An Historical View of the Evolution of Low-Noise Concepts and Techniques

S. OKWIT, FELLOW, IEEE

I. Introduction

PRESENTING an historical paper on a broad technical subject such as this can be a more difficult task than describing the details of a technical contribution. The former is subjective while the latter, with its logic, mathematics, and measurement data is (usually) objective. Individual points of view of historical highlights differ, so it is important that some background on the author of such a paper be known by the reader to give him an aid in evaluating the perspective of the points of view presented.

Much of what is covered in this paper occurred before I was born and prior to my professional involvement in "noise." I joined the Applied Electronics Department of AIL in the Winter of 1955, after a few years of experience in the Army Chemical Corps working on the detection of nerve gases. The department was headed by Matt Lebenbaum, a well-known contributor in the field of low-noise reception. I was fortunate to obtain that position because Matt's department was a beehive of high-quality advanced state-of-the-art activity, and there were many inventive contributors who were well known to the community or were to become well known in the future. It was there that I got my exposure to low-noise techniques and was given the opportunity to "do my thing." This freedom was a trademark of Matt's and provided the opportunity for young engineers, such as myself, to flourish.

My walk through history in this paper is based on these early and mid learning years, as well as the maturity and growth I was exposed to at LNR Communications, Inc., where I have spent the last twelve years applying the products of low-noise techniques to the growth of a corporation.

The major part of this paper is on the evolution of concepts and techniques of noise rather than the details and embodiments of any specific discipline within the low-noise field. This paper would have been easier to write (but not as interesting to me), if it were on some specific invention or contribution with which I was heavily involved. It should be made clear that the material presented is what I perceive as highlights, and may have been quite different if it had been authored by someone else. From this point of view, references that have been left out should not be interpreted as being unimportant.

Manuscript received January 11, 1984.
The author is with LNR Communications, Inc., 180 Marcus Boulevard, Hauppauge, NY 11788.

In the writing of this, many pleasant memories of experiences with close friends and colleagues around the world were brought back to me. I hope that some of you, in a small way, may have the same pleasant experiences while reading parts of this article.

II. Historical Overview

It is difficult, during the evolutionary phase of a technology, to step back and objectively distinguish the warp from the woof of one's efforts, or to separate and recognize the framework or the shape and form that is taking place in front of your eyes. Only time and retrospect can remove the cataracts, giving you the clarity of hindsight that is so often needed to recognize the order and occasionally the beauty of the pattern created. The overall technologies of transmission and reception of electromagnetic signals and their many overlapping disciplines are no exception to this phenomenon; especially, in my view, low-noise techniques.

In an attempt to provide some historical perspective, I've included this overview section with the hope that it might tie together the development of many of the major technical ideas and the main subject of low noise, and show how these ideas dovetail into systems applications. The seeds of this attempt consist of:

1) subdividing antenna temperature (T_a) as a function of frequency into three natural regions and relating these regions to

2) the time frame of the extension of the actively utilized frequency spectrum from its low kilohertz range in the early days to the microwave range (40 GHz), and

3) coupling 1) and 2) to the effective receiver noise-temperature (T_e) improvements as a function of time.

It is well known today that the overall performance of any antenna/receiving system is limited by its operating noise temperature (T_{op})

$$T_{op} = T_e + T_a = (F-1)T_0 + T_a \quad (1)$$

where

T_a = antenna noise temperature (°K),

T_e = effective receiver input temperature (°K),

T_0 = 290°K,

F = noise factor (figure).

It took many decades for this simple but powerful concept to be recognized, popping up its head during

World War II. Today, system engineers regularly use T_{op} in their quantitative budgeting of subsystem performance, so that cost effective tradeoffs can be made on different system architectures and topologies. The intrinsic value of T_{op} is readily seen in the various figures of merit developed for system performance, such as

Communication Ground Station Figure of Merit (M):

$$M = \frac{G_{ant}}{T_{op}} \tag{2}$$

where

G_{ant} = receive antenna gain

Radar Range (R):

$$R \propto \left\{ \frac{P_T}{T_{op}} \right\}^{1/4} \tag{3}$$

where

P_T = transmitter power

Radiometry:

$$\Delta T = \frac{T_{op}}{K\sqrt{B\tau}} \tag{4}$$

where

ΔT = minimum detectable temperature (°K),
B = predetection bandwidth (Hz),
τ = integration time (s),
K = constant.

The general behavior of T_a as a function of frequency is given in Fig. 1, where the frequency spectrum has been divided into three basic regions.

Region I (Antenna Limited Region)

The high value of T_a in this region is caused by extraterrestrial galactic noise. It is quite clear that low-noise receivers are of no value here, and thus motivation to reduce internal receiver noise should have been noticeably absent in the early days, but it wasn't. Unfortunately, quantitative data of galactic noise was not available until Jansky's work [1] was published in 1937. There are times that fundamental limitations are difficult for investigators to recognize, and this was one of them, as briefly described later.

Region II (Receiver Limited Region)

This well-established ultra-low T_a region has its limitations only in atmospheric absorption due to oxygen and water vapor. It is clear that efforts to develop low-noise receivers here would reap significant system performance rewards. Although a theoretical model for oxygen and water vapor absorption was available via Van Vleck's 1947 publication [2], it wasn't until 1956 [3] that his theory was applied to sky temperature calculations and measurements. Thus, a quantitative view of this very attractive low-noise

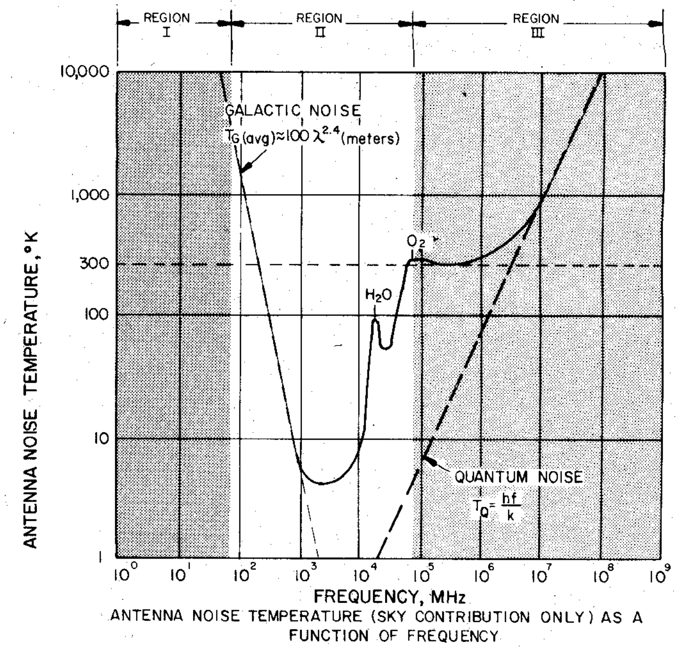


Fig. 1. Antenna noise temperature (sky contribution only) as a function of frequency.

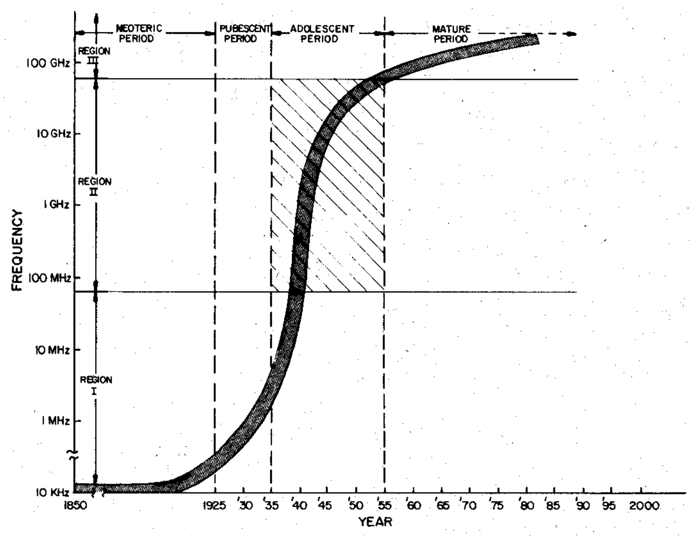


Fig. 2. The "opening up" of the frequency spectrum to practical system applications as a function of time.

"gap" didn't become fully appreciated until relatively late in the game.

Region III (Quantum Noise Limited Region)

This high T_a region is due to the quantized nature of electromagnetic radiation and, similar to the galactic region, makes low-noise receiver development of limited value. Fortunately, this limitation is in place and well established, being able to guide the technology needs of the presently evolving millimeter and far-infrared systems.

