise figure and its measurement," *Hewlett-Packard J.*, vol. 9, no. 5, pp. 3–5, Jan. 1958.

[55] H. L. Swain and R. M. Cox, "Noise figure meter sets record for accuracy, repeatability, and convenience," *Hewlett-Packard J.*, pp. 23–32, Apr. 1983.

[56] H. Lyons, "The atomic clock and atomic standard of frequency and time," *Nat. Bur. Stand. Tech. News Bull.*, vol. 33, pp. 17–24, Feb. 1949.

[57] J. C. Helmer, "Maser oscillators," Microwave Lab., Stanford Univ., Stanford, CA, Tech. Rep. 327, Sept. 1956.

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A Half Century of Radar

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I. INTRODUCTION

As THE IEEE celebrates its 100th anniversary, the practitioners of radar look back on fifty years of progress in their specialized field. Although microwave radar has been the dominant concern for most of this period, the earliest efforts and some of the most recent have used other regions of the spectrum—metric and now micrometer wavelengths. The evolutionary development of radar can be traced through this half century, punctuated by several major innovations in techniques and components: the microwave magnetron, high-power klystron and Amplitron transmitting tubes, coherent signal processing, monopulse tracking, pulse compression, electronically steered arrays, digital processing and control, and solid-state microwave devices. By comparing the appearance and performance of typical radar systems developed before and after each of these innovations, we can see how they have affected the art of radar, and we may also be able to predict what future developments will bring to this ever-changing field.

II. THE GATHERING STORM

The title of this section is taken from Winston Churchill's famous history of the 1930's, when the final stages of disarmament from the First World War overlapped the preparations for the Second. Even as the British and French were cutting their military budgets and forces, the future Axis partners were developing modern weapons and organizations to use them. Tactical and strategic air power was an important part of this growing offensive threat. British and U.S. defensive forces, denied the large budgets needed to match their potential enemies, turned to technology in an attempt to bolster their diminished capability. Radar became one of the key elements in this effort, and many military historians give the British Chain Home system equal credit with the Royal Air Force (RAF) fighter pilots in the successful defense of their home islands during the war that came all too soon.

Early radar equipment was adapted from the radio communications field, using HF, VHF, and UHF tubes and antenna techniques. The British, faced with the most urgent need to deploy equipment, designed the Chain Home system to work at 25 MHz. Its antennas were hardly distinguishable from those of short-wave radio stations (Fig. 1). Separate transmitting and receiving antennas were used, the duplexer not having been developed. Much of the rapid progress made by the early British developers can be attributed to Watson-Watt's doctrine of using the third best—the best being unattainable and the second best unavailable until too late [1]. Fortunately, for him and for the RAF his program review groups did not have access to today's procedures and techniques for ensuring optimal solutions to each problem.

In the U.S., time was not quite as pressing, and development of VHF equipment was carried out. By the time of our entry into the war, the 105-MHz SCR-270 (Fig. 2) and the 205-MHz SCR-268 (Fig. 3) were available for use [2]. The success of the SCR-270 in detecting the aircraft approaching Pearl Harbor, and the failure of the associated command and control system, are part of the history of that era. As an example of a phased array radar, the SCR-268 provided a preview of techniques used today.

Manuscript received February 13, 1984.
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