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TECHNICAL NOTE

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PROJECT ECHO — 960-MEGACYCLE, 10-KILOWATT TRANSMITTER

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SUMMARY

A 10-kw transmitter operating at 960 to 961 Mc was used at the eastern terminus of the Project Echo communications experiment. This transmitter is located on Crawford's Hill near Holmdel, New Jersey. The 10-kw output feeds into a waveguide line leading to a 60-foot dish antenna. Exciter-driver units are available to drive the power amplifier with various modulations, such as wide-deviation FM, low-index phase modulation, single-sideband or double-sideband modulation with or without carrier, 960.05 or 961.05 Mc constant-frequency CW, and radar on-off pulses at 961.05 Mc. The main output amplifier consists primarily of a four-stage, externally-tuned-cavity, water-cooled klystron, operating at a beam voltage of 16 to 18 kv.

The transmitter has been operated during many Moonbounce, tropospheric scatter, and Echo I tests with very satisfactory results. This paper describes its use before March 1, 1961.

PREFACE

The Project Echo communications experiment was a joint operation by the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), the Naval Research Laboratory (NRL), and the Bell Telephone Laboratories (BTL). The equipment described herein, although designed by BTL as part of its own research and development program, was operated in connection with Project Echo under contract NASW-110 for NASA. Overall technical management of Project Echo was the responsibility of NASA's Goddard Space Flight Center.

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INTRODUCTION

The main transmitter unit of the 960-Mc, 10-kw transmitter used in Project Echo, and its input stage driver unit, are standard commercial equipments supplied by the Federal Telecommunication Laboratory.† These units were selected because they came closest to meeting Project Echo's particular requirements for wideband FM transmission. These general requirements were that the transmitter could (1) deliver 10 kw of RF power into a 50-ohm load at a frequency of about 960 ± 2 Mc; (2) be frequency-modulated over the audio frequency band with deviations of ± 200 to 300 kc; and (3) be used with other types of modulation such as single-sideband (SSB), double-sideband (DSB), interrupted continuous wave (ICW), etc. The transmitter has performed satisfactorily for all required tests.

The main radio amplifier consists of a four-stage klystron (Eimac 4K-50,000 LQ) with external tunable cavities, and operates at beam voltages of 16 to 18 kv. The necessary power supplies, cooling system, and control units are also incorporated as part of the transmitter. The driving stage amplifier can deliver up to 10 watts but, for normal 10-kw klystron output, less than one-half watt is required; the klystron has a power gain of 40 to 50 db.

The modulating units have an output of about one watt at 70 Mc and feed into a mixer which is driven by an 890.05-Mc CW signal of the proper level. This latter frequency originates in a crystal controlled oscillator at 49+ Mc and is stepped up to the desired value by an 18-times frequency multiplier. The final output frequency is the sum of the 890.05 and the 70-Mc modulated frequencies, or 960.05 Mc.

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†Division of International Telephone and Telegraph Corporation.

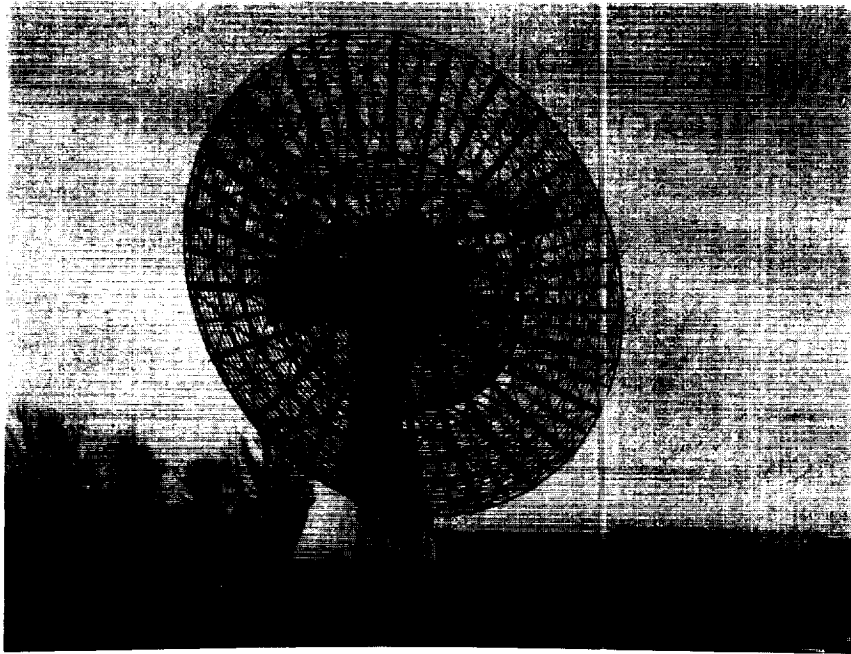


Figure 1—Transmitter building and Kennedy dish antenna at Crawford's Hill near Holmdel, New Jersey

The transmitter, with all the necessary controls, power supplies, cooling system, driver units, measuring equipment, and recorders is housed in a metal building 16 x 26 foot with a 10-foot ceiling, located at the base of the 60-foot-diameter Kennedy dish antenna (Figure 1). A control panel for manual operation and orientation of the dish antenna is also included in this building.

THE POWER AMPLIFIER

The 10-kw power amplifier consists primarily of the water- and air-cooled klystron. With its control circuits and power supplies it is contained in a three-compartment metal cabinet 152 inches long, 37 inches deep, and 85 inches tall. The heat exchanger, used for klystron cooling, has about the same height and depth and is 56 inches long; this is placed along the rear wall of the building and not in line with the transmitter proper. Figures 2 and 3 show the general arrangement of the equipment.

A liquid-cooled dummy load, consisting of a 6-foot length of 3-1/8-inch 50-ohm coaxial line, is provided for output power calibration and measurement. The RF power is dissipated directly into the coolant liquid; and by calorimetric measurement of