The "opening-up" of the frequency spectrum to practical system applications, as a function of time, is shown in Fig. 2. It is difficult to accurately assess when "practical system applications" occur, so Fig. 2 is somewhat qualitative. Fig. 2 is divided into four periods representing its "growing up" (from a low-noise reception perspective).

1) Neoteric Period (1850–1910): The early phases of telegraphy and telephony, when many relatively immature transmit–receive disciplines were being combined into a system and demonstrated. The period when efforts were geared to convince society of its economic and utilitarian value, vying for acceptance so that it could survive and flourish as an industry.

2) Pubescent Period (1920–1935): This was the period after the system's initial acceptance, when there was a technical scramble to develop a sound theoretical and experimental base of knowledge, necessary to understand and direct efforts to improve the "soft spots" of the system. It was the time when the fundamentals of noise-generating mechanisms and all of their ramifications in making the system more reliable, as well as economical, were established.

3) Adolescent Period (1935–1955): This was the high-energy period, when significant advances were made at a rapid rate. It was the period when the assimilation, digestion, and application of the sound body of knowledge developed during pubescence was expanded upon and put to practical use. During this period, the developments of second-generation concepts for the characterization, fabrication, and accurate measurement of major low-noise reception building blocks were formalized, yielding real and tangible improvements in system performance. It is in this period, for example, that North and Friis introduced their noise factor (figure) concepts.

4) Mature Period (1955–Present): Reasonably stable period when society doesn't realize the technology exists, taking it for granted in its everyday living. It is during this period that time is taken by the engineers to look deeply into sophisticated techniques, borrowing proven ideas from other related sciences, with goals of decreasing costs, improving performance, and extending equipment life and reliability.

It is interesting to note that starting as far back as World War I, the benefits of extending system operation into the UHF and higher frequencies were intuitively understood. The delay in this extension was due to the lagging progress in *transmitter technology*, delaying the start of the adolescent period. As early as 1927, Englund [4] published a paper describing the "Short Wave Limitation of Oscillation." Transit time and parasitics (lead inductance and stray capacitance) were formidable problems to solve. Progress on the solution to these problems created severe heat dissipation obstacles. A breakthrough occurred in the Summer of 1937 when the Varian brothers invented the Klystron. They formally published their work in February of 1939 [5]. Their ingenious invention was based upon the "join them rather than fight them" philosophy; *using* transit time to velocity modulate an electron beam. An excellent paper reliving the birth of the Klystron was published by Ed Ginzton [6]. Had this invention occurred 15 years earlier, I believe that most of the other disciplines were well enough in place to shift the chronology curve of Fig. 2 back a corresponding 15 years.

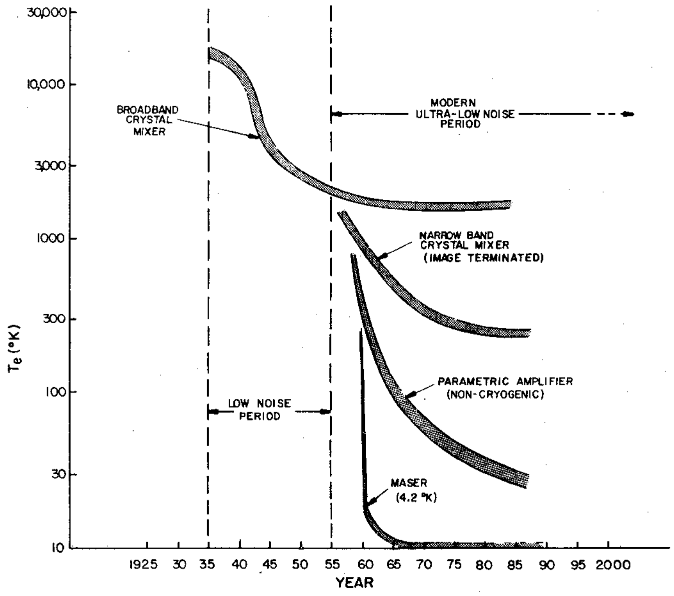


Fig. 3. A coarse view of the improvement of receiver noise performance (in the microwave region) as a function of time.

A coarse view of the progress of receiver performance (in the microwave region), as a function of time is given in Fig. 3. It is divided up into two periods (coincident with the Adolescent and Mature Periods).

1) Low-Noise Period (1935–1955): During this period, steady improvements in crystal mixers (circuit and diode technology) and IF amplifier performance were achieved.

2) Modern Ultra-Low-Noise Period (1955–Present): Introduction of modern ultra-low-noise technologies yielding masers, parametric amplifiers, tunnel diodes, image-enhanced mixers, transistor and FET amplifiers.

At the time workers entered the microwave range, it was *qualitatively* known that systems were receiver-performance limited. Thus, significant motivation existed to rapidly achieve receiver improvements. A long dormant (25 years) invention by Edwin Armstrong,[1] the superheterodyne, was waiting in the wings, ready to become a star performer. Over a period of a few years, crystal mixers evolved to meet the demands of the day. T_e's decreased from about 20 000°K to 3000°K, yielding a corresponding improvement in T_{op}.

The noise performance provided by the superhet served the system community well for many years. The advent of the modern ultra-low-noise receivers provided users the option for further performance improvement, however, at an increase in cost, necessitating performance/cost trade-off evaluations. But, in applications such as satellite communications and space exploration, successful links would not have been technically or economically possible without

[1]Armstrong had a few interesting squabbles during his lifetime. One with Lucien Levy, a Frenchman, who claimed the rights to the superhet invention (Armstrong eventually prevailed); and another long and bitter controversy with Lee DeForest (who was not known as a modest man) concerning frequency modulation, that persisted for a good portion of his life, filling him with a deep depression.

them, because of the limitations in ground-station antenna size and cost, as well as satellite transmitter power.

III. Characterization and Standardization of Noise

Early History

A succinct chronology of some key technological events having a bearing on the development of noise concepts is a must, and is presented below. During the early days of telegraphy, after the first commercial service was initiated between Baltimore and Washington, DC, (1844), it was found that disturbances were caused by external sources such as lightning, sunspots, and variations in the earth's magnetic field. However, these effects were not too troublesome since they occurred infrequently, and when they did occur, telegraphy, being a binary system, was not seriously impaired.

However, with the introduction of the telephone in 1878 (the first commercial telephone exchange consisted of eight lines in Hartford, CT), the interference problem was no longer trivial. The telephone, being a significantly more sensitive device, and being analog, was much more susceptible to these disturbances (NOISE), and thus interference became quite troublesome. This problem worsened with the installation of power systems, when cables (power and telephone) were being laid side by side.

It was believed that these noise limitations could always be improved by more shielding in the transmission systems. A great deal of work was put into system improvements without recognizing that there were fundamental limitations. Many errors and incorrect assumptions were made by the early investigators in trying to identify and eliminate these problems. It was not until the early 1900's, when electronics started to be applied to telegraphy and telephony, that it was recognized that *perhaps* some fundamental limitation existed. These limitations were not fully understood for many decades. A reasonably firm understanding of internally generated noise was not established until the early to mid 1930's, and the pieces of the external-noise puzzle weren't quantitatively put together until the mid 1950's.

Receiver Noise

Serious studies on noise limitations covered a span of about thirty years, starting in 1906 with Einstein's [7] investigations on spontaneous fluctuations of current and voltage in electrical circuits. The initial 20 years of this period considered physical sources of noise and the experimental classification of the type of noise these sources emitted. The early work uncovered and described relatively simple noise properties, until more sophisticated mathematical handles were developed (statistical theory), enabling the random processes to be better understood. The latter ten years of this thirty-year period yielded the bulk of the analytical work and experimentation and led to what we presently understand as modern-day noise theory. Vacuum tubes provided the impetus for this work, and the studies covered thermal noise, shot noise, partition noise, induced grid noise, flicker noise, etc. Although it would be exciting to trace the evolution of all the various noise-generating mechanisms, time and space preclude doing so, with the exception of a few contributions highlighted below, because of the special role they played in the development and characterization of modern-day receivers. However, an excellent tour of the technology can be taken by visiting the references contained in the 1938 publication of E. B. Moullin [8].

In 1918, a classic paper was published by Schottky [9], in which he predicted and theoretically treated the shot effect. He showed that the mean-square noise current $(\overline{i_s^2})$ is constant for the temperature-limited diode case (up to frequencies of the order of the reciprocal of the transit time) and is given by

$$\overline{i_s^2} = 2eI_sB \tag{4}$$

where

e = electronic charge $= 1.602 \times 10^{-19}$ (C),

I_s = average current (A),

B = bandwidth (Hz).

