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# PARTICIPATION OF BELL TELEPHONE LABORATORIES IN PROJECT ECHO AND EXPERIMENTAL RESULTS

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SUMMARY

On August 12, 1960, Echo I, a 100-foot-diameter spherical balloon, was placed in orbit around the earth by the National Aeronautics and Space Administration. The objective was to demonstrate the feasibility of long-distance communication by microwave reflection from a satellite. A two-way coast-to-coast voice circuit was to be established between the Jet Propulsion Laboratory (JPL) facility in California and a station provided by Bell Telephone Laboratories (BTL) in New Jersey. Similar tests were also planned with the Naval Research Laboratory and other stations.

This paper describes the general organization and operation of the Holmdel, New Jersey, station, and discusses the results of the experiments performed between the balloon launching and March 1, 1961. Successful voice communication was achieved through a variety of modulation methods including frequency modulation with feedback, amplitude modulation, single-sideband modulation, and narrow-band phase modulation. Careful measurements were also made of the loss in the transmission path.

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# 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.

This is the first of twelve articles published in the Bell System Technical Journal, Vol. 40, No. 4, July 1961, and republished, with minor revisions, as NASA Technical Notes by permission of Bell Telephone Laboratories. The other eleven are listed below.

1. Ruthroff, C. L., and Jakes, W. C., Jr. "Project Echo—System Calculations," NASA Technical Note D-1128, 1961
2. Schafer, J. P., and Brandt, E. A., "Project Echo—960-Mc, 10-kw Transmitter," NASA Technical Note D-1129, 1961
3. Ohm, E. A., "Project Echo—Receiving System," NASA Technical Note D-1130, 1961
4. Crawford, A. B., Hogg, D. C., and Hunt, L. E., "Project Echo—Horn Reflector Antenna for Space Communication," NASA Technical Note D-1131, 1961
5. DeGrasse, R. W., Kostelnick, J. J., and Scovil, H. E. D., "Project Echo—Dual Channel 2390-Mc Traveling-Wave Maser," NASA Technical Note D-1132, 1961
6. Kibler, L. U., "Project Echo—Standby Receiver System," NASA Technical Note D-1133, 1961
7. Ruthroff, C. L., "Project Echo—FM Demodulators with Negative Feedback," NASA Technical Note D-1134, 1961
8. DeLange, O. E., "Project Echo—Satellite-Tracking Radar," NASA Technical Note D-1135, 1961
9. Uenohara, M., and Seidel, H., "Project Echo—961-Mc Lower-Sideband Up-Converter for Satellite-Tracking Radar," NASA Technical Note D-1136, 1961
10. Klahn, R., Norton, J. A., and Githens, J. A., "Project Echo—Antenna Steering System," NASA Technical Note D-1137, 1961
11. Warthman, K. L., "Project Echo—Boresight Cameras," NASA Technical Note D-1138, 1961

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## INTRODUCTION

On August 12, 1960, Echo I, a 100-foot-diameter spherical balloon, was placed in orbit around the earth by the National Aeronautics and Space Administration. The objectives of Project Echo were:

1. To demonstrate two-way voice communication between the east and west coasts by microwave reflection from the satellite.

2. To study the propagation properties of the media, including the effects of the atmosphere, the ionosphere, and the balloon.

3. To determine the usefulness of various kinds of satellite tracking procedures.

4. To determine the usefulness of a passive communications satellite of the Echo I type.

It was anticipated that these objectives would be achieved primarily by conducting operations with the balloon launched by NASA, the satellite-tracking facility of the Jet Propulsion Laboratory located at Goldstone, California, about one hundred miles northeast of Los Angeles, and the Bell Telephone Laboratories (BTL) station located at Holmdel, New Jersey. Still further testing was planned in cooperation with the Naval Research Laboratory (NRL) facility at Stump Neck, Maryland, General Electric Laboratories in Schenectady, New York, and stations in Europe.

## DESCRIPTION OF THE EXPERIMENT

Figure 1 illustrates the general features of the experiment. An east-west channel was provided by transmission from a 60-foot paraboloid antenna at Holmdel to an 85-foot paraboloid at Goldstone Lake via reflection from the balloon, with a frequency of 960.05 Mc.

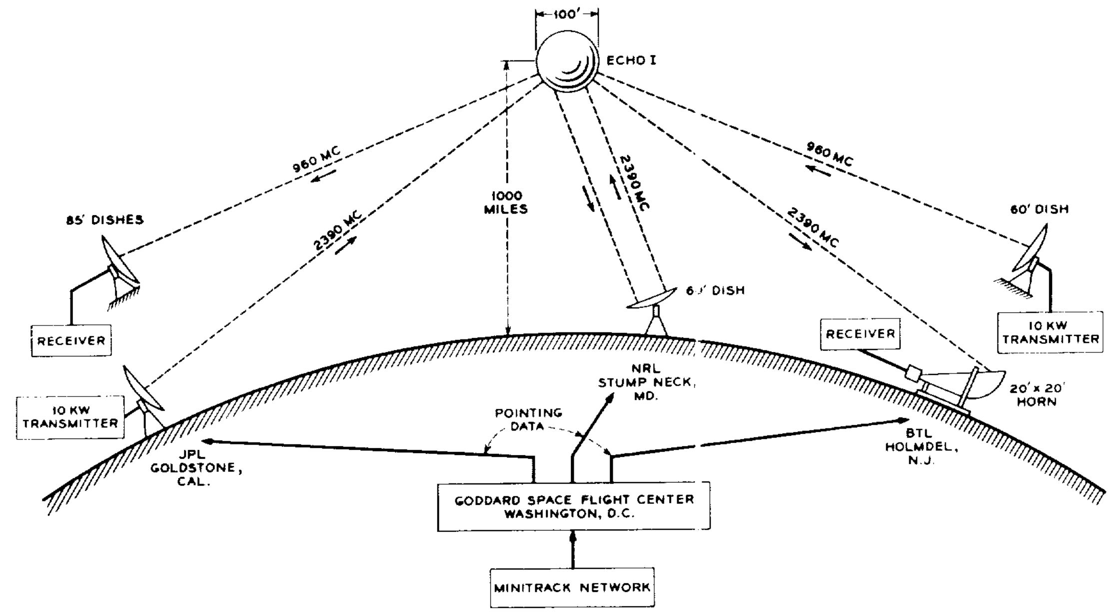


Figure 1 — General features of the Project Echo experiment

The west-east channel transmitted from another 85-foot dish at Goldstone (Goldstone Lake) to a specially constructed horn-reflector antenna, at Holmdel, having a 20- by 20-foot aperture. The radiation in each channel was circularly polarized to avoid the need for tracking polarization during the satellite pass. It was transmitted in a clockwise sense from the Goldstone Lake antenna and counter-clockwise from the Holmdel antenna. Reflection from the balloon reversed the sense of rotation of the field, so the major share of the field received by the Holmdel horn was expected to be polarized counter-clockwise, and that at the Goldstone Lake receiving dish to be clockwise. The Holmdel horn was equipped with a second receiver arranged to respond to the clockwise component of the incoming signal. Thus, more information could be obtained concerning the transmission properties of the medium.

The balloon was placed in an almost circular orbit with an inclination to the equator of 47.3 degrees, which provided periods of mutual visibility up to about 15 minutes for Holmdel and Goldstone Lake and 25 minutes for Holmdel and Stump Neck. The slant range from Holmdel to the balloon varied between 3000 and 1000 miles during a typical pass.

The NRL facility at Stump Neck, Maryland, consisted of a single 60-foot paraboloid equipped either to transmit at 2390.4 Mc or to receive at 2390 Mc. Ordinarily, both Holmdel and Stump Neck received from Goldstone Lake during the first part of a satellite pass while there was mutual visibility between Goldstone Lake and Holmdel. After the balloon had "set" for Goldstone Lake, Stump Neck transmitted to Holmdel, using counter-clockwise polarization. On a few passes Goldstone Lake and Stump Neck simultaneously transmitted to Holmdel and the two signals were separately recorded on two Holmdel receivers. Advantage was taken of the oppositely polarized radiation from Stump Neck and Goldstone Lake, and of the 0.4-Mc difference in transmitted frequency, to insure isolation of the two signals. Additional tests were conducted on 961.05 Mc at Holmdel, using a local receiver and an 18-foot paraboloid in a radar type of operation.

The communication tests were carried out primarily on frequency modulation with a peak index of 10, corresponding to $\pm 30$ kc deviation. This results in an FM improvement factor of about 25 db, provided the carrier-to-noise (C/N) ratio is above the FM threshold. The threshold in the Echo demodulators has been improved relative to that of conventional frequency modulation by the application of negative feedback to the FM demodulator (Reference 1). The threshold improvement for a modulation index of 10 and for 20 db of feedback is about 9 db, and occurs at an RF carrier-to-noise power ratio of about 14 db measured in a 6-kc bandwidth. Provision was also made for other types of modulation, including single sideband (SSB) and frequency or phase modulation of low index. It was expected that the maximum carrier levels would be about -113 dbm for reception from Goldstone Lake and Holmdel and -108 dbm from Stump Neck. Taking the expected system noise temperatures into account, this would provide maximum baseband rms signal-to-noise (S/N) ratios as follows, assuming the use of a modulation index of 10:

| | |
|---|---|
| JPL to BTL at 2390 Mc: | S/N = 57 db; |
| BTL to JPL at 960 Mc: | S/N = 49 db; |
| NRL to BTL at 2390 Mc: | S/N > 57 db. |

The signal-to-noise (S/N) ratio depends on the satellite position, since this determines the free-space path loss, atmospheric attentuation, and receiver noise temperature. Over most of the region of mutual visibility, however, the baseband S/N ratio was expected to be at least 45 db (Reference 2).

The threshold sensitivity of the BTL receivers is approximately -150 dbm, which correspondes to an effective system temperature of 23°K and a noise bandwidth of 6 kc, with a signal detection level 3 db below the average noise power. Under these conditions the maximum carrier-to-noise ratio was expected to be 34 db at 2390 Mc at Holmdel, which would permit making meaningful measurements of both the direct- and cross-polarized components of the incoming signal. Means for carefully recording and calibrating these signals were thus provided.

It was anticipated that tracking the satellite accurately enough to achieve the hoped-for signal levels would be a difficult problem; therefore a number of different tracking modes were provided at Holmdel. Primarily, the entire system was slaved to a teletypewriter tape containing predicted look angles for a given satellite pass. This tape was based on orbit-reduction calculations performed at the Goddard Space Flight Center (GSFC), Greenbelt, Maryland, utilizing observations from the Minitrack network. During the actual pass any differences between the position called for by the tape and the actual satellite position were then corrected using information derived from optics, radar, or maximization of the 2390-Mc received signal — whichever seemed best under the conditions of the moment. Alternatively, if no drive tape was available and if the satellite was visible, the system could be slaved to the optical system, which was then manually operated to track the satellite. All of the above methods were successfully used at one time or another; in fact, had they not all been provided, valuable data would have been lost.



## PRELIMINARY TESTS

In order to gain experience and check the capabilities of the equipment, a number of preliminary experiments were performed with Goldstone Lake, Stump Neck, Lincoln Laboratories in Round Hill, Massachusetts, General Electric, and others. A brief summary of these tests is given in Table 1.

### Moonbounce Tests

On November 23, 1959, shortly after the installation of the Holmdel 60-foot dish and the 10-kw, 960-Mc transmitter, the first operation was held with JPL. Successful contact was made with Goldstone Lake and some live voice was transmitted until a coaxial line broke down at Holmdel and operations were terminated. This was the first of a series of 17 such tests utilizing the moon as a reflector, continuing to the days immediately preceding the launching of Echo I on August 12, 1960.

As the tests progressed, more equipment was added at both terminals, until finally, on July 27, 1960, a two-way live voice communications circuit was established via the moon for the first time in history, using single-sideband modulation (SSB). Valuable information concerning system operation and calibration was obtained on all the tests and also some interesting data on the characteristics of the moon as a reflector. The data are summarized below:

1. The effective scattering cross section of the moon is $9 \times 10^{11}$ square meters, corresponding to a perfectly conducting sphere 670 miles in diameter. This is comparable to values obtained by others.

Table 1
Summary of Preliminary Experiments

| Date | Test |
|---|---|
| Moonbounce | |
| 11/23/59 | 960 Mc FM to JPL |
| 11/25/59 | 960 Mc FM to JPL |
| 12/23/59 | 960 Mc NBPM to JPL |
| 1/6/60 | 960 Mc NBPM and FM to JPL |
| 2/9/60 | 960 Mc NBPM and FM to JPL |
| 4/28/60 | 960 Mc SSB to JPL |
| 5/4/60 | 2390 Mc FM JPL to BTL |
| 5/10/60 | Two-way FM tests with JPL |
| 5/12/60 | 960 Mc to Jodrell Bank, England |
| 7/19/60 | Two-way SSB tests with JPL |
| 7/22/60 | Two-way NBPM tests with JPL |
| 7/27/60 | First two-way live voice, SSB, with JPL |
| 7/28/60 | 2390 Mc from NRL using FM and NBPM |
| 8/1/60 | Two-way SSB tests with JPL |
| 8/3/60 | Two-way SSB tests with JPL |
| 8/4/60 | Two-way FM tests with JPL |
| 8/7/60 | First BTL radar track of the moon |
| Tiros | |
| 4/28/60 | 960 Mc to JPL, no acquisition |
| 5/5/60 | 960 Mc to JPL, signal received |
| 5/11/60 | 960 Mc to JPL, signal received |
| 7/29/60 | 2390 Mc from NRL, contact throughout two passes |
| Shotput | |
| 10/28/59 | Optical track only |
| 1/16/60 | 960 Mc carrier to Round Hill |
| 2/27/60 | Voice to Round Hill using FM |

2. Speech as transmitted by SSB with a reduced carrier is of fairly good quality, is perfectly understandable, and usually permits identification of the speaker. The quality of music is much like that received on short wave from overseas.

3. The use of broad bandwidth modulation systems will degrade the speech quality. For example, FM of such index that only the first sidebands are present provides voice transmission of considerably reduced intelligibility compared to SSB. Wide-deviation FM (as used in the Echo experiments) renders speech virtually unintelligible.



## Shotput Tests

Five suborbital ballistic tests with the balloon payload were made prior to the final Echo launch. These launchings took place at Wallops Island, Virginia, and the trajectories were visible from Holmdel. Bell Telephone Laboratories performed the following duties:

Shotput 1 — Optically tracked the balloon to gain tracking experience and compare predicted with observed trajectory;

Shotput 2 — Successfully transmitted a 960-Mc carrier to the Lincoln Laboratories station at Round Hill, Massachusetts, via the balloon.

Shotput 3 — Demonstrated transmission of voice to Round Hill, via the balloon, using FM with feedback (FMFB) at 960 Mc. The threshold improvement of the FMFB demodulators was verified.

Tracking was again optical on the latter tests.

## Tiros Tests

In order to check the feasibility of satellite tracking by means of orbit predictions from the Goddard Space Flight Center, and to make sure that the Holmdel, Goldstone Lake, and Stump Neck stations were in proper operating condition, a number of carrier transmission tests using reflections from the satellite Tiros I were scheduled. The small size and low orbit of this satellite made it a much more difficult target; nevertheless, two successful contacts between Holmdel and Goldstone Lake and two between Holmdel and Stump Neck were achieved. On two passes Tiros I was briefly observed optically, and its position was within 0.1 degree of that predicted.

With the successful termination of these preliminary experiments, it was felt that the Holmdel station was ready for the Project Echo satellite experiment.

# SYSTEM DESCRIPTION

Most of the BTL facilities for Project Echo are located on top of Crawford's Hill, Holmdel, New Jersey, approximately 30 miles south-southwest of New York City, at 40.392° north latitude and 74.187° west longitude. An 18-foot paraboloid and other equipment used in the tracking radar are situated off the hill about 1-1/2 miles away, in order to increase the isolation between the transmitted signals from the 60-foot dish and the radar receiver. Figure 2 is a general view of the hilltop, and Figure 3 is a simplified block diagram of the BTL facilities. The small buildings visible in Figure 2 house the various pieces of system equipment, as shown in Table 2.

Table 2
System Equipment Locations at Holmdel

| Building | Location | Contents |
|---|---|---|
| 1 | Next to 60-foot dish | 960-Mc transmitter, monitors |
| 2 | Between dish and horn | System controls, digital-to-analog converter, FMFB demodulators, TWX terminals, audio and signal level recorders |
| 3 | Next to horn | Horn servo drive, helium recovery plant |
| 4* | At end of hilltop | Data storage and reduction equipment |
| Trailer* | Next to Building 2 | Plotting board, telescope, angular offset controls |

*Not visible in photograph of Figure 2

The system is briefly summarized in the following four sections, covering the functions of transmitting, receiving, tracking and communications. More detailed descriptions of certain components will be found in References 2 through 5, and 7 through 13.

## 960-Mc Transmitter

The BTL 960-Mc transmitter (Reference 3) is a commercially available item purchased from a division of the International Telephone and Telegraph Company. It provides a 10-kw output with an exciter capable of FM with deviations up to ±300 kc. In order to

Figure 2 — BTL Echo station facilities on Crawford's Hill, Holmdel, New Jersey

satisfy the various requirements for Project Echo, it has also been equipped with additional exciters and monitoring facilities.