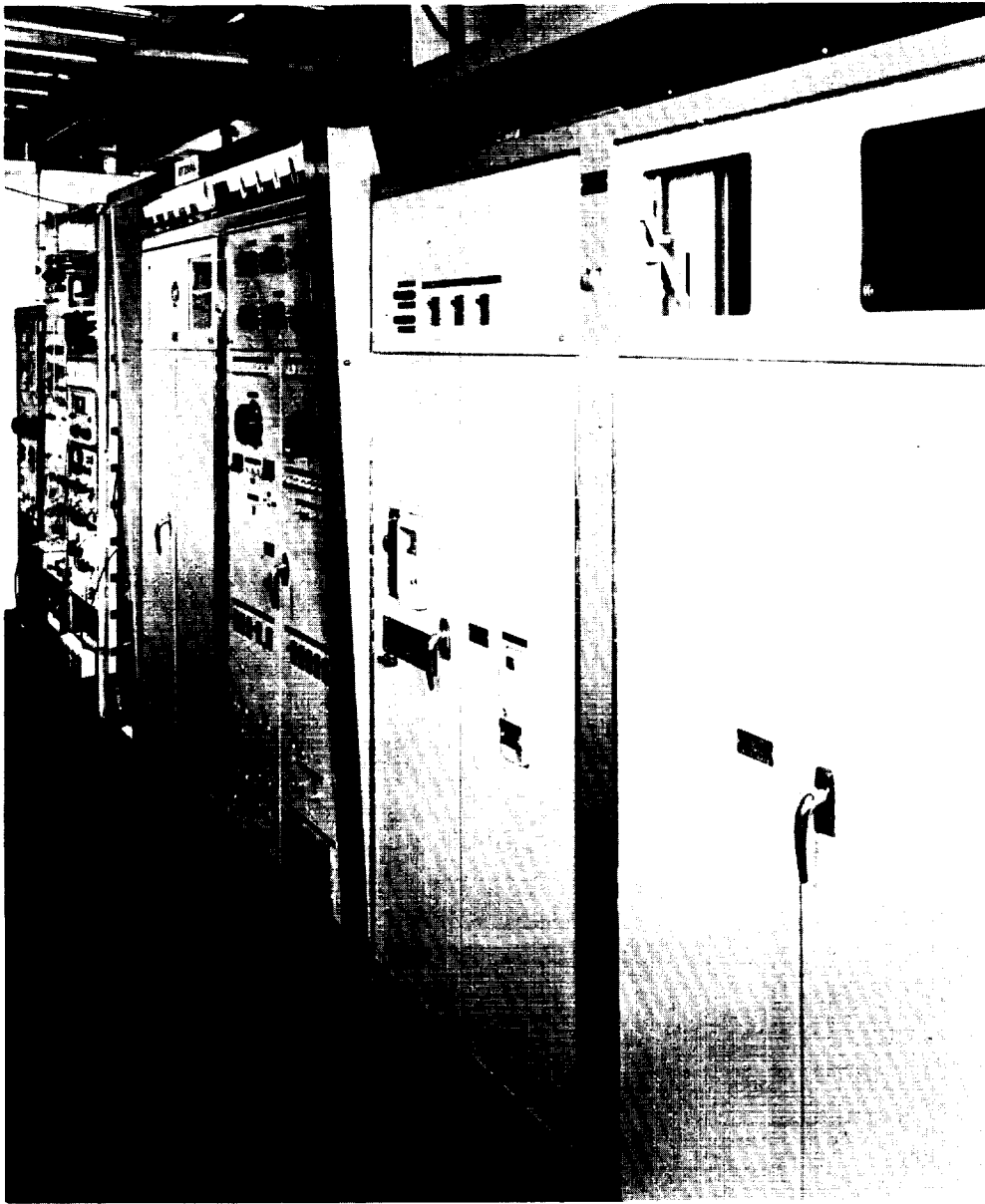


Figure 2—Front view of complete 960 Mc transmitter, showing FM driver unit, control and monitor panel, measuring equipment, and antenna manual control

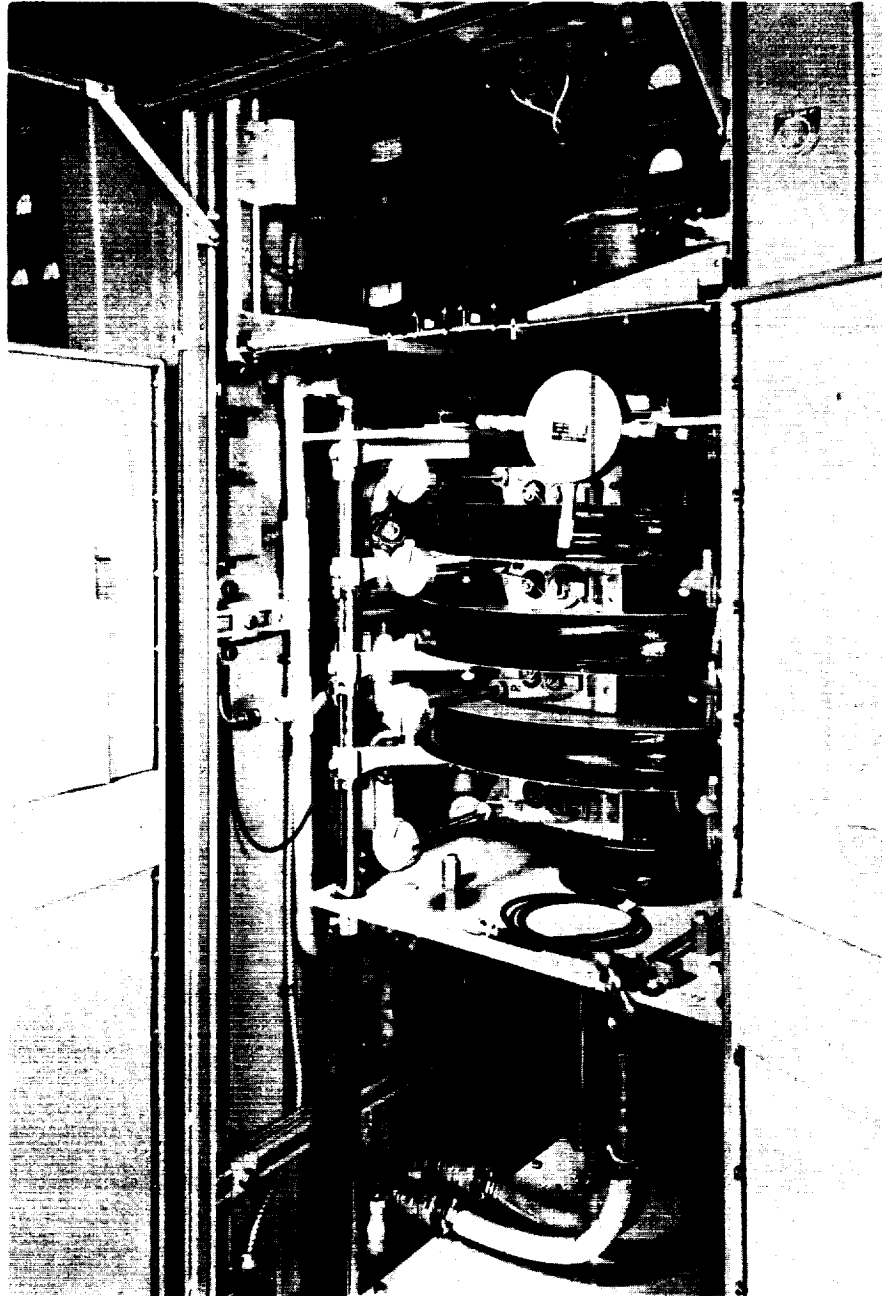


Figure 3—10-kw klystron in cabinet

temperature rise and flow rate, the power may be calculated. The coolant liquid used is a 50 per cent water and ethylene-glycol mixture for protection from freezing when the transmitter is not in use. The same coolant liquid and heat exchanger is used for both the dummy load and the klystron closed circulation system.

The power amplifier output terminates in a 3-1/8-inch coaxial line, coupled to the fourth-stage cavity of the klystron. The klystron output may be connected either to the dummy load or to the line feeding the antenna. A coaxial-to-waveguide transducer with pressure seal is used to convert from the coaxial output to the 4-7/8- by 9-3/4-inch rectangular waveguide going to the 60-foot dish antenna. The waveguide line is kept under about one-half pound pressure of dry nitrogen to prevent moisture leakage.

Circuits and meters are provided for continuous monitoring of the incident and reflected RF power at both the input and output of the power amplifier. The actual transmitted power is continuously recorded with an Esterline-Angus pen recorder.

The high-power klystron is capable of dissipating the total beam power in its collector (about 35 kw), and can therefore be safely operated without RF power drive. This makes it feasible to gate the driver stage, as is done for radar pulse and SSB transmission. Two high-voltage rectifiers are provided: one supplies 2000 volts at 0.7 ampere for the klystron bombarder; the other supplies 18 kv at 2.0 amperes for the klystron beam circuit. The beam voltage may be continuously varied from 12 to 18 kv. The primary power requirement of the transmitter, including the heat exchanger, is about 50 kw maximum (three-phase, four-wire, 208 volts).