This Schottky theorem was the basis of constructing vacuum tube noise generators, the workhorse that was used for many years to make accurate noise-figure (factor) measurements in receiver characterization.

In February of 1927, J. B. Johnson [10] reported his empirical discovery of thermal noise in a short paper that appeared in the Bell Laboratories *Record*. A year and a half later, in July 1928, a classic pair of papers were published in the *Physical Review*, in which J. B. Johnson [11] presented a more detailed description of his discovery, and H. Nyquist [12] presented an elegant theoretical analysis substantiating Johnson's measurements. Nyquist showed that the mean-square thermal noise voltage $\left(\overline{e_n^2}\right)$ in a conductor of resistance R can be represented by the equation

$$\overline{e_n^2} = 4kTRP(f)B \tag{5}$$

where

k = Boltzman's constant $= 1.38 \times 10^{-23}$ J/°K,

T = physical temperature of the resistor (°K),

$$P(f) = \text{Planck's factor} = \frac{hf}{kT}\left(\exp\frac{hf}{kT} - 1\right)^{-1},$$

h = Planck's constant $= 6.62 \times 10^{-34}$ J−s,

B = bandwidth (Hz),

f = frequency (Hz).

For the case where $hf/kT \ll 1$, $P(f) \simeq 1$, and (2) becomes the well-known thermal noise (Johnson noise) formula

$$\overline{e_h^2} = 4kTRB. \tag{6}$$

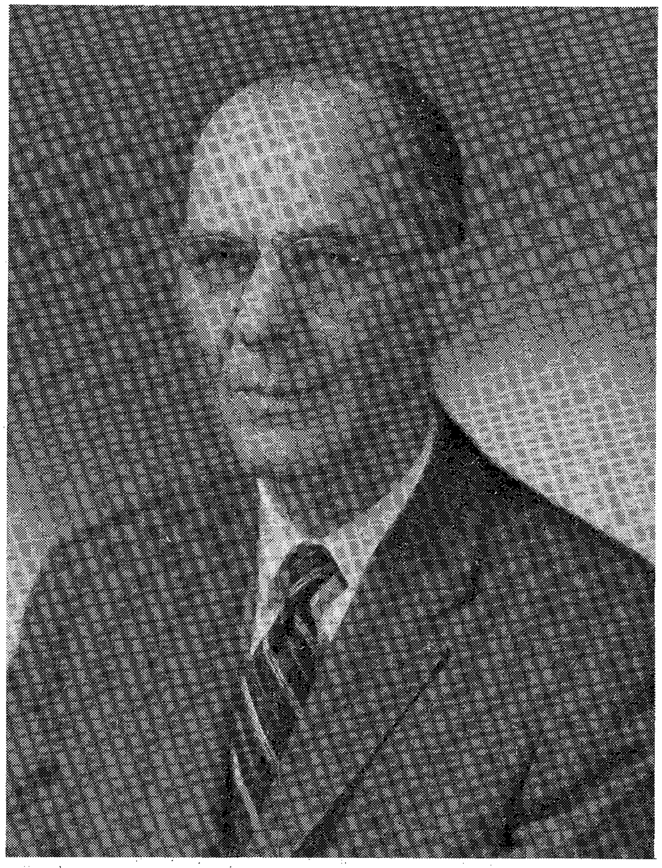


Fig. 4. Dr. Dwight O. North was born in Connecticut in 1909. He joined the Research and Development Laboratory of RCA Manufacturing Co. in 1934, where he worked on the design theory of vacuum tubes for high frequencies. His early investigations of the physical origins of noise in tubes led him to the development of his well-known theory of space-charge suppression of noise. In 1942, Dr. North became one of the charter members of RCA Laboratories, Princeton, where he led some of the early fundamental studies of solid-state electronics. The above photograph was taken a few years prior to his 1974 retirement from RCA. He is presently actively consulting for RCA at Princeton.

It was realized that the thermal noise emitted by the generator resistance at the input terminals of an amplifier would place a lower limit on the receiver sensitivity. This was later verified experimentally by Friis.

Receiver Figure of Merit

In parallel with the characterization of the receiver noise-generating mechanisms discussed above (in the late 1920's through the mid 1930's), the groundwork was laid for the development of a figure of merit for receivers. In 1931, Llewellyn [13] published a key paper on the attainment of a qualitative measure of the signal-to-noise ratio of high-gain receivers. He essentially compared the output noise of a receiver under the conditions of short-circuited input terminals, to the output noise under normal generator impedance loading. Several papers were later published [14], [15] extending Llewellyn's work which provided *quantitative* studies on S/N. These papers had essentially established the very important concept of an ideal noiseless receiver, by placing an equivalent resistance for the noise-generating mechanism at the receiver input terminals.

The above publications were all on low-frequency narrow-band receivers, until 1942, when E. W. Herold [16] extended the concepts of Llewellyn to broad-band receivers at UHF frequencies (up to 3 GHz). In this elegant paper, several fundamental ideas relevant to microwave low-noise amplifier design were established:

- consideration of second-stage noise contributions due to the low gains of the first amplifier stage and the frequent use of converters at UHF;
- the existence of an optimum antenna (source) conductance for maximum S/N performance, which is often considerably different from the source conductance for maximum gain.

Herold's paper was published during the formidable technology growth years of World War II, where broad bandwidth and microwave frequencies were essential for the war effort. These were the beginnings of the *electronic warfare* age.

The North–Friis era occurred during the Region II phase of the Adolescent period. Practical applications in the UHF and microwave regions demanded lower noise receivers since the corresponding system performance rewards were significant. Thus, there was a real need for being able to accurately compare and specify receivers on the bench.

The introduction of a practical receiver figure of merit, first appeared in the literature in 1942, when D. O. North [17] (Fig. 4) published his paper on noise factor N

$$N = \frac{\overline{e^2(f_0)}}{\overline{e_t^2}} \tag{7}$$

where

$\overline{e_t^2}$ = mean-square thermal noise voltage $= 4kT_0R_aB$,

T_0 = ambient reference temperature = 300°K,

R_a = effective antenna radiation resistance,

$\overline{e^2(f_0)}$ = mean-square signal voltage required to produce an output signal power equal in magnitude to the output noise power.

North's classic paper introduced many innovative and practical concepts, two of which are as follows.

- Noise factor was based upon predetection measurements, a departure from the prescribed IRE Standards [18] of post-detection measurements. This proposal was a major simplification, eliminating the complications associated with the need of knowing the modulation format and the frequency response of the post detection circuits.

- Introduction of "operating noise factor" (N_{op}),[2] a figure of merit for the performance of an overall operating system wherein N is modified through the use of a real rather than a dummy antenna ($T_0 =$ 300°K).

$$N_{op} = N + \frac{T_a}{T_0} - 1. \tag{8}$$

From (7), the total equivalent mean-square noise voltage at the antenna terminals is given by

$$\overline{e^2} = 4kT_0R_aB[N_{op}]. \tag{9}$$

$\overline{e^2}$ is the noise voltage that the signal ($\overline{E^2}$) must compete with. North defined $\overline{E^2}$ as the "absolute sensitivity," a term that presented a minor controversial exchange (basically semantic) between Friis and North.

Two years after North's publication, Friis [19] (see Fig. 5) introduced his concept of noise figure (F)

$$F = \left(\frac{S_i}{N_i}\right)\left(\frac{S_o}{N_o}\right)^{-1} \tag{10}$$

where

$S_i, S_o =$ available signal power, respectively, at the receiver's input and output terminals,

$N_i, N_o =$ available noise power, respectively, at the receiver's input and output terminals

$N_i = kT_0B,$

$T_o = 290°K.$

The clarity of Friis' paper and the thoroughness of his definitions, especially the concepts of "available power" and "available gain," made his paper an outstanding contribution in the classification and standardization of receiver noise-measurement techniques. His available output power concept applied to the partitioning of noise in cascaded networks allowed him to readily derive the simple but powerful expression for the overall noise figure (F_{ov}) of cascaded networks

$$F_{ov} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1G_2} + \cdots + \frac{F_n - 1}{G_1G_2 \cdots G_{n-1}} \tag{11}$$

where

$F_n =$ noise figure of the nth stage,

$G_n =$ available gain of the nth stage.

Although noise degradation in a receiver due to subsequent stage noise contributions was not new [16], Friis was the first to present a formal generalized expression for the degradation.

