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NRL Report 5903
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A VERY-HIGH-POWER HIGH-FREQUENCY PULSE TRANSMITTER AND ANTENNAS

[UNCLASSIFIED TITLE]

F. E. Boyd and D. C. Rohlfs

Radar Techniques Branch
Radar Division

May 2, 1963

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Washington, D.C.

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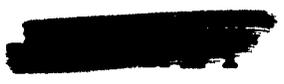
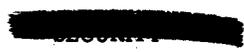
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"Madre Performance, Part 2 - Observations of February 8, 1962," F. M. Gager, W. C. Headrick, G. A. Morgan, D. C. Rohlf, C. B. Tesauero, and E. N. Zettle, NRL Report 5898 (Secret Report, Unclassified Title), Feb. 1963



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**A VERY-HIGH-POWER HIGH-FREQUENCY
PULSE TRANSMITTER AND ANTENNAS**

[UNCLASSIFIED TITLE]

**HIGH-POWER EXTENSION OF THE
HIGH-FREQUENCY MADRE RADAR**

[REDACTED] TITLE]

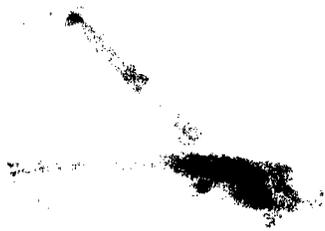
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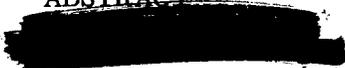


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ABSTRACT



The Madre system is a high-frequency radar employing crosscorrelation techniques and designed to have sufficient sensitivity to detect aircraft at ranges of 1500 miles, utilizing an ionosphere-reflection propagation path. Calculations have shown that both an antenna of high gain and a transmitter having an output of about 5 megawatts peak were required.

A high-power rf amplifier, antenna, and duplexer have been developed to add to the existing low-power Madre system. The 100-kw-average high-power amplifier operates class B linear to reproduce a sine-squared pulse of 4.6 megawatts peak power in the 10 to 30 Mc frequency range. The antenna systems include an array of 20 corner reflectors operating from 13.5 to 27 Mc. Electrical steering of this array over a 60-degree sector is accomplished with variable-length transmission-line phase shifters. A tower-mounted, azimuth-positionable, two-bay corner-reflector antenna has also been built.

PROBLEM STATUS

This is an interim report on one phase of the problem; work on this and other phases is continuing.

AUTHORIZATION

NRL Problem R02-23
Project RF 001-02-41-4007

Manuscript submitted December 12, 1962.

A VERY-HIGH-POWER HIGH-FREQUENCY
PULSE TRANSMITTER AND ANTENNAS
[Unclassified Title]

HIGH-POWER EXTENSION OF THE
HIGH-FREQUENCY MADRE RADAR

INTRODUCTION

A program in which correlation and bandwidth narrowing are exploited to increase the sensitivity of radar systems was proposed by Dr. R. M. Page, Director of Research of the U. S. Naval Research Laboratory, prior to 1949. Pursuit of these ideas involved other investigations (see Bibliography). These investigations included the necessary circuit techniques as well as the feasibility of applying these techniques to a radar. It was felt at the time that if environmental conditions permit, the large, theoretically predicted gain could be employed to detect moving targets over the horizon at extremely long ranges using the ionosphere-reflection path to provide illumination of the earth's surface far beyond the ranges reached by conventional radar systems.

There were unanswered questions; for example, the degree of coherence of the moving target echo signals was not known, and there was the possibility that the ionosphere would further degrade the signal. Exploratory work on the nature of aircraft and rocket target returns was encouraging, and an examination of frequency-standard comparison between WWV and Rugby in the high-frequency range indicated that an adequate short-term stability of the ionosphere had already been demonstrated, even with a multiple-hop propagation path. With this knowledge as a background, a simulated radar was built to explore the circuit techniques required as well as to verify experimentally the theoretically predicted gains. This foothold seemed secure by 1952, and in 1954 an experimental research radar, the Music system with electrostatic storage,* was placed in operation at the U. S. Naval Research Laboratory. This limited system demonstrated all that was desired on moving targets of the period, and plans were laid for a more sensitive system in the future.

The Music radar system was in the process of being evaluated during the period 1954 to 1957 when, in the latter portion of this period, the magnetic-recording art had advanced to the point that a more sophisticated radar employing magnetic-storage techniques became a research goal. The heart of such a system would be the magnetic-storage drum. NRL prepared specifications for the desired signal-processing system, and a contract was let with General Electric Research Laboratory, Syracuse, N.Y., to develop a suitable drum and the associated circuits. Within six months the development work on this drum showed so much promise that the contract was amended several times to include suitable indicators, a 50-kw-peak, 1.1-kw-average-power transmitter, and some receiving equipment. This research equipment, with an antenna and duplexer added by NRL, received the name Madre, or Magnetic Drum Recording Equipment. The method of data processing and presentation was reported in 1957, though much has been added since this early period.

*R. G. Cumings and G. A. Skaggs, "An Improved Pulse Radar Transmitter System for Cross Correlation Radars," NRL Report 5324 (Secret Report, Unclassified Title), July 10, 1959.

During the evaluation period, 1954 to date, of both the Music and Madre low-power research radars, the term "moving target" took on a broad meaning. Today it includes aircraft, air breathers, missiles at or near take off, and missile- and atomic-blast punctures of both the ionosphere and subionosphere. Since the early evaluation of the Music radar showed that the theoretically predicted gains were obtainable, the detection of this general class of moving targets beyond the horizon, via ionospheric reflection, became more distinctly a possibility, because the Music radar had already pioneered in the detection of atomic explosions and missile perturbations of the ionosphere.

However, it was realized that insufficient power was available for the all-important phase of skin-track detection of moving targets, such as aircraft and missiles at extended ranges. In order to determine the required power for detection at some nominal range, certain assumptions were made:

1. The receiver sensitivity N would be limited by cosmic noise, which is 10 to 20 db above thermal noise in the frequency band of interest.

2. The average loss L_i due to ionospheric reflection is 10 db per reflection, or 20 db for a two-way, one-hop propagation. Other losses L , such as transmission-line loss and duplexer loss, are relatively small compared with L_i and therefore are neglected on this basis.

3. A signal-to-noise ratio S of 10 db at the system output is required for reasonably positive detection.

4. An antenna gain G of about 25 db relative to an isotropic radiator is a practical upper limit, first because experience has shown that larger gains on reception of ionospheric signals may not be dependable or practical due to noncoherence of the wave front, and second due to sheer physical size and cost.

5. The detection range R is assumed to be 1500 naut mi.

6. The target reflection area σ is one square meter.

The known factors in the system are:

Effective system minimum bandwidth $B = 1/20$ cps
 Rf wavelength $\lambda = 11.3$ meters
 Duty factor $d = 1/46$.

With the assumptions and known factors, the required power P_t can be computed:

$$P_t = \frac{(KTB) NSLL_i (4\pi)^3 R^4}{G^2 d \lambda^2 \sigma}$$

where K = Boltzmann's constant, 1.374×10^{-23} joules per degree and
 T = absolute temperature $\approx 300^\circ$ K.

The required peak power under these circumstances is $P_t = 8.5 \times 10^6$ watts.

The original Madre transmitter has a peak power output of 46 kw, and since most power amplifiers can conveniently provide 20 db gain, the power that could be obtained was fixed at 4.6 megawatts peak output, 100 kw average. Such a system could then be reasonably expected under fair ionosphere conditions to detect aircraft and air breathers

as well as missiles under power over the horizon, since their effective cross sections at the frequencies in question are many times the assumed one square meter.

Thus when the 50-kw-peak-power Madre system was installed at NRL in the fall of 1958, its evaluation showed encouraging performance, and existing plans were executed to provide this low-power system with more suitable antennas, a high-power amplifier, and associated duplexer to determine the feasibility of skin tracking of aircraft, over the horizon, in the nominal range 1000 to 1500 naut mi. It was known that any demonstration of this feat would provide one with a superior tool for the detection of all the other targets mentioned.

Accordingly, in the period 1958-59, specifications for a high-power addition to the Madre system were drawn up by NRL. RCA, Moorestown, N.J., was selected competitively as the contractor, with work starting in 1958 on an installation which was substantially completed in August 1961 at the Chesapeake Bay Annex of the U. S. Naval Research Laboratory. This contract called for two antennas, one for aircraft-detection research and another for missile-detection research. Both antennas were to be capable of handling at least 4.6 megawatts peak power from a 100-kw average-output-power amplifier. The desired frequencies of operation are in the band 10 to 30 Mc, with the two-to-one range, 13.5 to 27 Mc, preferred. The gas-tube duplexer was initially conceived as a broadband device, but the urgency of time required the use of a tuned type so as not to delay an evaluation program which work on the high-power amplifier and antenna installation had already delayed one year. It is believed that a broadband duplexer is practicable. Companion research, now in progress at NRL, also shows that a solid-state switch as a replacement for the gas tubes has exceptional promise.

Although this research radar has considerable experimental flexibility, it was conceived to be without certain features which would class it as an operational radar. Thus it is stressed that the equipment about to be described is research gear; experience with its use would allow one to set up specifications for an operational radar or a system of such radars, if such were desired. Therefore the faults or shortcomings one finds with the equipment, when seen from an operational viewpoint, were accepted for reasons of economy in cost and time.

The high-power Madre radar system, operable in the frequency range 13.5 to 27 Mc, has a shaped pulse (sine-squared) and a nominal pulse width of 322 μsec ,* with a choice of repetition rates 180, 90, 60, 45, 22, and 11 pps. At present it has operating-frequency assignments which are shared by other Navy uses, and at no time do the evaluation teams enjoy really free-channel operation. The unambiguous range is 450 miles, but there are means to display certain blocks of 450 miles to assist one in removing or resolving ambiguities. The unambiguous velocity display has a maximum of 1000 knots (at 26.6 Mc carrier frequency), deemed adequate for research purposes.

THE RF GENERATION SYSTEM

The output of a crystal oscillator is modulated, shaped, and amplified through linear circuits to give a peak power output of at least 4.6 megawatts. To obtain this level, and to operate an amplifier of this size, a great deal of supporting equipment is required. The following is a general description of the equipment used in this system.

*Pulse width is measured between the zero-percent points. For duty-factor computations, the equivalent rectangular pulse is 3/8 as long, or 121 μsec .

Exciter

The rf system begins with the output of a stabilized crystal-controlled cw oscillator, followed by two rf stages gated with a square wave (Fig. 1). (Several gated stages are needed to obtain rf isolation of 60 db or more from carrier power levels.) A video pulse having a sine-squared shape of the proper length is generated by passing a rectangular pulse through a filter. This sine-squared video pulse is then used to modulate the rectangular rf pulse, thus producing a sine-squared (voltage) shape. All amplifiers following this point must amplify linearly to preserve the desired rf wave envelope.

