# Participation of the Holmdel Station in the *Telstar* Project

By WILLIAM C. JAKES, JR.

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*The facility for satellite communication studies at Holmdel, New Jersey, was originally established to take part in Project Echo. This paper describes the modifications required to participate in the Telstar experiments and the results obtained during operations from July 10 to November 9, 1962. Reception of television from the satellite was successfully accomplished, studies were made of the signal levels, and the changes with time of the satellite spin rate and spin axis orientation were determined.*

AUTHOR

## I. INTRODUCTION

### 1.1 *Objectives*

The Holmdel station was originally established in 1959–1960 to carry out communication tests with the passive earth satellite Echo I. A complete description of the station and results obtained during Project Echo are given in Ref. 1. In the summer of 1961 it was decided to take part in the Project Telstar program, and the necessary modifications to the station were begun at that time.

The main objective for Holmdel was to receive an acceptable television picture from the Telstar satellite and relay it back to Andover by land routes for comparison with the original picture transmitted from Andover. The Andover station was also expected to receive a television signal, but it was felt that a demonstration of transmission between two separated points would be meaningful. It was not anticipated at the time that the European stations would be ready by the expected launch date. In addition, having two receiving stations would increase the probability of successful operation.

Secondary objectives for Holmdel operation were:

(a) Measure the 4-gc signal levels to check the satellite transmitted power.



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(b) Determine the location of the spin axis of the satellite and the spin rate.
(c) Carry out any other scientific experiments of value.

### 1.2 *Preliminary Tests*

Before the Telstar launch a number of transmissions were made at 4079.73 mc from Holmdel to Andover via reflections from Echo I and the moon. A 200-watt transmitter was connected to the Holmdel horn-reflector antenna for this purpose. These tests made it possible for Andover to check their tracking capabilities under actual operating conditions. The 961-mc "Project Echo" radar system was used to point the Holmdel horn at the target.

## II. SYSTEM DESCRIPTION

The facilities used in Project Telstar were essentially those used for receiving in the Project Echo experiment. The 20-foot horn-reflector antenna was used for reception and modifications were made in the receiving equipment for use at 4170 mc instead of the 2390 mc used in Project Echo. The 18-foot tracking antenna from the radar system was also modified to permit operation with the 4080-mc beacon signal from the satellite. A simplified block diagram of the system is shown in Fig. 1, and the system is briefly described in the following four sections, covering the functions of reception, tracking, optics, and data recording.

### 2.1 *Receiving System*

#### 2.1.1 *Antenna and Waveguide*

The properties of the horn-reflector antenna are described in detail in Ref. 1. Additional tests were made at 4170 mc before the spacecraft launch, and the resulting characteristics are:

| | |
|---|---|
| Gain | 48.0 db |
| 3-db beamwidth | 0.78° (circular polarization) |
| Projected area | 380 square feet |
| Effective area | 274 square feet |

As anticipated,[1] a difference in elevation boresighting was noted for CW and CCW circular polarization. The measured value was 0.09°, which compares favorably with the calculated value of 0.10°. Final boresighting was done with CCW polarization, which would actually be transmitted by the satellite.