[2] This 1942 concept is totally compatible with the modern T_{op} concept of (1)

$$N_{op} = \frac{T_{op}}{T_0}.$$

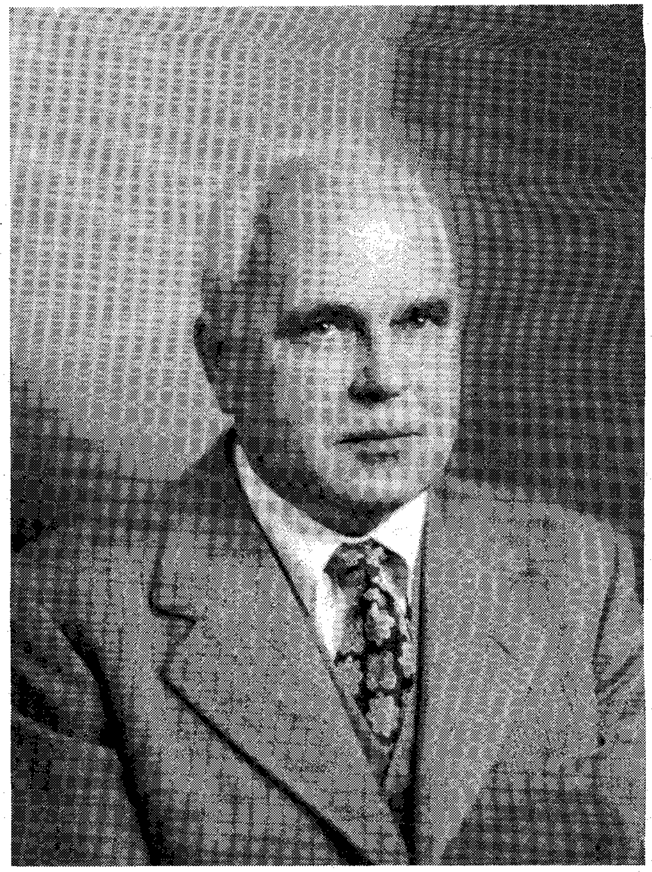


Fig. 5. Dr. Harold Trap Friis was born in Denmark in 1893 and died in 1976. In 1920, he joined Western Electric's research department, the predecessor organization to Bell Laboratories. He was a pioneer in the development of radio communications and an initiator of microwave radio transmission and radio astronomy. Referring to his development of microwave transmission, Friis called his "formula for radio transmission in free space" his most important contribution to communications technology. The above photograph was taken in 1957, one year prior to his retirement from Bell Labs, where he was the Director of Research in High Frequency Electronics.

Several months after the Friis paper appeared, a discussion between North and Friis was published in the *IRE Proceedings* [20]. The bulk of this short exchange, elegantly written, was on nontechnical matters, and was most interesting to me in that it related to the human side of these two giants. It appeared to me that North, who initiated the discussion, was somewhat taken aback in that Friis did not make more direct use of the terms and definitions that North had introduced earlier. Two of the issues covered in the exchange were:

1) the merits and use of the term noise factor versus noise figure, and
2) the choice of standard temperature (T_0); 300°K versus 290°K.

Both of these topics were to be bandied about in the literature for the next twenty years, creating confusion as well as considerable pedantic debate. It is my opinion, that if Friis had used North's "noise factor," and his 300°K reference temperature, the entropy in the technical community would have been significantly reduced, but perhaps at the expense of the loss of several archival articles written with style.

Of the numerous discussions in the literature on the North and Friis noise measures, the first (to my knowledge) appeared in April of 1944, authored by D. K. C. MacDonald [21]. MacDonald's excellent paper always struck me as somewhat unusual, although well written. First of all, the paper, about ten pages in length, discussed noise figure (factor) in detail without once mentioning or referring to North or Friis. Secondly, it appeared in the literature a month prior to the Friis publication.

Putting this aspect aside, some interesting views of this early paper impressed me (although in hindsight) as showing objectivity and significant insight on the two noise measures.

MacDonald called noise figure the "fundamental" definition, and noise factor the "secondary" definition. Moreover, he stated that the general terms in the "fundamental" form (Friis) would most likely appeal to the "radio physicist" while the "secondary" form (North) would be more suited to the ideas of a "radio engineer." He proceeded to show the important fact that noise factor and noise figure are equivalent and, in the process, carefully led the reader through the reasoning behind his conclusions of "fundamental" vis-a-vis "secondary" definitions. He points out that care must be taken when using noise factor to avoid potential errors. An example of such an error is cited in Herold's [16] paper.

Little did MacDonald realize that scores of papers would follow his, attempting to clarify and help in the standardization of the North–Friis concepts. Unfortunately, many of these papers, as pointed out before, created confusion, by selecting reference temperature (T_0) values that ranged from 288°K to 293°K, or totally neglecting to assign any value for T_0. This is highlighted in the various definitions on noise factor (figure) that were tabulated by Mumford and Scheibe [22], and shown in their Table 1 on page 54.

In general, the selection of most of the values for T_0 were based upon an author *trying* to simplify a calculation; two examples of this are as follows.

1) Lawson and Uhlenbeck [23] used $k = 1.37 \times 10^{-23}$ J/°K and $T_0 = 292°K$ so that $kT_0/e = 1/40$ V. Had they used the accepted value of 1.38×10^{-23} for k, they would have obtained 290°K.

2) Goldberg [24] selected $T_0 = 288°K$ to simplify the calculation in the equation used for temperature-limited vacuum tube diode noise-figure measurements

$$F = \frac{2eI_sR}{kT_0} \tag{12}$$

for the values

$$R = 50,$$
$$e = 1.59 \times 10^{-19}\ \text{C},$$
$$T_0 = 288°\text{K}.$$

Equation (12) simplifies to

$$F = I\ (\text{in mA}). \tag{13}$$

Ironically, if Goldberg had used the accepted value of 1.602×10^{-19} for e, he also would have selected $T_0 = 290°K$ for his simplification.

Attempts to clarify matters were made by the IRE Standards Committee. The early 1938 Radio Receiver Standards were modernized and updated in 1952, 1953, and 1957, formalizing the North–Friis concepts. It is interesting that the Committee made a firm decision in adopting Friis' 290°K as the standard reference temperature (T_0), but could not come to grips on the term for figure of merit, making the Solomon-like decision of adopting "noise factor (noise figure)." This gesture was their way of recognizing the contributions of both men, a decision I was pleased with.

The North–Friis noise muddle spanned over a fifteen-year period, until the late 1950's, when we entered the modern ultra-low-noise receiver period of masers, parametric amplifiers, etc. Because of the ultra-low-noise properties of these amplifiers, it became inconvenient to talk in "db's," and the term "effective input noise temperature T_e, (°K)," was introduced [25]. It was then possible to make comparisons on, for example, a 75°K versus 80°K receiver, vis-a-vis a 0.999-db versus a 1.058-db receiver.

Representing noise powers by an effective noise temperature was not new, being used by workers in the fields of crystal mixers and noise generators, for many years prior to the introduction of T_e. P. D. Strum [26] published an excellent paper reviewing effective noise temperature and showing its many applications.

The concepts of T_e and F were fully compatible, it being a simple matter to convert from one to the other

$$T_e = (F-1)\,290°\text{K}$$
$$F = 1 + \frac{T_e}{290}. \tag{13}$$

Additionally, the cascade formula (11) simplifies to

$$T_e = (T_e)_1 + \frac{(T_e)_2}{G_1} + \frac{(T_e)_3}{G_1G_2} + \cdots + \frac{(T_e)_n}{G_1G_2\cdots G_{n-1}}. \tag{14}$$

Consequently, in January 1960, without having to change any of the prior standards, the Standards Committee (recognizing its simplicity and utility) adopted the concept of "effective input noise temperature."

In my view (certainly not unanimous), the introduction of T_e was a benchmark, making for efficient communication in the technical community, providing a more accurate baseline for measurement techniques, and eliminating many ambiguities. The simple fact that there was no longer a need for 290°K as a reference temperature (T_0) (since T_e uses 0°K as its reference) avoided much confusion. This is where the art rests today, with no significant changes in the past twenty years. But interesting debate continued. For example, a proposal appeared in the *IRE Proceedings* to abandon noise factor (figure) [27] in favor of the universal adoption of T_e, while a companion correspondence [28] appealed for the preservation of both measures $\cdots$.

The Standards Committee should be commended for the speed with which it adopted the new T_e concept. Matt Lebenbaum was a member of that committee (as well as past committees), and I was fortunate enough to be a close spectator during the trying days of making decisions on standards that would be unambiguous and stand up to the test of time.