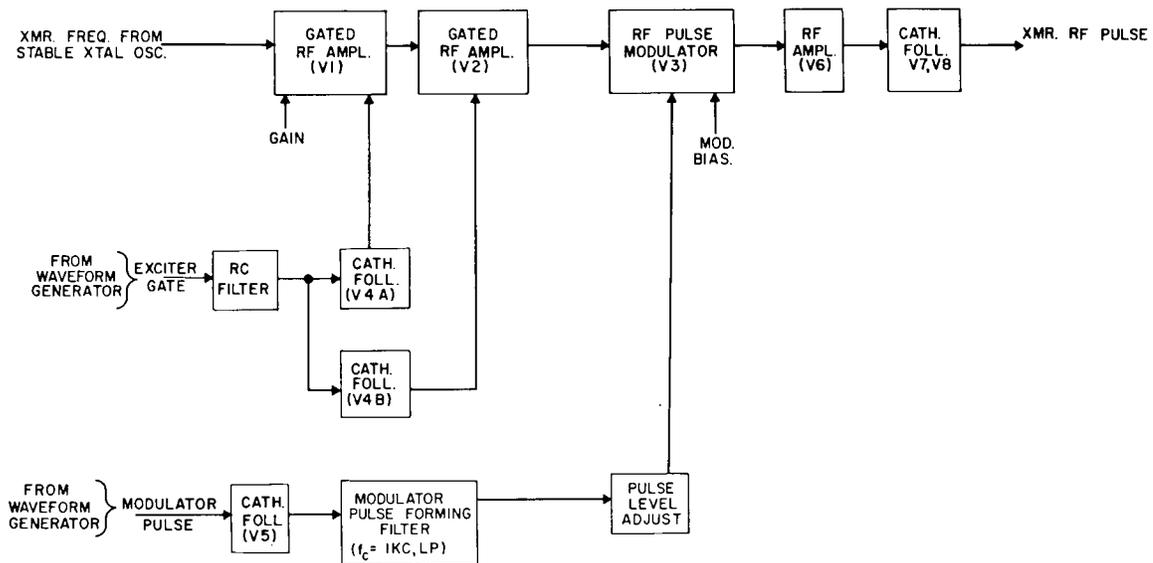


Figure 1 - Block diagram of the exciter

Intermediate-Power Amplifier

Output from the exciter is applied to the intermediate-power amplifier (IPA) through Hewlett-Packard Model 355A and Hewlett-Packard Model 355B step attenuators. This allows extreme flexibility in power output from the IPA without distortion of the pulse shape. Figure 2 is a block diagram of the IPA, consisting of a preamp, first and second buffer, driver, and a power amplifier. The output of this unit is capable of linear amplification to 46 kw peak power with less than one-quarter watt of excitation. A directional coupler, M. C. Jones type MM-41158, is attached to the output terminal and is used to monitor the VSWR of any load that might be placed at this point. The center conductor of the coax is tapped with a pin to allow measurement of the rf voltage with a peak-reading voltmeter.

All of the stages except the preamp are grid pulsed into conduction during the pulse interval. This results in an interpulse noise better than 60 db down from the normal peak-to-peak pulse level. The output stage of this unit uses an Eimac type 4CX5000A tube.

The exciter and the IPA described were designed and built by the General Electric Company, Electronics Laboratory, Syracuse, New York, to the specifications of the U. S.

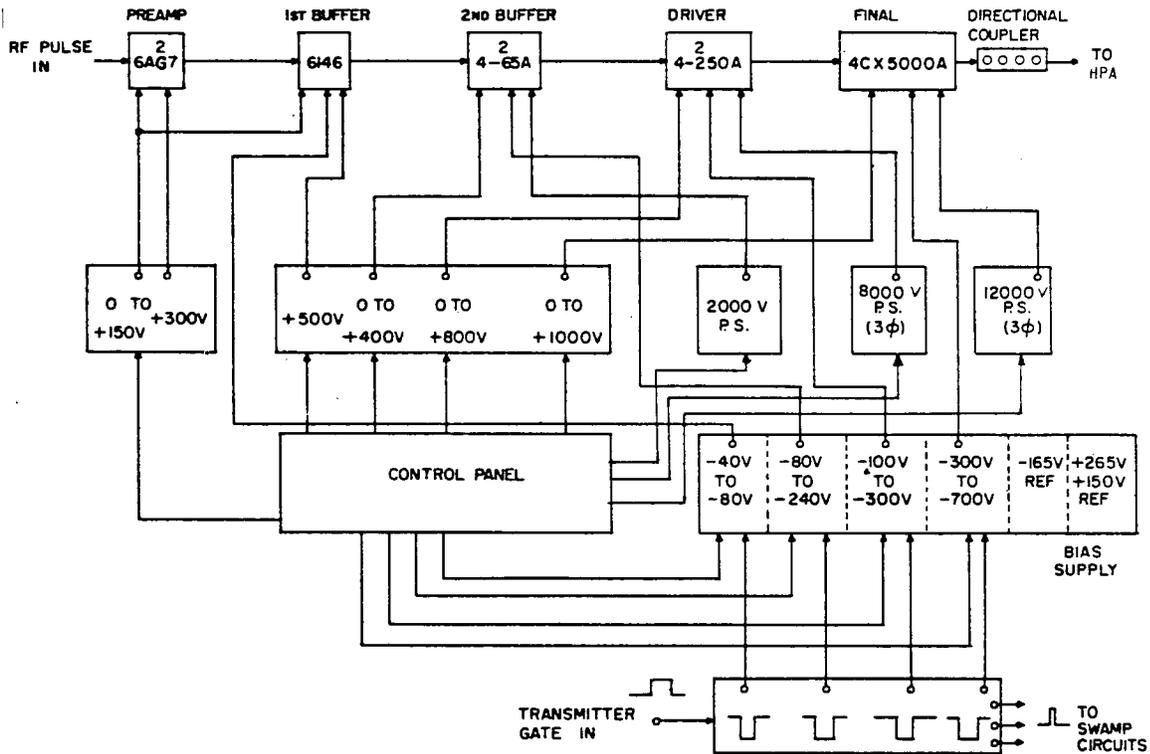


Figure 2 - Block diagram of the intermediate-power amplifier

Naval Research Laboratory. A complete description, along with circuit diagrams, is contained in the Instruction Book for these equipments.* A number of alterations to the equipment have been made over the past few years which improved the performance of the original equipment. The linearity and power output were not quite sufficient to drive the high-power amplifier under all conditions. NRL consequently designed and constructed another IPA unit which is capable of operating in the desired frequency range to produce 80 to 100 kw peak output power. The latter unit is now in limited use, and further development is in process. It is planned to use this unit as the main exciter and to maintain the General Electric exciter as a spare.

High-Power Amplifier

The high-power amplifier (HPA) is a single-stage unit using four RCA type A-15041 super-power triodes in a push-pull parallel configuration capable of operation between 10 and 30 Mc. Figure 3 is a schematic diagram of the amplifier. It is unique in its use of distributed constants (uhf techniques) as well as lumped-constant circuits over the frequency range. The plate circuit is tuned with a balanced shorted transmission line, W6; coarse tuning is accomplished by moving the short on the line. The plates are also connected to a phase-inverter transformer of the balun type for conversion to 50-ohm

*"Madre Instruction Book and Engineering Report," General Electric Co. Electronics Lab., Syracuse, N.Y., Contract NOnr 1771(00), 30 June 1955 to 29 May 1959 (Secret Report), Sept. 1959.

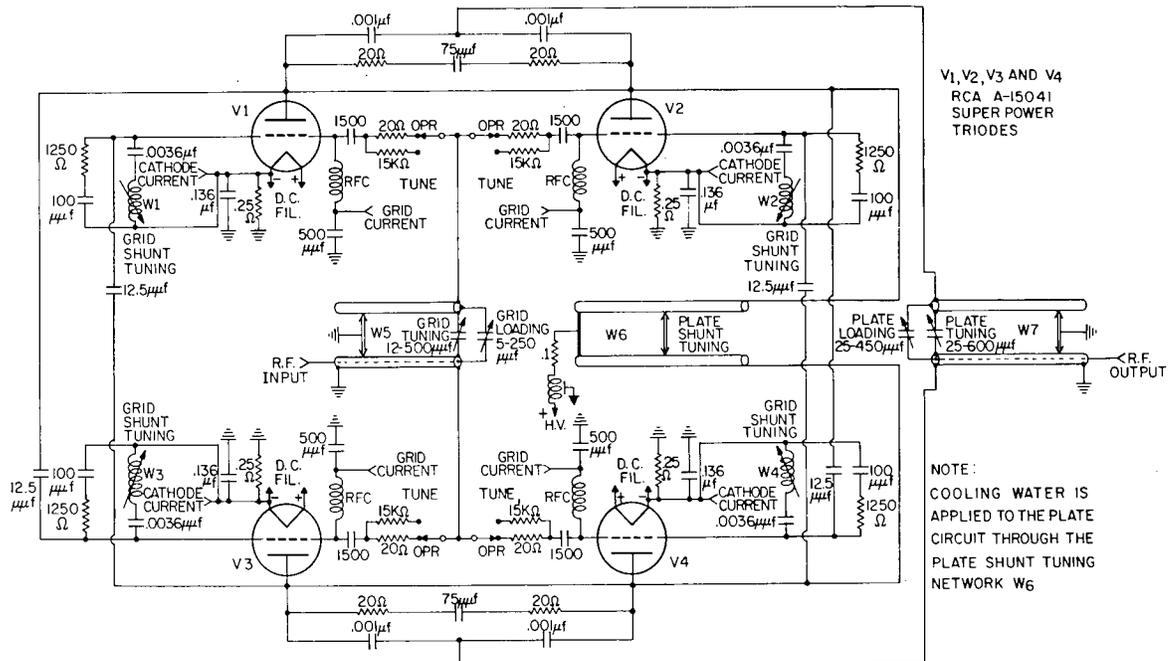


Figure 3 - Schematic diagram of the high-power amplifier (HPA)

unbalanced output. The balun contains a series-variable and a shunt-variable capacitor which are used as the fine tuning and loading adjustments. These components may be seen in Fig. 4. This balun has sufficient tuning range to cover the entire 10 to 30 Mc band. The grid circuit is similar except that the four tubes are separately tuned with four coaxial shorted transmission lines, W1 to W4. Each line is split at the grid end into four lines, allowing four connections to the grid of each tube. This accounts for the large number of lines visible in Fig. 5.

The plate tuning line is also used to feed the high voltage to the tube anodes and to pipe the anode coolant to and from the tubes. This removes the need of rf chokes and any other special rf isolation for the tube water. The tubing connected between the anodes of the tubes is for the plate coolant. The cover running between the tubes (Fig. 4) is used to shield the balanced-plate output transmission line and to give a more symmetrical configuration to the amplifier to prevent spurious oscillations. Seven fixed ceramic capacitors in series are used for each one of the four neutralizing capacitors. Resistors are connected between the plates of parallel tubes to suppress spurious oscillations. The small series LRC circuits (Fig. 4), connected to each of the neutralizing circuits, are for suppressing resonances in this circuit.

During normal operation the HPA filaments require 7.3 volts at 1140 amperes dc while the plate requires about 26 kv at 9 amperes. The interpulse noise is reduced by the same technique as that provided in the G.E. IPA, namely by decreasing the grid bias to the point of normal operation only for the duration of the pulse. The external view of the grid pulser may be seen on the far left of Fig. 6, while Fig. 7 shows the internal construction.

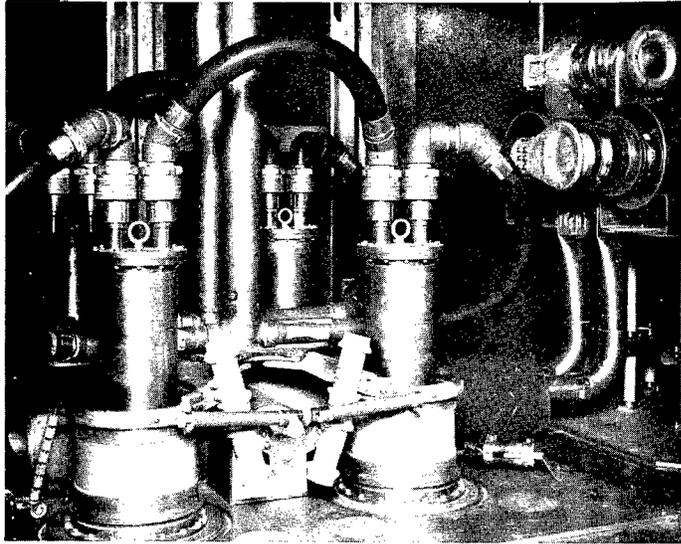


Figure 4 - HPA configuration, top side. The four tubes are visible with their connecting water hoses on top for plate cooling. The plate shunt tuner extends beyond the top of the picture. A series string of neutralizing capacitors is seen in the lower left, while at the upper right can be seen the plate loading and tuning capacitors.

