**PROJECT ECHO**

# Satellite-Tracking Radar

By O. E. DE LANGE

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*This paper is concerned with the radar employed at Bell Telephone Laboratories, Holmdel, New Jersey, site for tracking the Echo I satellite. The radar was originally designed for the sole purpose of antenna pointing. Recently, however, it has also been employed to measure earth-balloon-earth path loss at regular intervals of time in order to keep track of the condition of the balloon.*

*The performance of the system and some of the data obtained are discussed. There is a general description of the system followed by more detailed descriptions of the various components.*

## I. INTRODUCTION

The operational plan of the Project Echo experiment provided for pointing of the transmitting and receiving antennas from calculated orbital data. The angle-tracking radar was intended as a "back up" to this system.* In operation the radar has been found to provide appreciably better pointing accuracy than is obtained from the computed data. As a result, the orbital data are employed only to keep the antennas pointed approximately on target, with the radar (or optical telescope during periods of visibility) providing for more exact alignment.

According to the original concept the radar was intended to serve only the purpose of keeping the antennas positioned during communications experiments. In recent months these experiments have practically ceased, which leaves us with only the radar as a regular source of signal for studying transmission effects. Under the present plan of operation the balloon is tracked approximately once per week and its cross section determined from the strength of the reflected radar signal.

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* Although this equipment was designed by the Bell System as part of its research and development program, it was operated in connection with Project Echo under Contract NASW-110 for the National Aeronautics and Space Administration.

## II. GENERAL

### 2.1 *Antenna-Positioning Plan*

The antenna-positioning plan for the complete Holmdel terminal* is shown on Fig. 1. Orbital information is taken off paper tape by the tape reader and is converted from digital to analog form by the digital-to-analog converter. This unit's synchro generators control the positions of the transmitting dish and the receiving horn, as well as the optical telescope in the M33 gun director. The readout synchros on the transmitting antenna control the position of the radar receiving antenna. The pointing-error information derived from the radar is displayed before an operator at the M33 director who applies corrections by means of a device which puts in controlled amount of offsets in azimuth and elevation until the indicated errors are reduced to zero. During periods of visibility the optical telescope can also be employed to determine pointing information. It is evident that, once a signal is acquired, pointing could be carried out entirely with information from the radar or optical system. However, the control provided by the digital-to-analog converter makes acquisition much easier and provides an excellent tracking aid, with the radar or optical system simply indicating the corrections which are needed.

Up to the present time there have been no attempts at auto-tracking the satellite. Some limited experiments on automatic following of the moon are described in a later section.

### 2.2 *Design Objectives*

The radar was designed to meet the following requirements:

1. It had to be capable of tracking the 100-foot balloon to a range of 3000 miles.
2. A pointing accuracy of about ±0.1° was desired.
3. Accurate range information was not required.
4. It had to be compatible with the communications system, although both shared a common transmitter and transmitting antenna.

### 2.3 *Radar Performance*

Except for some initial operating difficulties, the performance of the radar has been satisfactory. More than 100 successful tracking runs have been made up to the time this was written. It has almost always

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* For a complete description of the Holmdel terminal see a companion paper.[1]

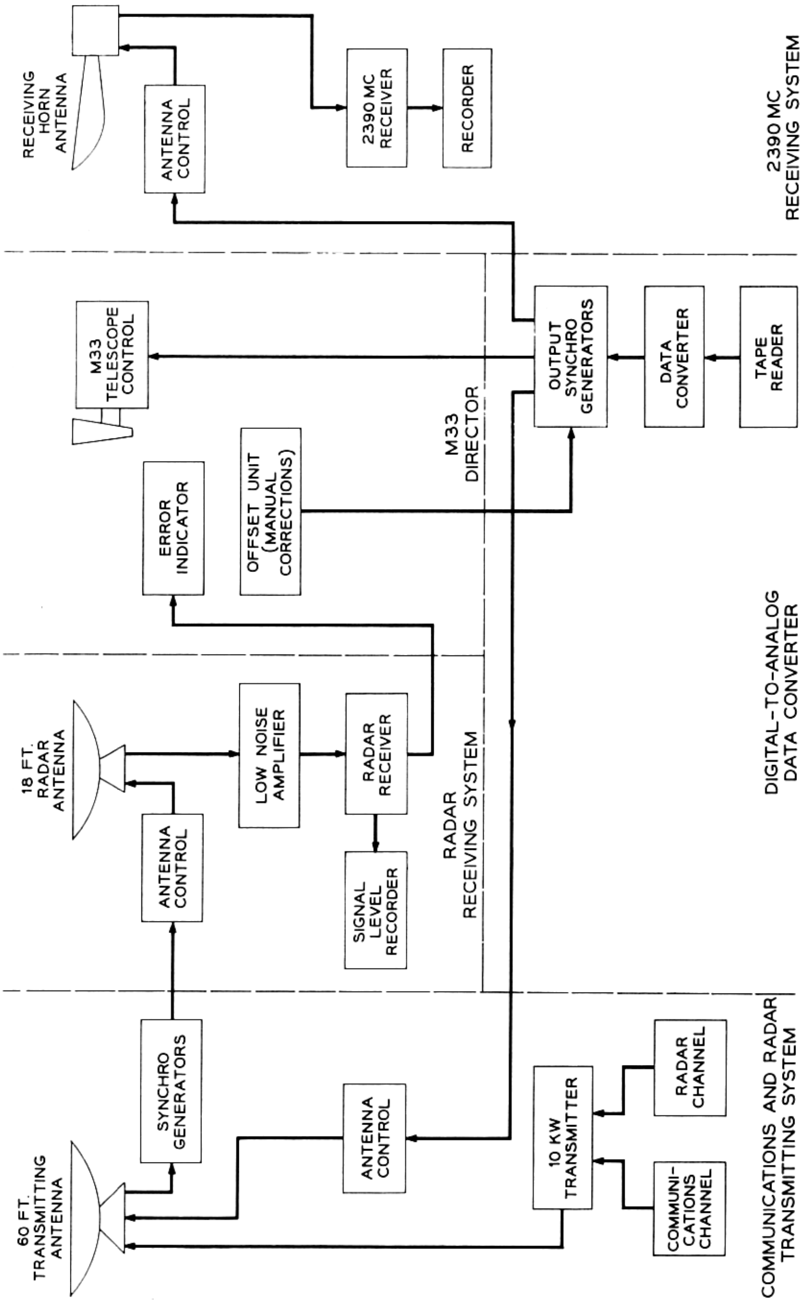

Fig. 1 — Antenna positioning plan.

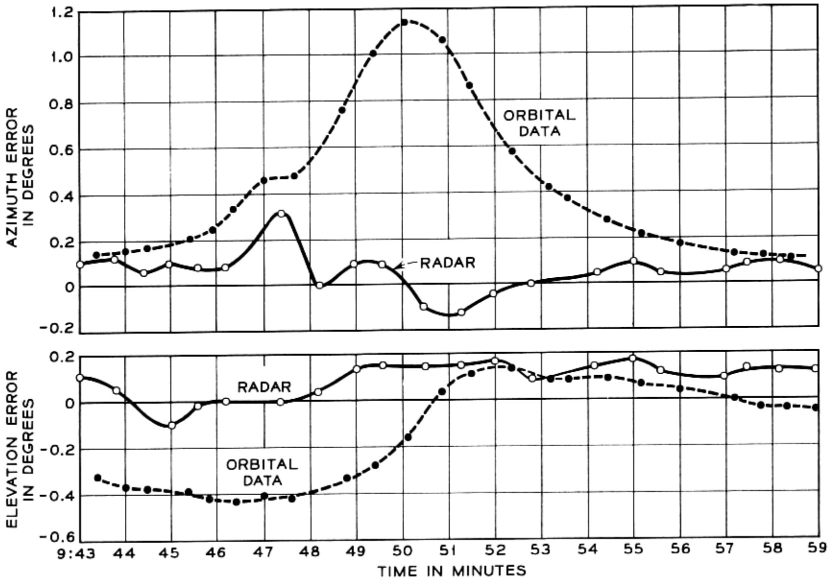

Fig. 2 — Radar vs. optical pointing.

been possible to acquire a signal from the balloon as soon as it has risen a few degrees above the horizon and to maintain contact until it has dropped to within a few degrees of the opposite horizon.