Basically, the transmitter provides two output signals. One, centered at 960.05 Mc, is designated the communications channel, and may be modulated with FM of indices from 1 to 10, phase modulation (PM) with a 0.5 radian index, single-sideband modulation (SSB), double-sideband modulation (DSB), or AM. The modulation bandwidth extends from 200 to 3000 cps, corresponding to a satisfactory telephone circuit. The other output is centered at 961.05 Mc, and is only used for the BTL radar. It is amplitude-modulated by a square wave whose frequency may be varied from 15 to 100 cps, depending on the range of the object being tracked. The power outputs in each channel may be independently varied from 0 to 10 kw, subject to the restriction that their sum cannot exceed 10 kw. Normally the communications channel is set at 7.5 kw and the radar channel at 2.5 kw. The simultaneous use of these two channels is made possible by the final amplifier in the

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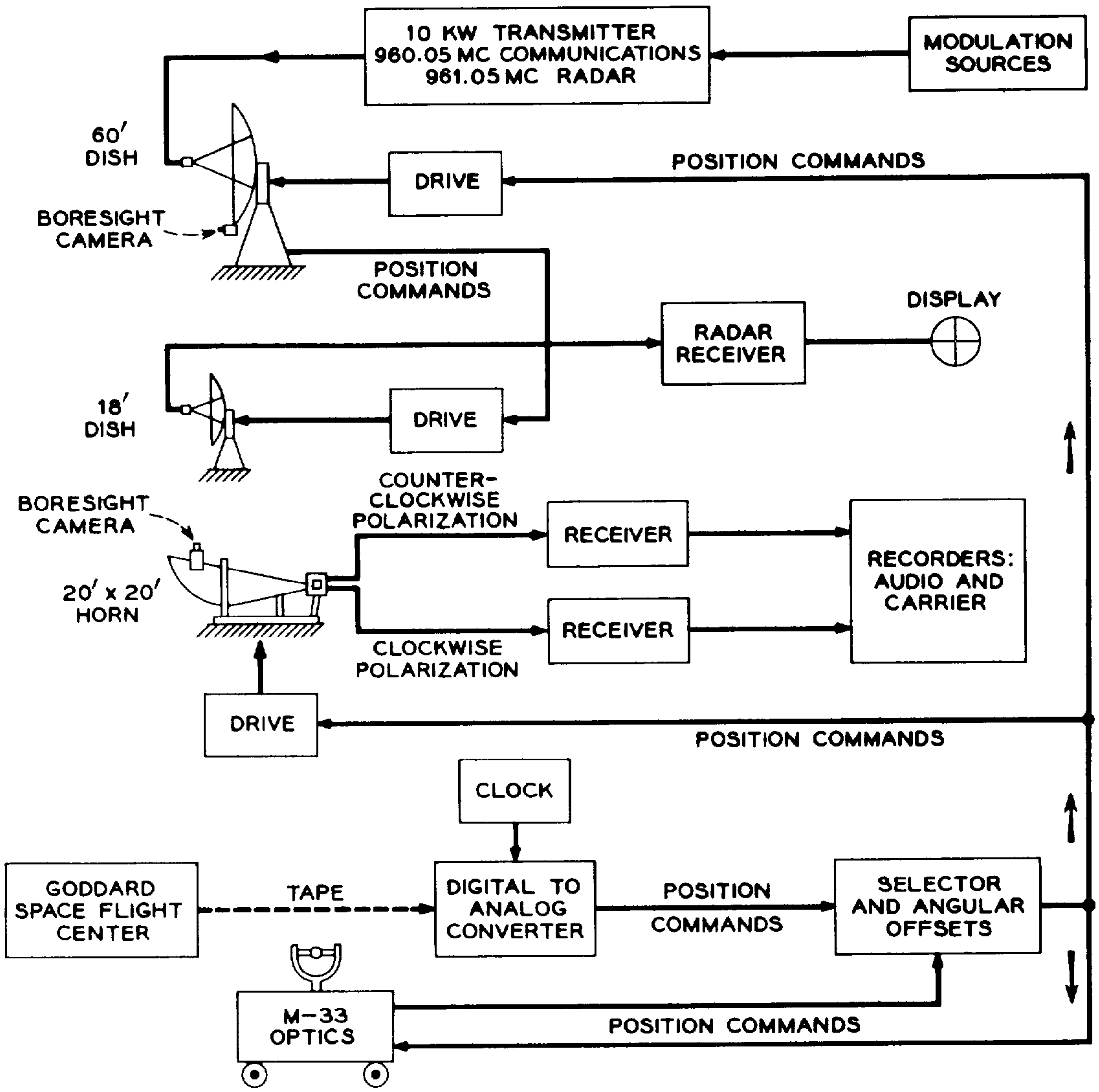


Figure 3 — Block diagram of the BTL facilities

transmitter. This employs a klystron with four external cavities arranged to give an overall passband of 3.5 Mc. A gain of more than 40 db is available so that only a watt or less of excitation is necessary. The klystron has a fairly linear amplification characteristic, and thus it can handle the various excitations listed without appreciable distortion or cross modulation.

Means for monitoring the various transmitter characteristics were provided, including frequency print-out accurate to ±30 cps, power recording accurate to ±0.1 db, and receivers for recovering and recording the transmitted modulation. All monitor records were time-tagged with Greenwich Mean Time (GMT).

The overall frequency stability of the transmitter depends on the particular exciter being used, and considerable effort was spent in making this as good as possible. Table 3 gives the results of these efforts.

Table 3
Frequency Stability Achieved with Different Exciters

| Exciter | Stability at 960 Mc |
|---|---|
| Wide-band FM | ±150 cps |
| Narrow-band FM or PM | ±50 cps |
| Radar | ±50 cps |
| SSB, DSB, or AM | ±20 cps |

## The Holmdel 60-Foot Paraboloid

This antenna is a standard item purchased complete with pedestal and servo drive from the D. S. Kennedy Company. The servo drive uses 20-hp dc motors in each axis and can position the antenna to an accuracy of ±0.05 degrees in winds up to 35 mph at angular rates more than adequate to satellite tracking. The maximum slew speed is 10 degrees per second. The antenna will withstand winds up to 70 mph in the stow position and will survive 110 mph winds when locked in place. The Kennedy Company also supplied and installed the complete feed system, including the microwave plumbing down to the transmitter. This feed was designed so that any polarization whatever could be transmitted, whether linear of any orientation, circular of right- or left-handed sense, or even elliptical. As has been mentioned before, counter-clockwise circular polarization was always radiated for the Echo tests. On a few occasions it was reversed during a Moon-bounce test between Holmdel and Goldstone Lake to check the cross-polarization characteristics of the moon. The transmission line from the feed horn to the transmitter output is waveguide, except for a short section of coaxial cable required for the two rotating joints. Total transmission-line loss was measured as 0.5 db.

After the antenna was installed in August 1959, several months of testing and alignment by Bell Telephone Laboratories personnel followed. The gain, cross polarization, and radiation patterns were all carefully measured, using a 960-Mc source on a hilltop about 12,000 feet away. This distance is large enough so that the field produced at the antenna by this source is essentially flat (as was verified by direct measurement). The results of the tests are shown in Table 4.

Table 4
Results of Tests on the Holmdel 60-Foot Paraboloid Antenna

| Test | Result |
|---|---|
| Gain | 43.1 ±0.1 db |
| 3-db beamwidth | 1.2 degrees |
| First sidelobes | -20 db |
| Axial ratio | 1 db |
| Return loss | 20 db. |

## Receiving System

A detailed discussion of the receiving system at Holmdel will be found in Reference 4. A brief description is in order here.

A horn-reflector antenna (Figure 2) was used for 2390-Mc reception at Holmdel (Reference 5) because of its demonstrated low-noise properties (Reference 6) and other features. The aperture of the antenna is approximately 20 by 20 feet, the overall length about 50 feet. Careful measurements were made of the gain and radiation patterns before the Echo I launch with entirely satisfactory results (Table 5).

Table 5
Gain and Radiation Patterns of the 2390-Mc Horn Reflector Antenna

| Test | Result |
|---|---|
| Gain | 43.3 db |
| 3-db beamwidth | 1.2 degrees |
| Axial ratio | 1.2 db |
| Projected area | 380 square feet |
| Effective area | 288 square feet |

The drive for the horn is very similar to that for the 60-foot paraboloid. A 10-horsepower dc motor is used for positioning in each axis, making possible maximum slew speeds of 5 degrees per second and accurate tracking in winds up to about 30 miles per hour.

The horn throat tapered down to round waveguide inside the antenna cab. A rotating joint with a very low loss coupled the horn to the waveguide system, which contained: the 90 degree phase-shift section for converting the two orthogonal circularly polarized waves to orthogonal linear waves; polarization takeoffs; and transducers to the coaxial lines leading down into the maser. Means were also provided for injecting a known amount of noise or 2390-Mc reference signal into the waveguide for calibration purposes.

Two masers (Reference 7), both located in one dewar in the field of a single magnet, were used for the two polarizations of the incoming signal. The maser gains were sufficient so that the noise figure of the crystal converter which followed did not appreciably affect the overall system noise temperature. Liquid helium was used to cool the masers to operating temperature. A dual 2390-Mc parametric amplifier was also provided (Reference 8), and in the event of maser failure it could be switched into the system in place of the maser in a few minutes. The C/N ratio is degraded by about 10 db when a parametric amplifier is used.

The crystal mixers or parametric amplifier down-converters were followed by 70-Mc IF preamplifiers, which raised the signals to levels suitable for transmission to the control building via slip rings in the horn and coaxial cable. The remainder of the receiving system was located in the control building. This included the FMFB demodulators, Sanborn pen recorder, frequency monitor, and audio recording and distribution equipment. The FMFB demodulators also included an AGC circuit which was used for signal-level recording. On occasions when SSB or NBPM was used, an SSB receiver was substituted for the FMFB demodulators (Reference 9), and in this case phase lock was used to remove the Doppler shift. A second conventional SSB receiver then recovered the modulation.

Since the voltage-controlled beating oscillator in the feedback demodulator automatically tracked the incoming signal frequency, its frequency was directly proportional to the Doppler shift. Its output at 68.8 Mc $\pm f$, where $f$ was the Doppler shift, was measured by a frequency counter and displayed by Nixie* lamps for photographic recording once every second.

A four-channel Sanborn recorder was used for recording the signal levels of the clockwise and counter-clockwise circularly polarized components. The system noise temperature was also continuously recorded during each pass.

The audio output of the system was recorded on magnetic tape, and also was made available for local or outside telephone lines, or for the station public address system.

*Nixie lamps are number-indicating lamps that are often used in frequency-counting circuits.

Measurements show that the overall system noise temperature, including sky noise, was about 45°K or less throughout the significant part of the Project Echo experiments, the minimum value observed being about 21.5°K. The sky noise is a function of antenna elevation, as had been pointed out elsewhere; thus, the system temperature varies during a satellite pass.

## Tracking

### General

As mentioned in the Introduction, several means were provided for tracking the balloon. From Figure 4 it is evident that the antennas were pointed principally using

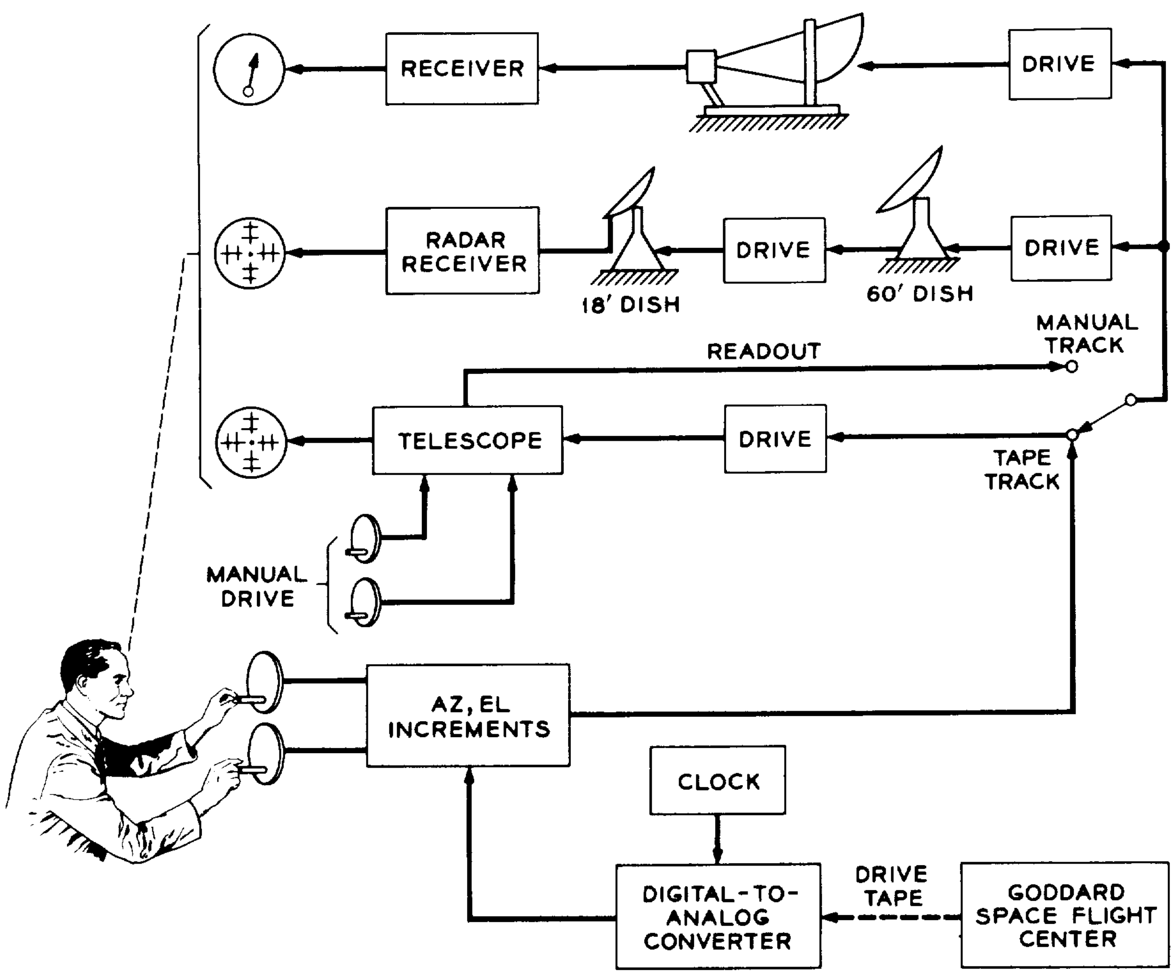


Figure 4 — Block diagram of BTL tracking modes

information from a predicted drive tape, with corrections being inserted manually using current data yielded by optics, radar, or carrier peaking. This was the usual mode of operation. An alternative mode was available in which the system antennas could be slaved to the positional read-outs of the optical tracker, which was then operated manually to track the satellite. Positional commands were all of the analog type obtained from synchro control transmitters. A two-speed, 36:1 system was used in each coordinate. The device for manually inserting angular offsets, or corrections, utilized synchro differential generators and was located in the trailer which carried the optical tracking telescope. Displays from the optics, radar, and carrier-level indicators were adjacent to the differential control unit, so that one operator could select the most suitable display and insert the corrections accordingly. Angular offsets up to 360 degrees in azimuth and 90 degrees in elevation could be used.

Drive units for the 60-foot dish and the horn are similar, consisting basically of Ward-Leonard-type systems using dc motors.



### Digital-to-Analog Converter

The DAC unit (Reference 10) serves to convert the digital information contained in the drive tape to the analog (synchro) positional commands for controlling the antennas and optics. The drive tape supplies a block of five separate quantities, called a data point, every four seconds. These quantities are time, azimuth, elevation, azimuth rate, and elevation rate of the satellite. They appear on the tape in binary-coded decimal form, using four bits for the digit and one for a parity error check. The decoding equipment in the DAC utilizes the rate information to provide positional commands between the four-second data points, so that the antennas will move smoothly.

With commercial 60-word-per-minute facilities, it takes 20 to 30 minutes to transmit the usual drive information for Echo I. For the first several months after launching, the computer at the Goodard Space Flight Center supplied the drive tapes. Since the beginning of 1961 the tapes have been obtained from a computer at Bell Telephone Laboratories, and are based on orbital elements supplied by the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts.

The drive tapes are read photoelectrically at a time corresponding to the time of the data point. As the tape advances from one point to the next, the angular quantities are read into transistorized logic circuits, where they are sorted and decoded. The decoding process results in a rectangular pulse output whose duration corresponds to the input quantity, causing a motor to turn a gear train to the appropriate angular position with an accuracy of ±0.02 degree. A number of snychro transmitters are fastened to the gear train. These supply positional command signals to the dish, horn, and optical drives.

The DAC also includes a very stable clock, used as the station master clock, as well as for the time comparison involved in reading the drive tapes.



## Optical Tracker

A component of a surplus M-33 fire-control radar system was obtained on loan for use as the tracking telescope. It consists of a large trailer carrying a periscope-type optical train which leads down to convenient operator positions inside the trailer. The field of view is about 6 degrees, with a magnification of 8X and an objective lens about 2 inches in diameter. Stars down to a magnitude of about +8 can be seen on a clear night. Modifications were made to the angular data-takeoff units so that the telescope could be: (1) slaved to the command signals originating from the DAC; and (2) manually controlled to follow an object and provide suitable positioning signals to the antennas. Both complete manual and aided manual modes were available. Star sights were used to check alignment, and in general showed residual errors of ±0.02 degree. In normal use the operator watched through the telescope while it moved in accordance with the commands derived from the drive tape; then, if errors were detected, the appropriate angular offsets were inserted, causing all the system antennas and the telescope to track the target accurately.

Several plotting boards were included in the M-33 trailer as part of the normal fire-control equipment. One of these was modified so that a plot of azimuth versus elevation of the telescope could be obtained during a satellite pass. Timing marks spaced 30 seconds apart were also provided, and a plotting accuracy of about ±0.5 degree was obtained. These plots were quite useful in making rapid examinations of tracking, and showed bad data points graphically.

## Tracking Radar

A separate 18-foot paraboloid is used to receive the 961.05-Mc signal reflected from the satellite (Reference 11). It is equipped with a rotating feed which produces a conically scanned beam for obtaining angular error information. The radar antenna is slaved to the angular read-out synchros associated with the 60-foot dish, and follows to an accuracy of ±0.05 degree.

Since the radar transmitter and receiver are fairly close together, gating had to be used to prevent masking of the signal from the satellite by the transmitter. As mentioned before, the radar carrier is at 961.05 Mc, 1.0 Mc away from the communications frequency of 960-05 Mc, and is 100 per cent square-wave modulated. There is a 3-db loss in average signal level due to the square-wave modulation. The lowest pulse repetition frequency is 15 cps, corresponding to a range of 3,000 miles. This means that the reflected signal arrives just after the end of the transmitted pulse. As the range decreases, the pulse repetition frequency is increased correspondingly to compensate for the decrease in the width of the received pulse.



The radar receiver is equipped with a 961-Mc parametric amplifier (Reference 12) which is followed by appropriate IF and detection circuits for obtaining the azimuth and elevation errors. These were derived by two phase detectors, fed in parallel by the input signal and separately by reference square waves 90 degrees apart produced by cam-operated switches at the antenna feed. The dc error signals were then brought to the M-33 trailer, where they positioned the spot on a cathode ray tube, thus showing the operator the position of the satellite with respect to the system pointing axis in much the same manner as that given by the tracking telescope. The operator then manually inserted the proper angular offsets to center the spot.

The overall system sensitivity is about -150 dbm, and good pointing information was obtained for levels of -145 dbm and higher. Predetection bandwidth is 500 cps. Since the incoming signal frequency is Doppler-shifted by ±35 kc during a typical pass, a very good automatic frequency control circuit is necessary. A postdetection filter with about a one-second time constant was used to increase the tracking signal-to-noise ratio.

In addition to angular error data, the radar receiver was used to measure the scattering cross section of the satellite by recording the automatic gain control (AGC) voltage. A distant test source was used for calibration purposes, but this part of the system was not put into operation until about October 1960.

