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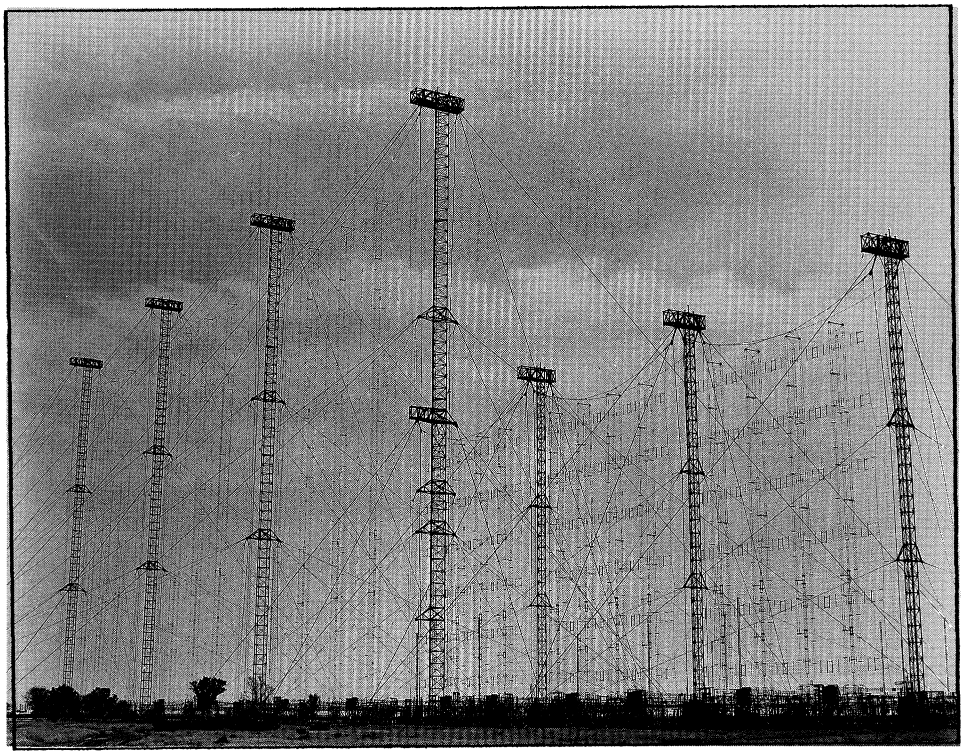

The Antenna Arrays of the Voice of America's Jack R. Poppele Transmitting Station at Delano, California. (Courtesy of the Voice of America)

A frontal view of the developmental antenna at the Jack R. Poppele Memorial Transmitting Station. The high frequency section of the antenna is seen to the right, and the low to the left. The height of the towers of the low frequency section is 420 feet. The ground works containing the extensive elements for the control of the beam forming parameters are seen behind the antenna radiator structures.

Proceedings of The Radio Club of America, Vol. 66, no. 3, November 1992

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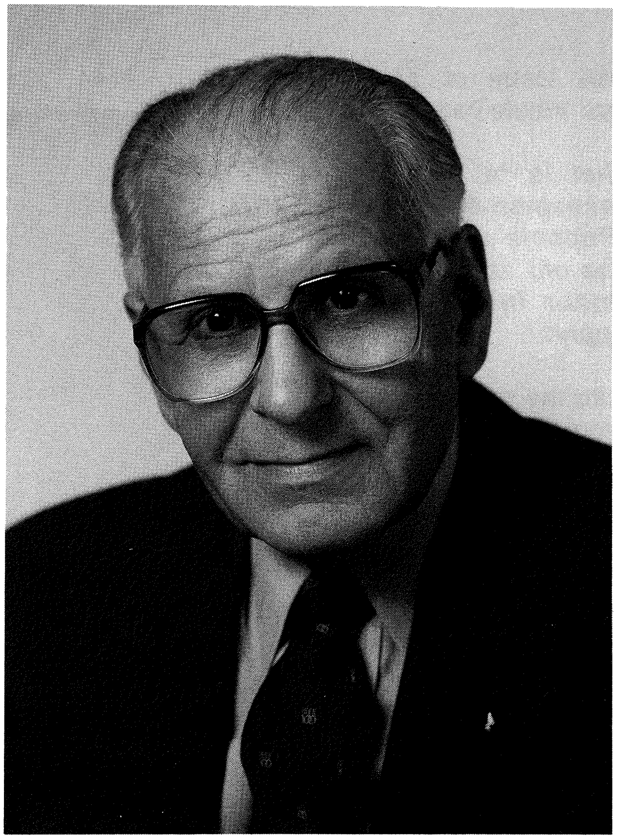
1993 PRESIDENT EMERITUS

FRED M. LINK



LINK, FRED M., W2ALU (M 1968, F 1968, L 1983), Communications Consultant, r. Robin Hill Farm, Pittstown, NJ.; b. York, PA., October 11, 1904; m. 1930, Mildred Catherine Coover, dau. Joanne C.L. Sotres; educ. Pennsylvania State University (BSEE 1927); Tau Beta Pi; Eta Kappa Nu; Pi Kappa Alpha; York (PA) College (Ph.D. [hon.] 1988) ; professional employment: New York Telephone Co. 1927/1928 (plant engineer); De Forest Radio Company 1928/1931 (Asst. Chief Engr.); Link Radio Corp. 1931/1950 (founder and President); Allen B. DuMont Labs. 1954/1959 (director - mobile radio operations); RCA Mfg. Corp. 1959/1966 (consultant); Fred M. Link 1967- (industry consultant). Public Safety Director 1940/41 & Mayor 1942/1952, Borough of Westwood, NJ; member Board of Adjustments 1975- Union Twp., NJ. Military service: Lt. USNR. Recipient of National Service Award of NARTE together with scholarship award to Pennsyslvania State Univ. in his name. IEEE Fellow Award "for contributions to mobile radio communications."

Other IEEE awards: Charter Member VTS/IEEE 1980; VTS Board of Governors 1975-; and Centennial Medal 1984. Member Nat'l. Assn. of Bus. & Educ. Radio (Board of Directors 1985-; Other awards: Honorary Life Member, Assoc. Public Safety Communications Officers, 1970; De Forest Audion Award, De Forest Pioneers Assn., 1971; De Forest Award, Veteran Wireless Operators Assn., 1973; Sarnoff Citation, Radio Club of America, 1976; Allen B. DuMont Citation, Radio Club of America, 1983; Fred M. Link Land Mobile Radio Award, Radio Club of America, 1986; Life Member, QCWA; Member: Board of Directors, NABER Assn.; New York Athletic Club; Soc. Wireless Pioneers; Veteran Wireless Operators Assn.; Old Old Timers Club; American Horse Show Assn. Avocation: raising, training and showing American Saddle Bred horses. **President, Radio Club of America, 1968/1992.**

THE JACK R. POPPELE TRANSMITTING STATION OF THE VOICE OF AMERICA.

In the November 1986 issue of *The Proceedings*, our **In Memoriam** tribute began:

One definition of a prophet is "a person regarded as a leader, a spokesman of some doctrine or cause." Jack Poppele certainly fits that description. But the old adage: "A prophet often is without honor in his own country" certainly doesn't apply.

His work brought him into the presence of seven successive Presidents -- from Franklin Delano Roosevelt to Gerald Ford. In 1953, President Eisenhower appointed Poppele to the position of Director of the Voice of America. The job's responsibilities were those of directing broadcasts in 43 languages through 83 transmitters located throughout the world.

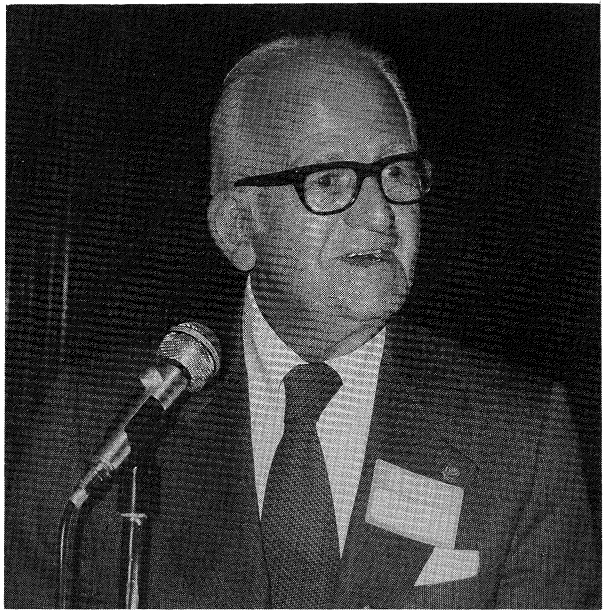
At long last, the United States Information Agency through its Voice of America has honored Jack Poppele by naming its relaying facilities in Delano, California as **The Jack R. Poppele Transmitting Station.**

We first heard about the plans early in May.

The news came in a letter from Jerry S. Stover, P.E, (Fellow and former Director) who wrote: *"As you may have heard, the VOICE OF AMERICA is dedicating their Delano station to Jack Poppele. Jack was the first engineer to become a Director of VOA, and did a great deal for radio broadcasting in general."*

The station was named in honor of Jack Poppele on February 24, 1992, the VOA's 50th Anniversary. The dedication ceremonies were held at the Delano site on May 14, 1992 under the auspices of the Broadcast Engineering Advisory Committee of the VOA, chaired by Lt. General Walter E. Lotz, Jr. (F). The station now is officially named:

THE JACK R. POPPELE
TRANSMITTING STATION.
DIRECTOR - VOICE OF AMERICA
1953 - 1956.



Jack R. Poppele

Here was the long over-due recognition of the "prophet." Here, in California, the Voice of America already was using state-of-the-art versions of the directional antennas that Jack Poppele had developed with two teams of research scientist from Bell Laboratories. Working with only theoretical data, Poppele had convinced the owners of radio station WOR that a supertransmitter of 50 KW plus a directional antenna would give the station exceptional coverage. Winning approval, the world's first super-station was built in 1935. With the new directional antenna beaming a strong signal at population centers and not over the ocean or the westerly woodlands, WOR's income tripled in the first year.

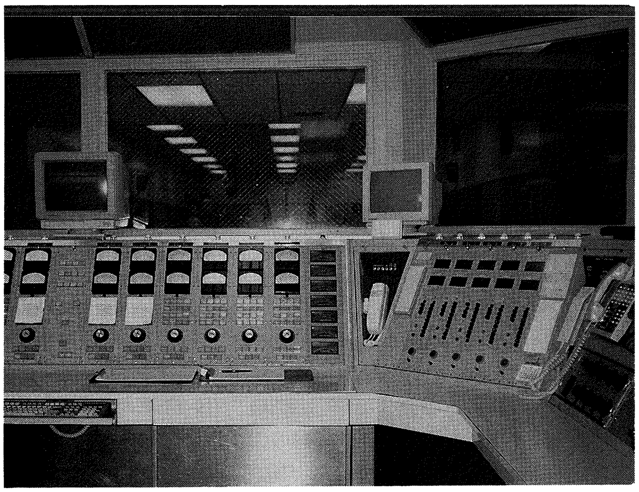
OVERVIEW

The Jack R. Poppele Transmitting Station, previously identified as the Delano Relay Station, is one of the 15 worldwide radio relay facilities of the Voice of America. It occupies an 801 acre site in the San Joaquin Valley of California.

The transmitting site, located about two miles west of the city of Delano, has a main building containing the transmitters and administrative offices. A mechanical shop, equipment shelters, pump house and storage buildings are nearby. Most of the site's acreage is covered with a complex system of transmission lines and antennas.

The station has three 250 kilowatt automatically-tuned Collins and four 250 kilowatt Brown Bovari transmitters for regular AM short-wave broadcasting. Additionally, there are two 50 kilo- watt Continental Electronics independent side-band transmitters used in relaying VOA programming to overseas relay stations.

The transmitters can be connected by way of a "full matrix" antenna switching system to any of 12 curtain or 5 rhombic antennas which may beam the signals into Latin America, the Pacific territories, or the Far East.



MASTER CONTROL POSITION

FUNCTIONS

The Jack R. Poppele Transmitting Station broadcasts primarily to Central America, South America, and to the Central Pacific area from the Northern Mariana Islands south to Fuji. The station transmits about 10.5 hours daily of programs in Spanish and English. However in special instances such as the 1991 coup d'etat in Haiti, the station may readjust its broadcast schedule to include programming in Creole to bring the only source of news and information available to a people whose local radio stations have been silenced.

The programming is sent to the station from Washington, DC via the Satellite Interconnect System (SIS), an advanced technology that has improved the quality and reliability of the program feed and, concurrently, reduced the operating costs versus the former feeds via telephone company facilities.

By special agreement, the station also relays about 7.5 hours daily of Spanish-language programming originated by the BBC, using from one to four of the 250 kW transmitters.

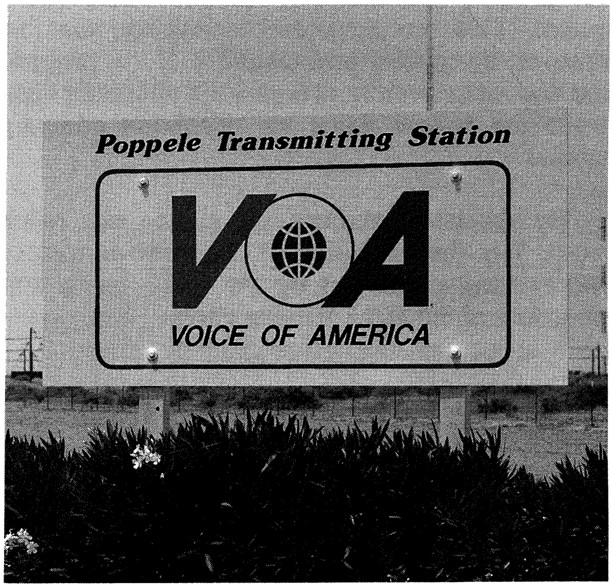
HISTORY

In 1942, the Office of War Information (OWI) was established to disseminate information during World War II. It was immediately recognized that radio transmitters were needed on the West Coast for broadcasts to those involved in the Pacific War effort. Delano was selected and the construction of the station was finished in November 1944. The station went on the air immediately under a contract with the Columbia Broadcasting System (CBS).

With the termination of World War II, the Office of War Information ceased, and parts of its operations including the Voice of America were transferred to the U.S. Department of State. The Voice of America remained under the State Department's supervision until 1953 when then President Dwight D, Eisenhower consolidated all of the overseas information activities into the United States Information Agency. CBS, however, continued to operate the Delano Relay Station until 1963 when the U.S. Information Agency assumed complete control.

In 1968, the facilities of the station were completed with the addition of three of the 250 kW short-wave transmitters and the two 50 kW independent side-band transmitters. These facilities more than doubled the station's power output.

In 1975, two curtain antennas were installed to improve the overseas reception and, in 1977, a new steerable curtain antenna was constructed. Then, in 1985, the three original 40-year old transmitters were replaced by four 250 kW Brown Bovari transmitters. In 1988 and 1989, the computer-controlled, high-gain, multi-band curtain array was installed. This addition allowed the transmitters' signals to be switched rapidly, and the antennas to be pointed toward various reception areas, with a simple key stroke.



The Entrance to the VOA Delano, California
Jack R. Poppele Transmitting Station

President Gerald Ford and Jack Poppele

THE VOICE OF AMERICA: A Brief History

The Voice of America has reported many changes in the world -- changes that have occurred with almost lightning speed in the last five years. In many respects, the broadcasts may have provided encouragement for change.

The media called it "The Fall of the Berlin Wall." Maybe it should have said that the Wall was pushed down by the power of the broadcast word. Freedom has swept the planet: in 1989, hundreds of thousands of demonstrators -- armed only with thoughts of freedom -- took to the streets of Prague, Leipzig, and Bucharest to change the political face of Central and Eastern Europe.

In June of the same year, Chinese students challenged their own government's policies with demonstrations in Tiananmen Square. And more recently, in 1991, the People of the USSR stood up to and defeated an attempted coup in their country.

The Voice of America first went on the air on February 24, 1942 to inform the people of occupied Europe of the status of the U.S. war effort. Since then, broadcasting "comprehensive, accurate, and objective" news has remained the VOA trademark.

Last year, for example, the Voice of America informed people around the world about the collapse of the Soviet Union and the Persian Gulf crisis and war.

Seated in a row of glass-walled studios, radio newscasters are reading the news in Arabic, Estonian, and Urdu. In a nearby newsroom, a reporter is typing out a story in Mandarin Chinese and, in a hotel room across town, a Tibetan reporter is interviewing the Dalai Lama. A few hours later, Tibetans hear the first broadcast commentary by their spiritual leader since he was exiled from Tibet in 1959.

The service philosophies of the VOA have changed since 1942; then, the U.S. considered getting information to Europe to be very important. VOA broadcasts in Danish, Finnish, Norwegian, Flemish and Italian -- all begun in 1942 -- are no longer transmitted. VOA also discontinued broadcasting in French to France although the French-to-Africa Service continues.

During its first year, VOA placed a total of 29 language services on the air. Twenty-two of the original languages remain on the schedule. Fifty years ago, VOA broadcast in Afrikaans, Amoy, Japanese and Tagalog -- none of which are on the air today. Of the 22 original language services, German is the oldest.

The first broadcast using the term "Voices from America" occurred during the German language broadcast of February 24, 1942. That date, just 79 days after the U.S. entered World War II, saw the first program -- a fifteen minute presentation in German by announcer William Harlan Hale who opened the broadcast with the words: "Here speaks a voice from America."

RELAY STATIONS

The Voice of America sends its programs from its Washington, D.C. studios to its transmitter stations via satellite. Here, short-wave -- and in some cases, medium wave -- transmitters broadcast the programs. Currently, fourteen stations are operated with three built in the United States at Delano, California; Greenville, North Carolina; and Bethany, Ohio. In the whole of the 14 transmitter stations, nine medium wave and 105 short-wave transmitters are used. Together they generate 27 million watts.

The VOA network requires the services of 3,019 full time personnel of whom 645 are foreign nationals. The operating budget is approximately U.S. $231 million for operating expenses in 1992 plus an additional $98 million for modernization of the broadcast facilities.

Additionally, 320 personnel and $37 million are required for the operation of Radio and TV Marti, a service established in 1985 to provide the Cuban people with information unavailable from other sources. Radio Marti broadcasts 24 hours a day from a transmitter in Marathon, Florida.

The Radio Club of America was represented at the dedication by Miss June Poppele (HF), Mrs. Lorraine Poppele Flower (H), Mrs. Connie Conte (F), and Messrs. Robert L. Everett, Ph.D., (F), Mal Gurian (F), Loren McQueen (F), Stuart F. Meyer (LF), Thomas R. Poor (F), and Jerry S. Stover, P.E., (F).

The idea for TV Marti grew out of Radio Marti's success. It began broadcasting in March 1990 from a tethered aerostat (balloon) at Cudjoe Key, Florida. TV Marti's programs offer viewers news, entertainment, and features on life in the United States

Now, at age 50, the Voice of America continues to serve as a consistently reliable and authoritative source of news -- accurate, objective, and comprehensive. Soviet ex-President Gorbachev, speaking at a press conference on August 22, 1991, following an attempted coup, said: "Our people found some old service radio receivers, rigged up an antenna and began catching whatever was available: the BBC, Radio Liberty and the Voice of America...I would like to express my thanks to the domestic and foreign media."

And in response, Evdoklya Gaer, a member of the Council of Nationalities from the Russian Republic, speaking at the USSR Supreme Soviet on August 27, 1991, asked: "How could we allow [during the coup attempt] in the enormous spaces of our country, for the Soviet population to remain totally without access to news? The news was 24 hours late! So we listened to foreign radio stations: the Voice of America...I demand that these radio stations never again be jammed, for in such extreme, troubled situations, they are the only way for us to find out what is going on in our country."

And from a Russian woman in Moscow after the failed coup: "We listened to the Voice of America. It was our only link. Please give our thanks to America."

Members of The Radio Club at Dedication of Jack R. Poppele Transmitting Station. Left-to-Right: Lorraine Poppele Flower; Dr. Robert L. Everett; June Poppele; Loren McQueen; and Stuart F. Meyer.

SPEECH OF JUNE POPPELE (HF)

On behalf of my sisters Lorraine Flower, and Virginia Endres who could not join us, I want to express our deepest appreciation to the Voice of America for this fine tribute you have bestowed upon our father's memory. We are extremely proud of this honor and extremely proud of our Dad.

Jack Poppele was one of those many self-made men who started at the very bottom and climbed the ladder of success. His father told him he should stay with machine-shop work which was a steady job and to "forget that newfangled thing called Radio." But Dad loved the wireless sound and through lots of hard work and being in the right place at the right time he was able to put a radio station -- WOR in New York City -- on the air. And that station continues to be one of America's great stations.

Dad was perhaps most proud of his directional signal which he developed with two teams of research scientists at Bell Telephone Laboratories in Whippany, New Jersey, in 1935. It allowed more than one station to transmit on the same frequency and audience coverage was more intense. With the new transmitter, WOR's annual income rose from $385,000 to $1,2 million the first year. For this and many other precedent-setting ideas and successful applications of new technology, WOR made Jack Poppele a vice president and put him on the company's Board of Directors.

Dad was very involved in many radio and television associations. And among them is The Radio Club of America -- an extremely active group of electronic, radio and communication enthusiasts and with whose help, especially Jerry Stover's, this dedication became possible.

In 1953, President Eisenhower appointed Jack Poppele as Director of the Voice of America -- "Just at the time when the Soviets were jamming the heck out of us" -- he said. I wish Dad could know the progress that has developed in our countries' relationships today. (But perhaps he does know.)

After leaving the Voice, Dad went on to design and build an amusement park in Vermont which is still in full operation. And his final enterprise was a television communications business in New Jersey called Tele-Measurements.

Gordon Bishop, an admirer of my father and an editor of a Newark, New Jersey paper, said of him and it is most appropriate today, "that Jack Poppele probably is looking down from that big studio in the sky sending out those wireless impulses to all of us here and, in his own gracious way, thanking us for keeping him in our thoughts and deeds."

You should all feel proud of the good work that you and the Voice of America have done (as reported in a paper on the History of the VOA) -- to show how "Communication is more powerful than tyrants." "For without firing a single shot -- the Iron Curtain was torn down, Communism has been broken, and Democracy has become known."

DELANO RELAY STATION CEREMONY

SPEECH OF WALTER LaFLEUR
VOICE OF AMERICA
Director of Engineering and Technical Operations

I am pleased and honored to represent the Voice of America in its 58th Anniversary Year, in this ceremony to rededicate the Delano Relay Station in the name of former VOA Director, Jack R. Poppele.

We, at VOA, are grateful to members of The Radio Club of America for suggesting this honor in behalf of Mr. Poppele. We're especially grateful to Jerry Stover, Loren McQueen, General Walter Lotz (who, unfortunately, cannot be with us today, and our own Dr. Robert Everett. Most of us were not aware of Jack Poppele's many contributions to the field of broadcasting and his role in our heritage.

It has been fascinating to read the accounts of Jack Poppele's life, all the way from his *Federal Wireless License* in 1915 through AM and FM radio, and through the pivotal early days of television. A review of his accomplishments clearly defines a man of extraordinary vision, an incredible engineer, and a persuasive salesman for the medium. As important as those talents were to the dynamic era in which he influenced the development of broadcasting, they still are in demand today.

Think how incredibly valuable it would be to the Voice of America today, for example, to have a person with the vision of Jack Poppele to sort out the right mix of AM, FM, short-wave radio, television, and affiliation that would best serve each of VOA's 46 language areas; how helpful it would be to predict unerringly the future of new technology such as various schemes for the delivery of digital audio, either ground or satellite based, as well as AM stereo or radio data delivery. Then how valuable to have the engineering ability and energy to bring it all to fruition despite the formidable bureaucratic and economic hurdles we all face. Lastly, think of the inestimable value of having someone to energetically and persuasively market the service to Congress and the Office of Management and Budget. Thus, either in retrospect or as measured by today's broadcast environment, Jack Poppele was an incredible individual ...one of a kind. How fitting, then, to name the Delano Relay Station in his honor.

I am sure he would have been enthralled by the sight of the giant short-wave antenna that was described to him by Dr. Everett some years ago when it was a mere concept. This state-of-the-art antenna allows us to direct the signal where needed most. Jack would have enjoyed hearing how we brought the beam from this antenna to bear on Panama in that crisis -- providing a signal that could not be denied, and doing so with economy and precision. Tonight, he would have appreciated our new digital satellite service which, with perfect fidelity, delivers programs from studios in Washington to the station for relay. He would have liked the automation features (many developed right here by station staff) that have so dramatically changed the nature of station operation. Jack Poppele garnered many prestigious awards in his illustrious career but I bet that he would find this modest tribute, today, very satisfying.

VOICE OF AMERICA DEVELOPMENT OF BEAM-SWITCHING ANTENNAS

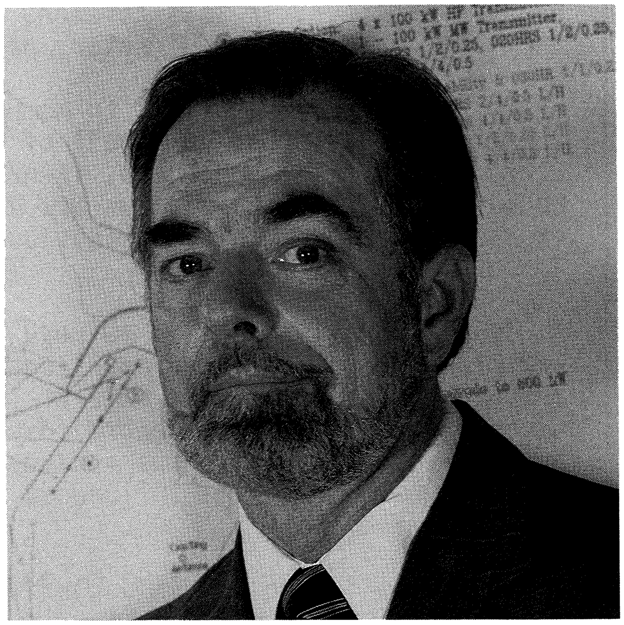
by **Robert L. Everett, Ph.D.** (F)
Chief, Broadcasting Systems Engineering Division
Systems Engineering Directorate
Voice of America

1. INTRODUCTION

For external service broadcasting agencies such as the Voice of America, high frequency (short-wave) broadcasting has long been the usual manner of delivery of program material across international boundaries. This broadcasting medium presents a very effective and efficient mode of long-distance communication, because it utilizes the principles of ionospheric propagation. In this, a radio signal is beamed upwards into the sky, and is eventually reflected back to Earth by the ionosphere. As the ionosphere is typically some hundreds of kilometers above the Earth, the signal is effectively transferred some hundreds and thousands of kilometers from the point of origin to the reception area.

Efficient use of the ionosphere as a radio transmission medium is tricky. The properties of the ionosphere are highly variable. They change as a function of location around the Earth, the time of day, the season and sunspot activity, and the frequency of the signal. Effective high frequency (HF) broadcasting is highly dependent upon having a precise knowledge of the properties of the part of the ionosphere which will be the reflection medium for a given broadcast. From this knowledge, the skilled HF broadcast planner can determine the proper frequency for the transmission, and the required parameters of the radio beam launched from the antenna which will most efficiently cover the desired broadcast service area.[1]

In present-day international HF broadcasting thinking, the antenna which forms this beam is considered more of a form of transducer than a simple radiating device. As a transducer, it must match the beam it generates to the then-and-there requirements of the ionosphere in order to deliver the best possible signal to the specified broadcast service area.



Dr. Robert L. Everett

Precise tailoring of the antenna beam to optimally meet the requirements of the ionosphere has always been important from a variety of points of view. From the broadcaster's point of view, we see that audiences usually have a choice of program material from which they may choose. Thus, the quality of the signal delivered to the listener must be competitive with that of the best competitor, or the listener may well be lost to the competitor. From the world spectrum management point of view, the delivered signal spillover into areas where the signal is not useful contributes to the increasing chaos resulting from broadcasting band resources strained to the utmost. So, signal delivery must be limited as much as possible to the designated service area. Also, from the operational cost point of view, energy costs for high-powered transmissions do not permit the luxury of signal spill-over into areas where the signal is neither needed nor wanted.

---

[1] Kenneth Davies, *Ionospheric Radio*, Peter Peregrinus Ltd, London, UK, 1990

It is apparent then, that a considerable degree of control of the beam formed by an antenna is desirable for broadcasters. The most commonly controlled beam parameters of modern antennas are the azimuthal direction in which the beam is directed; the vertical angle above the horizon at which the beam is launched (its take-off angle); the horizontal width of the radio beam; and the vertical width of the beam. It is necessary that these parameters be appropriately controllable at each frequency band in which the antenna is capable of operating.

2. THE CURTAIN ANTENNA

Nowadays, the curtain antenna is preferred for international HF broadcasting purposes. This antenna is a vertically-oriented broadside array of (usually) horizontal dipole radiators, commonly with a reflector screen. Its use, even in its early days, was largely due to the fact that its beams were more appropriate for broadcasting, its efficiencies higher, and its land area requirements less than those of its then rival, the rhombic antenna.

The CCIR[2] descriptor for these antennas, *HRS m/n/h*, provides sufficient information for the user to adequately describe their nominal beam performance within their operation bandwidth. Here *H* signifies a horizontally-oriented radiator dipole; *R* (if used) signifies the presence of a reflector screen; *S* (if used) signifies that the beam the antenna produces can be slewed (changed) about its azimuthal boresight; *m* denotes the number of dipoles in the horizontal aperture of the antenna; *n* the number of dipoles in the vertical direction; and *h*, the height of the bottom dipole above ground.

For these antennas, there is a fixed relation between the physical parameters of the antenna, and the beams it generates. Simply enough, the horizontal aperture of such an antenna determines the horizontal width of the beam it generates. Its vertical aperture does the same for the vertical beamwidth. In addition, for an Earth-surface mounted antenna, its height above ground governs the vertical take-off angle of the antenna. The azimuthal radiation direction of the antenna is fixed by the azimuthal direction in which the broadside of the antenna is pointed (its boresight), together with any azimuthal radiation direction deviations (slews) about boresight accrued by progressive phase advance or retard between the radiators in the horizontal direction.

3. CURTAIN ANTENNAS, AND THEIR OPERATIONAL ASPECTS

Curtain antennas have undergone a considerable developmental history in order to arrive at their present state. The principal driver for these advancements has been economic. This pressure is now higher than at any time in the past. To understand the delicate interactions which lead to this intense push for advancing the sophistication of curtain antennas, let us examine their early use in HF broadcasting stations.

3.1 Old but Good

Curtain antennas have been used in broadcasting for a considerable length of time. The VOA, certainly not the first user, has operated with such antennas since at least 1962.

The first versions of these antennas were simple arrays of narrow-band, full-wave dipoles. Usually, the dipoles were fat cages made of parallel wire mounted on hoops, effecting some degree of broadbanding. Then, as now, the dipoles were individually fed by a parallel transmission-line corporate feed structure, in which impedances are normalized by the use of parallel transmission-line impedance transformers. As the antenna had to function as a broadside array, elaborate care had to be taken so that the total transmission line length between the antenna input port and each individual dipole remains a constant.

However hard they may have been to design (remember the slide rule!), they were relatively simple structures: some towers, a lot of wire, a considerable number of insulators. They look like orderly spider webs.

Conceptually and structurally simple though they may have been, the systems planning and design of a station utilizing them was considerably more complex. It was tough to determine the minimum set of antennas which would deliver the required signals to the service areas at minimum cost.

The problem was, and still is, that for each broadcast requirement, a set of antenna performance requirements must be identified, in terms of frequency, vertical take-off angle (TOA), azimuthal broadcast direction, horizontal beam

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[2] Comite' Consultatif International des Radiocommunications, Geneva, Switzerland

width, and vertical beam width. The catch was, that serious broadcasters must transmit their programs according to schedule, whether the ionosphere is in a mood to make it easy, or not. The usual outcome of an antenna requirement analysis for a given station and specified broadcast requirements is that there is a specific need for large numbers of antennas, some of which might remain unused for years on end, until some particular combination of hour of day, season, and sunspots calls them into play.

For example, it is not unusual to see a large transmitting station with three antennas aimed at the same broadcast service area, each with a different height above ground, to support the same broadcasts under different time of day and ionospheric conditions. Or, a station which might have been specifically designed to provide a high degree of contingency broadcasting, so as to be able to broadcast a signal to service areas in any direction, at any radial distance, at any time of day, at any season and sunspot condition. Such a station might have up to 10 different antennas per transmitter, most of which are idle most of the time.

The problem is immediately evident. The old technology generated only one beam per antenna. And commonly, HF transmitting stations require a variety of different antenna beams to accommodate the same broadcast at different hours, seasons, and sunspots.

The real impact of this problem comes when the implementation costs are totaled up. Antennas using the old technology may be old-fashioned nowadays, but they were giants in their day, and still are so. For example, the commonly used 6-7 MHz. *HRS 4/4/1.* antenna could have towers in excess of 500 feet high, with an approximately equal width.

They were big, they were expensive, and for a big multipurpose transmitting station such as the VOA requires, they took up a lot of real estate. For example, VOA Greenville Transmitting Sites A and B each cover over 2700 acres; our site at Kavala, Greece 2000 acres, and at Tinang, Philippines, 2400 acres.

Added to this, some of the correlated costs were high. Usually, these sites were designed with a single transmission line to each antenna from a central switchbay. A single site could easily have as much as 35 km of 500 kW transmission lines. Switchbays -- big arrays of switches used to connect transmitters to these antennas -- have to be big and complex. For example, VOA Greenville Sites A and B each have a switchbay with 11 transmitter input rows, and 39 antenna output columns. Each switchbay is as big as a house.

The costs for all of this was prodigious. And naturally, a considerable amount of analysis and ingenuity went into designing and building stations with significantly reduced costs, while maintaining acceptable performance levels. Substitutions were made. Experiments with vertical beam take-off angles (TOA's) were made, and antennas with several different (but not particularly useful), TOA's were produced. Site selection criteria to minimize the required variety of antennas became a fine art.

3.2 Transition Times

In those good old days, big numbers of big antennas added up to good performance which, considering the times, was an acceptable cost/benefit tradeoff. But, there is always room for improvement, and improvement eventually came about.

This was largely a result of the increasing availability of computers within the reach of commercial enterprises, large and small, along with acceptably accurate antenna simulation software to run on them. So there was a general development phase and, by the early 1980's, there was a multiple source general availability of HF transmitting antennas with significantly improved performance over the older generation.

