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This issue of The Bell System Technical Journal is devoted to extensive discussion of Project Echo, an experiment in satellite communication conducted by Bell Telephone Laboratories in cooperation with the National Aeronautics and Space Administration, Jet Propulsion Laboratories, the Naval Research Laboratory, and others. The first paper describes the experiment and the results obtained. It is followed by eleven more detailed papers, each describing one of the parts of the Project Echo system.

Participation of Bell Telephone Laboratories in Project Echo and Experimental Results

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On August 12, 1960, 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 means of reflection of microwaves from a satellite. It was intended that a two-way coast-to-coast voice circuit be established between the Jet Propulsion Laboratories facility at Goldstone, California, and a station provided for this purpose by Bell Telephone Laboratories at Holmdel, New Jersey. Similar tests were also planned with the Naval Research Laboratory and other stations.

Construction of the Holmdel station was begun early in 1959. This paper describes the general organization and operation of the station, and discusses the results of the Project Echo experiments that took place between the launching of the balloon and March 1, 1961. Successful voice communi-

cation was achieved a number of times using 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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I. INTRODUCTION

1.1 *Purposes of the Project Echo Experiments*

Several years ago Bell Telephone Laboratories became interested in studying the feasibility of providing long distance communication facilities by means of reflection from orbiting earth satellites. Participation in NASA's Project Echo was undertaken as a first active step in this program, and it was hoped that the following objectives would be achieved:

i. To demonstrate two-way voice communication between the east and west coasts.

ii. To study the propagation properties of the medium, including the effects of the atmosphere, the ionosphere, and the balloon.

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

iv. 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 the National Aeronautics and Space Administration and the satellite-tracking facility of the Jet Propulsion Laboratories (JPL) located at Goldstone, California, about one hundred miles northeast of Los Angeles. The Bell

Telephone Laboratories (BTL) station is located at Holmdel, New Jersey. In addition, tests were planned in cooperation with the Naval Research Laboratory (NRL), facility at Stump Neck, Maryland; General Electric, Schenectady, New York; and stations in Europe.

1.2 *Description of the Experiment*

The diagram of Fig. 1 illustrates the general features of the experiment. An east-west channel was provided by transmission from a 60-foot paraboloid antenna at BTL to an 85-foot paraboloid at JPL via reflection from the balloon, using a frequency of 960.05 mc. The west-east channel utilized transmission from another 85-foot dish at JPL to a specially constructed horn-reflector antenna at BTL having a 20- by 20-foot aperture. The radiation in each channel was circularly polarized in order to avoid the necessity of tracking polarization during the satellite pass, and was transmitted in a clockwise sense from the JPL antenna and counter-clockwise from the BTL antenna. Reflection from the balloon reversed the sense of rotation of the field, so that the major share of the field received by the BTL horn was expected to be polarized counter-clockwise and that at the JPL receiving dish to be clockwise. In addition, the BTL horn was equipped with a second receiver arranged to respond to the clockwise component of the incoming signal, in order to obtain more information concerning the transmission properties of the medium.

The balloon was placed in an almost exactly circular orbit with an inclination of 47.3°, which provided periods of mutual visibility up to about 15 minutes for BTL and JPL and 25 minutes for BTL and NRL. The slant range from Holmdel to the balloon varied between 3000 and 1000 miles during a typical pass.

The facility at NRL consisted of a single 60-foot paraboloid equipped to either transmit or receive at 2390 mc. Ordinarily, both BTL and NRL received from JPL during the first part of a satellite pass while there was mutual visibility between JPL and BTL. After the balloon had "set" for JPL, NRL then transmitted to BTL, using counter-clockwise polarization. On a few passes JPL and NRL simultaneously transmitted to BTL and the two signals were separately recorded on the two BTL receivers, taking advantage of the oppositely polarized radiation from NRL and JPL and a slight difference in transmitted frequency of 0.4 mc 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 using frequency

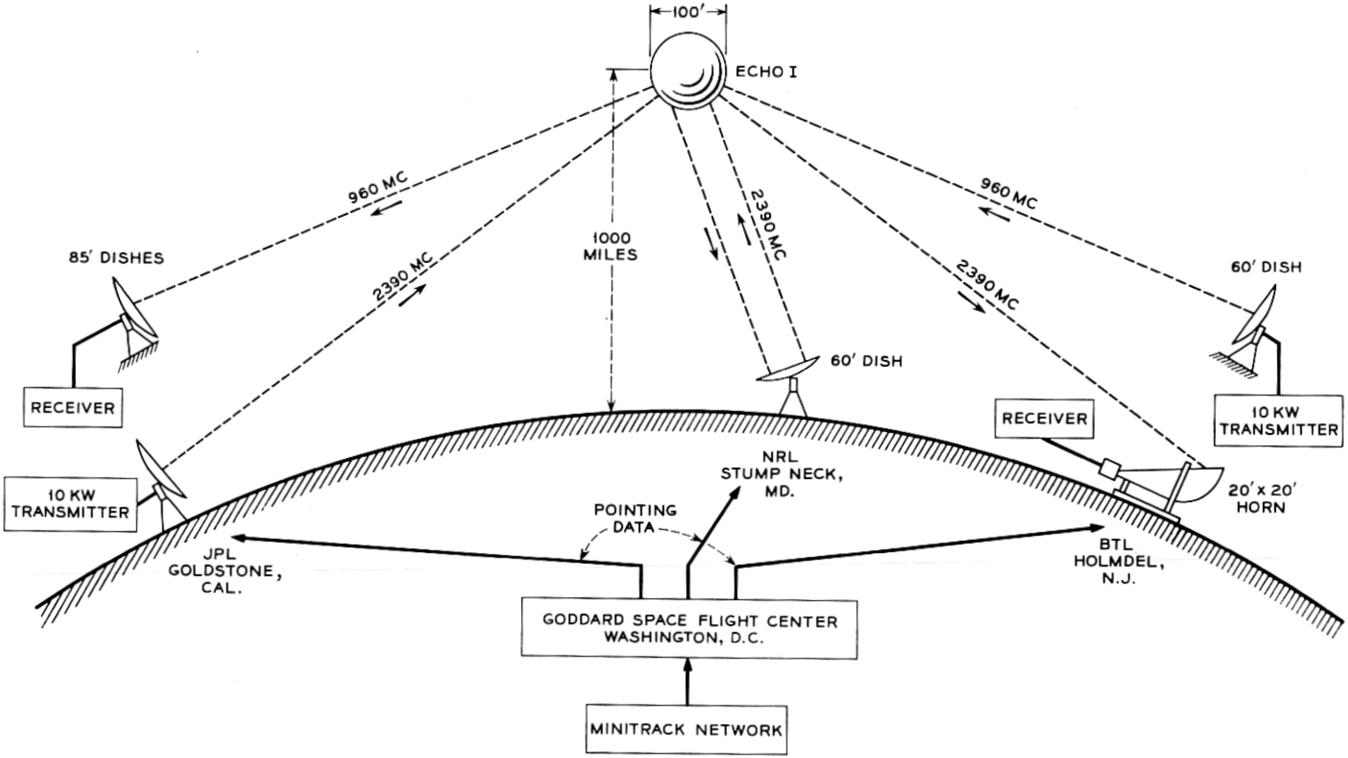


Fig. 1 — General features of the Project Echo experiment.

modulation with a peak index of 10, corresponding to ±30 kc deviation. This results in an FM improvement factor of about 25 db, provided the carrier-to-noise ratio (C/N) 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.[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 and frequency or phase modulation of low index. It was expected that the maximum carrier levels would be about −113 dbm for reception from JPL and BTL and −108 dbm from NRL. Taking the expected system noise temperatures into account, this would provide maximum baseband rms 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 attenuation, 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.[2]

The threshold sensitivity of the BTL receivers is approximately −150 dbm, which corresponds 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 BTL, 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 BTL. 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 obtained 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 by means of information derived from optics, radar, or maximization of the 2390-mc received signal — whichever seemed best to use 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.

1.3 *Preliminary Tests*

In order to gain experience and check the capabilities of the equipment, a number of preliminary experiments were performed with JPL, NRL, Lincoln Laboratories, General Electric, and others. A brief chronological summary of these tests is given in Table I.

TABLE I — 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
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

1.3.1 *Moonbounce Tests*

On November 23, 1959, shortly after the installation of the BTL 60-foot dish and the 10-kw, 960-mc transmitter, the first operation was held with JPL. Successful contact was made and some live voice was transmitted until a coaxial line broke down at BTL 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 successful 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, incidentally, some interesting data on the characteristics of the moon as a reflector, which are summarized below:

1. Effective scattering cross section is 9×10^{11} square meters, corresponding to a perfectly conducting sphere 670 miles in diameter. This is comparable to values obtained by other workers.

2. Speech as transmitted by SSB with 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. Use of broad bandwidth modulation systems will degrade the 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.

1.3.2 *Shotput Tests*

Five suborbital ballistic tests on 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 participated in the first three, as follows:

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 via the balloon using FM with feedback (FMFB) at 960 mc, again to Round Hill. The threshold improvement of the FMFB demodulators was verified.

Tracking was again optical on the latter tests.

1.3.3 *Tiros Tests*

In order to check the feasibility of satellite tracking by means of orbit predictions from Goddard Space Flight Center, and to make sure that BTL, JPL, and NRL indeed possessed stations in proper operating condition, a number of carrier transmission tests using reflection from Tiros I were scheduled. The small size and low orbit of this satellite made it a much more difficult target; nevertheless, two successful contacts with JPL and two with NRL were achieved. On two passes, Tiros was briefly observed optically, and its position noted to be within 0.1° of that predicted.

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

II. SYSTEM DESCRIPTION

Most of the BTL facilities for Project Echo are located on top of Crawford Hill, 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 one and a half miles away, in order to increase the isolation between the transmitted signals from the 60-foot dish and the radar receiver. Fig. 2 is a general view of the hilltop, and a simplified block diagram is shown in Fig. 3. The small buildings visible in the photograph house the various pieces of system equipment, as follows:

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

The system is briefly summarized in the following four sections, cover-

Fig. 2 — Bell Telephone Laboratories Echo station facilities on Crawford Hill, Holmdel, New Jersey.

ing the functions of transmitting, receiving, tracking, and communications. For more detailed descriptions of certain components the reader is referred to the companion papers in this issue.[2-5, 7-13]

2.1 *Transmitting System*

2.1.1 *960-mc Transmitter*[3]

The BTL transmitter is a commercially available item which was purchased from a division of the International Telephone and Telegraph Company, and provides a 10-kw output with an exciter capable of FM with deviations up to ±300 kc. In order to 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 is centered at 960.05 mc and is designated the *communications* channel, and may be modulated with FM of indices from 1 to 10, phase modulation (PM) with 0.5 radian index, single-sideband modulation (SSB), double-sideband modulation (DSB), or AM. The modulation bandwidth extends

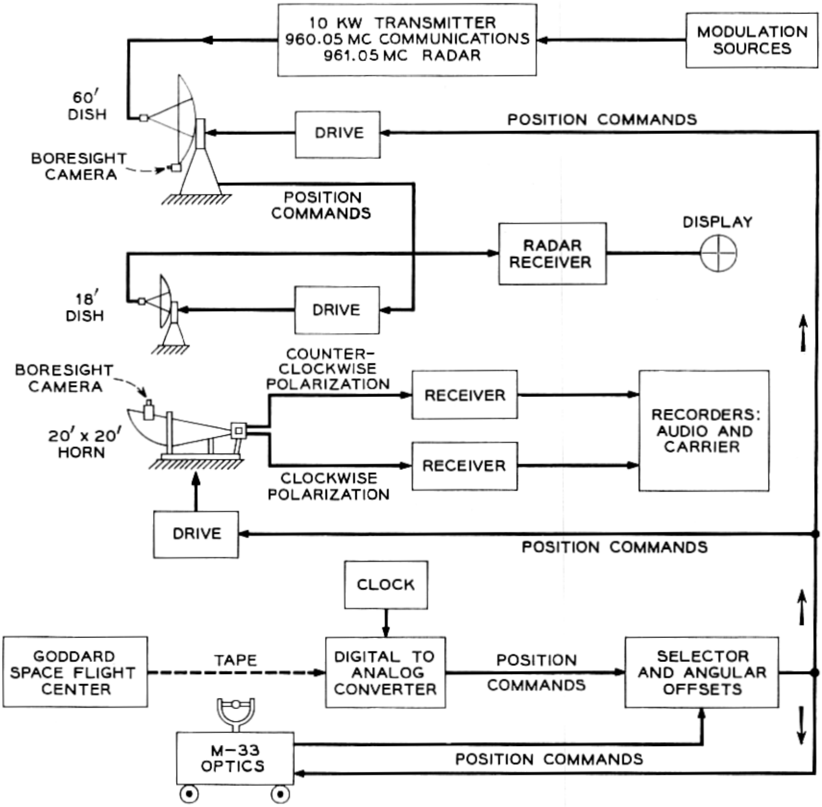


Fig. 3 — Block diagram of the BTL facilities.