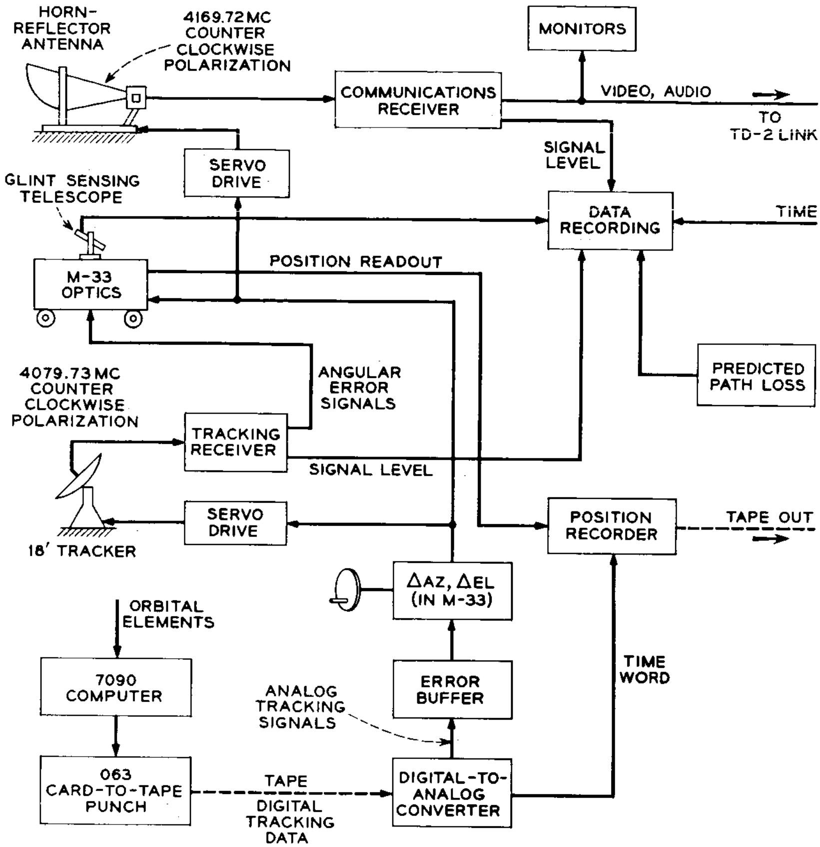



Fig. 1 — General block diagram of Holmdel facilities for Telstar satellite communications experiment.

The horn throat tapered down to round waveguide inside the antenna cab. A low-loss rotating joint was provided between the horn and the waveguide system, which included a 90° phase shifter to convert to linear polarization, a transducer to couple to the maser, and a directional coupler for the introduction of either a noise source or signal source for calibration purposes.

### 2.1.2 *Low-Noise Amplifiers*

The first stage of RF amplification was a maser operating at 4.2°K in liquid helium. This was followed by a parametric amplifier cooled with liquid nitrogen, and then by a traveling-wave tube amplifier. The maser would operate for about 20 hours on one filling of liquid helium, and the paramp for about 10 days on one filling of liquid nitrogen. A certain amount of equalization was provided between the paramp and TWT amplifier to achieve an RF band flat to within $\pm 1$ db over 20 mc. This rather elaborate array of low-noise amplifiers was felt necessary in order to achieve a system with the lowest possible noise temperature and capable of operating over the wide band necessary for television reception. Calculations indicated that if all system objectives were realized a good quality picture could be obtained from the satellite out to a range of 5,000 statute miles. In addition, a certain amount of flexibility was provided in that operations could still be carried on at reduced ranges in the event of failure of any one amplifier. The characteristics of the amplifiers are listed in Table I.

The over-all system noise temperature was measured to be somewhat less than 17°K pointing at the zenith, which included about 4.5°K for waveguide losses, 2.5°K sky noise, 2.5°K for antenna side lobes and heat losses, and 5°K for the maser.

The TWT amplifier was followed by a filter to remove the undesired noise sideband, and then a balanced crystal mixer with 70-mc cascode IF preamplifier. The mixer-preamp noise figure was about 11 db. The IF signal was then brought from the antenna to the main control building via a wrap-around coaxial cable for distribution to the various receivers located there.