The improvements were largely in the area of increased antenna bandwidth, and the institution of really useful horizontal slews of the antenna beam center, azimuthally about the antenna boresight. Increased bandwidth came about because of the substitution of approximately half-wavelength dipoles of very large bandwidth, complemented by the addition of very broadband multistage Tchebycheff transmission line impedance transformers. The end result of this excellent work were curtain antennas of a variety of sizes and types which had a total of one octave frequency response. For the first time the entire international HF broadcasting spectrum could be covered by only two radiating structures, one from 6 to 12 MHz., and the other from 13 to 26 MHz!

The ubiquitous availability of horizontal slews of up to plus/minus 30 degrees about antenna boresight feature was also due to the systematic use of half-wavelength dipoles as radiators. These radiators were closely enough spaced to avoid the emergence of severe grating lobes resulting from the large progressive phase shift across the antenna horizontal aperture required to provide useful beam slew.

In general, the operating characteristics of these antennas were, and are, quite acceptable considering their bandwidth capabilities. Their power-handling capability is equal to the highest-powered transmitter. Their driving-point VSWR, while in general not as low as that available from their low bandwidth progenitors, is reasonably acceptable, and of the same range as ordinarily available from rhombic antennas. They can be made in a variety of heights-above-ground to accommodate any desired vertical takeoff range.

In short, these antennas appear to be the answer to an HF broadcaster's prayer. However, their most pleasing virtue, their frequency bandwidth, also causes certain operational difficulties. These come about because of the variability of their beam shape parameters as a function of operating frequency. Table 1. shows the general manner of this variation of important beam shape parameters of a typical antenna of this type. In this table, frequency is a quantity normalized to the center frequency of the antenna, expressed as the mean of its highest and lowest frequency of operation.

f_n (Normalized Frequency)	0.7	1.0	1.5
Gain	18.8	21.4	23.6
HBW (Horizontal [-6 dB] Beamwidth)	48.0	34.8	25.6
VBW (Vertical [-6 dB] Beamwidth)	19.9	13.9	9.9
TOA (Vertical Take Off Angle)	13.4	9.5	6.8

$$f_n = \frac{\text{Operational Frequency}}{\text{Antenna Center Frequency}}$$

Table 1.

The operating parameters of an *HRS 4/4/.5* curtain antenna, and their variation as a function of normalized operating frequency. For low-range antennas operating between 6 and 12 MHz., the center frequency is about 8.5 MHz. For antennas operating between 13 and 26 MHz., the center frequency is about 18.4 MHz. Gain is in dB above an isotrope, and angles are in degrees.

The approximately +/- 50% variation of all these critical beam shape parameters about the antenna center frequency shown in this table may be acceptable for the variety of broadcasts required for service in some specific situations. However, in general, the flexibility required for these antennas to be effective signal transducers for all-hours, all-seasons, all-sunspot broadcasts is not present. As a result, operational compromises must be made in choice of broadcast band; signal delivery footprints do not provide proper match to the desired coverage area; and signal delivery quality is compromised.

As can be seen, these antennas did not solve all the broadcasters' radiator problems. Frequency variation of the beam-shape parameters creates a new category of planning problems. Required beam control is lacking unless, of course, a variety of antenna sizes and heights above ground are implemented.

Where these antennas really made problemless contributions to the HF systems planners' quality of life was in the area of azimuthal slew. Under quite general broadcast conditions, this excellent quality saves a goodly number of antennas and a considerable amount of money.

In general, though, many HF broadcasters weigh the advantage of having an antenna which broadcasts some signal, non-optimal though it may be, against the cost alternatives, and decide these antennas are that something which beats nothing. This is an acceptable compromise under a variety of commonly encountered broadcasting scenarios.

3.3 The VOA Developmental Effort - Delano Antenna

In late 1983 and early 1984, VOA analysts in the Advanced Planning Division of the Systems Engineering Directorate had evaluated the worldwide situation with respect to antennas. Along the lines described above, it was concluded that, although the world marketplace was not supplying the variable-beam antennas which would be ideal for the VOA's newly embarked-upon Modernization Program, it was certainly in a condition to do significantly better than it was doing.

Thus, in an effort to stimulate the marketplace to produce a cost-effective antenna which would more nearly meet performance requirements established for its antenna systems, the VOA issued a performance-requirement-based Request for

Proposals (RFP) for antenna development. The performance requirements embodied in this document were established from detailed analyses of a great variety of broadcast situations which the VOA was to encounter in its pursuit of new transmitting station constructions and existing station refurbishments.

A direct object of this RFP was to establish how much of the idealized performance it specified could be met by available and cost-effective antenna industry designs and hardware. The ideal outcome of this exploration would be an antenna design or designs which would generate a sufficient variety of antenna beam shapes, so that one or two antennas per broadcast would suffice for the usual conditions to be encountered by the projected VOA transmitting stations.

In a contractual action resulting from this RFP, a contract was issued for the design and construction of a proposed pair of *HRS 12/6/.5* antennas, each with an octave frequency bandwidth, and each with a considerable amount of beam control circuitry to meet the various beam shape parameters specified in the RFP. This antenna was to be installed at the (now) VOA Jack Poppele Memorial Transmitting Station, in Delano California. In due course of time the proposed antennas were designed, fabricated, erected, tested, and delivered.[2]

Table 2 presents a synopsis of the general performance objectives of this antenna system. As can be seen, it is designed to project beams of a great variety of different shapes within each band of the HF international broadcasting spectrum. In particular, over the its entire bandwidth, a great many of this variety of beams are useful for broadcasting purposes. This was one of the first antennas which, in general, did not constrain the operator to accept whatever beam which it could form at the selected operating frequency. This antenna is shown on the front cover.

This antenna forms its different horizontal beam widths essentially by employing high-power switches to switch in or out sections of its large aperture, usually in increments of 2 dipoles. For example, it achieves its 35 degree horizontal beamwidth (at center frequency) by using a horizontal aperture of only 4 dipoles. The remaining horizontal aperture is not used. Azimuthal slew is accomplished by the insertion of progressive phase shift between the horizontally adjacent antenna radiators.

- o Two separate HRS 12/6/.5 antennas:
    - 6 to 12 MHz.
    - 13 to 26 MHz.
- o Each antenna fed by a separate transmission line from the switchbay.
- o Four horizontal beamwidth selections:
    - 70°
    - 35°
    - 17°
    - 10°
- o Nine different vertical radiation patterns, each with different take-off angles and vertical beamwidths.
- o Horizontal slew of up to +/- 30° about boresight, in 4.5° nominal increments.

Table 2.DESIGN OBJECTIVES

Overview of the design objectives of the developmental antenna installed at the Jack R. Poppele Memorial Transmitting Station in Delano, California. Each horizontal beamwidth, vertical beamwidth, and slew could be employed in any combination.

Vertical control is accomplished by switching in vertical dipole pairs, switching them out, or by exciting them in phase reversal (counterphase). In this antenna, switches are available which generate nine different vertical beam patterns, each with a distinct beam width and beam take-off angle. Only five of these combinations are very useful for purposes of international broadcasting, but they are very useful indeed.

For purposes of discussion of the operation of this antenna system, we at the VOA developed a specialized vocabulary. For operation of the antenna at a certain horizontal aperture, we refer to its "width"... for example, when the antenna is used for broadcasts with a 35° beam width by exciting only four horizontal stacks of radiators, we would say we are operating it "four wide". We refer to each distinct vertical excitation pattern as a "mode". For this, we specify the excitation of the vertical pairs, starting from the bottom, to the top pair. For example, a ++-- mode has the bottom and middle vertical dipole pair excited in phase, and the top pair excited in counterphase. A +00 mode has the

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[2] R. Wilensky, "High-Power, Broad-Bandwidth HF Dipole Curtain Antenna with Extensive Vertical and Azimuthal Beam Control", *I.E.E.E. Transactions on Broadcasting*, June 1988, vol. 34, no. 2, p. 201.

bottom pair excited, but the other two pair not excited. This antenna operated in the 4 wide + + 0 mode would have beam shape properties very similar to an *HRS 4/4/.5* antenna.

Operationally this antenna was successful. Its VSWR characteristics in general suffice for ordinary operation without undue transmitter stress. Its beam-forming switching, and the resultant beams are predictable, and usable. It has no apparent corona or heat problems.

There are, however, two new kinds of tradeoffs associated with this antenna. The first of these is in the area of maintainability, reliability and availability. In the olden days, an antenna was that "big thing in the back pasture" which always seemed to work. If it didn't, you looked out the back door to see if it was still standing. Maintenance was usually limited to greasing its guys every once in a long while, and cleaning its insulators when the local volcano blew up.

But, this new antenna has a lot of moving parts in the form of 196 two-position transmission line switches, and 12 giant three-deck 7-position rotary switches. We bought our operational flexibility with movable switches but, at the same time, introduced maintenance and repair requirements.

The second tradeoff associated with this antenna is really a new variation of the old problem. In antenna layouts using the old technology, one might not use the entire set of antennas all or even much of the time. In this antenna, we don't use all the antenna aperture all the time. This is a consequence of the manner in which the various beams are formed, as described above.

For this particular antenna, the extreme nature of the problem comes about from its large horizontal aperture, required for its narrowest horizontal beamwidth, 10 degrees. When we need 10 degrees, its good to have. But for the VOA, few distinct broadcast service areas are small enough to need so narrow a beamwidth. Typical language service examples of this requirement are Latvian, Lithuanian, and Estonian broadcasts from anywhere. Normally, VOA broadcast service areas tend to be wider, say from 30 to 70 degrees.

Fortunately, the problem was easily converted to a non-problem. After the contractor settled on a specific design approach, we requested that he give us input ports, and other facilities, such that we could eventually use separate 2 dipole and 4 dipole wide sections of the antenna as separate antennas. Using these input ports, we subsequently added four new transmission lines which connect transmitters to these sections of the antenna. The end result is that we have a large, multipurpose antenna which can generate super-narrow beams for single transmissions, and which can be used for as many a 6 separate transmissions if the horizontal beamwidth requirements for each transmission are not less than 35 degrees at the center frequency. Other transmission combinations involving lesser numbers of transmissions are possible.

One more intensely practical and significant in-house VOA addition has been made to this antenna system. This was the simple addition of phase sensing and measuring equipment on each of the transmission lines feeding separate 4-wide sections of the antenna. This, together with phase lock and phase control of the transmitters powering the antenna, allows us to use it as an elementary phased array.

As a phased array powered by multiple transmitters, it is a fine and useful broadcasting tool. When the transmitters are properly cophased and the antenna properly configured, this antenna can form superpower beams which are nearly 36 dB stronger than that available from a single, identical transmitter operating into an isotropic antenna. These beams are sufficiently powerful that they have the potential for affecting the performance of the ionosphere itself. In fact, they are used for testing this hypothesis by the Air Force Geophysical Laboratory who partially defrayed the cost of the additional transmission lines and phase monitoring and control apparatus.

There is also a very practical broadcast use for antennas with superpower beam capabilities. For example, when the VOA lost the use of its Monrovia relay station due to civil war in Liberia, we were able to use this antenna, excited by two 250 kW transmitters, to transmit a very effective signal into South Africa, over a path of more than 16,000 km.

But, perhaps more importantly, this concept may be applied across the board for VOA systems planners, with resultant cost savings. Simply stated, for those few service areas which require specially tailored and high-powered beams, one does not have to build special antennas with wide apertures. It suffices to provide antenna field layouts with antennas with common characteristics and boresights, closely situated next to each other.

During ordinary broadcasts these antennas may be used for separate broadcasts. For those occasional narrow/superpower beam requirements, they may be used together, with the addition of low-cost control apparatus, as a cophased array. At VOA stations, it is common to have a number of identical antennas with identical boresights, so this is an elegant and very low cost solution to a troublesome problem.

4. FORMULATION OF THE PRESENT VOA ANTENNA REQUIREMENTS

The above-described experiences with the Delano antenna, together with associated analyses and investigations firmly established that the technology employed in this developmental antenna had the highest cost/benefit potential for proper specifications for antennas for new and refurbished stations within the VOA system. It was clear that the world market industry had the technical capability to design and produce antennas based on this technology. It also was clear that the pattern production capabilities of such beam switching antennas were sufficiently good approximations of the desired beam formations as to have advantageous cost/benefit tradeoffs.

As the final step in our formulation of antenna specifications and layouts for future transmitting stations, we performed a broadly-based cost/benefit tradeoff analysis, taking into account the limitations of the technology, its systems performance, and cost. In the course of this analysis, it became apparent that for the VOA's purposes, substantial performance advantages were accrued from fairly elementary approximations to refined beam formulations in terms of take-off angle, vertical and horizontal beam widths, and azimuthal slews.

What we arrived at was the conclusion that for VOA purposes, the vertical antenna beam configurations from 2 dipole high, 4 dipole high, and 6 dipole high antennas, with .5 wavelength height above ground, would suffice to meet the great majority of ionospheric requirements; beam widths generated by 2 and 4 dipole wide antennas would cover most service areas; and that slews of +/- 24°, in increments of 8° to 12°, would provide the required azimuthal coverage capability.

As all these beams are handily generated by an appropriately specified *HRS 4/6/.5* beam switching antenna, that antenna was defined as the most complex antenna building block required for VOA systems planning. An overview of its basic performance parameters of such an antenna is presented in Table 3.

The antenna described in Table 3 is to be implemented in pairs, with suitably arranged frequency ranges. The low-range antenna is to cover the nominal frequency range from 6 to 12 MHz., and the high-range antenna from 11 to 22 MHz. The one-band overlap at the high end of the low-range antenna, and the low end of the high-range antenna is a fundamental aspect of the system design using these antennas.

In practice, we operate these antennas by directing them at our service area, with a beam width which will provide the required horizontal coverage, and we launch the beam upward with the right beam shape parameters and frequency so that it comes down where we want it. That is to say, vertical beams and frequency band selection are used to meet the demands of the ionosphere; horizontal beam width and azimuthal beam pointing direction (boresights and slews) are used to provide appropriate coverage of the service area.

In somewhat over-simplified terms, this implies that the horizontal beam width must stay pretty much the same at any operating frequency, and that the correct vertical beam shapes will be available at the required operating frequency. The first condition, for the very generally applicable horizontal beam width of 35° is reasonably met by the high-low pair of beam switching antennas. This performance is obtained in the following way. The low-range antenna is set for 4-wide operation. At the lowest operating frequency, the HBW is 47°. At increasing operational frequency, the HBW decreases, until at the 9 MHz. band (31m), it becomes 32°. At 12 MHz. the HBW would narrow to 25°; if this is unacceptable, then operation is transferred to the high-range antenna, set to 2-wide operation. At 12 MHz. (25m), this has an HBW of 77°, which more than covers the desired area. Thus, by changing between antennas of the beam switching pair, and changing their beam parameters to suit the desired coverage area, the HF broadcasting system performance is stabilized, and signal delivery need not suffer from inadequate antenna coverage.

This performance may be contrasted with the performance of a similar pair of non-beam switching antennas, whose performance would be expressed by the parameters of Table 1. For a pair with

4-Wide + + + Mode			
f_n	0.7	1.0	1.4
Gain	20.3	23.0	25.0
HBW	47.4	34.6	25.4
VBW	16.8	9.6	6.9
TOA	9.3	6.0	4.7

2-Wide + + + Mode			
f_n	0.7	1.0	1.4
Gain	18.2	20.3	22.3
HBW	77.2	66.0	52.8
VBW	16.8	9.6	6.9
TOA	9.3	6.0	4.7

4-Wide + + 0 Mode			
f_n	0.7	1.0	1.4
Gain	18.8	21.4	23.6
HBW	48.0	34.8	25.6
VBW	19.9	13.9	9.9
TOA	13.4	9.5	6.8

2-Wide + + 0 Mode			
f_n	0.7	1.0	1.4
Gain	16.8	18.8	20.7
HBW	78.0	66.4	54.0
VBW	19.9	13.9	9.9
TOA	13.4	9.5	6.8

4-Wide + 00 Mode			
f_n	0.7	1.0	1.4
Gain	16.3	19.0	21.4
HBW	50.8	36.0	26.0
VBW	36.7	25.2	17.9
TOA	23.7	17.3	12.7

2-Wide + 00 Mode			
f_n	0.7	1.0	1.4
Gain	14.3	16.4	18.5
HBW	81.4	68.0	54.6
VBW	36.7	25.2	17.9
TOA	23.7	17.3	12.7

$$f_n = \frac{\text{Operating Frequency}}{\text{Center Frequency}}$$

Table 3. BEAM PERFORMANCE

Table of the main beam performance of an *HRS 4/6/.5* beam switching antenna as a function of normalized frequency. The left side of the table demonstrates the 4-wide operation of the antenna. The right side of the table shows the 2-wide operation of the antenna. Gains are in dB above an isotrope, and beamwidths and Take-Off Angles are in degrees. Antennas with these specifications are implemented in pairs, of which the low-frequency antenna has a nominal range of 6-12 MHz., and a center frequency of about 8.5 MHz., and the high frequency antenna a range of 12 - 24 MHz., with a center frequency of 16.9 MHz.

operational ranges identical to the antennas described above, the HBW's fall to that desired at bands near the mid-frequency range of the antennas. Clearly then, at operational frequencies above the center frequency of both antennas, a coverage deficit would result.

With respect to vertical beam performance, examination of Table 3 shows that at all operating frequencies there is a broad range of vertical take-off angles, suitable to broadcasts in a variety of radial ranges from 900 km to more than 10,000 km. With these antennas, we do not have independent TOA and vertical beamwidth control. However, the tendency of these antennas to widen their vertical beamwidths with increasing TOA conveniently conforms to usual ionospheric and broadcast service area requirements. Thus, the availability of these modes meets the majority of VOA vertical beam requirements. The performance of non-beam switching antennas, as is apparent from Table 1, is clearly inadequate to meet ionospheric beam requirements for broadcasts of varying radial range.

It is plain from the above discussion that in many cases, these antennas will illuminate areas outside of the required service area. However, the usual alternative is the use of an antenna which always has a beam much larger than the service area. The VOA specified antennas provide the required service with minimal spillover.

A legitimate final question may be made with respect to areas which do not conform to the 35° HBW angular range so exemplified in the above section. The answer is simple. These antennas and their capabilities are built into the overall world network coverage planning of the VOA. Thus, in our network planning, we essentially carved up the world's languages into the required 35° angular sectors. Our stations, their layouts, and their specifications provide antennas to suit. Very few of our requirements exceed this basic angular sector requirement and, if they do, it is because of the ability of the antennas to provide the required service.

5. CONCLUSION

When we started this work about ten years ago, we knew we needed a lot of antennas. Our analyses revealed that the older technologies, and the existing state-of-the-art antennas both would exceed our expectations for funding and land availability. We used the developmental antenna procurement to test and extend the marketplace for antennas. Our experiences and experiments with this antenna resulted in a formulation for antennas for our future work, and in a more mature antenna industry capability for supply of such antennas.

At the end of it all, the VOA was able to formulate a specification for antennas which will provide admirable service for our broadcasts; the Jack R. Poppele Memorial Transmitting Station has a very fine antenna; the taxpayers are saved a lot of money; and a good time was had by all.

ADDENDUM

In his paper published in the May 1992 issue of The Proceedings of The Radio Club of America, *Lt. General Walter E. Lotz, Jr., Ph.D. (F) gave a brief history of the operations of the Voice of America. Because parts of the technical description will augment the information in Dr. Everett's paper, we are including those parts herein:* (Ed.)

THE VOA TODAY

The headquarters of the VOA is located, appropriately, in *Independence Avenue,* in Washington. Included in its facilities are an ultramodern news room for collecting, sorting and translating the news; 29 studios staffed by native-speaking announcers/newscasters; and a Master Control Center which routes the program material to the transmitting stations, and designates the frequency and power to be used.

There are 15 VOA transmitter stations; four are within the United States. These are located at Delano, CA., Bethany, OH., Greenville, NC., and Marathon, FL. All of these stations broadcast to overseas target areas. Program material is transmitted from Washington to the Greenville station which distributes the material to the other transmitter stations over a satellite network. Greenville has the largest antenna field occupying three sites with the combined area of nearly ten square miles or about half the area of Manhattan Island.

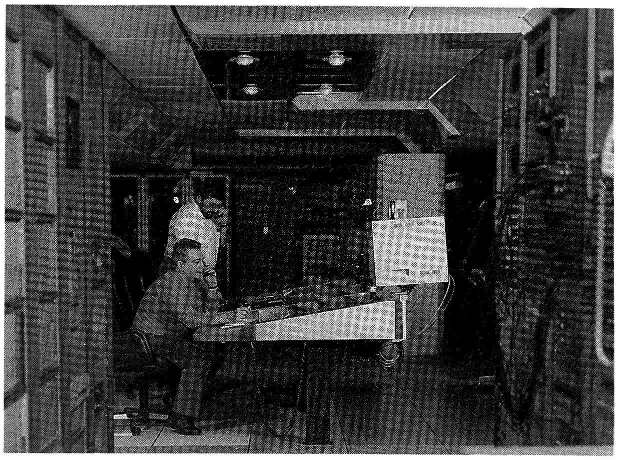
The VOA operates eleven overseas transmitters in Central America, Europe, Africa, and Asia. Last June, the station in the Philippines was showered with volcanic ash during Mount Pinatuba's eruption. Although it still is operating, a second eruption or a change in the attitude of the Philippine Government could cause its permanent loss.

The Voice operates medium-frequency transmitters at a number of sites in close proximity to target areas. For example, a 50 kW medium-wave radio station at Marathon beams Spanish language programs to Cuba. Television programs also are broadcast from this station. For the signals to reach Cuba, the transmitter and its antenna are elevated on an aerostat -- a large balloon tethered to the station.

THE RADIO SPECTRUM

The technical objective of the VOA is to provide intelligible voice signals throughout areas that are typically 3,000 km wide, 1,500 km deep, and 3,000

The VOA Newsroom



The VOA Master Control in Washington, DC

km from the transmitter site. This requires carefully selected frequencies. The VOA has developed its own frequency prediction model, VOACAP. It is based on IONCAP which commonly is used in point-to-point service. Because the VOA is interested in satisfactory signals over a large area, computer runs of IONCAP are made along successive radii from the transmitter station until the total area within the range of the station is covered. There may be several thousand radii in the iteration requiring about 24 hours of time on a VAX 8250.

Until May 1987, the signals of the VOA were jammed by the Soviets, their satellite nations, and China. Even in today's jam-free European environment, the VOA's high-frequency broadcasts are significantly degraded by interference. In the late 1960s, the number of 500 kw broadcast transmitters and the number of countries using them more than quadrupled. Today, frequency piracy and signals from unlicensed sources are everyday occurrences. For the transmissions to reach its foreign listeners, the VOA have high-gain antennas.

ANTENNAS

At the VOA transmitter station in Delano, California, TCI Corporation, Technology for Communications International, has constructed for the Voice an electronically-steerable high-frequency antenna, capitalizing on technology used on many Earth satellites -- phased-array dipoles.

This array delivers a high-frequency beam capable of being steered vertically from 4 to 20 degrees above the horizon, and azmuthally from +30 to -30 degrees relative to its boresight. The antenna, when fed by three 500 kw co-phased transmitters provides an effective radiated power of 2.3 billion watts. The installation consists of two separate radiating structures, one covering 6 to 12 MHz and the other 13 to 26 MHz. The low-frequency structure consists of three adjacent sections, each section consisting of 24 dipoles arranged 4 wide and 6 high. The 72 dipoles in the structure are fed through computer-driven switches that control the power and phase of the radio energy fed each of them.

The structure requires four towers 410 feet high spaced equally over a span of 850 feet. The adjacent upper-sideband structure is similar but half the size of the lower-band structure. Because of the wavelength of the high frequencies, the physical dimensions of the VOA array are of the orders of magnitude greater than those in orbit. The whole antenna is a quarter-of-a-mile long and requires towers that are up to 410 feet high. Impractical as these antennas may be for Amateur radio operations, they give the VOA great flexibility in laying down maximum signal strength into targets that arise in unpredictable areas throughout the world.

FESSENDEN AND THE BIRTH OF RADIOTELEPHONY*

by L. A. Geddes, ME, PhD, FACC
Showalter Distinguished Professor Emeritus of Bioengineering
Purdue University

"What do professors do in their spare time?" is a question frequently asked by administrators, alumni -- and the public.

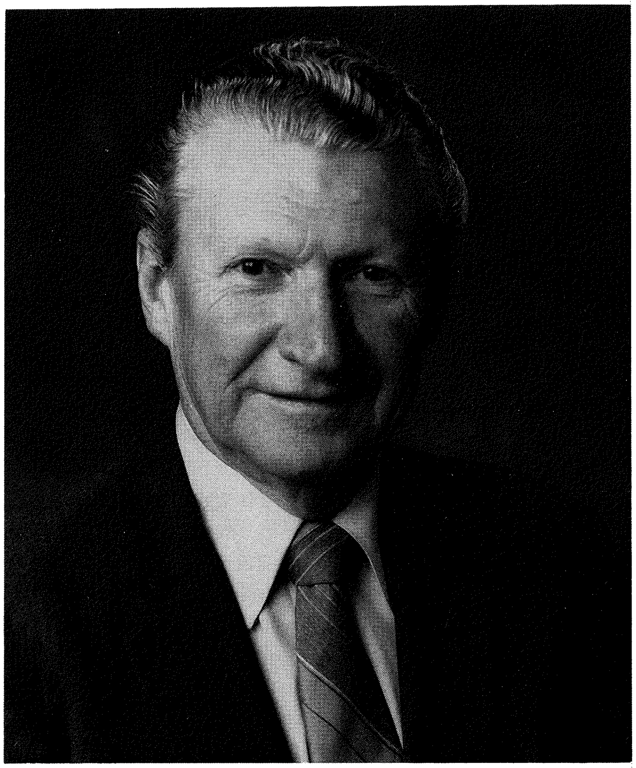
The answer is a long one. In addition to teaching, composing and grading exams, counseling students and recruiting them, seeking funds for research, committee duties, public-service activities, writing papers and presenting them at scientific meetings, professors make time to pursue their curiosity about nature and its laws.

Perhaps one of the best to perform all of these duties was Reginald Aubrey Fessenden, third head and the first professor of Electrical Engineering at Purdue (1892-93). Despite his many professional obligations, being head of the EE School and creating the first Purdue course in electrical machinery, Fessenden found time to start experiments at Purdue that led directly to wireless transmission of the human voice and music-radio as we know it today!

Although he remained at Purdue for only one year, his talent as a teacher and experimenter, and his later success as an inventor established him as a major figure in EE history. Reciprocally, Fessenden felt indebted to the University that gave him his start. In gratitude, his estate provided fellowships for students in EE at Purdue.

Fessenden had two heroes: Alexander Graham Bell and Thomas Alva Edison. From an uncle, he had heard an account of Bell's demonstration of the telephone in nearby Brantford, Ontario, which had profound influence on his life.

Edison was the acclaimed inventor of the day and Fessenden was determined to become his assistant, which he did -- although the road was by no means direct. It was while working with Edison that Fessenden decided to do what Bell had done, but without wires.



Professor L. A. Geddes, ME, PhD, FACC

The idea of transmitting the human voice by wireless originated during a conversation with Kennelly, Edison's scientific director. "You will talk into a microphone, say one like Bell's," Fessenden said, "then turn your voice over to some sort of modulator...Suppose we call the modulator a kind of sculptor...(that) can carve the voice sound onto these electromagnetic (Hertzian) waves; let's call them carrier waves because they will carry the sound." Fortunately, the many obstacles that Kennelly brought up did not discourage Fessenden.

The telegraph had been in use for about half a century and telephone service was expanding. The Atlantic telegraph cable had been laid and carried messages at the rate of a few words per minute. Marconi had not yet sent his wireless code message across the Atlantic, but Hertz had demonstrated the transmission of electromagnetic waves over varying distances and through non-metallic solid objects.

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*Excerpted from *A Century of Progress: The History of Electrical Engineering at Purdue (1888 - 1988)* by L.A. Geddes, copyright 1988, by Purdue Research Foundation, West Lafayette, Indiana 47907. Reprinted with permission.

All of these events had occurred before Fessenden came to Purdue to combine mathematics and electricity. He had been trained as a mathematics teacher in Ontario, Canada, and had taught in Bermuda; he also had learned electricity from Edison, his former employer.

One of the factors that attracted Fessenden to Purdue was President Smart's statement, "You have a free hand at purchasing equipment." Purdue provided Fessenden the opportunity he sought -- a teaching position, a well-equipped laboratory, and the freedom to get on with his idea of transmitting the human voice without wires.

Fessenden proved to be a gifted teacher who made the complex seem simple. Students flocked to him and worked everywhere in his laboratory in the old EE Building, transmitting wireless messages from one end of the laboratory to the other. Fessenden integrated the results of these experiments into the design of sending-end and receiving-end apparatus (transmitter and receiver).

Unfortunately for Purdue, George Westinghouse enticed Fessenden to the University of Pittsburgh where the chair of electrical engineering was vacant. The chair, the financial support of Westinghouse, and the promised resources of the Westinghouse Company made it impossible for Fessenden to remain at Purdue; although the Purdue Trustees made valiant efforts to retain him. It was not generally known that Westinghouse's interest in Fessenden lay in Fessenden's ownership of a patent on an electric light bulb which could give Edison's lamp stiff competition.

At Pittsburgh, Fessenden developed his designs for a detector (coherer) for Hertzian (radio) waves. One model was a cylinder of iron filings, and the other was a platinum needle dipping into sulfuric acid. The former was a solid state rectifier -- the latter an electrolytic rectifier which, surprisingly enough, was better -- so he patented it, as he did some 300 other inventions.

Despite the material support at Pittsburgh, the academic environment did not suit Fessenden's taste and he soon departed. However, he did not lose sight of his goal to transmit the human voice and music by wireless.

The next step in pursuit of this goal was to convince the U.S. Weather Bureau to create wireless telegraphy stations to transmit weather reports. He succeeded in this goal and established the first station on Cobb Island in the Potomac and the second at Roanoke, Virginia. During off-hours, Fessenden experimented with various methods of "sculpturing the waves," i.e., applying modulation to the radio-frequency carrier. He succeeded sometime in December 1900.

According to his wife, he did not have an easy time with his first transmission and reception of the human voice over a one-mile path. Time was his enemy. On December 12, 1907, Marconi had sent three dots (the letter S in Morse code) by wireless from England to Newfoundland where it was received. It is important to recognize that Marconi's transmission was unidirectional and in Morse code.

It is also important to note that when Marconi transmitted his wireless telegraph message, Fessenden had already developed a technique for sending multiple Morse code messages over a single radio-frequency carrier. He did this by applying tones of different frequencies to the carrier and keying the individual tones with the Morse code. This technique, for which Fessenden was awarded a U.S. patent in 1903, was the logical predecessor to applying the human voice to a radio frequency carrier

While employed at the Weather Bureau, Fessenden had been told that he could retain all of his inventions and discoveries. However, his supervisor recognized that voice transmission by wireless was practical and that it would be valuable in the future. Thus, in August 1902, when long-distance wireless voice transmission was in sight, Fessenden's superior demanded inclusion in all of Fessenden's patent applications.

Fessenden could not accept this demand; although he knew that if he refused he would lose access to the the equipment that he needed to continue his experiments. Nevertheless, he refused and promptly resigned.

He then sought financial support to continue his research and, ultimately, secured it from two businessmen, Givens and Walker, of Pittsburgh. In return for sharing in his patents, they created the National Electric Signaling Company which was dedicated to wireless telegraphy among the stations that Fessenden would build in New York, Philadelphia, and Washington, D.C. Wireless telegraphy was not Fessenden's goal, but association with it again gave him the opportunity for experimentation without a capital investment.

While these events were occurring, an Ontario commission hired Fessenden to draw up plans for a power station at Niagara Falls. In addition to his other duties, he completed the study and submitted his plan. It was so far reaching that the conservatives on the commission thought it too radical -- but Fessenden had attracted the attention of influential Canadians, and he vowed to do something for his native land.

He proposed the creation of a dependable two-way, transatlantic wireless telegraphic system. The plan was accepted and, on July 20, 1906, an Act of Parliament created the Wireless Company of Canada. Its mission was to set up stations on both sides of the Atlantic for two-way communication by wireless telegraphy. However, before the plan could be implemented, the rights for this service were awarded to the Marconi Company.

Fessenden, meanwhile, was still employed by Givens and Walker who also desired to create two-way, transatlantic telegraphy, and directed Fessenden to develop the necessary equipment. The sites chosen for the transatlantic stations were Brant Rock, Massachusetts, a two-hour journey by train from Boston, and Machrihanish, Scotland. Between them lay 3,000 miles of open ocean.

The sites were selected on the basis of the absence of obstructions and minimal coastal winds -- for the towers were to be about 400 feet high. Figure 1 illustrates Fessenden's Brant Rock station and antenna.

At the time, only two devices were available for generating high-frequency current: the spark gap, and the high-frequency alternator. The former could not generate the power needed. Fessenden commissioned the General Electric Company to develop a high-frequency alternator. Although such a device was delivered, its performance did not please Fessenden, so he rebuilt it to operate at a higher speed which generated a higher frequency. It was connected to the Brant Rock station to establish transatlantic telegraph service. Since the Scottish station had no alternator as yet, it was used as a receiving station. When the signal was received, the response was to be sent via the transatlantic cable and then relayed by telephone to Brant Rock. Fessenden was irritated by having to rely on wire confirmation of a wireless signal, but his use of this procedure saved many months.