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 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 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 over-all frequency stability of the transmitter depends on the particular exciter being used, and considerable effort was spent in making this as good as possible, with the following results:

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

2.1.2 *60-Foot Paraboloid*

This antenna is a standard item and was 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 is capable of positioning the antenna to an accuracy of ±0.05° in winds up to 35 mph at angular rates more than adequate for satellite tracking. 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 mentioned before, counter-clockwise circular polarization was always radiated for the Echo tests. On a few occasions it was reversed during a Moonbounce test with JPL 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 to be 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 by this source at the antenna is essentially flat (as was verified by direct measurement). The results of the tests were as follows:

Gain	43.1 ± 0.1 db,
3-db beamwidth	1.2 degrees,
First sidelobes	−20 db,
Axial ratio	1 db,
Return loss	20 db.

2.2 *Receiving System*[4]

2.2.1 *Antenna*[5] *and Waveguide*

A horn-reflector antenna (see Fig. 2) was used for 2390-mc reception at Holmdel because of its demonstrated low-noise properties[6] and other features. The aperture of the antenna is approximately 20 by 20 feet; the over-all length of the antenna is about 50 feet. Careful measurements were made of the gain and radiation patterns before the Echo launch with entirely satisfactory results, as listed below:

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 having very low loss coupled the horn to the waveguide system, which contained the 90° 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.

2.2.2 *Low-Noise Amplifiers*

Two masers were provided,[7] both located in one dewar in the field of a single magnet, and were used for the two polarizations of the incoming signal. The maser gains were sufficient so that the noise figure of the following crystal converter did not appreciably affect the over-all system noise temperature. Liquid helium was used to cool the masers to operating temperature. A dual 2390-mc parametric amplifier was also provided,[8] and, in the event of maser failure, 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.

2.2.3 *IF Preamplifiers and Demodulators*

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, including 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,[9] and in this case phase lock was used to remove the Doppler shift. A second conventional SSB receiver then recovered the modulation.

2.2.4 *Recording*

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 available for local or outside telephone lines, or for the station public address system.

2.2.5 *System Sensitivity*

Measurements show that the over-all system noise temperature, including sky noise, was about 45°K or less throughout the significant

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

part of the Project Echo experiments, with the minimum value ever observed being about 21.5°K. The sky noise is a function of antenna elevation, as pointed out elsewhere, so that the system temperature varies during a satellite pass.

2.3 *Tracking*

2.3.1 *General*

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

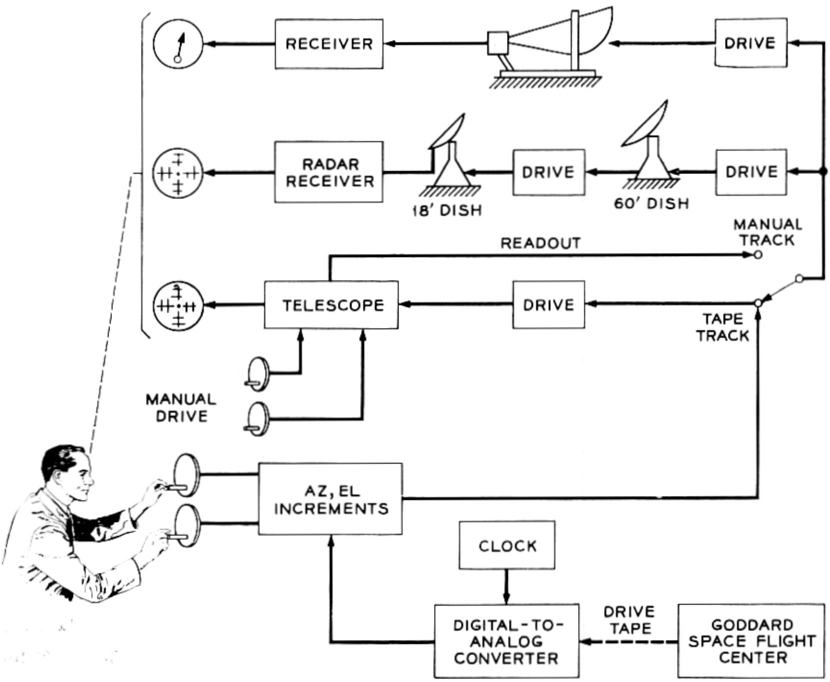


Fig. 4 — Block diagram of BTL tracking modes.

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 located 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° in azimuth and 90° in elevation could be used.

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

2.3.2 *Digital-to-Analog Converter (DAC)*[10]

This unit 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. This gives time, azimuth, elevation, azimuth rate, and elevation rate of the satellite, with these quantities appearing 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 in between the four-second data points, so that the antennas will move smoothly.

Using 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 Goddard 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 $\pm 0.02°$. To the gear train are fastened a number of synchro transmitters, which supply positional command signals to the dish, horn, and optical drives.

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

2.3.3 *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 leading down to convenient operator positions inside the trailer. The field of view is about 6°, with a magnification of 8× 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 (a) slaved to the command signals originating from the DAC and (b) 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°. 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° was obtained. These plots were quite useful in making rapid examinations of tracking, and showed bad data points graphically.

2.3.4 *Tracking Radar*[11]

A separate 18-foot paraboloid is used to receive the 961.05-mc signal reflected from the satellite. 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°.

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[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° 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 position of the satellite with respect to the system pointing axis to the operator 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 over-all 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 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.

2.3.5 *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°. Part of this error would inevitably be due to antenna misalignment or bore-sighting errors; hence, some time was spent in measuring and adjusting to keep these errors within at most ±0.05°. 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, and 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, and these were then 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°.

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° for the Echo satellite at closest approach.

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

2.3.6 *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 synchro 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°, and time to 0.5 second. An enlargement of one frame of such a record is shown in Fig. 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[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° and a time-coded counter.

2.4 *Communications*

2.4.1 *Telephone*

A variety of telephone services were provided for both local and long distance communications. Each of the four buildings on Crawford Hill

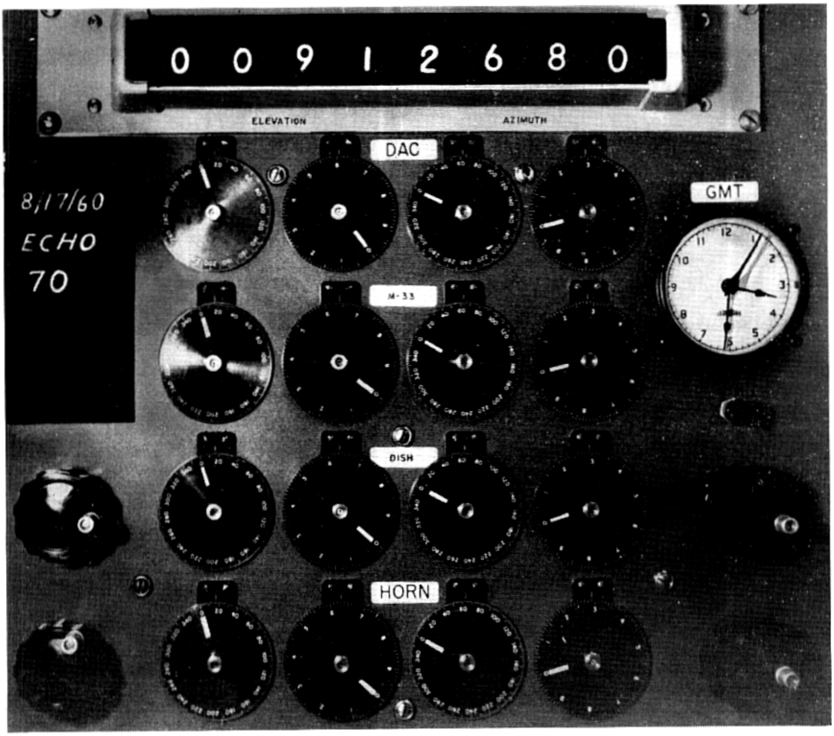


Fig. 5 — Reproduction of one frame of the data-recording camera film.

was tied in with the Holmdel PBX for routine internal calls. Three direct lines were also provided to the Middletown central office: one serving all four buildings in parallel and a second going to the transmitter and control buildings (1 and 2). The third went to the control building, and was used only for calls to facilities other than JPL for consultation during an actual operation. Finally, a private four-wire line was established to the Goldstone site with provision at each end for switching the instrument between the land line and the satellite facility 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;
3. West-to-east by satellite, east-to-west by land line;
4. Two-way by satellite.

2.4.2 *Teletypewriter*

Two teletypewriter lines were brought into the control building. One was a private full-time service to the space control (SPACON) of the Goddard Space Flight Center. This was used to maintain contact with SPACON and other stations tied into this net, and also for the transmission of drive tapes from the GSFC computer to BTL.

The other line provided a general utility TWX service, and included a tape puncher for receiving drive tapes from other sources.

2.4.3 *Intercommunications*

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.

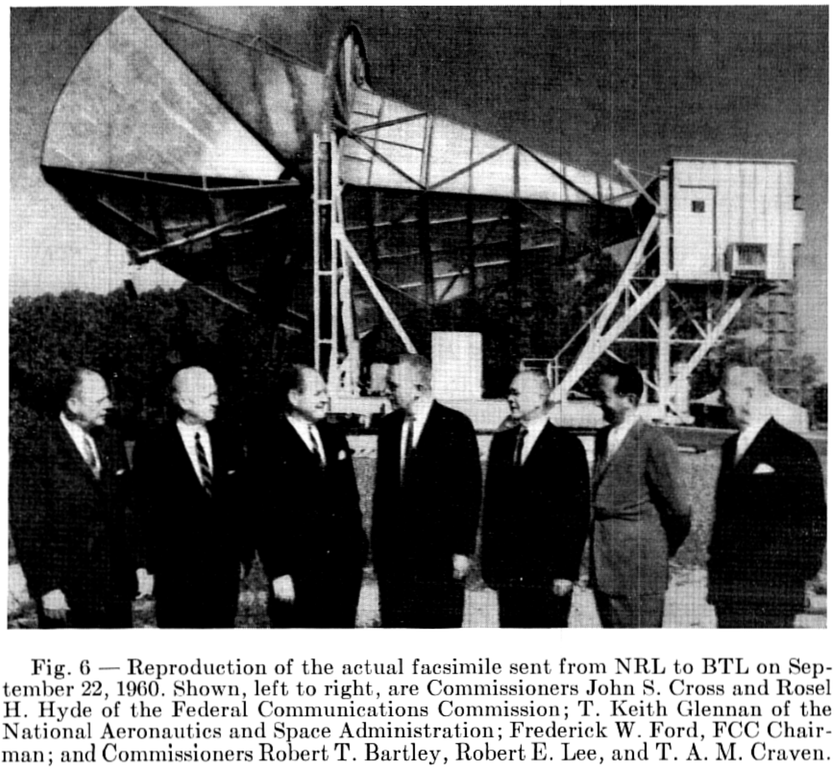


Fig. 6 — Reproduction of the actual facsimile sent from NRL to BTL on September 22, 1960. Shown, left to right, are Commissioners John S. Cross and Rosel H. Hyde of the Federal Communications Commission; T. Keith Glennan of the National Aeronautics and Space Administration; Frederick W. Ford, FCC Chairman;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

III. EXPERIMENTAL RESULTS

Since the successful launching of the Echo I balloon on August 12, 1960, operations were carried on by the BTL station for about 120 passes up to March 1, 1961. Of these, four were with JPL only, 50 were with NRL only, 27 were with both JPL and NRL during the same pass, and 39 were with the BTL 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.

3.1 *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 Fig. 6. Listed below are some of the more significant tests performed in 1960:

Pass No.	*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.

Measurements of the signal-to-noise ratio in the audio band were made during many of the 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 the balloon in conjunction with the existing terminal equipment at BTL and JPL provided an excellent circuit with the designed bandwidth of 200 to 3000 cps, and that any service that could be transmitted in this bandwidth could equally well be handled by the satellite circuit.