DRIVER MODULATION UNITS

Various types of exciter-modulator units have been provided to drive the power amplifier, as is shown in Figure 4. Each generates a signal at about 70 Mc, either CW or modulated, which is mixed with a very stable and accurate frequency of 890.05 Mc to produce the final output frequency of 960.05 Mc (961.05 for radar). Figure 5 is a block diagram of the frequency generation and mixer-amplifier arrangement; it may be seen that the stability of the output frequency is primarily dependent upon the crystal supplying the 49.44+ Mc output, which is multiplied by 18 to give the 890.05-Mc mixer signal. The crystal and oven in the original equipment did not meet the Echo requirement, and they were replaced by a high-stability Western Electric crystal oscillator and oven assembly operating at 4.944+ Mc. This was followed by a ten-times multiplier arrangement to give the desired 49.44+ Mc frequency. In order to remove residual FM noise from the oscillator-multiplier output frequency, a phase-lock oscillator was interposed between the ten-times multiplier and the driving point of the three-times multiplier. The 890.05 Mc frequency is now stable to about two parts in 10^9 . This new arrangement is an

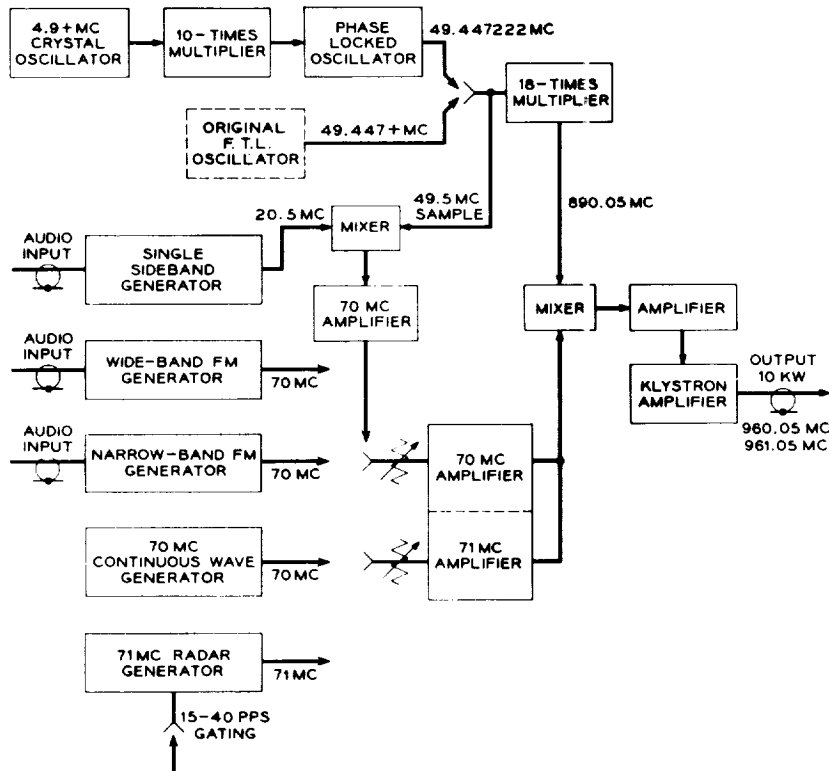


Figure 4—Overall block diagram of the transmitter

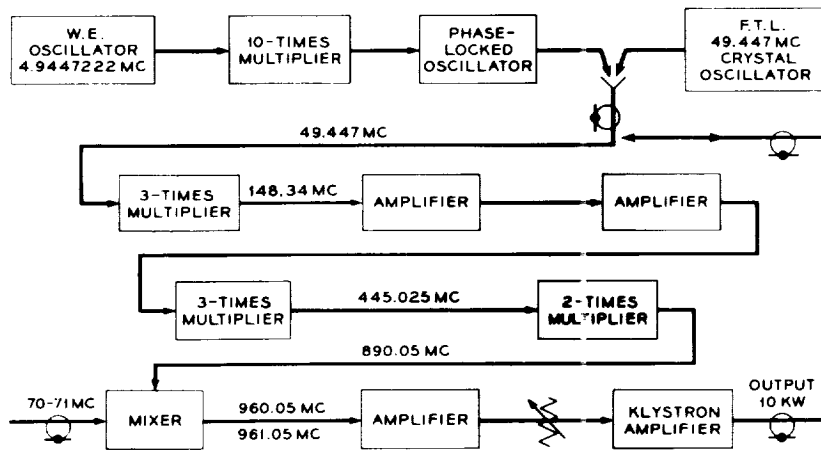


Figure 5—Block diagram of crystal generator and multiplier, showing mixer-amplifier arrangement

integral part of the driver circuit for all types of modulation, which are all added to the mixer at the 70-Mc frequency level.

Wide-Deviation FM Modulator

The wide-deviation FM modulator is an FM modulator-exciter provided by the Federal Telecommunication Laboratory (Model NUS 3315.3) and is the basic one used in the Echo tests. This unit can produce an FM driving signal with deviations of ± 300 kc, for baseband frequencies from 0 to 500 kc. Figure 6 is a block diagram showing the arrangement of the FM generator circuits.

The wide-deviation FM exciter operated satisfactorily in conjunction with the FM with feedback (FMFB) method of reception during the Echo tests. The actual deviation used was ± 30 kc, determined by quality overload tests with the FMFB receiver (Reference 1), using audio and voice frequency modulation.

SSB Exciter

The single sideband exciter is also a commercial unit, Technical Materiel Corporation, Model SBE-3. Figure 7 shows the general method of signal generation, and Figure 8 shows the equipment. This unit can produce single- or double-sideband modulation with controlled amounts of carrier and has an audio bandwidth of 350 to 7500 cycles. Its output at a frequency of 20.55+ Mc is mixed with a sample of the 49.447+ Mc crystal-controlled output to give the 70 Mc desired for introduction to the F.T.L. driver.