## Alignment

In order to conduct meaningful communication and transmission tests, it was felt that the system antennas should be able to track the balloon to an accuracy of ±0.1 degree. Part of this error would inevitably be due to antenna misalignment of bore-sighting errors; hence, some time was spent in measuring and adjusting to keep these errors within ±0.05 degree. Since the predicted look angles for the satellite would always be referred to the assumed local geocentric coordinate system, it was first necessary to establish that the mechanical axes of the antennas and tracking telescope were properly aligned with respect to these coordinates. To do this, an initial alignment was made using surveying methods. Then this was checked by mounting a telescope on the unit under test and taking star sights for a number of stars over the entire sky hemisphere. Analysis of these data then revealed any systematic errors, such as tilt of the azimuth axis; then these were corrected and checked by more star sights.

The next step was to adjust the electrical axes of the antennas to coincide with the mechanical axes. This was done, in the case of the 60- and 18-foot dishes, by aiming the antenna at a distant microwave source whose position was accurately known, and adjusting the feed until the peak signal occurred at the proper position. Time limitations prevented carrying out a similar procedure for the horn. In this case, mechanical and optical methods were used to align the reflector. Subsequent electrical checks showed a residual error of less than 0.1 degree.

Finally, the data comparison units used in the servo drive follow-ups had to be aligned so that all units pointed in the same direction for a given positional command signal. No allowance for parallax was made for any units, since the largest separation (between the radar receiving antenna and the rest of the system) only corresponded to an error of 0.08 degree for the Echo satellite at its closest approach.

The results of these tests were generally satisfactory, and indicated that the desired objectives had been achieved.

### Tracking Data Recording

In order to have a record of the positions of the various moving elements of the system during a satellite pass, each element was provided with snychro read-outs which were periodically photographed. Pictures were taken (at one-second intervals) of a panel carrying the two-speed azimuth and elevation position dials for the DAC, M-33 (optics), 60-foot dish, and horn antenna. A Greenwich Mean Time clock also appeared in the photographs. Position angles could be read to ±0.01 degree, and time to 0.5 second. An enlargement of one frame of such a record is shown in Figure 5. Also shown are a set of Nixie lamps for recording the 2390-Mc received signal frequency.

The 60-foot dish and horn antennas were each equipped with a boresight camera (Reference 13) that could be started at will whenever the satellite was visible. Pictures were taken at four frames per second, and included a reticle for indicating angular offsets to an accuracy of ±0.01 degree and a time-coded counter.

## Communications

A variety of telephone services were provided for both local and long distance communications. Included was a private four-wire line between Holmdel and the Goldstone site, with provisions for any of four modes of operation:

1. Two-way conversation by land line;

2. East-to-west by satellite, west-to-east by land line;

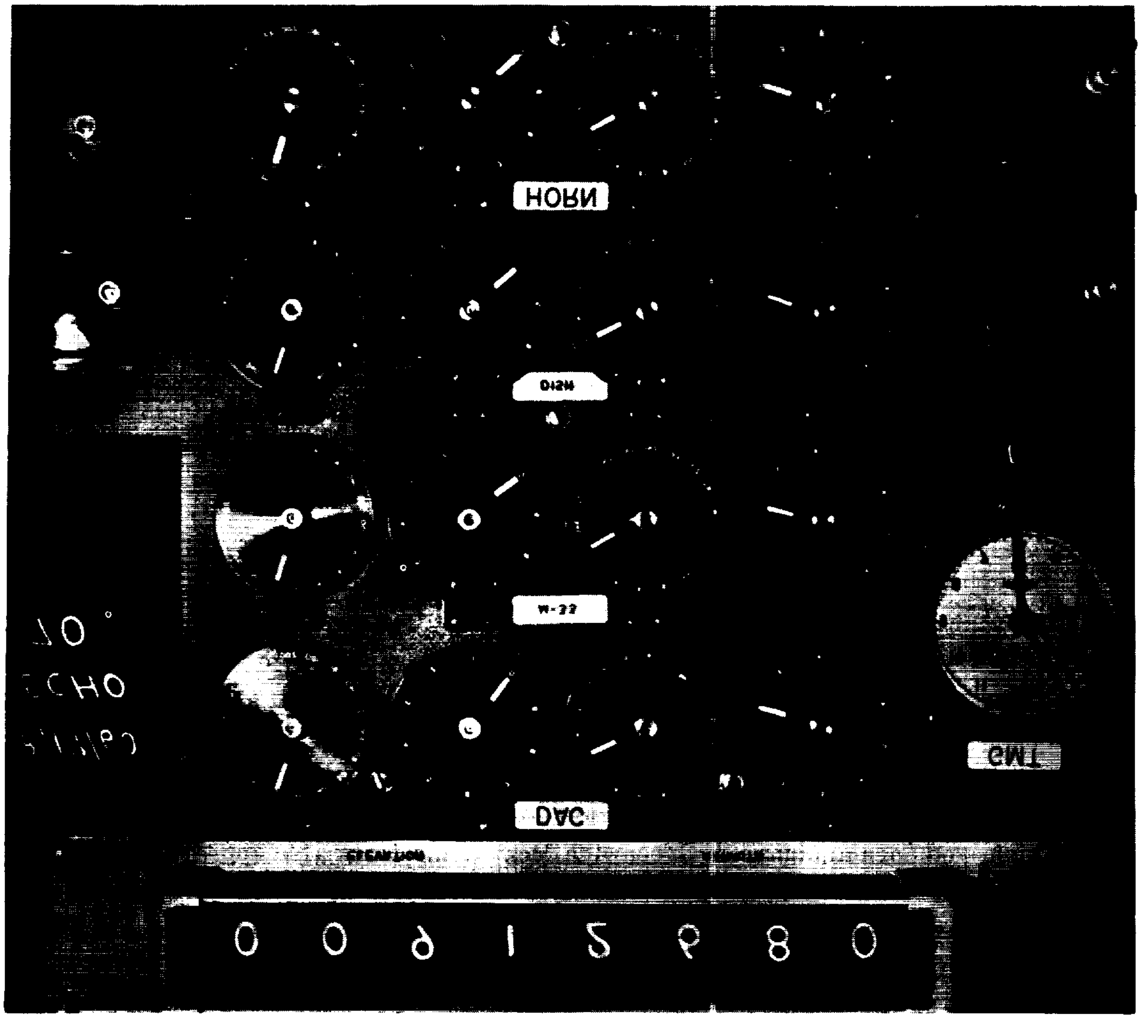

Figure 5 — Reproduction of one frame of the data-recording camera film

3. West-to-east by satellite, east-to-west by land line;
4. Two-way by satellite.

Two teletypewriter lines were brought into the control building. One was a private full-time service to the space control center (SPACECONN) of the Goddard Space Flight Center. This was used to maintain contact with SPACECONN and other stations tied into this net, and also for the transmission of drive tapes from the GSFC computer to Holmdel. The other line provided a general utility TWX service, and included a tape puncher for receiving drive tapes from other sources.

During operational activities all station personnel concerned were in touch with each other by a headset-type intercommunication system. Conversation on this loop was also recorded on magnetic tape as a matter of record.

A public address system was provided which served as a general announcing system for all locations, both indoors and outdoors. When appropriate, the signals being carried by the satellite circuit could be connected to the public address system for the benefit of all station personnel.

## EXPERIMENTAL RESULTS

After the successful launching of the Echo I balloon on August 12, 1960, tests were carried on by the BTL Holmdel station for about 120 passes up to March 1, 1961. Of these, four were with Goldstone Lake only, 50 were with Stump Neck only, 27 were with both Goldstone Lake and Stump Neck during the same pass, and 39 were with the Holmdel radar only. Tests with other stations were carried on during 29 of the 120 passes. In general, the objectives of the experiment have been achieved, as will be discussed in detail in the following sections.

### Audio Tests

Modulation tests of various kinds were performed on a total of 51 passes with JPL and NRL. Breaking this down further: voice and music transmission were tried using FMFB on 16 passes with JPL and 15 with NRL, using SSB on two passes with JPL, using NBPM on one pass each with JPL and NRL, and using AM once with NRL. Data-type transmission either of facsimile or frequency-shift keying was tried on 15 passes with NRL using FMFB. A sample of facsimile transmission is shown in Figure 6. Some of the more significant tests performed in 1960 are listed in Table 6.

Measurements of the signal-to-noise ratio in the audio band were made during many passes. After accounting for some residual noise in the audio output circuits, good agreement was obtained with the predicted values for all types of modulation used. The superiority of the FM over SSB or NBPM was clearly evident. The quality of voice or music using FM was excellent, and indistinguishable from that of a land-line circuit. With the successful demonstration of facsimile on later passes, it was concluded that: (1) the balloon, in conjunction with the existing terminal equipment at Holmdel and Goldstone Lake, provided an excellent circuit with the designed bandwidth of 200 to 3000 cps; and (2) any service that could be transmitted in this bandwidth could be handled equally well by the satellite circuit.

Table 6
Significant 1960 Project Echo Results

| Pass | Date | GMT | Event |
|---|---|---|---|
| 1 | 8/12 | 1140 | First demonstration of transmission via the balloon: President Eisenhower's message sent from JPL to BTL |
| 11 | 8/13 | 0705 | First two-way audio transmission between JPL and BTL: prerecorded messages of President Eisenhower and Senator L B. Johnson |
| 12 | 8/13 | 0911 | First two-way live voice: W. C. Jakes of BTL and P. Tardani of JPL talked briefly |
| 21 | 8/14 | 0233 | R. M. Page's message received with excellent quality from NRL |
| 23 | 8/14 | 0644 | Music sent from BTL to JPL |
| 24 | 8/14 | 0850 | Double bounce of live voice: NRL to BTL to JPL |
| 33 | 8/15 | 0212 | Two-way live voice with JPL using standard outside telephone lines connected to the satellite circuit |
| 35 | 8/15 | 0623 | SSB with JPL |
| 60 | 8/17 | 0744 | NBPM with JPL |
| 70 | 8/18 | 0311 | F. R. Kappel, L. Dubridge, and J. B. Fisk talked between California and the East Coast via the satellite |
| 503 | 9/22 | 1541 | Demonstration of facsimile picture transmission from NRL |
| 1097 | 11/10 | 0703 | Reception of speed mail from NRL by facsimile |

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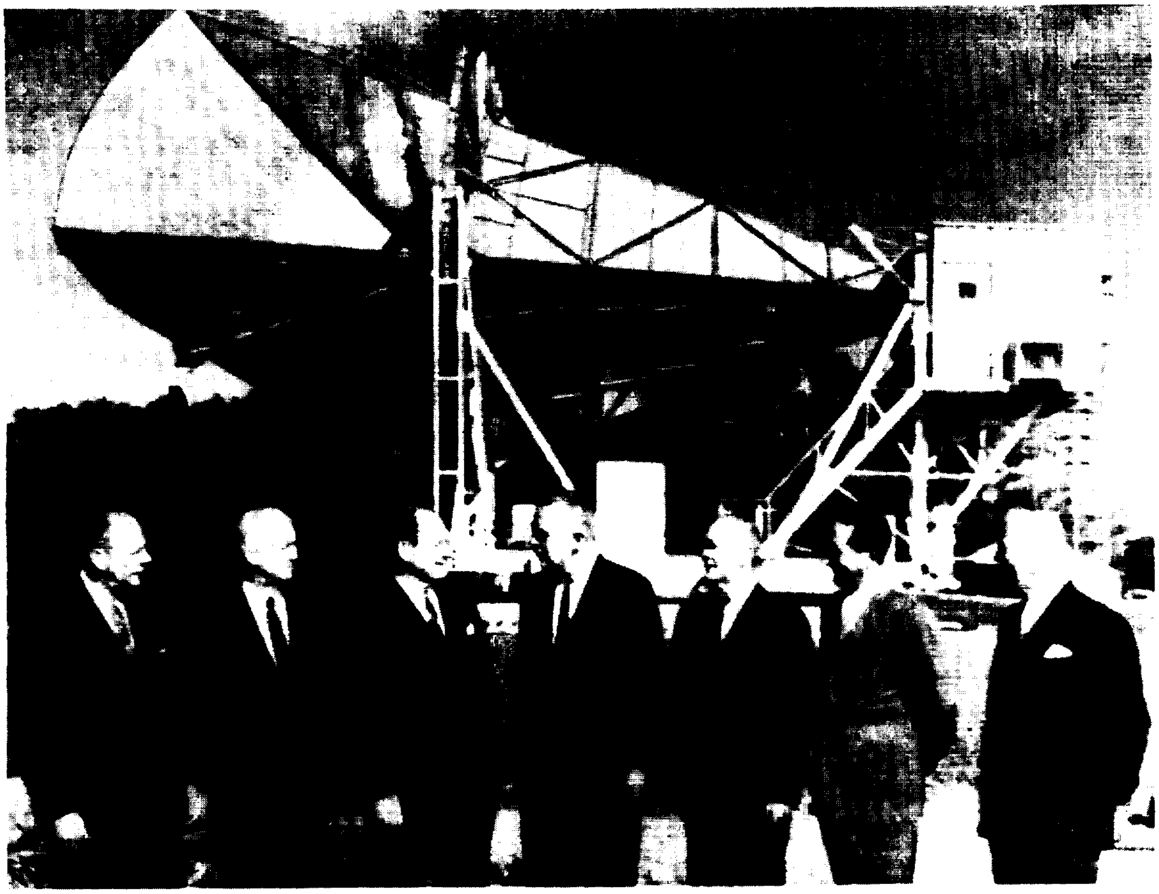

Figure 6 — Reproduction of the facsimile sent from Stump Neck to Holmdel on September 22, 1960. Shown, left to right, are Commissioners John S. Cross and Rosel H. Hyde of the Federal Communications Commission; T. Keith Glennan of the National Aeronautics and Space Administration; Frederick W. Ford, FCC Chairman; and Commissioners Robert T. Bartley, Robert E. Lee, and T. A. M. Cravan

## Balloon Scattering Cross Section

Measurements of the actual received power from the balloon were made during all passes worked, and data are available for at least one or more of the following modes of transmission on each pass:

JPL to BTL at 2390 Mc;

BTL to JPL at 960 Mc;

NRL to BTL at 2390 Mc;

BTL to BTL at 961 Mc (BTL radar).

By comparing these measurements with theoretical values, an estimate may be made of the average scattering cross section of the balloon and its variation with time. The received power may be calculated from the usual free-space transmission formulas (Reference 2), provided that the system parameters (such as transmitted power, antenna gain, slant range to the balloon, frequency, and effective scattering cross section of the balloon) are known.



There are a few additional factors that must be taken into account before comparison with the observed data can be made. Obviously, if either of the two antennas involved in a transmission path is not properly aimed at the satellite, the full antenna gain will not be realized. In this case it must be determined where the antenna actually was aimed, using boresight camera data or a comparison of positional recordings with the predictions, and allowance must be made in accordance with the antenna patterns.

A factor which becomes important at low elevation angles is power absorption by the atmosphere. This effect has been calculated (Reference 14), and the curves of Figure 7 show the variation in one-way loss with elevation angle and frequency. Since the antenna elevation angle at each end of the path is known, the loss can be evaluated and included.

Normally, the effects of atmospheric refraction would not be involved, since the antennas either were tracked by optics or radar, in which case refraction would be automatically compensated, or by predictions that would include this effect. Through a programming error, however, the drive tapes before October 6, 1960, included a refraction correction in the wrong sense. The error was rectified and proper corrections made after that date. The only antenna appreciably affected was the Stump Neck 60-foot dish, since the Holmdel antennas had comparatively wide beams, and the Goldstone Lake antennas were almost always tracked by radar or optics. Assuming a reasonable pattern for the Stump Neck 60-foot dish at 2390 Mc (no measured patterns were available) and a standard atmosphere, the calculated received power levels were appropriately modified by using the correction curves shown in Figure 8, if optical corrections were not being used by Stump Neck at the time.

Records of transmitted power were kept at all stations, and were reasonably complete over all passes worked. Nominally Goldstone Lake radiated 9 kw at 2390 Mc, Stump Neck radiated 9 kw, and Holmdel radiated a total of 10 kw at 960 Mc — the power being split between the communications channel and the radar channel, as described earlier. All of these records were made available so that the appropriate corrections could be made.

Comparison of actual received power with that predicted has been made on 96 passes. For each pass studied, the predicted receiver power was computed for one-minute intervals in time and plotted on the actual records. In general, it was found that the observed values differed from the predicted by an approximately constant factor during the significant part of each pass, so that a single number, expressed in db, served to characterize

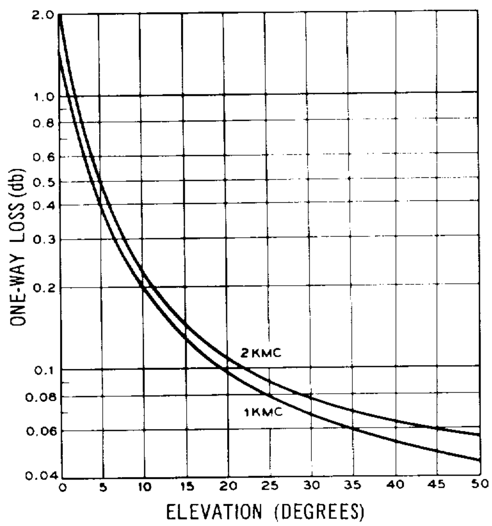


Figure 7 — Absorption due to atmospheric oxygen and water vapor

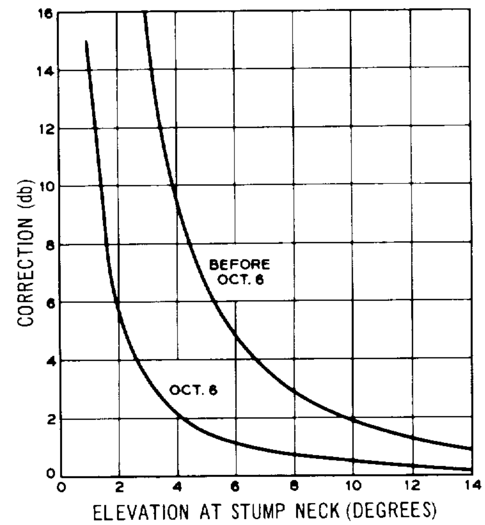


Figure 8 — Correction curves for refraction at Stump Neck (NRL)

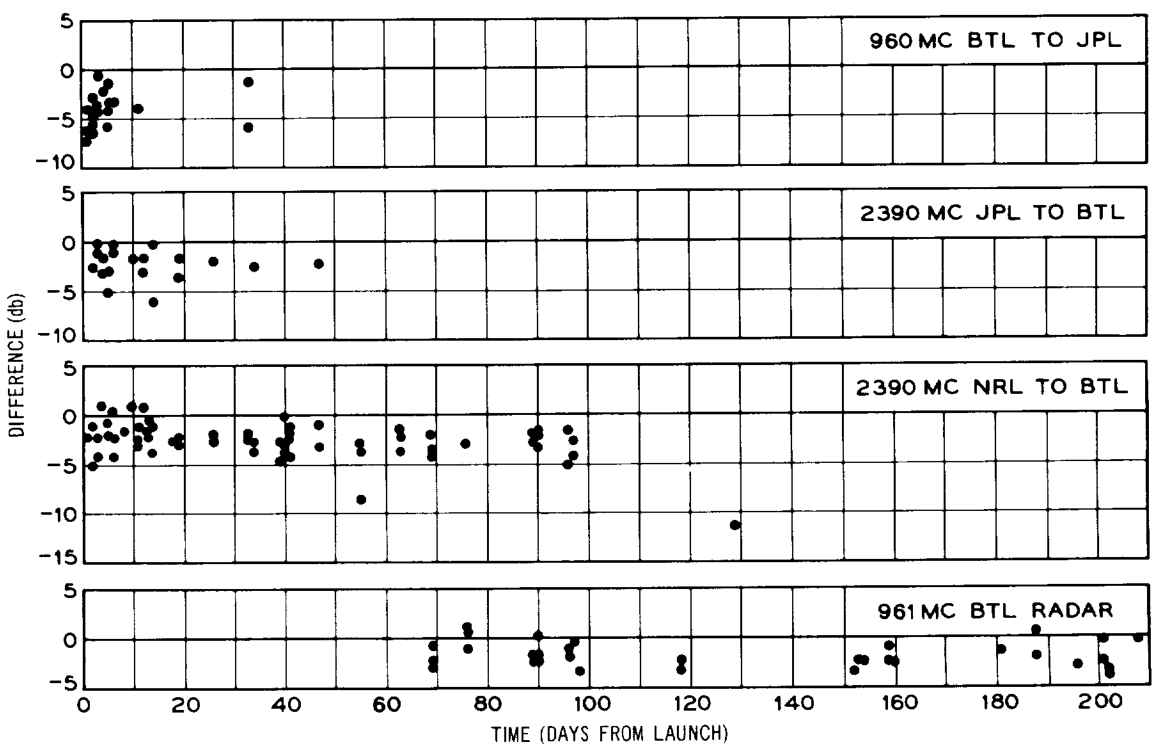


Figure 9 — Difference in decibels between predicted and observed signal power

the difference (Figure 9). Figure 9 contains the plots of these points as a function of time from launch and transmission mode, each point representing one pass. In all cases, attempts were made to correct for atmospheric loss, transmitter power, and atmospheric refraction, where necessary. However, errors in pointing were not accounted for in all cases.