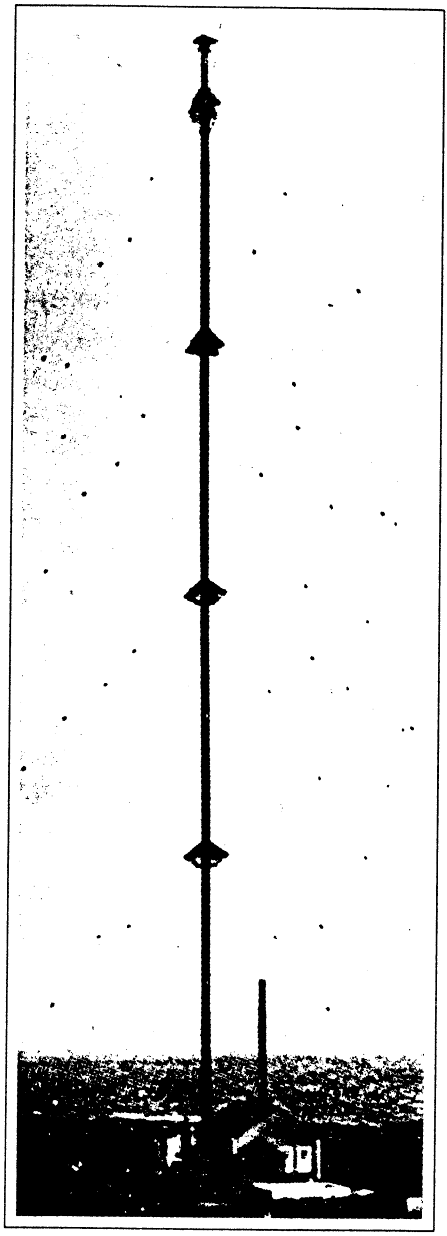


Figure 1.
The first radiotelephone station at Brant Rock, Massachusetts, created by Reginald A. Fessenden.

One-way telegraphic signaling to Scotland had begun. Soon, the telephone at Brant Rock rang and the relayed message was, "Getting you, Brant Rock, loud and clear." Shortly thereafter, a suitable high-frequency alternator was installed in the Scottish station and, beginning in Spring 1906, two-way transatlantic wireless telegraphic signals became a daily event.

There were, however, two more disasters on Fessenden's doorstep. The first occurred as summer approached. Reception was poorer, as predicted by Kennelly (who then was at Harvard), and seasonal change in the height of the ionosphere was about to defeat the whole plan. The second disaster was the destruction of the Scottish tower by unusually-high coastal winds.

Fessenden dealt with each event separately. To combat the first, he needed a higher power 100 kHz alternator, so he obtained a 1.5 kW machine.

Fessenden built a second experimental station at Plymouth, Massachusetts, about 11 miles distant. During off-hours, he used this station to test improvements in modulation and detection. While these tests were going on, he received a letter from Scotland in mid-November 1906 indicating that they had overheard these voice-test communications. The text of the letter matched, word-for-word, the entry in Fessenden's log of that day.

Meanwhile, the United Fruit Company had bought Fessenden's apparatus for receiving wireless telegraphy for the banana boats plying the Caribbean and South Atlantic. Fessenden knew then that he had to demonstrate that the human voice could be transmitted over a great distance without wires. Accordingly, he arranged a demonstration to be presented at the end of a routine wireless telegraphic communication with the United Fruit Company ships.

At 1:00 AM on December 24, 1906, Fessenden, Stein, and Fessenden's wife faced the asbestos-covered microphone at Brant Rock. First, the CQ-CQ-CQ general call to all stations was sent in Morse code. Then Fessenden stepped to the microphone and gave a short speech, after which an Edison phonograph playing Handel's *Largo* was broadcast. Fessenden then played *O Holy Night* on his violin and sang the last verse at the same time.

The others were supposed to sing along with him, but they could not. They may, perhaps, be recorded as the first persons to have "mike-fright", a condition that later was to plague so many performers.

Fessenden finally wished his listeners a Merry Christmas and promised a repeat performance on New Year's Eve. The performance was repeated and included vocals from his associates who had overcome their fear of the microphone. Mail soon was received from the United Fruit Company ships and from a number of other ships in the North and South Atlantic. Fessenden had reached his goal!

Radio broadcasting did not start immediately, although amateur communications did. Two events about to occur were needed to make wireless telephony practical and important. The first was the invention of the vacuum tube diode by J. A. Fleming (1904) in the United Kingdom, and the triode by Lee de Forest (1906) in the United States. Both made excellent detectors; the latter provided the much needed amplification and also the generation of clean high-frequency current. The second event was the out-break of World War I (1914 - 1918), which dramatically identified the need for rapid, long-distance wireless telegraphic and voice communication.

About two years after the cessation of hostilities (1918), evening radio broadcasting in the U.S. was started on an experimental basis. The broadcasts originated from station 8XK which later became KDKA (Westinghouse), Pittsburgh. Close to this time, in 1922, Purdue's radio station, WBAA, built by students and faculty of the EE School, went on the air as Indiana's first radio station. It is still on the air with the same call letters.

Fessenden's Asbestos-Covered Microphone

Asbestos is an excellent thermal, as well as electrical insulator. The bridge from wireless telegraphy to wireless telephony was the asbestos-covered microphone. Although the high-frequency alternator provided a clean, unmodulated carrier, it had to be modulated. There were no vacuum tubes at the time, but there was the carbon-granule telephone microphone developed by Edison (who did not believe in alternating current or, later, in radio).

The Edison microphone is nothing more than a capsule of carbon granules with one fixed and one movable electrode -- the latter firmly mounted to the microphone diagram. When the diaphragm vibrates in response to acoustic waves, the resistance varies accordingly. In his inimitable way, Fessenden had built a heavy-duty carbon-granule microphone capable of carrying high current (Figure 2).

The manner in which the microphone modulated the antenna current is perhaps surprising. The microphone was connected to the

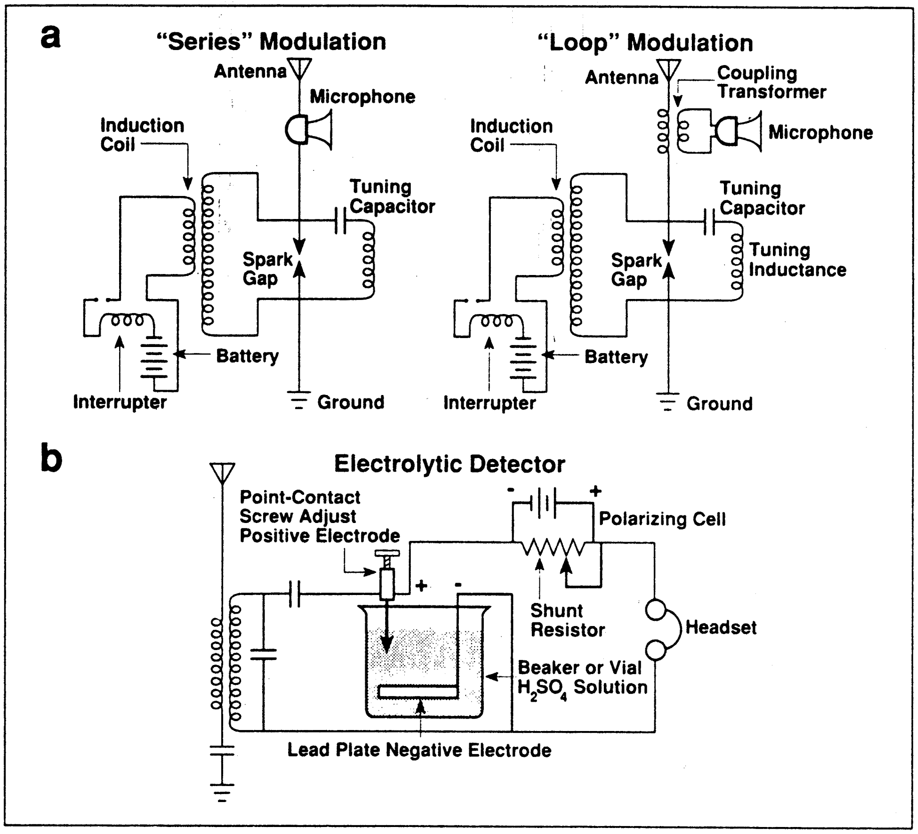


Figure 2.

Two early versions of Fessenden's spark-gap (interrupter) transmitter (a) and receiver (b), which employed an electrolytic rectifier (needle point electrode in a beaker of sulfuric acid).

Courtesy of Mr. George Elliott, Picton, Ontario, Canada

primary of a special air-core transformer, the secondary of which was in series with the antenna circuit. This microphone was capable of carrying 15 amperes for periods of two hours -- according to Fessenden.

Because the voice-induced resistance change (which modulated the antenna current) was small, the percentage modulation must also have been small; nonetheless it was enough to demonstrate wireless transmission of sound. The microphone current was substantial and it was in a circuit that was considerably above ground potential. Thus, the hot (thermally and electrically) microphone needed asbestos insulation to protect the performers.

POSTSCRIPT

If one of the roles of a university is to advance the careers of students and faculty, Purdue achieved both goals by giving Fessenden the opportunity to develop a new teaching program and provide research time for the creation of the essentials for wireless telephony.

Fessenden did not forget Purdue. After his death in 1932 and the death of his wife, Helen May Trott in 1980, the Fessenden-Trott Scholarships were established. On July 11, 1980, the Purdue School of Electrical Engineering was informed by the Bank of Bermuda (Fessenden's Trustee) that "it seemed appropriate that one of the first of these fellowships be offered to American students attending Purdue." The fellowships are awarded annually.

"WHO WAS FESSENDEN ?"

by **George Elliott, VE3GTF** (M)

"Who was Fessenden?" For those who have some knowledge of the technical discovery role played by Reginald Aubrey Fessenden (RAF) and for those encouraging public awareness of his place in history, it is gratifying to hear this question being asked more often. In this paper, we shall outline his life history and touch upon some of his accomplishments. He was granted over 200 U.S. patents: most of them applying to telecommunications. Chart No. 1 shows these inventions related to time. In Chart No. 1, we can see that RAF's patents were granted over a 45 year period and his peak inventive time began at the turn of the century and continued until around 1921.

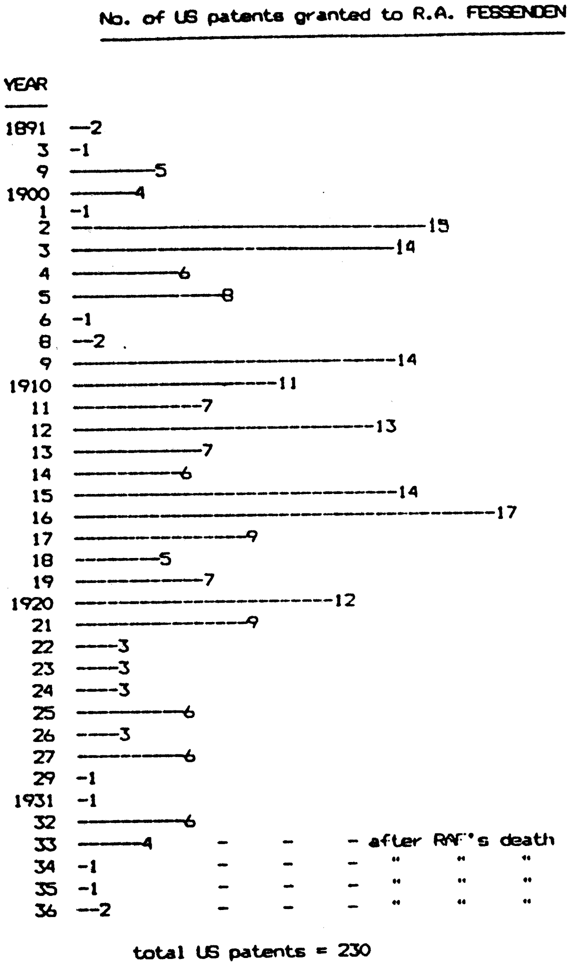
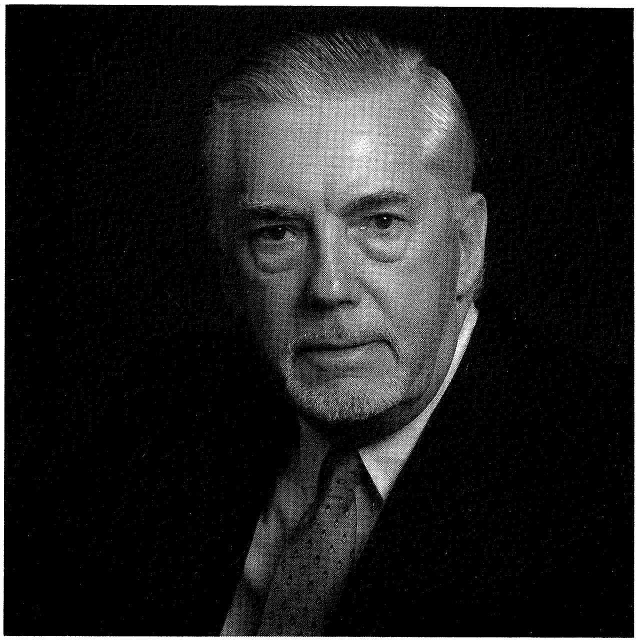


CHART No. 1



George Elliott, VE3GTF

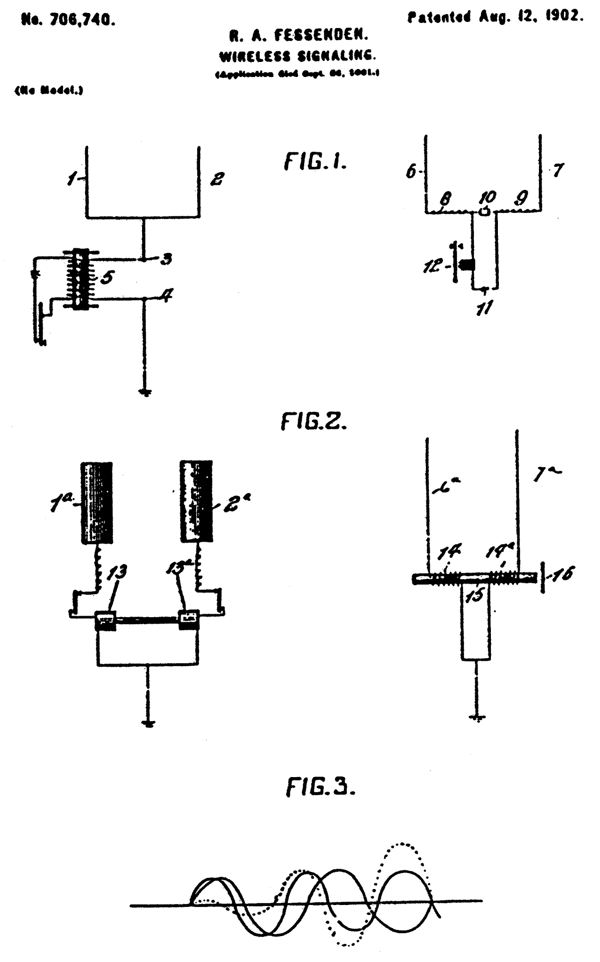
One of Fessenden's patents deserves special attention this year, since 12 August 1992 was the 90th anniversary of the granting of *U.S. No. 706740* which is RAF's patent on the "heterodyne principle". The Word heterodyne was coined by Fessenden and based upon the Greek words:

heteros -- meaning "other or difference".
dyne -- meaning "force".

Refer to Figures 1, 2, and 3

In the specification of U.S. No. 706740, RAF claims his wireless signaling system includes a CW transmitting station emitting two different frequencies at the same time. He further states that his system includes a receiver which combines the RF signals of two different frequencies into a usable, single, audio-range frequency.

Figure 1 shows his heterodyne transmitter and receiver in diagrammatic form. In Figure 2, two HF alternators, 13 and 13a are shown connected by a common drive shaft to permit rotation by a common drive source. The RF alternators that RAF anticipated were to be in accordance with those specified in his patent application U.S. 62301, filed 29 May 1901. Alternator 13a was to be adjusted for a frequency output about 3% greater than alternator



13. The two transmitting antennas are shown as 1a and 2a, with 2a being tuned to a frequency about 3% greater than antenna 1a.

In Figure 2, the two receiving antennas 6a and 7a of the heterodyne receiver are tuned to the same frequencies as were transmitting antennas 1a and 2a. Detail 16 is an earphone diaphragm with a common iron-core 15. The received signals of different frequencies appear as voltages, differing in time, across earphone coils 14 and 14a. The result is a "beat" frequency in the audible range, actuating diaphragm 16. Figure 2 represents Fessenden's CW transmitting and heterodyne receiving system in its simplest form.

In Figure 3, the solid sine waves illustrate the phase relationship between two incoming signals of different frequencies. The dotted sine wave is meant to show the resultant beat frequency. RAF's "heterodyne principle" patent was a brilliant conceptual discovery earning him a place in radio history even without his other inventions.


Kathryn Elliott

Professor Reginald Aubrey Fessenden
(1886 - 1932)

What did Fessenden look like and how did he act? To answer this particular question, we have selected the period of his life from 1903 to 1911 when he was part owner and General Manager of the National Electric Signaling Company (NESCO). Imagine a man distinctly different from his contemporaries, large in body and girth, well over six feet tall, with ginger-colored hair and beard, occasionally wearing a flowing black cape on his shoulders, topped with a seafarer's cap on his head.

With his razor-sharp mind, his attempts to try to command all situations, his use of his classical scholarship, his lack of patience with slow minds, his restlessness and probing vitality, he seemed to qualify as a character out of a Victorian novel. Chomping on his ever-present cigar, he would argue with one and all on any subject.

He was sometimes on the verge of poverty and, to continue his experiments, had to negotiate the purchase of railway tickets, lodging, clothes, supplies, etc. at discount prices. He wore the mantle of being an EE professor at two U.S. universities with great pride. Although his time as a faculty member lasted only eight years, he continued to be addressed as "Professor" by associates for the balance of his life.

Some of his friends and adversaries reaped financial benefits from his early inventions until the last few years of his life when pressure from lawsuits forced the Radio Trust (AT&T, GE, Westinghouse, RCA, et al.) to make some recompense. Through working as a consultant during his post-NESCO years, he earned substantial sums of money particularly for his sonar detection and earth-strata measuring patents. One may speculate on the notion that if a novelist created a book character like RAF, it would have been considered improbable.

While overly aggressive and perhaps domineering, Fessenden had some endearing qualities. Dr. Alexanderson, developer of GE's RF alternator said he was a charming and kind person, and was forthright in business matters. Some insight into RAF's tendency to exhibit compassion is revealed by his solicitude for his cat, "Mikums," especially at the time of its sickness and death.

He was successful in earning the loyalty of his associates and employees. This characteristic was well expressed in the following letter written in 1910 to Hay Walker, President of NESCO, by John L. Hogan. Later, Hogan (1889 - 1960) was to become a founder of the Institute of Radio Engineers (IRE), and then President in 1920. At the time of this letter, Hogan worked for RAF and NESCO as an on-site telegraph superintendent for NESCO's wireless station at Brant Rock, Massachusetts. Hogan's letter is quoted in its entirety:

Dec. 30, 1910

TO: HAY WALKER jr.
President - National Elect. Signaling Co.,
Farmer's Deposit Bank,
Pittsburgh, Pa.

"Dear Sir:

"On arriving at Brant Rock on the evening of December 28 Mr. Kelman brought with him 2 men who were introduced about the plant as additions to the construction force.

"On the afternoon of December 29 Mr. Kelman produced a typewritten letter dated December 24, alleged to be signed by you, stating all the company records should be shipped to Pittsburgh. He proceeded to execute this order in a very ungentlemanly manner and the records were taken from the main office to the construction office and packed in cases.

"At 8 o'clock last evening several of us called at the office and learned that Prof. Fessenden, our General Manager, had just ordered by telephone that no records should be shipped from the plant. We found that Mr. Kelman had made up ten packing cases of goods and secretly, under cover of the darkness, carried 6 of these cases (containing company records) off the plant of the Company, but had left the 4 remaining boxes, which were found to be dummies, and not to contain anything of value, in the construction office, with the evident purpose of conveying to anyone looking into the office that records had not been shipped to Pittsburgh.

"On account of the later Company order, issued by the General Manager December 29 to the effect that no records should be shipped from the Company's plant, we prepared to enforce this order.

"Because of the suspicious nature of Mr. Kelman's activities early in the evening, we deemed it advisable to anticipate trouble and therefore were sworn in as special policemen for the duty of safeguarding the property of National Electric Signaling Company.

"We then proceeded to the place where the boxes containing the records had been hidden, and waited a short time until the team arrived which had been supplied by Mr. Thomas. The team was obtained from Mr. Thomas by Mr. Weagent under the false pretense of wishing to haul some machinery away for a test, without Professor Fessenden's knowledge until after the machinery had been tested.

"Mr. Kelman aided by Messrs. Weagent, Gubing, Burns and the two "construction men" who were later found to be armed detectives, attempted to have the boxes containing the Company records placed aboard the truck and carted away. We explained to Mr. Kelman that Professor Fessenden had given orders to the contrary, but Mr. Kelman would not listen to reason. We then, with the authority invested in us as special policemen, had all the records taken back to the construction office and left there, considering that by so doing we were taking the best steps to protect the interests of the Company.

"Mr. Kelman naturally objected strongly to this procedure and showed the order dated December 24 which he claimed was signed by yourself. As most of the employees did not know your personal signature and the letter was typewritten on Company paper exactly like that in common use on the plant, it was considered advisable in view of Mr. Kelman's extremely suspicious actions, to follow the course of action pursued.

"The need for this action was further emphasized by our having a Company order more recent than that which Mr. Kelman produced, stating that Mr. Kelman had been dropped from the Company's payroll.

"We beg to respectfully call your attention to the following facts:

1: We have received no orders from the Company to the effect that Mr. Kelman has any authority other than that as Superintendent of Construction.

2: The 4 employees who assisted Mr. Kelman in the surreptitious removal of the Company records were practically certain of being dismissed for inefficient service.

3: Mr. Kelman entered the employ of the Company about a year ago with absolutely no knowledge of wireless telegraphy and with very little experience of any sort. His absolute unfitness as a director of design of the apparatus was demonstrated in the first few weeks of his work at Brant Rock, and our experimental engineers assisted him in every possible way and so made his deficiencies less apparent. In spite of his year's work he today is not acquainted with the most elementary technical knowledge, and in fact some of his statements with respect to the design of the apparatus are standing jokes among the Company engineers. Quite aside from his lack of technical experience, association with him for a year has proved him to be a man with whom it is absolutely impossible for us to work in harmony.

4: This letter is written entirely without the knowledge of Professor Fessenden and is being sent away from the plant before he returns.

"We are sending this merely to present our reasons for following the course of action outlined above."

Very respectfully,

J.L. Hogan jr. (signature)
(plus 9 other signatures)

END of LETTER.
****

There is little doubt that Kelman was carrying out orders from NESCO. At that point in time, Givens and Walker, the majority stockholders in NESCO, were in the process of discharging Fessenden from the Company. Hogan knew that RAF's life work was consolidated in the Brant Rock field office records. From NESCO's viewpoint the security of those files was important. However, it is curious that instead of being discharged by NESCO for stopping the removal of RAF's records, Hogan was appointed the NESCO Technical Manager by Givens and Walker. While Hogan's 1910 letter could be considered a script outline for a TV scene, it is hardly singular in Fessenden's total career. Uncommon events appeared to occur in Professor R.A. Fessenden's life that miss most of us.

At the time Fessenden was born, on 6 October 1866, his father was a Church of England minister, stationed at East Bolton in the Eastern Townships of the Province of Quebec, Canada. The actual birthplace was his grandmother's house in the nearby town of Knowlton, Quebec. The house still stands but is no longer in the family name. The Fessendens emigrated from England to Cambridge, Massachusetts, in 1628. RAF's father, Elisha, was born in Armada, Michigan, eventually graduating from McGill University in Montreal. He then became a divinity student at Bishop's University in Lennoxville, Quebec where he graduated as an ordained minister in 1884.

Prior to 1867, the Province of Quebec was called, first, Lower Canada, and then Canada East. For reader recognition purposes, we have used the name Quebec throughout this paper. The present Province of Quebec was called Lower Canada from 1791 to 1840. From 1840 to 1867, that province was called Canada East, and then became the present Province of Quebec in 1867. These name changes reflect the long-term differences between what is called by the Canadian Government: the Founding Peoples -- the French and the English. The on-going Canadian constitutional change debate may add a third Founding People -- the Aboriginals -- who predated the English and French by some 10,000 continuous years of occupation.

RAF's mother was a Trenholme whose family arrived from England in the early 1800's and founded the Quebec village of Trenholmville (now named Trenholm). RAF's maternal grandfather, Edward, was an inventor who included in his successes the grain elevator, a type of grain cooler and a railway snowplow.

From his posting at the Church of England at East Bolton, RAF's father was transferred in 1871 to a church in Fergus, Ontario (north of Guelph). RAF was five years old at the time. The parsonage house there still stands and is now a private dwelling. Further transfers followed, first to Niagara Falls, Ontario, and then to Chippewa, Ontario in 1876. At the age of eleven, in 1877, Fessenden entered Trinity College in Port Hope (on the shores of Lake Ontario, east of Toronto). This was a high-level institution run along the lines of a British "public" school, emphasizing a curriculum based on the classics and mathematics. This school still flourishes today in Port Hope.

He left Trinity in 1879 at the age of 13, too young to enter Bishop's University. For about a year, he went to work in various clerical positions at the Woodstock, Ontario branch of the Imperial Bank (now The Canadian Imperial Bank of Commerce). He returned for two years, to Trinity College passing near the top of his class in the Honours Examinations. He entered into residence at Bishop's University in Lennoxville, Quebec during January 1885 at 19 years of age. He had won a mathematical mastership which involved teaching mathematics, Greek and French to younger scholars, as well as attending regular college classes. In a few months, he felt constrained in his desire to progress at a quicker pace and left Bishop's in June 1885, at the age of 19 years. He did not earn a degree. He never again was a student at any school.

Fessenden received an offer of the principalship of the Whitney Institute in Bermuda which he immediately accepted; taking up residence there during the Summer of 1885. While in Bermuda, RAF met his future wife, Helen Trott.

Early in 1886, he reached the conclusion that his future, if it was to include discovery of technical innovations and if it was also to include marriage, required his emigration to the United States and then, hopefully, to work for Thomas Edison. This way, he could be brought to a personal high-technical level and earn a living at the same time.

RAF entered the United States in 1886 and, since he was under 21 years of age and his father had been an American, he was able to choose at that time between remaining a Canadian or becoming an instant U.S. citizen. He decided on the latter and he remained a citizen of the U.S. for the rest of his life.

In 1886, Fessenden obtained a position with the Edison Machine Works, based in Schenectady, New York. His job was that of Assistant Line Tester , and he was assigned to DC mains-laying work initially in New York City in an area which included Madison and Fifth Avenues. In December,1886, his dream came true when Edison assigned him to be one of his assistants at his new Edison Laboratory, at Orange, New Jersey.

Soon, RAF became Edison's Chief Chemist, directed to find improved insulating materials for wire coverings. One of his co-workers at the Edison plant was Arthur Kennelly (1862 - 1939), later to be a co-discoverer of the Kennelly-Heaviside skip-distance layer and its effect on HF transmission. Later, the identification was changed to the 'D' and 'E' layers of the ionosphere. Dr. Kennelly went on to become a university professor at two institutions at the same time: Harvard - 1902 to 1936; and MIT - 1913 to 1924. Fessenden's only son, Reginald Kennelly Fessenden, was named after his good friend, Arthur Kennelly. Fessenden first became aware of the existence of radio waves while working for Edison. The Edison Laboratory at Orange, New Jersey maintained a good technical library which subscribed to most technical periodicals. Together, RAF and Kennelly would take advantage of the library particularly during 1888 - 1889, when the monumental reports about Hertz and his confirmation of the existence of radio waves as predicted by the Maxwell electromagnetic wave theories, appeared in print.

Fessenden became intrigued by the possibility of communication without wires and obtained tentative approval from Edison to begin experiments in wireless. We can say with some assurance that 1889 was the year that Fessenden became fully aware of the electromagnetic-wave-in-space phenomenon and the place was the Edison Laboratories.

Like our current year (1992), the year 1892 was bad for business. In a rapid string of events, Fessenden was released by Edison (Edison was unable to keep his promise re: wireless communication), and then he worked for Westinghouse and the Stanley-Kelly-Chesney Company. The business panic of 1892 continued and, when an offer of the Chair of Electrical Engineering at Purdue University (in West Lafayette, Indiana) materialized, RAF readily accepted.

At Purdue University, R.A. Fessenden occupied the Electrical Engineering Chair during 1892 - 1893. His assigned objective was to combine the teaching of mathematics and electricity. By this time, his mind had become fixed on the possibility of transmitting the human voice without wires and, at Purdue, he had the freedom to pursue that objective. Dr. L.A. Geddes, of Purdue, has advised that records indicate that RAF was a gifted teacher who made the complex seem simple. Students flocked to him and worked everywhere in the laboratory, transmitting Morse wireless messages from one end to the other. From these experiments, RAF developed designs for a wireless receiver and a transmitter.

An 1893 offer of the professorship of electrical engineering at the University of Pittsburgh enticed RAF away from Purdue despite the efforts of the trustees to convince him to stay in Indiana. George Westinghouse was responsible for this move having pressured the Pittsburgh trustees to make the offer. RAF was also given money by George Westinghouse and the promise of the use of the Westinghouse laboratories. Seemingly unknown to RAF, the main Westinghouse interest was Fessenden's ownership of patents on electric light bulb improvements that would assist in competing with General Electric. These lamp patents were RAF's U.S. No. 452494 of May 1891, and U.S. No. 453742 of June 1891.

During his stay at Pittsburgh, RAF continued his radio work concentrating on receiver detectors such as the coherer and the electrolytic detector. Eventually, RAF obtained a patent, U.S. No. 727331 of May 1903, covering his electrolytic detector. Fessenden called this device the "liquid barretter", coining this word from his classical language background. The term is a derivation from the French word "exchanger" inferring the change from AC to DC.

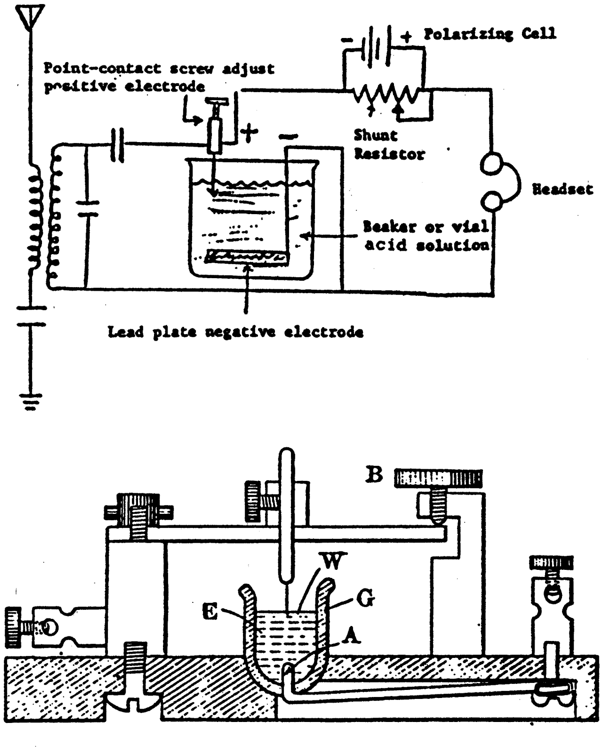


Figure 4. Fessenden's Liquid Barretter.

A cross-section of the barretter. It contained a platinum-coated Wollaston wire point-contact **W**, lightly touching a 20% solution of nitric acid.

This detector became the standard until the appearance of the galena crystal and the vacuum tube. To overcome the rolling motion-aboard-ship effect on the contents of the container G, RAF patented the sealed electrolytic detector, U.S. No. 793648 of December 1904. During the Russian/Japanese Naval War of 1904 - 1905, this shipboard electrolytic detector was employed -- believed to be the first time radio was used in actual sea combat.

One can form the opinion that RAF might not have completely understood why his barretter worked. In his early years, he rejected the opinion of his contemporaries that the action was electrolytic. Fessenden considered the action within this detector to be thermal. Despite its general acceptance, the electrolytic detector did not satisfy RAF since it could not copy the continuous wave (CW). Fessenden went on to develop a remedy for this: the heterodyne principle, previously detailed in this paper.

During 1899, Fessenden decided that the environment at the University of Pittsburgh, despite the adequate material support received, had become unattractive and he resigned to accept an offer from the U.S. Weather Bureau (USWB). He never returned to the academic life.

Spurred by reports of wireless communication success by Marconi and others in Europe and the United Kingdom, the United States Weather Bureau was directed in 1899 to "systematically investigate the various methods of electric communication without wires." At that time, the USWB was a division of the U.S. Department of Agriculture and an innovative, fast response, and reliable weather reporting system was being sought.

The task was to develop an American wireless system that would exceed the performance of both the British Marconi system and the German Arco-Slaby system. The USWB selected RAF to head this program because his work at the University of Pittsburgh had shown promise, and his paper *The Possibilities of Wireless Telegraphy* read before the AIEE (now the IEEE) in November 1899 received critical acclaim.

The USWB's letter offer of 4 January 1900 to make Professor Reginald Aubrey Fessenden a Special Agent in charge of developing radio communications suitable to the Bureau's needs, was accepted by RAF. He was to receive a salary, expenses, assigned personnel, facilities, and to own all patents secured by him as a result of his wireless work for the Bureau. The U.S. government had the right to use such patents for their own use without royalty payments. The USWB selected the North Carolina Outer Banks and the Virginia Capes as its designated wireless experimentation area. This region was prone to Atlantic weather damage including the loss of overhead landlines and under-water telephone cables. After proving out experimentally the RAF wireless system at Cobb Island, three stations were built: 1) near Manteo on Roanoke Island; 2) Buxton on Cape Hatteras Island; and 3) Cape Henry at the entrance to Chesapeake Bay.