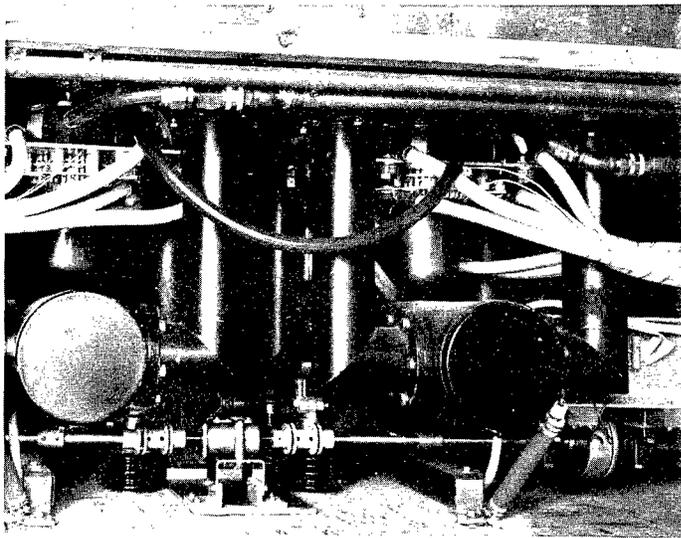


Figure 5 - HPA configuration, bottom side. The 3-1/8-in. coaxial lines contain the grid shunt tuners. The water hoses and filament-supply leads are nearly the same size. Resistors at the bottom are for parasitic suppression.

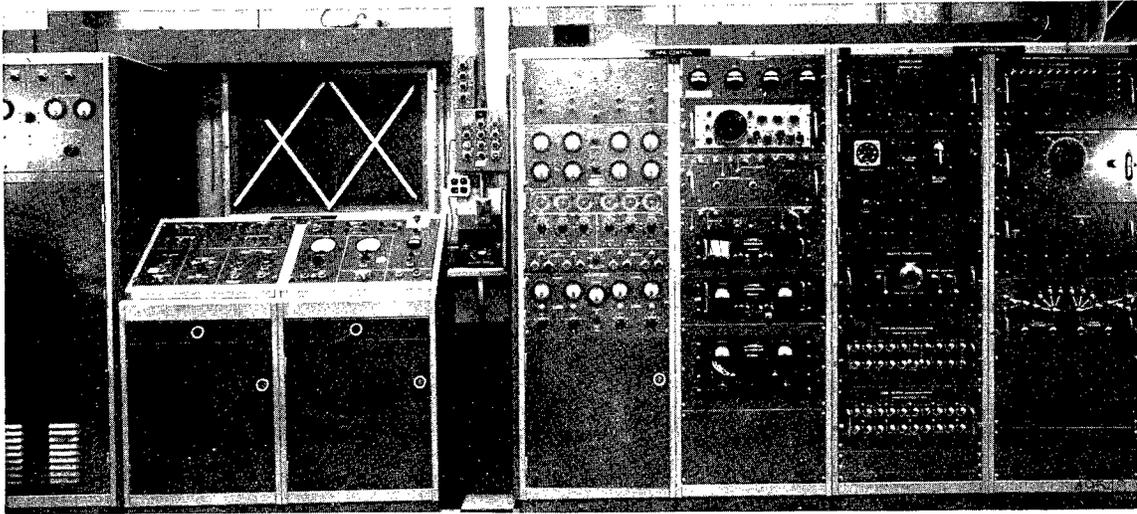


Figure 6 - Control panel and equipment located in front of the HPA shielded room. Arranged from left to right is the grid pulser (two racks), the HPA main control panel (sloping), the HPA tuning rack, the HPA monitor rack, and the two racks for the controls of the two antennas and the antenna monitor.

Dummy Load

Complete development and testing of the HPA were accomplished while using a dummy load. After several attempts to use commercially available loads failed, RCA designed and built the water load shown in Fig. 8.* This load uses a polyethylene slug as the dielectric between the turns of the center conductor, which is made into the form of a helix. Water having a resistivity of 10,000 ohm-centimeters is used as the dissipating medium between the helix and the outer conductor (ground). The load is capable of handling 5 megawatts peak power. The water normally flows through the load at a rate of 40 gallons per minute with an average temperature rise from 97° to 114° F.

High-Voltage Power Supply

The high-voltage power supply (HVPS) is adjustable from 5,000 volts to 27,000 volts under full load. A General Electric type LIRT 4160-volt, 60-cycle, 3 ϕ induction voltage regulator (IVR) is used to control the amplitude of the input voltage to the I.T.E. Circuit Breaker Co. model S.O. K-70957 unitized type power supply. The input to the IVR is through an I.T.E. type 5HV150 5-kv, 3-phase circuit breaker. The output of the IVR is connected to the high-voltage transformer through three Jennings type RH5G class H fast-acting vacuum switches. The IVR, fast-acting vacuum switches, and the unitized power supply are shown in Fig. 9. The high-voltage-transformer step-up ratio is only 1.84, since the IVR output may be varied from 1370 to 6430 volts. The output of the transformer is rectified by a total of 1140 IRC type 25H40 silicon diodes, 190 in each half phase. The rectified ac is then stored in the 48- μ f capacitor bank shown in Fig. 10.

*E. M. Leyton and J. T. Coleman, "High Power Load and Attenuator Design," Proc. 1961 Conference, 5th IRE National Convention on Military Electronics, June 1961.

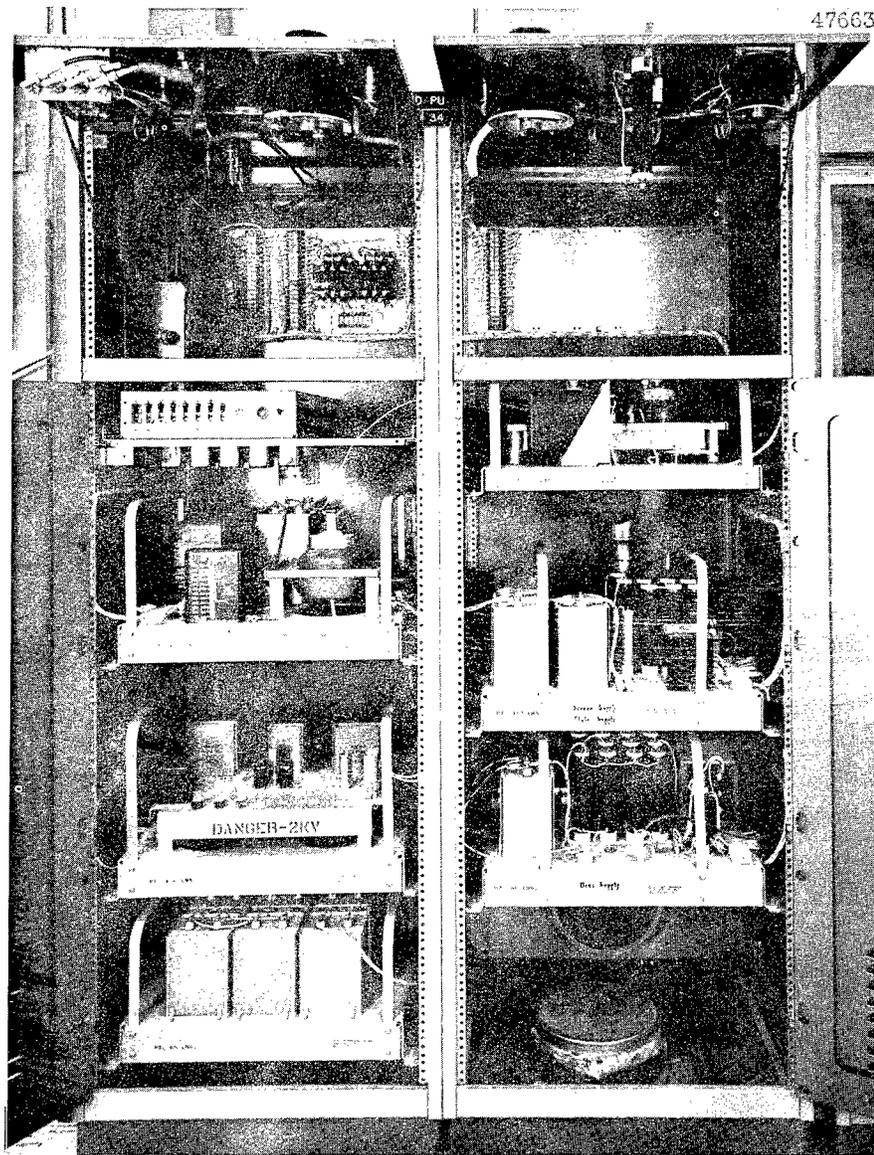


Figure 7 - Grid pulser, internal view

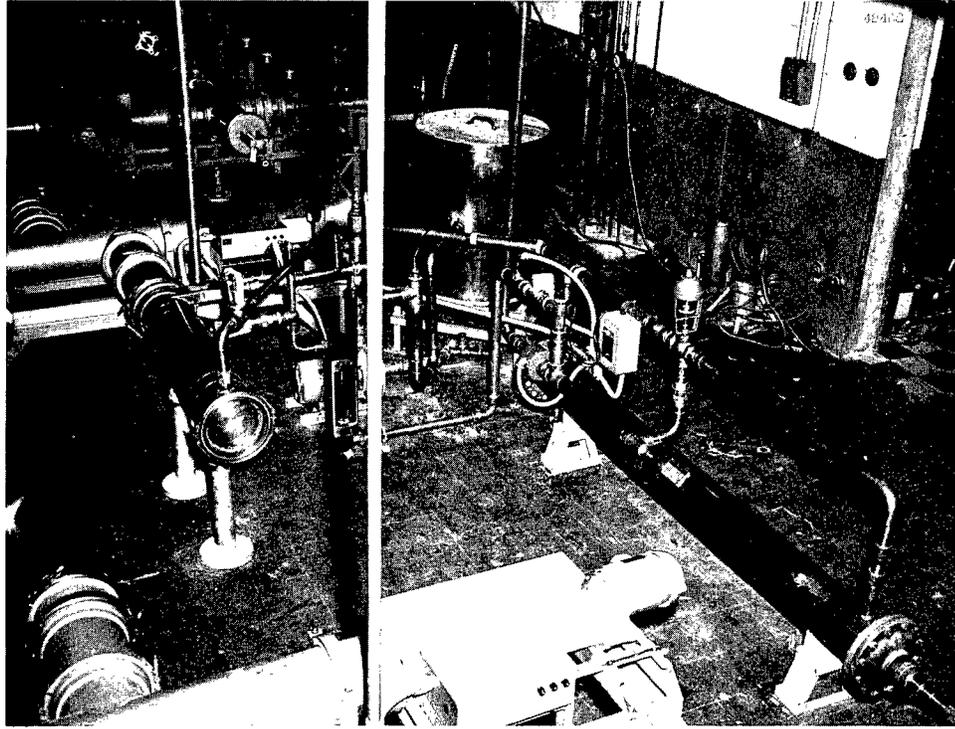


Figure 8 - Water load. The load itself is located in the left center, connected to a 9-in. coaxial switch. The large tube on the right is the water-to-water heat exchanger, while the tank at the top center is the reservoir, which is open to atmospheric pressure.