The Goldstone Lake antennas were almost always pointed very accurately at the balloon by their radar or optics, as evidenced by boresight camera pictures and examination of a few angular read-outs. Occasional pointing errors were mostly due to momentary loss of radar lock and could be identified as such and subsequently ignored. Pointing of the Holmdel antennas was good for the same reasons; again, the occasional errors in pointing were obvious and could be ignored. No pointing data were available from the Stump Neck antenna, so it had to be assumed that the drive tapes were accurate or that optical corrections were being used.

It is felt that the most significant data were obtained from the Goldstone Lake-Holmdel transmissions at 2390 Mc. This path involved the fewest unknowns and had the most accurately calibrated receiver. From the plot in Figure 9, it can be seen that on several passes the received signal power was equal to that predicted for reflection from a perfectly conducting 100-foot sphere. On the basis of these data alone, it can be assumed that a successful inflation of Echo I was achieved.

The data for the 960-Mc Holmdel-Goldstone Lake transmissions show a much greater spread between predicted and observed values. This may be in large part attributed to the fact that the Goldstone Lake 960-Mc receiver was usually calibrated only once before a series of passes which might take four hours or more, and during this time calibration drifts were inevitable. The Holmdel 2390-Mc receiver was completely calibrated before and after every pass. There is also some uncertainty about the gain of the Goldstone Lake receiving dish at 960 Mc, since it was equipped with a rather complicated dual-frequency feed and there was not enough time to measure the gain accurately.

Although there was no time before launch of Echo I to determine accurately the antenna gain or transmission-line loss for the Stump Neck transmitting dish, the use of the estimated values showed good agreement with theory on a number of passes. The spread of values of the difference between observed and predicted power was essentially the same over both 2390-Mc paths.

The Holmdel radar did not become useful for scattering cross-section measurements until about two months after the launch. Since January 1, 1961, it has been the only source of such data, and is probably accurate to ±1.5 db. These data indicate that, as of March 1, 1961, Echo I was probably an approximately spherical object with a diameter of not less than 70 feet and a somewhat wrinkled skin. However, there may be a few flattened areas, as indicated by a rare deep fade in the Holmdel radar signal.

## Transmission at 2390 Mc

A four-pen Sanborn recorder was used at BTL during the Echo experiment to record the incoming signals and the system noise temperature, as described earlier. Samples of these records, taken during certain passes of particular interest, are shown in Figures 10 through 21 and described in the following sections.

Pass 1 (Figure 10):

This was the first passage of the balloon over the United States following its launch from Cape Canaveral, Florida. As shown by the record, a signal was received from Goldstone Lake for three periods of one to three minutes duration. The gaps in reception were due to incorrect data points on the drive tape, which caused the antennas to slew away from the satellite track and drop out of servo lock. There was no optical visibility at Holmdel during this pass, and, since the Holmdel radar was still unproven, tracking was accomplished by inserting angular offsets to maximize the output meter of the 2390-Mc receiver. The drive tape used was supplied prior to the launch and corresponded to one of the nominal trajectories, with reference time appropriately adjusted to correspond to that of the launch. If the launching had not been virtually perfect, there would have been no reception at all on the first pass because of the severe acquisition problem. The upper record in Figure 10 shows the variation of the direct polarization component (counter-clockwise) with time, and the third record shows that of the cross-polarized (clockwise) component. Also plotted are the computed values of received power, assuming perfect pointing and a fully inflated, perfectly reflecting balloon. The cross-polarized component was calculated assuming only the ellipticities of the Goldstone Lake dish and Holmdel horn to be effective in producing this component, i.e., no allowance was made for Faraday rotation or any other possible effects in the transmission path, such as a distorted balloon. These ellipticities are known to be about 1.2 db for each antenna (although there is some evidence that the Holmdel horn ellipticity may be less), or a maximum/minimum axial ratio $e = 1.155$. The maximum value of the cross-polarized component is then

$$E = \frac{e^2 - 1}{e^2 + 1} = 0.142,$$

or 17 db less than the direct component.

The differences between the observed and calculated signal level of the direct component may be entirely accounted for, during the second and third periods of reception,

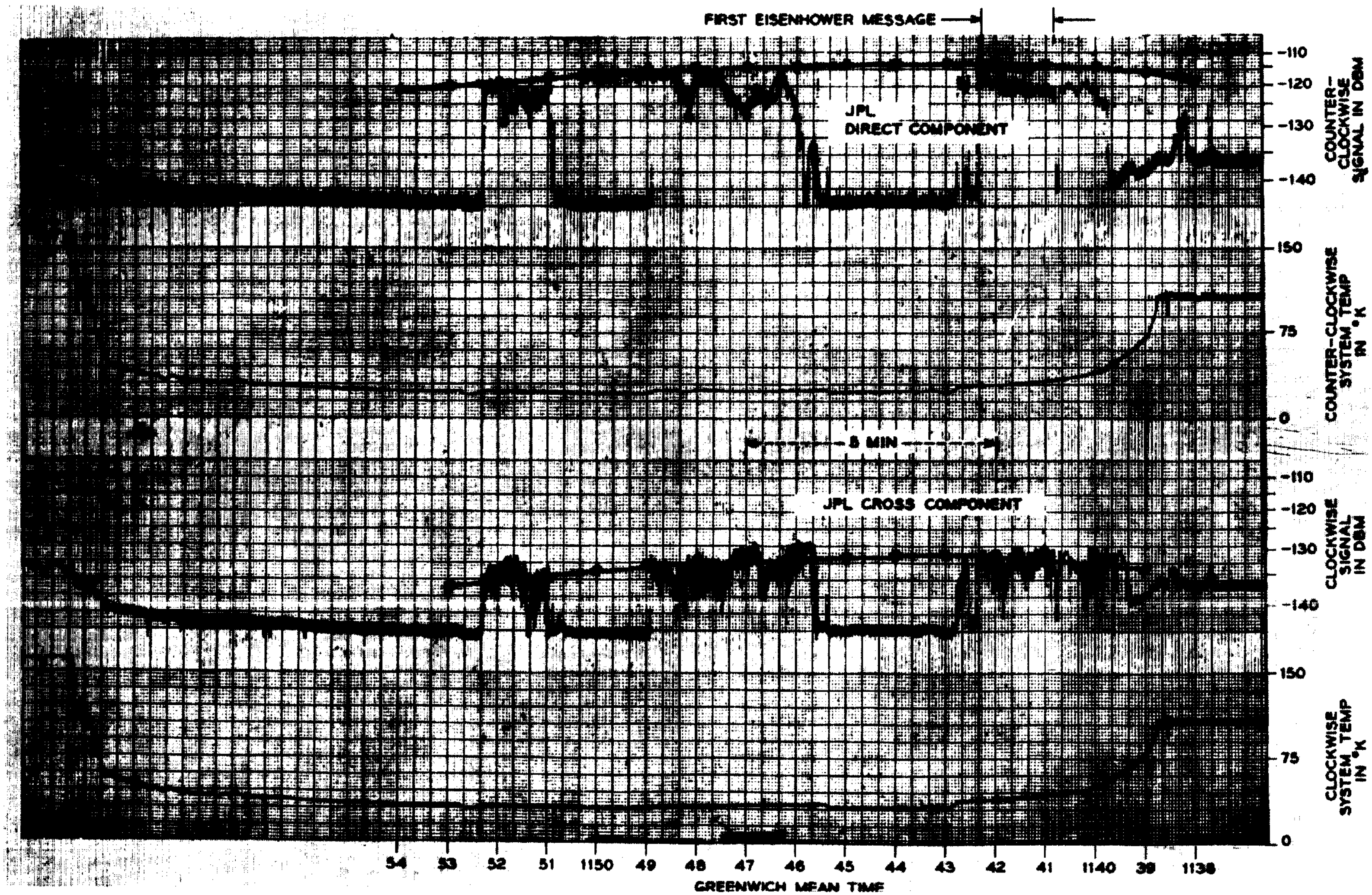


Figure 10 — First pass of Echo I (August 12, 1960)

by the errors in pointing the Holmdel horn. These were established by comparison of the horn angular recordings with the predicted values obtained from a later, more accurate determination of the orbit. The Goldstone Lake antenna was in smooth, accurate track during these two periods, according to a similar comparison. The corrected values of calculated level, taking these pointing errors into account, are shown as small circles in Figure 10 and the excellent agreement is obvious. Accurate read-out data for the Holmdel horn were only available for the last minute of the first period (due to a momentary failure of the data-recording camera); hence no corrected values are shown for the first period. There are indications, however, that pointing inaccuracies of both the Holmdel horn and the Goldstone Lake dish were responsible for the difference between calculated and observed level during this time.

About one minute after initial reception, word was passed to Goldstone Lake to start modulation; President Eisenhower's message was then successfully transmitted in its entirety, and was repeated during the second and third periods. Modulation shows up on the record as small, dense scintillations superimposed on the larger average variations.

During the 12 minutes of the pass the drive tape predictions were found to be in error by an amount varying progressively from +1 to -1 degree in elevation and from -1 to -3 degrees in azimuth. These errors were compensated by the insertion of angular offsets, as mentioned earlier.

The second and fourth tracks in Figure 10 show the variation in system noise temperature for each of the two receiving channels. Before the pass the noise was fairly high, since the horn was pointing almost at the horizon and received a large amount of thermal radiation from the ground and atmosphere. As the antenna moved up to follow the balloon, the temperature rapidly dropped, so that at 2.5 degrees elevation the temperature was down to 75° K. At 5 degrees it was 50° K, then it slowly decreased to its minimum value of about 25° K near the middle of the pass. The small irregularities in temperature during the pass correspond to the slewing of the antenna caused by bad data points.

Note that there are indications of signal reception starting shortly after 1138 GMT, before the antennas actually started tracking. This proved later to be a very common occurrence and is caused by atmospheric refraction.

Pass 70 (Figure 11):

This is probably the best example of a completely successful pass with both Goldstone Lake and Stump Neck by Holmdel. By this time the drive tape predictions were accurate to within a few tenths of a degree and personnel at all locations had become more proficient in tracking and station operation. The level of received signal from both

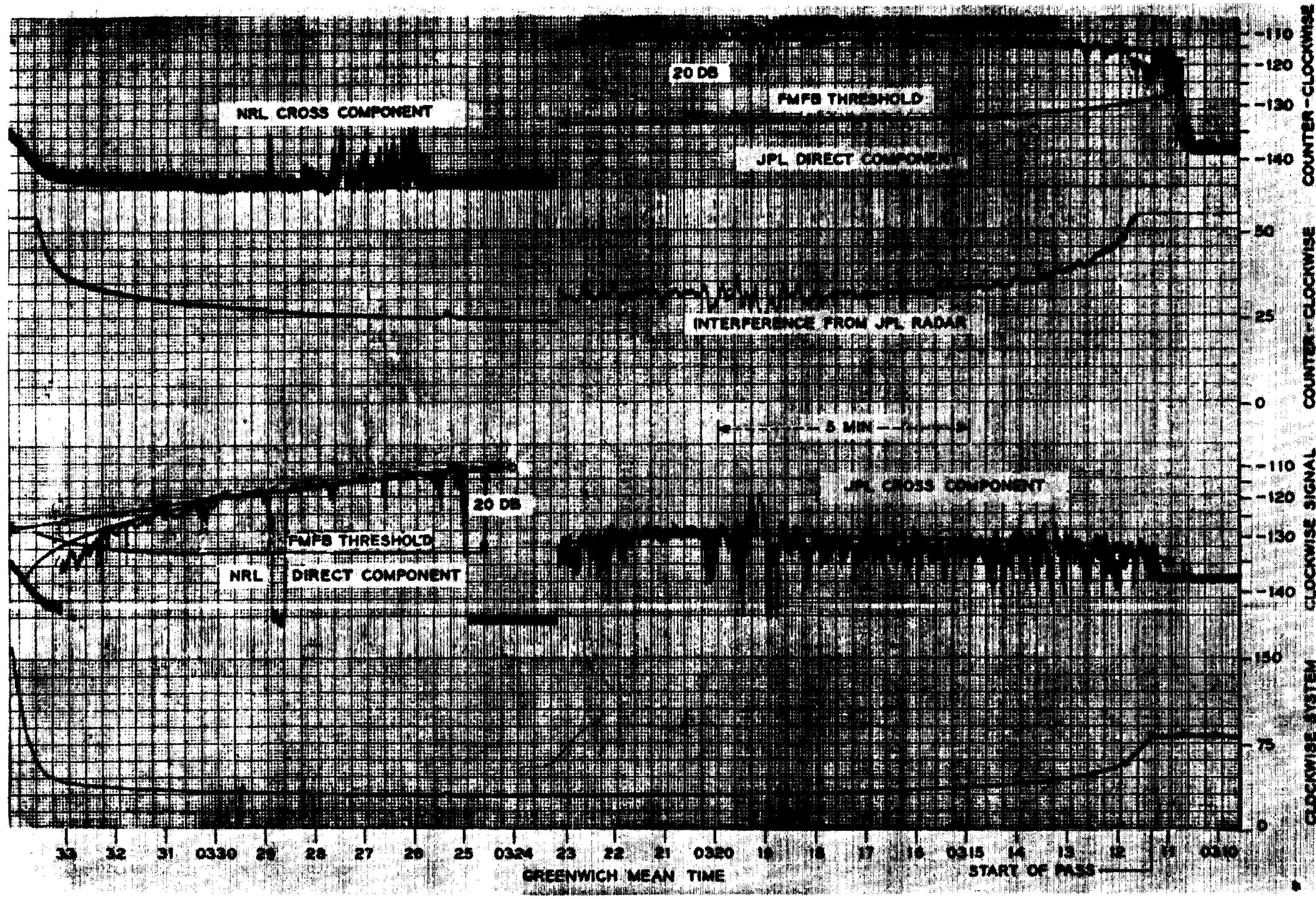


Figure 11 — Pass 70 — alternate reception from Goldstone Lake and Stump Neck (August 18, 1960)

JPL (upper record) and NRL (lower record) was in excellent agreement with theory almost throughout the pass. An interesting event occurred at 0319 GMT, when the direct signal component from Goldstone Lake showed a few fades while the character of the cross-polarized signal changed appreciably, resulting in increases at the exact times when the direct component was decreasing. Inspection of boresight camera data at Holmdel and pointing readout at Goldstone Lake showed that this could not be accounted for by pointing errors. System errors, such as momentary changes in transmitted power or receiver gain also were ruled out, since the same effect was observed at 960 Mc on the east-west path. It was not observed on the Goldstone Lake 2388-Mc radar, however, leading to the conclusion that either an airplane flew between the Holmdel site and the balloon, or the balloon had a large section of surface with anomalous curvature which was common to the Holmdel-Goldstone Lake path but not effective in the Goldstone Lake radar path. The included angle at the balloon between Goldstone Lake and Holmdel at that time was very nearly 90 degrees; thus, geometrically at least, the latter conclusion is tenable. It seems unlikely that an airplane could have been responsible, since the effect lasted about 45 seconds and the Holmdel antenna beam was at an elevation angle of 38 degrees at the time. It is difficult to imagine a possible airplane trajectory that would keep it in the beam for this long. In addition, it would be expected that the lights on the airplane would appear in the boresight camera film, and this did not happen. The conclusion, then, is that the balloon very likely had a deformity at this time.

The theoretical curve for Stump Neck at the end of the pass (circled points) assumes refraction corrections were properly inserted. Assuming that the pointing data provided to Stump Neck had corrections put in with the wrong sign, the smooth curve below was obtained using the corrections from Figure 8, which obviously is in better agreement with the observations.

The apparent agreement of the cross-polarized signal with theory tends to support the conclusion that there is no strong mechanism in the transmission path to produce birefringence at this frequency. No curve is plotted for the Stump Neck cross component, since no data were available on the ellipticity of the Stump Neck dish. It appears to be of a lower value than Goldstone Lake, however.

The odd appearance of the counter-clockwise system temperature record was traced to a spurious harmonic from the Goldstone Lake radar transmitter. This harmonic was produced by slight nonlinearity effects.

The value of the incoming carrier level corresponding to the break point of the FM system is shown on the records as "FM threshold," Note that good voice communication was possible during almost the entire pass.

Pass 119 (Figure 12):

The helium transfer process at Holmdel failed shortly before the pass, preventing operation with the maser. The standby parametric amplifiers were connected in place of the maser, allowing operation with about 10 db less signal-to-noise ratio. This can be clearly seen from the record, although the signal was still above the FM threshold for a good portion of the pass. Goldstone Lake was received briefly, and then Stump Neck. Note again the good agreement between calculated and observed signal levels, including also the refraction correction at the end of the pass.