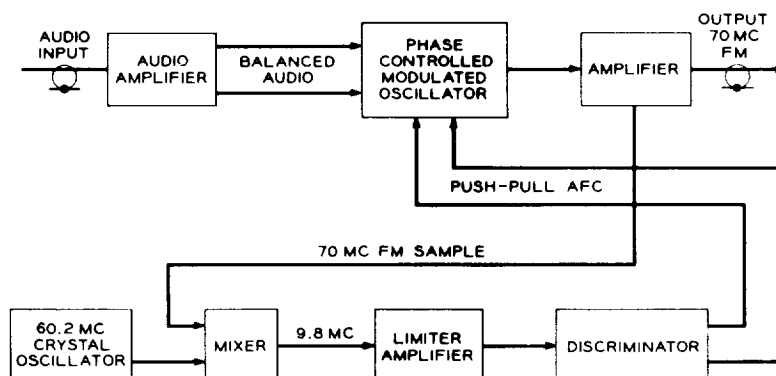


Figure 6—Block diagram of wide-deviation FM modulator

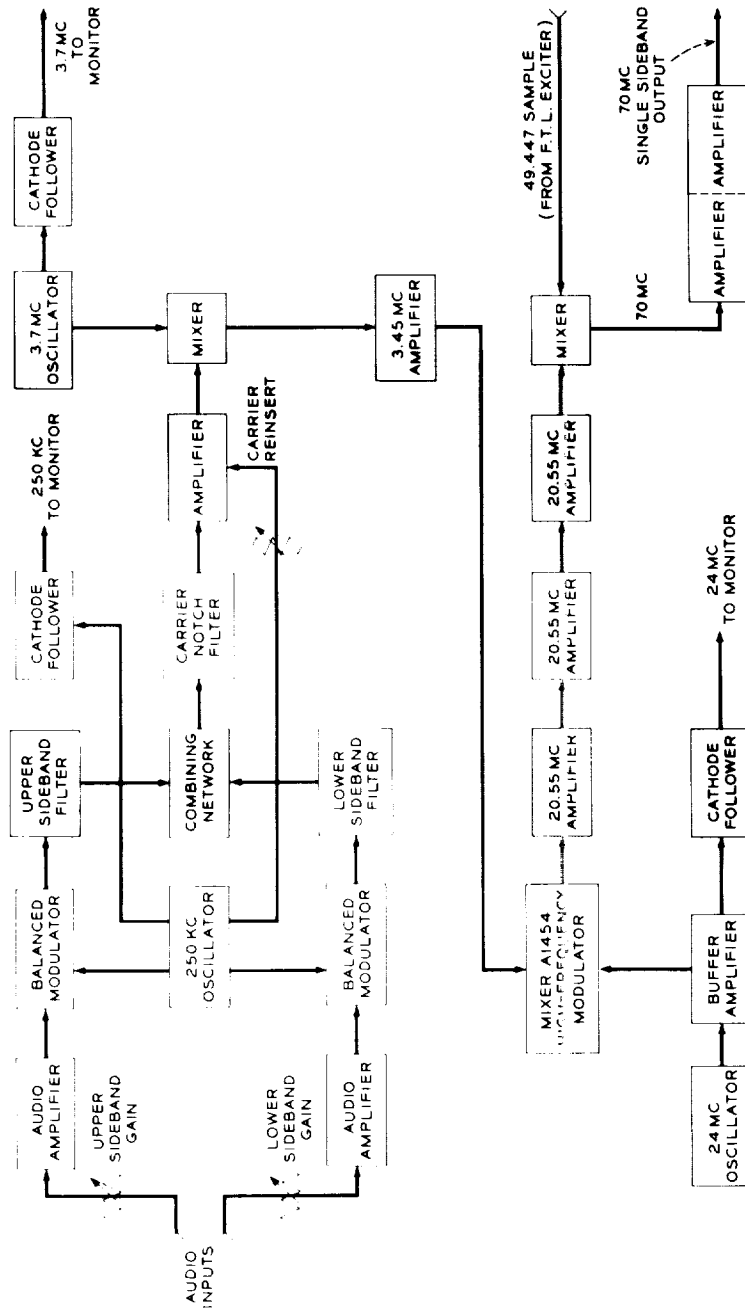


Figure 7—Block diagram of single-sideband modulator

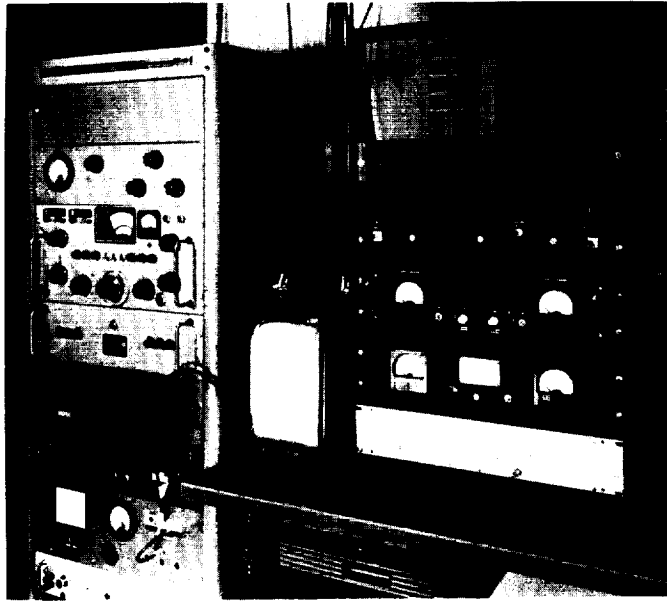


Figure 8—Left, single-sideband generator and monitor; center, RF power-level recorder; right, double-sideband generator

Low-Index Phase Modulator

The low-index phase modulator unit was built for use during comparison tests of various types of transmission; it replaced one furnished for the original Moonbounce tests by the Jet Propulsion Laboratory. This new unit is much smaller and more compact than the JPL unit and, like all the driver units, has an output frequency of 70 Mc. It can produce phase modulation of at least one-half radian over the audio-frequency voice band. It is crystal-controlled with a 35-Mc crystal, and this frequency is doubled and phase-modulated in a buffer stage. Figure 9 gives the principal circuit details.

70- and 71-Mc CW Units

The crystal-controlled oscillators for the 70- and 71-Mc CW units were made by the Bulova Watch Company. A buffer stage and amplifier were added to each oscillator output and provision was made for controlling the pulse-gating of the 71-Mc unit. These units were provided in order to produce a very stable frequency, with a minimum of

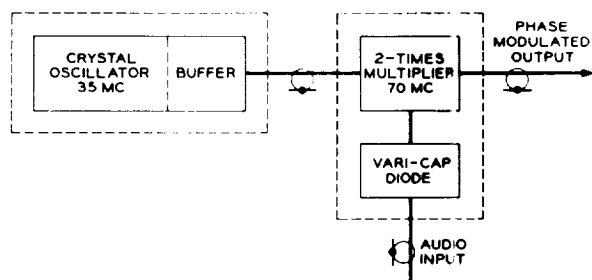


Figure 9—Block diagram of low-index phase modulator

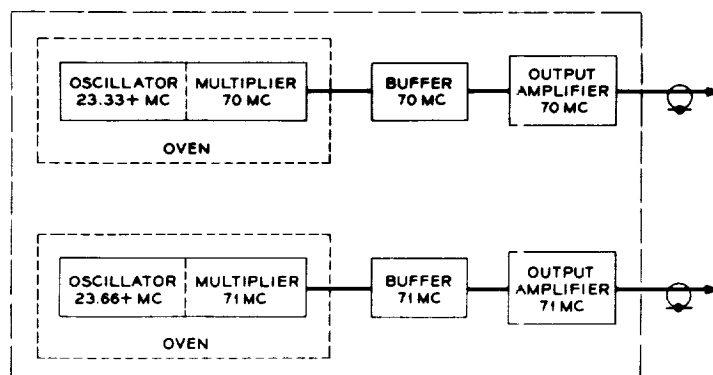


Figure 10—Block diagram of 70- and 71-Mc crystal oscillators and amplifiers

residual FM modulation, when used to drive the F.T.L. mixer, again producing 960.05 or 961.05 Mc antenna power. The former frequency is used for constant-frequency transmission during doppler measurements and the latter for radar pulse tests. Figure 10 is a block diagram of these exciters.

Radar 71-Mc Unit

A separate 71-Mc crystal-controlled oscillator was built to replace the Bulova unit just described, because of some difficulties encountered when the latter was pulse gated for radar transmission. The principal trouble was that the duty cycle of the on-and-off pulses changed as much as 3 to 1 when the keying frequency was changed from 15 to 45 cycles. This was corrected by the new unit. Figure 11 shows a block diagram of the arrangement.

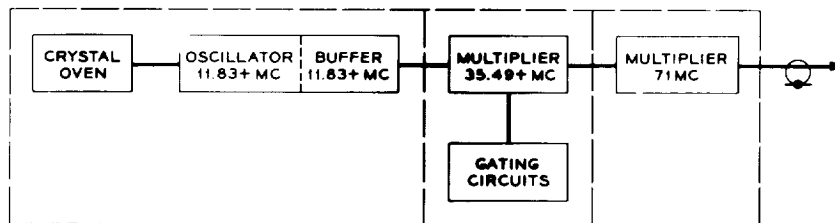


Figure 11—Block diagram of 71-Mc radar oscillator

A twin 70- and 71-Mc amplifier was provided so that the transmitter could be excited with either a 70-Mc modulated signal (for FM, PM, SSB, etc.) or the on-off 71-Mc radar pulses, or both. These two signals are fed in separately through attenuator controls so that any desired level is introduced (see Figure 4). The sum of the two signals then drives the regular F.T.L. mixer. The total output antenna peak power is kept at 10 kw.

The radar gating is done by a relay controlled from the radar receiver location and is described in more detail in Reference 2.

MONITORING EQUIPMENT AND CONTROL PANELS

During normal operations it was necessary to monitor or record such characteristics of the transmitter as transmitted frequency, transmitted power, modulation quality, and time.