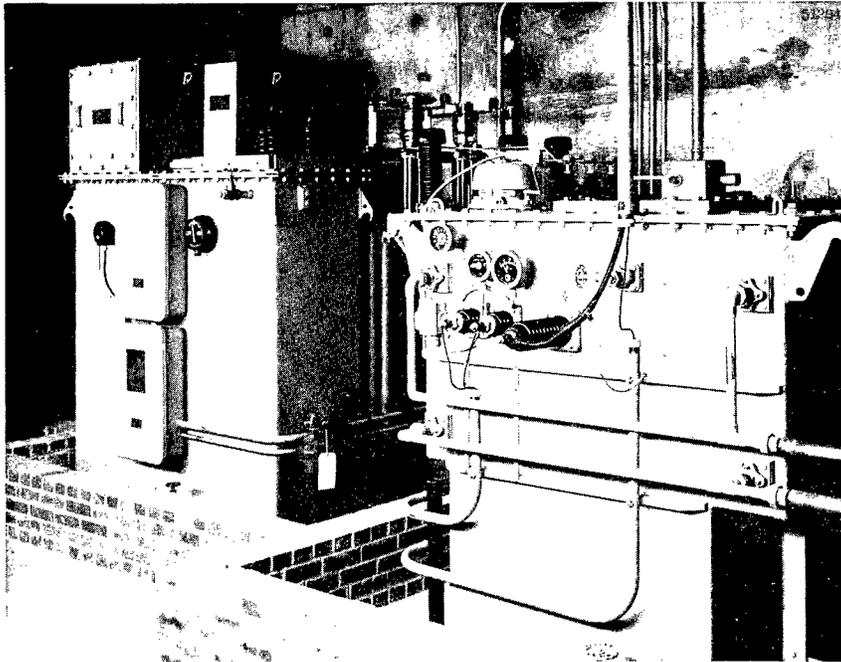


Figure 9 - High-voltage power supply and induction voltage regulator

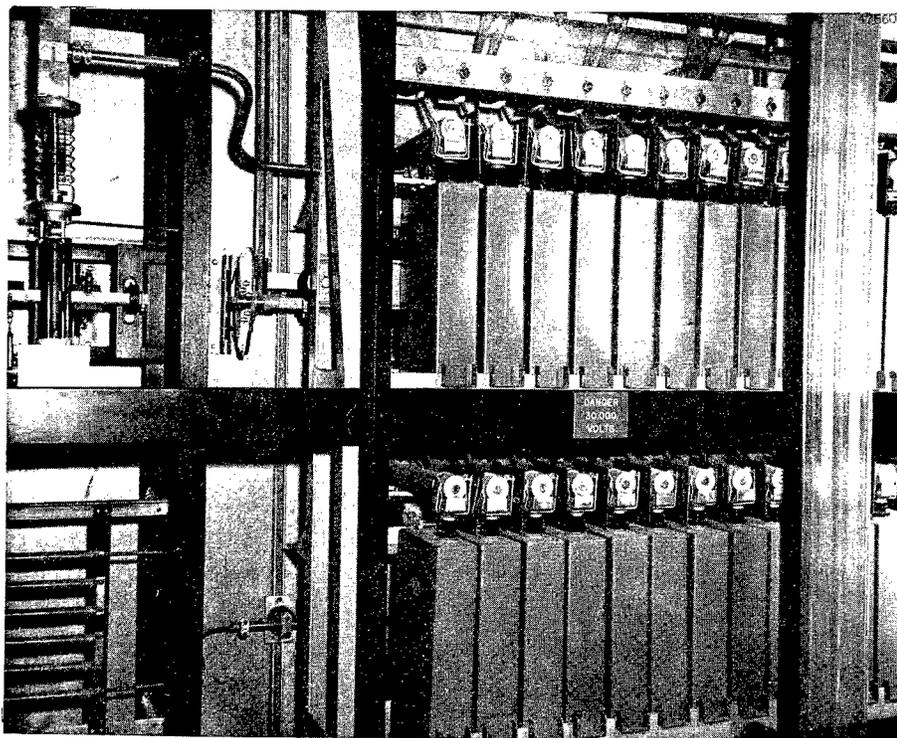


Figure 10 - Capacitor bank, showing a manual safety switch on the left and fuses in series with each capacitor

The capacitor bank contains 24 Sangamo 8- μ f, 12,500-volt capacitors connected in series parallel to give the total of 48- μ f at 25 kv. The cylinder located immediately on top of each capacitor is a fuse used to disconnect the associated capacitor from the rest of the bank if it should become defective.

Water Systems

With the HVPS at full load, and assuming that the auxiliaries operate simultaneously (air conditioners, pumps, antenna motors, etc.), 538 kva of primary power would be required for operation of the equipment. The complexity of the equipment and the power-handling capabilities require large amounts of water for cooling. To fulfill the water requirement, four different systems are required. Furthermore, to conserve the water, each system is a closed system, with water added only when small losses dictate. The four systems are amplifier-tube water, rf load water, temperature-regulated water, and raw water.

Amplifier-Tube Water - The water required for cooling the A-15041 super-power tubes must be of high purity, since it is used for cooling the anodes of the tubes. The apparatus used for purifying this water is shown in Fig. 11. Tap water is added to the system through three filters: a demineralizer, a deoxygenator, and a submicron filter. The resistivity of this water is 18 megohm-centimeters when it leaves the filter system. Each A-15041 anode requires cooling water flow of 60 gallons per minute, while the beam-forming and grid elements require 8 gallons per minute. Also, an additional ten gallons

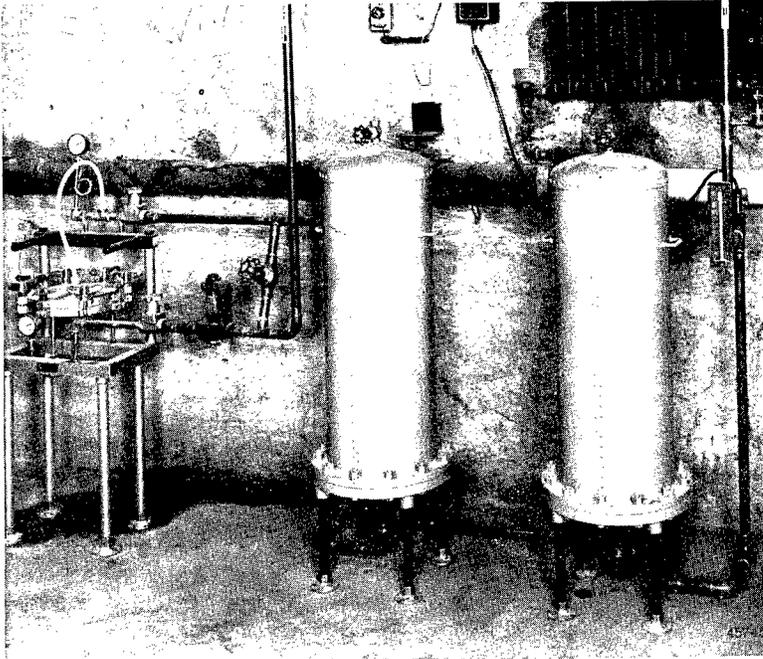


Figure 11 - Tube water-treatment system. The micron filter is on the left, the demineralizer is in the center, and the deoxygenator is on the right.

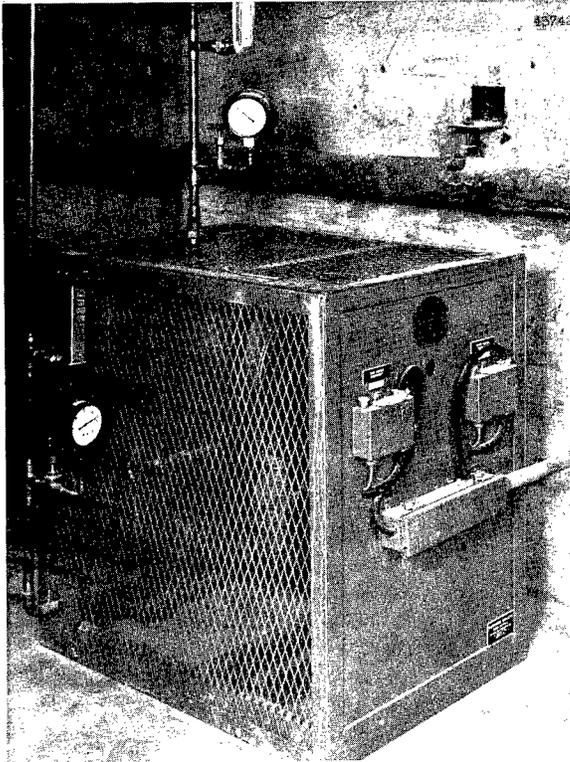


Figure 12 - Regulated-temperature water heat exchanger

per minute is required to cool the TR tubes in the duplexer. The heat in the tube water is transferred to the raw water through a water-to-water heat exchanger.

Rf Load Water - Water for the dummy load is required to have a resistivity of ten kilohm-centimeters for normal operating impedance; therefore the dummy load must also be a closed water system. The load-water heat exchanger, along with the load, is shown in Fig. 8. Initially the system is filled with high-purity water and then contaminated with citric acid to obtain the desired conductivity. The load was designed to operate with a nominal water temperature of 104° F to give an impedance approximately equal to 50 ohms. Therefore, an immersion heater was added to keep the water at this temperature while the load is not under power. The load water-to-water heat exchanger is fitted with a temperature-controlled bypass to maintain constant temperature while the load is under power.

Temperature-Regulated Water - A G.E. type 6228 ignitron used in the

protective system must be kept between 85° and 125° F to insure instantaneous firing should it be required. Hence the water which is used for this purpose must be heated by an external source. The water heater for this system is shown in Fig. 12.

Raw Water - The raw-water system, in addition to exchanging heat from the systems described previously, is also used with the six 7-1/2-ton Trane air conditioners placed throughout the operating space. The heat picked up in the raw-water system is transferred to the air outside the building through a 150-ton water-to-air cooling tower (Fig. 13). This system, with a flow of 316 gallons per minute, is a closed system filled from tap water only when needed. As a means of guarding against excessive dissolved solids, water at the rate of three gallons per minute is bled off whenever the system is in operation.

Compressed-Air System

When an A-15041 tube is to be removed from the amplifier, the cooling channels must be purged to remove the water from the tube waterways. Also, as a precaution against the accumulation of moisture in the rf coax transmission lines, their air pressure is kept 0.5 psi above ambient. The apparatus for compressing the air is shown in Fig. 14. A Nash Hytor type CD663 centrifugal type compressor having a capacity of 70 SCFM* is used. The compressed air goes through a water separator and into a storage

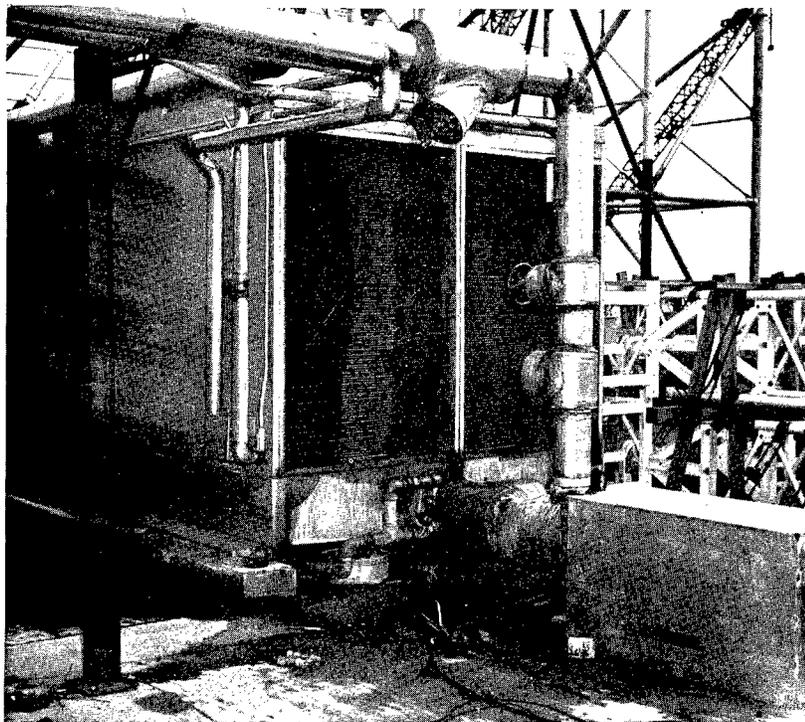


Figure 13 - Hot water from the air conditioners, tube heat exchangers, air compressors, and dummy load heat exchanger is cooled in this 150-ton-capacity cooling tower

*SCFM is standard cubic feet per minute. A SCFM is measured at 60° F and 30 in. of mercury barometric pressure.