Pass 156 (Figure 13):

Only Stump Neck was received on this pass. It is noteworthy because this was the first time that an eclipse of the balloon occurred during a pass, as noted at 0503:20 GMT. This was actually the tenth eclipse of the balloon. About 40 seconds later, at 0504, the signal began a strikingly periodic variation of ±2 db amplitude and 6 seconds period, which disappeared at 0506. This had never been seen before and at the time was attributed to changes in environment associated with the eclipse. These periodic scintillations have since been observed from time to time, but there has not been any observable correlation between their onset and eclipses. Many hypotheses have been advanced to account for them, but as yet no data exist to determine the mechanism.

Comparison of signal level with the calculated curve shows that the average cross section is apparently less than nominal. Occasional signal peaks rise slightly above the theoretical curve. This is significant, and is consistent with a hypothesis of a balloon not fully distended, so areas of much greater radius of curvature can develop. It should be noted that the balloon was predicted to lose positive gas pressure around this time.

Pass 169 (Figure 14):

On this pass Goldstone Lake and Stump Neck were simultaneously received by Holmdel for about eight minutes in an attempt to determine whether the different geometry involved in the transmission paths would have any bearing on the received signal levels. The results are consistent with a balloon that is more or less randomly deformed from its original spherical shape. Note that the Goldstone Lake signal was in better agreement with the calculated values than that from Stump Neck. This was because the satellite eclipsed, and optical tracking could not be maintained by Stump Neck throughout the pass.

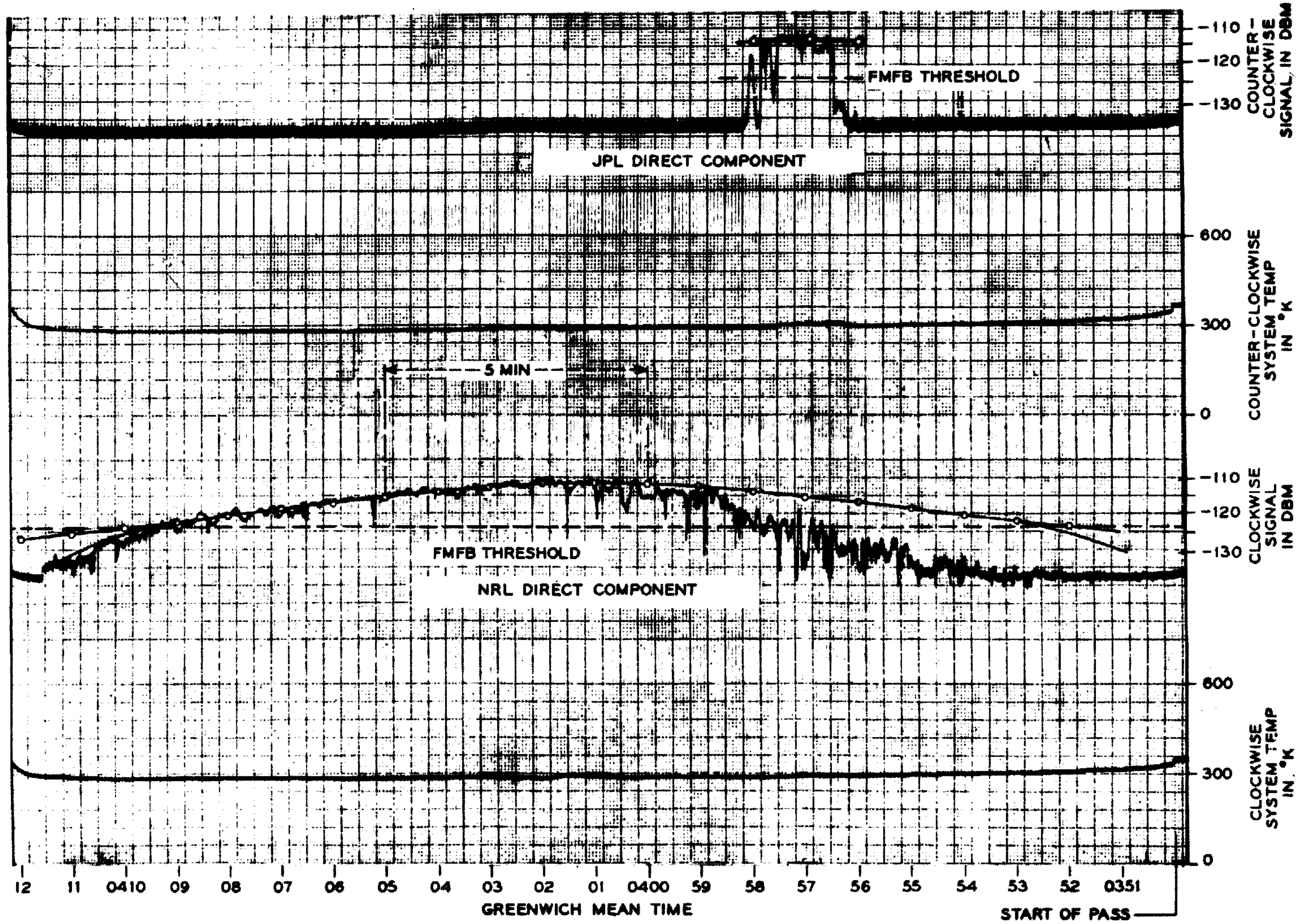


Figure 12 — Pass 119 — parametric amplifiers used instead of maser (August 22, 1960)

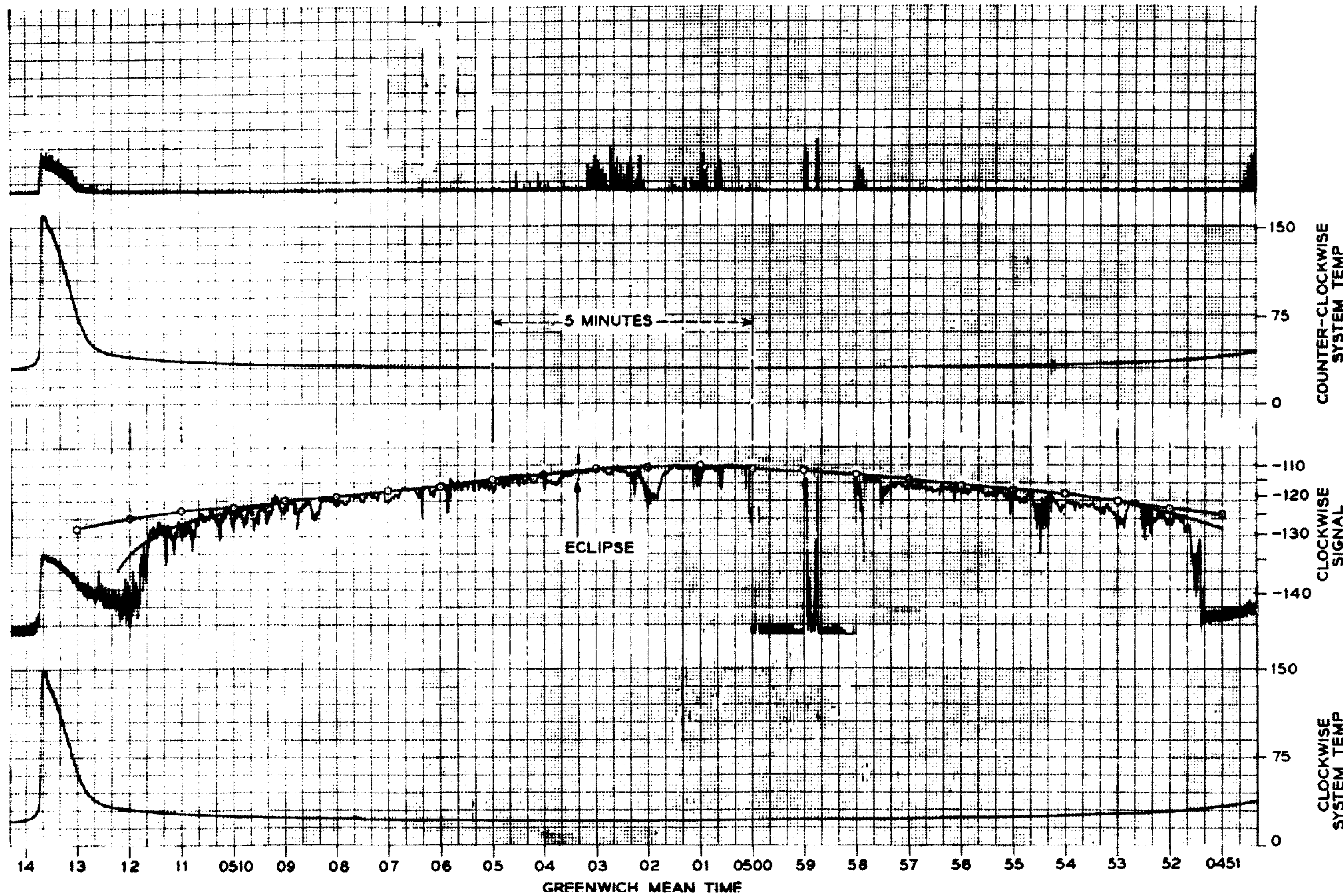


Figure 13 — Pass 156 — tenth eclipse, reception from Stump Neck only (August 25, 1960)

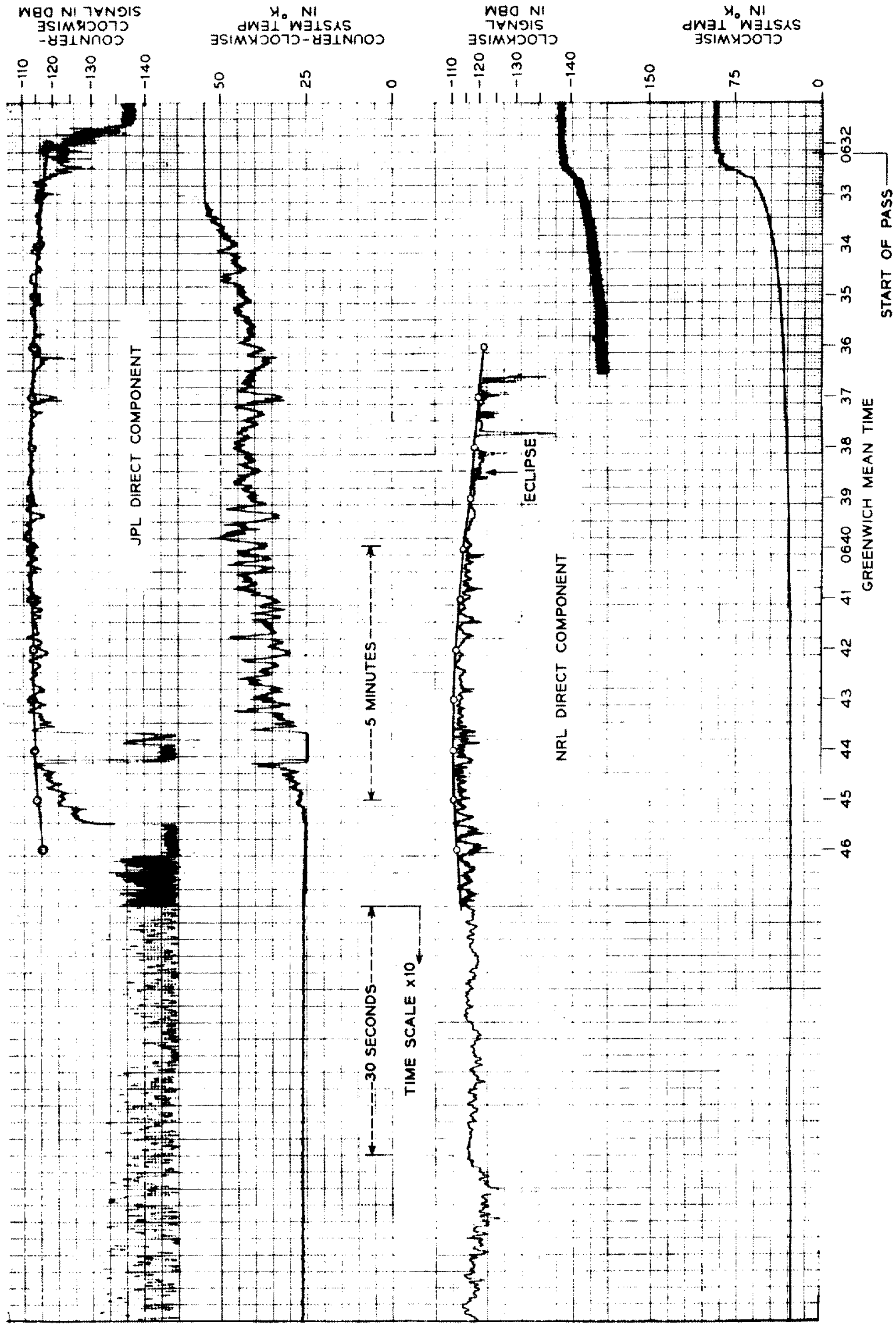


Figure 14 — Pass 169 — simultaneous reception from Stump Neck and Goldstone Lake (August 26, 1960)

Pass 229 (Figure 15):

The operations on this pass were similar to those on pass 70. The average balloon cross section is still apparently within a few db of the theoretical value, although the effects of shrinking have become more pronounced, as shown by the increased scintillations of the received signal.



An eclipse occurred at 0450:30 with no observable effect, except that the Goldstone Lake signal gradually decreased. It was later discovered that Goldstone Lake lost radar track at 0448 and reverted to the drive tape at that time The small error in the tape must have slowly moved the Goldstone Lake antenna away from the balloon, causing the loss in signal strength. The cross-polarized signal level from Goldstone Lake was still no higher than the nominal computed value.

Pass 411 (Figure 16):

This was the last pass during which Holmdel received Goldstone Lake. Note the increased scintillations of both the Goldstone Lake and Stump Neck signals, and also the apparent loss in average cross section. The cross-polarized component is again close to its theoretical value, although it is somewhat lower, on the average, than for earlier passes.

Pass 503 (Figure 17):

During this pass the Stump Neck signal was switched to the upper record when facsimile transmission was demonstrated from Stump Neck to Holmdel (Figure 6) with excellent results. Goddard Space Flight Center took special care with the drive tapes for this event, and optical checks at Holmdel showed the predictions to be accurate within $\pm 0.1^\circ$. This was one of the first passes during which it was discovered that the balloon could be seen in broad daylight with the M-33 optics. The air was exceptionally clear, however.

In spite of the good tracking at both stations, the signals still showed appreciable scintillations, and especially noteworthy are the strikingly periodic variations from 1546 to 1551 GMT. Also significant is the fact that the signal exceeded the theoretical value many times, sometimes by as much as 5 db. The only explanation for this that has been advanced requires the balloon surface to have one or more large flat areas.

The several small humps in the two system temperature records between 1552 and 1556 GMT probably resulted because the side lobes of the horn were looking at the sun.

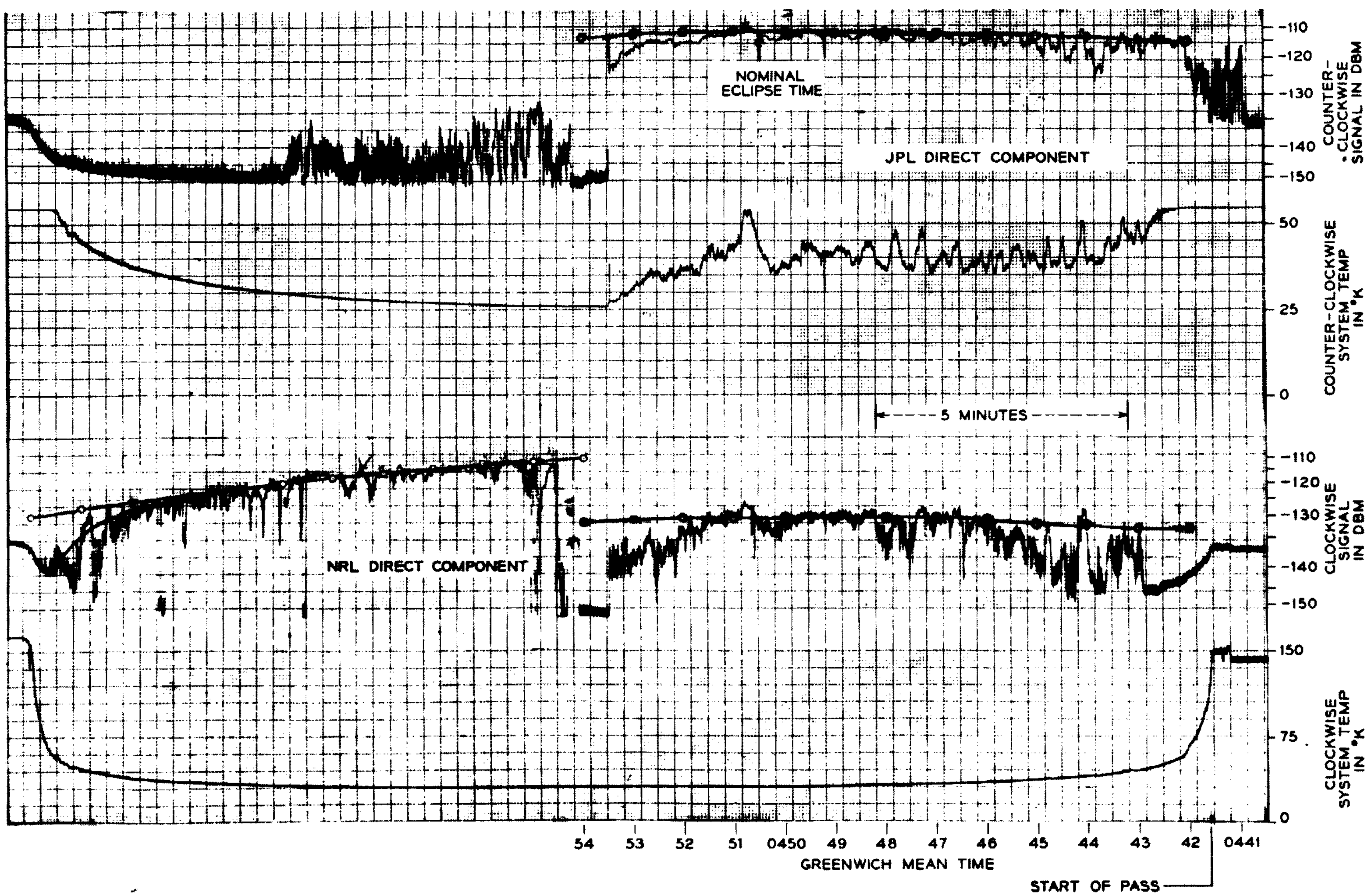


Figure 15 — Pass 229 — typical scintillations (August 31, 1960)