3.2 *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 four 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,[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 can be made with the observed data. Obviously, if either of the two antennas involved in a transmission path is not aimed at the satellite properly, 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 predictions, and allowance 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,[14] and the curves of Fig. 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 up to October 6, 1960, included the refraction correction in the wrong sense. The error was rectified and proper corrections made after that date. The only antenna appreciably affected was the NRL 60-foot dish, since the BTL antennas had comparatively wide beams, and the JPL antennas were almost always tracked by radar or optics. Assuming a reasonable pattern for the NRL 60-foot dish at 2390 mc (no

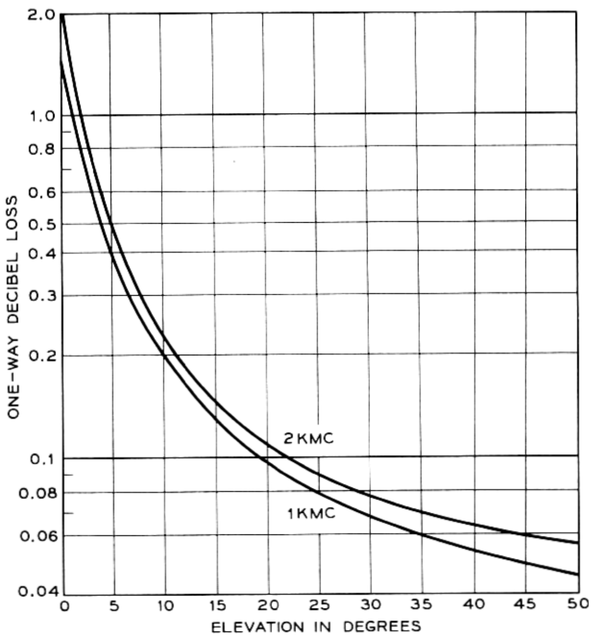


Fig. 7 — Absorption due to atmospheric oxygen and water vapor.

measured patterns were available) and a standard atmosphere, the calculated received power levels were appropriately modified using the correction curves shown in Fig. 8, providing optical corrections were not being used by NRL at the time.

Records of transmitted power were kept at all stations, and were reasonably complete over all passes worked. Nominally JPL radiated 9 kw at 2390 mc, NRL radiated 9 kw, and BTL 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.

3.2.1 *Results*

Comparison of actual received power with that predicted has been made on 96 passes. For each pass studied, the predicted received 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 values by an approximately constant factor during the significant part of each pass, so that a single number expressed in db served to characterize the difference between the observed and predicted received power. Fig. 9 contains the plots of these points as a function of time from launch and transmission mode, each point representing one

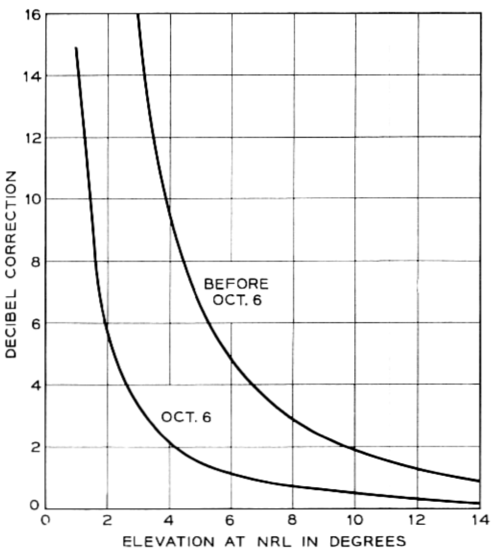


Fig. 8 — Correction curves for refraction at NRL.

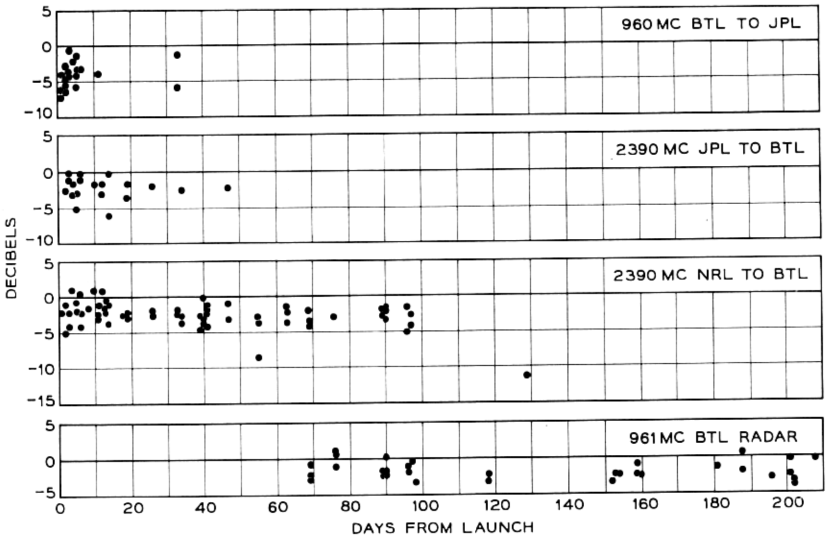


Fig. 9 — Difference in decibels between predicted and observed received signal power.

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 JPL 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 BTL antennas was good for the same reasons as for JPL; again, the occasional errors in pointing were obvious and could be ignored.

No pointing data were available from the NRL 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 JPL–BTL transmissions at 2390 mc. This path involved the fewest unknowns and had the most accurately calibrated receiver. From the plot in Fig. 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 was achieved.

The data for the 960-mc BTL–JPL transmissions show a much greater spread between predicted and observed values. This may be in large part attributed to the fact that the JPL 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 BTL 2390-mc receiver was completely calibrated before and after every pass. There is also some uncertainty about the gain of the JPL 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 NRL 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 received power was essentially the same over both 2390-mc paths.

The BTL 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 about ±1.5 db. These data indicate that, as of March 1, 1961, Echo I was probably an approximately spherical object with a diameter no less than 70 feet and a somewhat wrinkled skin. There may be a few flattened areas, as indicated by a rare deep fade in the BTL radar signal, but it is evident that it could still be used for voice communication.

3.3 *Detailed Study of Selected Passes*

3.3.1 *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 Figs. 10 through 22 and described in the following sections.

Pass 1 (Fig. 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 JPL 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 BTL during this pass, and, since the BTL 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. It is obvious that, had the launching 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 Fig. 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 JPL dish and BTL 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 BTL 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 by the errors in pointing of the BTL 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 JPL 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, and the excellent agreement is obvious. Accurate read-out data for the BTL 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 BTL horn and the JPL dish were responsible for the difference between calculated and observed level during this time.

About one minute after first reception, word was passed to JPL to start modulation, and President Eisenhower's message was then success-

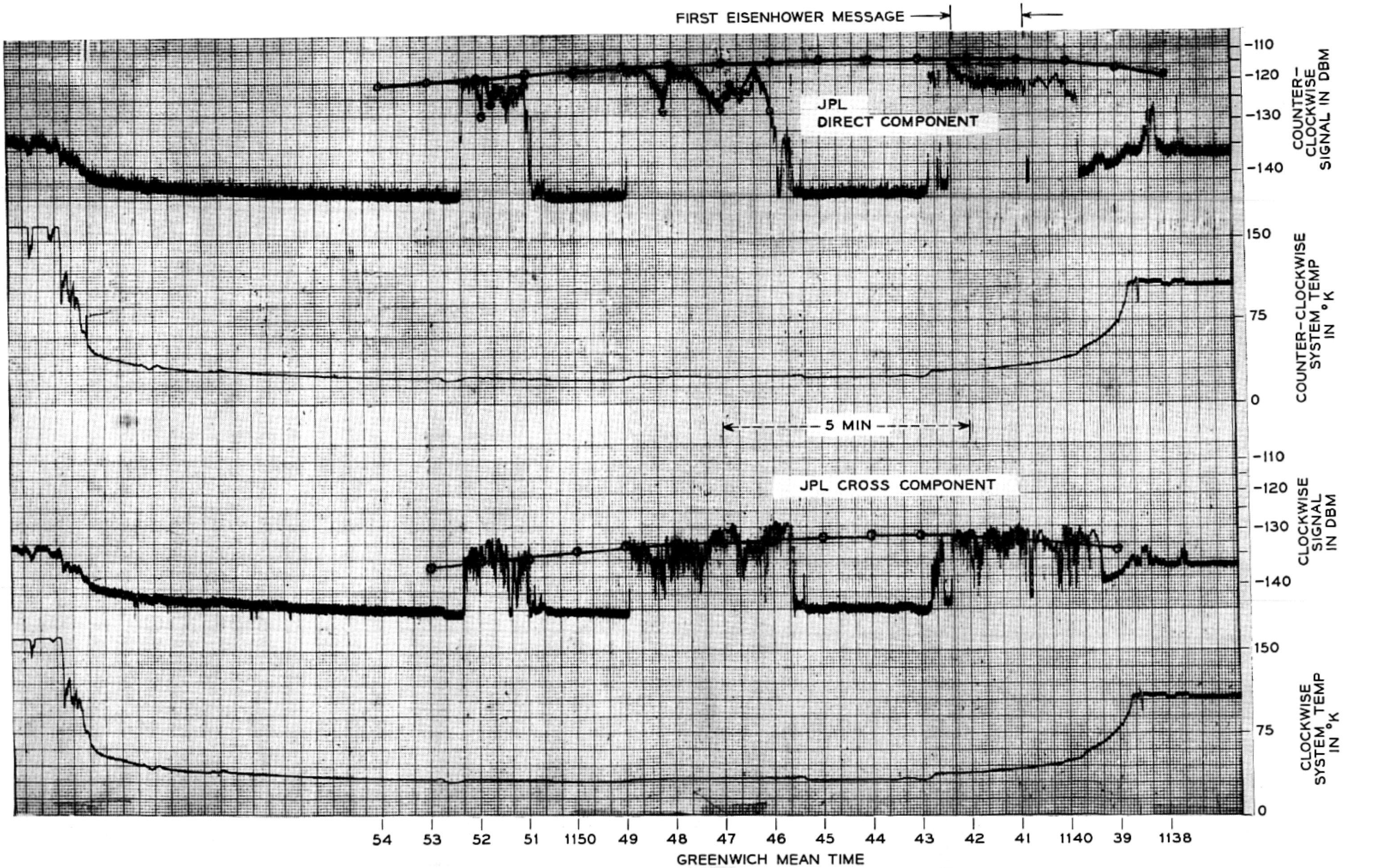


Fig. 10 — First pass (August 12, 1960).

fully 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 $-1°$ in elevation and from $-1°$ to $-3°$ in azimuth. These errors were compensated for by the insertion of angular offsets, as mentioned earlier.