Digression

Evolving meaningful definitions and standards by which technologists can communicate, exchange ideas, and compare results both on a qualitative and quantitative basis, is essential to the successful evolution of any technology. Usually, when one looks back and traces the path by which a set of standards comes into being, one will find it circuitous, fraught with controversy, and significant emotional involvement by the technical contributors. The achievement of the present-day standards for the figure of merit for receivers was no exception to this slow evolutionary process. As a slight digression, I would like to share with you an event relating to standards that I was exposed to (by chance) in 1969 while I was Editor of the TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES.

A paper was presented for publication in the *Journal of Chemical Physics* in which the author wanted to introduce a new term for angular frequency (ω). Since there already existed the term Hertz (Hz) as a unit of measure for circular frequency (f), he felt there should also be a unit for angular frequency (ω) (radians per second). Consequently, he adopted the term "Avis" (A_s), representing *A*ngular *V*elocity in *I*nverse *S*econds. During the review processes of this paper, much controversy developed (both lighthearted and serious) concerning the proliferation of standards, symbols, and units, which involved editors, professors, and industry researchers. After many letters exchanged hands, it was pointed out by several astute participants, that since 1 Hertz $= 2\pi$ Avis, Hertz was still first and Avis was second and trying harder. Needless to say, the proposal was not adopted, being considered redundant and unnecessary. I leave you with the thought: If terms such as the Barn, mho, daraf, and yrneh made the grade, why not AVIS?

IV. Evolution of Noise Measurement

Prior to 1940, when most receiver work was in the antenna temperature-limited frequency range (Region I), there was little need for sophisticated noise-measurement techniques. However, from World War II through the mid to late 1950's, significant efforts on receiver development were concentrated in the microwave range (Region II), where its noise was the dominant limitation in system performance. Consequently, reasonably accurate characterization of receiver noise became a priority, demanding the development of

1) efficient and accurate measurement techniques, and
2) microwave noise generators having relatively high excess noise over a broad band.

The first description of measuring F appeared in Friis' 1942 paper [19], detailing a CW method using a signal generator. This method was relatively accurate but very tedious and inefficient, requiring separate gain–bandwidth measurements to be made before F could be calculated. Several months later, E. J. Schremp proposed using a temperature-limited vacuum-tube diode as a noise generator (previously described by North [29]), in a "3-db" Y-factor measurement technique. The diode had a uniform and predictable excess noise temperature (Schottky's formula) over a broad band, thus avoiding tedious CW gain–bandwidth measurements resulting in measurement simplicity, accuracy, and economy.

These noise diodes unfortunately had a limitation. Due to transit time effects, their upper frequency bound was about 300 MHz. Because of the measurement convenience afforded by broad-band noise generators, efforts were expended to extend their usefulness into the important microwave range. Prior to the diode work, attempts had been made to use a hot filament [30], [31] (Hot-Wire noise source) as a broad-band thermal noise generator. However, excess noise ratios were limited to less than 10 db, marginal for most applications of the day. Rudy Kompfner [32] *et al.*, had an interesting solution to the problem. He introduced a coaxial noise diode configuration, which minimized the transit time problem up to frequencies of 3 GHz. His diode (Bendix TT-1) was mounted and matched into a waveguide, yielding excellent excess noise ratio, in the 16-db range. Unfortunately, it was very expensive, did not extend far enough into the microwave range, required cooling, and had a limited life. The coaxial noise diode was not the answer.

A major breakthrough occurred in October 1949, when Bill Mumford [33] described his invention of the gas discharge tube. This noise generator, which replaced the diode as the workhorse of the industry, had all of the desired characteristics required by the receiver community:

- high excess noise ratios—15 db (argon) to 18 db (neon),
- broad-band operation, in coaxial and full waveguide bands,
- useful at microwave through millimeter wavelengths,
- relatively high accuracy,
- rugged construction and moderate cost.

The discovery of the gas discharge noise source had an unusual beginning, *à la* the "Newton-apple-gravity" story, which Bill Mumford related to me, and I would like to share with you.

After World War II, Bill was assigned the job of building a microwave circuit for the 1553 "Close Spaced Triode" that Jack Morton was designing for possible use in the TD-2 (3.7–4.2-GHz band) microwave transmission system. The noise figure of several tubes had been measured by the method of using a standard signal generator, which, as pointed out above, was tedious, requiring a great deal of time and precision.

Bill's boss, H. T. Friis, told him that he ought to have more data on these new triodes and asked him to get some more noise-figure measurements. Not having a setup to do this, he started planning on one that would make the measurements simpler, without sacrificing accuracy.

After much work and little headway, Bill was relaxing at home one evening watching TV, when suddenly a lot of "noise" came on the screen. He traced it to a fluorescent lamp that was faulty, which his wife had just turned on in the kitchen area. It occurred to Bill that if that lamp had so much noise at TV frequencies, maybe it would be a potent noise source at microwave frequencies.

The next day, he placed his desk "Dazor" lamp next to his microwave receiver and observed an increase in the output noise power. This was encouraging, so he had a circuit built to measure the lamp's impedance and then matched it into the waveguide. The output noise of the receiver, using the "1553" triode as an amplifier, would just about double when the noise source was applied to the input.

Previous measurements of the noise figure of these triodes had indicated a value of between 15 db and 20 db, so now he had a noise source that was equal to the task. *Thus, was born the gas discharge noise source.*

Unknown to Mumford, the theoretical basis behind his invention (electrical discharges in gases), was lying dormant for ten years, having been published in 1939 [34]. From 1949 to 1953, workers established reasonable agreement of excess noise measurement with theory, ± 0.5 to 1 db. Over the next few years, further refinement by Mumford *et al.* [38] narrowed the gap to ± 0.3 db, more than adequate for receiver evaluations of the day. Not being satisfied, investigators [39]–[42] continued through the early 1960's, leading to today's discriminating agreements of ± 0.1 db.

Putting the 1960's standards work in perspective, relative to the needs of modern-day low-noise receivers (without trying to detract from the fine results of these efforts), the measurement-theory agreement achieved was only of academic interest. In the late 1950's, the receiver art entered the Modern Ultra-Low-Noise Period, changing the performance demands placed on noise sources.

An error analysis presented by Sard [43] showed that the most accurate measurement of T_e is obtained using the Y-factor method that employs noise-source effective temperatures given by

$$T_e = \sqrt{T_c T_h} \tag{15}$$

where T_c and T_h are the cold and hot effective noise temperatures, respectively. Thus, in order to obtain maximum accuracy, T_c and T_h should have the geometric mean T_e. As a general rule, for a large T_e, a high T_h should be used, and for a small T_e, a low T_c is indicated. Clearly, the 15.3-db gas discharge source did not fit the bill for modern low-noise receivers. Thermal noise sources were unquestionably more practical. Maintaining well-matched loads at convenient, precisely known physical temperatures, such as the boiling points of liquid nitrogen and water (77.3°K and 373.1°K at atmospheric pressure), were simple and economical. These noise sources, being relatively simple, were generally designed and fabricated by the investigators of the low-noise receivers in their own laboratories for their own use.

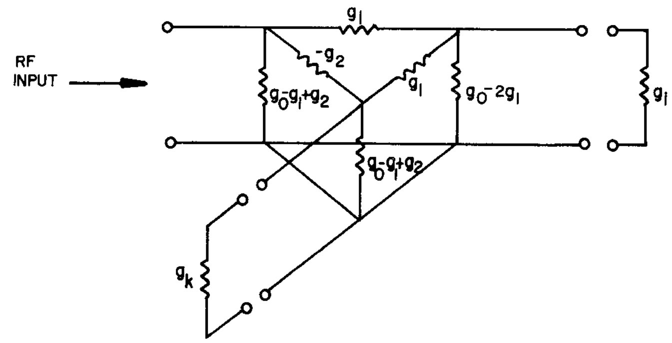


Fig. 6. Equivalent network of a crystal-mixer with an image frequency admittance.

Extreme care was required in ultra-low-noise amplifier measurements, where subtle problems often led to misleading results. Frequently, articles appeared in the literature quoting questionable measurement data, and occasionally manufacturers were offering equipment having questionable performance. This prompted Jack Greene [44] to publish a short dissertation "Noisemanship—The Art of Measuring Noise Figures Nearly Independent of Device Performance." This very well-written tongue-in-cheek article was in cookbook style, leading the reader through the many subtleties that result in inaccurate measurements. The two sets of procedures that Jack presented

CASE I[3] Procedures to be Followed for High-Noise-Figure readings, and

CASE II[4] Procedures to be Followed for Low-Noise-Figure readings

should be enough to whet the appetite of the reader to hunt up an old copy of the July 1961 *IRE Proceedings*.