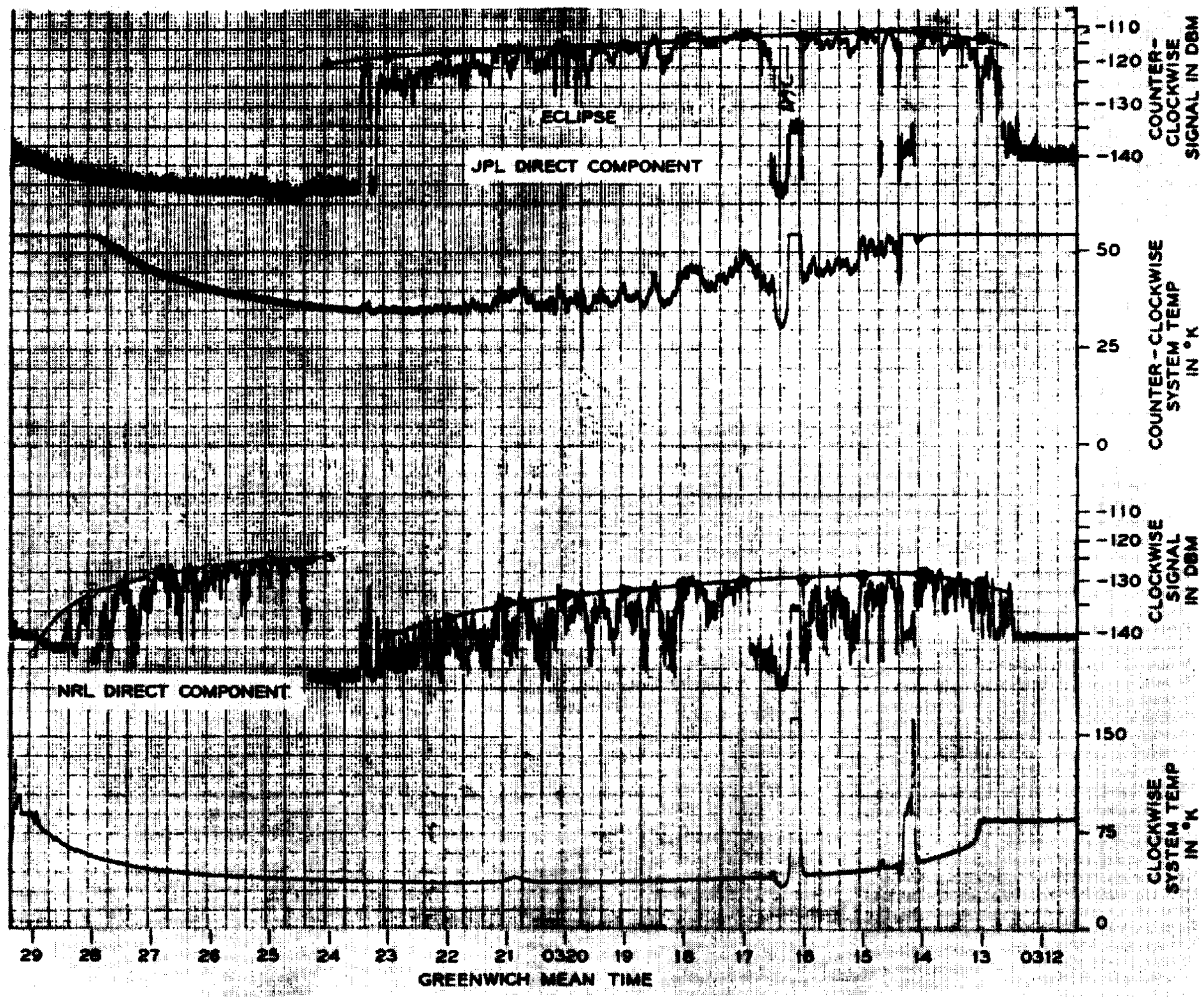


Figure 16 — Pass 411 — last operation with Goldstone Lake (September 15, 1960)

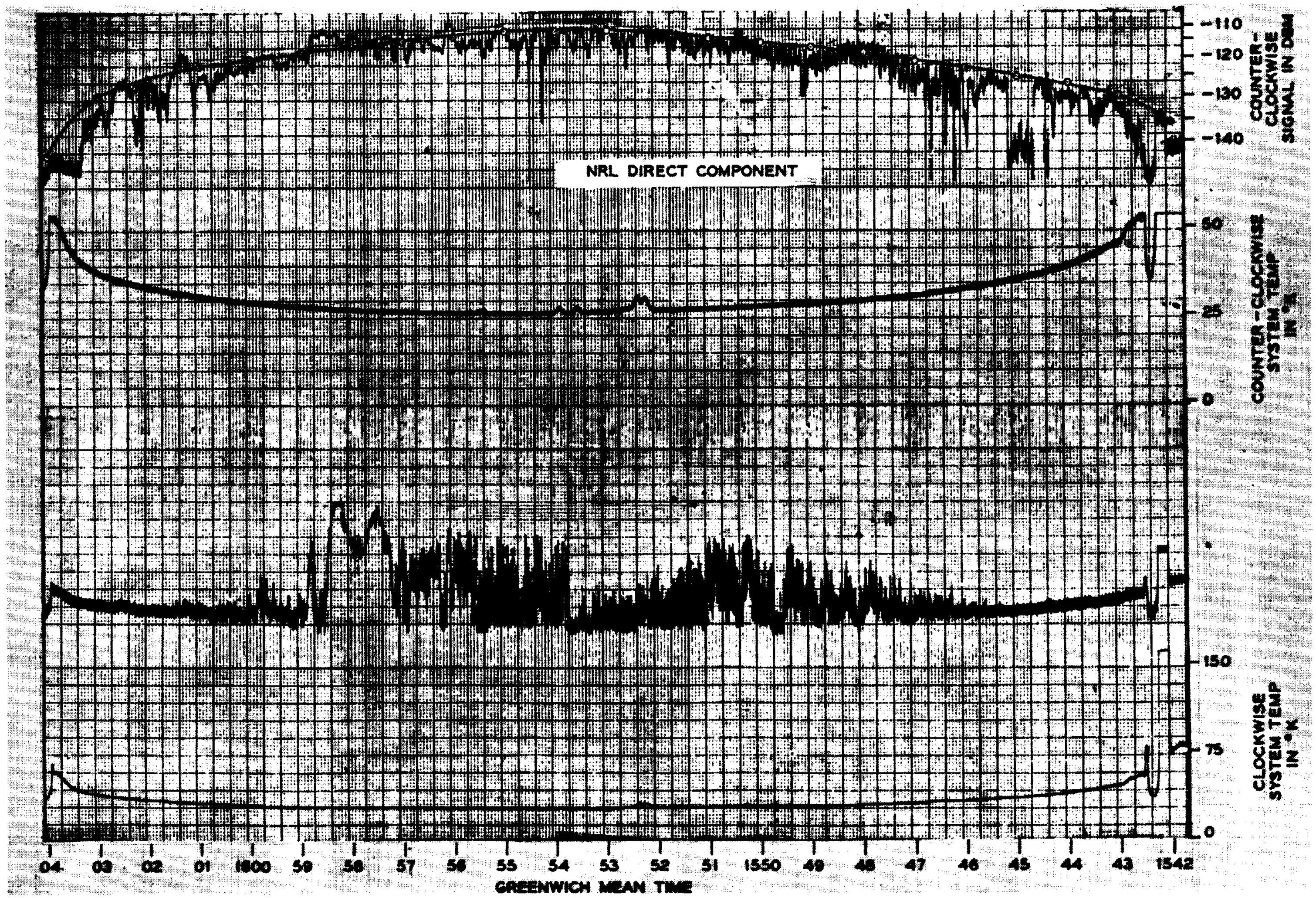


Figure 17— Pass 503 — facsimile reception from Stump Neck (September 22, 1960)

Pass 674 (Figure 18):

This is another example of the periodic scintillations observed before. The general character of the signal is very similar to that of pass 503, although the fading range seems to have increased.

Pass 842 (Figure 19):

It is apparent that the drive tapes for this pass were somewhat in error. The satellite was obscured at Stump Neck, preventing optical tracking; and thus, in an effort to improve the pointing there, Stump Neck inserted small angular offsets from time to time. The rather deep fading that is shown by the graph is probably due more to the tracking difficulties than to effects from the satellite itself.

The balloon was in complete sunlight throughout passes 674 and 842; so there is no apparent correlation between an eclipse and the onset of the periodic scintillations.

Pass 1086 (Figure 20):

The balloon was in eclipse until 0943:40, when the signal reception from Stump Neck improved immediately, since optical tracking aids could then be employed. Scintillations were still heavy, but the general character of the signal was not as bad as on some previous passes. The odd performance of the cross-polarized signal record was due to Holmdel equipment troubles in that channel.

Pass 1192 (Figure 21):

On this pass, Holmdel and Stump Neck used optical offsets to the drive tape from 0107 to 0116 GMT, at which time the balloon eclipsed and there was virtually no reception. Scintillations were not too severe, and were of a somewhat different periodic nature than before.

## Transmission at 960 Mc

Transmission to Goldstone Lake was attempted on the first pass of Echo, but results were marginal and no modulation was received. Apparently a combination of bad data points on the drive tape caused the Holmdel dish to slew off course; and low gain in one of the dish servo control amplifiers resulted in a sluggish return to the track after the bad data point had passed. The low gain evidently developed shortly before the pass,

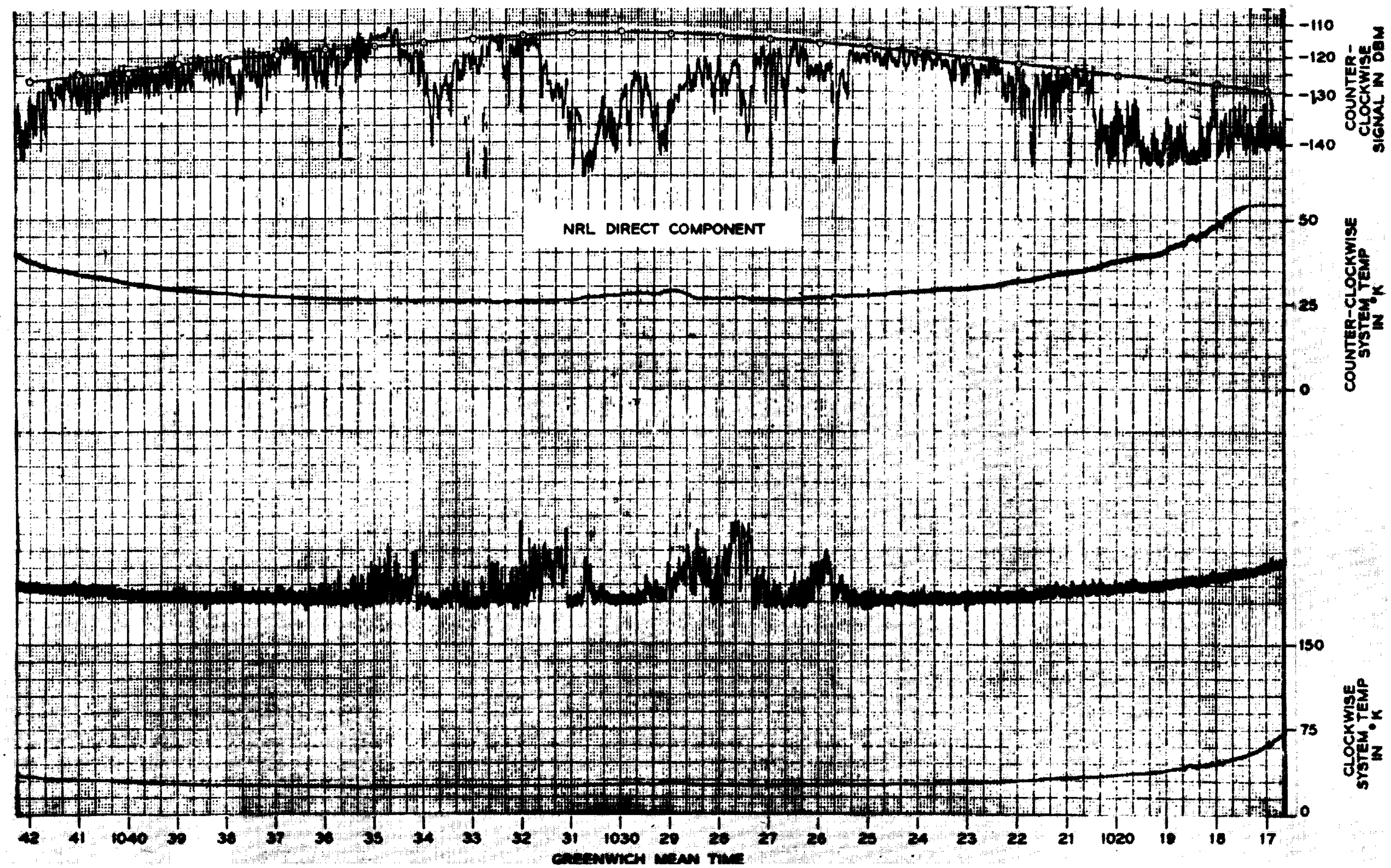


Figure 18 — Pass 674 — periodic scintillations (October 6, 1960)

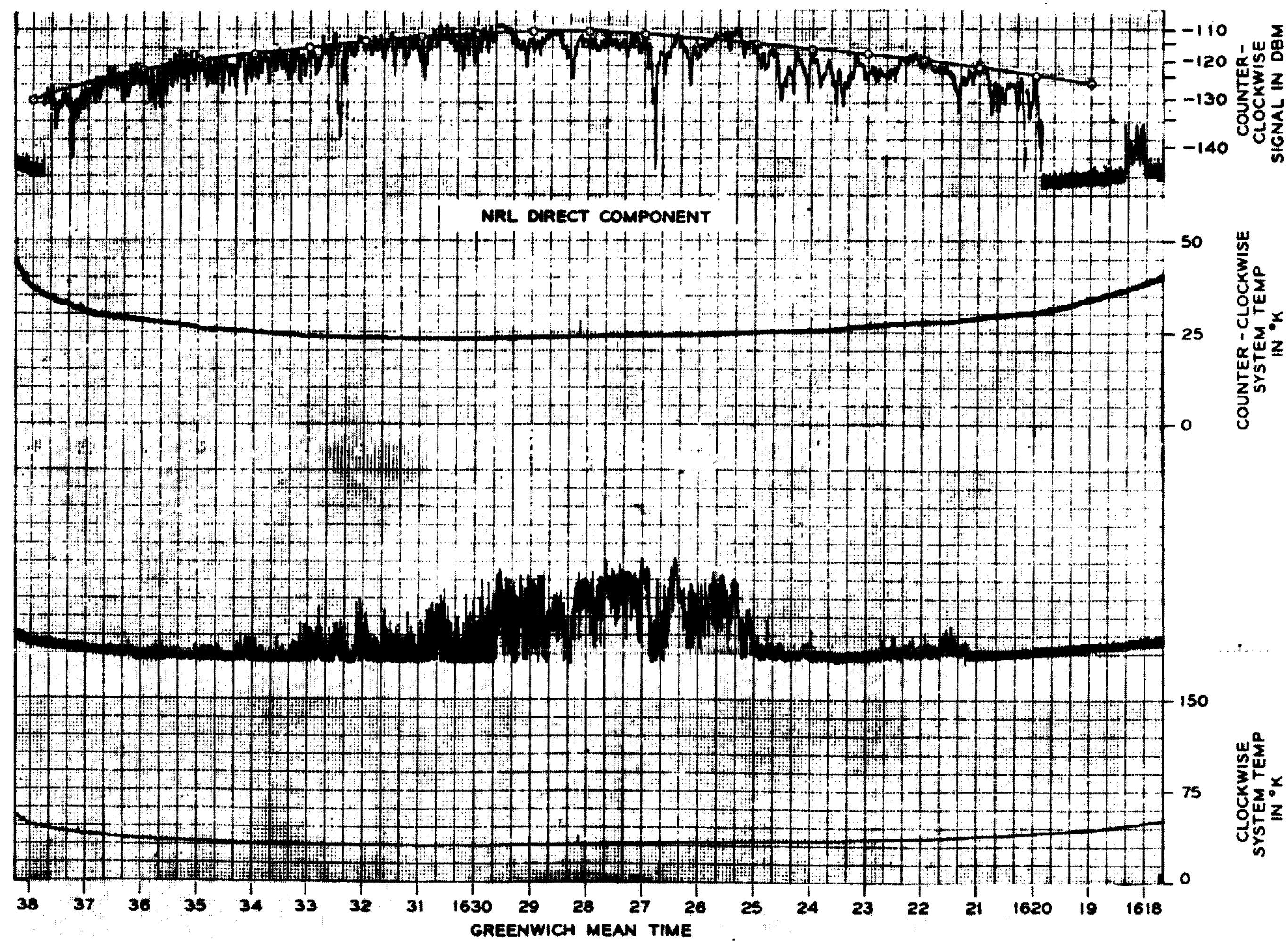


Figure 19 — Pass 842 — periodic scintillations (October 20, 1960). Drive tapes for this pass were somewhat in error