### 2.1.3 *Television Receiver*

The heart of the television receiver was the frequency compression demodulator which was used to obtain an improvement in the S/N threshold. This unit and underlying design principles are described in detail in Refs. 2 and 3 and will be only briefly discussed here. As shown by the block diagram in Fig. 2, the incoming 70-mc IF was up-converted to 263 mc and then mixed with a voltage-controlled oscillator (VCO) to give a 70-mc IF. This signal was then amplified, filtered, limited, and demodulated in a frequency discriminator. The baseband signal was

TABLE I

| | Maser | Paramp | TWT |
|---|---|---|---|
| Gain, db | 27 | 31 | 20 |
| 3-db bandwidth, mc | 20 | 30 | >50 |
| Noise temperature, °K | $\approx 5$ | 70 | 625 |

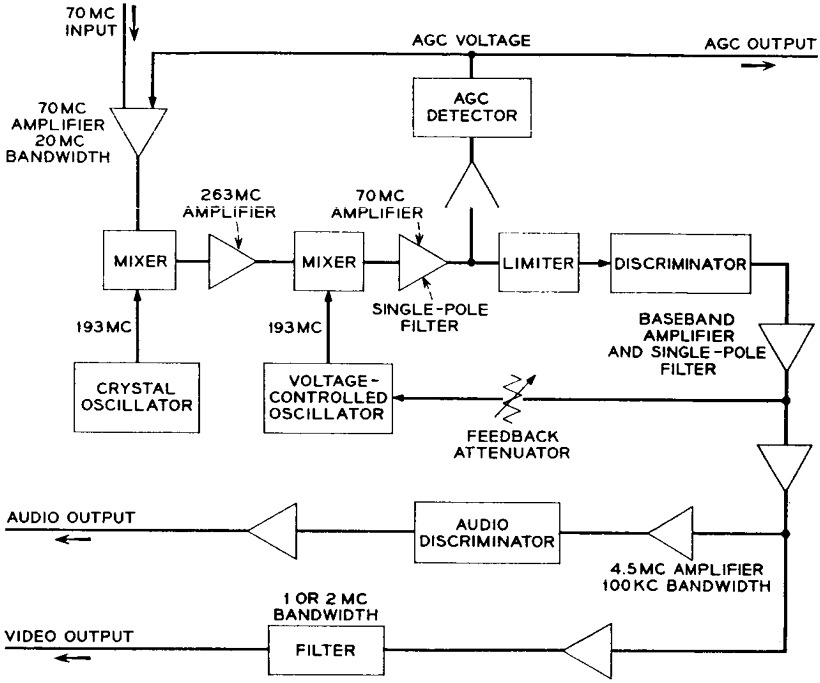



Fig. 2 — Block diagram of frequency compression demodulator.

then amplified, filtered, and applied to the VCO in the proper sense to cause a reduction in the FM index. The baseband signal was also passed on to television monitors for local viewing and to the Bell System microwave relay terminal for transmission to New York City and Andover. The audio portion of the signal was carried on a 4.5-mc FM subcarrier in the baseband, and was separated from the video signal by a filter of 100-kc bandwidth. AGC was supplied by a separate amplifier and detector, and also made available for recording signal strength. The system specifications were:

| | |
|---|---|
| Video frequency deviation | ±7 mc |
| Audio channel deviation | ±0.7 mc |
| Audio subcarrier deviation | ±0.05 mc |
| Open loop bandwidth | 1.0 mc |
| Closed loop bandwidth | 6.7 mc |
| Feedback factor | 12 db |
| Threshold improvement | 5–6 db. |