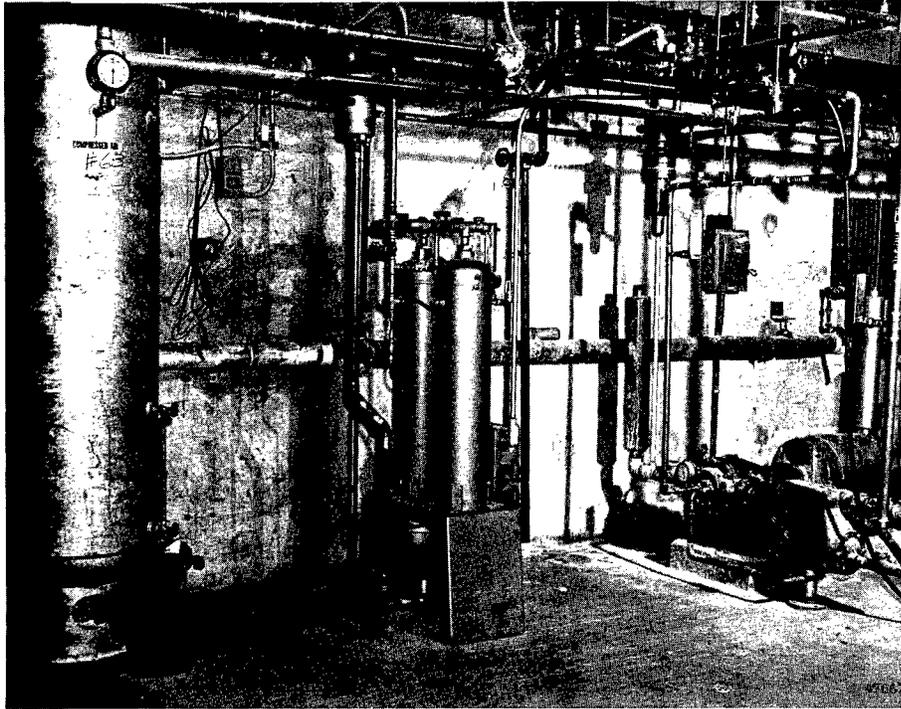


Figure 14 - Compressed-air system. The large tank on the left is the compressed-air storage tank, the two smaller tanks in the center are the air dryer, and the compressor is on the right.

tank which contains a water trap. The air then filters through a mechanical trap and finally through a Trinity Equipment Co. Model 100HA2X two-cycle air dryer to the output lines. The outgoing air is available at about 80 psig and at 1 psig, through a pressure reducer, for the coaxial transmission lines.

This air system was later expanded by the addition of two more Nash Hytor centrifugal compressors, one 70 SCFM and one 50 SCFM, and a Desomatic 70-SCFM air dryer. This additional capacity was required to drive an air bearing and air-turbine-drive magnetic-drum recording equipment used for data processing. The system was marginal and is being replaced by a Joy piston compressor capable of 210 SCFM and a Desomatic 210-SCFM air dryer. The original system will then be used as a backup for the Joy compressor.

Control and Safety

Figure 15 shows the transmitter control panel, which controls all power to the HPA, supporting apparatus, positionable antenna motors, antenna auxiliaries, motors, and the HVPS. The primary-power-on switch applies power to everything except the HVPS. The HVPS power switch allows the HVPS to program to its operating potential. The IPA interlock switch allows application of the rf drive to the HPA. Flashing red lights throughout the building indicate that high voltage is turned on. Safety switches are located around the building which, when pushed, will turn off the primary power to the HPA equipment.

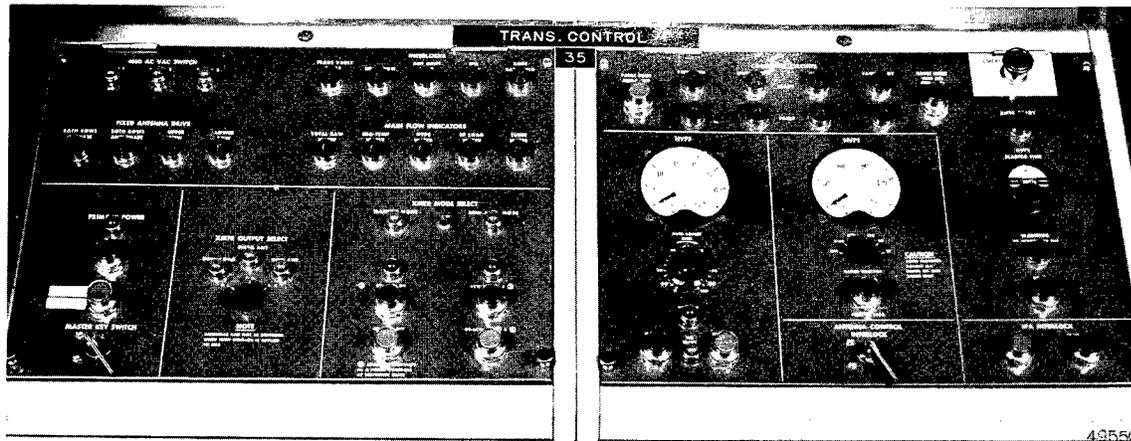


Figure 15 - Transmitter-control panel

Key Interlock System - As another safety precaution, the HVPS cannot be turned on unless a master key is in place on the transmitter control panel and turned on. Access to the amplifier room and the transformer vault is obtained only when the key interlock system is used. This system requires the master key to be removed from the power-control panel and placed in a position remote from the latter. The capacitor bank is then discharged, the high-voltage lead to the HPA grounded, and the proper key obtained for the space desired. Figure 16 shows this key interlock system.

A second key used on the transmitter control panel may be removed to prevent application of rf to the antennas during maintenance periods. However, removal of this key will not prevent the amplifier from being fed into the dummy load for maintenance and testing of the amplifier and duplexer.

Fault Sensing - Protection for the super-power tubes (valued at \$20,000 each) is obtained by the use of a fault-sensing system and an electronic "crowbar." If one of the tubes should develop a fault, if the voltage standing-wave ratio as indicated by the power monitor described subsequently is too great, if the capacitor bank should develop a short, or if a short is applied directly across the high-voltage line, then the fault-sensing equipment will function to send a trigger pulse to the electronic crowbar. The sensing system contains fast-acting circuits using 2D21 thyratrons. Not only does this system cause the crowbar to fire, but also it energizes a relay which lights an indicator light on the power-control panel or the HPA control panel to indicate the nature of the fault.

Protective Electronic Crowbar - Actuation of the electronic crowbar will cause the energy stored in the capacitor bank to be dissipated. The pulse coming from the fault-sensing equipment is amplified and used to ignite a GE type GL-6228 ignitron. This throws a short across the capacitor bank through a very small resistance which limits the discharge current to 10,000 amperes. Hence the stored energy is dissipated in the resistance and not across any vital circuit or tube component. The electronic crowbar is shown in Fig. 17. The small, hydraulically operated switch located on top of the electronic-crowbar frame is used to test the operation of the fault-sensing system and the electronic crowbar by grounding the high-voltage lead. A thin roll of aluminum foil used as the ground side of this switch is the indicating element. A one-eighth-inch (or less) hole will be seen in the foil when the fault sensing and the electronic crowbar are

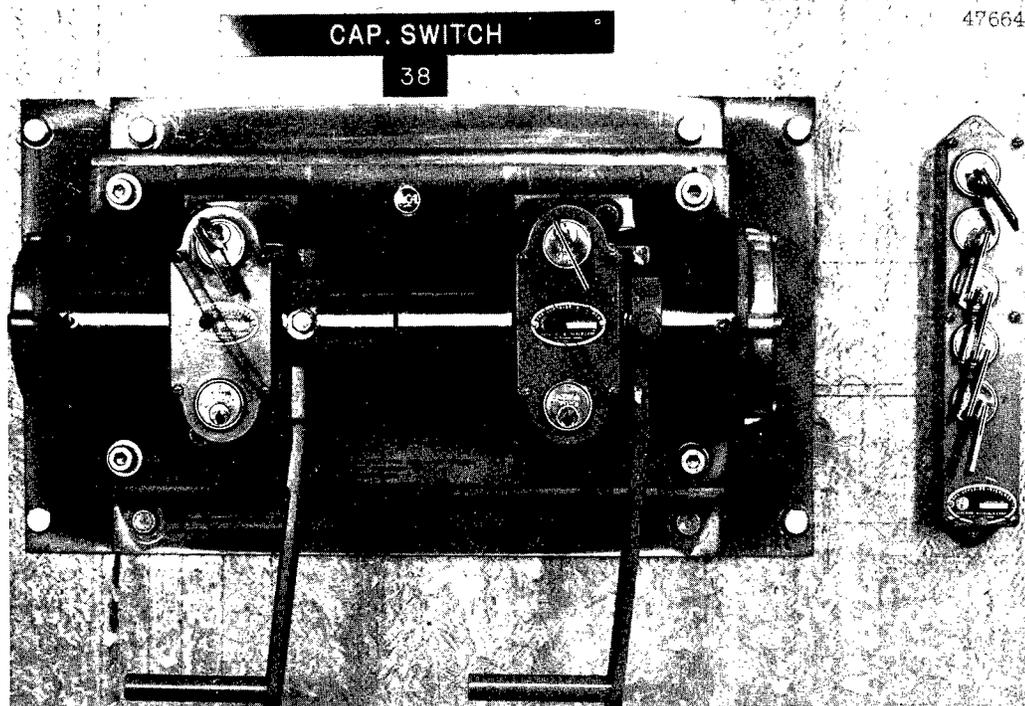


Figure 16 - Key interlock system. The large switch on the left discharges the filter capacitors through a resistance, then the large switch to the right places a short circuit across the filter.

functioning properly. Excessive current drain resulting from operation of the ignitron will deactivate the 4160-v circuit breaker and the fast-acting switches on the power transformer. By these means, ac power is removed from the rectifier in 15 milliseconds, and the 4160-v circuit breaker operates in 50 milliseconds.

THE DUPLEXER

The duplexer (Fig. 18) consists of two strip-line contradirectional couplers and two TR-tube cavities. When the TR tubes are energized by the transmitter signal, a short circuit is presented across the TR arms of the large coupler, thereby forcing nearly all of the energy to leave at the antenna terminal. On reception the signal leaves the large coupler via the TR arms, which are now very loosely coupled so as to have little or no effect, and is recombined in the small coupler. To provide additional protection to the receiving equipment, two silicon diodes are connected back-to-back across the receiver line. Both couplers are wide band and need not be adjusted over the 13.5-to-27-Mc range unless desired. Four special TR tubes are used, two in each cavity. They are constructed similar to vacuum capacitors, filled with argon and water vapor, and are water cooled. Tuning of the TR cavity (in reality a tuned coaxial stub) is accomplished by a vacuum variable capacitor. This must be adjusted when changing frequency for minimum loss on reception.