The low-noise parametric amplifier has been very stable with respect to both noise figure and gain. Over a period of months the sensitivity of the receiver has remained at −150 dbm in a 100-cycle band; i.e. the minimum detectable signal is near this level. This is consistent with the receiver noise power output as calculated in Appendix A.

During periods of visibility it has been possible to compare the radar pointing information with the more accurate information obtained by optical means. This is accomplished by alternating between the offset required to make the indicated optical error zero and the offset required to make the indicated radar error zero. The radar and optical data usually agree to within one to two tenths of a degree, except for short periods on some adverse passes. Fig. 2 is a plot of one set of data obtained in this manner, with the optical data being used as a standard of comparison.*

The abscissa on this plot represents time, with each division equal to one minute; the ordinates are angular errors in degrees. The dashed

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* The experiments described herein were performed in connection with National Aeronautics and Space Administration Contract NASW-110.

curves represent the errors in the orbital data, the solid curves the radar errors. Between 0950 and 0951 GMT the balloon was passing through its point of nearest approach. As is usually the case, the error in the computed orbital azimuth data reached a maximum at this time, being nearly 1.2°. It is evident that the radar data are considerably better than the computed data, especially in azimuth.

The system is subject to errors due to parallax between the transmitting and the receiving antennas, to antenna lag at the higher rates of rotations, and to lack of exact alignment between the various axes in the receiving antenna. Although each of these errors is small, they can add up enough to become significant for parts of some adverse passes. Fortunately, the enhanced error does not last long and is maximum at the point of nearest approach of the balloon, where the signal level is great enough to allow for some discrepancy in pointing. The radar data have been found to be more accurate than the orbital data, even on these adverse passes.

Fig. 3 represents the received signal, as indicated by the AGC voltage, for part of pass 2407, which was recorded on February 24, 1961. The smooth curve is a plot of the theoretical value of signal strength. Over the period of time shown, the actual signal is not very different from the calculated value except during periods of deep fades. The fades shown on this chart are typical, except for the one at the right-hand side which is somewhat deeper than usual. Scintillations are usually considerably greater at the beginning and at the end of a pass than at the midpoint, probably due to atmospheric effects when the balloon is near the horizon.

Charts similar to the one shown on Fig. 3 have been prepared for 40 passes of the satellite. From these charts the average difference between the actual signal level and the theoretical value has been obtained for 33 passes between October 20, 1960, and March 2, 1961. These differ-

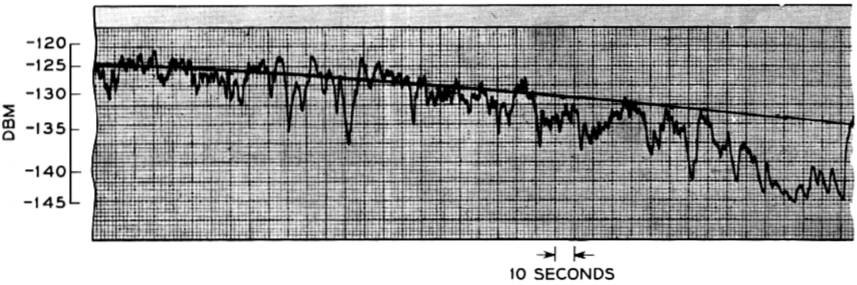

Fig. 3 — Return signal from the satellite, pass 2407 (February 24, 1961).

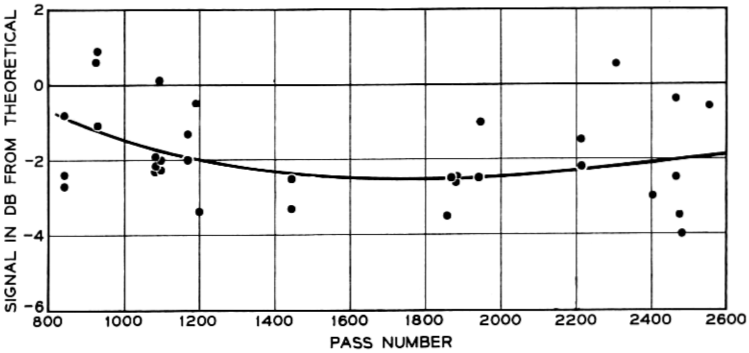

Fig. 4 — Received signals compared with theoretical values.

ences are shown plotted on Fig. 4. A smooth curve was drawn through an average of these points in an attempt to determine any long-time trend. The curve indicates that there has been some falling off in average signal strength since we started recording, though not more than about 1.5 db. This is less than the spread from one pass to the next, and may not be really significant. There has been no significant change in scintillations over the period for which we have records. It is evident that there has been no great change in the size or shape of the balloon up to the present time. Unfortunately, equipment was not set up to record accurate data before October 20.

On numerous occasions the radar has been used to track the moon. Fig. 5 is a recording of the received signal for part of one such operation. An outstanding feature of the record is the rapid and continuous fading of the signal. These fluctuations are known to be greater and more rapid than indicated on this chart, where the indications were limited by the time constant of the recording equipment. From the average signal level the earth-moon-earth path loss was calculated to be 268.7 db, compared to 268.1 db quoted by Trexler[2] for our frequency. (See Appendix B calculations.)

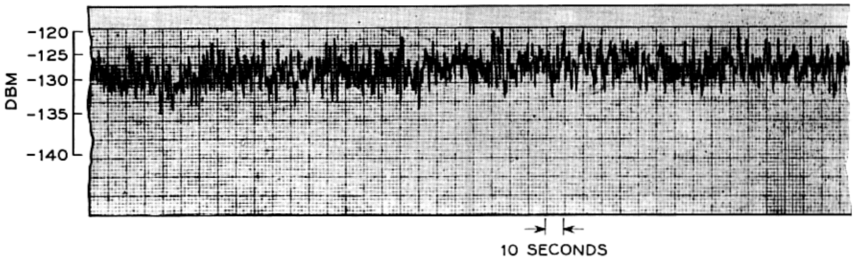

Fig. 5 — Return signal from the moon (February 8, 1961).

## III. DESCRIPTION OF RADAR SYSTEM

### 3.1 *General Arrangements*

To provide a separate high-powered transmitter and large transmitting antenna for the radar would have been rather expensive and added considerably to the complexity of the systems. For these reasons it was decided that the transmitter and transmitting antenna employed for communications should be shared by the radar by means of frequency division. The 4-mc bandwidth of the transmitter would have allowed us a wide separation between the communications and radar frequencies; frequency assignment, however, limited this spacing to one megacycle, with the radar at the higher frequency. Although this spacing was sufficient to allow separation of the signals in the receivers, a somewhat greater spacing would have been advantageous.

The radar transmitter and receiver are each gated to be on one-half of the time and off one-half. In this way diplexing is accomplished by having the receiver on only during times when the transmitter is off. The gating rate is varied between 15 and 45 cycles depending upon the range to the balloon. To avoid overloading of the early stages of the radar receiver by the ungated communications transmitter, a radar receiving site was chosen at a distance of approximately one and one-half miles from the transmitter. The receiving antenna, which is provided with conical scan, is "slaved" to the transmitting antenna by means of synchro signals carried over telephone lines (see Fig. 1). There is no lobing of the transmitting antenna. Pointing-error signals are sent over telephone lines back to the antenna-control center, where the appropriate corrections in antenna pointing are made manually.

### 3.2 *Transmitter*

Since the transmitter is described in detail in a companion paper[3] it will be discussed only very briefly here. From the block diagram of Fig. 6 we can see that the radar section of the exciter consists of a crystal-controlled oscillator, a gated harmonic generator, and an attenuator. The radar signal is combined with the 70-mc communications signal in a mixing amplifier. In the mixer and amplifier unit which follows the mixing amplifier the 70-mc signal is modulated up to 960.05 mc and the radar signal up to 961.05 mc. These two signals are amplified simultaneously by the klystron power amplifier which has a bandwidth of 4 mc.