V. Evolution of Low-Noise Receivers

The Crystal Mixer

The mixer, after being relatively dormant for decades, was revived in the mid to late 1930's to become the workhorse receiver for the Low-Noise Period during which UHF and microwave frequencies were seriously being considered for practical radio and radar applications.

Analytically, the diode mixer, being a nonlinear element, was not well understood until, in 1939 [45], it was shown that, except for the fact that frequency translations implicitly occur, the laws of linear network theory were applicable. In 1945, this work was extended [46], [47], and a generalized six-pole equivalent network of linear conductances was presented (Fig. 6). From Fig. 6, the important design parameters of available conversion loss (L_c), optimum source conductance $(g_s)_{\text{opt}}$, IF output conductance, and RF input conductance could be calculated for any arbitrary value of image-frequency termination. Three con-

[3] To be used when measuring competitor's equipment.

[4] To be used when measuring your own equipment.

ditions of image-frequency termination were of interest:

Case 1) short-circuited image terminals (narrow-band case),
Case 2) matched image terminals (broad-band case), and
Case 3) open-circuited image terminals (narrow-band case).

In 1939, much of the theoretical and experimental techniques were well in hand to make a major assault on low-noise mixer design:

- Friis' cascade formula (11) gave the overall noise figure (F_{ov}) for the mixer–IF amplifier

$$F_{ov} = L_c(t_m + F_{if} - 1) \tag{16}$$

where

L_c = mixer conversion loss,

t_m = relative mixer temperature = $\frac{T_m}{T_0}$,

F_{if} = IF noise figure.

- Friis [19] also showed that F_{ov} was minimized when the mixer is designed for minimum available conversion loss $(L_c)_{min}$, implying an optimum source conductance.
- Roberts [48] provided insight into t_m and presented measurement techniques for its evaluation.
- Crystal diodes (silicon and germanium), having reasonable quality, were available [49].
- IF amplifiers (usually in the 30-MHz range) were well into their low-noise design phase yielding about 2-db noise figures.

Indeed, during a short period of time (World War II years), mixer noise figures showed dramatic improvement, from the 20-db to the 10-db range; a very rewarding improvement for system performance.

Almost all of the work during those years was on broad-band mixers (Case 2)), and their circuit progress was well ahead of the diode technology. However, circuit engineers worked closely with semiconductor physicists and were able to impart to them their knowledge of the degradations associated with package parasitics, resulting in practical ceramic, coaxial, and pigtail (used mostly for video detection) diode cartridges (see Fig. 7). Diode designs were optimized for specific frequency ranges, and were identified by the well-known JAN-type number designations:

1N25 (1-GHz range)
1N21 (3-GHz range)
1N23 (10-GHz range)
1N26 (30-GHz range).

As semiconductor manufacturing techniques improved, yielding better diode parameters, a suffix was added to the designation; 1N21 A, B, C, $\cdots$.

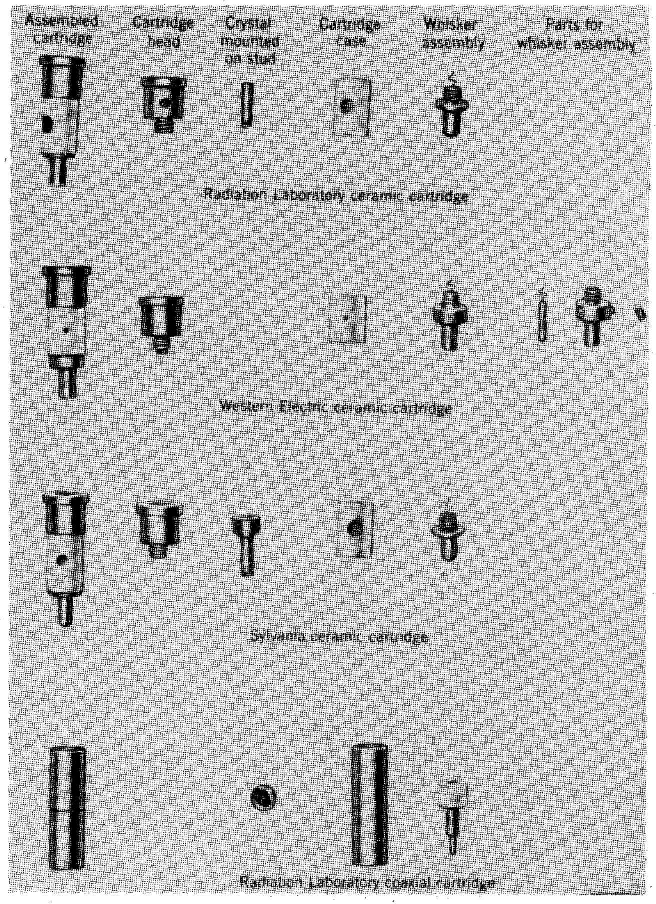


Fig. 7. Parts for representative ceramic and coaxial cartridges used in crystal mixer diodes during WWII. (From [49].)

From 1945 to the late 1950's, further improvements in diode technology (extending diode suffixes to E, F, and G series) and IF noise figures resulted in mixer noise figures being further reduced from the 10-db to the 6-db range. Excellent theoretical understanding of the role of spreading resistance (R_s) and barrier capacitance (C_b) on conversion loss [50]–[52], and the tradeoff relationship of R_s versus C_b in the semiconductor geometry (for both silicon and germanium), enabled diodes to approach the fundamental limits of their performance.

In 1953, P. D. Strum [53] published what I consider to be a classic paper on the design of mixers for both broad-band (Case 2)) and narrow-band (Cases 1) and 3)) image terminations. He developed a relatively simple mathematical method of relating the measured crystal $E-I$ characteristics to the conductance elements of the mixer network (Fig. 6), so that $(L_c)_{min}$, $(g_s)_{opt}$, etc., can readily be calculated for each of the cases of image termination. Strum also introduced a refinement of mixer temperature t_m, a term characterized by the manufacture in a broad-band mixer measurement, enabling one to calculate its change (increase) in narrow-band applications. By assigning a temperature (t_x) to the conductance element of the mixer network, t_m was readily calculated as a function of t_x and L_c. Further work on this was done by Pritchard [54]. Consequently, by simply measuring the crystal $E-I$ characteristics, all of the mixer design parameters were able to be calculated in meaningful implementation terms, including the IF output conductance, allowing for the IF amplifier optimum source conductance design for minimum noise figure.

In 1960, R. J. Mohr and I [55] presented an article extending some of Strum's work. It showed that from a knowledge of the crystal dc characterization, an LO drive level can be found at which the crystal input conductance equals the optimum source conductance, for any of the three cases of image termination. This established an accurate and convenient technique of measuring and achieving a proper input transformation network.

The above paper was an outgrowth of my first assignment (1955) at AIL, during which an amusing incident occurred between Dick Mohr, myself, and our supervisors, Art Hendler and Jack Greene, which pleasantly sticks in my memory. I'm sure you have had similar experiences, so I would like to relate it to you. Dick and I were assigned to work on a one year RADC contract to improve the state-of-the-art of mixers in the L, S, S_c, and C bands, using image-enhanced techniques. For the first three months, Dick and I, being green engineers (more me than Dick, who had about a year of experience), had our noses buried in books, trying to educate ourselves on low-noise theory, measurement technique, mixer networks, etc. Three months into the program, Art and Jack had a design review meeting with us. After some discussion on our progress, Art said that he hadn't seen any experimental work, only paper studies, and he reminded us that we were working on a hardware program. Dick commented, "You seem worried Art! Don't worry!" Art's reassuring comment was, "I'm not worried, just a little concerned." After another two months passed, we had our next review meeting and Art asked the same question on our experimental work, to which Dick commented, "You seem worried Art! Don't worry!" Art again reassured us, "I'm not worried, just a little concerned." A week later, one early Monday morning, Art, unannounced, came to us and, without any introductory remarks calmly said, "You know guys, I've thought about this and you're right, I'm not concerned, I'm worried!" At the end of the year, AIL delivered to RADC four receivers, each having a different topology: stripline, coaxial, waveguide, single-ended, and balanced. They all used IN21E crystals in the Case 3) (open-circuited image) configuration, having noise figures as low as 5.5 db and an average improvement in the art of about 1.0 db. Art and Jack were pleased.