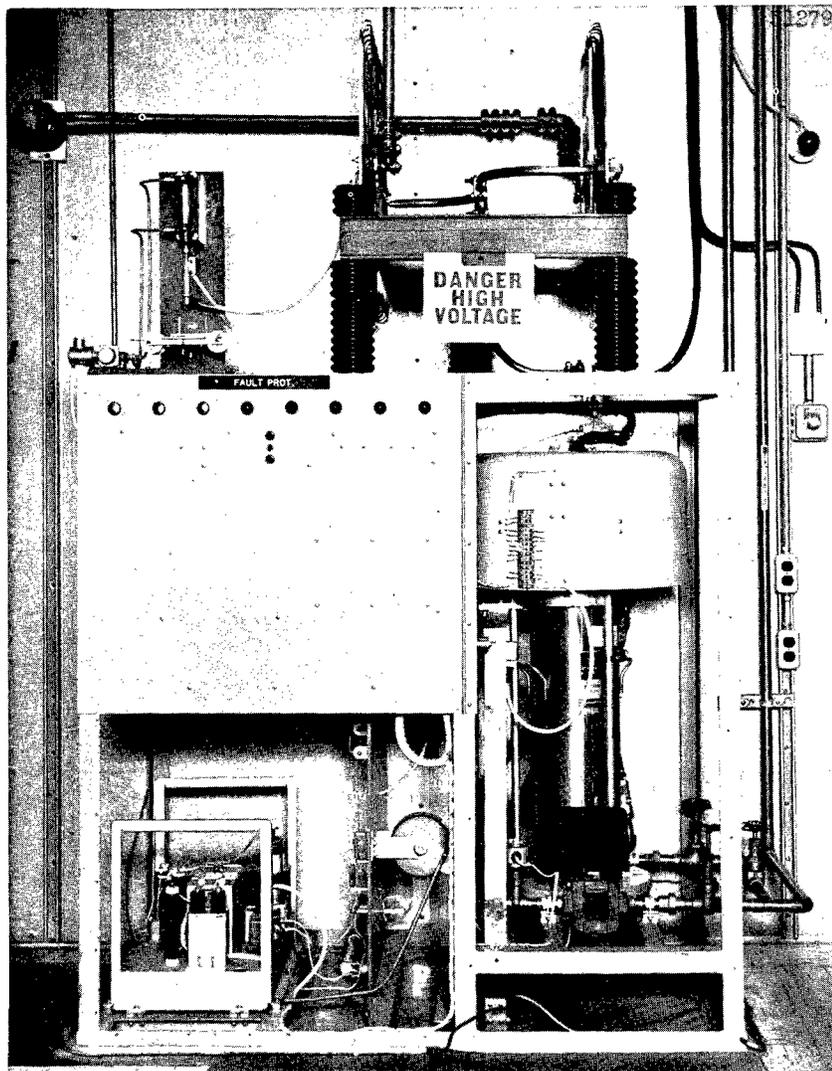


Figure 17 - Electronic "crowbar" fault protector. The ignitron is located on the right-hand side of this unit.

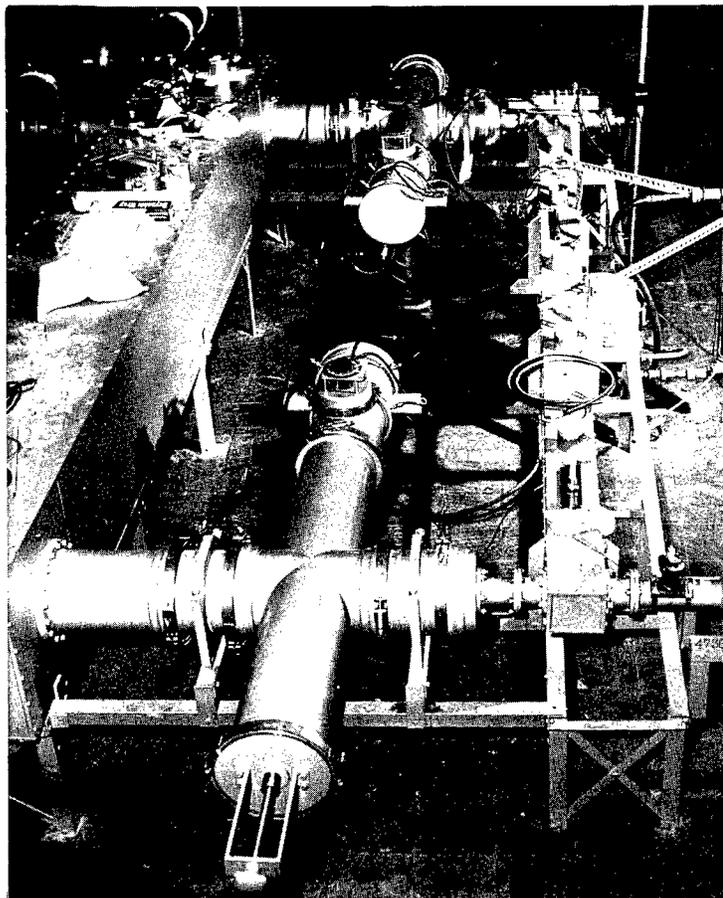


Figure 18 - Duplexer. The high-power contradirectional coupler is on the left, with the lower-power one on the right. In the center are the two tuned coaxial transformers containing the TR tubes.

The duplexer was designed by Microwave Electron Tube Company, Salem, Mass. They in turn subcontracted the manufacture of the couplers and cavities to the Dielectric Products Company of Raymond, Maine.

Some difficulty has been experienced in manufacturing TR tubes capable of long life (at least 500 hours); however, the solution to this problem appears imminent. Hence a development program was begun at NRL to make use of solid-state devices as the TR's. The objective is to have solid-state devices as the TR's mounted in a broadband holder. The program is still progressing.

THE RF RADIATING SYSTEM

Rf Power Distribution

Power leaves the transmitter on 9-3/16-in. coaxial transmission line flowing through a power-monitor section, the triple-stub tuner, the duplexer, and the coaxial switches, in that order (Fig. 19). One of the 9-3/16-in. coaxial switches, designed and manufactured.

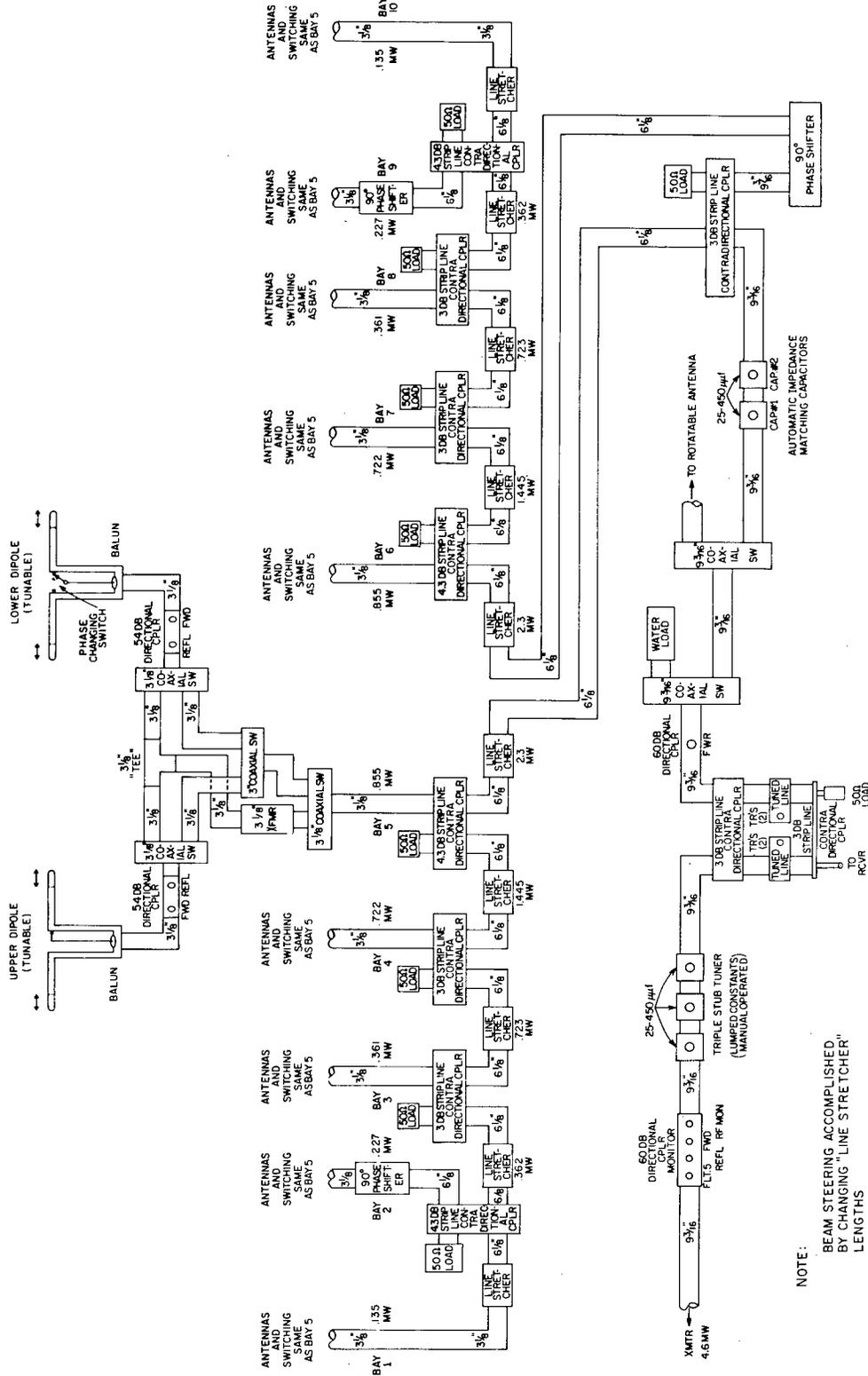


Figure 19 - Block diagram of the rf power flow

NOTE:
BEAM STEERING ACCOMPLISHED
BY CHANGING "LINE STRETCHER"
LENGTHS

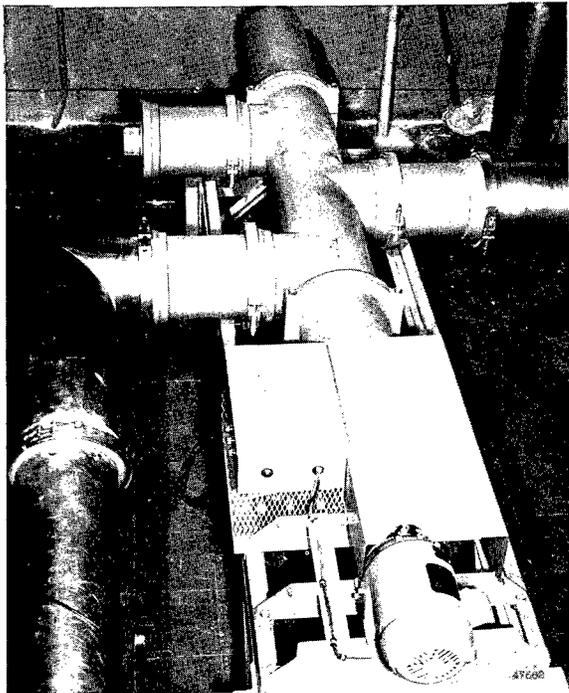


Figure 20 - SPDT 9-3/16-in. coaxial switch. The drive motor is in the lower right; the common arm is on the right.

by Dielectric Products Company, is shown in Fig. 20. The first coaxial switch selects either the dummy load or the antenna system, while the second switch selects either the positionable antenna or the fixed antenna.

The transmission line to the fixed antenna first encounters two variable capacitors, connected across the line, which are used for automatic impedance tuning. Power then flows into a 3-db strip-line contra-directional coupler employed as a power splitter. The two outputs from the power splitter have 90 degrees of phase difference, and therefore a 90-degree phase shifter is connected to one output of the splitter. (Another strip line is used for this purpose.) The in-phase power is now carried on two 6-1/8-in. coaxial lines to two phase shifters. All phase shifters are of the trombone line-stretcher type. These two phase shifters at the feed center of the antenna are used as part of the automatic impedance tuner and for beam steering. All other phase

shifters are used for beam steering only. They are motor driven and programmed to permit continuous beam steering through an angle of ± 30 degrees.

Reference to the block diagram for bay 5 on Fig. 19 shows that the energy can be applied to the upper dipole alone, the lower dipole alone, both dipoles in phase, or both dipoles out of phase. For simplicity, only the coaxial switching, directional couplers, and the dipoles of bay 5 are shown on Fig. 19; all the other bays are identical to bay 5. Each dipole has its own directional coupler, which can be used to monitor the relative power and phase of the energy between dipoles.

The impedance of the antenna changes appreciably with steering, and in order to maintain a reasonably constant load for the transmitter the automatic impedance tuner has been provided. The use of contradirectional strip-line power splitters also helps to alleviate this problem.

The transmission line to the positionable antenna contains a 50-to-25-ohm transformer of the three-section step type. A coaxial tee is connected at the 25-ohm point, and the tee in turn is connected to the feed for the two dipoles in the positionable antenna. The antenna proper consists of two dipoles side by side in a corner reflector.