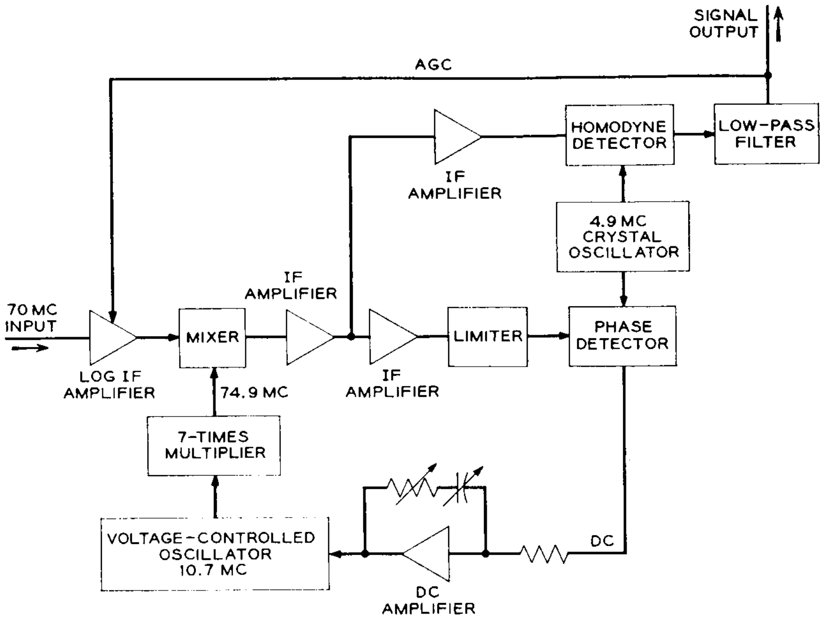



Fig. 3 — Block diagram of phase-locked loop.

### 2.1.4 *Phase-Lock Receiver*

In order to obtain signal level measurements at times when the signal might be below the threshold of the frequency compression demodulator, a phase-lock receiver was provided with a much narrower bandwidth. Because of the narrow band it was expected that for these tests it would be necessary for Andover to transmit a crystal-controlled, unmodulated carrier.

A block diagram of the receiver is shown in Fig. 3. The 70-mc input was passed through a logarithmic IF amplifier, and then converted to 4.9 mc by mixing with a 74.9-mc signal from the VCO. This IF was amplified, limited, and then phase-detected by comparison with a 4.9-mc crystal oscillator. The output of the phase detector was then passed through a filter to the VCO in the proper sense to cause the VCO frequency to lock in to the incoming frequency. The 4.9-mc IF was also separately detected in a homodyne detector with a low-pass output filter. The output voltage was then recorded for signal level determinations.

Receiver characteristics:

| | |
|---|---|
| Closed-loop bandwidth | $\approx$100 cps |

| | |
|---|---|
| Maximum tracking rate | 20 kc/sec$^2$ for large signal |
| Signal channel bandwidth | 2 kc |
| Tuning range | ±200 kc. |

### 2.1.5 *Video Relay*

The video baseband signals were connected to standard Bell System video relay equipment in the control building, passed by cable to a microwave relay transmitter connected to a small paraboloid antenna, and transmitted to a nearby TD-2 microwave relay tower for transmission to New York City. The audio portion of the signal was sent by regular land-line circuits.

### 2.1.6 *Expected Signal Levels*

Ignoring effects such as atmospheric attenuation and tracking errors, the received signal level may be calculated from

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2$$

where
$P_t$ = satellite transmitted power
$G_t$ = satellite transmitting antenna gain
$G_r$ = receiving antenna gain
$\lambda$ = wavelength
$r$ = slant range.

Two cases were of importance at Holmdel: reception of the 4079.73-mc beacon signal on the tracking antenna, and reception of the 4169.72-mc communications signal on the horn-reflector antenna. For the nominal transmitted power, the expected received levels and S/N ratios are summarized in Table II for a maximum practical operating range of 5,000 statute miles. The receiving system temperature is specified at an antenna elevation of 15°.

The values of S/N ratio given are the worst that would be encountered, since at higher elevation angles the system temperature and slant range both decrease. Taking into account the acceptable operational

TABLE II

| Frequency mc | $G_t$ db | $G_r$ db | $P_t$ dbm | $P_r$ dbm | Bandwidth kc | Rec. Temp. °K | S/N Ratio db |
|---|---|---|---|---|---|---|---|
| 4079.73 | 0 | 38.9* | 13 | −130.9 | 0.1 | ≈420 | 21 |
| 4169.72 | 0 | 48.0 | 33 | −102.0 | 2000 | ≈30 | 19 |

* Includes cable and scanning loss.