Since there are many different modes and conditions of transmission, the monitoring apparatus became relatively complex, as is shown by the block diagram, Figure 12, and the photograph, Figure 13. If the functions are examined according to the four categories listed above, operation should be readily understood.

Transmitted Frequency

Frequency counters to operate at 960.05 Mc were not available, so a sample of the transmitted signal (obtained from a probe in the output coaxial line and fed to all monitoring equipment) was mixed with a 960.00 Mc signal. The difference frequency of 50 kc is read by a Hewlett-Packard 524C frequency counter and also printed out on a paper tape by a Dymec 560A digital recorder. A 10-Mc signal available from the frequency counter is multiplied by the harmonic generator to 960 Mc and provides a beating oscillator with a stability and accuracy equal to that of the frequency control crystal oscillator in the

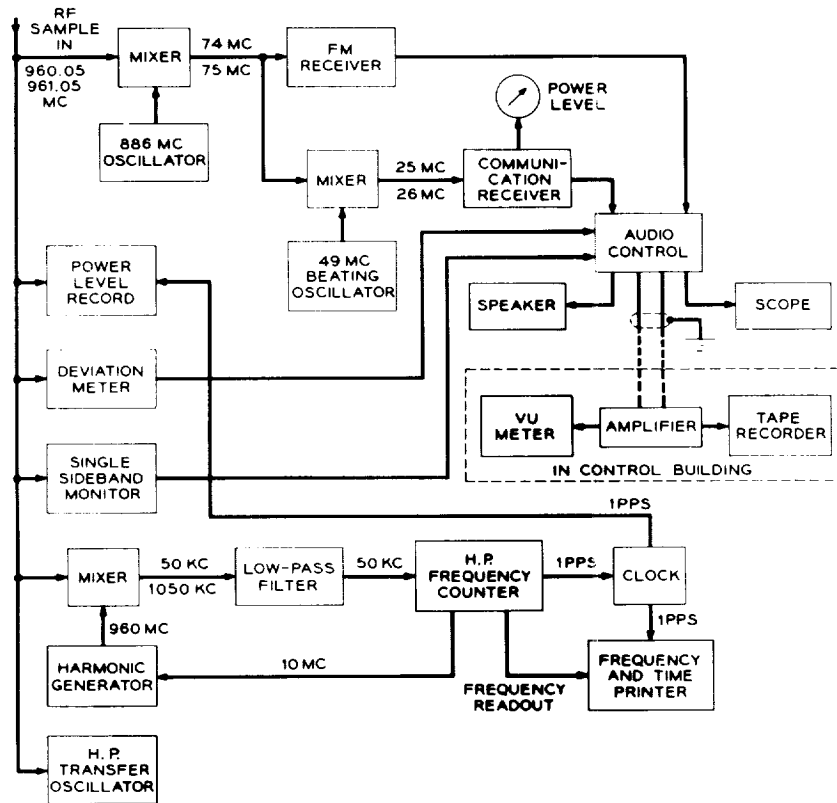


Figure 12—Block diagram of RF monitoring equipment

counter. The manufacturer's specifications indicate a short term stability of three parts in 10^8 or approximately 30 cycles at 960 Mc. The counter cannot determine whether the signal is above or below 960 Mc, but this is done by means of a Hewlett-Packard type 540B transfer oscillator.

When both radar and communication channels are being transmitted, there are two frequencies, of approximately 50 kc and 1050 kc, coming out of the mixer. The frequency counter is unable to distinguish between these two, so a low-pass filter with a cutoff frequency of 80 kc is inserted between the mixer and counter in order to eliminate the 1050 kc and measure the 50 kc. Similarly, a high-pass filter could be used to eliminate the 50 kc and measure the high frequency.

Transmitted Power

Two different methods are employed to monitor output power. In the first, a probe in the output coaxial line powers a diode rectifier. The crystal current drives an

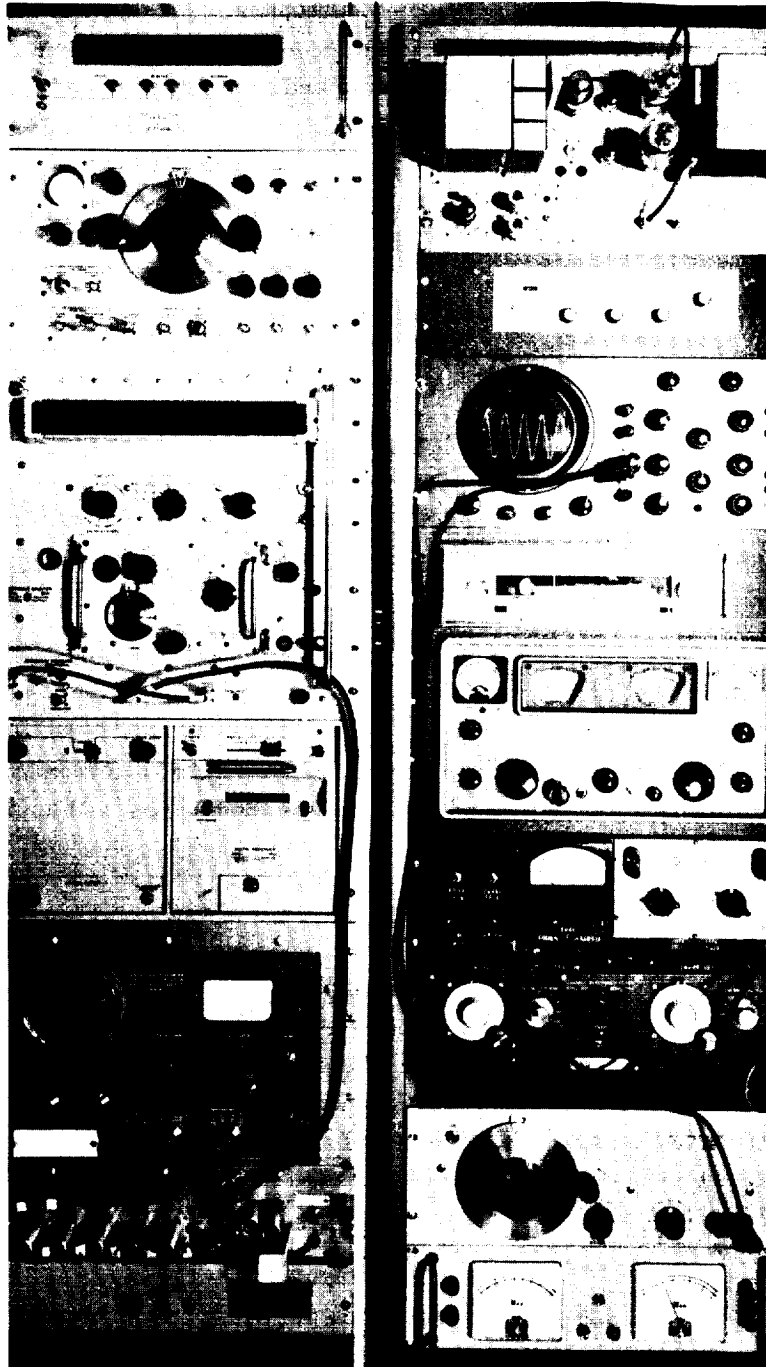


Figure 13—Monitoring and measuring equipment

Esterline-Angus strip recorder and provides a continuous ink record of the average power output. A second probe and diode powers the regular output power meter. When only one carrier is transmitted this is quite satisfactory. However, when more than one carrier is being transmitted (especially when one of them is a pulsed carrier) the indicated powers are meaningless. Measurement under these conditions requires a selective system which will accept one carrier frequency and reject all others.