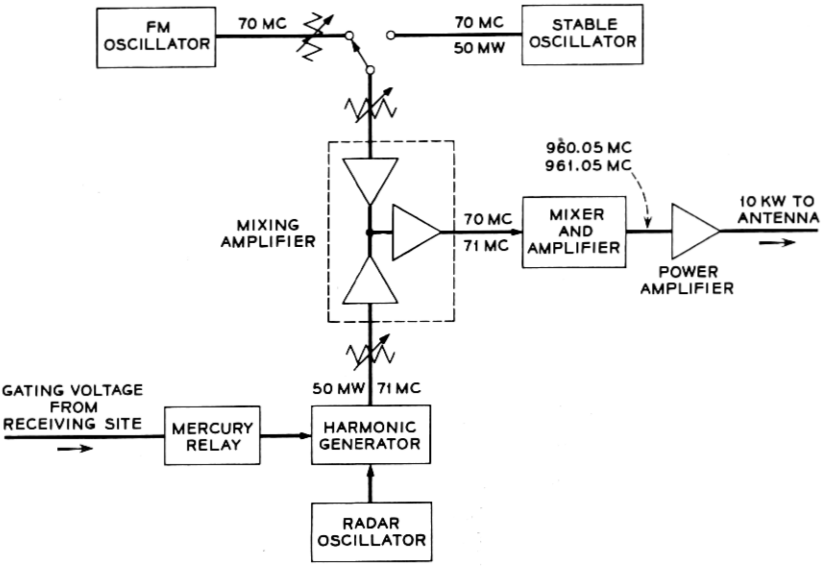

Fig. 6 — Block diagram of Echo I transmitter.

Because of the extremely high sensitivity of the receiver it is necessary to have the transmitter turned off at all times when the receiver is on. It was found by experience that intolerable interference at the receiver occurred whenever a 71-mc oscillator was on at the transmitting site, even though the oscillator was well filtered and shielded and disconnected from the exciter. This resulted from the high gain of the transmitter between the 71-mc input and the antenna. Because of this it was found necessary to employ an oscillator operating at a subharmonic of 71 mc and gate the harmonic generator that is required to obtain the desired frequency.

During simultaneous operation the transmitter power is shared, with 7.5 kw normally going to the communications channel and 2.5 kw to the radar. Because of amplitude nonlinearities in the transmitter, there is interaction between the two signals. In the first case, pulsing of the radar signal produces amplitude modulation of the communications signal at the pulse-repetition rate. It has been possible to reduce this crosstalk to a tolerable value, largely because the pulse-repetition frequency is very low. Secondly, the radar signal is compressed by a significant amount when the communications signal is present simultaneously. For this reason it is necessary to adjust the two signals to the desired values with both present rather than adjusting each individually. This is discussed more fully in Ref. 3.

The transmitting antenna is the same one that is used for communications, i.e. the 60-foot Kennedy dish.

### 3.3 *Receiving System*

#### 3.3.1 *General*

Fig. 7 is a block diagram of the complete radar receiving system. The 961.05-mc signal received by the conically scanned antenna is amplified by a low-noise parametric amplifier and heterodyned down to 30 mc. To avoid the need for rotary joints, this amplifier and a section of the 30-mc IF amplifier are mounted directly on the antenna and move with it both in azimuth and elevation. The 30-mc output is conducted to the radar shack through a length of flexible coaxial cable. This IF signal is passed through a crystal filter having a bandwidth of 200 kc, which is sufficient to take care of Doppler shift but is also narrow enough to remove the interference picked up from the communications transmitter. After filtering, the 30-mc signal is amplified by the main IF amplifier, which has a bandwidth of about one megacycle.

At the second converter the signal frequency is reduced to 199.1 kc by mixing the 30 mc with the 29.8009-mc output of the voltage-controlled local oscillator. The AFC control voltages are applied to this oscillator.

At the output of the 199.1-kc IF amplifier, which has a bandwidth of approximately 4 kc, the signal divides into two paths. One path contains a filter with a 100-cycle bandwidth; the other includes a filter with a 500-cycle band. The dc output of the detector supplied by the 100-cycle filter is used both to indicate the presence of a signal and as the AGC control voltage for the main 30-mc amplifier. From another detector, which is energized through the 500-cycle filter, we derive the four-cycle lobing frequency. This lobing frequency is filtered, amplified, and applied to the lobing detectors. At these detectors the lobing voltage is compared with the reference voltages derived from the antenna lobing unit. The resultant signals, which represent errors in azimuth and elevation, are indicated on meters at the receiving site and also on error indicating devices at the antenna-control position on Crawford Hill.

Because of Doppler shift, the received-signal frequency may differ from that of the transmitted signal by as much as ±35 kc. Automatic frequency control circuits are provided to keep the receiver in tune. To

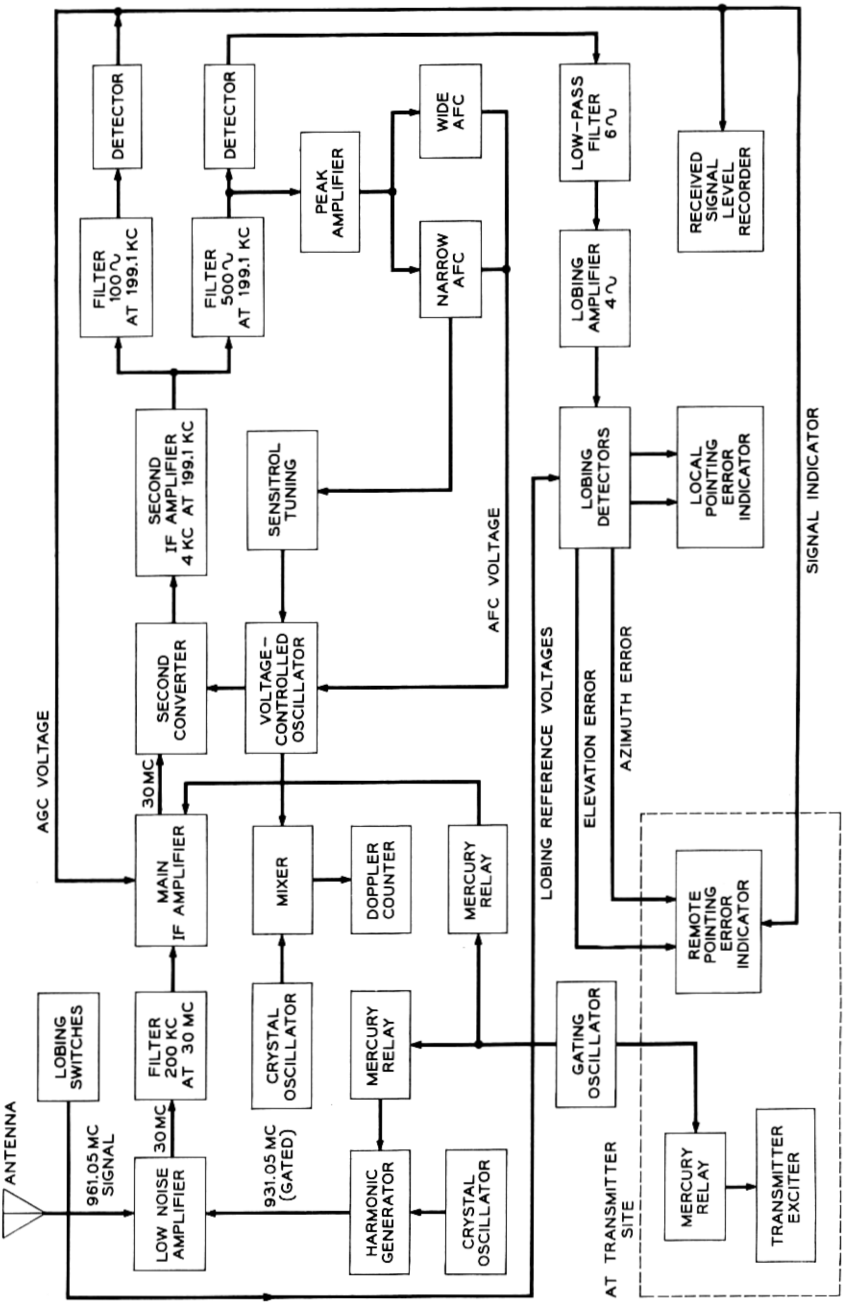

Fig. 7 — Block diagram of radar receiving system.

aid in acquisition, a sample of the voltage-controlled oscillator output is mixed with the output of a crystal-controlled oscillator operating at the nominal beating-oscillator frequency of 29.8009 mc. The frequency difference between these two oscillators is counted on an electronic counter. To tune in a signal, the voltage-controlled oscillator is adjusted to make the measured difference frequency equal to the expected Doppler shift.