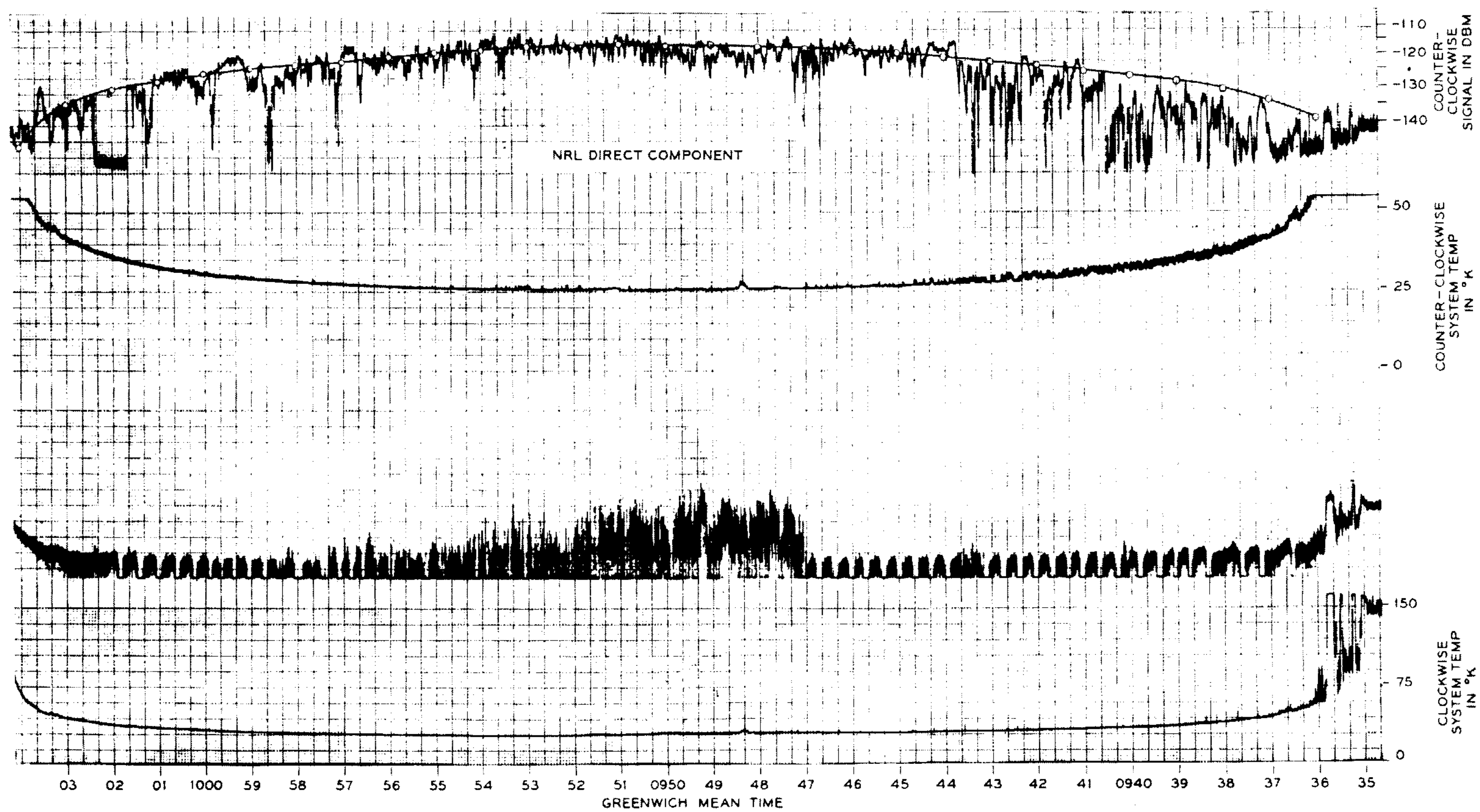


Figure 20 — Pass 1086 (November 9, 1960)

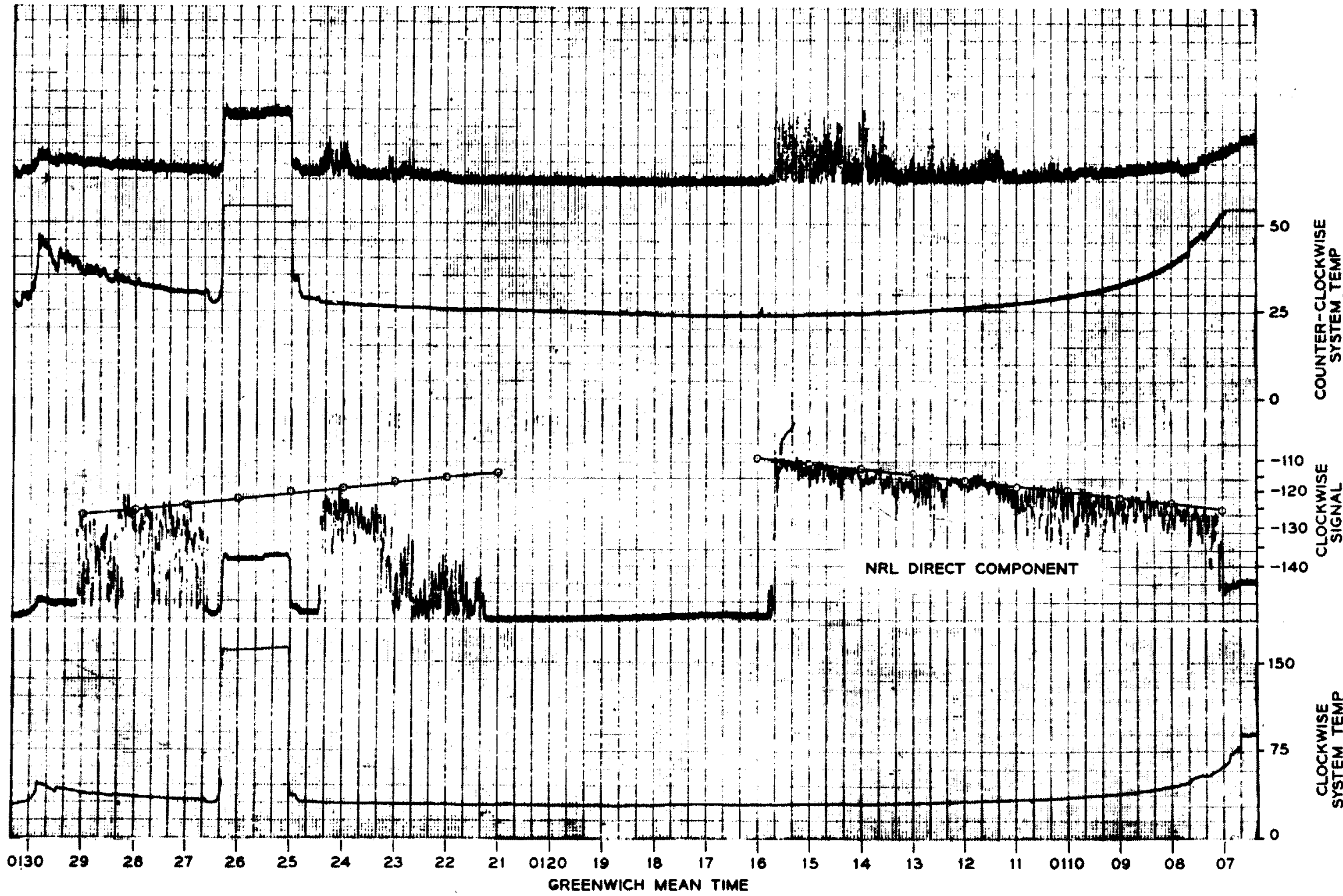


Figure 21 — Pass 1192 (November 18, 1960)

since earlier checks had shown normal performance. The net result was that the dish was in smooth track only for the brief durations indicated in Table 7. These times were determined by comparison of the dish read-out records with the true orbit.

Table 7
Times Holmdel Dish was in Smooth Track During First Echo I Pass

| Time of Start (GMT) | Duration (seconds) |
|---|---|
| 1142:29 | 15 |
| 1145:04 | 32 |
| 1145:44 | 30 |
| 1146:46 | 126 |
| 1150:00 | 16 |
| 1151:40 | 70 |

During these periods the Holmdel dish pointing accuracy was no better than that of the horn, since both were receiving the same angular offsets. The 2390-Mc received signal record shows that the average level was down some 8 to 10 db, and approximately the same numbers would then apply to the dish. This means that the level of the available signal at Goldstone Lake was probably no better than -123 dbm, which is significantly below the FM threshold, and therefore accounts for the poor results.

Out of 27 remaining passes when successful transmission took place from Holmdel to Goldstone Lake at 960 Mc, a total of 18 resulted in usable signal recordings at Goldstone Lake. Fifteen of these have been copied and are shown in Figures 22 and 23, along with the theoretically computed values. This series of passes covers the first 11 days after launch, and it is quite evident from the steady signals that tracking was generally excellent and that the balloon had a fairly smooth surface. As mentioned before, the apparent discrepancy between the observed and calculated levels of signal strength may have been caused by the uncertainties in receiver calibration and antenna gain.

Note the dip in level at 0319 GMT on pass 70; this corresponds to the dip noticed at the same time on the 2390 Mc records.

## Doppler Shift

The variation of received frequency with time on two selected passes is plotted in Figures 24 and 25, together with the computed curves. These were all taken at 2390 Mc, where the Doppler shift is:

$$\Delta f = -7.97\,(v_1 + v_2)\ \text{cps},$$

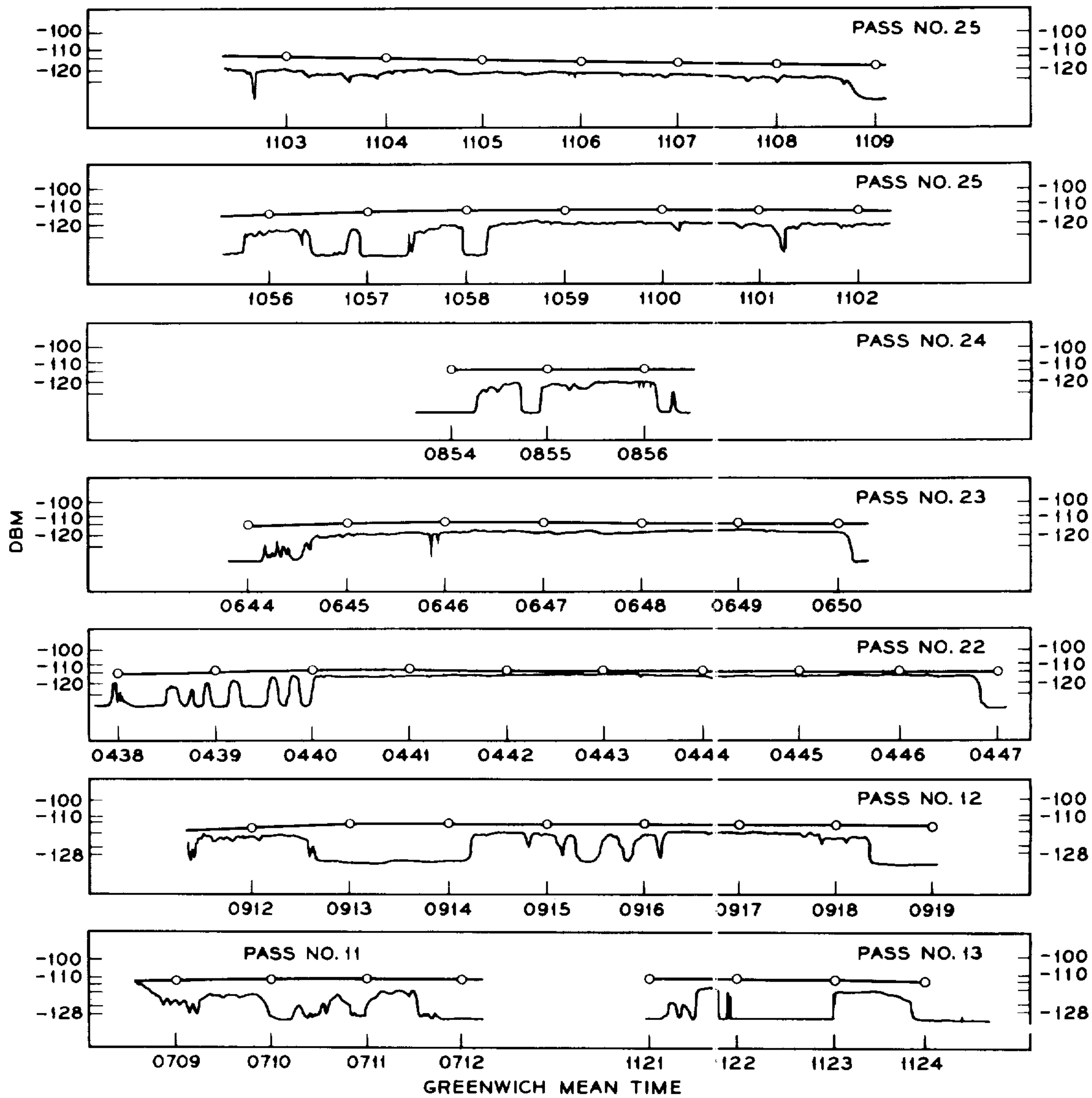


Figure 22 — Variation of power received by Goldstone Lake for various passes at 960 Mc

D-1127

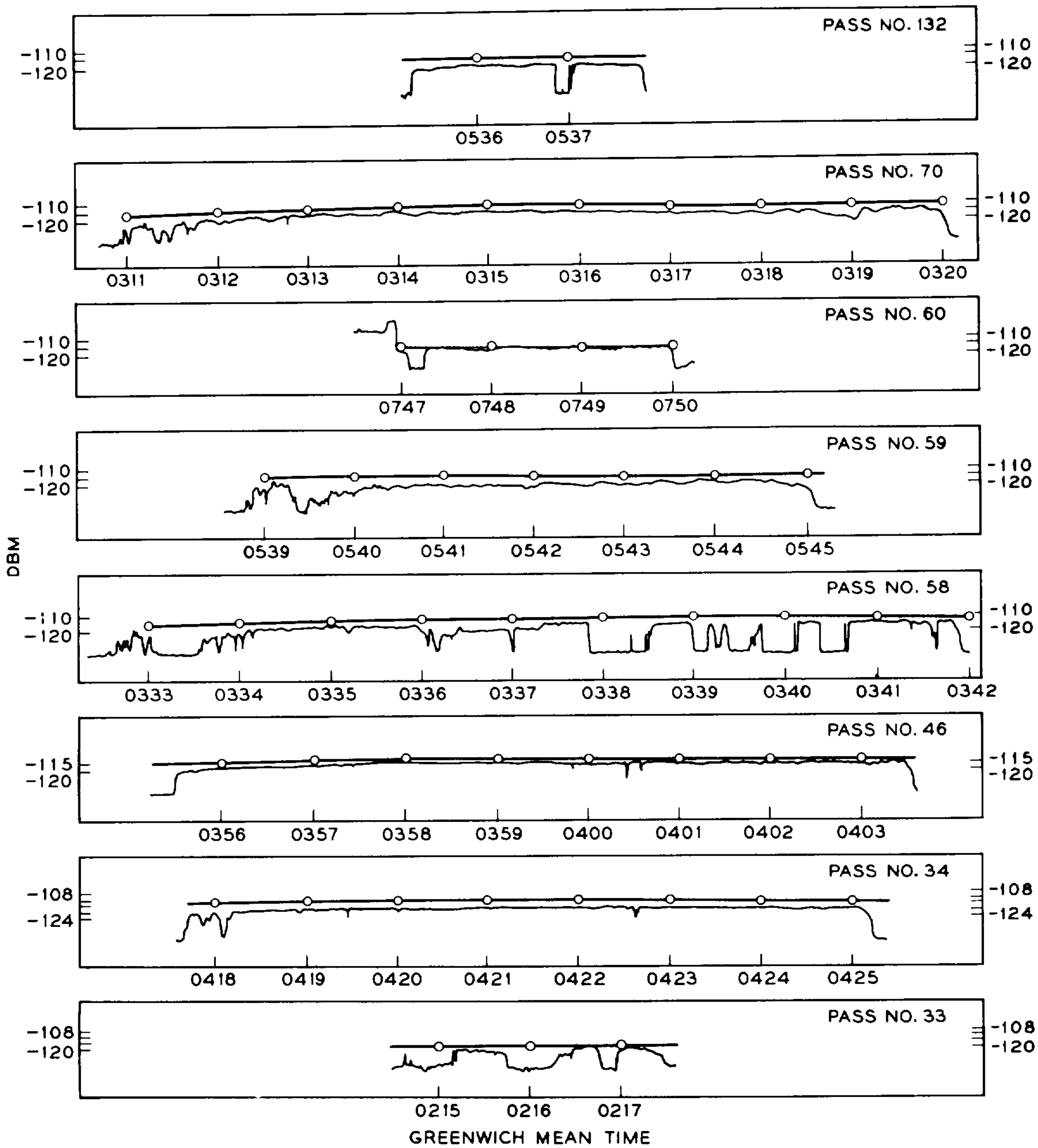


Figure 23 — Variation of power received by Goldstone Lake for various passes at 960 mc

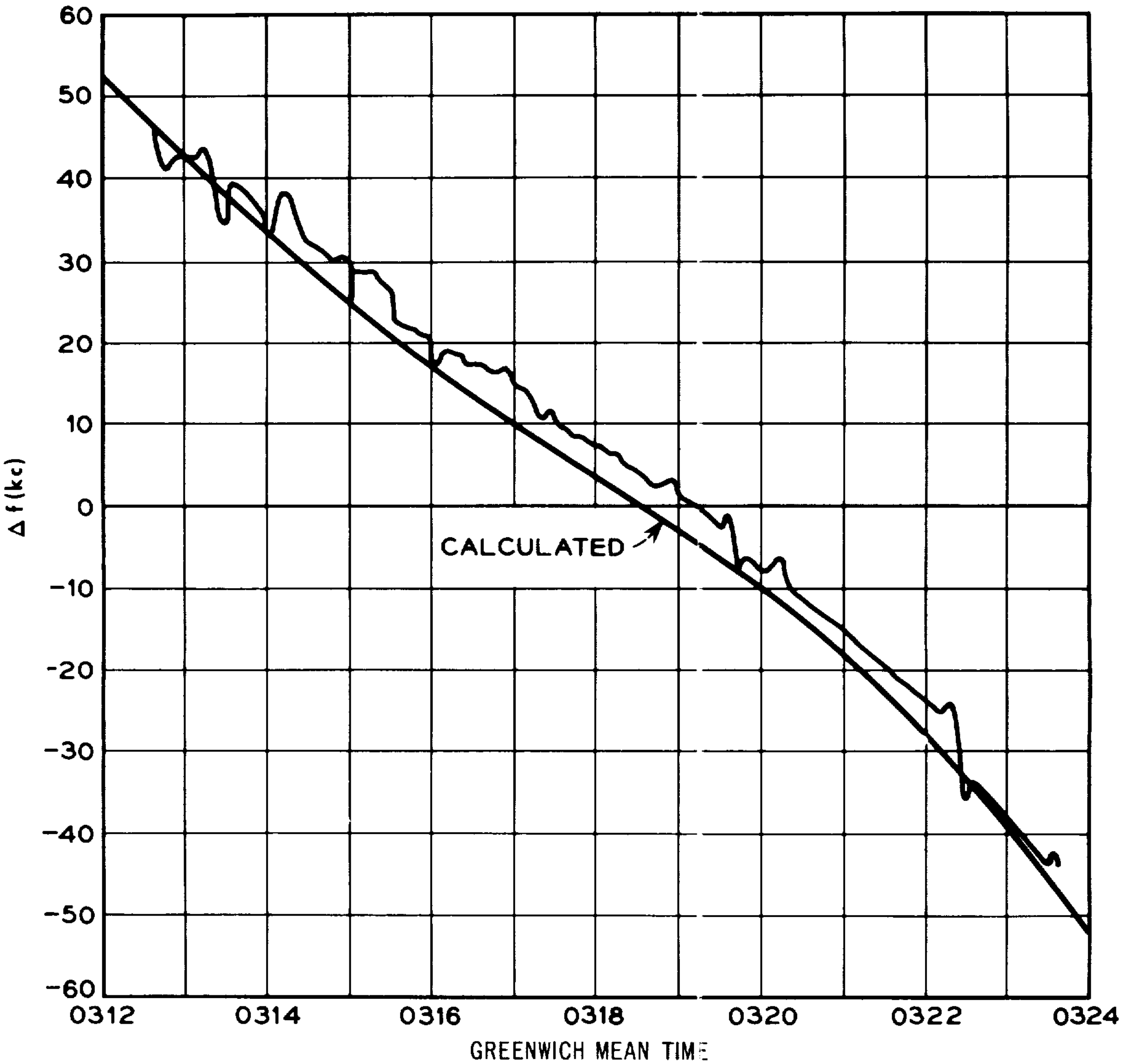


Figure 24 — Observed doppler shift on pass 70, Goldstone Lake to Holmdel at 2390 Mc

with $v_1$ and $v_2$ being the range rates to each station in meters per second. The range rates for these passes were supplied by the GSFC computer.