In the second method of monitoring power a sample is taken from the RF monitoring line and heterodyned to 74 Mc. (This frequency is also used for the FM monitoring described later.) A second converter reduces the frequency to 26 Mc. A Hammarlund HQ 110 communications receiver is then used as a variable-frequency IF amplifier with a bandwidth adjustable between about 3 kc and 500 cps. An additional detector was installed to drive a microammeter calibrated to read directly from 0 to 12 kw.

With this system it is possible to adjust and monitor each carrier to a specific power level, including each sideband of double-sideband transmission.

Modulation Quality

Three different methods are employed in the measurement and monitoring of wide-band frequency modulation, narrow-band FM or phase modulation, and amplitude modulation.

For wide-band FM a sample of the signal was heterodyned to 74 Mc (as discussed previously) and received on a Sherwood S-30000 II FM tuner whose input circuits were modified to cover a range of 70 to 80 Mc. The detected output is amplified in the audio control unit to be described later; and it may be monitored visually on an oscilloscope or audibly on a loudspeaker. Spurious noise and hum are measurable down to about -70 db below the normal signal deviation of ± 30 kc. Frequency deviation is measured by a Marconi TF-791D deviation monitor. The actual signal-to-noise ratio for normal FM operation is about 45 to 50 db. Deviation of narrow-band FM or phase modulation is also measured by the Marconi deviation meter. The audio output available from this instrument is monitored through the audio control.

Amplitude-modulated signals are received on the same communications receiver and detector described under power monitoring. Audible and visible presentations are available through the audio control.

The single-sideband monitor is shown in block form in Figure 14. Its operation, in brief, is as follows: A sample of the 960.05 Mc SSB output signal is mixed with a sample of the 890-Mc exciter drive to produce a modulated 70-Mc output in a General Radio (G.R.) 874-MR mixer. Frequencies of 3.7 and 24 Mc, available from the SSB generator,

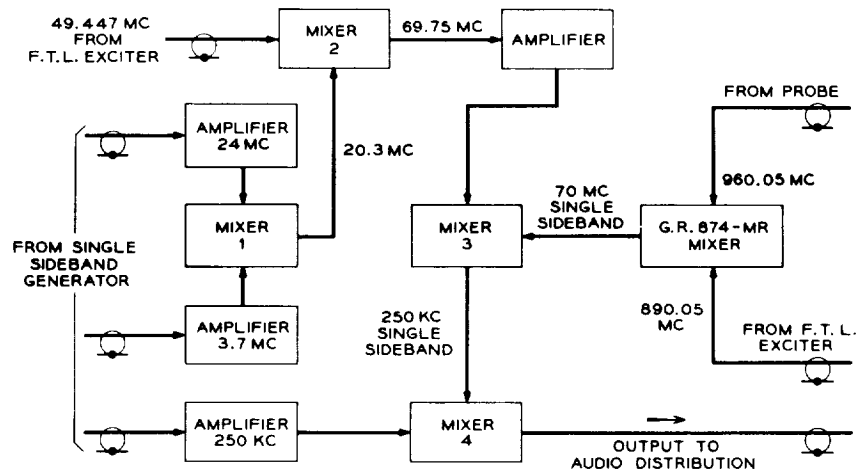


Figure 14—Block diagram of single-sideband monitor

are combined to produce 20.3 Mc in mixer 1. In mixer 2 this frequency is added to a sample of the 49.45 Mc driving the F.T.L. exciter to produce 69.75 Mc, which is subtracted from the 70 Mc out of the G.R. mixer to produce a modulated 250-kc signal in mixer 3. By beating this with a sample of the 250-kc oscillator in the SSB generator, audio output is recovered in mixer 4 and routed to the audio distribution control. Small frequency variations are cancelled out and complete synchronization is assured by utilizing the same oscillators for both transmitting and monitoring.

Time

Comparison of frequency or signal-level recordings of a received reflected signal with the corresponding frequency and power-output recordings at the transmitter requires that there be a time reference permanently impressed on each recording.

The Hewlett-Packard frequency counter furnishes highly accurate one-per-second pulses. These trigger a Dymec DY 2508A clock which indicates hours, minutes, and seconds on a Nixie tube readout, and can also furnish time data to a Dymec 560A digital recorder. Frequency count data from the 524C counter are also fed into the printer, and the result is a paper tape printed record containing the last five digits of the frequency and six digits indicating time. The printout rate may be varied from one each 20 seconds to five per second.

The Esterline-Angus (E-A) power-level recorder charts are printed with a time scale of three inches per hour; this is generally of sufficient accuracy. When a short

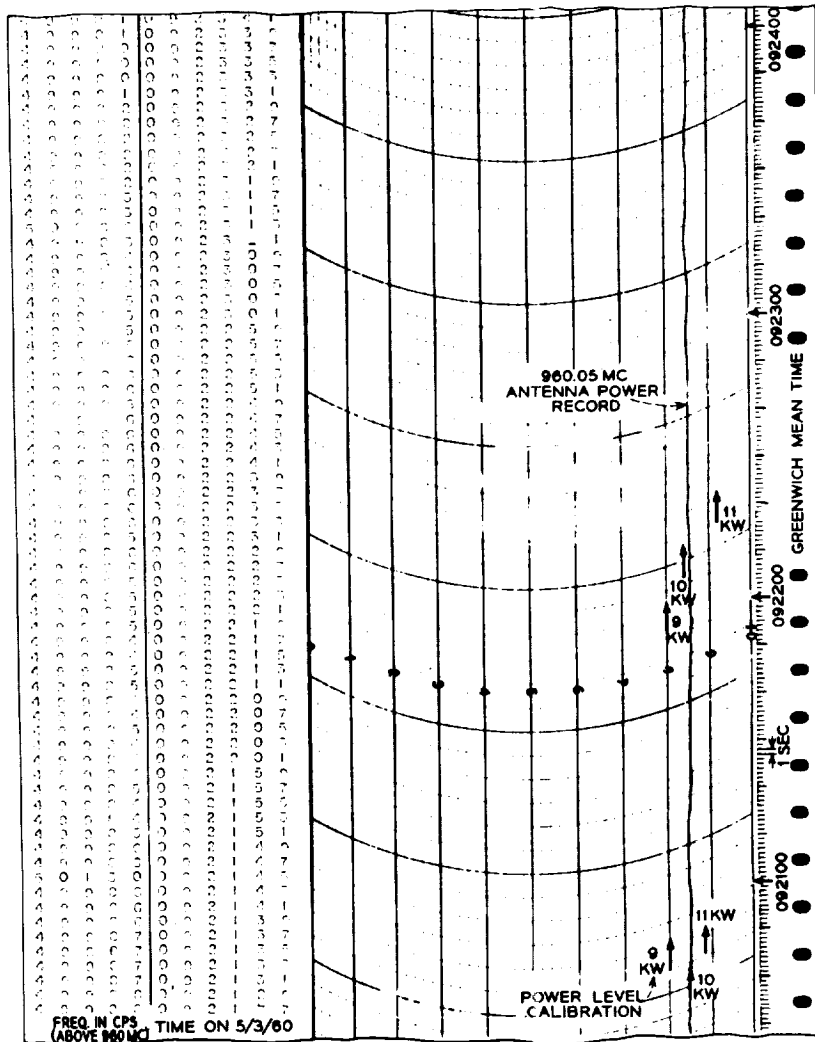


Figure 15—Typical frequency counter printout (left) and high-speed RF power-level recording

transmission with a higher resolution is required, the tape may be speeded up to three inches per minute and a second recording pen, driven by the one-per-second pulses from the digital clock, records one-second intervals along the chart. Thus, by accurately setting the digital clock to a known time standard such as WWV or CHU, both the frequency and power recordings are accurately indexed in time. Samples of the frequency counter printout and the high-speed operation of the E-A power level recorder are shown in Figure 15.