With the satellite at its maximum range of 3000 miles and with the transmitter and receiver each gated to be on for one-half of the time, the optimum gating frequency is about 15 cycles per second. At a minimum range of 1000 miles the optimum pulse-repetition frequency increases to 45 cycles. Gating voltages are provided by an AF oscillator driving mercury relays. To prevent overload, it is desirable to gate the receiver at a point where the signal level is low. The most practical such point appeared to be the circuit of the local oscillator supplying the low-noise amplifier. Gating is done in a harmonic generator supplying this beating-oscillator voltage, and additional gating is applied to the main IF amplifier.

The lobing frequency of four cycles was chosen as being consistent with a 15-cycle pulse-repetition frequency and a one-second integrating time for the lobing-detector outputs.

With the exception of the parametric amplifier and the early stages of the 30-mc IF amplifier, all the electronic components of the receiver are mounted in a standard relay rack 7 feet high. This bay of equipment is shown on the left-hand side of Fig. 8. The cabinet on the right-hand side of the figure contains the antenna-control equipment.

### 3.3.2 *Parametric Amplifier*

Although the lobes from the back and sides of our antenna are not small enough in magnitude to warrant use of a maser amplifier, we are able to profit from the low noise figure provided by a parametric amplifier. Such an amplifier does not require cooling and is, therefore, considerably simpler than a maser. Our amplifier was designed and constructed under the direction of H. Seidel of the Murray Hill Laboratory of Bell Telephone Laboratories and is described in detail in a companion paper.[4]

The design of this amplifier provides for approximately 8 db of gain by frequency up-conversion by means of a nonlinear capacitance. Additional gain is derived from the negative resistance obtained by pumping such a capacitance (see Fig. 9). The amplifier is coupled to the

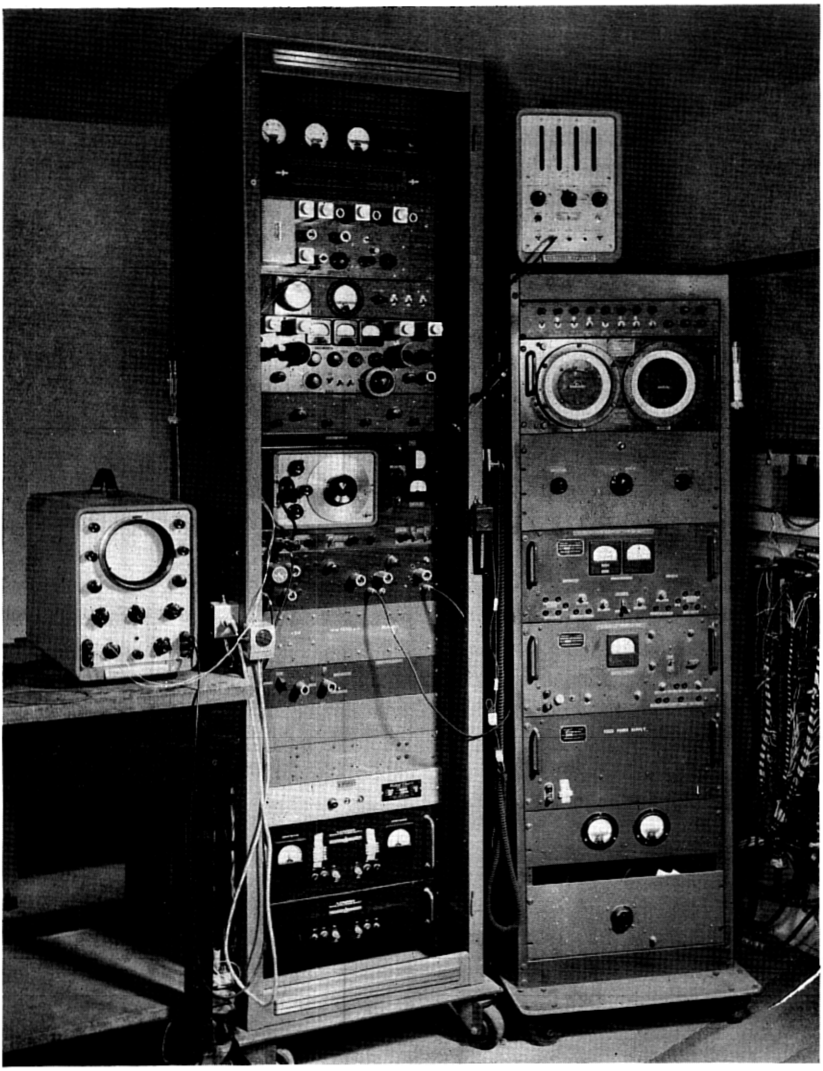

Fig. 8 — Receiver and antenna controls.

antenna by means of a circulator which is enclosed in a heat-insulated container and maintained at 120°F by means of heating tapes and a thermostat. In this way it is stabilized against variations in ambient temperature. An isolator could have been used in this position if one having the required degree of ruggedness and stability had been available.

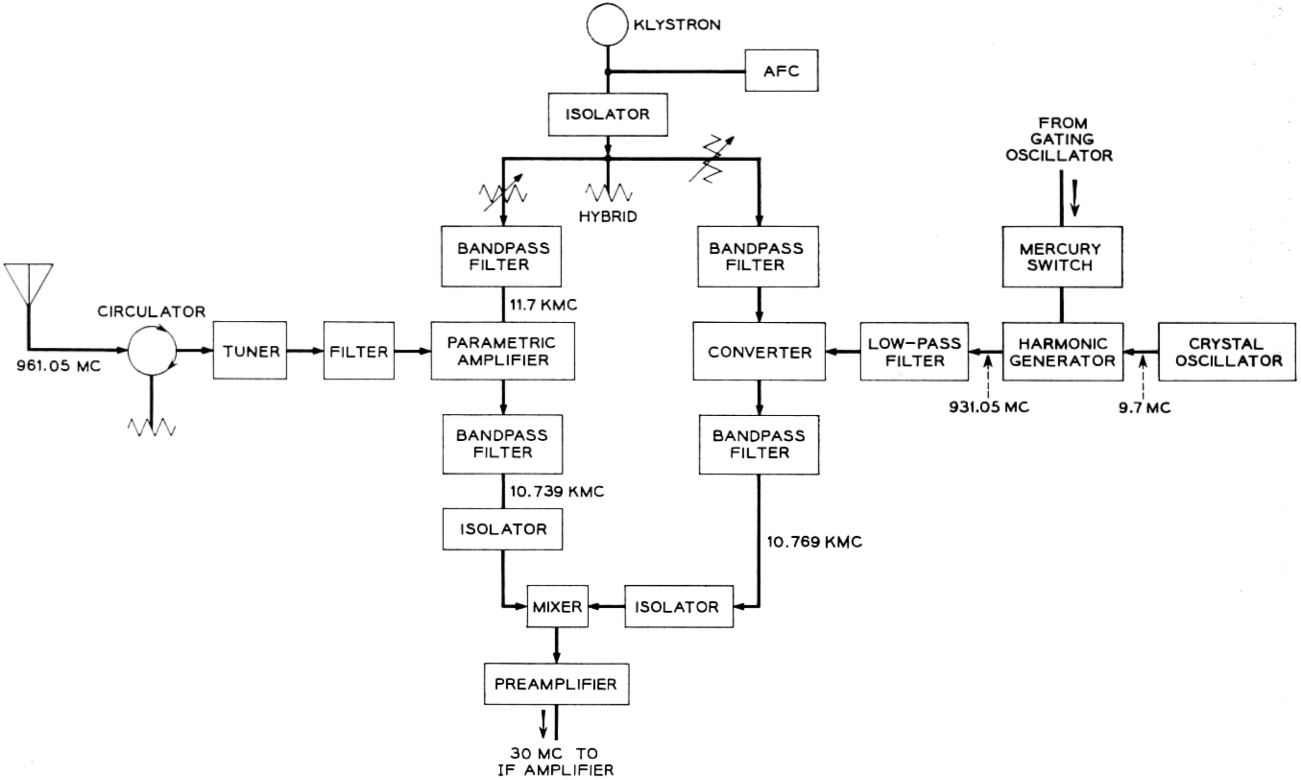

Fig. 9 — Block diagram of radar parametric amplifier.