S/N thresholds of 14 db for the television receiver and 6 db for the tracker it is evident that both systems would operate satisfactorily over the major portion of every satellite pass with some margin.

### 2.2 *Tracking at Holmdel*

As shown in Fig. 4, the tracking information was principally derived from the predicted satellite trajectory. Corrections were then manually applied during the pass by using the angular error information provided by the beacon tracker. At times when the satellite was close enough to be seen optically the corrections could also be provided by means of the tracking telescope. As a last resort the corrections could be determined by scanning the horn-reflector antenna manually in azimuth and elevation to maximize the signal.

#### 2.2.1 *Determination of Predicted Position*

The local azimuth, elevation, and corresponding rates of change of these quantities as a function of time were computed from the "modified orbital elements" of the Telstar satellite orbit for each pass. Details of the

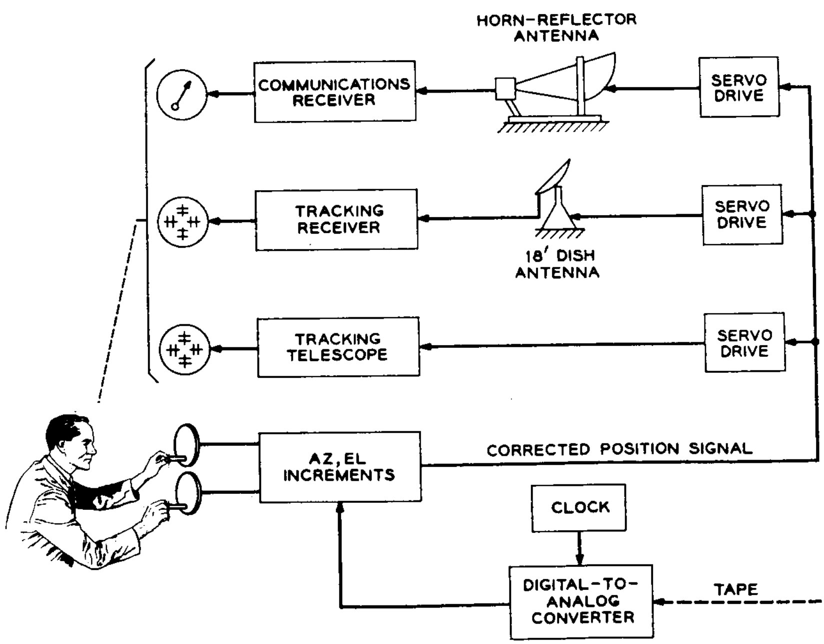



Fig. 4 — Block diagram of tracking modes at Holmdel.

method are given in Ref. 4, and hence will be only briefly summarized here. It was assumed that the orbit could be defined at a given time (epoch), $T_0$, by six parameters unchanging with time: eccentricity, $e$, and focal distance, $f$ (perigee), of the ellipse and its inclination, $i$, to the earth's equator; the angle of perigee $\omega_0$ (measured from the equator in the plane of the ellipse), the ascending node longitude, $\Omega_0$, (determined by the intersection of the orbital plane with the equator), and the perigee-perigee period, $P_0$. In addition, the two main precessions, apsidal and nodal, were assumed to vary linearly with time. From this description of the orbit it was possible to calculate local "look-angles" by first solving Kepler's equation and then using simple geometric transformations. The Telstar satellite orbit proved to be so stable that predictions accurate to a few tenths of a degree for more than a month could be made using this method and an accurate set of orbital parameters.

Following determination of the azimuth and elevation of the satellite referred to the Holmdel station for a given pass by the 7090 computer, the data were transferred to a standard five-hole paper tape along with the corresponding time for each point. The tape was then read automatically in real time by the digital-to-analog converter[1] (DAC) which provided appropriate analog output signals for positioning the various elements of the system. An error buffer unit, which stored the current azimuth rate, was also provided in the azimuth channel. If an obvious error occurred in the azimuth signal from the DAC (caused possibly by an erroneous punch in the tape) the error buffer sensed the fact and switched the drives to the stored rate, which would then keep the antennas moving along an approximately correct path until remedial steps could be taken. It was the intent to provide a similar unit for the elevation channel, but time did not permit.