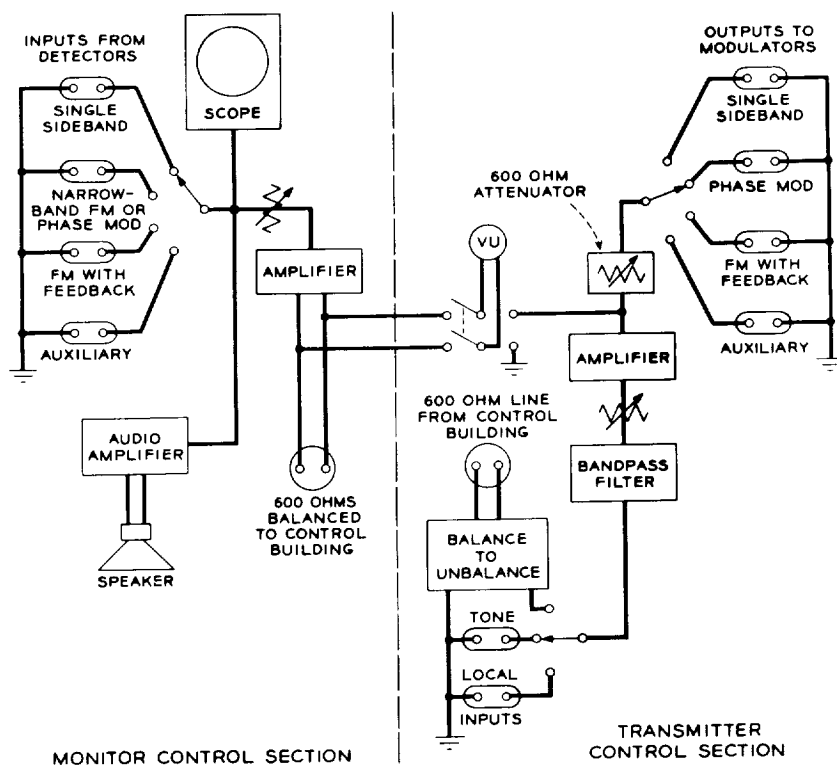


Figure 16—Block diagram of audio control panel

AUDIO DISTRIBUTION

All audio circuits required for transmission or monitoring are routed to an audio control panel, shown in block form in Figure 16.

In the monitor control section, outputs from the various detectors are selected and amplified by a one-stage amplifier having a 600-ohm output impedance and variable gain. A balanced 600-ohm line transmits the signal to the main console in the station control building. An oscilloscope and a high-impedance input audio amplifier, driving a monitor loudspeaker, allow visible and audible checking of the inputs to the control panel, while a VU-meter measures the level being transmitted to the control building.

In the transmitter control section a switch selects either the signal from a balanced 600-ohm line from the console in the control building; a sine wave from a local audio oscillator; or an audio signal of any type from a local source. An amplifier similar to the one in the monitor section amplifies the selected signal and transforms it to 600 ohms unbalanced. A second switch routes this output to the desired modulator. A VU-meter

and a Hewlett-Packard 350A attenuator allow the measurement and adjustment of the level into the modulator.

The frequency response of the audio distribution system is ± 1 db from 30 to 12,000 cps, and it is linear up to 1.8 volts rms into 600 ohms. However, any desired restricted audio bandwidth at the transmitter input may be provided by means of a Spencer-Kennedy 302 variable electronic filter. This versatile unit consists of two filters, each adjustable for cut-off frequencies from 20 cps to 200 kc, and may function as either a high-pass or low-pass unit, or as a combination band-pass unit. The rate of cut-off is 18 db per octave, and the two sections may be operated in series to provide a slope of 36 db per octave.

MEASUREMENTS AND CHARACTERISTICS

A number of the overall transmission characteristics of the transmitter are of interest. Especially important for various types of transmission is the input-output overload characteristic, in terms of 70-Mc drive to the F.T.L. mixer and the 960-Mc (or 961-Mc) power in the antenna. For straight FM modulation, the linearity of this characteristic is not important. This is, of course, the type of transmission for which the set was designed. However, for SSB or any type of amplitude modulation, particularly when radar transmission is added, a departure from linearity will introduce some distortion; this makes it difficult to determine the division between the 960- and 961-Mc power output.

Most non-linearity occurs in the power klystron. The higher the beam voltage used, the straighter the characteristic and the lower the distortion. Figure 17 shows some typical characteristics of the relationship between the 70-Mc input and the 960-Mc output. It will be seen that there is no departure from linearity for the low-power driver stage over the range required to drive the klystron to full power (one-half watt). The klystron characteristic at 17 kv shows a curvature above about 3 or 4 kw output and is about 3 kw down from the ideal at 10 kw. The characteristic at 18 kv is somewhat better than the one at 17 kv, and this is the one used during tests when linearity is of any importance (18 kv is the maximum voltage available with the present equipment). These load characteristics have also been checked at 961 Mc and are essentially identical with those at 960 Mc.

The over-all frequency characteristic of the transmitter is determined by various parameters, such as the tuning and adjustment of the mixer-amplifier of the exciter, the tuning of the klystron cavities, and the coupling adjustments to the load. The band can be adjusted to about 4 Mc at the 3-db points and 2 Mc at the 0.5-db points. For the particular application in which it was used for Echo tests, in which only relatively narrow frequency

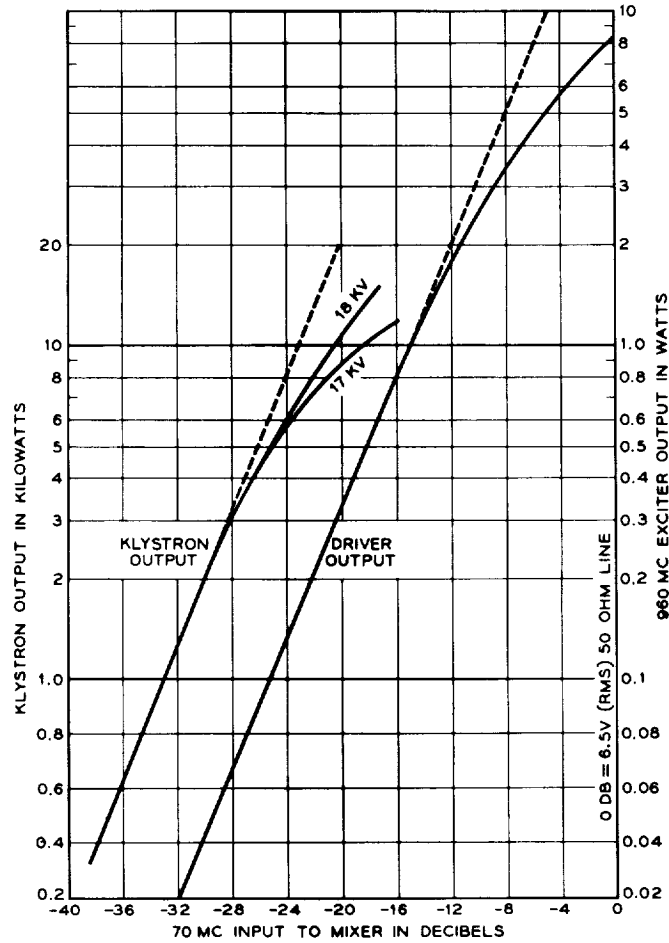


Figure 17—Input-output characteristics of 960-Mc driver and 10-kw klystron amplifier

bands were used, the main concern was that nearly equal outputs at 960 and 961 Mc be obtained for equal 70- and 71-Mc drive amplitudes. This was easy to accomplish.

The transmitter output circuit operates into a fairly well matched load with either the dummy water load or the 60-foot dish antenna. The actual reflected power with 10 kw output is about 100 watts for the antenna and about 30 watts with the dummy load, corresponding to return losses of 20 and 25 db respectively.