The pump power is supplied by a Western Electric 445A klystron, operating at a frequency near 11.7 kmc. This frequency is maintained by a mechanical AFC circuit controlled by a Sensitrol* relay which is energized by the signal from a reference cavity. The lower sideband at 10.739 kmc is taken as the output of the amplifier. To obtain the 30-mc intermediate frequency a beating oscillator frequency of 10.769 kmc is combined with the 10.739-kmc signal in a nonlinear-resistance mixer.

Since the final predetection bandwidth of the receiver is only 100 cycles, it is obvious that the short-term stability of the 30-mc intermediate frequency must be exceptionally high. This frequency must, therefore, be made independent of the pump frequency, which is only roughly stabilized. The required independence of intermediate frequency is achieved by employing the klystron frequency in the process of heterodyning down as well as in heterodyning up. Changes of klystron frequency therefore cancel out in the process of going up in frequency and then back down. The beating-oscillator signal for the down-converter is obtained as follows: The output of a crystal-controlled oscillator operating at approximately 9.7 mc is multiplied up to 931.05 mc by means of a harmonic generator. (Gating of the receiver is accomplished by applying a gating voltage to the grid of one of the harmonic generator tubes.) By subtracting the 931.05 mc from the klystron output, the 10.769 kmc beating-oscillator frequency is obtained.

The bandwidth of the microwave section of the parametric amplifier is 20 mc. This is reduced to approximately one megacycle by a bandpass filter at the input to the first stage of the 30-mc IF amplifier. The gain of the microwave section is 22 db; the over-all gain 46.5 db. Over-all noise figures in the neighborhood of 1.6 db have been measured.

One db of compression takes place in this amplifier for an input signal of approximately −26 dbm. If the receiving site had been located near the transmitting antenna, interference at the communications frequency would have exceeded this overload value.

### 3.3.3 *Main IF Amplifier*

The crystal filter at the input to this amplifier has a total bandwidth of 200 kc. Its characteristic has extremely steep sides, so that the loss at the communications frequency, which falls one megacycle from the center of the band, is probably limited only by leakage around the filter. The amplifier itself has a total bandwidth of approximately one mega-

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* Trade name owned by Weston Instruments Division of Daystrom, Inc., Newark, New Jersey.

cycle, and therefore provides some additional discrimination against the interfering communications signal. The design of this amplifier is conventional. Its gain is controlled by the AGC and gating voltages applied to the grids of its tubes.

### 3.3.4 *Voltage-Controlled Oscillator Unit*

This unit consists of an oscillator and a buffer amplifier. A pair of variable-capacitance diodes shunted across the oscillator tank circuit provides electronic tuning. Two separate circuits supply control bias to the diodes, one for AFC, the other for manual tuning. A one-volt change of bias is sufficient to produce a frequency change of nearly one megacycle, which makes it a fairly simple matter to obtain a very stiff AFC action. This high sensitivity does make it difficult to keep undesired frequency modulation of the oscillator down to acceptable levels. With a receiver bandwidth of only 100 cycles it is desirable to keep this modulation to 10 cycles or less. The modulation which was most difficult to eliminate was that produced by 60-cycle voltages and currents. Operating the heaters of the oscillator and all units near it on dc, and very careful filtering of all circuits reduced this modulation to a tolerable value.

### 3.3.5 *Second Converter and IF Amplifier*

A simplified schematic of this unit is shown in Fig. 10. The 30-mc signal comes in at an impedance of 50 ohms. A tuned transformer steps up this level on the grid of the Western Electric 6AK5 tube used as the converter. The 199.1-kc output of this mixer is amplified through a single tuned stage, then divided into two paths with an untuned single-stage amplifier in each path. One of these amplifiers supplies the input to a three-section, tuned filter with a total bandwidth of 500 cycles. The output of this filter is coupled to the AFC unit and the pointing detector through a cathode follower and 50-ohm cables. The crystal filter at the output of the second untuned amplifier has a total bandwidth of 100 cycles and a characteristic with very steep sides. The filtered output drives two detectors in parallel. One of these provides the AGC voltage and is back-biased to produce the desired threshold effect. The AGC voltage is amplified through a one-stage dc amplifier before being applied to the first IF amplifier. A time constant of approximately ten seconds is provided at the output of this amplifier to prevent the AGC circuit from affecting the four-cycle lobing modulation carried by the incoming signal. A second output from this dc amplifier has a much shorter time constant and goes to a Sanborn recorder on which a record of the strength

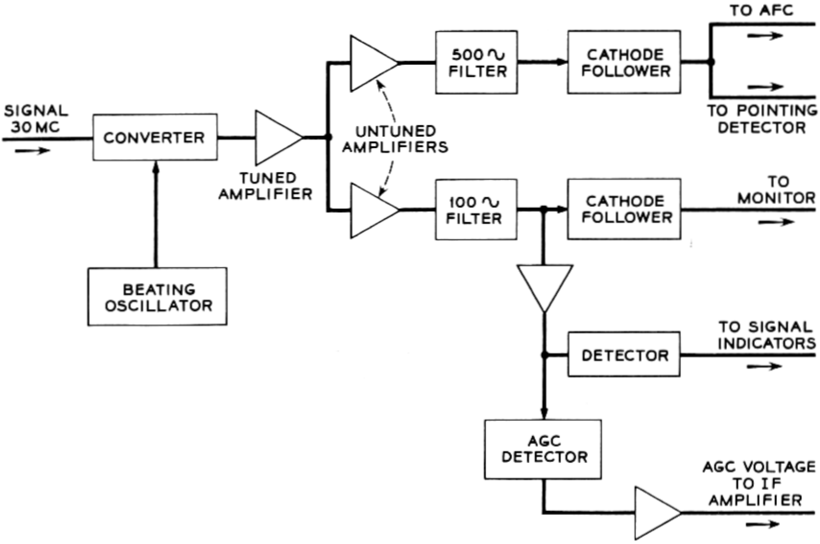

Fig. 10 — Block diagram of radar second converter and second IF amplifier.

of the received signal is provided. The other detector at the output of the narrow filter operates a meter used as a signal indicator.

### 3.3.6 *Lobing Amplifier and Detectors*

Before being applied to the lobing amplifier, the output of the detector with the 500-cycle bandwidth is filtered by a low-pass filter having a six-cycle cutoff frequency (refer to Fig. 7). The purpose of this filter is to prevent the pulse-repetition frequency from getting into the lobing amplifier. The input to the amplifier is provided with an adjustable phase-shifting network which makes it possible to maintain correct phase with respect to the lobing reference voltages. The lobing amplifier, which is untuned, employs simple *RC* circuits for coupling the various stages.