The second and fourth tracks in Fig. 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° elevation the temperature was down to 75°K. At 5° 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 (Fig. 11):

This is probably the best example of a completely successful pass with both JPL and NRL. 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 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 JPL 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 BTL and pointing readout at JPL 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 JPL 2388-mc radar, however, leading to the conclusion that either an airplane flew in between the BTL site and the balloon, or the balloon had a large section of surface with anomalous curvature which was common to the BTL–JPL path but not effec-

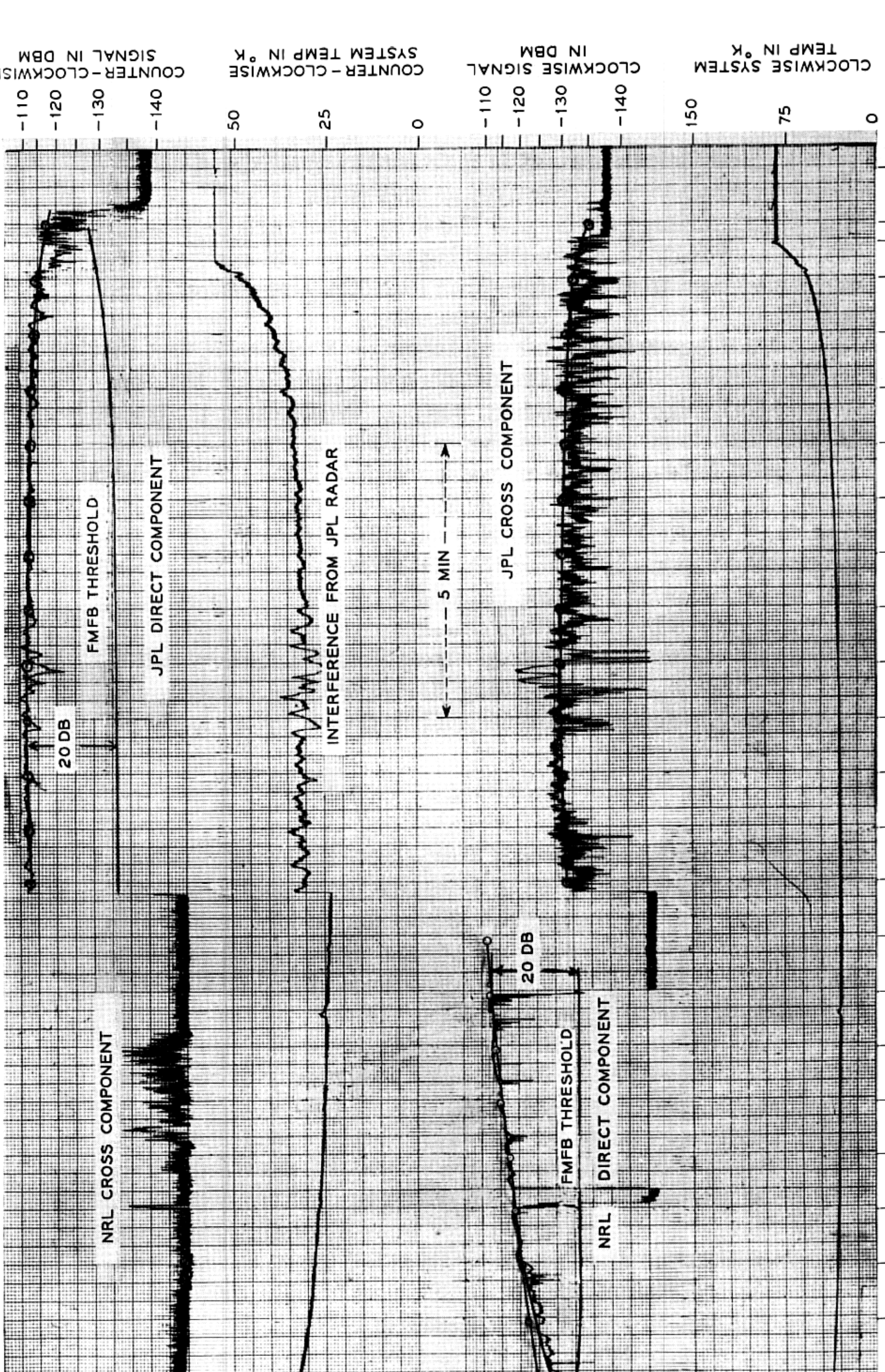


Fig. 11 — Pass 70 — alternate reception (August 18, 1960).

tive in the JPL–JPL radar path. The included angle at the balloon between JPL and BTL at that time was very nearly 90°; 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 BTL antenna beam was at an elevation angle of 38° at the time. It is difficult to imagine a possible airplane trajectory that would keep it in the beam for this long. In addition, one would expect to see the lights on the airplane in the boresight camera film, and no such evidence was observed. The conclusion, then, is that the balloon very likely had a deformity at this time.

The theoretical curve for NRL at the end of the pass (circled points) assumes that refraction corrections were properly inserted. Assuming that the pointing data provided to NRL had corrections put in with the wrong sign, the smooth curve below was obtained using the corrections from Fig. 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 NRL cross component, since no data were available for the ellipticity of the NRL dish. It appears to be of a lower value than JPL, however.

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

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

Pass 119 (Fig. 12):

The helium transfer process at BTL 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. JPL was received briefly, and then NRL. Note again the good agreement between calculated and observed signal levels, including also the refraction correction at the end of the pass.

Pass 156 (Fig. 13):

Only NRL was received on this pass. It is noteworthy because this was the first time that an eclipse of the balloon occurred during a pass,

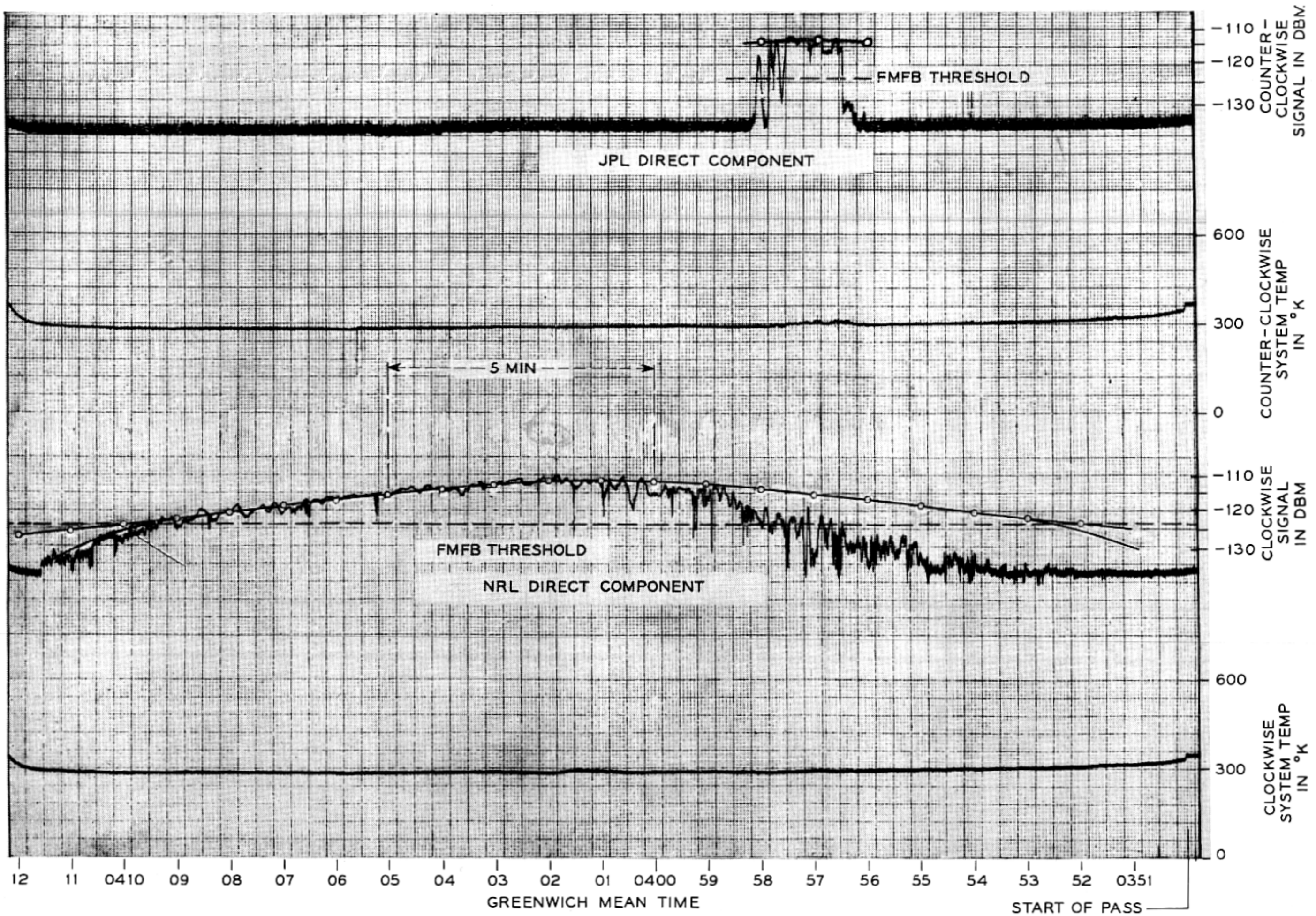


Fig. 12 — Pass 119 — parametric amplifiers (August 22, 1960).

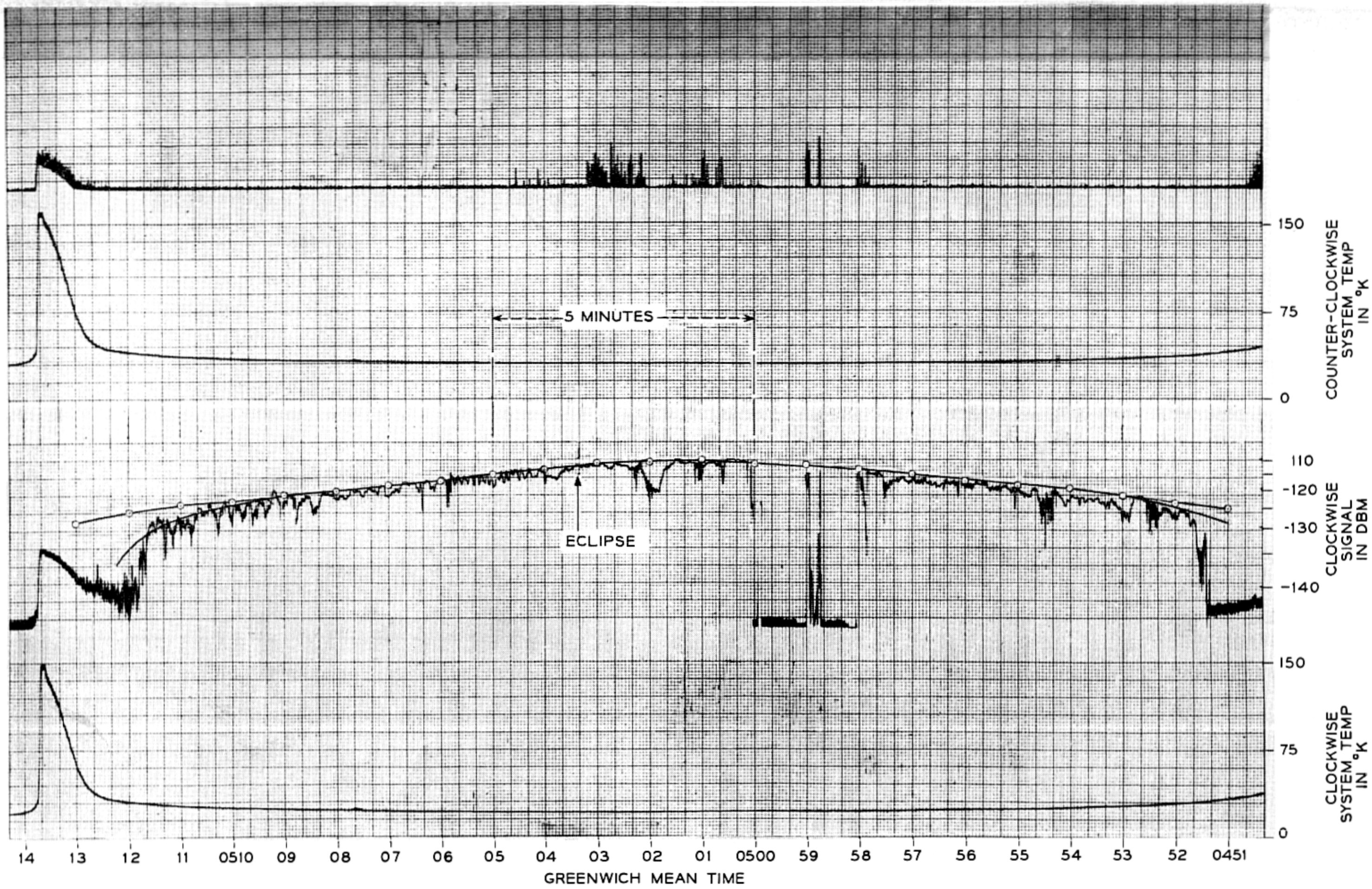


Fig. 13 — Pass 156 — tenth eclipse (August 25, 1960).