The agreement between calculated and observed values is fairly good. The average difference is probably due to uncertainty about the exact frequency of the first beating oscillator in the Holmdel receiver, nominally 2320 Mc; transient differences from the average are generally due to momentary manual adjustments in tuning.

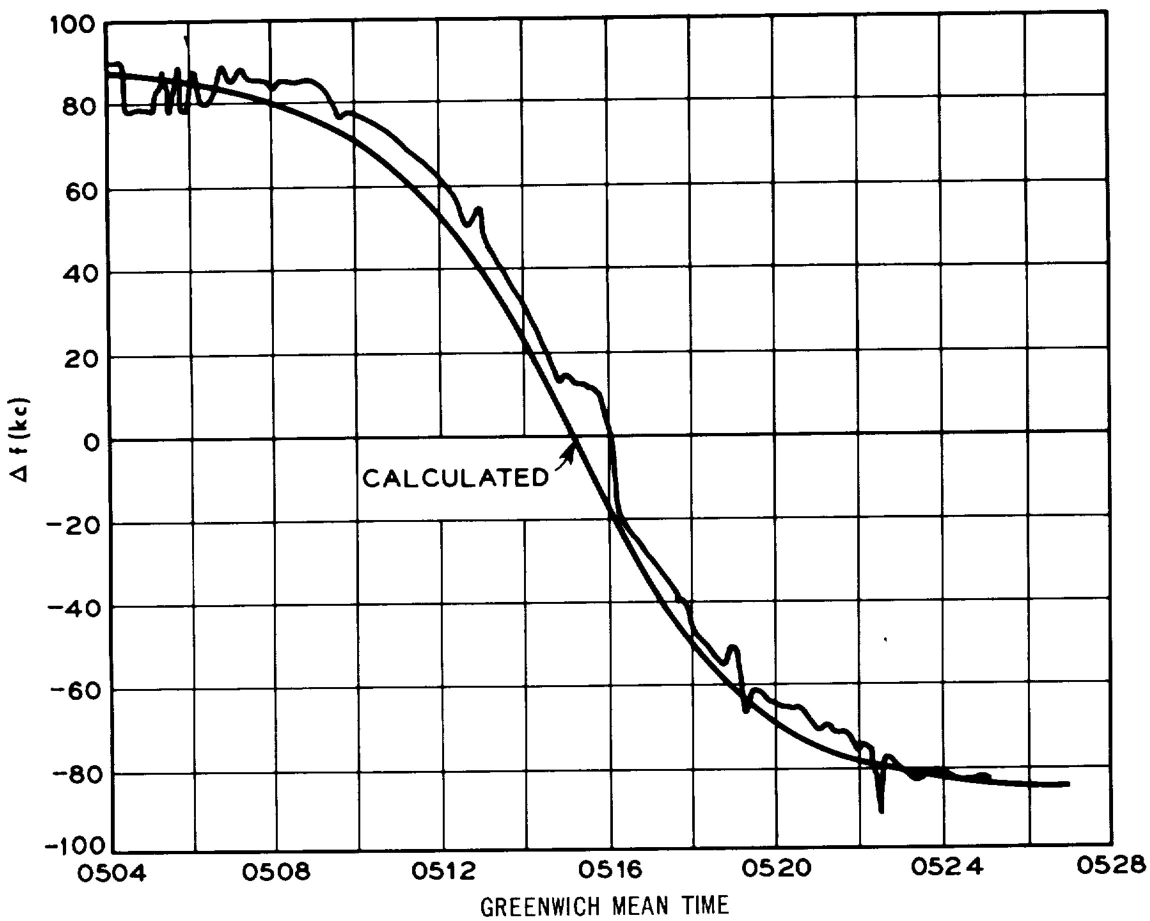


Figure 25 — Observed doppler shift on pass 217, NRL to BTL at 2390 Mc

## Scintillations of Received Signals

For all passes studied, an estimate was made of the average signal excursions above and below the median level. The data for each pass were obtained by first drawing in the computed received power and the visually estimated median signal. Those portions of each pass containing obvious systematic errors, such as transmitter failure or pointing difficulties, were excluded. Then an average curve was drawn through the maximum values of the signal, and the same was done for the minimum values. The difference between each of these two curves and the median was then recorded. These data were further condensed by plotting only the maximum departures from nominal scattering cross section for all the passes occurring on each day. These plots are shown in Figure 26, and include results from the Goldstone Lake and Stump Neck 2390-Mc transmissions to Holmdel and the Holmdel 961-Mc radar.

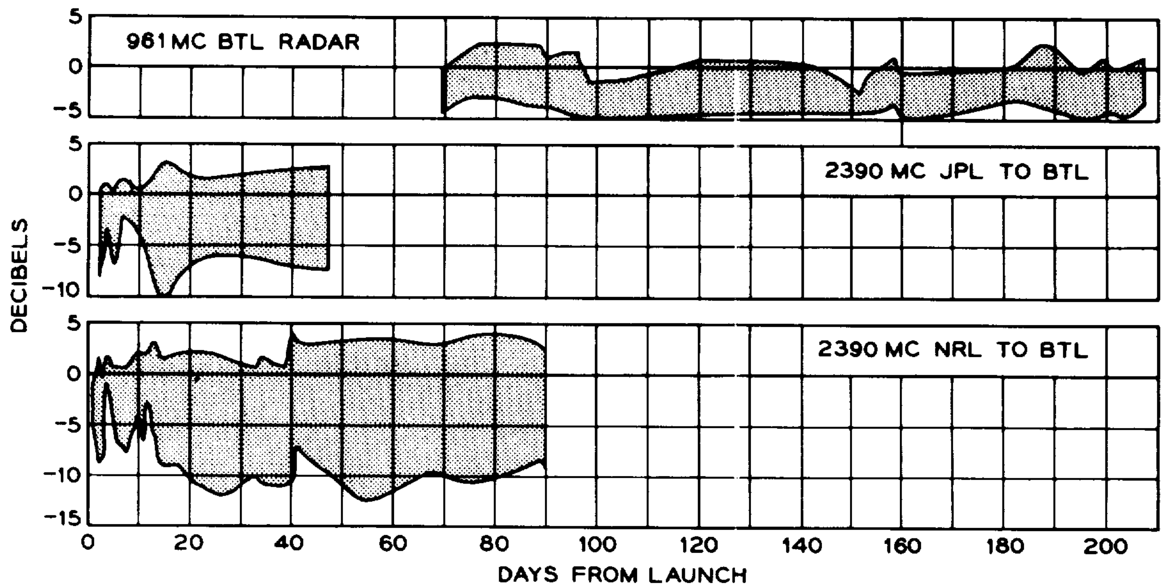


Figure 26 — Variation of peak-to-peak signal levels with time

Both the transmissions show about the same scintillation range during the first few days after launching, approximately +2 to -8 db. After 20 days, the scintillations of the Stump Neck signal were somewhat greater than those from Goldstone Lake. As noted earlier, the scintillations were generally random, except for the occasional occurrence of some having a strongly periodic characteristic of 4 to 8 seconds. These periodic scintillations were observed only on the Stump Neck transmissions.

The Holmdel radar records show considerably smaller scintillations than transmissions from Stump Neck or Goldstone Lake, as shown by the plot in Figure 26. From October 20 to December 20, a total of 14 passes occurred when the radar was in operation and records were available at the same time that a signal was being received from Stump Neck. These records were carefully examined but very little correlation was found between the fine structure of the scintillations of the two records. According to the radar records, the scintillations did not change appreciably from October 1960 to March 1961.

The occurrence of occasional signal peaks greater than theoretical values, assuming a 100-foot balloon, is consistent with the hypothesis of a slightly distorted balloon surface. There may be one or more flattened areas, any one of which could return more signal than a round balloon. On the other hand, it is possible that several signals reflected from these separate areas could add in phase, thus producing a signal stronger than that possible from an isotropic scatterer. Similarly, these various components could interfere destructively, and this is probably the reason for an occasional deep fade in the signal.

It should be noted that direct transmission between NRL and BTL has been observed by means of tropospheric scattering. But such transmission could not interfere with reception during a satellite pass since the frequencies, owing to the appreciable Doppler shift, are considerably different.

Greater scintillations were observed on all passes for low satellite elevations, regardless of whether operation was with Goldstone Lake, Stump Neck, or the Holmdel radar. These can be explained to some extent by operational effects, such as difficulty in acquiring and tracking the balloon at long range; but it is also possible that anomalous propagation through the earth's atmosphere contributed to the fading. This effect has been noted by others, and is quite severe, on occasion, for elevation angles below about 10 degrees.

## FM with Feedback Performance

On August 16 a series of tests was made on one of the FM demodulators at Holmdel while signals were being received at 2390 Mc. The noise power in the audio baseband, as a function of the input power and feedback factor, was determined with the use of a Western Electric 2B noise measuring set. The results are shown in Figure 27, together with the results of similar measurements made in the laboratory on another receiver of this type. The signal was measured above the threshold. Also plotted is the theoretical value based on simple FM theory, which holds above the threshold:

$$S/N = 3m^2 (C/N),$$

where

$S/N$ = rms signal-to-noise ratio in audio band,
$C/N$ = carrier-to-noise power ratio measured in a 6-kc bandwidth,
$m$ = modulation index.

With due regard to measurement difficulties during a pass, good agreement with the simple theory and laboratory measurements was observed.

## DAC Operation and Orbit Predictions

The digital-to-analog converter (DAC) proved to be very reliable, and required only minor repairs and adjustments. Occasional errors in pointing, while it was slaved to the drive tape, were usually due to errors in the tape itself arising from such causes as

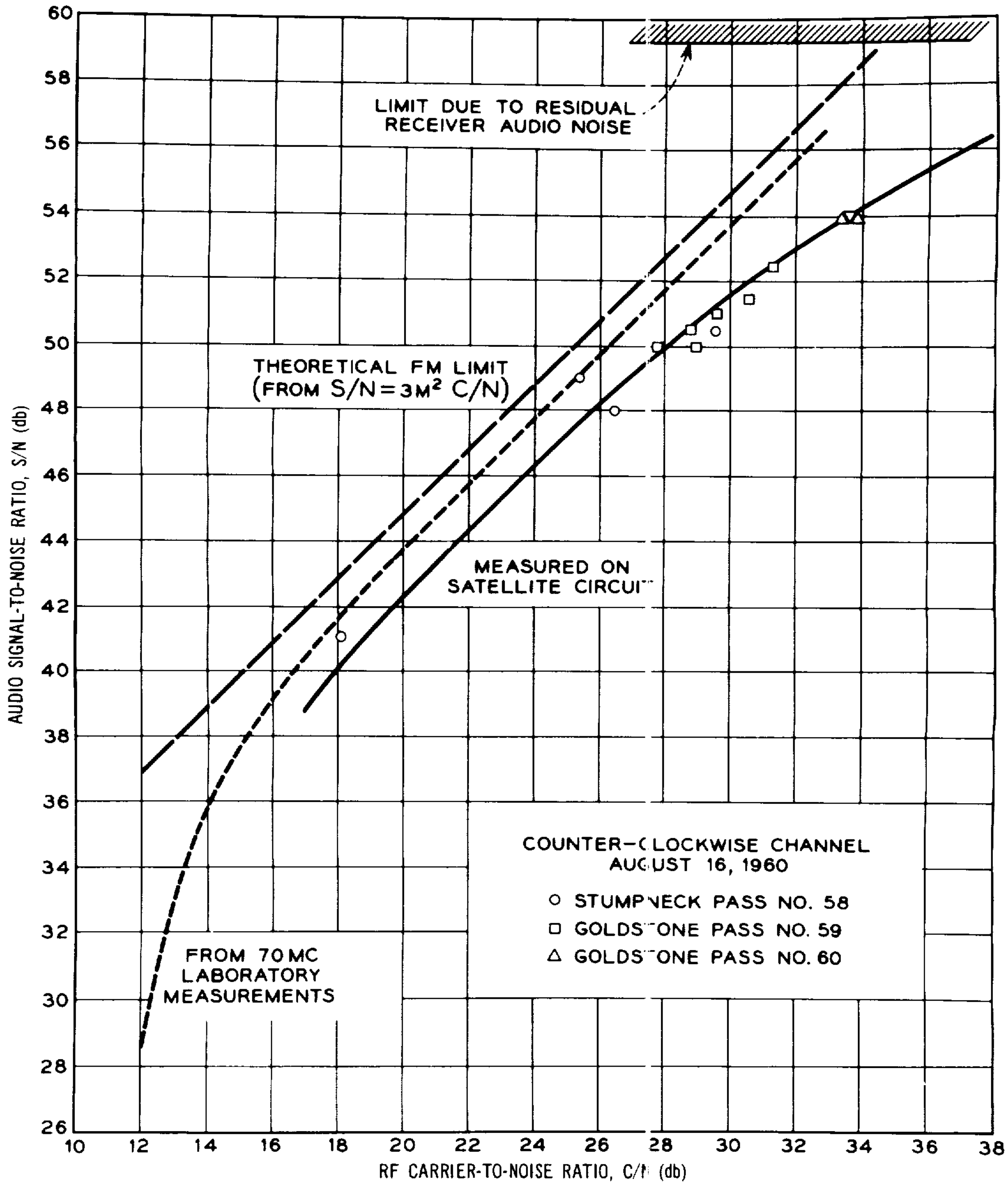


Figure 27 — Measurements of FM with feedback (db)

faulty operation of tape perforators, transmission anomalies in the TWX circuit between Holmdel and Washington, or a misplaced card in the deck used to generate the tape at the GSFC computer. The parity error-checking circuit in the DAC logic prevented about 90 per cent of these errors from appearing in the output positioning signals.

During each pass of the satellite an effort was made to assess the prediction accuracy of the drive tapes by a rough appraisal of the angular offsets* required to track the balloon. The results show that, on the average, the tapes from GSFC progressively deteriorated with time, with errors increasing from about 0.2 degree in August 1960, to about 1 degree in December 1960. Occasional tapes were much better – pass 503 on September 22 being a notable example with 0.1 degree errors – and a few were much worse. Several factors were responsible for errors:

1. Anomalies in upper air density occurred as a result of solar activity. This effect became more pronounced as radiation pressure increased the orbit eccentricity, and the balloon traveled through denser air during part of each orbit;

2. The Minitrack beacons on the balloon gradually grew weaker, until the signals were virtually useless for accurate orbit determination by the end of December;

3. On January 1, 1961, the steady increase in eccentricity reversed. This made it difficult to establish the proper values for the time rate of change of the orbital elements. After January 1961, the drive tapes were based on orbital elements supplied by the Smithsonian Astrophysical Observatory, as mentioned earlier, and the errors were on the order of 0.2 degree.

## Optical and Radar Tracking

Operation with optics was superior to any other tracking method when the balloon was visible. The errors could be kept within ±0.05 degree either through complete manual control or by inserting angular offsets with a drive tape.

On occasion, the satellite was visible while the radar was in operation, and these opportunities were used to make boresight comparisons between optics and radar. The results generally showed that the radar was accurate to the design objective, ±0.1 degree.

## Operation with Other Stations

During the course of the Echo experiments, occasional tests were carried out with stations other than Goldstone Lake and Stump Neck.

*Manual insertion of corrections (offsets) proved to be an extremely valuable procedure. Without this feature, it is believed that at least half the passes would have been missed completely and the rest would have been of doubtful value.

Transmissions were attempted to Jodrell Bank, England, on passes 141 and 142, August 24, 1960, using AM with voice and music modulation. Reception was reported, but the S/N ratio was very poor, rendering the voice barely intelligible. This was probably due to the following factors:

1. Using AM lost 9 db compared to SSB.

2. Tracking accuracy was marginal at the Jodrell station, since its dish was not designed to track fast-moving satellites and no means were available for correcting the prediction.

Reception was reported from Centre Nationale d'Etudes des Telecommunications, France, on pass 70. This occurred on August 18, 1960, at 960 Mc, using a fixed 10-foot dish and 20 cps bandwidth. On two later passes, 1447 and 1448 on December 8, reception was again reported using a 30-foot dish which tracked the satellite optically. A S/N ratio of 12 db in a very narrow bandwidth was achieved.

At the request of NASA and the Stanford Research Institute, Scotland, transmissions were attempted at 960.05 Mc to the 140-foot dish at the Stanford facility in Scotland on passes 118, 119, and 130 on August 22, 1960, and again during pass 142 on August 24, 1960. Weak reception was reported.

Successful transmissions from Holmdel to Malvern, England, were carried out on passes 213, 214, and 215 on August 29, 1960, at 960 Mc. The receiver used a 20-foot dish and a parametric amplifier with a 5 db noise figure.

Holmdel transmissions were heard by the General Electric Laboratories in Schenectady, New York, at 960 Mc during 11 passes in August, 1960. The receiver used a 28-foot paraboloid tracked along a predicted orbit and a parametric amplifier with 4 db noise figure. Later on, a number of two-frequency transmissions were made for the purpose of studying the amplitude and phase correlation of the signals (Table 8). The analysis of the results is being done by General Electric; a computer is being used to calculate the correlations.

Table 8
Two-Frequency Transmissions from Holmdel to Schenectady

| Pass | Date | Frequency Separation |
|---|---|---|
| 1584 | 12/20/60 | 10 kc |
| 1874, 1875, 1876 | 1/12/61 | 10 kc |
| 1946, 1947 | 1/18/61 | 10 kc |
| 1958, 1959 | 1/19/61 | 10 kc |
| 2118, 2119 | 2/1/61 | 1 Mc |
| 2131 | 2/2/61 | 1 Mc |

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Bell Telephone Laboratories' employees who were active in the overall preparation and operation of the experiment include L. R. Lowry, E. L. Frantsvog, W. E. Legg, R. A. Desmond, G. J. Stiles, and J. N. Hines. The first four named above also carried out the task of data reduction. The project was under the leadership of J. R. Pierce, R. Kompfner, and C. C. Cutler.


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