Each lobing detector consists of a Western Electric 276D mercury relay operated by one of the lobing reference voltages. These voltages, which are in quadrature, are derived from a pair of microswitches operated by cams on the antenna scanning unit. The simplicity of the lobing detection system is made evident by Fig. 11, which is a schematic of this system. It can be seen from this figure that the grids of a pair of phase-splitting triode tubes are supplied in parallel with the four-cycle lobing voltage. The plate of one triode is coupled to one input terminal of the

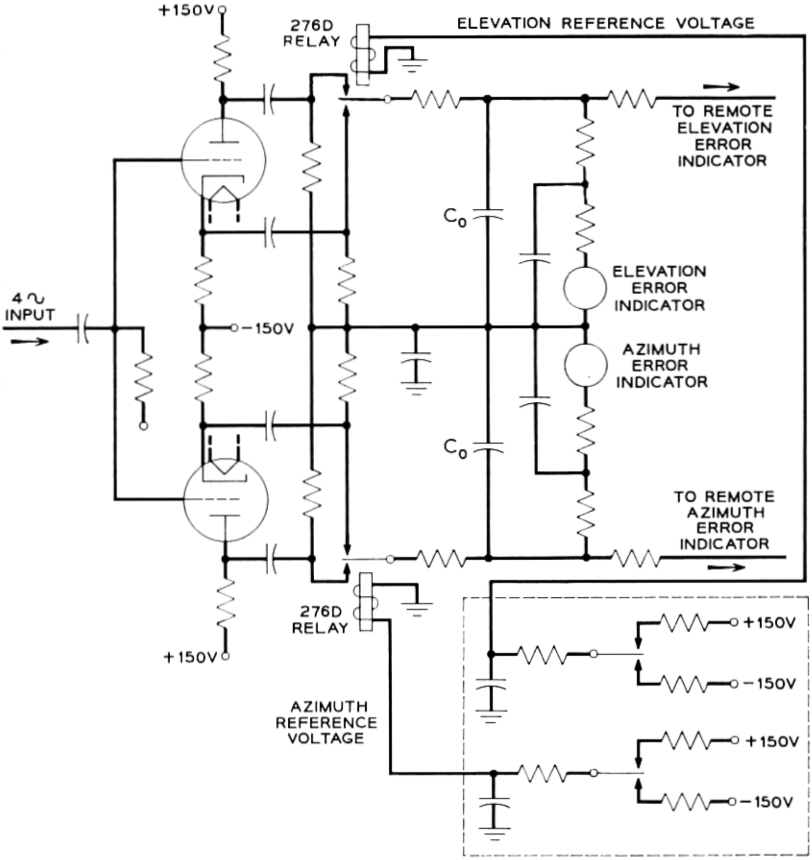

Fig. 11 — Schematic of radar lobing detectors.

elevation relay; the cathode of the triode is connected to the other input terminal of the same relay. The elevation error voltage is taken from the output terminal. If the four-cycle voltage has a component in phase with the reference voltage applied to that particular relay, there is a charge built up on the capacitor $C_0$ across the output terminal. A voltage component in quadrature with the reference voltage causes no change in the average charge on the capacitor; in this way, azimuth and elevation errors are separated. The voltage across $C_0$ indicates both the sense and magnitude of the pointing error.

The azimuth and elevation error voltages are displayed before operators in the form of meter readings and also as spot positions on a cathode ray oscilloscope. The time constants of these display circuits are adjustable. For satellite tracking a time constant of 3 seconds appears to be about optimum; for moon tracking the optimum time constant increases to about 7.5 seconds.

### 3.3.7 *Automatic Frequency Control*

At the 961-mc operating frequency the Doppler shift at the radar receiver can be as much as ±35 kc. To keep the signal within the 100-cycle band of the receiver requires a rather "stiff" AFC circuit. To meet the simultaneous requirements on sensitivity and stability a quartz crystal discriminator is employed; its characteristic is shown in Fig. 12. With the output of this discriminator connected to the voltage-controlled oscillator, nearly 60 db of negative feedback is obtained and the average frequency of the received signal is held to within a few cycles of the midband of the 100-cycle filter. To keep up with the change of Doppler frequency as a pass progresses, a motor-driven tuning control is also provided. The motor is controlled by a Sensitrol relay, which in turn is

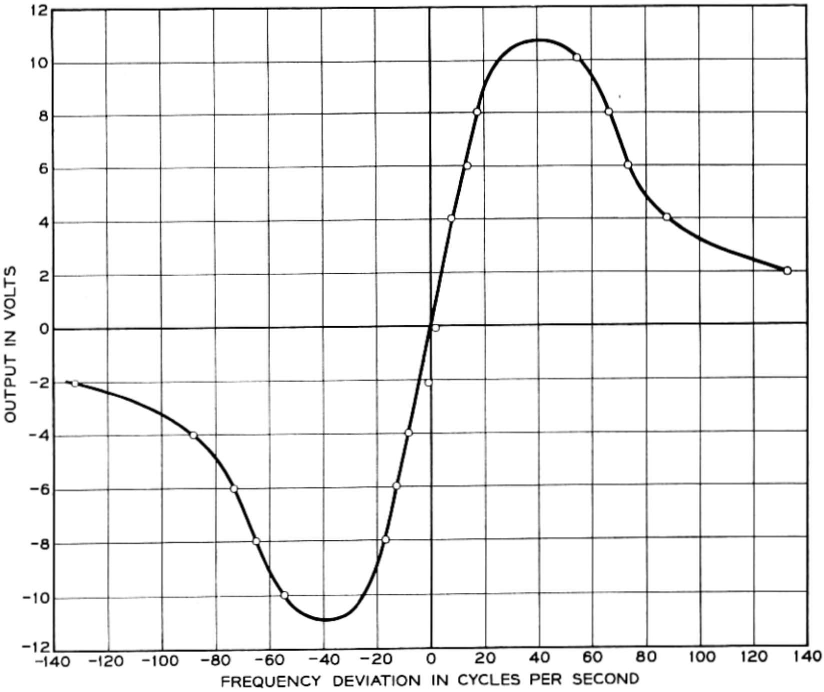

Fig. 12 — Frequency characteristic of frequency discriminator.

activated by the output of the crystal discriminator. This mechanical control keeps the receiver approximately tuned at all times and thereby takes much of the burden off the electronic AFC circuit.

As an aid in acquiring the signal, a wider-band discriminator is also provided. This circuit, which provides 30 db of feedback, brings the signal to within the pull-in range of the crystal discriminator, after which the latter takes control. The pull-in range of the wider circuit is about ±500 cycles.

It is obvious that there is a tuning problem in acquiring the signal when one considers the narrow bandwidth of the receiver, the constantly changing Doppler shift, and the short time available for acquisition. The difficulties are reduced considerably by the availability of data on the rate-of-change of range to the balloon at all times during the pass. From these data it is possible to calculate the corresponding Doppler shifts. Usually the only data required are those at the start of the pass. Referring to Fig. 7, we can see that one output of the voltage-controlled oscillator is combined in a mixer with the output of a crystal-controlled oscillator. The frequency of the crystal oscillator is equal to the nominal frequency of the voltage-controlled oscillator, i.e., the frequency at which it should be set to bring in a signal with zero Doppler shift. Any difference between the two frequencies applied to the mixer is read on the counter connected to its output.

With the above arrangement the procedure in tuning the receiver is as follows: From orbital data the Doppler shift at the time in question is calculated. The frequency of the voltage-controlled oscillator is adjusted to cause the counter to indicate a frequency equal to the Doppler shift. If the calculated Doppler were exact and if the various oscillators were perfectly stable, this procedure would result in perfect tuning. To make up for discrepancies, however, a small amount of manual tuning about the calculated frequency is usually required.

### 3.3.8 *Receiver Calibration and Testing*

Two reference-signal sources are available on Crawford Hill for the purpose of testing and calibrating the receiving system. By employing these sources it is possible to determine the gain and noise power output of the receiver as well as to check pointing accuracy. Checks and calibrations are usually made before each pass.