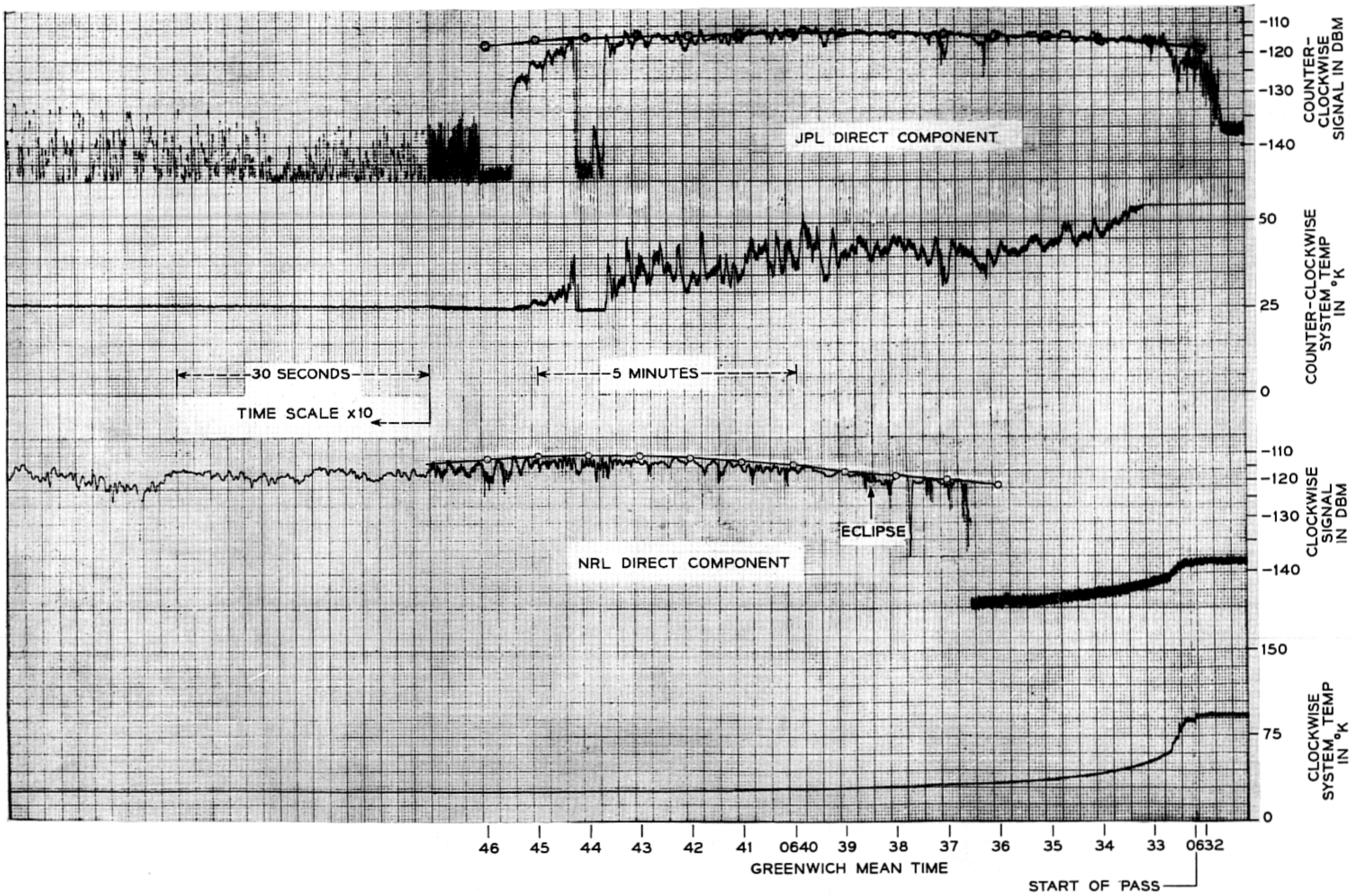


Fig. 14 — Pass 169 — simultaneous reception (August 26, 1960).

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 that areas of much greater radius of curvature may develop. It should be noted in passing that the balloon was predicted to lose positive gas pressure around this time.

Pass 169 (Fig. 14):

On this pass JPL and NRL were simultaneously received 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 JPL signal was in better agreement with the calculated values than was that from NRL, since the satellite eclipsed, and optical tracking could not be maintained by NRL throughout the pass.

Pass 229 (Fig. 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 theoretical, 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 JPL signal gradually decreased. It was later discovered that JPL lost radar track at 0448 and reverted to the drive tape at that time. The small error in the tape then must have slowly moved the JPL antenna away from the balloon, causing the loss in signal strength.

The cross-polarized signal level from JPL was still no higher than the nominal computed value.

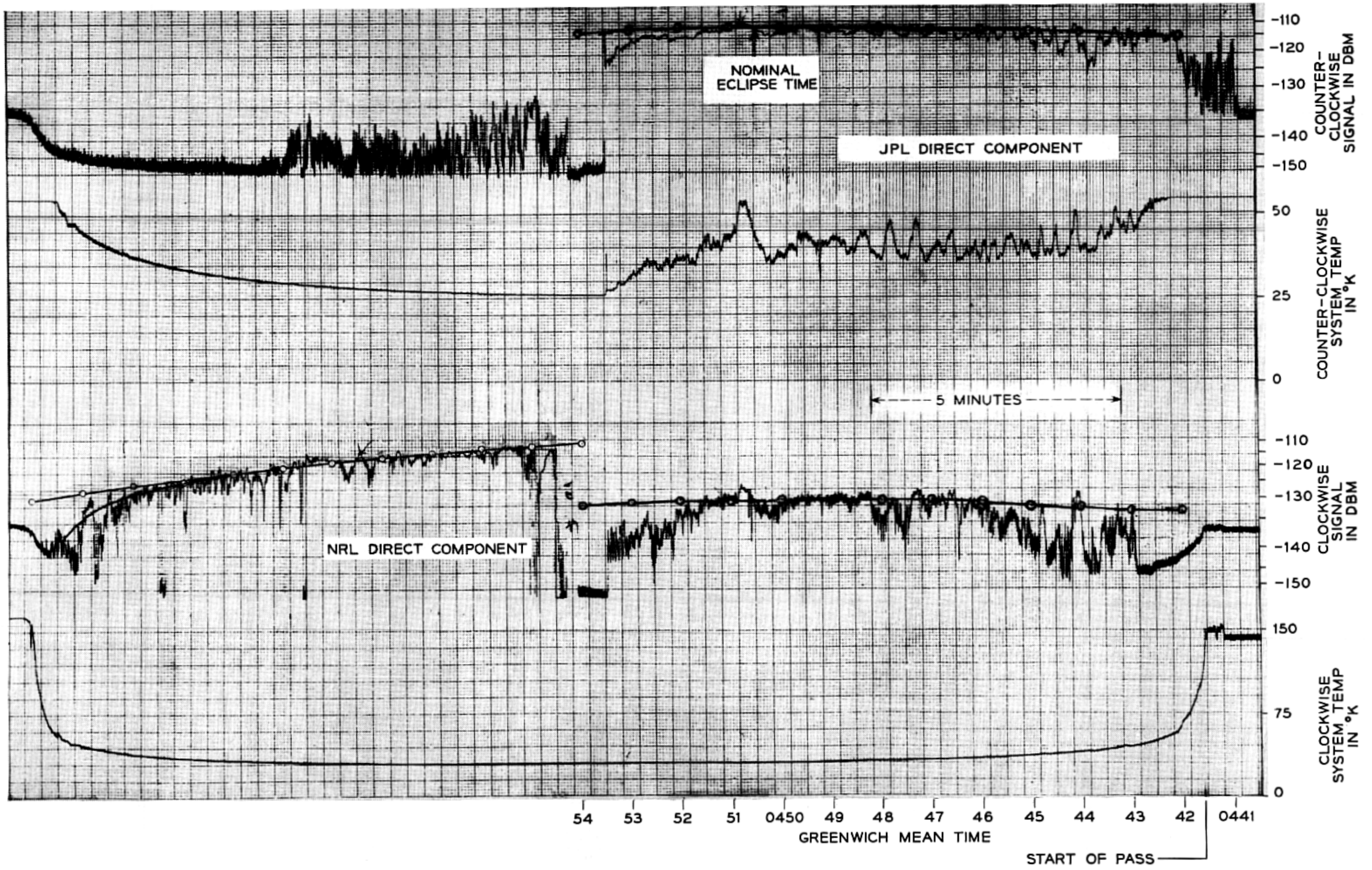


Fig. 15 — Pass 229 — typical scintillations (August 31, 1960).

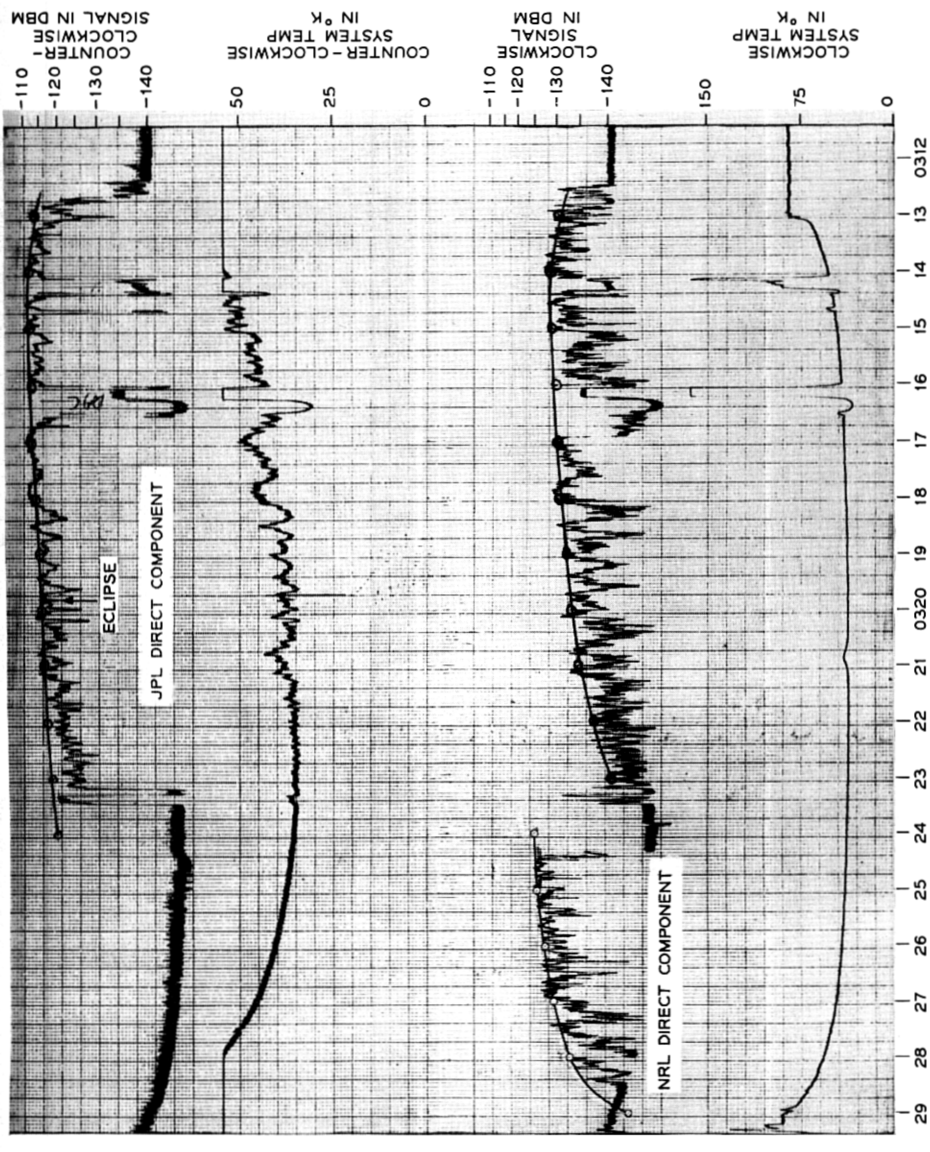


Fig. 16 — Pass 411 — last operation with JPL (September 15, 1960).