Power Monitoring

The main power monitor is located in the 9-3/16-in. rigid coax line adjacent to the transmitter output terminal. Figure 21 shows this component, which was manufactured by

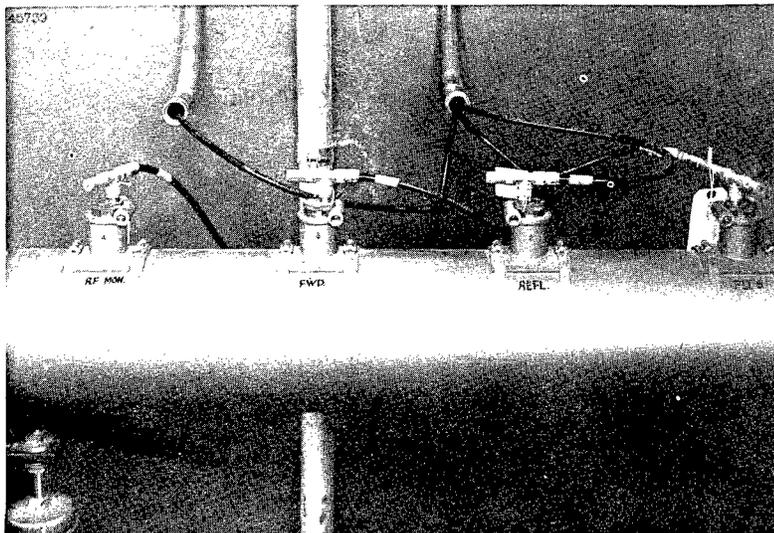


Figure 21 - Directional couplers for rf monitor. Appearing from left to right, the couplers are used as follows: power-output indicator, forward power, reflected power, and reflected-power fault sensing.

Dielectric Products Company. The monitor contains four 60-db directional couplers, one for monitoring the forward power, one for monitoring the reflected power, one for rf monitoring, and one for VSWR fault sensing.

Triple-Stub Tuner

From the power monitor the 9-3/16-in. coax then connects directly to the triple-stub tuner (Fig. 22). The tuner was designed by RCA and built by Dielectric Products Company. In place of distributed constants, as generally found in triple-stub tuners, lumped constants are used here. Three Jennings type VMMHC 25- to 450- $\mu\mu\text{f}$ vacuum variable capacitors are used as the reactive elements.

Fixed Antenna System

A fixed antenna deemed suitable for detecting aircraft at great distances was erected to look in a generally eastward direction. This fixed antenna is an array of twenty (2 X 10) corner reflectors. Physical vibration of the antenna will introduce unwanted doppler frequency components. Therefore, an attempt has been made to limit spurious doppler components that are greater than two cycles per second to below one milliwatt. Translated to antenna movement, this means that the antenna must not move more than 1/16 in. at its outermost extremities, unless the movement is at 2 cps or slower rate.

To meet this requirement, along with the gain and beam-steering requirement, RCA designed and built a broadside array of 20 corner reflectors. The elements (corner reflectors) are arranged in ten bays side by side (Fig. 23). The array is mounted on a cliff about 90 ft above the Chesapeake Bay. Each bay is two elements high. This type of

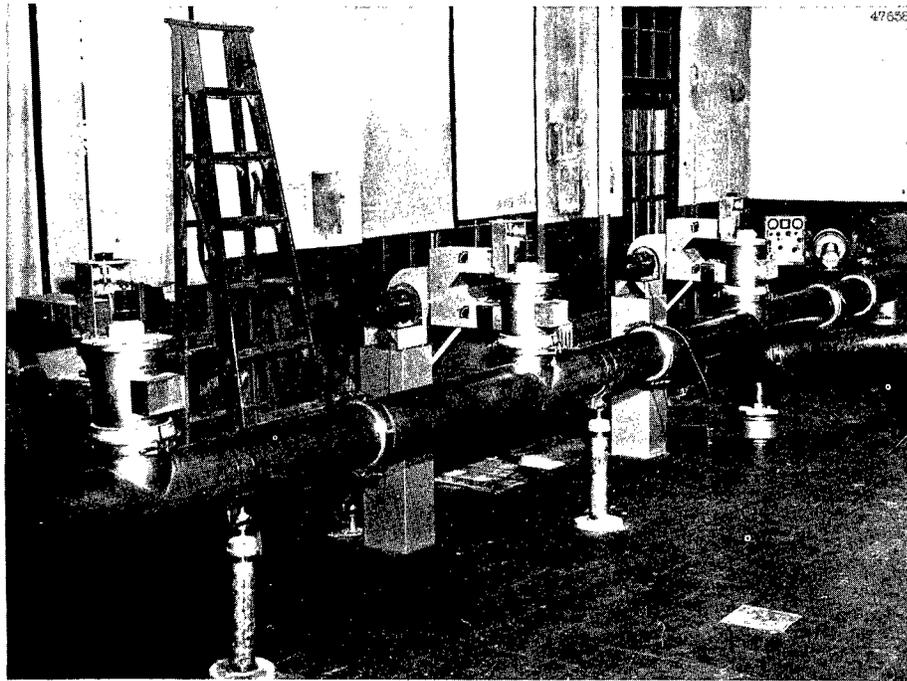


Figure 22 - Triple-stub tuner. Blowers can be seen behind each stub for cooling the vacuum variable capacitors.

structure has the inherent rigidity required. Each 45-degree corner reflector is 30 ft long, 70 ft high, and 35 ft deep. Fifteen feet extra is added to each end reflector to improve the resulting pattern. Thus the complete structure is 330 ft long, 140 ft high, and 35 ft deep. The polarization is horizontal. The structure is made of tubular pipe to reduce the wing drag, and to assist further in reducing the effect of antenna movement, each bay is mechanically isolated from its neighboring bay. In this manner the independent bay movements will have an rms effect rather than a coherent summing result. A rigid structure of this type could have objectionable resonances in the frequency band of interest (above 2 cps); therefore each bay is loaded with 55 tons of concrete placed at the 100-ft level. With this loading, the calculated resonance of each of the ten vertical bays falls below 2 cps. As a further deterrent to vibration, the main forward supporting members are built up of riveted parts to increase the damping. Soil tests were also made to determine the damping characteristics of the site. The stability of the soil was investigated by Dr. Dale Harroun of the University of Pennsylvania.

Detailed drawings and stress analyses were made for RCA by Hagy-Widdicomb's, Inc., Philadelphia. Model stress determinations on intermediate sections were made by Dr. Sidney Shore at the University of Pennsylvania. Fabrication and erection of the steel work was subcontracted by RCA to Luria Engineering Company, who in turn subcontracted subassemblies to Pollack Engineering and Tubular Products. Demolition and foundation excavations were done by Tantano Construction Company, Philadelphia, Pa., and foundations were placed by Tri-County Construction Company. Installation of rf and electrical components was subcontracted to Foley Electrical Contractors. Major rf components were manufactured by Dielectric Products Company; the tunable broadband dipoles were manufactured by RCA.

The corner reflectors are fed by broadband dipoles mounted at the end of a broadband balun. The reflecting surface of each corner is made up of 1-in. pipe spaced 2 ft on center. To cover the 13.5-to-27-Mc band, each dipole length can be changed by a remote electric motor. Six preset positions are used to cover the band.

An rf-plumbing enclosure (Fig. 23) runs the full length of the fixed antenna, just under the lower row of corner reflectors. Vertical chimney-like structures, visible to the rear of this enclosure, house the line stretchers. The inside of the rf enclosure (Fig. 24) shows all of the coaxial line, directional couplers, and switches used for switching and phasing. A line stretcher (trombone) is shown in Fig. 25.

The antenna control and monitor panels (Fig. 6) are physically near the transmitter-control panel (Fig. 15). Each dipole contains two directional couplers from which the VSWR can be monitored. All the flexible coaxial lines connecting the couplers to the monitor connectors on the antenna control and monitor panel are exactly the same length, which facilitates phase measurements. This antenna has a gain relative to an isotrope of 19 db at 13.5 Mc and 23 db at 27.5 Mc. When the beam is on boresight, its bearing is 77 degrees (east of true north).

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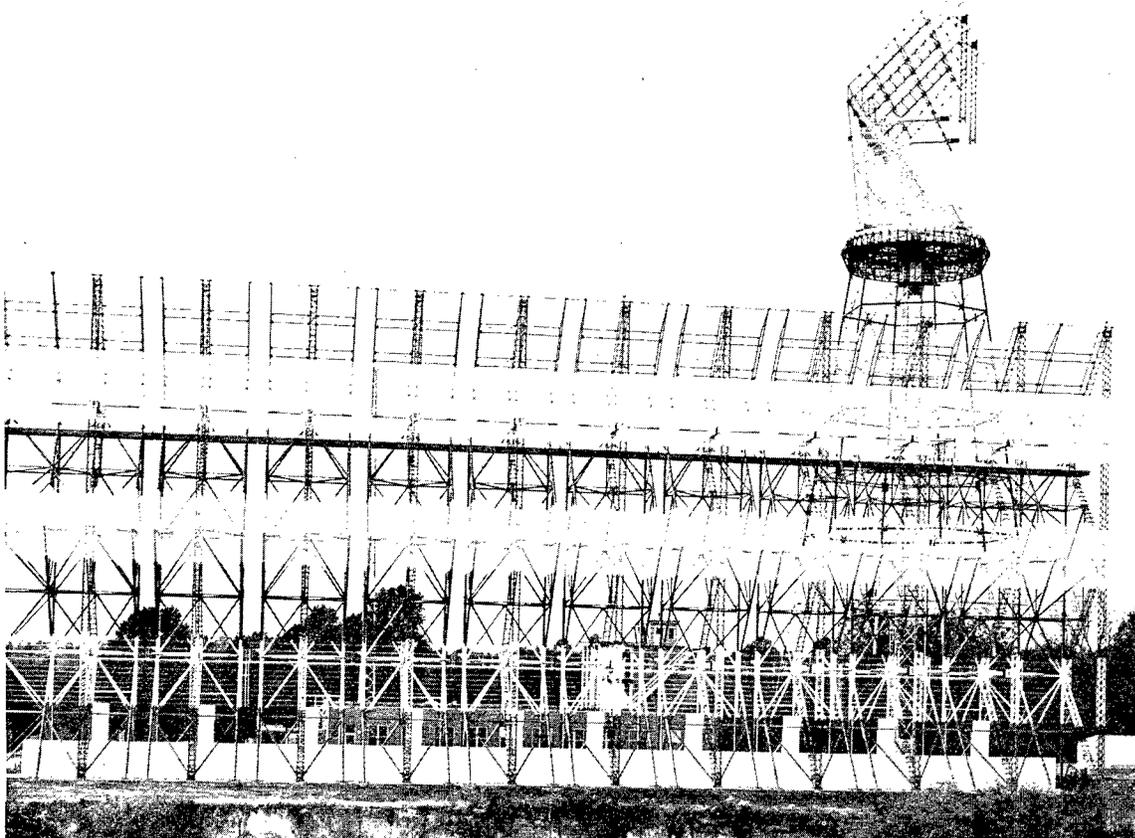


Figure 23 - Front view of the antennas. The fixed antenna is 330 ft long by 140 ft high. Behind it may be seen the positionable antenna, mounted on a 180-ft tower.