The calibration of the antenna output power meter is checked occasionally by transferring the transmitter output to the dummy load, where coolant flow and temperature measurements give a measure of actual power. From these readings a calibration curve for the power meter is obtained. This meter is a special dc milliammeter, calibrated in kilowatts, which is coupled to the output RF line through a crystal

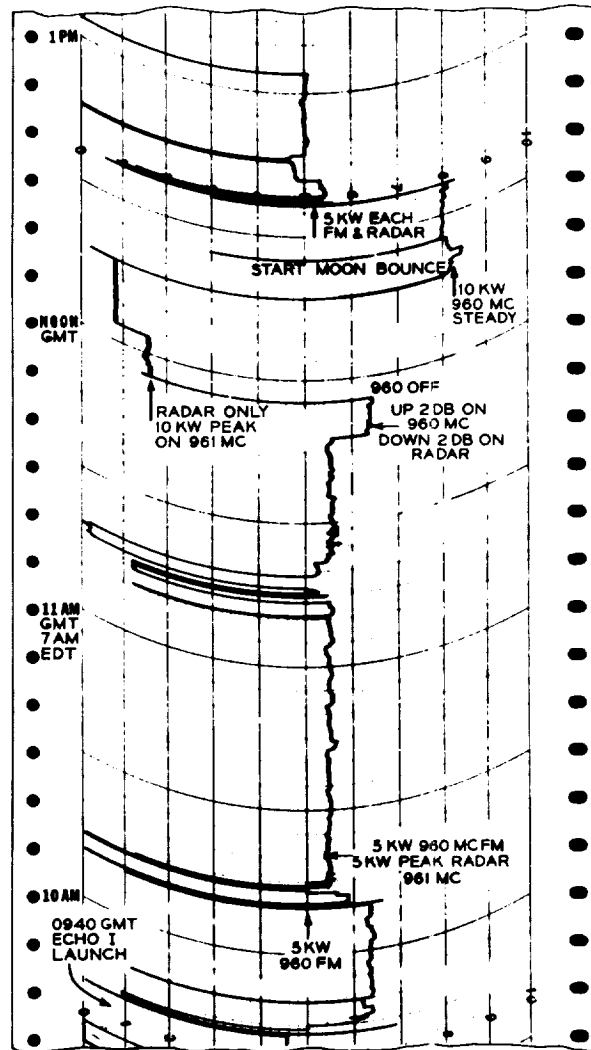


Figure 18—Antenna power-level recording for Echo pass 1 on August 12, 1960

diode. A similar arrangement is used to obtain a direct current to operate the Esterline-Angus recorder that gives a continuous record of output power when the transmitter is in operation. Figures 18 and 19 are sample recordings showing the variations in power with time for various types of emission. It is believed that the power as read by the meter or registered on the recorder is accurate to about ± 0.1 db.

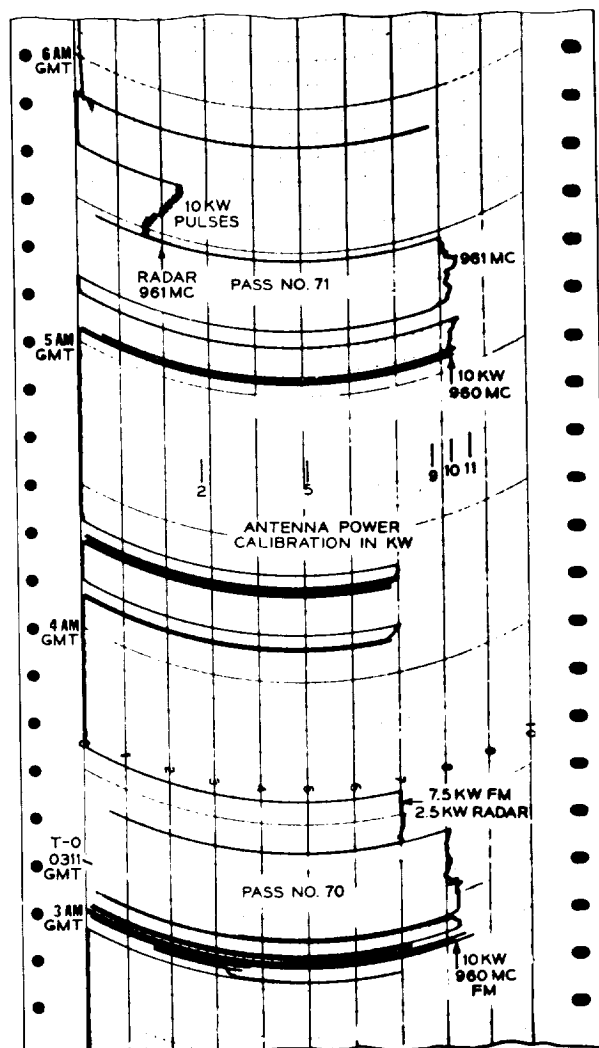


Figure 19—Antenna power-level recordings for Echo passes 70 and 71 on August 18, 1960

OPERATIONAL RESULTS AND CONCLUSIONS

The operation of the 10-kw transmitter has been very satisfactory since it was placed in service in July 1959. There have been a few minor equipment failures during this time, but fortunately they occurred at other than scheduled Echo I pass times. One interruption causing lost time in one of the early Moonbounce tests was due to arcing in some loose contacts near the rotary joints of the coaxial feed line to the dish antenna. This was corrected and no further trouble has been encountered from this source.

One annoying type of trouble which required considerable time to run down was what were termed "momentary interruptions." These would occur without regard to beam voltage or load and would last only for a second or two, which is the recycling time of the main high-voltage circuit breaker. Sometimes several interruptions would occur within a few minutes, and at other times they would be spaced several hours or days apart. These interruptions were finally traced to faulty vibration-sensitive relays in the beam current and body current overload circuit and to a faulty air-flow switch in the heat exchanger. They vibrated enough at certain times to open the relay contacts, which in turn opened the holding coil of the main circuit breaker. At once, this breaker would automatically reclose and power would be reapplied without giving a positive indication or warning light. Since the relays and the air switch have been replaced, the momentary interruptions have apparently been eliminated.

Many Moonbounce, tropospheric scatter, Shotput, and Echo test transmissions were made for long periods at full 10-kw output power, with beam voltages as high as 18 kv. From pass 1 on August 12, 1960, when Echo was launched, until pass 2407 on February 24, 1961, just previous to this writing, transmissions were made on 124 passes of the balloon.

Many different types of modulation have been used. These include wide-deviation FM, low-index phase modulation, constant-frequency cw, single-sideband and double-sideband modulation with varying amounts of carrier, and on-off radar pulses.

Radar pulse signals were employed to aid in tracking the balloon and therefore were transmitted simultaneously with the communication channel modulated frequency. This required a division of transmitted power between the two frequencies, the total not to exceed 10 kw. The power can be divided as desired. Sometimes it was advantageous to favor either the communication signal or the tracking radar. A nominal division frequently used has been 7.5 kw communication and 2.5 kw radar peak power.

The radar pulses are keyed at a low-frequency rate of 15 to 45 cycles, with a duty cycle nearly equal to 50 percent. Because of compression nonlinearity of the high-power klystron input-output characteristic, it is difficult to control the division of power between the two frequencies. If they are separately set to a given amount and then applied together, each signal and the sum will be lower than is desired. They must therefore be adjusted when both are operating. The value of the power at each frequency is obtained by the use of the narrow-band frequency-selective amplitude-measuring receiver described earlier (pp. 11 ff). A certain amount of amplitude modulation is introduced into the communication channel by reason of the klystron compression when the radar pulses are added, but this has not caused any trouble or added any appreciable noise in the monitoring FM receiver output. There is some low-level pulse noise in the SSB receiver output, but this has not been considered harmful to good speech quality. Low-frequency high-pass filters help to eliminate the interference due to radar keying.

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