### 3.3.9 *Antenna*

The radar receiving antenna consists of crossed dipoles mounted in front of a reflecting disk in such a way as to accept circularly polarized

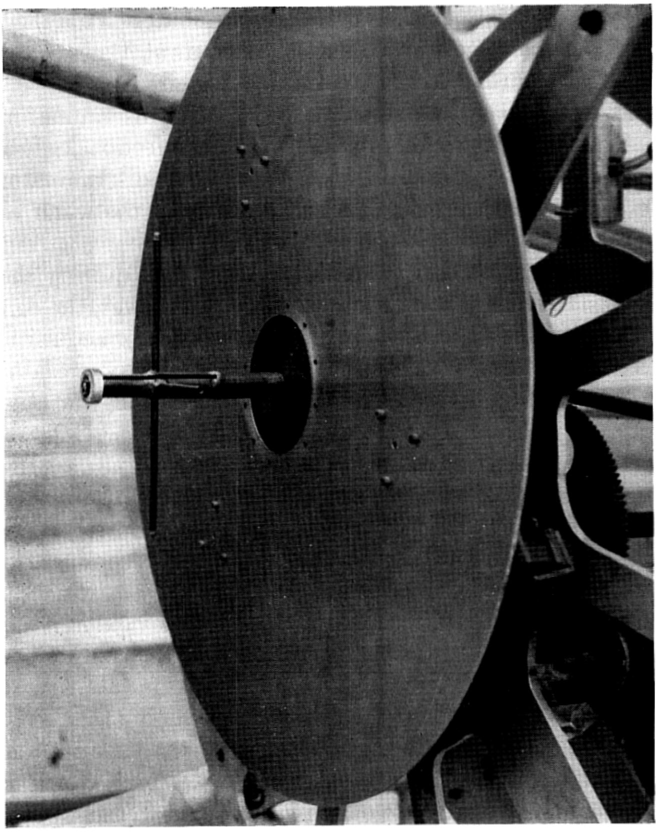

Fig. 13 — Antenna feed.

waves.* This feed, which is shown on Fig. 13, is mounted at the focus of an 18-foot parabolic reflector by means of a quadrupod consisting of four sections of aluminum tubing. The fiber glass cover which normally protects this feed from the weather was removed for the photograph. The parabolic reflector was fabricated of aluminum tubing and mesh by Prodelin, Inc.; it was chosen because it was lighter in weight than other available reflectors of the same diameter.

Fig. 14 shows the complete antenna, mounted on its supporting tower. The small building at the right of the picture houses the receiving equipment.

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* The design of this dipole assembly was based on suggestions by personnel of the Jet Propulsion Laboratory of the California Institute of Technology.

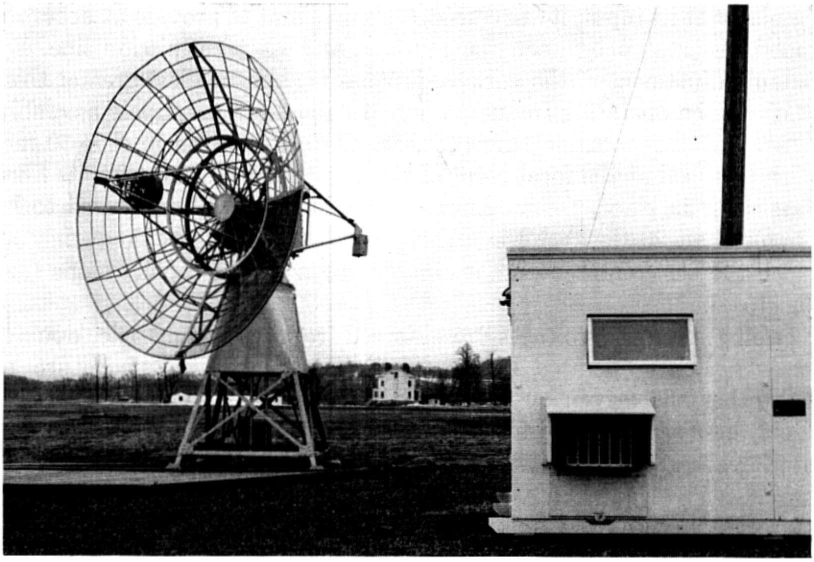

Fig. 14 — Echo I radar receiving antenna.

Since our received signal is circularly polarized it was not feasible to obtain conical scan by simple rotation of the feed. Rather, the feed was caused to rotate about the axis of the antenna in such a way that the radiators always remain parallel to themselves; i.e., the vertical dipole remains truly vertical and the horizontal dipole horizontal. The radiators are mounted at the center of the reflecting disk. This center point is caused to move in a circle about the antenna axis without any corresponding rotation of the disk about its own axis. The desired motion is obtained by supporting the disk on three motor-driven cranks.

To minimize losses, the coaxial line from the antenna feed to the low-noise amplifier has a diameter of $1\frac{5}{8}$-inches. This rigid line, which is pressurized, is connected to the rigid line supporting the dipoles by a short length of flexible cable. The flexibility of this section of line allows scanning of the feed. No rotary joint is required.

The antenna has a gain of 32.6 db and a beam width of 3.9°. Because of the conical-scan feature, the antenna feed is always displaced from the centerline of the reflector by two inches. This results in a beam shift of 1.2° with a resultant loss of approximately 1.5 db of gain along the antenna axis.

In spite of the fact that the parametric amplifier is equipped with a circulator at its input, it was considered important to provide an accurate impedance match between the antenna and its transmission line. By careful adjustment of the various dimensions, a return loss greater than 50 db at the operating frequency was obtained for the dipole assembly alone. This loss remained greater than 20 db over a range of ±50 mc. With this feed at the focal point of the mesh reflector and with its fiber glass cover in place, the minimum return loss was still measured to be greater than 20 db over the 100-mc band, although the frequency at which the best match occurs is different than for the dipoles alone (see Fig. 15).

Lobing reference voltages are obtained from two single-pole, double-throw switches operated by a pair of cams placed in quadrature to each other and driven by the lobing motor. It was found necessary to shield these switches and filter the leads going to them in order to avoid interference in the receiver.

## IV. ANTENNA MOUNT AND DRIVES

The receiving antenna is supported on, and driven by, a war surplus SCR-584 radar antenna mount. The mount is supported, in turn, on a steel tower fabricated for the purpose. The center of the reflector is approximately 15 feet above the ground (see Fig. 14).

This mount had originally carried an antenna only 6 feet in diameter,

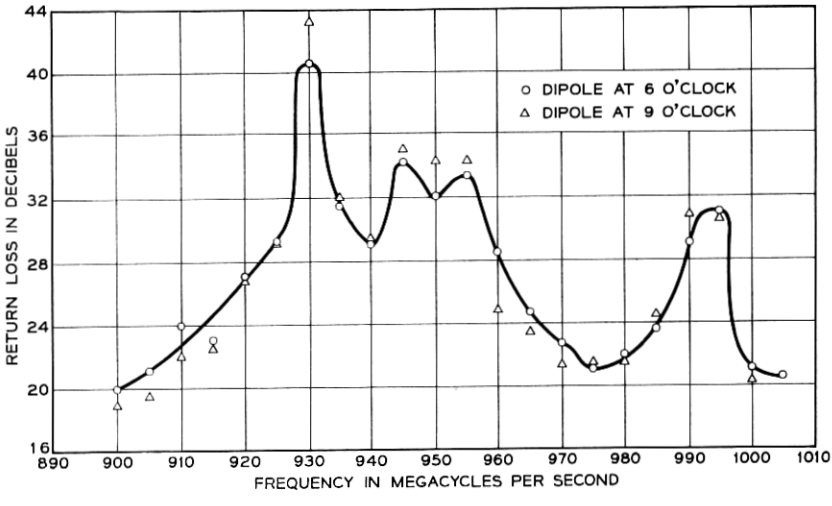

Fig. 15 — Antenna match. Feed with reflector.

and the much greater weight and inertia of our antenna increased the drive problems very considerably. As a result of corrosion and wear of gearing, the antenna drive was found to be very rough — a difficulty which was aggravated by substitution of the larger antenna. Furthermore, the increased inertia upset the characteristics of the feedback loop included in the positioning control system. The greater torque obtained by applying a 10:1 speed reduction to both the azimuth and elevation drive motors smoothed out the drive to a satisfactory degree. In spite of the speed reduction the antenna is still capable of a maximum rate of 4.5° per second in azimuth and 2.4° per second in elevation, which is sufficient for tracking the balloon.