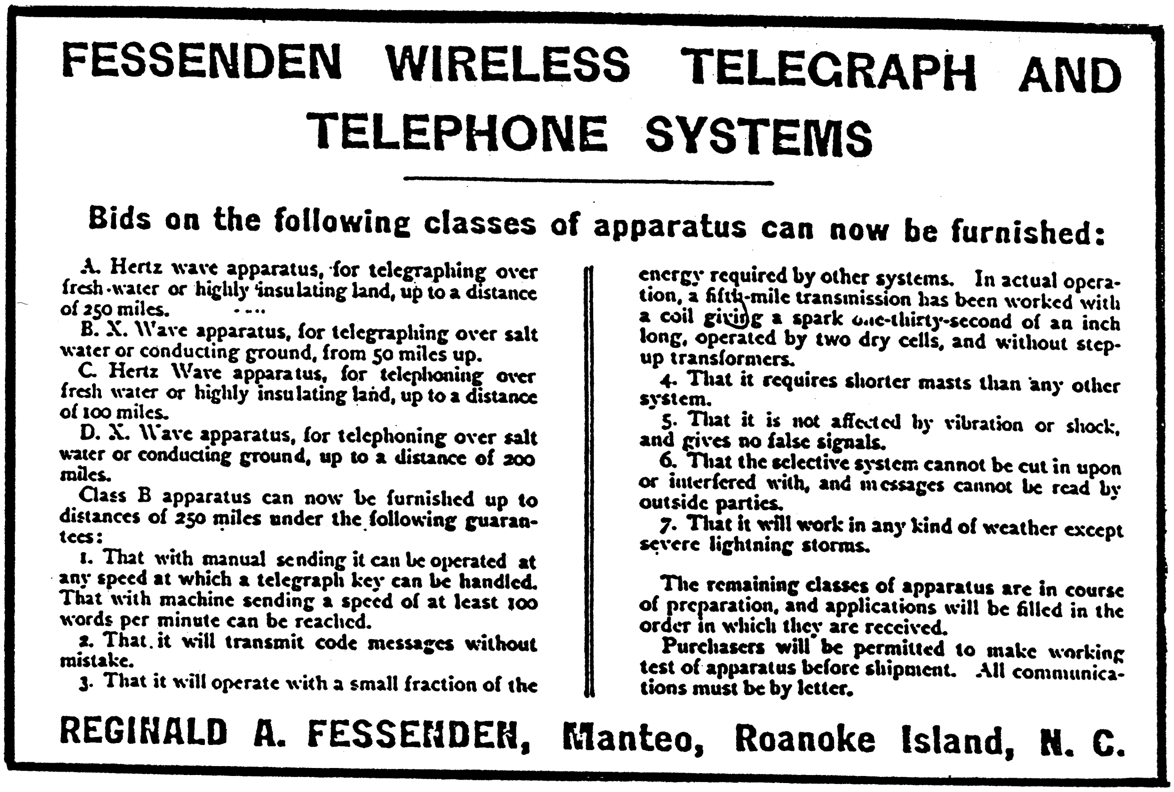
Fessenden's tenure with the USWB came to a sad ending during 1902 when the Chief of the USWB demanded an agreement-change wherein he, personally, would become the co-owner of RAF's patents. RAF complained to President Theodore Roosevelt, and was discharged by the USWB.

In his attempts to develop a market for his discoveries, RAF began taking orders for the supply of apparatus. See Chart 2 for his advertisement which appeared in a 1902 technical periodical.

Fessenden was one of the first to appreciate the value of receiver improvement through the refinement of resonant tuning circuits and detectors other than the coherer. His pioneering efforts to convince the industry to switch from "spark" to continuous wave (CW) transmission was ahead of its time.

During 1900 - 1902, Fessenden had created a new look for radio and stimulated such workers as de Forest, Fleming, et al. Also, he was one of the first radio pioneers who could conceptualize wireless as an AC phenomenon. This was a bit easier for RAF since he entered the radio age from the power engineering field rather than directly to wireless as had Marconi, et al. He had left the USWB with at least 35 very significant patents and patents- pending, intact. No other radio manufacturer could legally produce a complete, up-to-date wireless system without his permission.

The eight year and three month period beginning in November 1902 was the most turbulent time of Fessenden's career. Despite his dismissal from the U.S. Weather Bureau, the year 1902 appeared to offer a bright future. With his 35 patents, Fessenden was justified in believing technical fame and great riches awaited his bidding.



FESSENDEN WIRELESS TELEGRAPH AND TELEPHONE SYSTEMS

Bids on the following classes of apparatus can now be furnished:

A. Hertz wave apparatus, for telegraphing over fresh-water or highly insulating land, up to a distance of 250 miles.

B. X. Wave apparatus, for telegraphing over salt water or conducting ground, from 50 miles up.

C. Hertz Wave apparatus, for telephoning over fresh water or highly insulating land, up to a distance of 100 miles.

D. X. Wave apparatus, for telephoning over salt water or conducting ground, up to a distance of 200 miles.

Class B apparatus can now be furnished up to distances of 250 miles under the following guarantees:

1. That with manual sending it can be operated at any speed at which a telegraph key can be handled. That with machine sending a speed of at least 100 words per minute can be reached.
2. That it will transmit code messages without mistake.
3. That it will operate with a small fraction of the energy required by other systems. In actual operation, a fifty-mile transmission has been worked with a coil giving a spark one-thirty-second of an inch long, operated by two dry cells, and without step-up transformers.
4. That it requires shorter masts than any other system.
5. That it is not affected by vibration or shock, and gives no false signals.
6. That the selective system cannot be cut in upon or interfered with, and messages cannot be read by outside parties.
7. That it will work in any kind of weather except severe lightning storms.

The remaining classes of apparatus are in course of preparation, and applications will be filled in the order in which they are received.

Purchasers will be permitted to make working test of apparatus before shipment. All communications must be by letter.

REGINALD A. FESSENDEN, Manteo, Roanoke Island, N. C.

Chart 2. Fessenden Advertisement of Apparatus for Sale in *Electrical World and Engineer*, May 10, 1902

During 1902, he received an attractive offer from Queen and Company, a Philadelphia maker of U.S. Army Signal Corps apparatus, to form a new joint stock company to exploit his inventions. RAF was to own half of the stock plus receiving a payment of $200,000. Around the same time, a similar offer was made by Carnegie and Mellon interests: one-half of the new company's stock plus a payment of $250,000. RAF now had to make some decisions as to the best road to take toward his objective: the profitable development and manufacture of state-of-the-art radio equipment.

Fessenden sought decision making help as to which offer to accept, from a Pittsburgh lawyer named Darwin L. Wolcott who promptly convinced him to reject both propositions. Wolcott told Fessenden that he would get him more money from two of his friends. RAF accepted Darwin's offer to secure financial backing for their own new manufacturing company from two Pittsburgh bankers named Thomas Givens and Hay Walker, Jr. For this, Wolcott was awarded a one-third ownership of Fessenden's share of his patents.

On 27 November 1902, RAF and Wolcott formed the National Electric Signaling Company (NESCO). This new company was capitalized at $100,000 with 1,000 shares. Two days later, on November 29, 1902, Givens and Walker entered the picture, and this foursome concluded what came to be called the Fessenden-NESCO "Agreement No. 1", as detailed below:

a) RAF and Wolcott were to own 100% of NESCO stock.

b) RAF's patents were to owned 100% by NESCO.

c) Givens and Walker were to provide $30,000 of working capital.

d) If RAF's radio system tests were successful, Givens and Walker had the option to buy 55% of the stock for $300,000, or
   take 10% of the stock, or
   be paid $30,000.

e) The NESCO stock was to be placed in trust.

f) If Givens and Walker exercised the provisions of para. 'd', the NESCO stock was to be released from para.'e' provision.

g) RAF was to be NESCO's technical chief at $300/month.

h) Givens and Walker were to be NESCO officers.

i) Para. 'd' provisions could be exercised if RAF's system tests were successful over a radio path from the New York City / Philadelphia area to Bermuda.

With the conclusion of this "Agreement No. 1", Fessenden thought that he was now on the pathway to wealth. He was 36 years of age, an established pioneer wireless system inventor, and strong of body and mind. But this was not to be.

The test circuit path to Bermuda had to be scrubbed when NESCO could not quickly obtain a wireless operating license. Instead, a radio circuit path from New York City to Philadelphia was substituted. Para. 'd' as well as para. 'i' included the requirement "if RAF system tests were successful." Interpretation of this requirement was the root cause of Fessenden's long-term difficulties with his patents, resulting in his eventual loss of millions of dollars.

In Professor Fessenden's mind, his wireless system tests between New York City and Philadelphia in 1903 proved successful. Givens and Walker thought otherwise since they believed RAF's radio system should be able to handle the landline traffic between NYC and Philadelphia as well as the radio traffic.

This was an absurd interpretation by Givens and Walker since the landline contained over 40 circuits in that link. However, Fessenden asked Givens and Walker to exercise their option to purchase NESCO stock as per para. 'd'. Givens and Walker immediately charged RAF with misrepresentation and demanded return of their $30,000 as per para. 'd', within one week; otherwise, they would sell off NESCO and with it would go RAF's patents.

Fessenden now was in a dire situation. In an attempt to resolve this conflict, RAF and NESCO engaged Dr. Arthur Kennelly to examine and report upon the performance of the Fessenden system in dispute. Kennelly reported in RAF's favour and later supplied a written, sworn statement in RAF's favour which was disregarded by Givens and Walker. (See Affidavit No. 1.) Then Givens and Walker offered to tear-up the old "Agreement No. 1" and substitute an alternate. RAF felt that he had no choice but to agree.

"Agreement No. 2", of 1903, included:

a) Givens and Walker would now own 55% of the NESCO stock.

b) RAF was to receive no payment for this stock transfer.

c) If NESCO earned any net profits, RAF would be paid up to $300,000.

> *Arthur E. Kennelly, having been duly sworn, deposes and says:*
>
> *-----"I AM PROFESSOR OF ELECTRICAL ENGINEERING AT HARVARD UNIVERSITY, AND HAVE BEEN EXCLUSIVELY ENGAGED WITH THE APPLICATION OF ELECTRICITY DURING THE PAST 34 YEARS. IN APRIL 1903, I CONDUCTED AN ELABORATE SERIES OF TESTS OF THE WIRELESS TELEGRAPH SYSTEM OF THE NATIONAL ELECTRICAL SYSTEM COMPANY, WHICH HAD BEEN INVENTED AND PATENTED BY REGINALD A. FESSENDEN, THE COMPLAINANT HEREIN, AND REPORTED TO HAY WALKER, jr., AND T.H.GIVEN, AS A RESULT OF THESE TESTS THAT THE SYSTEM WAS ENTIRELY PRACTICABLE AND COMMERCIAL AND THAT IT WAS FAR SUPERIOR TO ANY SYSTEM AT THAT TIME USED BY THE US NAVY"-----.*
> *(signed) A.E. Kennelly.*
>
> *Sworn to 1 April 1911.*

Kennelly Affidavit No. 1

Fessenden now had lost control of NESCO as well as his patents. One may wonder why he would continue to retain the same lawyer.

By mid-Summer 1908, RAF realized the Givens and Walker did not intend NESCO to earn a profit, and he resigned from NESCO because the para. 'c' provision would be of no benefit to him. The NESCO reaction was swift with Givens and Walker convincing the Professor to sign yet a third agreement:

"Agreement No. 3", of 12 Sept. 1908, included:

a) RAF's anticipated profit share of $300,000 now was placed at the same claim level as was the 55% NESCO stock ownership held by Givens and Walker.

b) Fessenden's salary was increased to $600 per month.

On 8 January 1911, Fessenden was dismissed from all employment at NESCO. He had received no part of any NESCO profit and, on 20 March 1911, brought suit against NESCO for breach of Agreement No. 3, and he was awarded over $400,000 by the courts on 23 May 1913. RAF never collected this money since Givens and Walker convinced the New Jersey courts to allow NESCO to slip into bankruptcy. A further complication arose when, during 1913, the Appeals Court declared the NESCO/RAF "Agreement No. 3" of 1908, to be an invalid document. Reginald Aubrey Fessenden now was without funds as well as the use of his patents.

From the vantage point of the 1990's, it is hard to believe that RAF would sign yet another agreement with NESCO, but that he did -- and it was called: Agreement No. 4, of 16 August 1916, which included:

a) RAF was granted the right to make, sell or use hardware based on his patents.

b) RAF waived his rights to sue NESCO.

c) RAF waived his rights to any NESCO shares of capital stock.

In 1917, Givens and Walker began the formation of a series of four new companies replacing the NESCO entity. This action nullified the terms of NESCO "Agreement No. 4". RAF's situation worsened.

What RAF patents were lost to NESCO?

RAF lost to NESCO the rights to some 81 of his over-200 patents. Included in this group were some of his fundamental inventions. A partial list follows:

U.S. No. 706735 - Galvanometer Detector.
U.S. No. 706744 - Hot-wire Barretter.
U.S. No. 727331 - Liquid Barretter.
U.S. No. 793648 - Sealed Electrolytic Barretter.
U.S. No. 706737 - Wireless Telegraphy (CW).
U.S. No. 706742 - Oscillating Arc Transmitter.
U.S. No. 752894 - Selective Reception.
U.S. No. 706747 - Radiotelephony.
U.S. No. 706740 - Heterodyne Principle.
U.S. No. 706743 - Phototransmission.
U.S. No. 793651 - Vertical Antenna, Insulated Base.

Not all of RAF's over-200 patents were without controversy re: their validity and primacy as to time. To illustrate these points, let's review two of his patents granted on 8 February 1927. The General Electric Company presented objections to both patents, as follows:

U.S. No. 1617240 -- Method for Wireless Directive Signaling

RAF said, in his specification covering this patent, that it was the result of hundreds of his wireless experiments transmitting in the wavelength range of from a few centimeters to more than 6,000 meters. He maintained in this patent that he discovered that if a transmitted radio frequency was less than 70 KHz, reliable trans-Atlantic radio circuits were feasible. In this specification, Fessenden went on to say that in 1915, a review of his many experimental records showed that increased RF directional efficiency could be obtained if the wavelength used was between one meter and fifty meters. He said that signals within these wavelengths were transmitted with less atmospheric disturbance. Fessenden claimed this was a method-patent governing directive wireless signaling determined through his discovery of the advantages of the short-wave band between the wavelengths of one and fifty meters. In their objection to this patent, GE said the patent was invalid because it was a mere discovery of a law of nature and therefore without invention. GE went on to say that short waves had been in use long before RAF's claim and that he was in error inferring that the 5 meter band is particularly good for all distances.

U.S. No. 1617242 -- Wireless Transmission and Reception

See Patent Sketch No. 1617242 -- Figures 1 and 2

Fessenden's patent applies to a wireless signaling system in which horizontally-polarized radio waves are transmitted at an angle substantially inclined to the Earth's surface.

General Electric's objections to this patent included the opinion that RAF's claim was anticipated by prior work particularly in the use of the ionospheric reflecting layer. RAF claimed that he had disclosed the contents of the invention to GE's Dr. Pickard of the crystal detector fame. GE denied this occurrence and stated that Dr. Pickard himself had experimented in this fashion; therefore, Fessenden may have acquired the idea from Pickard. GE maintained that their experimental antenna work had shown no advantage in using Fessenden's patent and, moreover, the concept was preceded by prior art methods.

1,617,242

Feb. 8, 1927.

R. A. FESSENDEN

WIRELESS TRANSMISSION AND RECEPTION

Filed Oct. 15, 1924

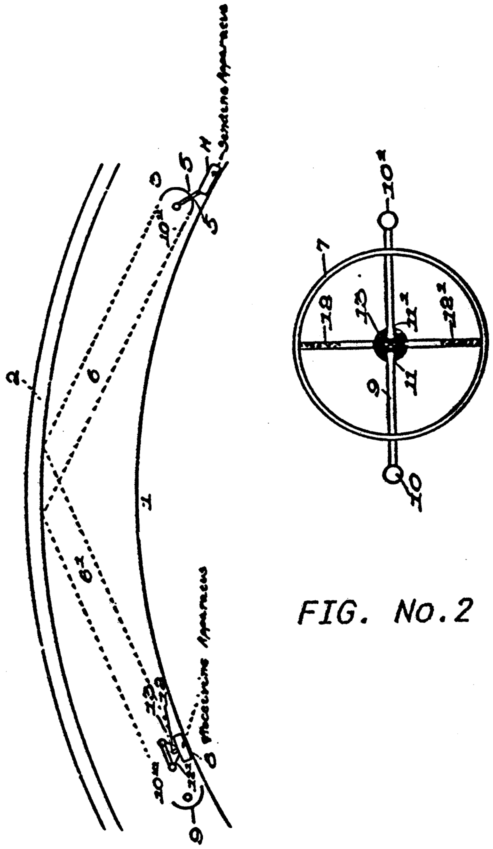


FIG. No.2

FIG. No.1

Patent Sketch No. 1617242

At the end of 1919, the Fessenden patents had been successively a part of the assets of each of the following successor companies:

National Electric Signaling Company -- formed November 1902.

International Signal Company -- formed November 1917.

International Radio Telegraph Company -- formed February 1918.

International Devices Company -- formed 1918.

The International Radio Telegraph Company -- formed May 1920.

The legal path to the Fessenden patents now was so convoluted that a legally-safe deal was difficult for the major radio-industry companies. The purpose of the last company formation was to allow Westinghouse to have a safe position in radio manufacturing via the Fessenden patents. To this last firm, The International Radio Telegraph Company, Westinghouse committed $2,500,000 in cash. Capitalization of this new company included 250,000 shares of common stock. Westinghouse owned one-half of these shares, and the Givens' Estate and family along with lawyer Wolcott owned the remaining 125,000 common shares. RAF received nothing.

On 20 June 1921, The International Radio Telegraph Company was purchased outright from Westinghouse by the Radio Corporation of America (RCA). The price was 1,000,000 common shares of RCA stock. By 1928, these shares were worth $110,000,000. RAF received nothing.

In 1926, Reginald Aubrey Fessenden filed the landmark "combination lawsuit" against the "Radio Trust" -- comprising GE, RCA, AT&T, Westinghouse, Western Electric and a few smaller firms. The suit was for tens of millions of dollars. The charges included monopoly of trade, curtailment of competition, restraint of interstate commerce, etc. This suit was settled out of court and, in a letter to the Internal Revenue Service dated 15 June 1929, RAF said that he settled for $2,500,000 with an initial payment of $500,000. He wrote that his legal costs were $200,000.

After winning the Radio Trust suit, RAF left the United States for Bermuda where he established a permanent residence.

One may wonder how Fessenden was able to withstand, mentally and physically, the barrage of negative events that befell him at the hands of NESCO, its owners and successors. The long-term grinding dissension took its toll. Stress caused Fessenden to develop circulatory problems which, at one time, made him uninsurable. His disposition suffered, making him short-tempered and difficult in discussions -- a far cry from his academic career days when he was much appreciated by his students and faculty associates. But for the constant support of Helen, his wife, he might not have reached the year 1932 when he passed away in Bermuda from a heart attack, on 22 July.

Fessenden's best-known invention, in the eyes of the general public, appears to be the radiotelephone: U.S. Patent No. 706747, of 12 August 1902. This was due to the many dramatic press reports of his actual transmission of the human voice, at that time. RAF's first R/T transmitter is shown in Figures 5 and 6.

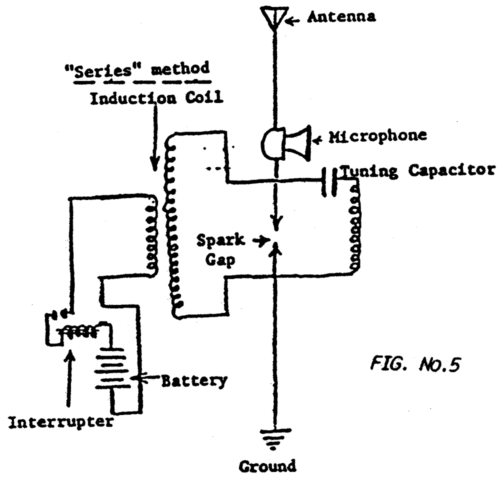


FIG. No.5

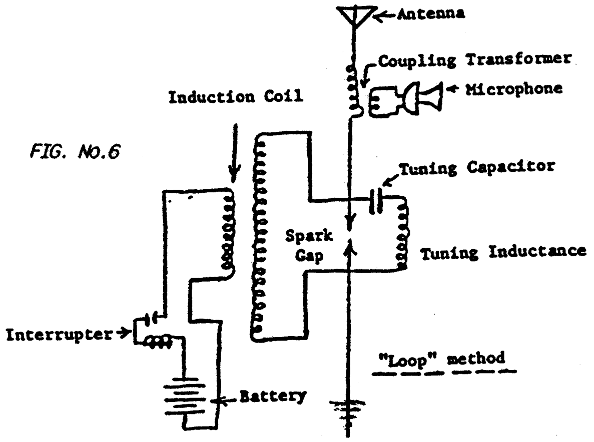


FIG. No.6

Figures 5 and 6. Fessenden's first R/T Transmitter

Fessenden made his first radiotelephone transmission during January 1901 from Cobb Island while employed by the U.S. Weather Bureau. Figure 5 shows how he modulated the RF output of a spark transmitter by placing a microphone in series with the antenna feedline; this modulation method came to be known as "series modulation". The method had a major fault in that the full RF output current passed through the microphone. He overcame this problem by inventing "loop modulation" whereby the microphone was inductively coupled into the antenna feeder; see Figure 6.

RAF knew that his radiotelephone commercial success would depend upon his ability to develop a successful CW transmitter in lieu of "spark" which was too noisy a carrier for quality audio modulation. He pushed the development of the RF alternator to a workable state as a CW source, during 1906. In December of that year, he broadcast his famous Christmas Eve radiotelephone program.

Fessenden's most spectacular event was the application of his radio system to trans-Atlantic communication. He acceded to Givens and Walker's wish for a wireless system operating over a range of at least 3,000 miles. He did this despite his belief that NESCO should be concentrating on radiotelegraphy and radiotelephony using the continuous-wave carrier instead of "spark". The purpose was to allow Givens and Walker to attract a potential major purchaser for the Fessenden system and his patents. The objective was to show that RAF had initiated the best commercial wireless system and that a working, full-scale operation from the United States to Great Britain should prove this point.

Brant Rock, Massachusetts, on Cape Cod, was selected as the U.S. station site, using the call letters 'BO'. The location of the station in Great Britain was at Macrihanish, on the west coast of Scotland, and this station adopted the call sign 'MA'. RAF's trans-Atlantic system operated briefly during 1906.

Figure 7 illustrates the vertical antenna constructed at Brant Rock during 1905, for the 'BO' station. This antenna was a top-loaded, insulated-base vertical over 400 feet in height. It was a riveted-steel tube with an internal diameter of three feet and had inside ladder rungs for access to the top-loading structure. There was a total of 16 guy wires holding the tower at four separate tie points. Each guy wire had an insulator at every 50 feet. The Scottish station 'MA' had the same antenna design.

The transmitters at both stations were developed by RAF, and were synchronous, rotary spark-gap types. The rotary spark was fed by a 35 KVA, 125 Hz alternator. The rotary spark-rotor was five feet in diameter and contained 50 electrodes, and was driven directly by the 125 Hz alternator shaft. The stator contained four poles and had a diameter of six feet.

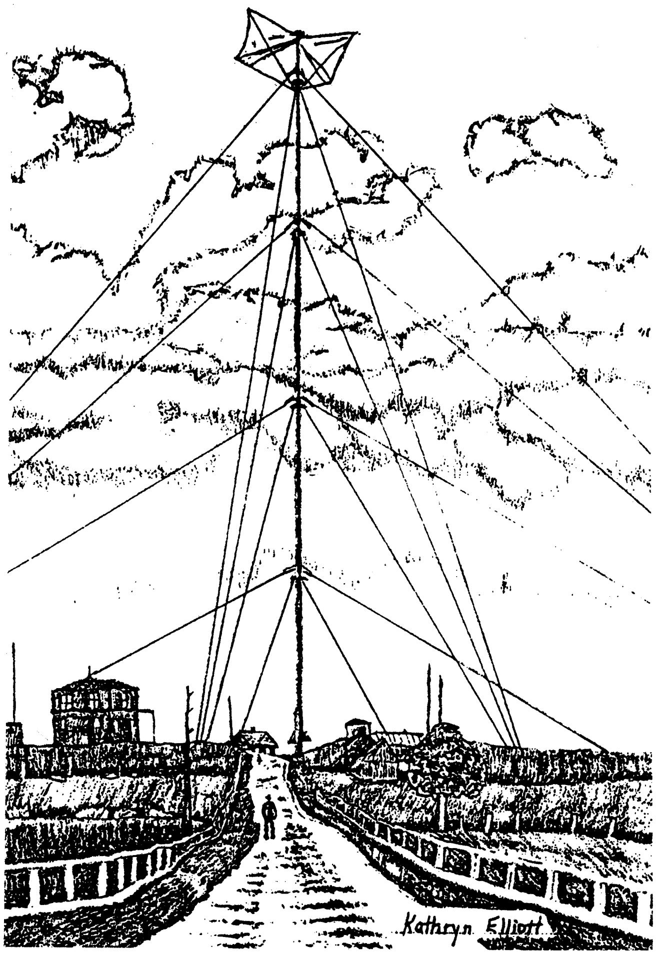


Figure 7. Fessenden's Brant Rock, MA. Trans-Atlantic Radio Station -- 1906.

On 10 January 1906, the first-ever two-way radio transmission across the Atlantic passed through Fessenden's stations 'BO' and 'MA'. During 1906, the operation of the transoceanic wireless circuit created much interest from the press and others, and included 'BO' on-site visits from potential system customers such as AT&T, Western Electric, General Electric, etc.

In the midst of this great breakthrough and the resultant excitement, disaster struck during the night of 5 December 1906. A Winter storm on the Scottish coastline had toppled the antenna tower at 'MA' and it fell across the station building, smashing much of the equipment. The backers would not invest further funds for this purpose and the interest of the system buyers waned. The antenna tower at station 'BO', Brant Rock, was demolished by the U.S. government in December 1917 due to security concerns related to World War I.

What was Fessenden's radio goal?

His objective was the development of commercial continuous-wave (CW) radiotelegraphy and radiotelephony systems, including the manufacture of associated apparatus. His RF alternator gave him a CW transmitter and his "heterodyne principle" gave him the companion receiver. RAF needed business acumen (other than bankers) to complement his technical genius. While his NESCO partners had the money, they could not provide the business knowledge and leadership that Fessenden desperately required to overcome the non-technical distractions of new product development.

Perhaps history would have been different if, instead of having to endure a technically-uniformed, unrealistic NESCO top management, R.A. Fessenden had been given first-class marketing, manufacturing, customer service, etc. support by Givens and Walker. Due to organizational default, he had to cover all these tasks in addition to radio development. Viewed today, the RAF - Givens - Walker- Wolcott quartet of 1902 - 1911, as organized, was destined for failure.

On 2 January 1909, Professor Fessenden became a founding member and was elected to the office of Consulting Engineer of the Junior Wireless Club, Ltd., at a special meeting held at the Ansonia Hotel, New York City. Two years later, the name of that organization was changed to The Radio Club of America.

INFORMATION SOURCES

Amateur Radio Fessenden Society
c/o P.O. Box 737, Picton, Ontario K0K 2T0
Canada

North Carolina State Archives
Raleigh, North Carolina

Canadian National Archives
Ottawa, Ontario, Canada

Bishop's University (Terry Skeats)
Lennoxville, Quebec, Canada

Purdue University (Dr. L.A. Geddes)
West Lafayette, Indiana

Queen's University
Kingston, Ontario, Canada

West Virginia University (Dr. William Squire)
Morgantown, West Virginia

The Continuous Wave by Dr. Hugh Aitken
Princeton University Press

A JOURNEY THROUGH THE TROPOSPHERIC RADIO EVOLUTION

by Paul Gruber (LF)

SUMMARY

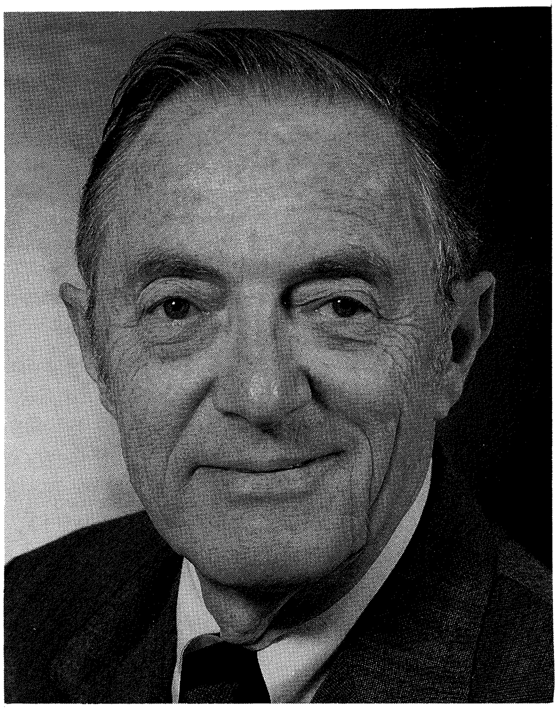
The Journey Through the Troposcatter Radio Evolution spans almost 40 years. Radio Engineering Laboratory (REL), which was born in 1922 and sold in 1986 to the Whittaker Corporation, offers the stage for this story. It is written through the eyes of an REL/Whittaker radio and system engineer whose advance in his profession correlated with REL's success in the tropo radio industry.

The story touches on the reason for developing troposcatter radios and the great impact that frequency modulation (FM) made on its application. We see Jim Day, inventor and V.P. of engineering of REL at his best and see how a new industry is born. We briefly meet Edwin Howard Armstrong twice -- happy to see that another application had been found for FM. Regrettably, space does not permit the telling of the war stories that go with the more than the 700 radio terminals installed throughout the world.

The solid-state introduction impacted tropo radio tremendously and advanced the radio design by a giant step. The digital revolution which was associated with the introduction of solid-state electronics, was destined to remedy many of the limitations of tropo that were due to FM modulation. The paper touches on the highlights of the trial and tribulations which finally led to a workable, adaptive digital tropo modem that fulfilled the wish list of both the commercial and military requirements. Unfortunately it came when satellite transmission had already suffused world-wide voice communications. As a final observation, the Greenland-to-Iceland tropo link is revisited. It always was a topic of stimulating discussions in the tropo community.

1.0 INTRODUCTION

1.1 WHAT IS TROPOSCATTER RADIO COMMUNICATIONS ?



Paul Gruber

Tropospheric radio communication is based on the forward scatter of radio signals, usually in the 0.7 to 5.0 Ghz frequency range. The RF signals make use of the common volume scattering* illuminated in the atmosphere by the intersection of the transmitting and receiving antenna beams. Since the common volume is located in the troposphere, a height up to about 6 miles above sea level, beyond the horizon radio transmission between terminals hundreds of kilometers apart can be established.

Tropospheric transmission is relatively inefficient since the reflection loss due to the forward scatter in the common volume is between 60 to 90 db. This is in addition to the additive line-of-sight loss. But this can easily be overcome with sufficient transmission power, antenna size, and receiver sensitivity.

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*A volume in the atmosphere that subtends a solid angle of the receiving antenna. In this region, a tiny portion of the transmitted signal is scattered by small changes in the index of refraction of the air, and by dust, clouds, and other naturally occurring particles in the troposphere.

Troposcatter is utilized to transmit telephone voice channels with reliability close to line-of-sight (LOS) transmission. Other applications include telex, fax, and high-speed data when digital transmission with suitable adaptive-demodulation implementation is used.

1.2 WHY WAS TROPOSCATTER COMMUNICATION USED ?

Troposcatter transmission was developed before satellite transmission appeared, to bring communication to parts of the world where normal microwave line-of-sight systems were impractical such as where the shortest route was over water. For example, communications between England and Spain, Greenland to Canada, or communication systems in the Aleutians and the Arctic are typical.

Practical troposcatter transmission was born when the Canadian and U.S. Bell Telephone Companies engineered the *Polevault* tropo scatter system, located in Northern Canada. The result of this mode of communication demonstrated reliability of communication almost equivalent to microwave repeaters. Based on the success of these installations which were used by both the military and the telephone companies, troposcatter terminals sprang-up all over the world. As an example, Figure 1 shows a 1 Kw tropo station used by the Spanish Telephone Company to transmit 240 telephone channels over the Mediterranean Sea from Almeria, Spain to Morocco. Figure 1a shows the radio terminal inside the station.

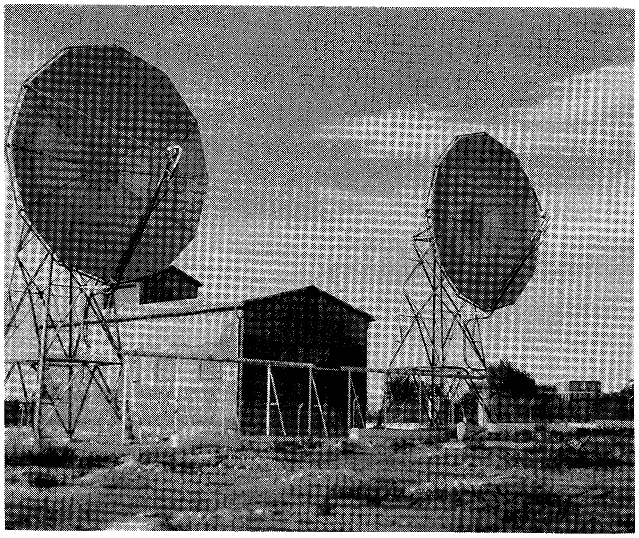


Figure 1. 1 Kw Terminal With 30 Foot Antennas operating in quadruple diversity between 1700 - 2400 MHz. Installed in 1977 at Almeria, Spain for the Spanish Telephone Company.

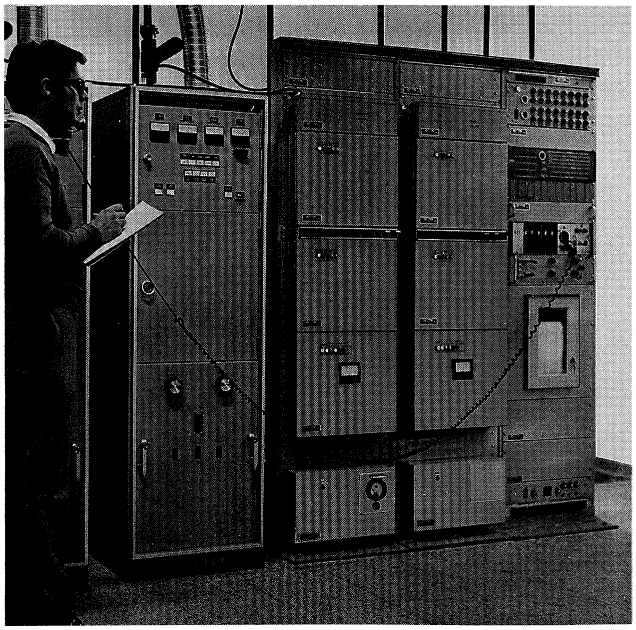


Figure 1a. Radio Terminal Inside Almeria Tropo Station.

Not only did over water spans find troposcatter applications, but the Arctic region and the northern parts of the world where microwave repeater communication was impractical actually were the first installation candidates. Figure 2 shows the *ADEK* station in the Aleutian Islands which transmitted at 10 Kw on 755-985 Mhz. using 60 foot parabolic antennas.