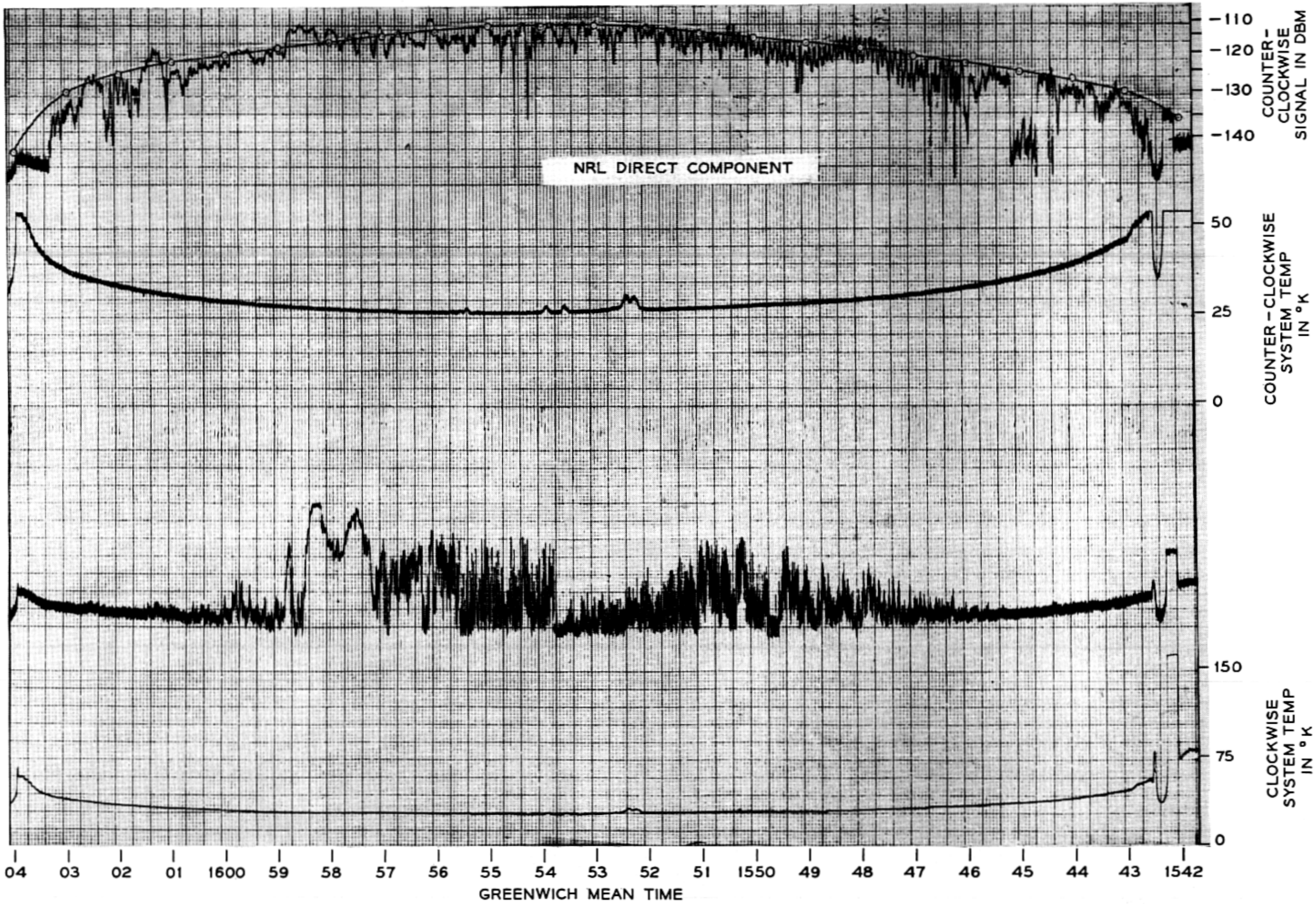


Fig. 17 — Pass 503 — facsimile reception from NRL (September 22, 1960).

Pass 411 (Fig. 16):

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

Pass 503 (Fig. 17):

During this pass NRL signal was switched to the upper record when facsimile transmission was demonstrated from NRL to BTL (see Fig. 6) with excellent results. Special care was taken at GSFC with the drive tapes for this event, and optical checks at BTL showed the predictions to be accurate within $\pm 0.1°$. Incidentally, this was one of the first passes during which it was discovered that the balloon could be seen in broad daylight using 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 were probably due to the side lobes of the horn looking at the sun.

Pass 674 (Fig. 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 (Fig. 19):

It was apparent that the drive tapes for this pass were somewhat in error. The satellite was obscured at NRL, preventing optical tracking, and thus, in an effort to improve the pointing there, NRL was requested to insert 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 both pass 674 and

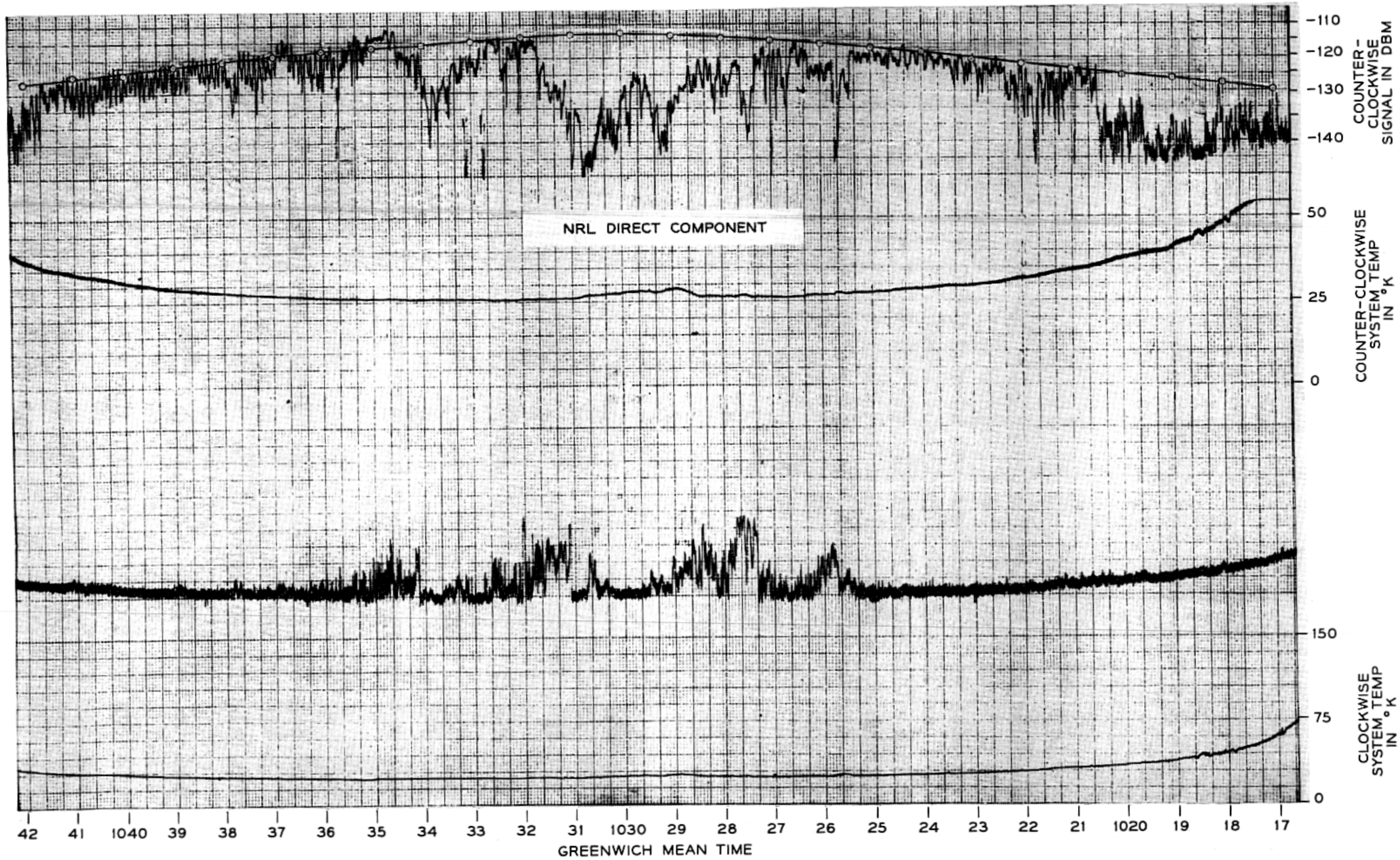
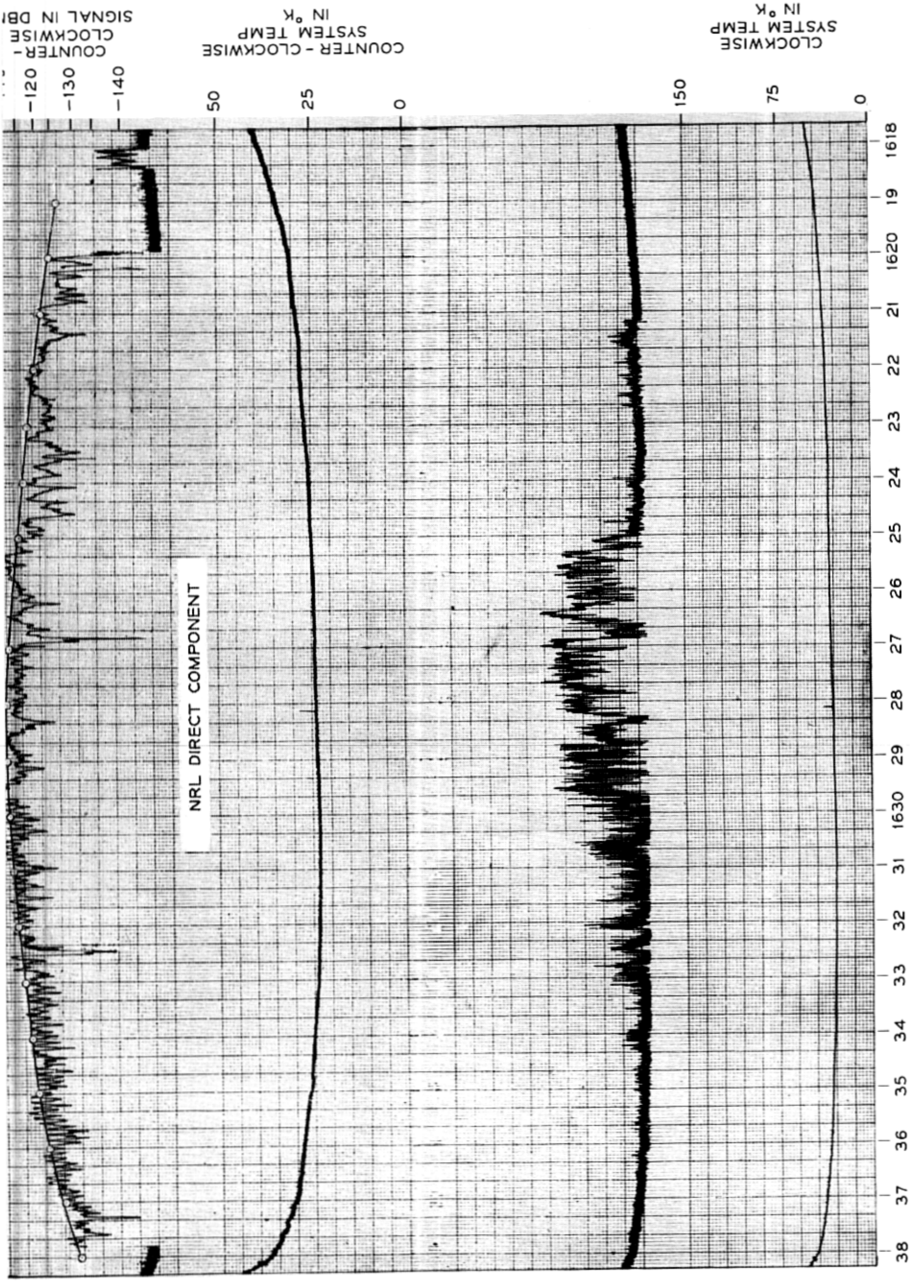


Fig. 18 — Pass 674 — periodic scintillations (October 6, 1960).