Fig. 16 is a plot of azimuth lag error versus angular rate. Except for rare orbits that pass directly overhead, the maximum rate is 0.5° per second. The corresponding lag error is seen to be 0.04° or less.

The SCR 584 antenna mount was originally equipped with only one-speed control transformers. In order to improve positioning accuracy and operate with the synchro generators on the transmitting antenna, the system was converted to 1-and-36 speed in both azimuth and elevation. The 1-and-16-speed position-read-out synchros were also converted to 1-and-36 speed in order to be consistent with the rest of the Echo system. These speed changes were accomplished by adding gear trains constructed in our local shop.

In one experiment it was found to be a simple matter to set up the system to provide auto-tracking of the moon by the receiving antenna only. In this case the transmitting antenna was positioned manually. Because of the low angular rates involved it should not be difficult to

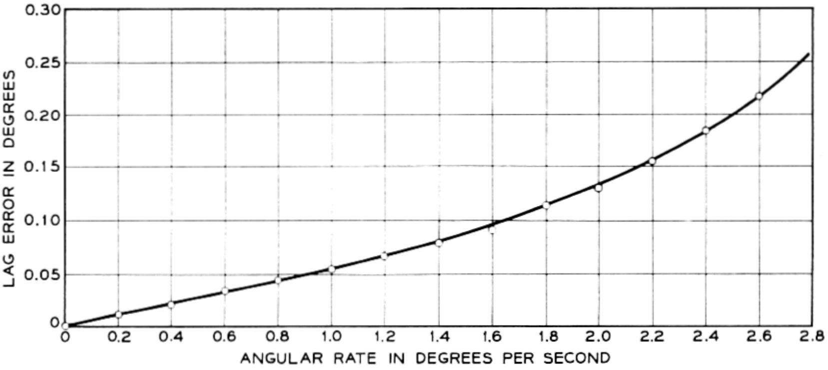

Fig. 16 — Azimuth lag error.

obtain completely automatic tracking of the natural satellite. But up to the present time we have not felt that it is worth expending the effort required to obtain automatic tracking of the balloon.

## V. CONCLUSIONS

Although the performance of the radar as designed is adequate, it could be bettered in several ways. There is considerable improvement when the transmitter is employed exclusively for radar, not only because of the 6-db increase in power but because of the absence of extraneous signals which result from some forms of modulation of the communications channel. A further reduction in the amount of residual frequency modulation of the beating oscillator supplying the second converter is also desirable.

Automatic adjustment of the pulse-repetition frequency to the optimum value at all times would also be a worth-while improvement. The present method — making these adjustments manually — is satisfactory when the radar is employed only for antenna pointing. When the system is engaged to make measurements of the path loss to the balloon and return, misadjustments of the pulse-repetition frequency reduce the accuracy of these measurements. Automatic control of the pulse rate should, therefore, provide more accurate results.

## VI. ACKNOWLEDGMENTS

Although it is not possible to give credit to everyone who contributed to the success of this project I do wish to acknowledge the many contributions of W. M. Goodall. I also wish to thank C. P. Frazee, F. E. Guilfoyle, and J. T. Ruscio of Bell Telephone Laboratories and L. G. Hegsted of Western Electric Company for the many long hours which they devoted to this radar.

## APPENDIX A

### *Calculation of Received Signal Level*

Let

$$P_R = \frac{P_T}{L},$$

where $P_R$ is received power, $P_T$ is transmitted power, and $L$ is path loss. For isotropic transmitting and receiving antennas and a spherical reflector,

$$L = \frac{2524.2R^4}{\lambda^2 D^2},$$

where $R$ is the distance to the reflector, $D$ is its diameter, and $\lambda$ the wavelength. At 961.05 mc, $\lambda = 1.025$ feet. For our case, $D = 100$ feet. Then

$$L = 0.2404\ R^4,$$

with $R$ in feet. For a range of 1000 miles $L = 0.2404\ (5.28 \times 10^6)^4$:

$$L = 1.87 \times 10^{26} = 262.7 \text{ db}.$$

Taking into account the transmitting antenna gain of 43.1 db and receiving antenna gain of 32.6 db, with a lobing loss of 1.5 db and total transmission line loss of 0.5 db, we have

$$L' = 262.7 - 43.1 - 32.6 + 1.5 + 0.5 = 189.0 \text{ db}.$$

For a transmitted power of 1 kw,

$$P_T = +30 \text{ dbw} = +60 \text{ dbm}.$$

For the 50 per cent duty factor employed the average power is 3 db less, or +57 dbm.

For a distance of 1000 miles and peak power of 1 kw,

$$P_R = +57 - 189 \text{ db} = -132 \text{ dbm}.$$

For other distances and powers we have

$$P_R = -132 \text{ dbm} - 40 \log R + 10 \log W,$$

where $R$ is the range in thousands of miles and $W$ is the transmitted power in kilowatts. For $R = 1000$ miles and $W = 2.5$ kw, $P_R = -128$ dbm. For $R = 3000$ miles and $W = 2.5$ kw, $P_R = -147.1$ dbm.

### *Noise Calculations*

At a temperature of 300°K, the $KT$ noise power is $-174$ dbm per cycle of bandwidth. For a 100-cycle band and a noise figure of 1.8 db the noise power is

$$W_N = -174 + 20 + 1.8 = -152.2 \text{ dbm.*}$$

At the maximum range of 3000 miles the predetection signal-to-noise ratio in the 100-cycle band is $152.2 - 147.1 = 5.1$ db. For the 500-cycle

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* This value of noise power is to be expected during measurements of system sensitivity, since the signal-generating equipment has a noise temperature of approximately 300°K. It is also to be expected when the antenna is at zero elevation as it is at acquisition. In this position there are trees, ground, etc., in the beam. It has been found experimentally that the noise power decreases about 2 db below this value when the antenna is pointed at the zenith.

band the noise power is 7 db greater and the predetection signal-to-noise ratio is −1.9 db.

For a considerable number of the passes which were tracked, the full 10-kw output of the transmitter was given over to the radar. This 6-db increase in transmitted power brings the calculated signal-to-noise ratio at the maximum range of 3000 miles up to 11.1 db at the output of the 100-cycle filter and 4.1 db at the output of the 500-cycle filter. At the minimum range of 1000 miles the ratios are 30.2 and 23.2 db respectively.

Postdetection filtering provides a very considerable improvement in the pointing signal-to-noise ratio. For example, a one-second time constant at the output of a phase detector is equivalent to a bandwidth of 0.16 cycle. This provides a reduction of 34.9 db in noise power when compared to a 500-cycle bandwidth. This improvement, however, cannot be realized under all conditions.

## APPENDIX B

### *Earth-Moon-Earth Path Loss*

The following values apply:

$$\begin{aligned} \text{Peak transmitted power} &= 10\ \text{kw} = +70\ \text{dbm}, \\ \text{Average transmitted power} &= 5\ \text{kw} = +67\ \text{dbm}, \\ \text{Transmitting antenna gain} &= 43.1\ \text{db}, \\ \text{Receiving antenna gain} &= 32.6\ \text{db}, \\ \text{Lobing loss} &= 1.5\ \text{db}, \\ \text{Total line loss} &= 0.5\ \text{db}, \\ \text{Received power} &= -128\ \text{dbm}, \\ \text{Path loss, } L &= 128 + 67 + 43.1 + 32.6 - 1.5 - 0.5 \\ &= 268.7\ \text{db}. \end{aligned}$$

According to Trexler[2] the path loss is 258 db at 300 mc and increases at the rate of 6 db per octave. At 961.05 mc,

$$\begin{aligned} L &= 258 + 10 \log (961.05/300) \\ &= 258 + 10.1 \\ &= 268.1\ \text{db}. \end{aligned}$$

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