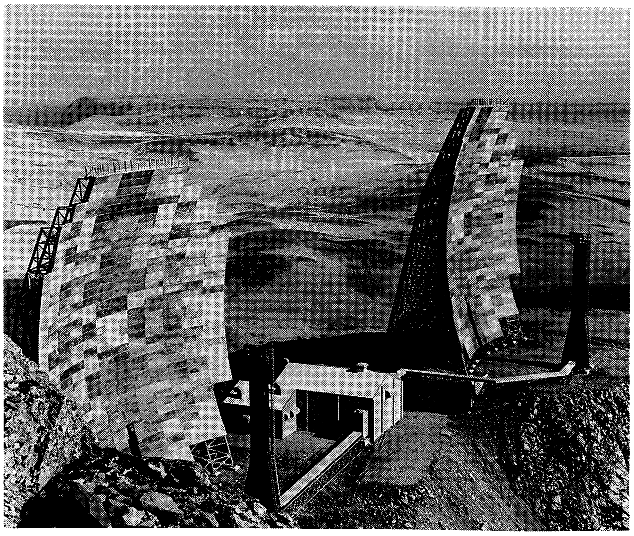


Figure 2. 10 Kw AN/FRC 39A(V) Repeater Terminal with 60 foot antennas, operating in quadruple diversity between 755 - 985 MHz. Installed at Adek, Aleutian Islands.

These systems installed in the middle and late 50s had spans of between 100 and 300 miles without repeaters. The longest tropo link ran between Fox in Canada and Thule in Greenland. It spanned 591 miles and operated for 25 years.

2.0 A FEW WORDS ABOUT TROPOSCATTER's OPERATION.

2.1 TRANSMISSION CHARACTERISTICS

As the name implies, tropo scatter operates by reflecting transmitted energy from the troposphere and receiving a minute amount at a selected site.

An FM carrier, generated at the transmitting site, is built up to between 1 and 50 kilowatts of RF output power and transmitted via a high-gain (up to 50 db) parabolic antenna of between 15 and 120 feet in diameter. The antenna is adjusted so that the lower edge of the beam grazes the horizon. This will illuminate the troposphere at a location which is based on the path parameters.

The antenna's feedhorn elevation is called the take-off or the inclination angle. If the antenna is located on terrain higher than the foreground, the antenna beam can be aimed below zero angle, resulting in a negative inclination angle: a desirable condition.

The receiver's antenna is pointed at the common volume; this offers optimized receiver antenna illumination. Even under the best conditions, the portion of the scattered signal received is 180 db to 240 db below the transmitted power. This looks worse than it is. For a 10 kw or 70 dbm transmitter output power and 45 db gain per antenna, the signal into the receiver input for a transmission loss of 200 db, is 70 + 90 - 200 = -40 dbm. This is an extremely strong signal for a tropo receiver whose noise floor is in the neighborhood of -100 dbm. To design a tropo path for reliable operation, reference is made to *NBS Technical Note 101*(1) which outlines the details of calculations. Another reference that is easy to read is a step-by-step procedure of a sample path prediction of the span between Hong Kong and Taiwan. It was written by REL.(2) Due to the lengthy calculations, a computer program normally is used.

2.2 WHY DID TROPOSCATTER WORK SO WELL?

The answer is simple. It was Armstrong's legacy: "FM". With the exception of the AN/TRC-170 U.S., (the *TRITEC* transportable tropo built in the late 1980's, which uses QPSK digital modulation) FM always has been the modulation of choice. The reason is the FM receiver's inherent noise-suppression capability, high-capture ratio and higher baseband signal-to-noise ratio for a given RF signal level, versus those characteristics in an amplitude-modulated (AM) receiver. As an example, for only +/-100 khz RMS per-channel-deviation of a 72 channel system, the upper baseband channel has, for a 10 db carrier-to-noise (C/N) ratio at the receiver input, a demodulated S/N (signal-to- noise) output of 36 db. This is 26 db higher than AM. (10 db C/N is the FM receiver "threshold"). This improvement is maintained for increasing levels of RF input, until intermodulation and residual receiver noise saturates the baseband output S/N. (Refer to the appendix for FM design formulas, and other useful associated receiver design information).

In addition to these receiver features, linearity is not a requirement in the FM modulated system. High-power amplifiers may be operated class C and saturated to full output power for high efficiency operation.

2.3 SIGNAL FADING

One of the tropo signal's idiosyncrasies is fading. There are two types of fading: short-term and long-term. At a particular instant, short-term fading is the vector sum of all individual signals arriving at the receiver with random phases and amplitudes. The magnitude of the resultant signal follows the Rayleigh probability distribution over a period of minutes. According to Lapadula,(3) "Short-term fast fading is caused by rapid changes in the scatter volume which are the result of changes in the magnitude of the intensity of turbulence and in its spatial distributions." Short-term fading is superimposed on the second type of fading which is called "Long-term Slow Fading". Long-term fading is caused by the tropospheric change in refractive index. It is measured in days and weeks and is also a function of the seasons. *NBS 101*(1) shows long-term fading for various climate types.

2.4 DIVERSITY OPERATION

To counteract short-term fading, diversity techniques were developed so that the demodulated signal S/N will follow, as a minimum, the highest received-signal level. In general, the demodulated signal reflects a signal-to-noise (S/N) ratio which is the sum of the S/N's of the receivers.

To obtain the maximized demodulated-baseband output independent of RF fading, uncorrelated diversity paths have to be utilized. The most common approach is to use two frequencies with a separation of 5% or higher. (Dual-frequency diversity). For this type of operation, only one transmitting and one receiving antenna are required.

If only a single frequency is available for transmission, two receiving antennas have to be used, separated by at least 100 wavelengths for non-correlated signal transmission. (Space diversity). For more reliable operation, both frequency and space diversity are combined into quadruple frequency/space diversity, which essentially removes all fading.

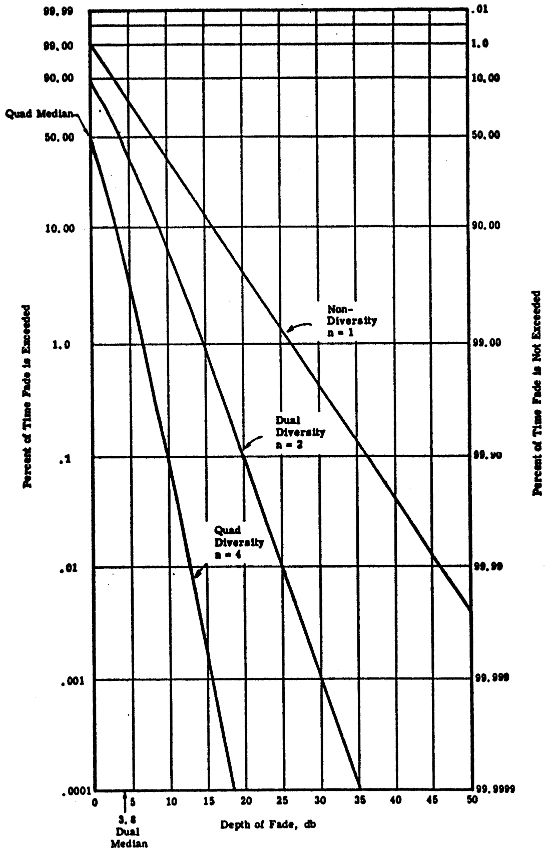


Figure 3. Distribution of Maximal-Ratio Combined Rayleigh-Fading Signals.

As an example, consider a time frame of 0.1 percent of a year or 8.76 hours. It can be shown, see Figure 3, that, for quadruple diversity, a 10 db depth of fade is exceeded by 0.1% only during 8.76 hours distributed over a long time period, such as a year. In other words, for 99.9% of the time, a depth of fade of 10 db is not exceeded. For dual diversity it is 20 db and without diversity it is 36 db.

A third and not commonly used method is angle diversity. This technique requires off-setting the transmitting antenna feedhorns to establish different paths. See Monsen. (4) Godet gives an interesting analysis.(5)

As a by-product of diversity, reliability is dramatically improved. Since for quadruple diversity, two independent transmitters and four receivers are employed, the possibilities of transmission interruption is remote. The receiver combiner, addressed later, which is the receivers common point, is normally designed as an independent adding entity.

3.0 1953 - THE ADVENTURE BEGINS

3.1 JIM DAY, REL's V.P. of ENGINEERING

Jim Day sent his secretary to see me. She said breathlessly: "The Man wants to see you. You better go right away; he didn't sound too friendly."

By now, I was no longer petrified when entering the lion's den. I entered, sat relaxed, and almost expected him to say, "Take off your shoes." His chain smoking of Camel cigarettes created a haze, a lot like a light fog. This made Jim Day look more obscure...and his visitors prone to coughing attacks.

Dead silence. He started to read something, ignoring me. One thing I had learned: keep your mouth shut when you don't know what to do. He finally put down the document and stared at me and said the famous words: "We are going into the troposcatter business."

Not to show my ignorance I thought a brilliant statement like, "That's great!", showed enthusiasm and implied a certain knowledge of what he was talking about.

I continued by saying that I was familiar with Marconi's predictions that beyond-the-optical-horizon communication at microwave frequencies would be the radio service of the future.

"Yes, yes, yes!" Day said impatiently, since he was not interested in Marconi's prediction; " I'm making you the receiver project engineer because to your experience and work on the *DIANA* receivers and modulators." There again was silence which I thought was a cue to leave his office.

He said: " Sit. How familiar are you with the applications of tropo transmission?"

"To tell you the truth, all I know is that hundreds of miles of transmission is feasible with one hop."

"Good, the less you know about the subject, the less your mind is contaminated with the wrong ideas."

3.2 POLEVAULT, THE FIRST TROPO SYSTEM

The next action of Jim Day was to ask his secretary for coffee; black for him and milk-and-sugar for me. The young lady was a Jill-of-all-Trades, a translator to the king's English, and a competent secretary in the art of management.

She made a remark of what I was going to be exposed to, but left before Day could surprise her with a less than Shakespearean response. Jim Day, in a tutorial tone, very precise and without any self-imposed authority, started to explain what was going to happen. He lit another cigarette with one already burning in the ashtray, and said that Bell of Canada, Bell Telephone Labs of Holmdel, N.J. and, possibly, Lincoln Labs would participate in the system design. REL was going to build the radio.

"Obviously, We'll use FM due to its dynamic improvement over other types of modulation, and use the serrasoid(6) crystal- controlled modulator with its high-deviation ratio capability. Oh yes! We'll build 10 kw klystron transmitters. Since we have Perry Osborn aboard, itis going to be a cake walk."

He continued explaining that "the total *Polevault* path was 1600 miles and would operate in the 700 and 900 Mhz frequency range, carrying 36 telephone channels. Nine links would be implemented for this job. Sixty-foot parabolic reflectors driven by 10 kw power amplifiers and operating in dual- frequency diversity would be used. This means we'll build thirty-six 10 kw amplifiers and 18 dual-frequency diversity receivers. Each dual-diversity receiver will need a combiner. Troposcatter signals have up to 40 db signal fades lasting anywhere from 0.1 to 10 seconds. Since we'll use frequency diversity with 5% separation, we'll have un-correlated paths and minimize fading. Since both paths carry the same information, it's statistically rare that both frequencies will have simultaneous fades. Therefore, if we combine the two signals by suitable means, we should've conquered the fading problem." (I wondered what he meant by suitable means.)

3.3 THE HEART OF THE TROPO RADIO

It did not take very long until thunder and lightning broke loose. You could hear Jim Day down the hall when he emphasized in graphic language so that even wiser heads in management could hear, that the heart of the tropo radio is the combiner. "If we don't invent one promptly and without spikes or transients, we'll have a disaster." The combiner didn't really bother me, since Jim Day previously had suggested a dual-triode cathode follower. By elementary circuit analysis, one could show that this did not generate transients at the dual-connected cathode output when controlling the grids with the receiver signal. "What about the combiner control?", I asked. "Work on it. I want it yesterday." was the rely.

It turned out that FM again saved the day. Since, in FM, the noise varies linearly above threshold and as a function of signal strength, it was easy to build a combiner-control amplifier. As a by-product, when using noise of at least twice the baseband, the transmission intermodulation-distortion noise is super-imposed on the combiner control. This permitted a true quality replica control of the transmission.

3.4 THE INCIDENT

When I met Major Armstrong in 1951 for the first time at his Alpine radio station, I was impressed. This was not due only to his inventions or to the authority in his speech, but by his ability to help us with a 50 kw 150 Mhz transmitter which we needed for the *DIANA* moon-bounce project. For all practical purposes, we used his 50 kw FM broadcast transmitter design with a Machlett 50 kw output power tube. Apparently he did not trust us too much because, very shortly thereafter, he transferred his transmitter engineer, Perry Osborne, to REL to complete the transmitter.

The year was early 1954. I was battling the combiner-control design and, also, a logarithmic amplifier design for a path-loss measuring test set, when someone slapped me on my back with such force that I thought one of my vertebrae had been broken.

I quickly turned, attempting to defend myself with a hot soldering iron. When I saw Edwin Armstrong, smiling and laughing and stretching out his hand to congratulate me, I rapidly put my brain into gear and smiled back. It turned out that he was pleased with the tropo FM circuit implementations and the progress made on the combiner control. Mr. Randy Runyon, REL's president and one of Armstrong's best friends, was standing behind him smiling from ear to ear.

4.0 THE TROPO RADIO DESIGN APPROACH

The *Polevault* project was followed by *White Alice*, installed in 1955 and 1958 respectively. Figure 4 shows a *White Alice* repeater terminal with 60 foot antennas. Numerous other troposcatter programs created a steep learning curve. It produced sophisticated Low Level (exciter and receiver) and 1, 10, and 50/75 kw HPAs (high-power amplifiers) which used klystron tubes. See Figures 5 and 6 showing a complete 10 kw HPA and a 100 kw RF amplifier cabinet. The HPA'S operated at 755 to 985 Mhz, and 425-475 Mhz respectively.

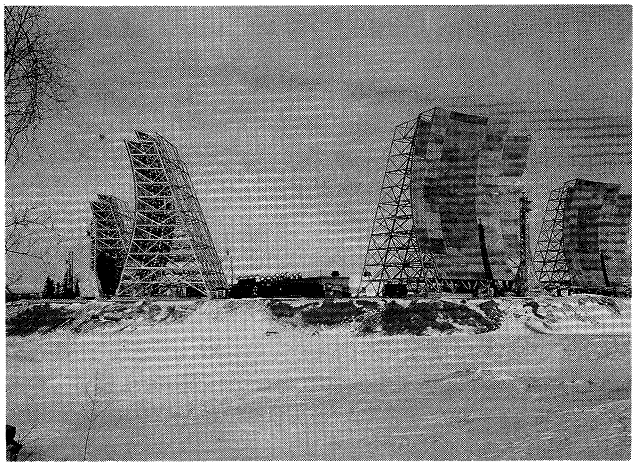


Figure 4. *White Alice* Repeater Terminal installed in northern Canada in 1957, transmitting 10 Kw in quadruple diversity using 60 foot antennas at 755 - 985 MHz.

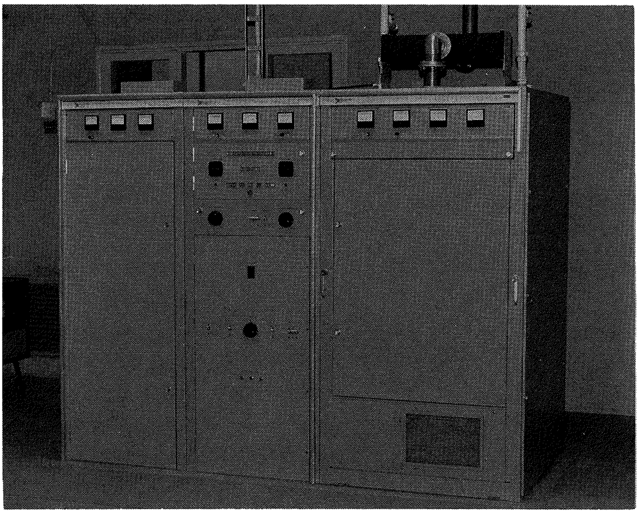


Figure 5. 10 Kw High-power Amplifier. Operational at L, S, and C band depending on insertion of RF klystron carriage.

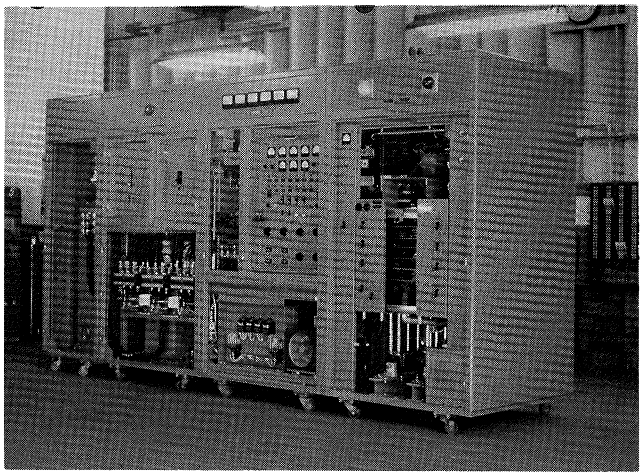


Figure 6. 100 Kw RF Amplifier Cabinet, operating at 450 MHz. Installed at Thule, Grenland and Fox, Canada.

4.1 THE HPAs.

Due to the new technology, the designers had to bring themselves quickly up to speed to understand the klystrons operational characteristics such as the phase-pushing factor (degree/V), the amplitude sensitivity (Watts/V), AM/PM conversion (degrees/db of drive level change), AM noise, intermodulation distortion, and line-frequency phase noise due to the beam-power supply.

As an example, if the filtering of an 18,000 volt beam supply is 50 volts peak-to-peak, the phase excursion due to line frequency components would be 0.056 radians or 3.2 degrees.(7) This would be sufficient for analog, but might become a problem for certain digital applications.

One of the HPA's design challenge was the beam-power supply transformer and the associated 12 phase-rectifiers which developed up to 30 kv of beam voltage. The degree of DC filtering was only determined by the degree of AM and FM noise, to meet the system specifications.

4.2 THE LOW LEVEL

The first receiver's baseband combiner for troposcatter was described by Chuck Mack in 1955,(8) and a later version by Paul Gruber in 1958.(9) In 1959, D.G. Brennen(10) published his classic paper on linear-combining techniques which analyzes selection, equal-gain and maximum-ratio diversity systems. For reference, REL used a modified version of the maximal ratio. The poorer channel was cut off when the signal decreased to one-half of the best channel. This was done to prevent a poorer signal from getting control of the combined signal due to a possible drift in the combiner control or other potential errors.

The serrasoid FM modulator of the exciter was also a key circuit in the tropo success story. Figure 7 shows an early demonstration of the Serrasoid modulator to FCC Commissioner Wayne McCoy and to Edwin Armstrong. The serrasoid's frequency stability could be made as high as the crystal oscillator technology permitted. Its inherent large phase shift capability required relatively low multiplication for the troposcatter per-channel-deviation requirements. One of the modulator's disadvantage was the tuning of the multiplier's filter for minimum group delay, to obtain low NPR (noise power ratio) or intermodulation distortion.

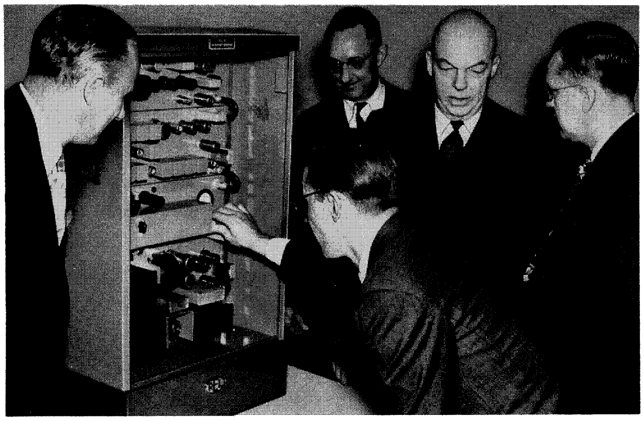


Figure 7. Demonstrating the Serrasoid FM Modulator in 1948. From left to right: Frank Gunther, Randy Runyon, Edwin Howard Armstrong, FCC Commissioner Wayne McCoy, and Jim Day explaining its operation.

The test equipment available in those days for this type of alignment was very limited. For historical reference, the AN/FRC-39A(V) radio's exciter used the latest version of the serrasoid modulator. It also was the last time that REL used this circuit on a new design.

Another critical items was the system's phase-noise requirement. The U.S. Air Force, the major customer of tropo-scatter radio equipment, set the specifications usually at 72 db below test tone. This established the residual per-channel receiver noise. As an example, for +/- 100 khz RMS deviation, and the noise at 72 db below this test tone, only 100,000/12,589 or 7.9 hertz noise-deviation appeared at the receiver baseband output. This requirement was overcome with high-stability quartz-crystal local oscillators. The higher the stability, the lower the phase noise.

One of the challenging developments was the continuing improvement of the receiver noise figure. The noise figures between 700 to 985 Mhz started at 6 db for *Polevault*, which did not use a preamplifier; 4db when using the Western Electric 416-B tube as an RF amplifier; 3 db for the tunnel-diode amplifier and finally 2 db for the first parametric amplifier. Noise figure reduction was always a stimulating development and even had its side benefits.

4.3 THE PERK

The date was August 1961. Mr. Day came to my office. It already was past 12 noon and Jim Day hadn't yet gone to lunch. This indicated big troubles. He stared at me and said: "The combiner on *DYE 5* (the Iceland 75 kw tropo site of the BMEWS system, which faces Greenland) is oscillating. "Nonsense", I said. "The damn parametric preamplifier is improperly tuned," I managed to squeeze out before Day's face started to take on a dark red color.

In very icy language, he advised me that this message came from the Bell Lab engineers on site, checking out the system for turnover to the Air Force. Further efforts to explain why the combiner could not oscillate went into deaf ears. He just said, "You are leaving at 4:30 PM from Idlewild airport for Iceland. Don't waste your time with lunch; you'll eat on the plane. Go get a suitcase with some clothing and be at the airport at 3:00 PM."

I did make the airport on time after twice fighting the Long Island expressway traffic. Since this was my first airplane ride, I felt somewhat uneasy. But when I saw the plane had four engines I felt better. "Relax," said the Icelandic stewardess, as she gave me what turned out to be a large glass of cognac, "You will be with us for 16 hours." "Sixteen hours? Where are we refueling?", I asked. "This is a DC-6B," she replied, "We don't refuel, we fly right through." Since these words of wisdom made me feel better -- or may be it was the cognac -- I relaxed.

As I passed the thundering 3 Megawatt redundant-power station and the four 120 foot billboard reflectors on the *DYE-5* site the next morning, I was really impressed. As I entered the radio building at about 6 AM, the so-called combiner problem jumped straight into my face. The parametric amplifiers doors were closed! This meant that the input stub tuners, which matched the antenna to the parametric amplifiers RF input were completely detuned. Before my escort could say "Oscillation", I took the Gruber meter (an RF diode rectifier connected to a 50uA meter) out of my briefcase, connected it to the RF output and requested an HP-612 signal generator which was then put at the RF input. After adjusting the input stub of the parametric amplifiers and reducing the klystron-idler pump power for an amplifier gain of 17 db, the crisis was over.

Figure 8 shows the author on the *Dye 5* Icelandic site. The parametric amplifiers shown in the picture are the four large enclosures with the round meters at the center, and mounted on the end relay racks.

A word of explanation. Northern Electric of Canada, the designer of the parametric amplifier, did a wonderful job on this original design. The 2 db noise figure of the unit was never before obtained at these frequencies on production units. The design consisted of a 755 to 985 Mhz tunable RF input frequency to a related 10 GHz up-convertion and down-convertion approach, with the RF output frequency the same as the RF input frequency. Since, in those days, circulators between 755 and 985 Mhz were not available, the design was a cutting edge challenge. The pressure of shipping the units to the sites had prevented a redesign of the cabinet. Even though much criticism was thrown at the units instability, a major cause was that the operators attempted to squeeze more than 17 db, the upper safe level of amplification, out of the units.

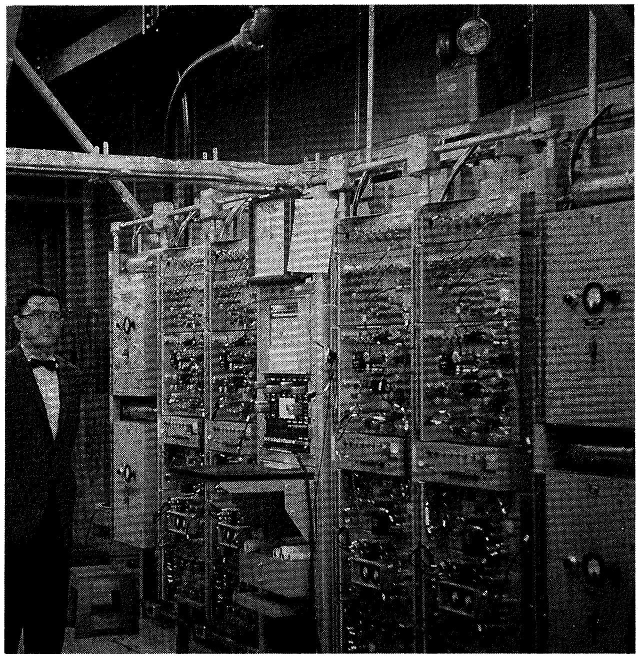


Figure 8. Author at *DYE-5* Site, showing quadruple receivers with parametric amplifiers and threshold extension units during acceptance tests.

A week on the site witnessing the actual operation of the radio transmission and watching the HPA's pushing 50 kw of RF power into the 120 foot antenna was a thrilling experience. The stay was without any problems with the exception that the transmission from *DYE 4*, the Greenland site, was impaired with substantial intermodulation due to the long 450 mile over-water link. We discovered rather quickly that the path was intermodulation and not power limited.

5.0 A NEW INDUSTRY IS BORN

5.1 THE EXPLOSION OF TROPOSCATTER'S USE.

The year is 1961. The use of troposcatter was exploding. Telephone communication was established with reliability never seen before via the interleaving network of NATO's *ACE HIGH 86* troposcatter system from the Aleutian Islands through Canada, Greenland, Iceland to the UK and through Europe. A 591 mile tropo link, the longest ever to be established, was to run from Thule, Greenland to Fox, Canada. It was implemented in 1963 with 100 kw HPA's operating at 450 Mhz and driving 120 foot bill-board reflector antennas.

The US Air Force, one of the prime movers in the use of fixed-station tropo, implemented their tactical communication needs with 10 kw transportable tropo terminals which could, within eight hours (the time to erect the 30 foot antennas), transmit up to 132 channels to distances of at least 200 miles.

This explosion of troposcatter communication all around the world is most vividly described in Frank Gunthers classic paper on tropo scatter.(11) He not only lists the operating links established between 1955 to 1965, but also gives maps on the existing interconnecting systems previously mentioned. Most of REL's tube radio equipment built at that time, was of the AN/FRC-39A(V) variety. Figure 9 shows a Low-Level and Figure 10 shows an HPA repeater station. Figure 11 shows the 10 kw transportable derivative of the AN/FRC-39A(V).

For the more curious, Figure 12 shows a simplified radio block diagram of a typical transportable tactical shelter using a 1, 2 or 10kw HPA. The block diagram is self explanatory. It could just as well be a fixed station arrangement. It shows the major radio blocks and their interconnection.

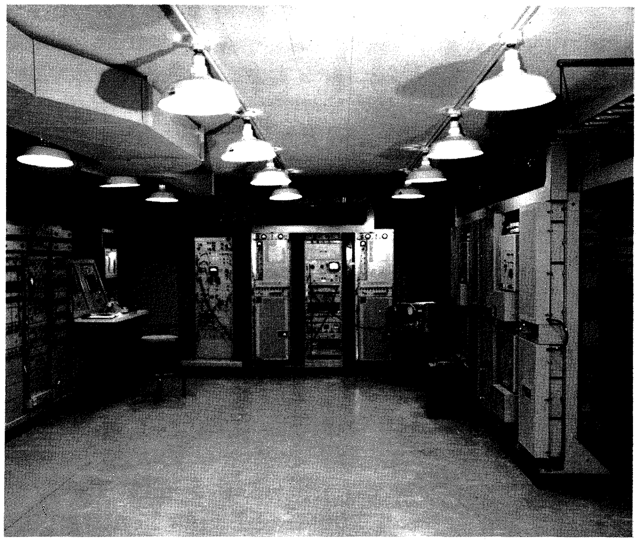


Figure 9. AN/FRC-39A(V) Quadruple Diversity Exciter, Receiver, Multiplex and Technical Equipment (low-level) Terminal.

This diagram is applicable for FM or digital modulation. When using digital modulation, normally a high stability clock (5 Mhz master oscillator) with very low phase noise is used. Depending on the modem, 10E-9 or even an atomic standard such as a Rubidium or Cesium (10E-10 or

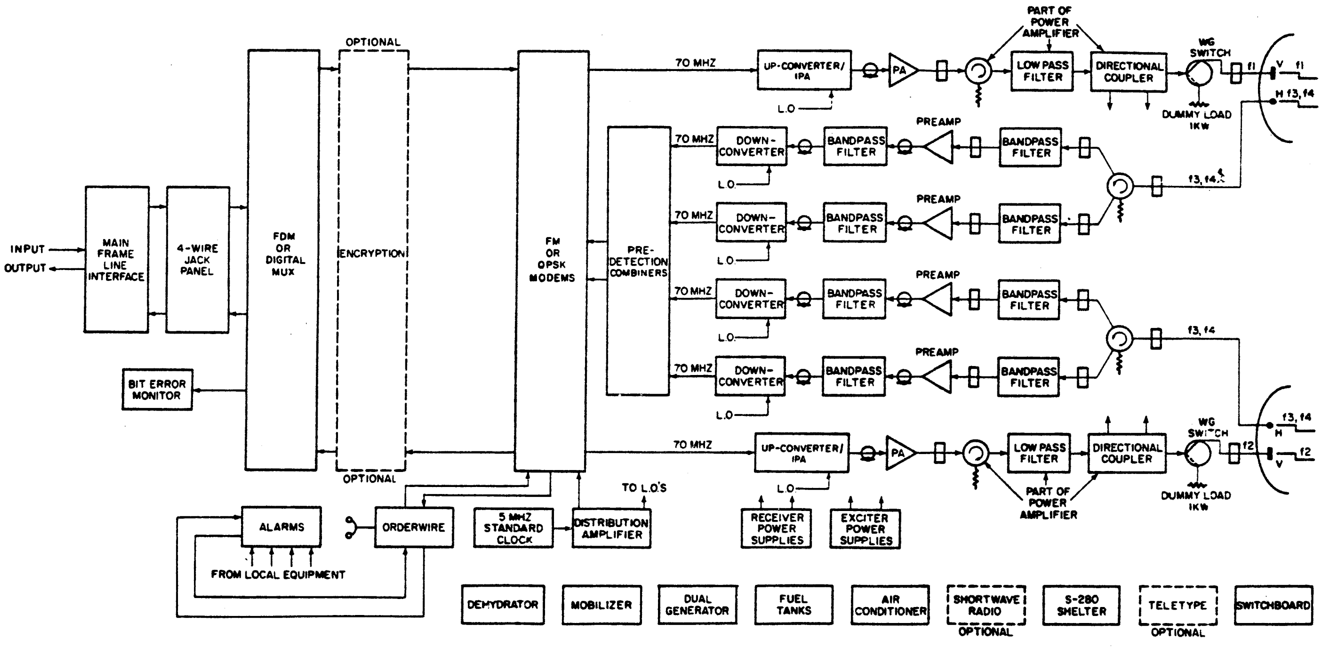


Figure 12. Simplified Block Diagram of a Tropo Radio's Terminal.

better) standard clock may be required. This clock drives the local oscillators which could be of a fixed frequency or a synthesizer controlled version.

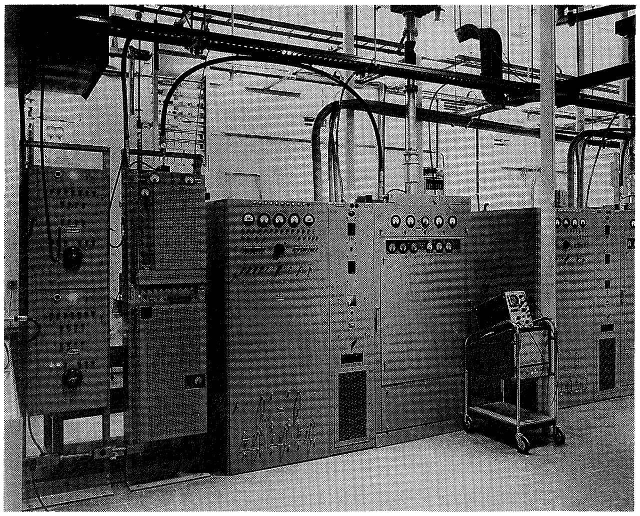


Figure 10. 10 Kw Quadruple Space/Frequency Diversity Terminal operating between 755 - 985 MHz, installed at Thrutch Island, British Columbia.

Figure 11. AN/MRC-98 Transportable Terminal, operating at 755 - 985 MHz. with 30 foot transportable antennas.

5.2 THE SOLID STATE EVOLUTION

The year is 1963: REL introduced the first solid-state FM low-level tropo radio. The design started with a clean sheet of paper -- a fresh development approach. All the experience gained over the years was translated into this new design. Even the FM wide-band modulator was changed from a serrasoid to a crystal-referenced 70 Mhz FM modulator. In later years, it was phase-locked to any desired stability.

The inherent nonlinearity of voltage-controlled FM oscillators was corrected with a diode function-generator which matched the transistors nonlinearity in opposite directions. Intermodulation distortion results of better than 60 db were obtained. A synthesized local oscillator for rapid frequency changes in tactical tropo terminals was developed. Even though archaic in today's technology, very-low phase noise was obtained with an electromechanical device, using a high Q mechanically-tuned master oscillator circuit. The receiver's face lift produced 4 db transistor RF amplifiers which covered the complete L, S and C bands -- and with an improvement in noise figures. Each of the four quad receivers automatically removed itself from the combiner interconnection in case of failure. Or one could manually remove a receiver for servicing, by disconnecting a coaxial cable, without disturbing the reduced diversity operation.

The demodulator received further attention. Limiting was increased to six stages using rapid acting back-to-back, hot-carrier silicon diodes driving a reverse diode discriminator. The Major would have whistled with joy seeing this design.