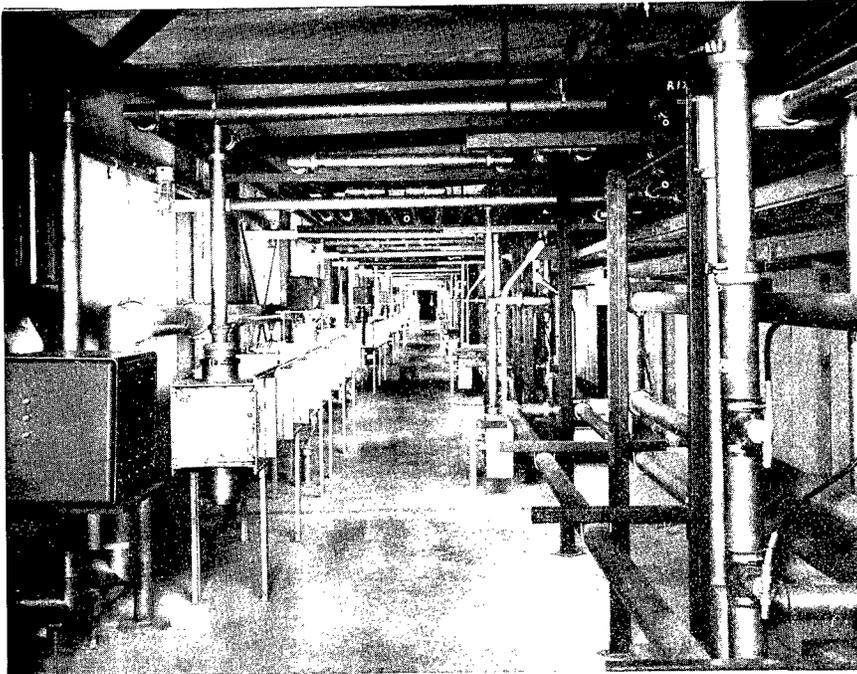


Figure 24 - Rf enclosure, inside view. A row of power splitters may be seen on the left.

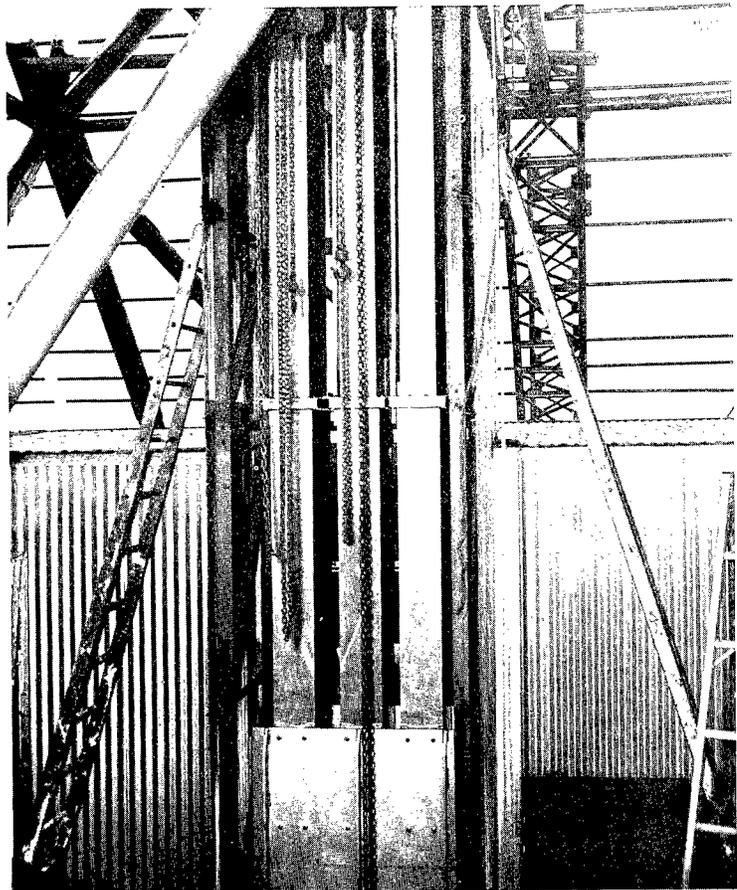


Figure 25 - Rear view of a phase shifter (trombone-type line stretcher) with cover removed

Positionable Antenna System

A rotatable antenna was deemed desirable, to permit missile observations in any direction. A proposal submitted by RCA resulted in the design and construction of the tower and rotatable antenna shown in Fig. 26. Tubular steel was used throughout the structure. Dresser-Ideco Company and Pollack Engineering Company fabricated the steel while Cornell, Inc., of Philadelphia, Pa., erected the structure. Tri-County installed the foundation.

Tower - The tower base forms a hexagon with a span of 100 ft between opposite legs. The height is 180 ft to the bottom of the rotatable antenna. To increase the strength of the tower, the legs are filled with concrete to the 75-ft level.

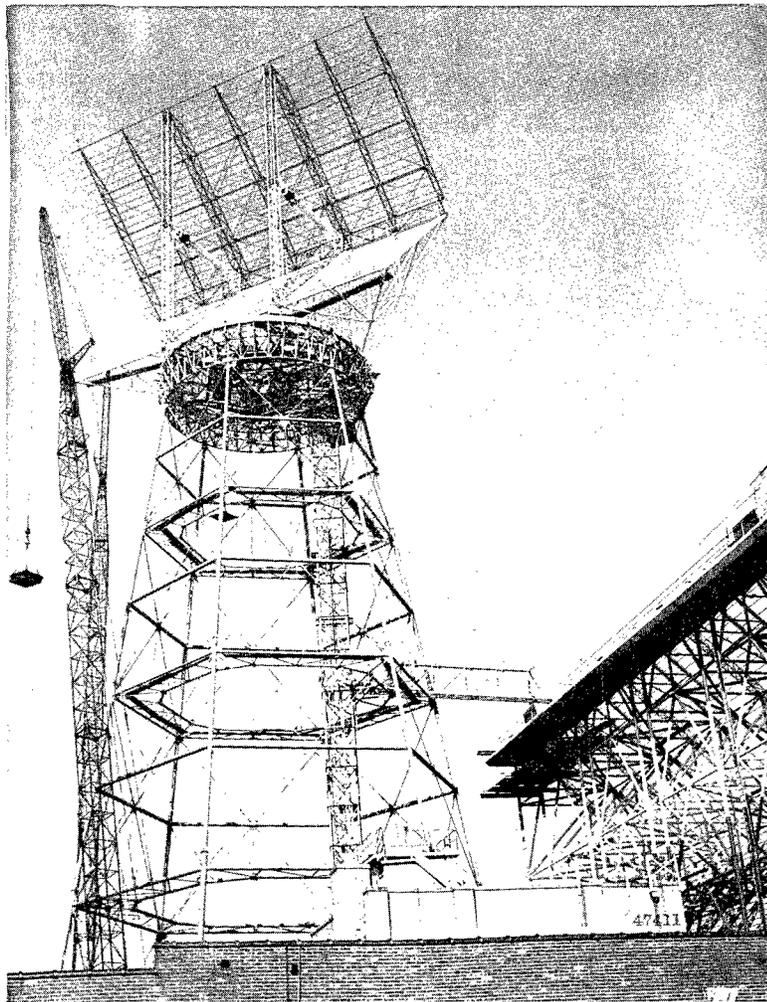


Figure 26 - Positionable antenna. The elevator shaft and catwalk are visible. To the right, a portion of the rear of the fixed antenna is visible, showing the concrete loading weights.

Positionable Antenna - A corner-reflector array is again used as the rotatable antenna. Thus much of the design of the rotatable antenna was carried over from the fixed antenna. Two corner reflectors mounted side by side form the antenna, making it 90 feet long and 70 feet high. This antenna is also made of tubular steel. The lower tubular-steel members of this structure are also filled with concrete to lower the center of gravity of the antenna. The total weight of the rotatable antenna and tower is 55 tons.

The dipoles of this antenna (Fig. 27) are similar to the ones used in the fixed antenna. Because of the amount of power each dipole must handle, the physical construction is slightly different from those in the fixed array, but electrically they are identical to the fixed-antenna dipoles.

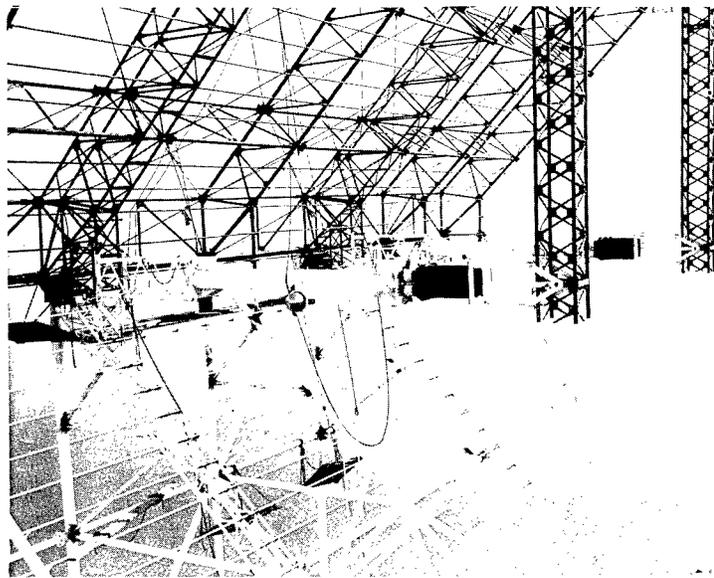


Figure 27 - Close-up of positionable antenna, showing dipoles

Rotation of the antenna is accomplished through the use of four one-horsepower motors. These are shown as the square boxes at the base of the rotatable antenna (Fig. 26). An anemometer is located at the top of the rotatable antenna and will disable circuits to prevent the antenna from being rotated in winds greater than 35 knots. A slip ring and rotatable joint designed and built by RCA are mounted at the base of the antenna. The slip rings carry the driving-motor power, FAA lighting power, anemometer indicating circuits, control monitor circuit, and driving-motor break control circuit. The rotatable joint is capable of handling 100 kw peak power while rotating; the full peak power of 5 megawatts is applied only while the antenna is stationary.

The gain of this antenna is from 10 db at 13.5 Mc to 15 db at 27 Mc, relative to an isotropic radiator. The controls for rotating or positioning the antenna are also shown in Fig. 6. Tuning of the dipoles must be accomplished at the top of the tower. However, the dipoles have been adjusted to have a VSWR of less than 2:1 over the 2:1 frequency range.

The antenna center is 305 ft above the bay water and 215 ft above the immediately surrounding land.

TOWER ELEVATOR

To facilitate servicing and adjusting the positionable antenna, and the upper portion of the fixed antenna, an elevator is installed off the center of the tower. The capacity of this elevator is 1000 pounds, which is sufficient to handle several men and any necessary test equipment. The elevator shaft can be seen to the right of the middle of the tower in Fig. 26. As an aid to adjusting and servicing the fixed antenna, an exit from the elevator is provided at the 100-ft level. Access to the fixed antenna is via a cantilever bridge, also shown in Fig. 26. Because of the requirements for stability of the fixed antenna, there is no mechanical connection between the bridge and the fixed antenna. However, if the cables holding the bridge should fail, the end of the bridge would drop only about eight inches before it would rest on the concrete slab of the fixed antenna.

AUXILIARY EQUIPMENT

All operations utilizing the high-power Madre equipment are backed up by communications. To facilitate the hf communications, two Collins 51S-1 radio receivers, one Collins AN/URC-32 SSB transceiver, and a Collins 237A-1 Log Periodic antenna are used. An AN/ARC-1 transceiver is used for vhf communications, while an AN/ARC-55 transceiver is used for uhf communications. Additional equipment used for radio studies are two RAO radio receivers, an RCX Panoramic Radio adaptor, a TMC portable master oscillator, a model 19 teletype printer, and a Sanborn model 150 four-channel recorder. Also available is a Viking CDC all-frequency transmitter and a Johnson Thunderbolt KW amplifier.

Recently a Granger model 116, 100-kw-peak-power distributed amplifier was obtained. This unit will be used as a backup driver for the HPA and as an amplifier for a Cossor Ionospheric Sounder. When used with the sounder, the amplifier will feed a log periodic antenna oriented vertically.

CONCLUSIONS

The high-power Madre equipment has performed in a satisfactory manner and has amply demonstrated its ability to detect aircraft, missiles, and other moving objects via ionospheric reflection. While this equipment has often been quite cumbersome for some purposes, it has demonstrated its flexibility in varied research applications. The system has been in a continual, although slow, state of change, with improvement and still further flexibility being the object.

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