In 1967, Barber [56] published a paper, extending P. D. Strum's [52] concept of improving conversion loss via LO impedance adjustments. Strum had suggested that by changing the frequency response of the circuit in series with the crystal (at the LO frequency), one could change the shape of the current pulse, causing a corresponding change in the conductance pulse. This results in an improvement in the effective $E-I$ characteristics of the crystal, yielding improved L_c. Barber introduced the idea of "pulse duty ratio" of the diode current, presenting a

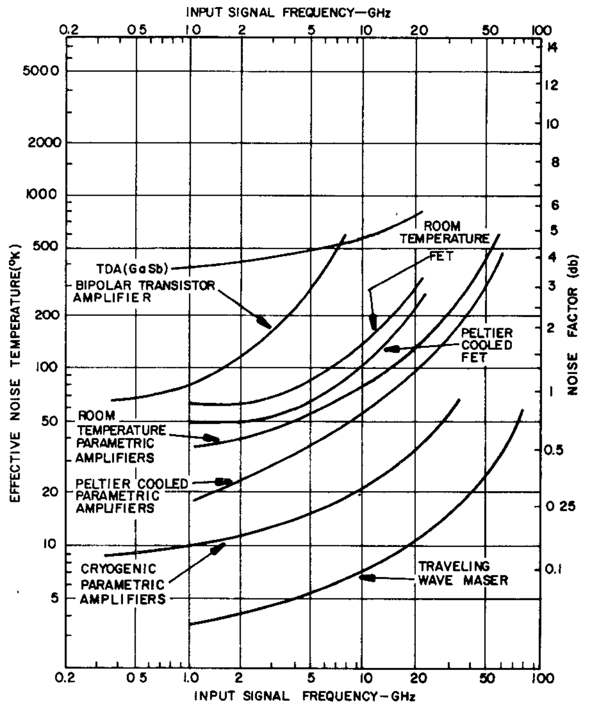


Fig. 8. State of the art performance of low- and ultra-low-noise amplifiers.

quantitative means of evaluating Strum's qualitative concept. Barber showed that application of pulse duty ratio to high cutoff frequency GaAs epitaxial Schottky-barrier diodes should yield single sideband overall noise figures as low as 3 db at X-band.

Further work was done on cryogenically cooling mixers [57], [58] to achieve improvement in noise performance. It did not prove to be practical except in limited applications such as radio astronomy continuum observations where double-sideband noise figures are applicable.

Today, the mixer is still widely used in all microwave systems, but rarely as a low-noise front end. It will, however, be the workhorse in the emerging millimeter and submillimeter wavelengths [50], [59]–[62], where there are no rivals in sight to challenge its front-end dominance.

Modern Ultra-Low-Noise Receivers

An historical survey of the Ultra-Low-Noise Period is presented from a macroscopic point of view, relating how its fruits were absorbed into the overall technology rather than a detailed technical description of each of the amplifier principles and embodiments. It is planned to present this latter description as Part II at a later date. Transistor amplifiers (bipolar and FET) are not included in this discussion, but will be presented in Part II. Fig. 8 shows the state-of-the-art of ultra-low-noise amplifiers.

The introduction of the mixer into the Low-Noise Period occurred under a different set of circumstances vis-a-vis the way modern amplifiers entered the Ultra-Low-Noise Period. The mixer, lying dormant for many years, had to wait for the critical needs of World War II before being seriously exploited. On the other hand, the Ultra-Low-Noise Period experienced unbelievable good fortune—the coinci-

TABLE I
CHRONOLOGY OF ULTRA-LOW-NOISE AMPLIFIER AVAILABILITY

Type	Year of Discovery or Proposal of Principle	Year of Reduction to Practice
Electron beam parametric amplifier (EBPA) [63], [64]	1958	1959
Tunnel diode amplifier (TDA) [65], [66]	1957	1958
Solid-state maser (3-level) [67], [68]	1956	1957
Parametric amplifier (PA) [69], [70]	1957	1957

TABLE II
CHRONOLOGY OF EARLY U.S. SPACE AGE REQUIREMENTS

Year	Project	Application
A) Satellite Communication		
1955	Initial proposal	Proposed by J. R. Pierce [71]
1958	SCORE	First commercial satellite (33-day life)
1960	Echo I	Launched to prove feasibility of passive satellites
1960	Courier	Delay-repeater satellite (17-day life)
1962	Telstar	AT&T experimental link between U.S. and Europe
1962	Relay	NASA experimental link
1965	Intelsat I (Early Bird)	COMSAT's first experimental/ operational link
⋮	⋮	⋮
B) Space Exploration (Probes)		
1958	Pioneer 1	Moon
1960	Pioneer 5	Moon/Venus
1962	Mariner 2	Venus
1964	Mariner 4	Mars
1965	Pioneer 6	Orbiting the sun
1966	Pioneer 7	Orbiting the sun
1967	Mariner 5	Venus
1969	Mariner 6	Mars
⋮	⋮	⋮

dence of amplifier availability and a critical need for its performance. All of the ultra-low-noise amplifiers, having different scientific principles, sprung up spontaneously, arriving on the scene at the same time (Table I). Miraculously, the Space Age entered the scene at the same time (see Table II), with its disciplines of satellite communications and space exploration, each having an unquenchable thirst for low-noise amplification.

The beauty of the above set of circumstances never ceases to amaze me. Unlike the Laser, which was a solution looking for a problem, the ultra-low-noise amplifiers and their applications had a fairy tale relationship. It had a short courtship, a quick marriage, and immediately began to raise a happy and healthy family.

The fortunes of each amplifier type, in its race for product acceptance, economic survivability, and longevity, is briefly outlined below. (The details of the race will be presented in Part II.)

1) *EBPA*—An elegant runner that never got out of the starting blocks, finding itself mismatched for the race. It died at the young age of about 5 years.

2) *TDA*—A middle distance high-school runner who didn't realize it was in a class race. It never had a chance because of its shot-noise limitations on T_e, and its relatively poor dynamic range. It had some moderate commercial success in the mid 1960's through the early 1970's, but was forced to drop out of the race. Its career ended after about 12 years.

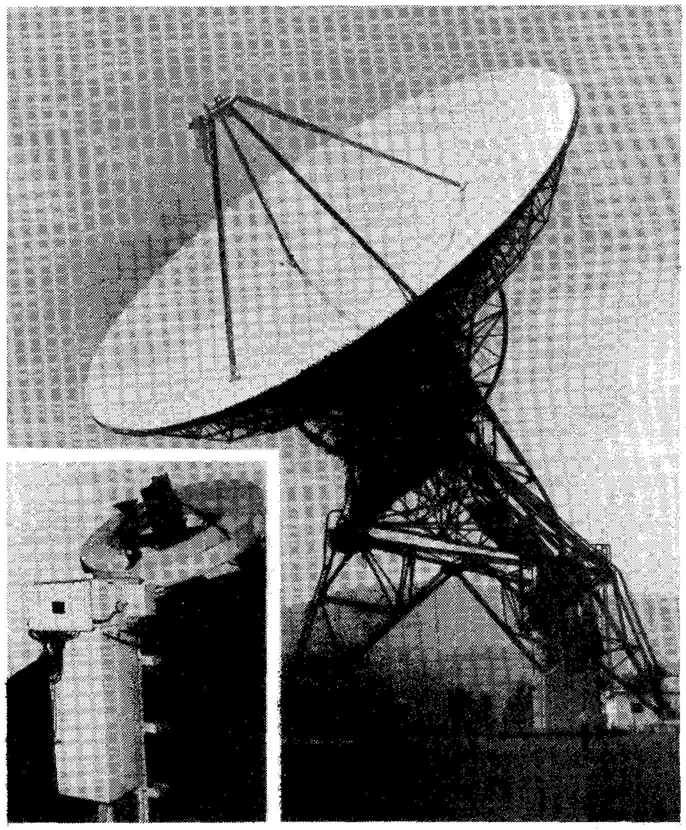
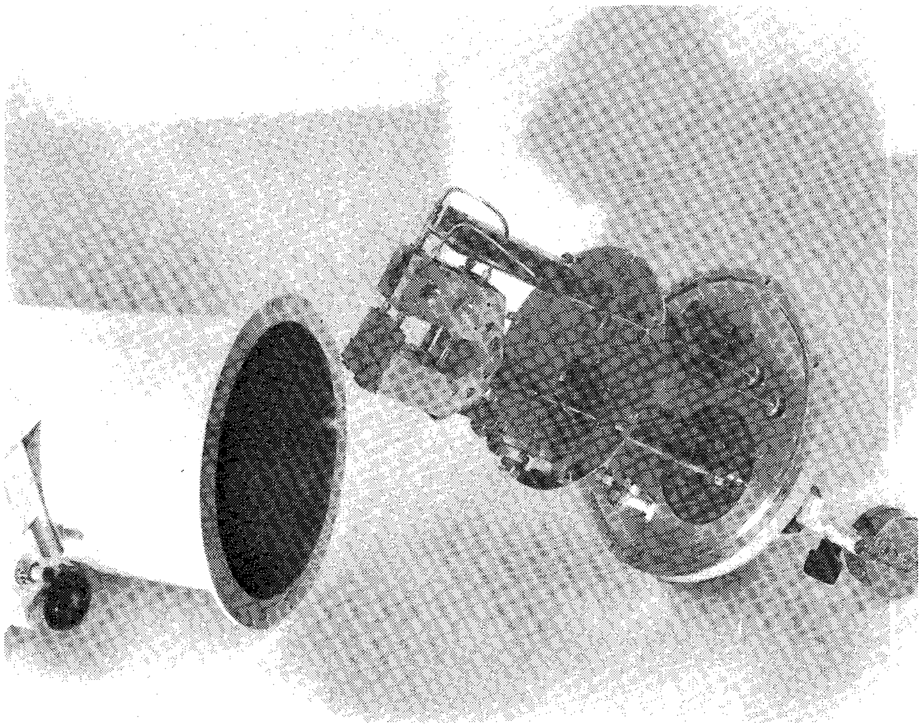