The FM threshold extension feedback unit was completely redesigned to eliminate the drifting problems of the tube version. It was also extensively field tested by the Air Force(12) on two over-the-air links with very good results. In addition to all solid-state advantages, the size reduction of the Low Level was dramatic. Figure 13 shows a commercial, complete quadruple-diversity terminal installed in Mozambique. Figure 14 shows a 10-watt dual- frequency diversity Low Level terminal built to military specifications, operating in the *S* (1.7-2.4 Ghz) or *X* (7.25-7.75 Ghz) band. Environmental testing alone took one year. We were happy to see that the equipment could run flawlessly forever at +52 degree C and 100 % humidity, especially since it eventually was installed in an air- conditioned building with controlled humidity.

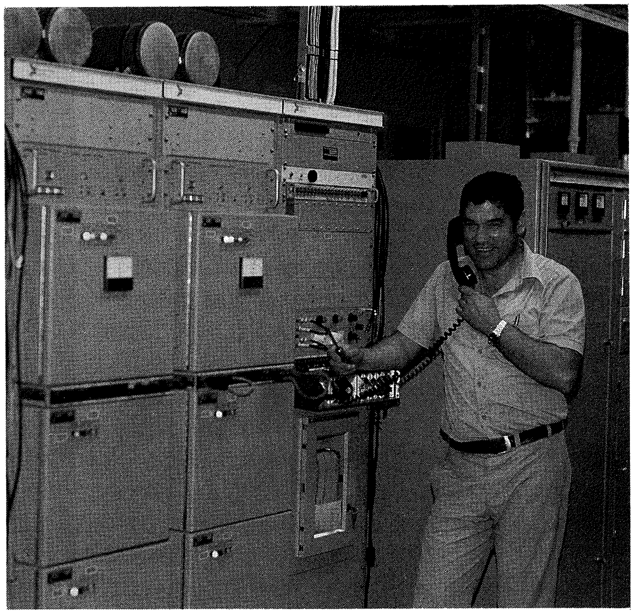
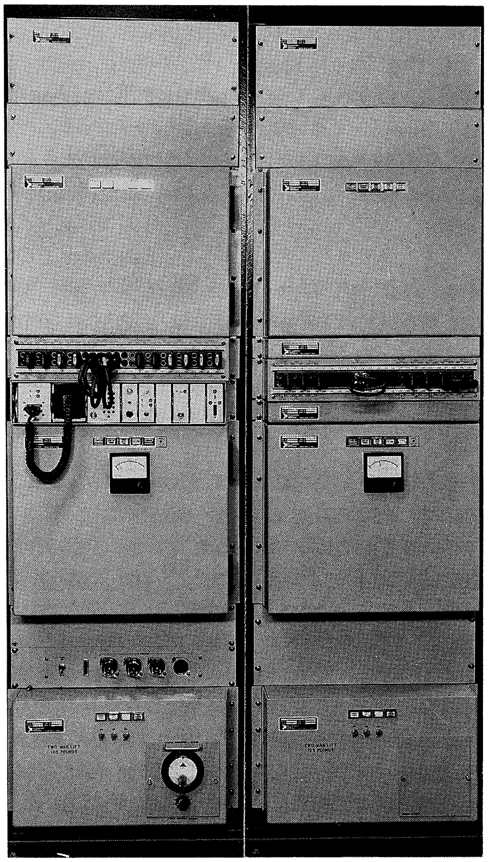


Figure 13. Quadruple Space Frequency Divesity 10 Kw Terminal operating between 755 - 985 MHz, installed in Mozambique.



Figue 14. Dual-frequency Diversity Militarized Low-Level Radio Terminal operating at 1700 - 2400 MHz, or 7250 - 7750 MHz

5.3 THE GREAT EXPERIMENT

During 1966, the Bell Telephone Laboratories, in Holmdel N.J., were still engaged in troposcatter systems analysis. REL received a call from George Travis advising us that BTL had received a contract to investigate intermodulation reduction on the Greenland-to-Iceland tropo link. Travis said, "BTL's approach will make use of a 10° angle diversity feed horn arrangement, in conjunction with a solid-state pre-detection combiner called *FALC* (forward acting linear combiner).(13) Since the *FALC* required 10E-7 carrier-frequency stability -- higher than the existing equipment possessed -- REL had to modify the local oscillators on both sites to stay within +/- 100 hertz of the carrier frequency of 800 Mhz.

The *FALC* operated at 70 Mhz and accomplished in-phase addition of different receivers by a heterodyne phase-stripping method which removed the carrier-phase flutters. Since the IF frequency was part of the generation of the *FALC* local oscillator, which had a 3 khz noise bandwidth, greater stability than the usual 10E-5 was needed.

BTL claims in their final report(14) of this investigation that substantial improvements with 6-way angle-diversity and predetection combining were obtained. "Winter month outage could be improved from 5% to an estimated 1% or less".

Angle diversity was never implemented. With today's digital technology, the intermodulation could have been substantially reduced or possibly eliminated using QPSK (quadratic phase shift keying) with an adaptive modem. See section 6.3, The Adaptive Modem Development.

6.0 1970 - THE START OF THE DIGITAL REVOLUTION

6.1 WHY USE DIGITAL TRANSMISSION ?

FM, the original modulation technique of troposcatter due to its noise immunity and its signal-to-noise (S/N) advantage over AM, was the obvious choice for tropo application. But, in today's environment, digital modulation does have certain advantages when compared to FM modulation.

These are:

a) Digital transmission can be made completely secure.

b) The digital transmission can be regenerated. This means that many links in tandem can be made as high in quality (low in errors) as a single link.

c) With an adaptive digital modem, inter-symbol distortion due to multipath dispersion (delay spread) over a tropo path can be corrected. Channel intermodulation created in the radio will also be substantially reduced. In addition, as a by-product, implicit diversity, which results from the coherent re-combination of multipath components, is generated as a function of multipath spread. This has the effect of multiplying the order of diversity as a function of the delay spread magnitude.

6.2 DIGITAL TRANSMISSION CONSIDERATIONS

When troposcatter transmission exceeds 100 km, the quality of digital transmission without equalization is usually adversely affected by delay spread. Delay spread is caused by the multipath characteristics of the communication path and is a function of the antenna take-off angle, the antenna diameter and path distance. The received digital signal appears as both a primary signal and delayed signals. This causes inter-symbol interference (ISI). Standard digital modulation employing phase-shift keying (PSK) has a low tolerance for ISI. Irreducible bit errors will occur when the ratio of the delay spread (2s) to the symbol interval (t) is more than 0.05.(15)

6.2.1 THE DELAY SPREAD

An estimate of delay spread causing inter-symbol interference was initially investigated by Bello.(16) Godet also has analyzed the delay spread and generated a very readable document(17) which gives the delay spread magnitude as a function of distance, antenna take-off angle, frequency and antenna reflector diameter. His analysis may be on the conservative side for frequencies in the C band (4.4-5.0 Ghz). Figure 15 show graphs for various antenna sizes operating at the 0.8, 2, and 4.4 Ghz frequencies with a zero-degree take-off angle. Negative take-off angles will show lower delay-spread. Positive take-off angles will show larger delay-spreads.

Sherwood et al.(18) ran interesting experiments at various test ranges using 6 to 15 foot antennas which identified the magnitude of delay spread as a function of percent of time. Measurements at 4.8 Ghz showed that the delay spread due to multipath fluctuated about 8:1 between 1% and 99% of time. Loosely speaking, it was shown that 1% of the time the delay-spread peaks could hit twice the average, and appear to go even higher for lower percentages.

6.3 THE ADAPTIVE MODEM

6.3.1 THE BEGINNING

During the later part of the 1960's time frame, the engineering group under Mark Tidd, Bell Telephone Laboratories' supervisor for radio transmission at Holmdel, was pursuing adaptive digital modem techniques, potentially usable in troposcatter. George Travis, a member of this group, still remembers the bread-boards that were built and used on a 180 mile digital tropo test path which stretched from Holmdel, N.J to Monrovia, Maryland. The antenna diameters were 60 and 30 foot respectively, and operated at 6 Ghz in angle diversity. According to Travis, the results were encouraging and were published in 1970 in five papers at an IEEE conference in Montreal.

6.3.1.1 THE ADAPTIVE EQUALIZATION APPROACH

It appears that BTL's experimentation was a forerunner to a November 1973 award by USAECOM to GTE/Sylvania, as prime contractor, and Signatron, as sub-contractor, to build an adaptive digital modem for troposcatter application, identified as MDTS (Megabit Digital Troposcatter Subsystem).

The requirements called for transmission rates of 6.276 Mb/s for up to 250 nautical miles (nmiles), and 12.552 Mb/s up to 150 nmiles. The modem was to be "quadruple diversity using coherent 4 psk modulation and demodulation uniquely employing forward equalization at IF, and feedback equalization at baseband to counteract inter-symbol interference and timing jitters".(19)

To determine the required delay-spread correction capability of the modem, consider as an example, the 6.276 Mb/s data rate at an RF transmission frequency of 2 Ghz, using a 30 foot antenna reflector at zero take-off angle. This is possibly the worst case condition since for this theoretical 250 nmiles link and a confidence factor of only 50%, the time availability for a BER of 10E-6 is only about 99%. This calculation is based on *NBS 101* and the BER performance achieved by the MDTS. The calculated delay spread for 250 nmiles (469 km) is 415 nanoseconds. See Figure 15b. The symbol interval for 6.267 Mb/s is 319 nsec. Therefore 2s/t = 1.3. Considering the delay spread peaks of 2:1, the maximum delay-spread correction requirement turned out to be 2.6.

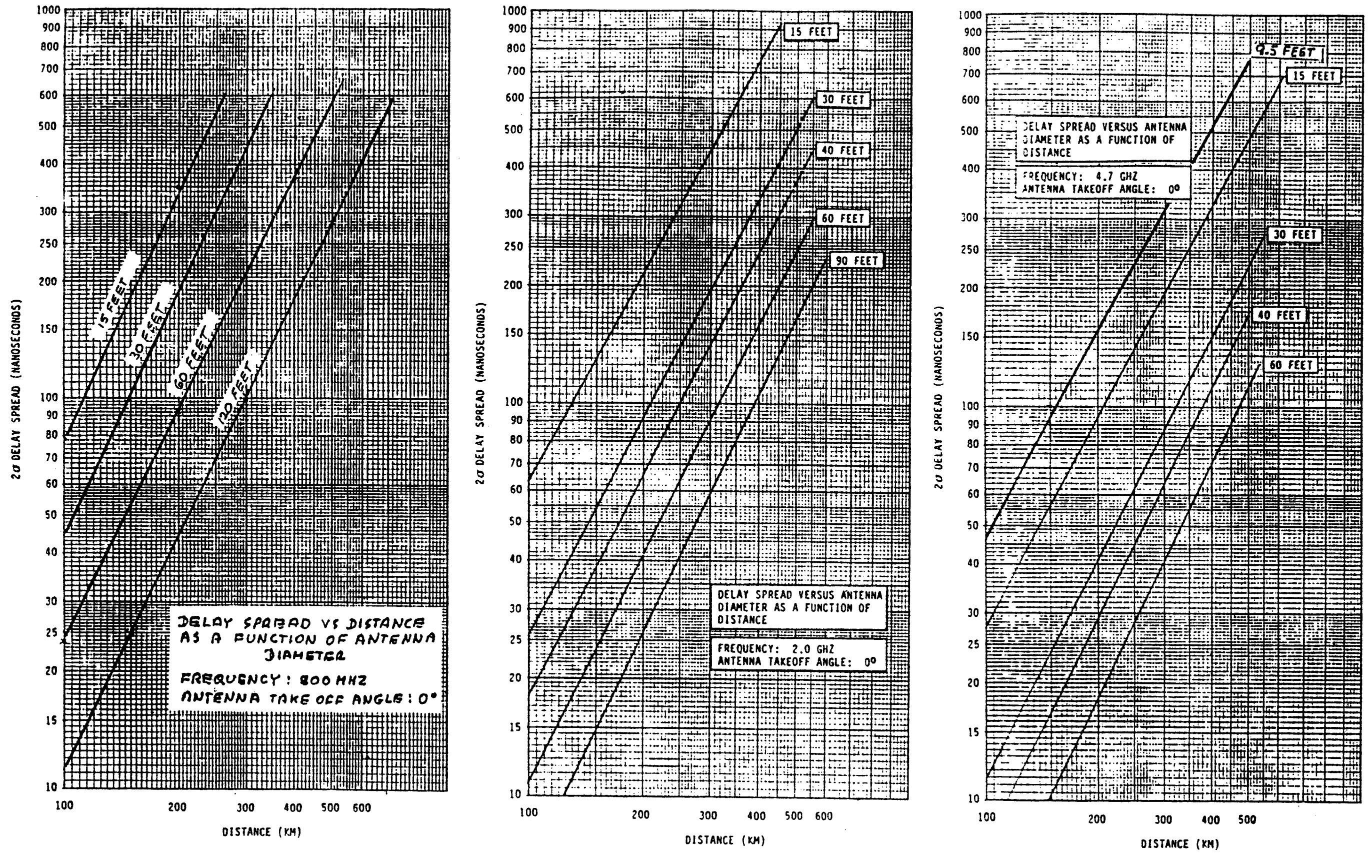


Figure 15. Delay Spread vs. Distance As a Function of 2s/t.

To eliminate inter-symbol interference, decision feedback equalization was incorporated. This took the form of IF forward-tapped, delay-line filters and backward-baseband equalizer filters. These patented filters(20) which were actually the heart of the adaptive demodulation technique were furnished by Signatron. The principal of operation is explained by Monsen(21) and GTE's final report. (22)

This development, which produced eight prototype modems, nomenclatured MD-918/GRC, met the BER specifications and demonstrated predicted implicit diversity. This success fostered a second generation of modems, nomenclatured DTM-9000, and also built by GTE with equalization filtes furnished by Signatron. It was reduced in size, and used by REL in systems testing with HPAs, for future applications. This system testing experiment included the specially developed S-band 10 Kw vapor-phase-cooled klystron tube intended for high-speed digital troposcatter transmission. This klystron had wider bandwidth, lower power consumption, and high reliability.(23) The testing and comparison to similar klystrons is described by Gruber et al.(24)

6.3.1.2 THE FINAL SOLUTION

The year is 1985. ESD decided to have a militarized modem produced, designated the MD-1208. It was to be used for future digital upgrading of DCS tropo links. The job went to GTE who subcontracted most of the program to Signatron, who completed the adaptive modem to the ESD specifications. Signatron developed, in parallel, a commercial version of the modem which had similar advanced features such as a 2s/t of 3.7 capability, remote control and contained the second-level multiplex. The modem, designated S-575, obtained its ability to combat such high multipath dispersion by using a 6 tap forward IF equalizer with a tap spacing of t/2 and a 4 tap backward equalizer with simple spacing.

After 20 years of uncertainty, this evolutionary process appears to have finally created a digital modem which fulfilled desired specifications for both the government and commercial wish lists. The time frame certainly was governed more by economics than brain power.

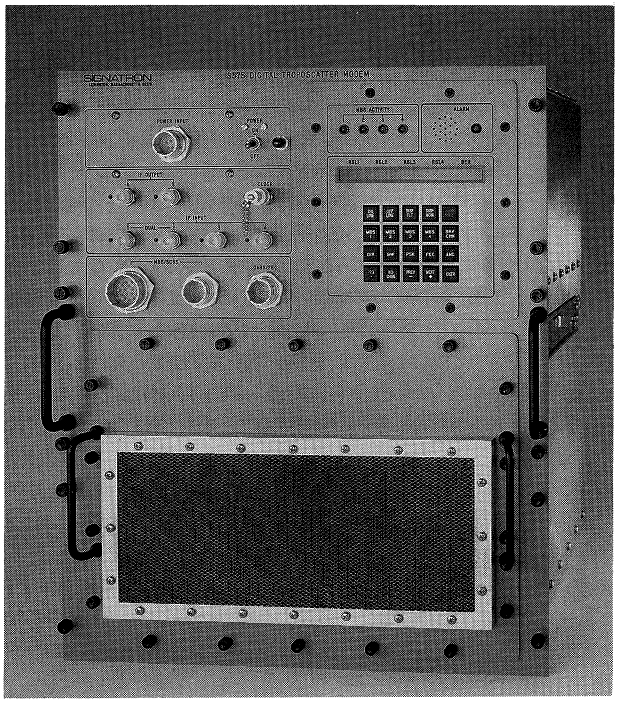


Figure 16. Signatron S-575 Adaptive Digital Modem.

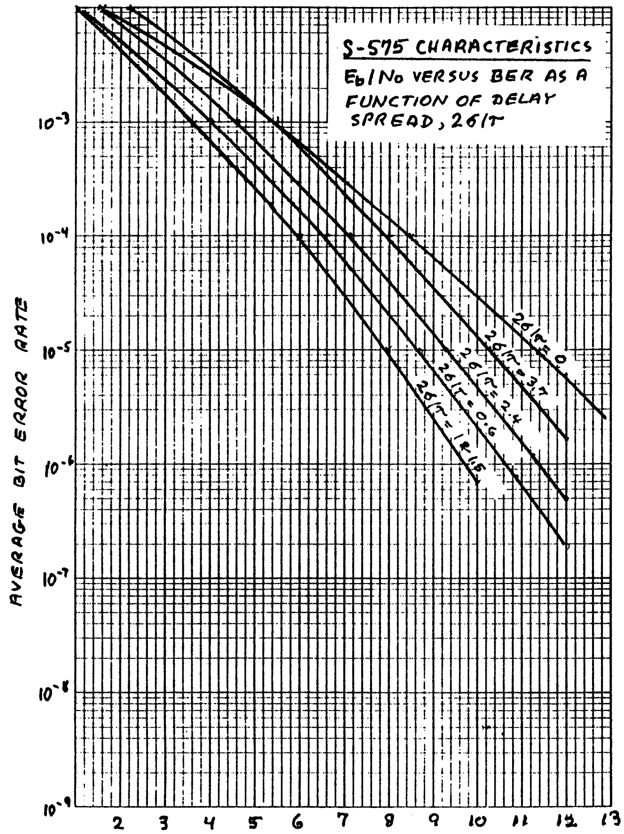


Figure 17. E_b/N_o vs. BER as a Function of 2s/t

6.3.1.3 THE STRATEGIC MODEM, FINALLY

Figure 16 is a photograph of the modem, courtesy of Signatron. Its size is relatively small, considering its redundancy obtained by automatic switch over. (This feature which makes the diversity tropo terminal completely redundant permits unattended station operation.) The modem size is especially startling when compared to its ancestor, the MD-918/GRC, which was non-redundant and took up a six-foot relay rack. The modem which is computer-controlled and has remote-control capabilities, contains the modulator, the IF amplifiers with associated equalizers, the pre-detection combiner, demodulation process, backward equalizers and second-level multiplex. The current design of up to 240 CVSD (continuously variable slope delta) channels in 15, 30 and 60 channel mission bit-stream rates is similar to FM modems in capacity. But surprisingly, the digital modem is more bandwidth efficient than high quality FM. Using QPSK modulation, the bandwidth efficiency of 1.4 bits/hertz means that only 5.85 Mhz bandwidth is used by the digital modem, compared to 10 Mhz for 240 FM channels. This means that the receiver's sensitivity has been improved by 2.3 db due to the bandwidth reduction. (A 192 pulse-code modulation (PCM) channel system which the manufacturer states is in the planning process, will carry 12.6 Mb/s and will require a minimum bandwidth of 9 Mhz.)

6.3.1.4 THE MODEM'S PERFORMANCE[**]

The implicit diversity gain, a by-product of an adaptive digital modem, turns out to be about 3 db for the S-575. This is a 3 db diversity advantage over FM. Implicit diversity gain can be seen from Figure 16 by comparing 2s/t = 0 to a 2s/t between 0.6 and 1.5. Figure 17 was measured with a troposcatter simulator.

This is really the performance's bottom line. A 10 db per-diversity- receiver input signal in quadruple diversity will give a BER (bit error rate) of at least 10E-5 which is considered the lower limit of an acceptable baseband signal output for telephone channels. (This assumes that some delay spread exists.) It might be compared to the equivalence of the threshold carrier-to-noise of an FM receiver. The digital performance assumes a certain window of delay-spread as may be seen from the graph.

6.3.1.5 A BIT OF IRONY

The first application of the strategic modem, the MD-918/GRC, was for the Berlin-to- Bocksberg link in Germany. Four prototype units originally built in 1975 were installed while East and West Germany still were split.

The link is probably only interesting conversation today, but at least it demonstrated that the digital system worked.

The major current application of the S-575, the first production version of the 1973 beginning, is its use in the tactical transportable S-280 shelter and strategic terminals.

6.4 THE TACTICAL ADAPTIVE MODEM

6.4.1 HISTORICAL BACKGROUND

The Raytheon Company, during the early 1970s, also worked on the development of a time-gated adaptive digital modem with QPSK modulation. Their approach was to use "adaptive matched filtering demodulation" to combat the inter-symbol distortion produced by the multipath dispersion. This was in contrast to the adaptive equalization pursued by GTE/Sylvania.

The Raytheon design technique was named DAR (distortion adaptive receiver). The original development, testing and theory may be found in an 1976 RADC report(25) More recent and very readable articles describing the current status of the modem are by Smith et al.(26) and Unkauf.(27,28,29) Godet(30) analyzed the demodulator in simple algebraic mathematical form.

[**] Digital transmission is controlled by E_b/N_o, and 2s/t for a given error rate. Also $E_b/N_o = (C/N)(BW/f_b)$, where:

E_b = energy per bit or carrier power times bit period, CT_b.

N_o = spectral density of noise (average noise power in 1 Hz bandwidth.

2s = rms delay spread (twice the standard deviation of the channel delay power spectrum)

t = symbol interval (two bit interval for differentially-encoded QPSK).

BW = noise bandwidth of receiver

f_b = transmit bit rate $(1/T_b)$.

6.4.2 THE APPLICATION

When the US government decided to have digital tactical transportable troposcatter terminals developed, the Raytheon Company won the award in the late 1970's. We believe that this was due to the DAR modem which was smaller and much simpler than a derivative of the MD-918/GRC. Even though the DAR had much less dispersion combating capabilities than the GTE modem (about 2s/t=0.5), it was sufficient for the 150 mile transmitting requirements of a 2 kw system. The transportable uses two 9.5 foot antennas, operates in the C-band (4.4-5.0 Ghz) and can handle a maximum traffic capacity of 4096 Kbps. (This addresses the V2 system, the larger of the two currently available options. Figure 18 shows the latest version of the DAR modem, courtesy Raytheon.)

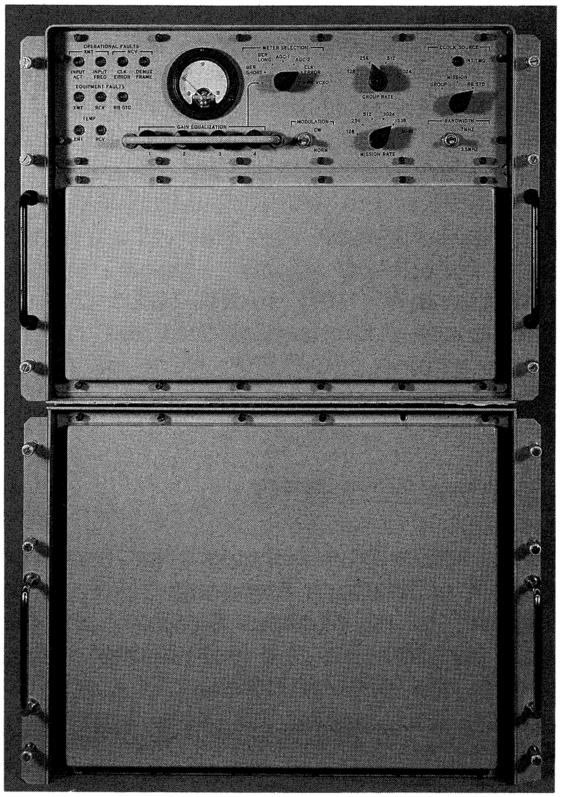


Figure 18. Raytheon DAR Adaptive Digital Modem

As an example, consider a worst case condition. A 150 mile (240 km) path, zero degree antenna take-off angle, elevation only 10 meters above sea level, and a 4096 kb/s data rate. From Figure 15, we see the delay spread is 222 nanoseconds. Since a bit stream of 4096 kb/s has a symbol interval of 488 nanoseconds, 2s/t=0.45 will only be exceeded 1% of the time. This indicates that the quality of performance is signal limited and not delay-spread limited. For a take-off angle of -5 milliradians, the 2s/t improves to 158/488=0.32.

6.5 THE GODET ADAPTIVE MODEM APPROACH(31)

During 1984, an attempt was made by REL to find a simplified and low-cost solution to the adaptive modem design and still operate within the high 2s/t region normally encountered in troposcatter transmission for distances greater than 100km.

Delay-spread, resulting from the characteristics of the tropo path, causes the response from a short pulse emitted from the transmitter to be spread out over a finite time interval at the receiver. Therefore, Godet reasoned, if a single pulse of length "t" (which he called the sounding symbol) is transmitted, one could analyze the pulse contamination due to the dispersion of the transmitted signal, and correct the data stream based on this finding. To assure that the pulse will not be contaminated by future and past signals, a minimum of four silent symbol spaces will appear before and after the pulse. By deduction, we can see that the higher the delay spread, expressed as 2s/t, the more silent symbol spaces have to be used.

The sounding symbol must be repeated before the characteristics of the tropo medium change appreciably. To establish a record of data contamination, the I and Q channels have to be sampled more than once per symbol. We shall assume that each channel is sampled 40 times per symbol for the interval including the sounding symbol and the 4 silent symbols following it. This will store 40 referenced voltage values for each sounding symbol for the I and Q channels. Using this information, Godet shows that by suitable circuitry, a reverse correction to the data stream can be made and the inter-symbol interference greatly reduced.

Due to the large estimated development cost, the relatively small projected application and the availability of the Signatron equalizer technique, the project was discontinued.

7.0 CONCLUSION

After almost 40 years of tropo operation, FM is still the form of modulation for existing stations. Few new commercial troposcatter terminals are being installed, since satellite transmission spans the whole world giving access to every country. In addition, the military and government troposcatter budget is severly limited and essentially supports only existing operational stations. Oil company requirements and some Third World Countries, where satellite transmission is not economical, keep tropo expansion alive.

Tremendous progress has been made in reliability, permitting unattended operations. Twenty-four hour staffing used to be a heavy economical burden.

Tactical military tropo terminals with secure transmission requirements use digital modulation. As an example, the AN/TRC-170 is the standard US military transportable troposcatter radio set and finds continuous applications. The S-575 adaptive modem is used in both strategic and transportable versions where large delay spread and high bit speed (6.3 Mb/s) requirements are encountered.

8.0 EPILOGUE

The large FM intermodulation distortion of the Greenland-to-Iceland path (*DYE-4* to *DYE-5*), is due to its 450 miles over water path. Substantial intermodulation distortion improvement now could be made if digital modulation would be used. This would not reduce the existing 72 channel capacity or require changing the frequency/space diversity method of operation.

To do this, a change from FM to QPSK digital modulation would have to be made. The digital modulation must incorporate an adaptive demodulation process such as the Signatron S-575 adaptive modem, or equivalent. The average calculated *DYE-4* - *DYE-5* RMS path delay-spread as per Godet's method, is about 454 nanoseconds. In addition, there will be delay-spread peaks and water signal reflections creating additional differential delays. Both phenomena actually will enhance performance due to the adaptive modem's implicit diversity gain, which results from the coherent combining of the multi-path components. (Actually, there is a limit which, as an example, for the S-575, is 2s/t=3.7. Beyond this the performance would deteriorate.)

The 72 channel digital transmission would consist of three T1 channels operating at a mission bit speed of nominally 4.85 MHz when using PCM at 64 kb/s per channel. If the Drama MIL multiplex is used, it may require a mission bit stream of 6.464 Mb/s but would be capable of up to 96 channels. (Even for 96 channels at a mission bit stream of 6.464 Mb/s, 2s/t is only 454/309 = 1,47, a number which can easily be handled by the S-575 modem.)

BUT - this would probably require a substantial budget, since all the Low Level equipment (exciters and receivers) for both stations would have to be replaced; this would be in addition to the multiplex with A/D and D/A converters. The switch over transition without interruption of service plus acceptance testing foreshadows substantial problems. Based on the experimentation of digital transmission through HPA's(23) and considering that the modem also will correct some of the HPA's non-linearities, the HPA'S could be left alone but should be backed-off 1db. This still will generate a power output of 40 kw. Since, for digital transmission, not more than 20 db of carrier-to-noise interference into the receiver is required to meet 10E-7 BER, some latitude on the HPA power output operation will exist.

ACKNOWLEDGMENT

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RADIO PAGING IN THE NETHERLANDS

by **Louis Meulstee, PA0PCR** (M)

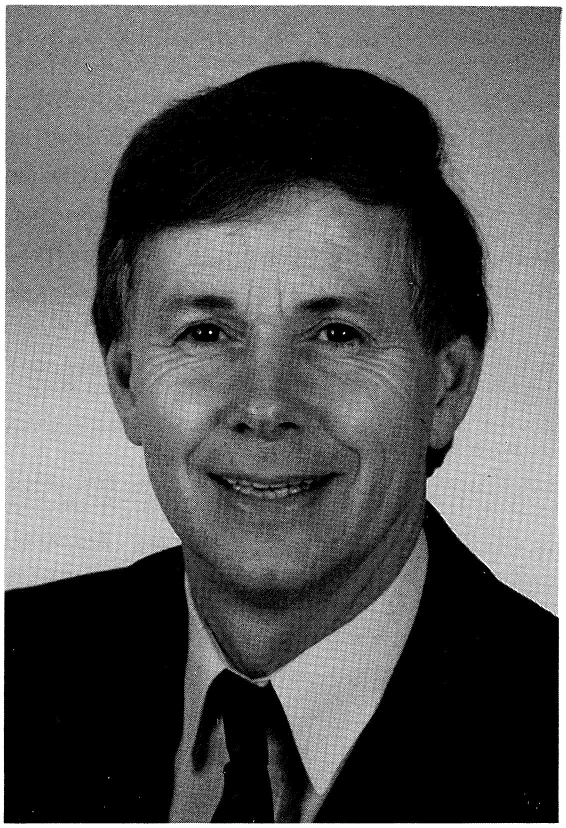
SUMMARY

An historical and technical description is given of the *Semaphone*, the National public radio paging service of the Dutch PTT, with the emphasis on the early developments.

The service, a fully-automatic, individual, public paging system accessible by any telephone subscriber, was the first of its kind in the world. At its inauguration in 1964, it had a national coverage; within a few years, the coverage was expanded to Belgium and Luxembourg.

The early Central Control System developed by the Dutch PTT in the early 1960s was continuously subject to expansion and modernization. The current *Semaphone System 3*, operational since 1988, differs considerably, technically from the initial and second systems: e.g., giving provisions for numerical and alphanumeric paging. Fully operational at this time, it still maintains Benelux coverage.

In the course of the years, the physical size of the paging receivers has been reduced from 4500 grams (approx. 10 lbs.) to 200 grams (approx. 7 ozs.). Receivers operating on the current system, available with a wide range of optional features, are much lighter in weight and smaller in size.



Louis Meulstee, PA0PCR

INTRODUCTION

The *Semaphone* is a radio paging service enabling any telephone subscriber to make a selective call to any portable paging receiver located anywhere within the Benelux countries. The system comprises a Central Control System (CCS) and a number of high power VHF transmitters. The input of the CCS is linked to the national telephone networks; its output is connected to the transmitter sites which are located throughout the countries.

A *Semaphone* call, dialed by a telephone subscriber, is stored and processed by the CCS and forwarded to the transmitters. On the pager, a beep indicates that a call is being received. The last dialed digit, providing a user pre-arranged message, is indicated on the *Semaphone* by a number of lamps or in a display.

Technical details were considered to be out of the scope of this paper, having been described in minute detail in other papers.

EARLY EXPERIMENTS

As explained in a previous paper*, soon after the opening of the National Public Radiotelephone Network in 1949, the need was felt for a selective radio paging system in order to call a mobile station. It was indicated, however, that a paging receiver should not be a part of the mobile radio-telephone system which, at that time, was being used in other countries.

* * * * *

*Louis Meulstee "Mobile Radio in the Netherlands" *Proceedings of The Radio Club of America*, Vol. 66, No. 1, May 1992, pp. 24 - 30.

After extensive trials, it became apparent that a nationwide paging service should not only include the mobile radio-telephone service but be set up as an independent service. It was anticipated that hand-held or portable paging receivers would be a future demand.

In 1955, the first trials with mobile paging receivers started with commercially-manufactured Swiss "Autoruf" (car paging) equipment, adapted especially for the PTT. Due to their weight and battery drain, the receivers could be operated only from a vehicle battery. A total of seventeen receivers were fitted into vehicles of potential customers such as general-practioner medical doctors, a veterinary surgeon, an ambulance, public transport, an emergency-breakdown service vehicle, the television service, and a number of PTT vans and vehicles.

The Hasler paging receivers were superheterodynes operating on 85.9 MHz, with a superregenerative detector operating on the intermediate frequency of 10.7 MHz. The amplitude-modulated transmitter, being a part of the complete system by Hasler, was located at the PTT laboratory near The Hague. Requests for calls, or urgent calls, were made via a telephone operator. A call comprised three different tones transmitted sequentially and repeated three times.

SIMOFOON

The trial system was called *SIMOFOON*, derived from ***Si****gnaling to a* ***MO****bilo****FOON*** The latter, *MOBILOFOON* (sometimes called *MOBILOPHONE)*, was a name devised by the Dutch PTT in the late forties as a translation from the English name *Mobile Radio-telephone.*

In the early days of the trial system, our veterinary surgeon paid a routine visit to "Duindigt", a large race-course near The Hague, in order to carry out an examination of a race horse. When finished and about to climb into his car, the Hasler paging receiver suddenly indicated a red emergency call. Still at the stables, he telephoned his home and heard about an accident with a race horse at an adjoining stable, which urgently needed his attention. Turning the car and driving only 450 meters (about a quarter of a mile) was the work of seconds. On arrival, he found the stable locked. In a few minutes, the groom arrived. He'd had to walk to a nearby telephone to report the emergency and found to his astonishments that, upon his return, the surgeon was already waiting at the stable, knowing all about the situation. (One should remember that Europe, in the mid-50s, had a considerable technical time-lapse behind the U.S.A., and the marvels of radio were generally unknown to the public.)