COUNTER-CLOCKWISE SIGNAL IN DBM
-120
-130
-140
COUNTER-CLOCKWISE SYSTEM TEMP IN °K
50
25
0
CLOCKWISE SYSTEM TEMP IN °K
150
75
0
NRL DIRECT COMPONENT
1618
19
1620
21
22
23
24
25
26
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29
1630
31
32
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34
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37
38
GREENWICH MEAN TIME

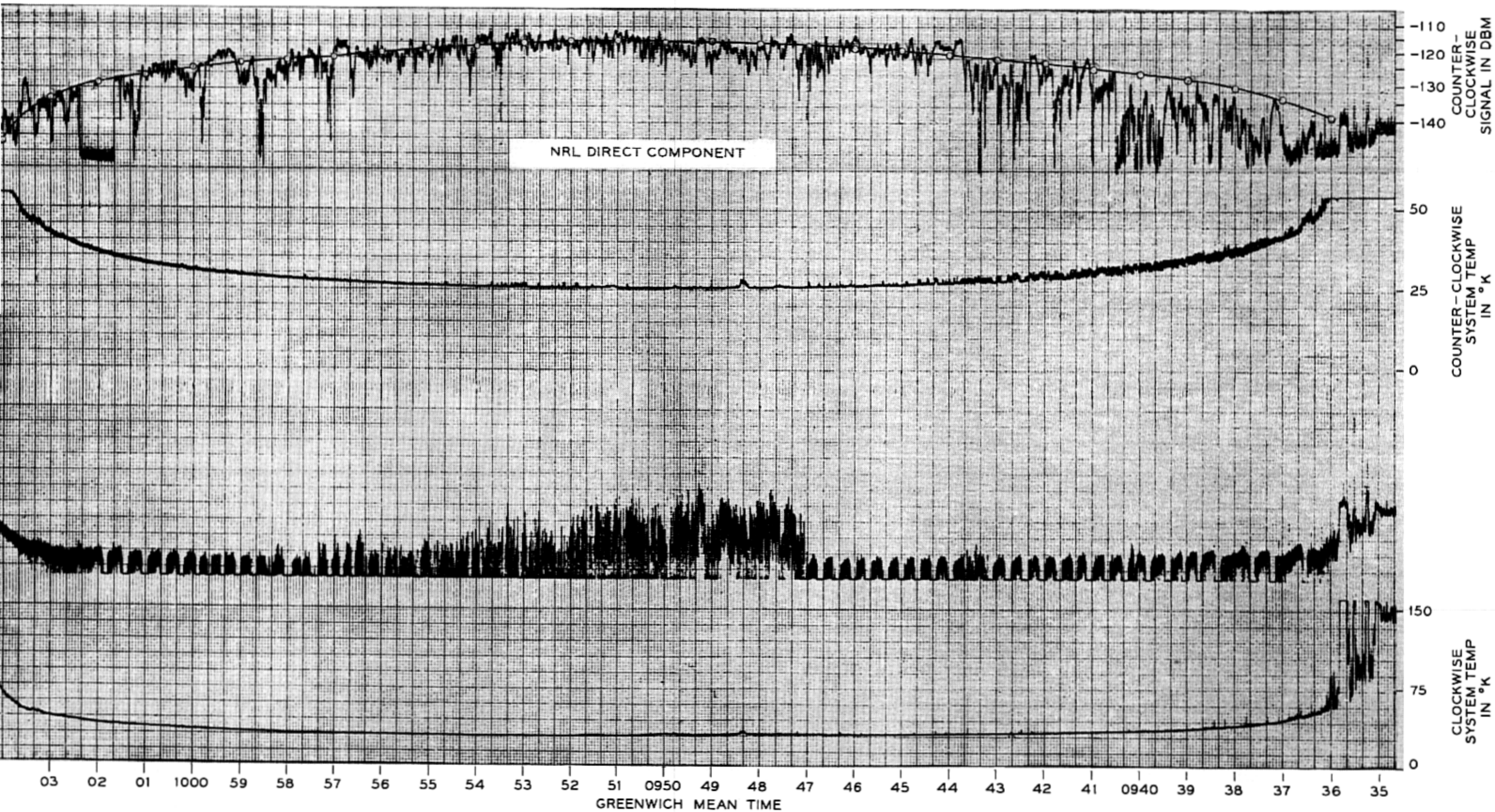

Fig. 20 — Pass 1086 (November 9, 1960).

842, so that again there is no apparent correlation between eclipse and the onset of the periodic scintillations.

Pass 1086 (Fig. 20):

The balloon was in eclipse until 0943:40, when the signal reception from NRL improved immediately, since optical tracking aids could then be employed. Scintillations were still heavy, however, although 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 BTL equipment troubles in that channel.

Pass 1192 (Fig. 21):

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

3.3.2 *Transmission at 960 mc*

Transmission to JPL 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 BTL 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, as earlier checks had shown normal performance. The net result was that the dish was in smooth track only at the following times (GMT) for the brief durations indicated, as determined by later comparison of the dish read-out records with the true orbit:

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

During these periods the BTL 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

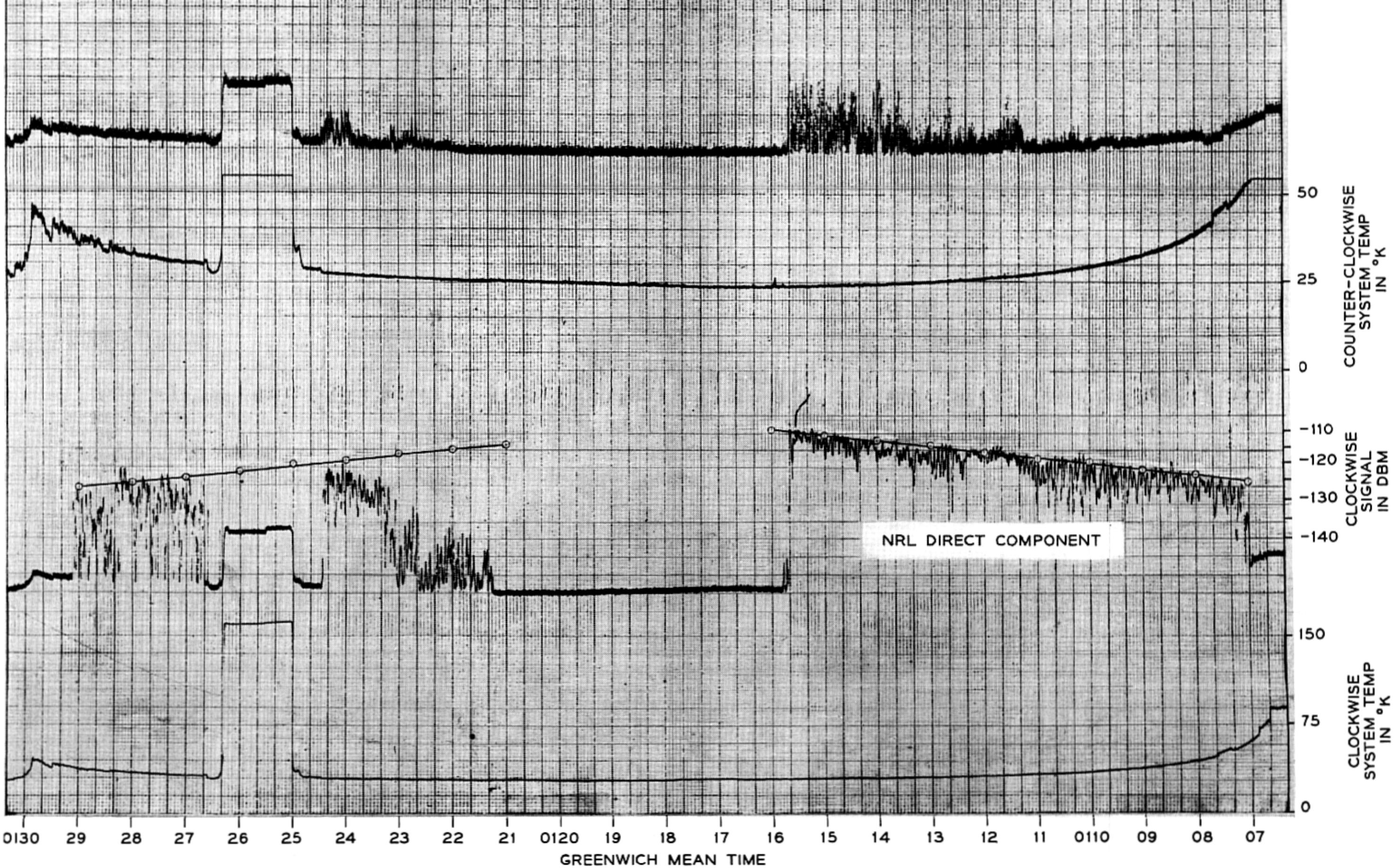

Fig. 21 — Pass 1192 (November 18, 1960).

apply to the dish. This means that the level of the available signal at JPL 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 BTL to JPL at 960 mc, a total of 18 resulted in usable signal recordings at JPL. Fifteen of these have been copied and are shown in Figs. 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 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.

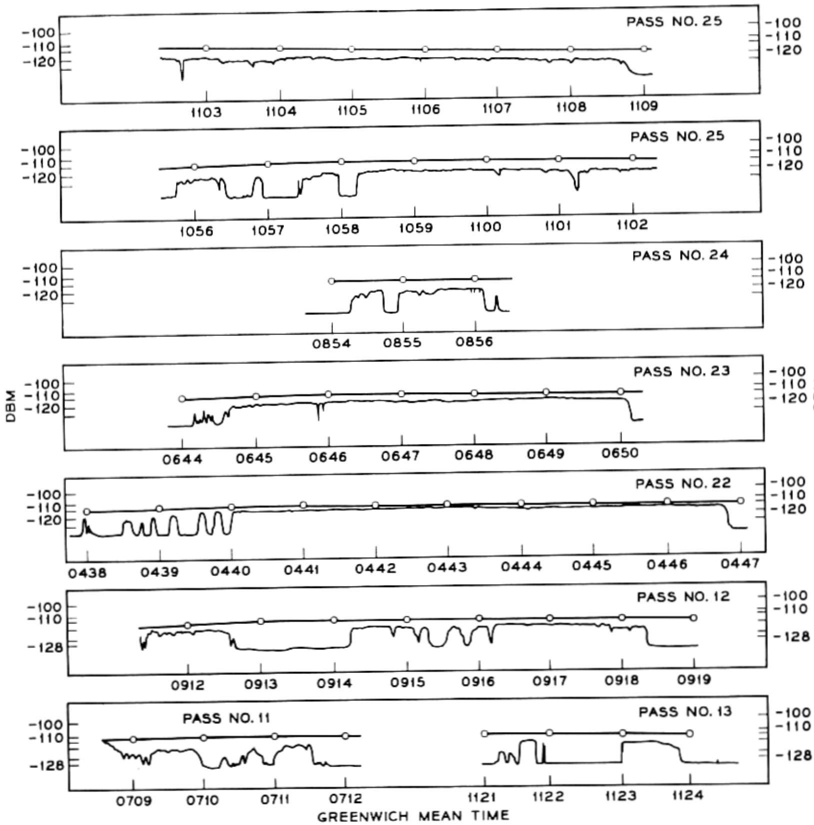

Fig. 22 — Variation of power received by JPL for various passes at 960 mc.

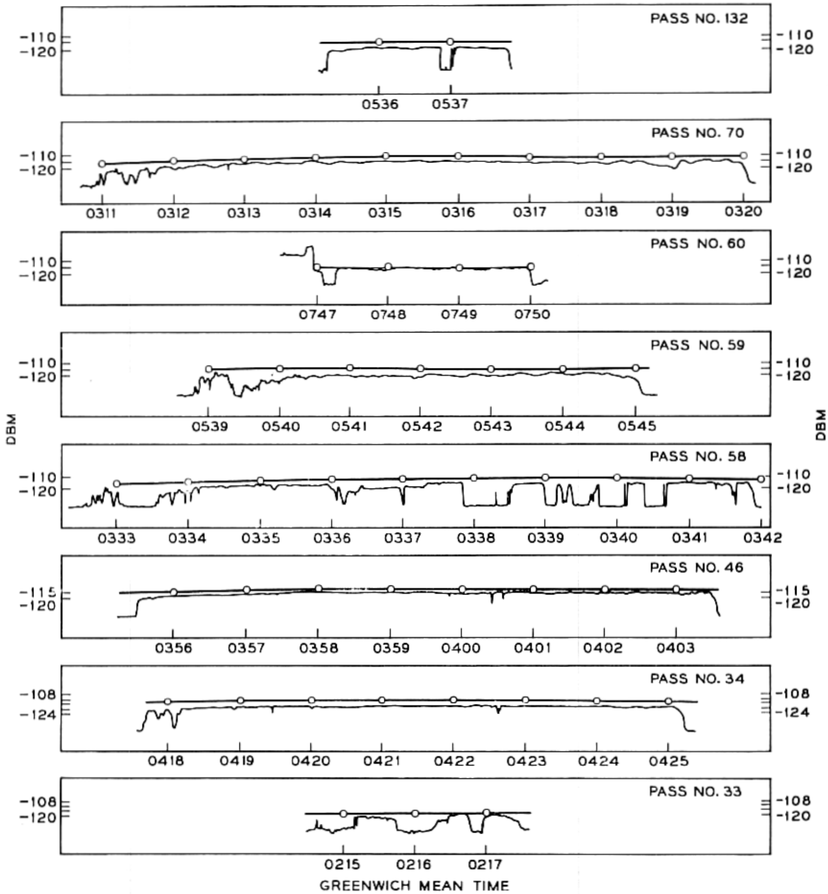

Fig. 23 — Variation of power received by JPL for various passes at 960 mc.