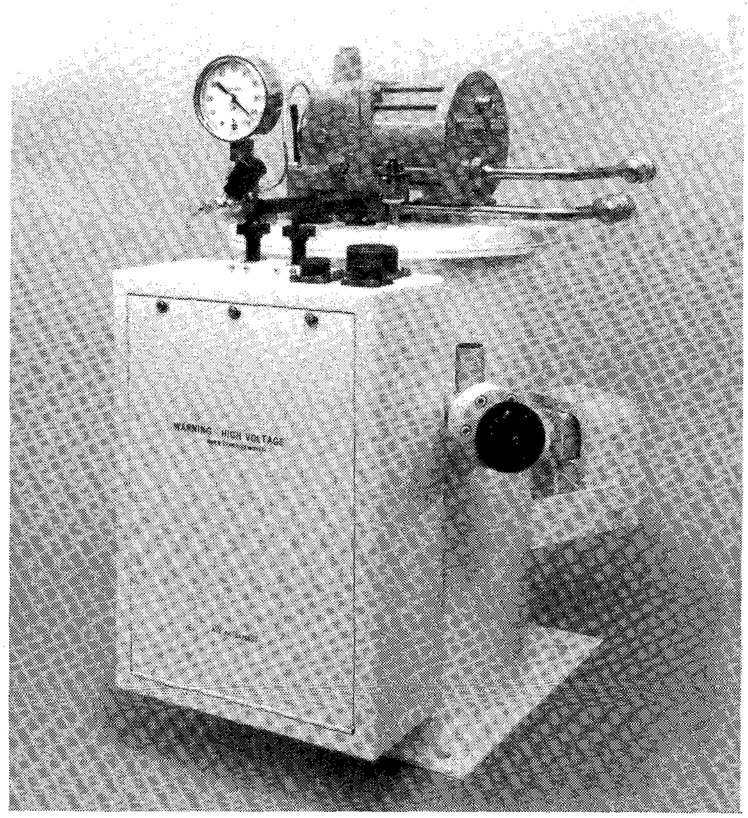
Fig. 9. NRAO 85-foot telescope with a maser mounted on the south feed support leg.

3) *Maser*—A class miler with style who didn't realize it was in a marathon race. It was first out of the starting blocks, being the first to find commercial applications in 1) the initial U.S. and Japanese gateway stations[5] for the Intelsat network and, 2) NASA's deep-space instrumentation facilities. It faltered early in the race with burdens of cryogenics, bandwidth limitations, and high cost. The maser had a flashy, exciting career that fizzled out after about eight years, except for the most stringent radio astronomy and deep-space requirements (Fig. 9).

[5]Andover, ME; Brewster Flats, WA; Jamesberg, CA; Paomalu, HI; and Ibaraki, Japan.



(a)



(b)

Fig. 10. Cryogenically cooled parametric amplifier for INTELSAT applications. (Courtesy of AIL.)

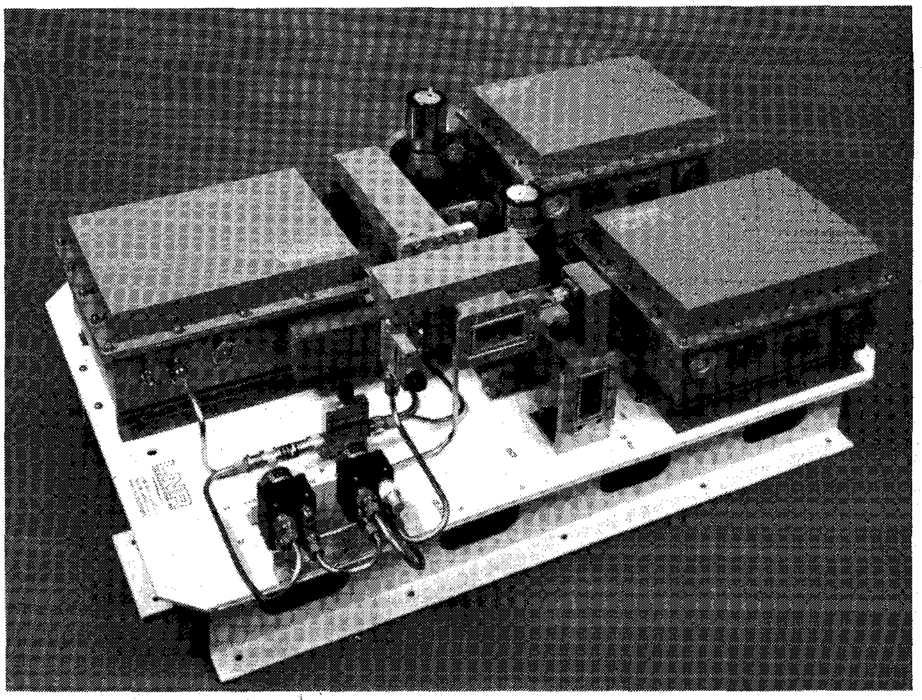


Fig. 11. Tridundant® low-noise paramp system for commercial satellite communications, having dual polarization and one-for-two redundancy. (Courtesy of LNR Communications.)

4) *Parametric Amplifier*—It had difficulty keeping up with the maser during the early part of the race, having gain–bandwidth product limitations and noncompetitive T_e characteristics. The paramp, however, was very resourceful. It picked up much of the T_e gap by applying cryogenic cooling (see Fig. 10). The paramp finally hit its stride in the mid to late 1960's with the use of sophisticated circuit broad-banding techniques yielding greater gain-bandwidths, and the availability of very-high-quality GaAs varactors, yielding lower noise temperatures. These factors paved the way for paramp ultra-low-noise performance without the complexity and cost of cryogenics, thus leaving the paramp alone on the track, the recognized winner.

In the early 1970's, Peltier-cooled paramps were the configuration of the day (see Fig. 11), and is still being used as the workhorse in most of the satellite communication ground stations.

VI. Temporary Conclusion

I have tried to relate what is to me an exciting story, which has no ending. Progress fortunately continues, and the paramp is presently being challenged by FET amplifiers. With its simplicity and cost advantages, the FET is encroaching on the previously exclusive property of the paramp, slowly eroding its monopoly. To be continued · · · .

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S. Okwit (A'55–M'60–SM'61–F'66) received the B.S. degree from Brooklyn College in 1952, the M.S. degree from Adelphi University in applied mathematics in 1957, and the M.S. degree from Adelphi University in physics in 1961.

He is presently President, Chief Executive Officer, and Chairman of the Board of LNR Communications, Inc., a company founded in 1971.

In 1966, he was elected to the grade of Fellow of the IEEE, for "Contributions to Solid-State Devices, particularly Masers, Parametric Amplifiers, and Ferrite Devices." In 1977, he received the "Distinguished Service Award" from the IEEE Microwave Theory and Techniques Society.

S. Okwit has been very active in IEEE affairs, having been Editor of the IEEE Transactions on Microwave Theory and Techniques from 1966 to 1968, and an elected member of the G-MTT Administrative Committee from 1966 to 1971. In 1971, he was elected to the position of President of the Administrative Committee for the MTT Society. He was a member of the IEEE Publications Board, Chairman of the Finance Committee of the Publications Board, and a member of the IEEE Budget Advisory Committee. In 1974, he was selected by the Microwave Theory and Techniques Society to be the National Lecturer on current microwave topics of communications, radar, and electronic warfare.