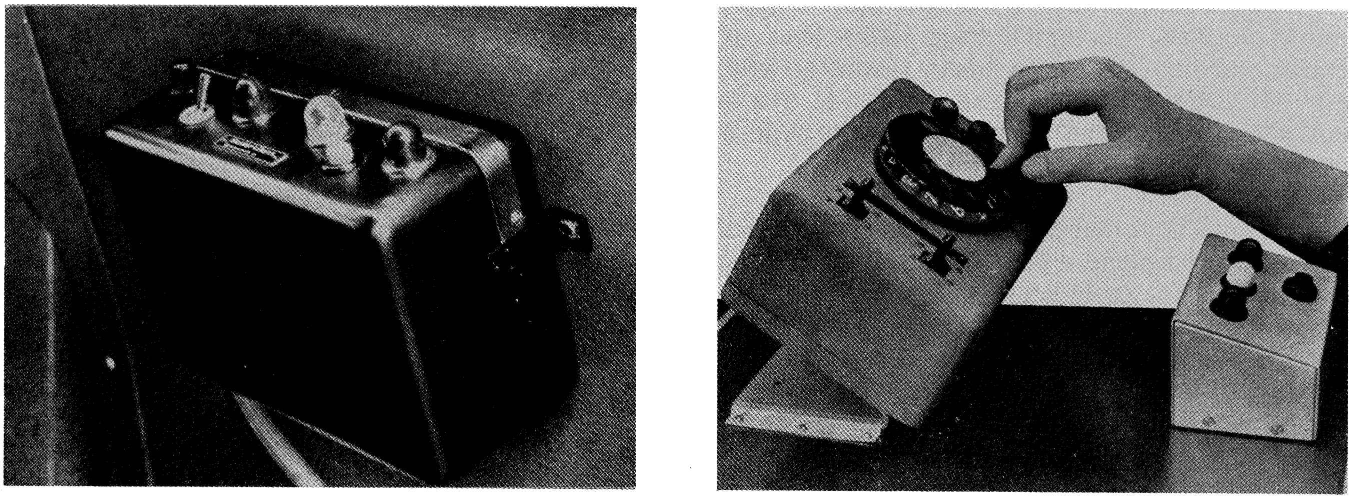


Figure 1. Hasler Paging System Used in Early Experiments in 1955.

(Left) Receiver remote control unit mounted in a vehicle and (right) operator console. The system worked basically with three different sub-audible tones transmitted sequentially and repeated three times. Tuned reeds in the receiver were utilized as selective tone receivers. In addition to the standard white calling lamp, a PTT modification included the fitting of a second (red) lamp which, when activated by the operator, indicated an emergency call. The receiver had two RF stages, a mixer with crystal-controlled oscillator and, in order to reduce battery consumption, it had a superregenerative detector operating on the intermediate frequency of 10.7 MHz. During the early Dutch experiments, the system operated on 85.9 MHz. The power consumption at 6 volts was approximately 18 watts.

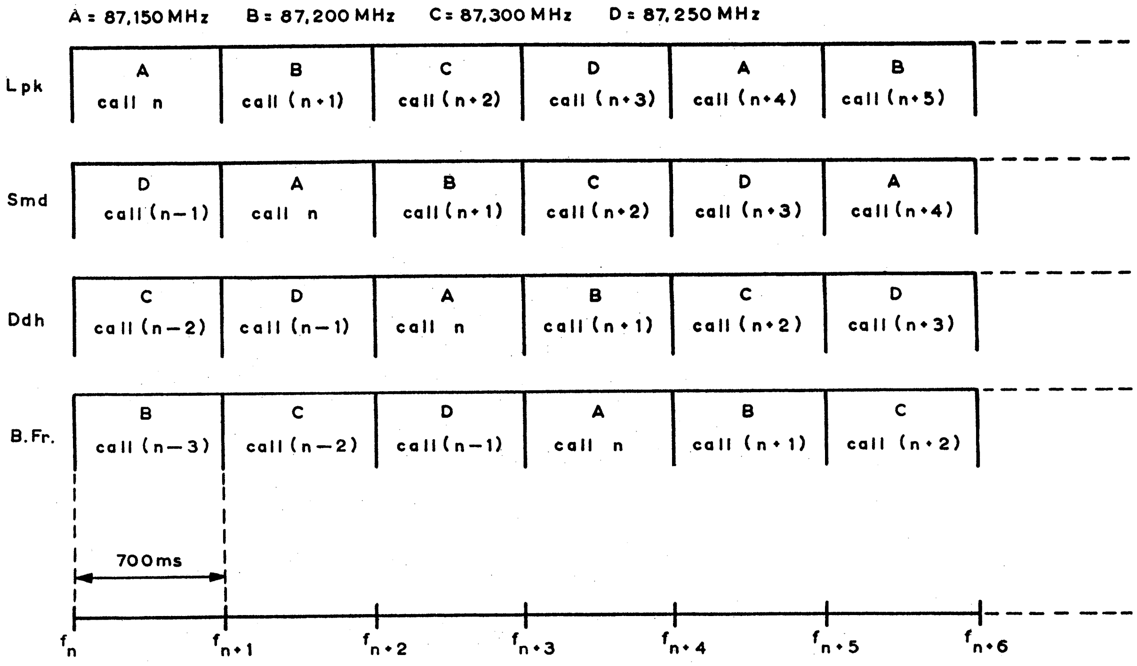


Diagram 1. Operation of the Network Transmitters
Showing how a call is transmitted on one frequency by four transmitter groups.
Four frequencies were assigned: 87.150, 87.200, 87.250, and 87.300 kHz.

LAND RECOVERY

After the first successful trials in The Hague, the Hasler equipment was used as an interim paging network covering East Flevoland, a vast area recovered from the sea, at the time that recovery was in progress. During this stage neither lines nor cables could be laid on the freshly recovered land, so all communications of the state agriculture-department officials were through a closed-network radio telephone system.

In 1959, a new paging system was installed in the East Flevoland area. Transistorized paging receivers were a great improvement over the early Hasler receivers not only in consuming a small fraction of the current but also in using frequency modulation resulting in a notably-better performance, reliability and operating range. Transmission of calls was still done by an operator who, after a call was answered, connected the radio telephone with the public landline telephone network.

SEMAPHONE

One of the major conclusions of the trials was that a huge number of subscribers could be expected, requiring a large number capacity and, more particularly, a large traffic capacity. This led to the formation of a fully-automatic service.

Specification of pagers and the Central Control System were set up in the late 1950s in cooperation with the PTT Laboratories and Philips Telecommunication Industries (PTI). In 1961, the new service was officially cleared to go-ahead, and orders were placed for the development and manufacturing of a CCS at the PTT laboratories, and for a number of paging receivers at Philips. Over the next two years, the system was tested and gradually improved until satisfactory results were obtained. The service was inaugurated on 24 September 1964, initially with three transmitters providing coverage in the Netherlands only.

It was decided to continue with the already generally-accepted name *SIMOFOON*. However, as a result of anticipated legal action of a certain manufacture whose product name had a close resemblance with the name *SIMOFOON*, it was altered into *SEMAFOON* (or *SEMAPHONE*) from the Greek *SEMA* = Signal, and *FONEIN* = Calling. Eventually, it was considered that this was an even better name for the new, public radio-paging service.

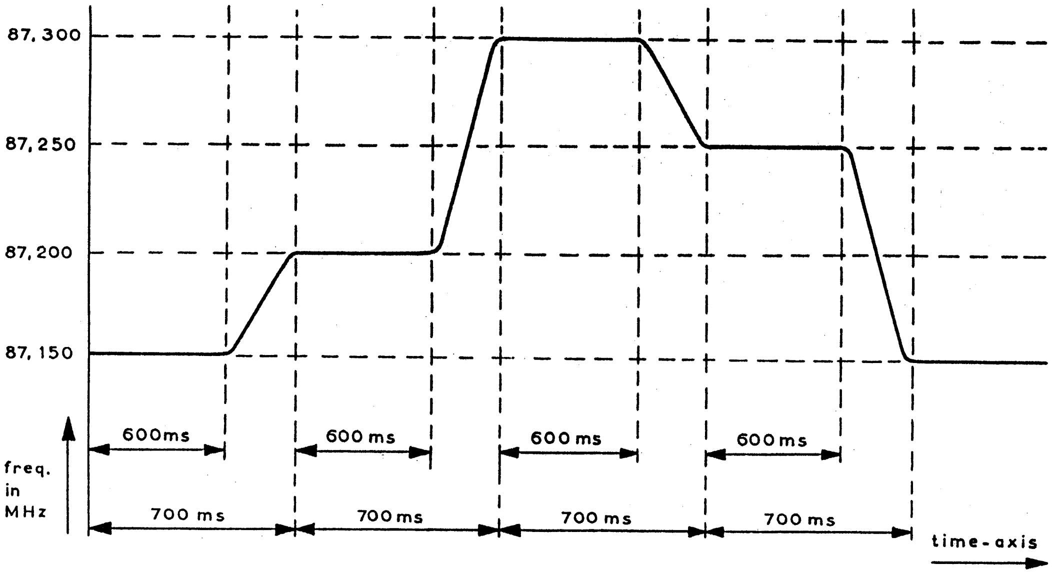


Diagram 2. Shifting Cycle Principle.

Explanation of shifting cycle principle of one transmitter group only.
A frequency shift of more than 100 kHz is avoided as a precaution against unwanted radiation.

TECHNICAL DETAILS

Transmitter Network

The system operated on two (later four) RF channels around 87 MHz, just below the FM broadcast band, permitting the use of high power and allowing the employment of standard FM broadcast transmitters.

The earlier *Simofoon* investigations and trials had already shown that FM or PM had preference to AM. A further advantage was that use could be made of developments of existing radiotelephone components such as RF low-power drivers and phase modulators driving the standard broadcast transmitters. Three transmitter were initially installed, later extended with transmitter sites in Belgium and then a number of auxiliary low-power transmitters.

RF Switching

To prevent interference between the transmitters and to avoid the addition of a channel switch in the paging receiver, a frequency-shift system was devised. Two frequencies (later expanded to four) were assigned, resulting in two (four) versions of pagers, each identical except in frequency. Diagram 1 shows that a call is repeated four times on one frequency in a fixed order by the four principal transmitters. Each transmitter is shifted in frequency every 700 milliseconds. Steps of more than 100 kHz shift were avoided as being a cause of possible radiation of an interference spectrum. The shifting principle for one transmitter is shown in Diagram 2.

Capacity

Trials with sequential and simultaneous transmission of calls pointed favorably towards a sequential system. In the selective call system, use was made of a series of thirty audio frequency tones in the range between 1,000 Hz and 6,000 Hz. Three tones with a duration of 100 milliseconds were transmitted in succession, providing about 24,360 combinations. With four RF channels each having 24,360 combinations, the network had a theoretical capacity of 97,440 users. However, limited by the duration of the call which was repeated after approximately 20 seconds, and given an average number of 0.5 calls per user per day, the traffic capacity of the system was calculated at about 51,420 users. In addition to an individual call, a group-call to a number of paging receivers could be made. Connecting to a private exchange was a feature of the CCS.

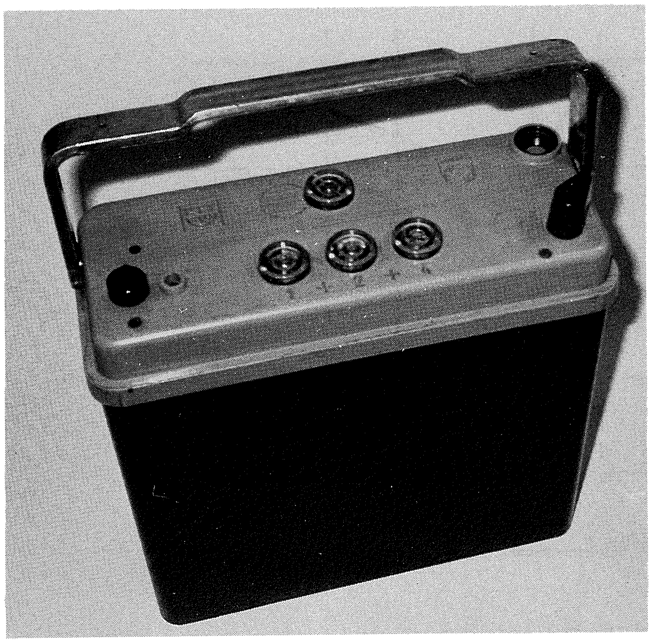


Figure 2. Prototype *ESCORT* (1963).

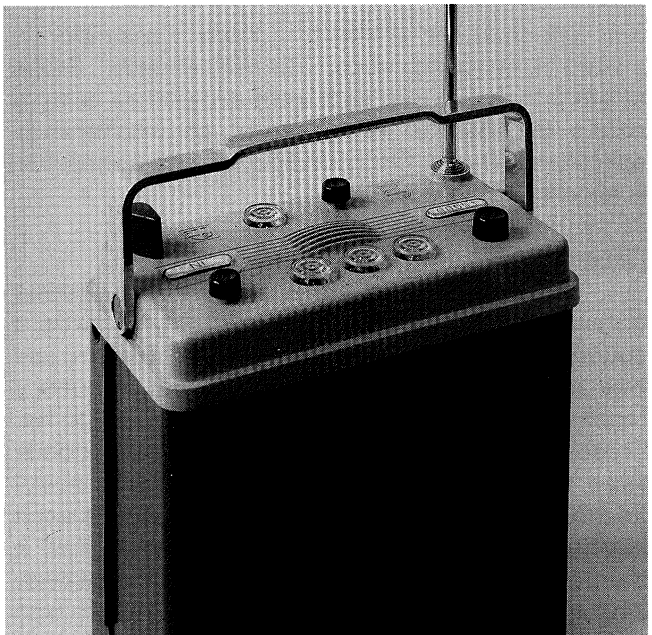


Figure 3. *ESCORT* Paging Receiver (1964 - 1990)

ESCORT PAGING RECEIVERS

In the late 1950s, with the advent of suitable RF transistors, it became possible to develop fully transistorized paging receivers. The first receiver of this kind in operational use by the Dutch PTT appeared in 1959 with the opening of the new, local closed-circuit *Simofoon* system in East Flevoland. Experience with these still rather bulky and crude receivers formed the base for the more compact *ESCORT Semaphone*.

A prototype became available for trials in the early 1960s and full scale production began in 1963. The *ESCORT Semaphone* saw 26 years of service due to the fact that many customers had a fixed installation aboard a vessel or in a vehicle and, consequently, in not having to care about size and current consumption, were very slow to exchange their receivers in the early 1980s.

An interesting feature of the *ESCORT* was its optional relay function providing six customer-usable contacts, activated by the call and code digits.

BENELUX COVERAGE

In 1966, the transmitter network was expanded with two transmitters in Belgium: Denderhouten in the west and Baraque de Fraiture providing coverage in the south and east of Belgium. The Dutch transmitter in the south then was used only in emergencies as it was found that one of the Belgian transmitters would give adequate coverage of that particular area. Although the participation with Belgium was agreed in 1964, the Belgium service was inaugurated only on 14 February 1967. In 1980, the Luxembourg PTT joined in the *Semaphone* system.

The transmitter network of the Belgian part of the *Semaphone* system was serviced by Dutch PTT. The Belgian site of Baraque de Fraiture was invariably and intimately called by our technical engineers as "Baraque de Friture", a pun at the Belgians who are famous for their French-fried potatoes usually sold along the streets as "fritures".

MINOR PAGING RECEIVER

In August 1971, a new paging receiver was introduced. The *MINOR Semaphone*, developed in close cooperation with Philips Telecommunica-

Figure 4. *MINOR Semaphone* (1971 - 1990)

The successor to the *ESCORT* was considerably lighter and smaller. It was powered by a NiCad battery and, when fully charged, provided 8 hours of continuous reception. It operated on the *Semaphone Systems 1 and 2*, with only a small difference functionally from the *ESCORT*. The readout of the three code digits is by three miniature lamps located on the top of the *MINOR*.

tion Industries, was equipped with a rechargeable NiCad battery providing approximately 8 hours operation with a fully-charged battery. Thin-film technology and general advances in manufacturing made it possible to reduce its weight to one-sixth of that of the initial *ESCORT Semaphone* while the size was reduced to that of a pocket-sized paper-back book. Basically, the *MINOR* operated similarly to the *ESCORT* -- the main difference being in the layout and operation of the controls. An incoming call was signaled by a beep and, in order to reduce current consumption, the displayed digit code was presented only when pressing a "readout" button. The readout of the code digit was still by three miniature lamps indicating the digits 1 + 2 + 4, providing an indication of six different, user pre-arranged messages.

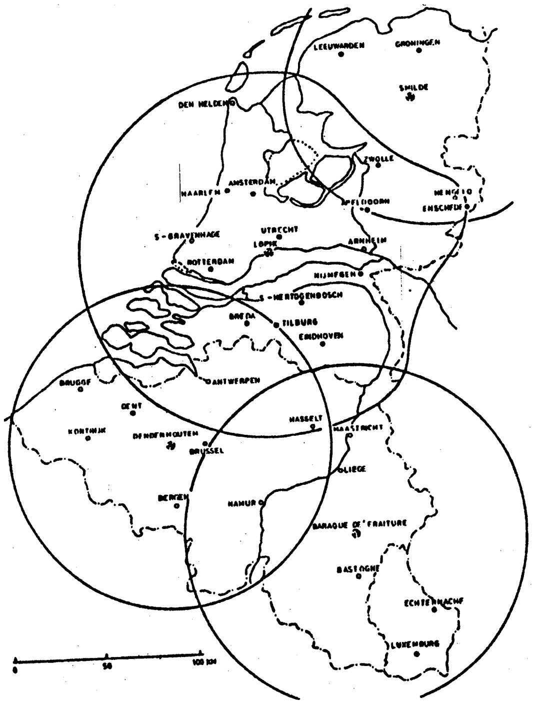


Figure 5. Basic Transmitter Network of the Dutch *Semaphone 1* and 2 System, Operational Until 1990.

Four primary transmitters were used: Smilde operating with 1 kW effective radiated power (erp) at 256 meters above sea level; the main Dutch transmitter at Lopik with 10 kW erp at 380 meters above sea level; in Belgium, Denderhoutem with 20 kW erp at 160 meters above sea level; and Baraque de Fraiture with 20 kW erp at 650 meters above sea level. Each transmitter operated sequentially on four frequencies in the 4 metre band. As interference to German VHF radio was anticipated, the Dutch transmitters at Smilde and Lopik used special antenna arrays providing attenuation towards the German border. After the introduction of the *MINOR* and *PICCOLO Semaphone*, both having inefficient aerials, a number of auxiliary transmitters had to be installed at locations having unreliable coverage.

DIGITAL BREAKTHROUGH (SYSTEM 2)

In the 1970s, it became necessary to expand the number and traffic capacity of the system. Until then, due to the anticipated huge demands, no particular steps had been taken to attract potential customers for the service.

Because the initial CCS could not be expanded easily, the CCS and transmitter driver stages were replaced in 1978 by a commercially- marketed digital system (Motorola Metro Pager 100) having a

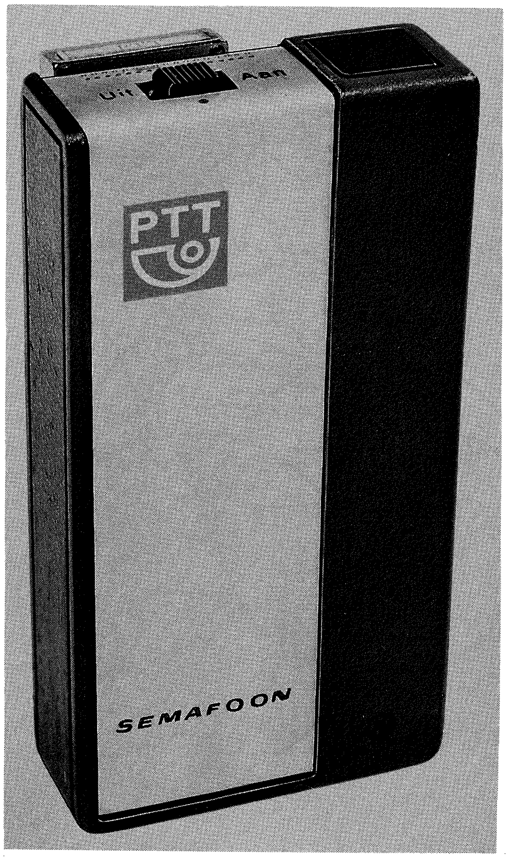


Figure 6. *PICCOLO Semaphone* (1978 - 1990)

Based on the Motorola *Metro Pager*, this receiver was custom-developed exclusively for the Dutch PTT. It operated around 87 MHz and provided a selection of eight different messages. The aerial is a loop which is made primarily by the metal cover. However, in not being very effective, it needed approximately 20 dB more field-strength than the *ESCORT Semaphone*.

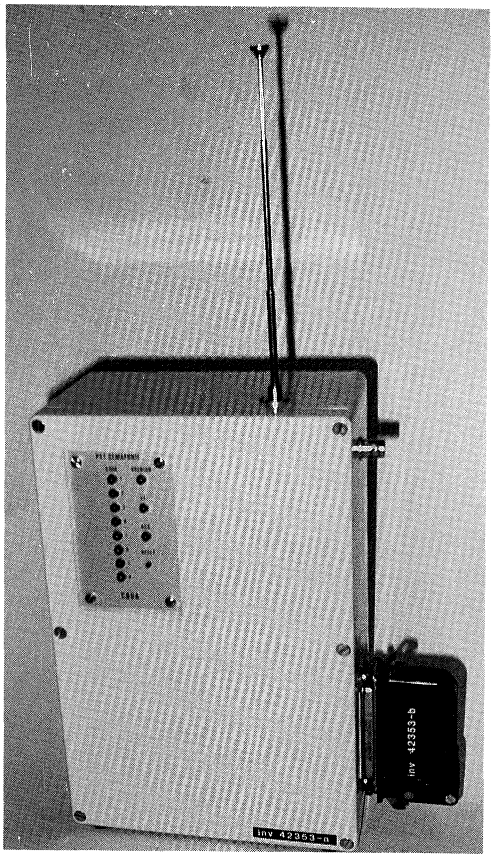


Figure 7. *CODA Semaphone* (1982 - 1990)

The *CODA* is basically a *PICCOLO Semaphone* connected to a PTT-developed circuit decoding the digital readout into a memory to provide eight customer-usable, voltage free contacts. Only one contact, viz. the last received code, is active at the time.

special adaptation for PTT to permit the use of the older pagers on the system. The new CCS allowed the allocation of 200,000 subscribers.

PICCOLO PAGING RECEIVER

Since, at that time, no digital pagers operating in the 4 metre band were available, it was decided to adapt the Motorola *Metro Pager* for the Dutch PTT. This led to a complete redesign. The new pager which was named *PICCOLO* would not have to work just on 4 meters but also should be able to select 8 code digits. Additionally, since it was shown that the capacity of the existing battery was too small, the pager was adapted to operate on a single pen-light battery. A call was indicated by a beep, and the code-digit readout by a 7-segment LED display on the top of the pager.

RF BLACK SPOTS

When the *MINOR Semaphone* was introduced a few years before, a number of the RF "black-out spots" were reported in several areas. Resulting from the *MINOR's* reduced aerial length, this problem became more serious with the introduction of the *PICCOLO Semaphone* which had a much smaller and less effective aerial. To solve this problem, a number of auxiliary low-power transmitters were installed throughout the Benelux countries.

CODA

In the early 1980s, the *ESCORT Semaphone* was due to be abandoned due to its age . However, it was claimed that its optional relay function, not available on the *MINOR* and *PICCOLO*, should continue to be available to the public.

In May 1982, a number of *PICCOLO Semaphones* were modified by the PTT. The new *Semaphones* were named *CODA* and provided a connector with eight contacts corresponding with the code indicated on the display. However, a number of customers were very slow in exchanging their *Semaphones*, and the *ESCORT* remained in use for this purpose until the closedown of the *Semaphone 2* CCS on 2 July 1990. It is noteworthy that the transmitters remained in operation until 30 January 1991.

REGIONAL *SEMAPHONE*

In 1975, a public regional *Semaphone* service was inaugurated in the Amsterdam area using Martin Marietta pagers . Although having only regional coverage and a limited capacity, this system was considered very successful. As a result, in 1980, a second regional *Semaphone* system (Motorola *Metro Page*) was opened in the region of Rotterdam, and later expanded to Ijmond.

The independently-operating regional *Semaphone* systems gave some relief to the continuously growing demand for National pagers and the nearly fully-occupied capacity of the *National Semaphone System*.

CURRENT *SEMAPHONE 3* SYSTEM

During the early 1980s when it became apparent that further expansion of the existing *National Semaphone System* was inevitable, research was directed to a new system having sufficient capacity to meet future public demands.

In not being able to continue the use of high-power transmitters operating in the 4 metre band, a different system had to be selected -- one operating with a large number of low-power (100 watt) transmitters working in the 160 MHz band. Eventually a Central Control System manufactured by NEC was selected while the transmitters (at over 130 sites) were developed in the Netherlands in close cooperation with the PTT. On 31 March 1988, the *Semaphone 3* system was officially inaugurated.

A wide range of paging receivers made by a number of manufacturers are being used. As explained in the earlier paper*, prior to the privatization of PTT Telecom, *Semaphone* paging receivers could only be leased from the PTT. Presently, paging receivers are offered on lease and for sale, with an additional monthly network fee being charged. Optionally, Benelux coverage may be obtained.

HARBOR LIGHTS

One of the remarkable applications of the *Semaphone* network is the control of the harbor lights of the Port of Rotterdam, and of other electrical installations by means of the optional relay function. Even more striking was the operation of a lock in a canal at East Flevoland, directed by means of remote control via an *ESCORT Semaphone*. Protection against an unwanted relay function was provided through the dialing of a second digit within a given time limit.

In the 1980s, the author used a number of *CODA Semaphones* to control aerial attenuators in a number of receivers as an interim measure against freak reception of interference from East European FM broadcast transmitters operating in the Dutch 75 MHz band. By dialing four different digits, the dispatcher of this particular network could insert 6, 12, 18 (or 0) dB attenuation in each of his receivers suffering from this problem.

CONCLUSIONS

Very soon after the start of the first Hasler experiments, it was evident that a future, nationwide paging system would have a very great expansion. Therefore, further development was directed to a fully-automatic system.

The decision to use the low end of the FM broadcast band permitted the utilization of commercially-available standard broadcast transmitters. Although the initial CCS was developed by the PTT Laboratories, and the early *Semaphone*

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*Louis Meulstee, "Mobile Radio in the Netherlands" *Proceedings of The Radio Club of America,* Vol. 66, No. 1, May 1992, pp. 24 - 30.

receivers were exclusively for the PTT, it became clear that later developments of commercially-marketed systems were more practical to implement in the future.

Over the years, the *Semaphone* system has proven technically and commercially to be a success. The parallel developments between the National Public Radiotelephone Network and the *Semaphone Systems 1 and 2* are remarkable. After conspicuous initial success, both services were expanded with independent-operating Regional Networks. Additionally, both services are claimed to be the world's first having nationwide coverage. Technically, both initially started with superregenerative receivers; later, exclusive use was made of FM or PM.

ACKNOWLEDGMENTS:

The author extends thanks to Mr. D. Fokkenrood, PTT Telecom (Field) Engineer, for providing information upon the early developments. Thanks also are due to Mr. Caspers of the PTT Museum, The Hague, for his help and the providing of photographs used in this paper.

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Figure 8. The Ultimate Use of a *Semaphone*...

WHATEVER HAPPENED TO THE Q-METER ?

by **Albert Helfrick, Ph.D., P.E., K2BLA (LF)**
Associate Professor,
Embry-Riddle Aeronautical University

INTRODUCTION

Recently a colleague, visiting my office at the University, spotted my Q-meter and inquired as to where I got the "museum piece." I informed him that the equipment in question was in regular use and that I had spare vacuum tubes to insure its continued usefulness. I went on defending the insulted instrument by explaining that I was measuring the very same parameters of inductors made the very same way they were 50 years ago when this particular Q-meter was manufactured. "But the modern method would be a network analyzer," my guest replied. "And how much does this network analyzer cost?" I asked; end of discussion.

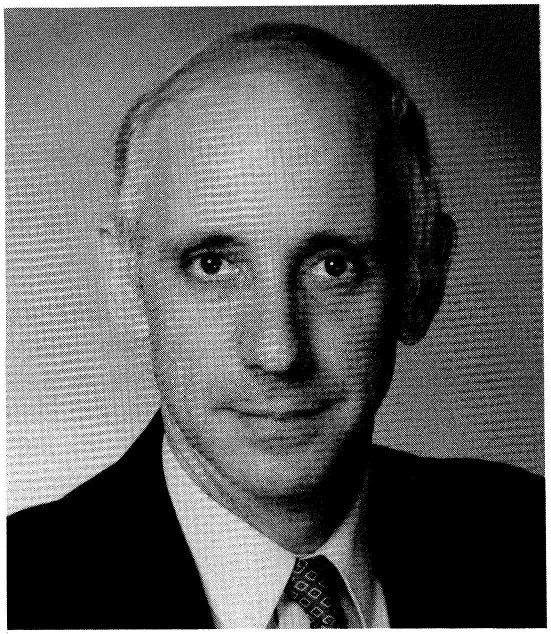
Many RF engineers have used the Q-meter for as long as we can remember and, if a Q-meter is still available to us, we continue to use it to verify coil designs before the inductors are placed in the circuit. Many manufactured inductors are still specified " as measured on a Boonton Radio model XXX Q-meter," in spite of the fact that there hasn't been a Q-meter made in 25 years. I believe the time is now for the Q-meter to return to the laboratory.

This paper describes Q, Q measurement, a short history of the Q-meter, and a modern Q-meter design.

WHAT IS Q?

If one were to ask a college student to define the parameter Q, most likely you would get an answer of X_1/R or R/X_1. If one were asking about a specific parallel or series resonant circuit, the answer would have a 50 percent chance of being right. Seldom is the answer what this author prefers, i.e. Q is 2π times the ratio of the total energy stored in a resonant system to the energy dissipated each cycle of oscillation.

Notice that this definition does not refer to an electrical circuit. It is important to understand that resonance is more than just electrical. There are nuclear resonances, lattice resonances and mechanical resonances of all sorts. Certainly the RF engineer is familiar with the quartz crystal which is, of course, a mechanical oscillation.


Albert Helfrick, Ph.D., P.E.

In a resonant system, the energy of the system is transferred from one energy storage element to another. All the while, energy is being lost by the dissipative elements of the system.

In an electrical circuit, the energy storage elements are the inductor and capacitor. The dissipative elements, represented on a circuit diagram by a resistance, can be rather complex. First, energy may be lost in the resistance of the wire of the inductor. It is a well-known fact that, at higher frequencies, this resistance, because of the skin effect, can be significantly higher than the DC resistance.

The inductor has other ways of losing energy. If the inductor is wound around a core such as ferrite or powdered iron, energy may be lost in that core material. Additionally, the inductor will allow some of the energy to dissipate because of radiation. The magnetic field around the inductor may not be totally contained and, consequently, the inductor becomes a miniature loop antenna and some of the energy is lost through the radiation of electromagnetic energy.

Another source of energy loss is in the capacitor. The majority of energy lost in the capacitor is lost in the dielectric from heating. However, like the inductor, the capacitor, too, can radiate. The electrical field may not be totally contained and the capacitor can become a miniature electric-field antenna.

Finally, there are parasitic circuit elements: the wires, the printed circuit board dielectric, terminals, etc. that have their own radiation characteristics and losses.

Regardless of the source of the energy loss, the resonant circuit can be shown with one resistance which represents the equivalent of all the energy losses. Thus the resonant circuit of Figure 1 shows the inductor and capacitor as perfect elements.

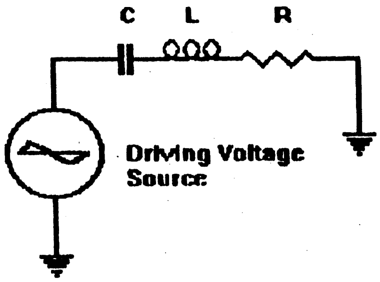


Figure 1. A resonant circuit showing a driving source and the equivalent resistance due to a finite Q.

To derive the equation for Q using the definition stated, an expression for the energy stored in the circuit must be written. For the series resonant circuit shown, it is easier to consider the energy stored in the inductor. Both the current through the circuit as well as the voltage across any circuit element is sinusoidal. Therefore, at the peak of the current waveform, all of the energy of the circuit is contained in the inductor. Using this fact, the following relationship is written:

$$Energy=\frac{1}{2}LI^{2'} \qquad (1-1)$$

Consequently, the circuit current as a function of time is:

$$I(t)=I\sin wt \qquad (1-2)$$

where I_t is the time dependent current and **w** is the angular resonant frequency.

The energy dissipated in the resistor per cycle is:

$$\int_0^{2\frac{\pi}{w}} RI^2(t)\,dt=RI^2(\pi\sqrt{LC}) \qquad (1-3)$$

Taking the ratio between the energy stored to the energy dissipated per cycle and multiplying by 2, the following result is obtained:

$$2\pi\frac{\frac{1}{2}LI^2}{RI^2(\pi\sqrt{LC})}=\frac{wL}{R}=\frac{X_l}{R} \qquad (1-4)$$

This is the familiar equation for Q in an electrical circuit. The parallel resonant circuit may be analyzed in a similar fashion by considering the energy stored in the capacitor and the circuit voltage.

MEASURING Q

The first Q-meter was made available to the radio industry in 1934 by the Boonton Radio Corporation, of Boonton, New Jersey. This company grew out of the Radio Frequency Laboratories (RFL) which spawned Aircraft Radio Corporation and figured indirectly with many other companies in the northern New Jersey area. Interestingly, of the famous Boonton, N.J. companies: Measurements, Inc.; Ballantine Laboratories; Ferris Instruments; RFL; and Aircraft Radio Corporation, only Ferris was in Boonton. The other companies were in adjacent towns that used the Boonton post office; one electronics company that bears the Boonton name never had a Boonton address.