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

3.3.3 *Doppler Shift*

The variation of received frequency with time observed on a few selected passes has been plotted in Figs. 24 and 25, together with the computed curves. These were all taken at 2390 mc, where the Doppler shift is given by

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

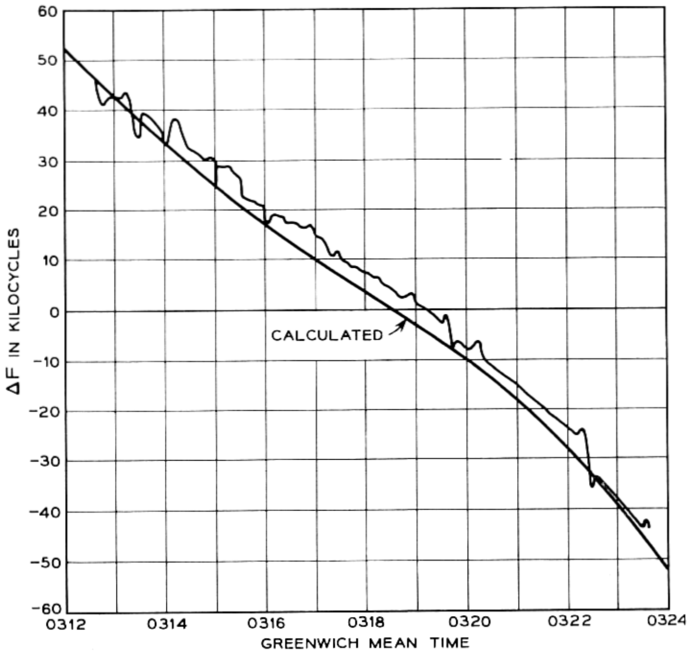

Fig. 24 — Observed Doppler shift on pass 70, JPL to BTL at 2390 mc.

with v_1 and v_2 being the range rates to each station expressed 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 as to the exact frequency of the first beating oscillator in the BTL receiver, nominally 2320 mc; transient differences from the average are generally due to momentary manual adjustments in tuning.

3.4 *Scintillations of Received Signals*

For all passes worked, 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 median signal (estimating an average by eye). 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

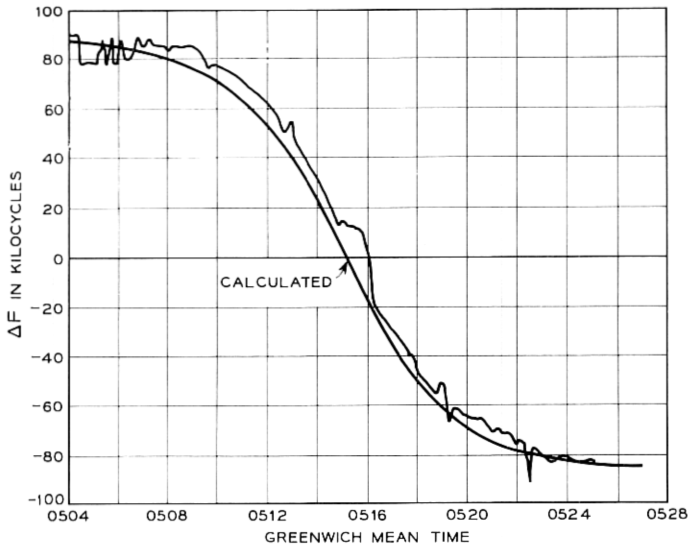

Fig. 25 — Observed Doppler shift on pass 217, NRL to BTL at 2390 mc.

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 Fig. 26, and include results from the JPL and NRL 2390-mc transmissions to BTL, and the BTL 961-mc radar.

Both the JPL and NRL 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 NRL signal were somewhat greater than those from JPL. 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 NRL transmissions.

The BTL radar records show considerably smaller scintillations than those for NRL or JPL, as shown by the plot in Fig. 26. From October 20 to December 20, a total of 14 passes occured when the radar was in operation and records were available at the same time that a signal was being received from NRL. 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,

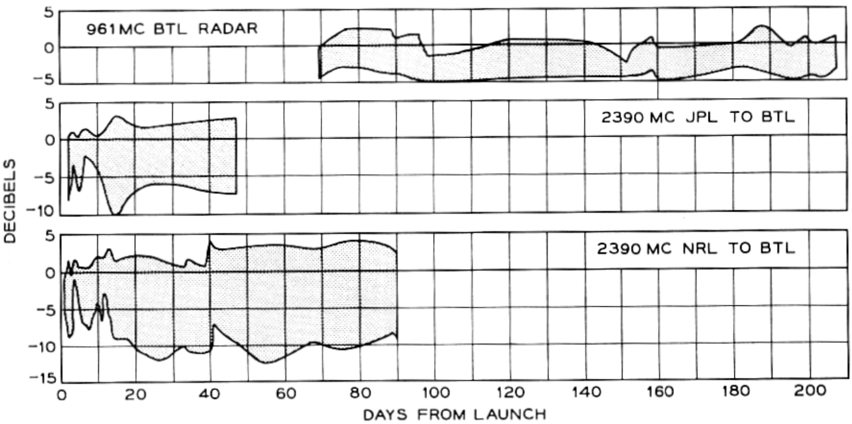

Fig. 26 — Variation of peak-to-peak signal levels with time.

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 it is probably this mechanism that produces an occasional deep fade in the signal.

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

Greater scintillations were observed on all passes for low satellite elevations, regardless of whether operation was with NRL, JPL, or the BTL 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 experienced by others, and has been found to be quite severe, on occasion, for elevation angles below about 10°.

3.5 *FM with Feedback Performance*

On August 16 a series of tests was made on one of the FM demodulators at BTL while signals were being received at 2390 mc. The noise

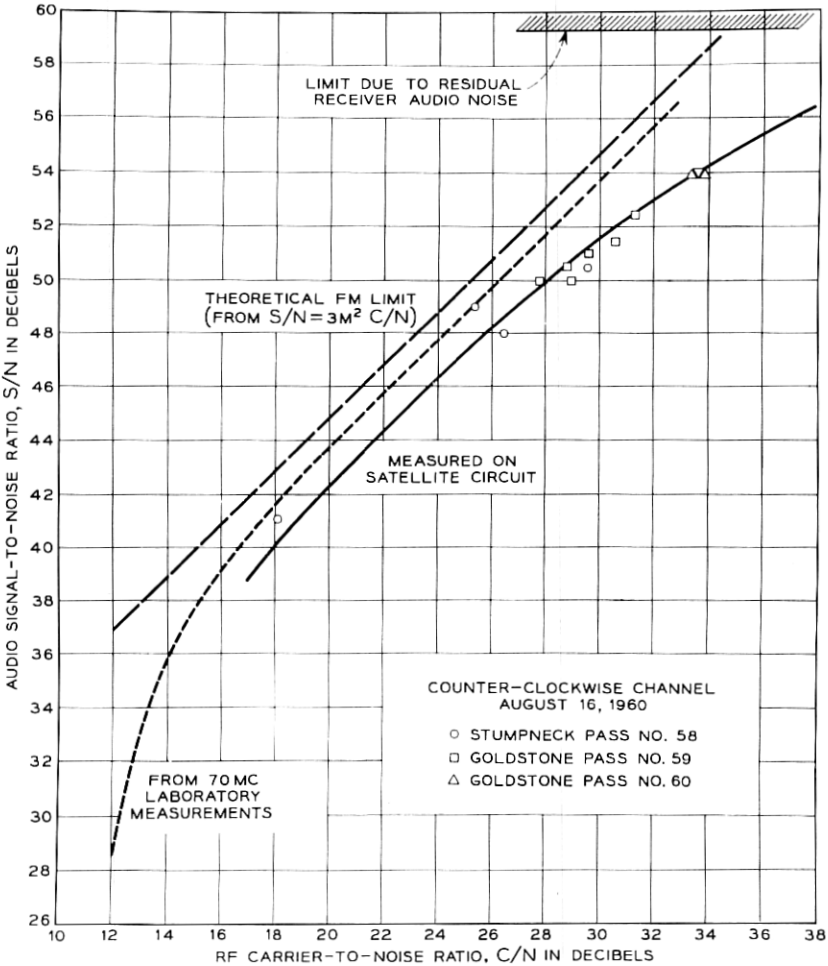

Fig. 27 — Measurements of FM with feedback.

power in the audio baseband, as a function of the input power and feedback factor, was determined using a Western Electric 2B noise measuring set. The results are shown in Fig. 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.

3.6 *Tracking Performance*

3.6.1 *DAC Operation and Orbit Predictions*

The digital-to-analog converter (DAC) proved to be very reliable, and has required only minor repairs and adjustments since installation early in 1960. 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 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° in August 1960, to about 1° in December 1960. Occasional tapes were much better — pass 503 on September 22 being a notable example with 0.1° errors — and a few were much worse. Several factors were responsible for these errors:

1. Anomalies in upper air density occurred due to 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

* The possibility of manually inserting corrections (offsets) proved to be extremely valuable. 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.

based on orbital elements supplied by the Smithsonian Astrophysical Observatory, as mentioned earlier, and the errors were on the order of 0.2°.

3.6.2 *Optical Tracking*

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

3.6.3 *Radar Tracking*

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

3.7 *Operation with Other Stations*

During the course of the Echo experiments, occasional tests were carried out with stations other than the principal participants (JPL and NRL).

3.7.1 *Jodrell Bank, England*

Transmissions were attempted to Jodrell Bank on passes 141 and 142, August 24, 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.

3.7.2 *Centre Nationale d'Etudes des Télécommunications, France*

Reception was reported on pass 70, August 18, 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.

3.7.3 *Stanford Research Institute, Scotland*

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

3.7.4 *Malvern, England*

Successful transmissions of carrier to Malvern occurred on passes 213, 214, and 215 on August 29 at 960 mc. The receiver used a 20-foot dish and a parametric amplifier with a 5 db noise figure.

3.7.5 *General Electric Laboratories, Schenectady, New York*

BTL transmissions were heard in Schenectady at 960 mc during 11 passes in August. The receiver used a 28-foot paraboloid tracked by 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, as follows:

Passes	*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

The analysis of the results is being done by General Electric; a computer is being used to calculate the correlations.

IV. ACKNOWLEDGMENTS

Project Echo could not have succeeded without a high degree of cooperation among the several organizations involved, and in particular the efforts of a great many people at the National Aeronautics and Space Administration, Jet Propulsion Laboratories, Naval Research Laboratories, and Bell Telephone Laboratories deserve recognition in bringing about the results described here.

For Bell Telephone Laboratories, the contributions of many individuals concerned with particular components of the project are acknowledged in the 11 companion papers that follow. Others who were active in the over-all 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 active leadership of J. R. Pierce, R. Kompfner, and C. C. Cutler, whose guidance and continuing interest are gratefully acknowledged.

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REFERENCES

1. Chaffee, J. G., The Application of Negative Feedback to Frequency-Modulation Systems, Proc. I.R.E., **27,** 1939, p. 317.
2. Ruthroff, C. L., and Jakes, W. C., Jr., this issue, p. 1029.
3. Schafer, J. P., and Brandt, E. A., this issue, p. 1041.
4. Ohm, E. A., this issue, p. 1065.
5. Crawford, A. B., Hogg, D. C., and Hunt, L. E., this issue, p. 1095.
6. DeGrasse, R. W., Hogg, D. C., Ohm, E. A., and Scovil, H. E. D., Ultra-Low-Noise Antenna and Receiver Combination for Satellite or Space Communication, Proc. Nat. Elect. Conf., **15,** 1959, p. 370.
7. DeGrasse, R. W., Kostelnick, J. J., and Scovil, H. E. D., this issue, p. 1117.
8. Kibler, L. U., this issue, p. 1129.
9. Ruthroff, C. L., this issue, p. 1149.
10. Klahn, R., Norton, J. A., and Githens, J. A., this issue, p. 1207.
11. DeLange, O. E., this issue, p. 1157.
12. Uenohara, M., and Seidel, H., this issue, p. 1183.
13. Warthman, K. L., this issue, p. 1227.
14. Hogg, D. C., Effective Antenna Temperatures Due to Oxygen and Water Vapor in the Atmosphere, J. Appl. Phys., **30,** 1959, p. 1417.