The Boonton Radio Corporation produced Q-meters for nearly 30 years. Boonton increased their product line to include RF bridges, signal generators, and other test equipment. They moved from their original buildings to a new building in a beautiful bucolic setting in Rockaway, N.J. and, shortly thereafter, were acquired by

Hewlett-Packard. Apparently, H-P wanted the building as the Boonton product line never was improved nor expanded. The Q-meter along with the Boonton R-X meter appeared in the H-P catalogue until about 1970, appearing about the way they did in the 1940s, still using vacuum tubes that were designed in the 1930s. About 1970, the Boonton products disappeared and a new Q-meter bearing only the H-P names appeared.

Boonton Q-meters had been measuring Q and inductance to 250 MHz since the late 1930s, but the new H-P Q-meter measured only to 70 MHz. In the mid-1980s, the H-P Q-meter was dropped from the catalogue index, and was given a small space amongst the RLC measuring systems, where it remains today.

Boonton Radio was not the only source of Q-meters. There were at least two other sources. The Marconi Company, in England, made a Q-meter well into the 1960s; this instrument was unique in that it was called a "circuit magnification meter." In the 1950s, the Heath Company made a Q-meter kit that was patterned after the Boonton Q-meter. It had the same characteristic, sloping front panel with the "unknown" terminals on the top. At that time, Heath made other inexpensive, look-alike versions of expensive laboratory equipment.

The principle of Q measurement is very simple. An unknown inductor is placed in a series resonant circuit and driven from an AC voltage as shown in Figure 2.

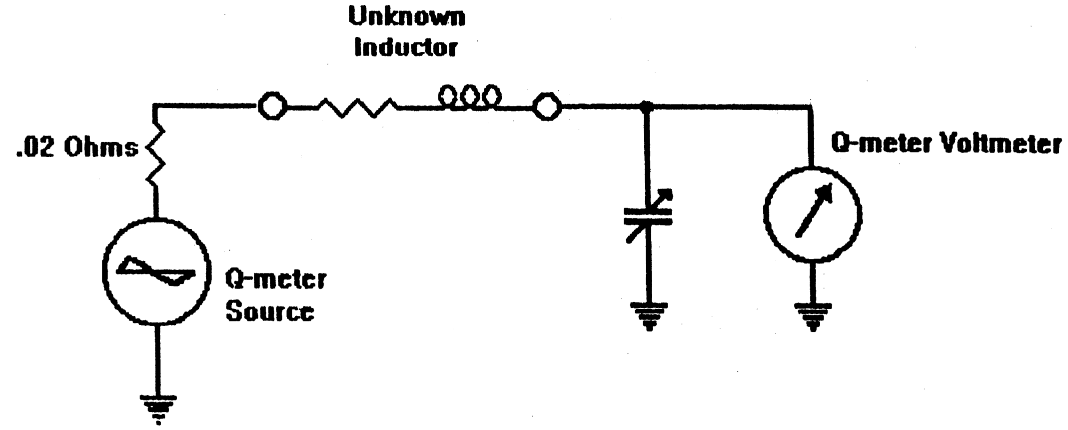


Figure 2. The Basic Q-meter Configuration.

Either the signal generator frequency or the series capacitance is adjusted to give resonance. The voltage across the capacitor is measured using a high impedance voltmeter, and the ratio of the capacitor voltage to the driving voltage is the circuit Q. It is the "magnification" of the driving voltage that gave the Marconi Q-meter its name.

To prove this voltage is the inductors Q, consider the circuit of Figure 2. The first requirement for a accurate Q measurement is that the voltage source resistance be small relative to the equivalent series resistance of the unknown. Additionally, the resistance of the voltmeter must be very large relative to this equivalent series resistance.

At resonance, a series resonant circuit has an impedance which is the circuit's resistive component. Therefore, the circuit current may be calculated by the relationship:

$$I=\frac{V}{R} \qquad (1-5)$$

where V is the source voltage.

Assuming the capacitor is perfect, that is -- has no parallel resistances, the voltage across the capacitor is:

$$IX_C=\frac{X_C V}{R} \qquad (1-6)$$

Because the inductive and capacitive reactances are the same at resonance, the equation above may be rewritten for the desired result:

$$V_c = \frac{X_l V}{R} = VQ \qquad (1-7)$$

This relationship holds only for a lossless capacitor and is nearly correct when the loss of the capacitor is much smaller than the inductor under test. The circuit shown in Figure 2 used for the derivation of Equation 1 - 7 is the technique used in the Q-meter.

The Boonton Q-meter's voltage source had an internal resistance of 0.02 ohms. This internal resistance was achieved with a 0.02 ohm resistor which was a short length of Ni-chrome wire. The coupling coil from the oscillator fed the 0.02 ohm resistor; the current through the resistance was measured using a thermocouple assembly. The thermocouple DC output drove the "multiply Q by" meter on the front panel of the instrument. The operator was required to set the oscillator power typically to "multiply Q by 1", but certainly below the red band on the meter. Failure to observe the red band would result in a destroyed thermocouple assembly and a costly repair.

Measuring the current through the resistance to deduce voltage assumes the Ni-chrome resistor is pure resistance and has no significant inductance or transmission line effects. For the 70 MHz range of the Q-meters employing this technique, this was a safe assumption.

For an accurate Q measurement, it is necessary that the voltmeter, used to measure the RF voltage across the capacitor, have a very high input impedance so that it will not affect the Q of the circuit. The Boonton Q-meters used an AM detector circuit called the "infinite impedance" detector. This is simply a vacuum tube that was biased near conduction. The cathode circuit had an RC circuit with a time constant considerably longer than the period of the RF that was being measured. Therefore, each RF cycle that exceeded the conduction threshold of the vacuum tube would increase the charge on the capacitor in the cathode circuit and push the vacuum tube bias back to near cutoff. Because the vacuum tube operated continually near cutoff, the input impedance was represented by a very small amount of leakage current and the input grid's capacitance.

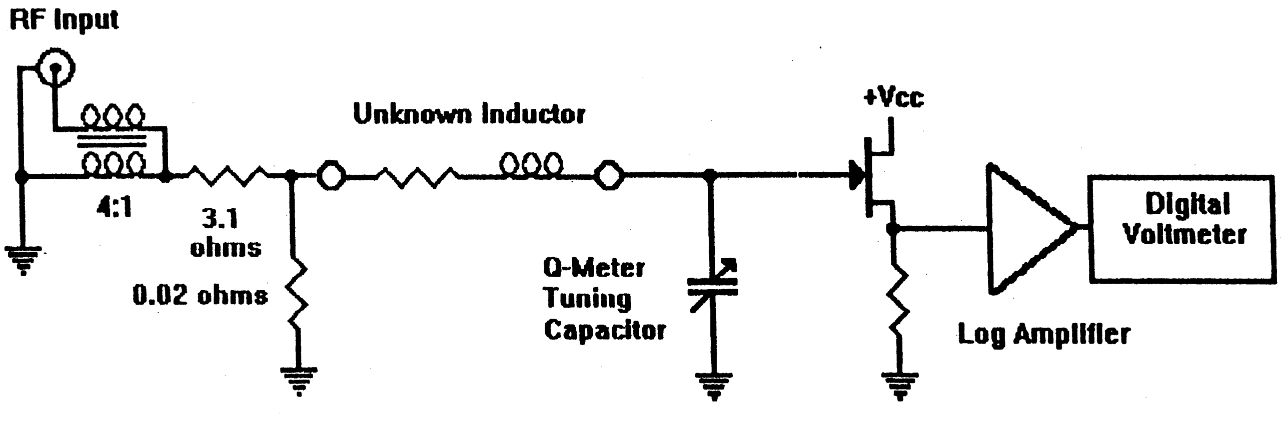


Figure 3. Block Diagram of the Modern Q-meter.

A MODERN Q-METER

It was desired to recreate the Q-meter using the same basic measurement topology but modern techniques. Some differences would be incorporated to decrease the cost of the instrument.

Some of the goals for the Q-meter were:

1. The Q-meter will not contain a signal source. This is an expensive item and any laboratory where serious RF design work is taking place and a Q-meter would be needed, has at least one signal generator.

2. The Q-meter will be able to operate with very low drive levels so that very small geometry devices may be measured without significant heating.

3. The Q-meter should be capable of operation from 100 kHz to 100 MHz.

An interesting difference between the modern Q-meter and the classic meter is that the Q measurement has been designed to be a logarithmic representation. This makes it easier to read a wide variation of Qs but, more importantly, it allows a measuring circuit with a very wide dynamic range. The voltage across the resonating capacitor is measured using a logarithmic amplifier preceded with a high impedance buffer amplifier, as shown in Figure 3.

The biggest hurdle in designing the modern Q-meter was finding an acceptable alternative to the variable capacitor. Mechanical variable capacitors are just not readily available and high-Q, precision variables will be expensive. Varactor diodes are not viable as their capacitance ratio is not sufficient for a Q-meter. Also, for the higher capacitance diodes, the diode Qs are not high enough to allow accurate measurements of high Q inductors. A digitally-switched variable capacitor was designed for the Q-meter. Five binary weighted capacitors are used plus a varactor diode for the remaining capacitor resolution.

The resonating capacitor consists of the relay- switched capacitors, the varactor diode and all of the parasitic capacitances in parallel. The relays chosen are specially designed for high-frequency signal switching and have very low parasitic capacitance. The voltmeter buffer amplifier adds a few *pF* to the parasitic capacitance. The design was chosen that the varactor diode would add 10 *pF* to the total capacitance. Since a comfortable tuning range for a varactor diode is about 4-to-1, a 3.33 *pF* to 13.33 *pF* diode will be suitable for the Q-meter. However, this adds 3.33 *pF* of residual capacitance to the Q-meter.

It is important that the voltage impressed on the varactor diode does not cause conduction in the diode. The usual techniques for preventing conduction in varactor diodes is to use two diodes back-to-back. This techniques, however, reduces the Q of the varactor diode as it requires the use of two diodes of twice the capacitance, and the larger geometry diodes have greater losses.

The technique used in the modern Q-meter is to prevent the varactor diode from conducting. The peak diode voltage should be less than about 500 mV peak or 354 mV RMS to prevent conduction at zero diode voltage. Assuming that the maximum Q ever measured by the modern Q-meter is 1,000, this requires a maximum driving source of 354 μV.

It was decided that a source generator level could be reduced to as low as 10 μV for the following reasons. First, it would insure that the varactor diode would never conduct or operate in the non-linear region. Second, there are some very small geometry parts such as small inductors, and inherently high-Q devices such as piezoelectric resonators that could be handled by the modern Q-meter if the driving power was kept to a minimum.

The classic Boonton Q-meter had a voltage source of 20 mV with an internal resistance of 20 milliohms. This voltage source was created by conducting a current of 1 ampere through a 20 milliohm resistor. The accuracy of the open circuit voltage was assured by measuring the current through the 20 milliohm resistor using a thermocouple RF ammeter. The energy dissipated in the resistor is only 20 mW but the energy coupling from the oscillator to the source resistor was very inefficient. At RF, impedances of significance relative to 20 milliohms, come from everywhere.: inductance of wires, copper losses, mutual conductance, etc. The source oscillators for the Boonton Q-meters were capable of providing an output of considerable power and the vast majority of the energy was wasted in the coupling.

A similar problem exists, even for a modern Q-meter. The design goal of the modern Q-meter was to interface with a laboratory signal generator with a 50 ohm output impedance. The impedance transformation required to provide a 20 milliohm source is 2500 to 1.

It was desired that the modern Q-meter be accurate to 100 MHz and useful to 200 MHz. On the other end of the spectrum, the Q-meter should be useful to areas where inductors are still being used, or around 100 kHz. Providing a large impedance transformation over this broad frequency range with a single transformer is nearly impossible, Therefore, it was decided that two impedance transformation networks be provided, each with its LO terminal. The frequency range of 100 kHz to 1 MHz is transformed by one network while a second network provides the 1 MHz to 100 MHz range.

For the high frequency region, a 4-to-1 transformer giving an impedance reduction of 16-to-1 is used, followed by a voltage divider. The impedance looking back into the transformer is 3.125 ohms which requires a 156-to-1 voltage divider.

When transforming from 50 ohms to 3 ohms, great care must be taken to insure tight coupling and low leakage inductance. Transformers of these characteristics are regularly used for high-frequency power amplifiers.

If the Q-meter is to read directly, it is necessary that the driving source as well as the measuring circuits have a flat frequency response. This is particularly difficult for a broad frequency range from 100 kHz to 100 MHz. Every effort was made to provide as flat a frequency response as possible but a different operating technique is used for the modern Q-meter.

For many measurements, precise Q is not important and a Q indication of 20% is sufficient. The frequency response is sufficiently flat to allow a direct calibration of Q to about 20%.

A more precise measurement of Q requires a calibration routine to be performed. The unknown inductor is tuned for resonance and the Q is noted. The inductor is replaced with a shorting bar, the capacitance reduced to the minimum, and the signal generator level is increased until the Q indicator reads the same value as the inductor at resonance. The ratio of the two signal generator voltages is the inductor Q.

As an example: an inductor reads a Q of 75 at resonance, and the signal generator was set to -30 dBm. The shorting bar is applied, and the signal generator must be increased to +6 dBm or an increase of 36 db to achieve the same reading of 75. This indicates a Q of the inductor, of 63.

With the use of a laboratory signal generator with the capability of precise frequency and level control, the modern Q-meter was used to make some Q measurements that would be difficult on the old Boonton Q-meter. The modern Q-meter was modified to measure the Q of very high Q devices such as ceramic resonators and quartz crystals. These devices, however, are not inductors but resonant circuits and cannot be measured by resonating in a series resonant circuit. The only hardware modification of the Q-meter is the addition of a ground terminal near the unknown terminals of the Q-meter. This will allow providing specific termination resistances to the voltmeter circuit. The design of the voltmeter for making Q measurements was for a very-high input impedance but for making measurements of resonators a much lower impedance such as 50 ohms is desired.

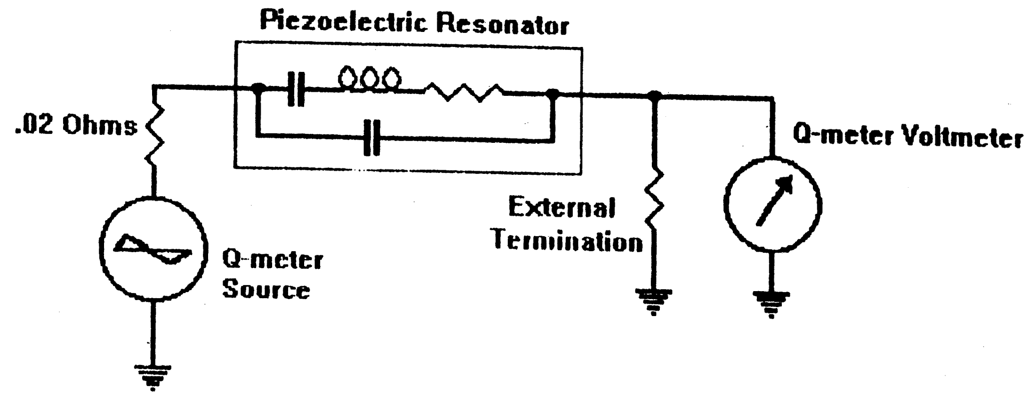


Figure 4. Schematic of the Technique for Measuring Piezoelectric Resonators Using a Q-meter.

To measure the resonant frequency of a piezoelectric resonator such as a ceramic resonator or quartz crystal, a 50 ohm resistor is connected from the voltmeter terminal to ground, as shown in Figure 4, and the resonating capacitor is set to minimum. The series resonant frequency is determined by adjusting the signal generator to the resonant frequency.

To determine the equivalent series resistance, the resonator is removed and replaced with the shorting bar, and the signal generator level is reduced to produce the same indication from the voltmeter. From this level reduction, the series resistance may be calculated.

As an example, if the signal generator was reduced 6 dB to produce the same voltmeter reading as a crystal under test at resonance when terminated in a 50 ohm resistor, the series resistance of the crystal is 50 ohms. By placing a capacitor equal to the desired load capacitance in series with the resonator, the modern Q-meter may be used to measure the parallel resonant frequency of a quartz crystal.

Using this technique, the modern Q-meter was used to measure the parallel and series resonant frequencies an the resistance of a quartz crystal with 1 PPM accuracy on frequency and 10% on resistance. Thus the modern Q-meter will serve as a crystal impedance, C-I, meter.

Devices that require a defined input and output impedance may be tested by inserting a resistor between the input of the device and the source terminal of the Q-meter. If the external signal generator is capable of swept frequency operation, the frequency response of the device may be displayed.

What makes this modern Q-meter capable of performing these high Q measurements that the older Boonton Q-meter could not is the use of an external signal generator with very fine frequency resolution, and a calibrated and adjustable output. Also, the use of an amplified voltmeter which allows very low driving power to be used prevents damage to these very fragile parts.

There are classic procedures for measuring the distributed capacitance of inductors and for measuring capacitors at RF with the Q-meter. These techniques may be learned from the references at the end of this paper.

Capacitance may be measured using the Q-meter by supplying a good quality inductor, and resonating the inductor using the internal capacitor at the desired measurement frequency. The unknown capacitor is applied to the HI terminal and ground, and the Q-meter is resonated again. The difference in the Q-meter capacitor is the capacitance of the unknown capacitor. The dissipation factor or Q of the unknown capacitor may be calculated from the differences in the before and after Q measurements. These formulae are available in the references.

CONCLUSION

The modern Q-meter was conceived to make simple Q measurements of inductors rather than using the more-expensive network analyzer. However, by providing various source resistances and terminations, the Q-meter was capable of some network measurements.

The Q-meter can still be a valuable tool for the RF laboratory when used with a signal generator capable of accurate frequency and amplitude settings. With the use of a sensitive voltmeter, the range of the Q-meter measurements can be greatly expanded.

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McLean, VA 22101
703-749-9536
703-847-8804 (FAX)

JAMES R. HENDERSHOT, WA6VQP
RF Design Engineer
5235 Lower River Road
Grants Pass, OR 97526-9628
800-343-9600
503-471-3489 (FAX)

CHARLES A. HIGGINBOTHAM P.E.
Land Mobile Consultant
85 Aspen Meadows Circle
Santa Rosa, CA 95409
707-539-8638

LAWRENCE M. HOLLINGSWORTH
Telecommunications Systems and
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Silver Lake, OH 44224
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216-923-4337 (FAX)

GEORGE JACOBS
International Consulting Broadcast
Engineer
8701 Georgia Avenue, Suite 410
Silver Spring, MD 20910-3713
301-587-8800
301-587-8801 (FAX)

LEONARD R. KAHN
Radio Communications Systems
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Carle Place, NY 11514
516-222-2221

JAMES A. LANG P.E.
Microwave System Consulting
24591 Summerhill Court
Los Altos, CA 94024
415-948-5914

FRED M. LINK
Consultant
Robin Hill Farms
Pittstown, NJ 08867
908-735-8310
908-735-9209 (FAX)

RALPH W. MAY
Management for Mobile and Mobile
Data Systems Development
604 Castle Lane
Los Altos, CA 94024
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415-949-1767 (FAX)

LOREN R. MCQUEEN
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Campbell, CA 95008-5698
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Radio Communications System
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FRANCIS H. SHEPARD, Jr., P.E.
Consulting Engineer
16 Lee Lane, Countryside
Summit, NJ 07901
908-273-5255

CARL E. SMITH, P.E.
Communications Consultant
8200 Snowville Road
Cleveland, OH 44141-3498
216-526-4386
216-526-9205 (FAX)

TOM SMITH
Manufacturers Representative
8300 Killian Drive
Miami, FL 33156
305-253-3289
305-255-0523 (FAX)

JOHN J. TARY
Electronic Systems - Measurement and Performance
7739 Spring Drive
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Roger R. Block, President, PolyPhaser Corporation, P.O. Box 9000, Minden, NV 89423, 702-782-2511, 702-782-4476 (FAX)

Armando Courir, I4AIJ, Italponti Telecom Syst., Inc., Via Reims 12, 50126 Florence, ITALY, 39-55-689706, 39-55-689529 (FAX)

Jeanne M. Crabb, President, Shasta Cascade Services, Inc., 422 A Chestnut Street, Mount Shasta, CA 96067, 916-926-2111, 916-926-3404 (FAX)

Daniel L. Duryee, KB0J, Manager, Gateway Electronics Inc. of Colorado,
2525 North Federal Boulevard, Denver, CO 80211,
303-458-5444, 303-458-5440 (FAX)

Joseph J. Fairclough, WB2JKJ, The Radio Club of Junior High School 22, NYC,
P.O. Box 1052, New York, NY 10002-0912,
516-674-4072, 516-674-9600 (FAX)

Robert S. Gaye, K2LGJ, Director, Research & Development, STI-CO Industries, Inc.,
11 Cobham Drive, Orchard Park, NY 14127,
716-662-2680, 716-662-5150 (FAX)

James R. Hendershot, WA6VQP, Principal Engineer, Radio Design Group, 5235 Lower River Road, Grants Pass, OR 97526-9628, 800-343-9600, 503-471-3489 (FAX)

Lawrence M. Hollingsworth, Telecommunications Consultant, Lawrence Hollingsworth Co.,
2888 Lee Road, Silver Lake, OH 44224,
216-923-4337, 216-923-4337 (FAX)

Duane L. Huff, Director, New Technologies, Comcast PCS Communications, Inc., 1234 Market Street, Philadelphia, PA 19107-3723, 215-981-7705, 215-981-7366 (FAX)

Leonard R. Kahn, President, Kahn Communications, Inc., 222 Westbury Avenue, Carle Place, NY 11514, 516-222-2221

Antoinette P. Kaiser, President/CEO, STI-CO Industries, Inc., 11 Cobham Drive, Orchard Park, NY 14127, 716-662-2680, 716-662-5150 (FAX)

Russell S. Lewis, President, Syntonic Technology, Inc., 7611 Derry Street, Harrisburg, PA 17111, 717-561-2400, 717-564-8439 (FAX)

Ralph W. May, Owner, Ralph W. May, dba,
604 Castle Lane, Los Altos, CA 94024,
415-948-5107, 415-949-1767 (FAX)

Harrison W. Moore Jr., Chairman, The New York Institute for Management Studies,
260 Millard Avenue, North Tarrytown, NY 10591,
914-631-3683

Emily C. Nelms, Director of Marketing, American Personal Communications, Inc., 1025 Connecticut Avenue, NW - Suite 904, Washington, DC 20036, 202-296-0005, 202-296-0018 (FAX)

Paulla A. Nelson-Shira, Radio Resource Magazine,
P.O. Box 24768, Denver, CO 80224,
303-771-8616, 303-771-8605 (FAX)

Donn R. Nottage, President, NRM Marketing Group, Inc., 7 Fennell Street, P.O. Box 421, Skaneateles, NY 13152-0421, 315-685-8991, 315-685-6199 (FAX)

Scott D. Prather, Technical Operations Manager, Interlink Communications of Colorado,
6810 South Tucson Way, Englewood, CO 80112,
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George A. Praul, Telecommunications Project Manager, S.E. Technologies, Inc.,
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Jack Reichler, Meridian Communications, 23501 Park Sorrento, #213A, Calabasas, CA 91302,
818-888-7000, 818-888-2857 (FAX)

Stanley Reubenstein, Aurora Marketing Company,
2018 South Pontiac Way, Denver, CO 80224,
303-758-3051, 303-758-6630 (FAX)

Francis J. Rodriguez, M.S., Senior Consultant, RAM Communications Consultants, Inc., 10 Woodbridge Center Drive, Woodbridge, NJ 07095,
908-636-6970, 908-636-7260 (FAX)

Herschel Shosteck Ph.D., President, Herschel Shosteck Associates, Ltd., 10 Post Office Road, Silver Spring, MD 20910-1192, 301-589-2259, 301-588-3311 (FAX)

Calvin D. Smith, RF Products, 1930-D Murrell Road, Rockledge, FL 32955, 407-631-0775, 407-631-0775 (FAX)

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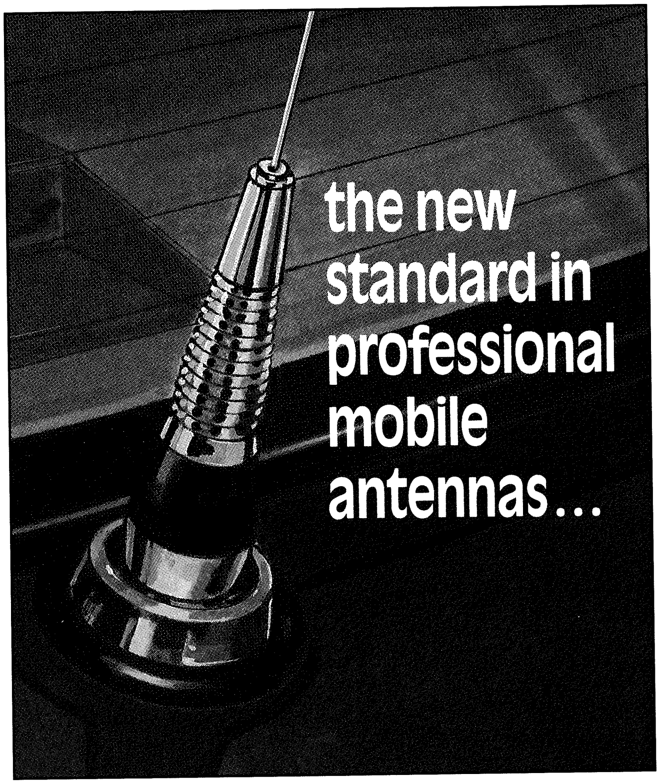

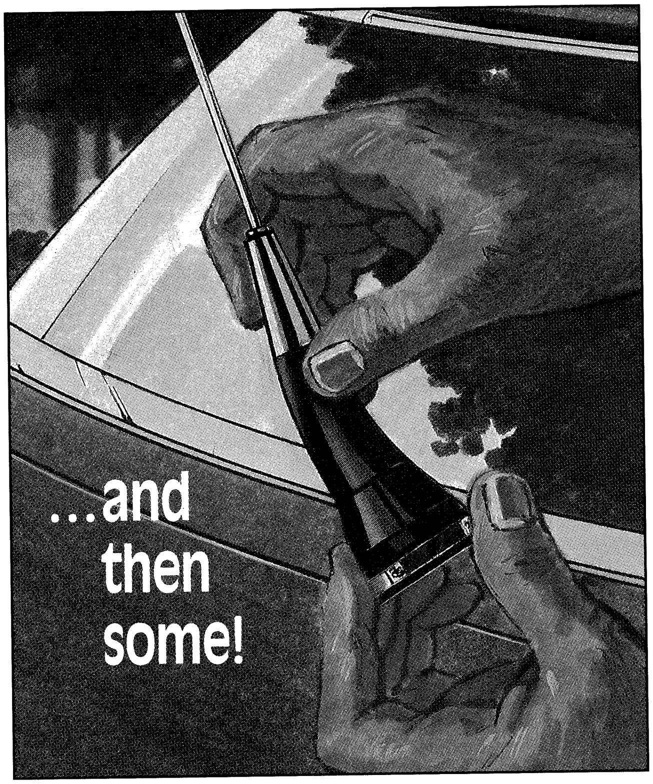

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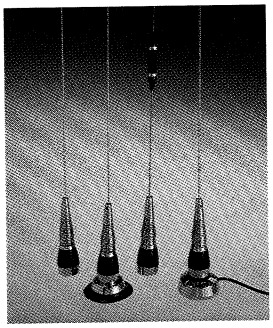

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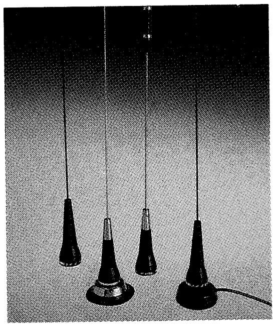

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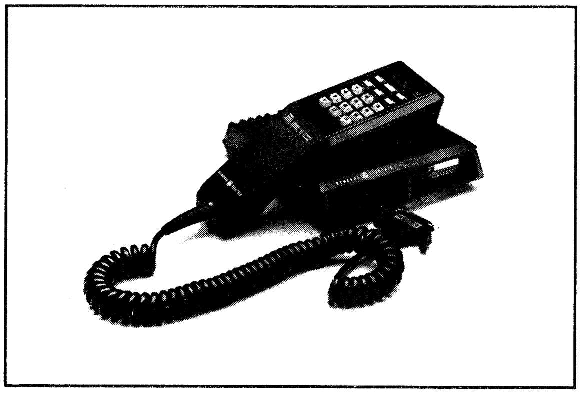

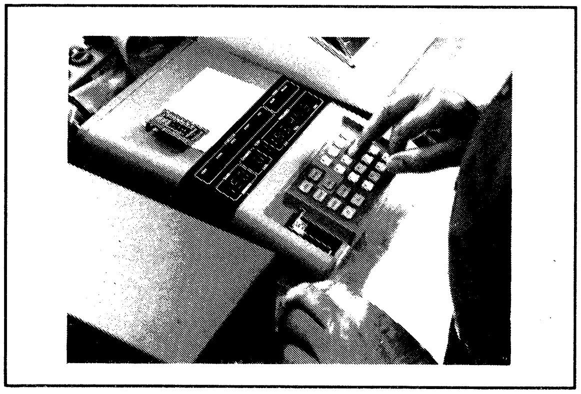

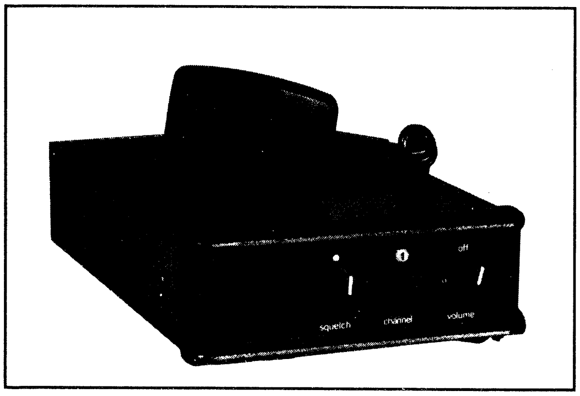

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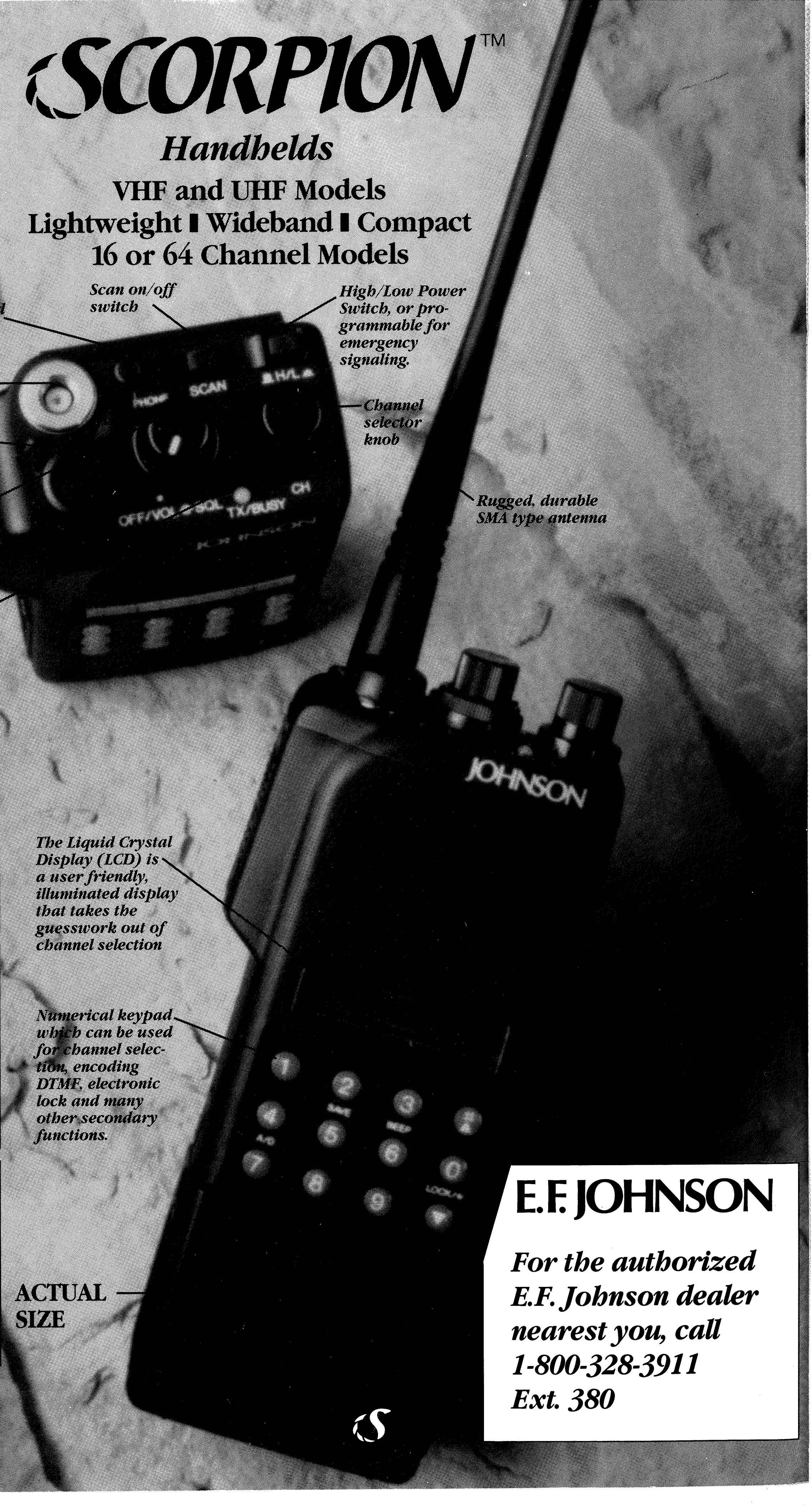

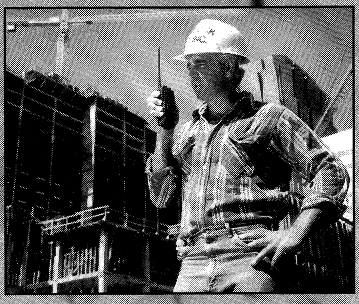

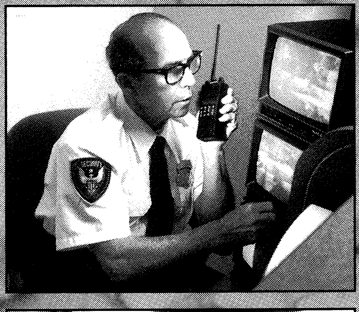

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