Before the analog position signals were transmitted to the antennas and optics, they were finally passed through the manually controlled device for inserting differential corrections in azimuth and elevation.

### 2.2.2 *Beacon Tracker*

The beacon tracker was essentially a modification of the Echo radar receiver.[1] Briefly, the original 961-mc receiver consisted of an 18-foot diameter paraboloid with a conically scanned beam for angular error determination, a low-noise RF amplifier and down-converter, AFC and gated narrow-band IF amplifier circuitry, quadrature phase detectors for extracting voltages proportional to azimuth and elevation errors, and appropriate error displays. The 4-cps conical scanning feature was preserved for angular error determination, but gating the receiver off and on was no longer necessary since the tracker worked on the CW signal from the Telstar spacecraft beacon.

The RF portion of the system had to be converted from 961 mc to 4080 mc, and for this purpose a new circularly polarized turnstile feed for the 18-foot paraboloid was provided, along with a parametric amplifier for the new frequency. The dish surface was lined with window screening to render it more opaque to the higher frequency. As shown in Fig. 4 the angular error was presented to the operator by the position of the spot on a CR tube, and by introducing offsets he could zero the indicated errors. Since the horn-reflector antenna and the tracking antenna had been previously boresighted together, the horn antenna would then also point at the target.

In order to measure the received signal level at 4080 mc the tracker AGC voltage was calibrated in terms of input signal power and recorded. A determination of the apparent beacon power output from the satellite could then be made. The beacon tracker system parameters were:

| | |
|---|---|
| Antenna gain | 42.4 db |
| Cable loss | 1.2 db |
| Radius of conical scan | 0.4° |
| Scanning loss | 2.3 db |
| Antenna 3-db beamwidth | 0.8° $\times$ 1.0° |
| System noise figure | 4 db |
| System threshold | $-145$ dbm |
| System pointing sensitivity | $\pm 0.03°$ |
| Tracking IF bandwidth | 500 cps. |

### 2.2.3 *Optical Tracking*

The telescope used on Project Echo[1] was also used for Project Telstar. It was part of an M-33 surplus fire-control radar, and was characterized more by convenience of operation than by high sensitivity. The field of view was 6° with a magnification of 8x and a 2-inch diameter objective lens. On a clear night stars of magnitude $+6$ to $+7$ could be seen, comparable to the magnitude of Telstar when it approached to 1000 miles or less.

In addition to the M-33 telescope a spotting telescope, mounted on the glint telescope, was available for checking the tracking optically. It had a 3-inch diameter objective lens and thus could see much fainter objects than the M-33 telescope. On the few occasions when the satellite was observed, the spotting telescope was used to check on the beacon tracker.

### 2.3 *Glint Telescope*

In order to maintain a favorable aspect of the satellite antenna patterns with respect to the earth and to insure that all solar cells received an equal amount of sunlight the satellite was given an initial spin of 178 rpm about an axis normal to the ecliptic plane. The interaction of a spinning conductor with the earth's magnetic field, however, introduced a force which tended to move the spin axis away from its preferred orientation. To follow this motion, and to check on the effectiveness of corrective measures when they were applied, three mirrors were mounted on the satellite's surface in order to reflect flashes ("glints") of sunlight to earth. Two mirrors were mounted tangent to the sphere at an angle of 95° from the spin axis spaced 120° apart in longitude, and a third mirror at 68°. For a given location of the spin axis there was then a unique time during a given pass when the sun-satellite-observer angle was such that the observer could see a glint from one of the two sets of mirrors. Conversely, knowing the time of the glint and the satellite position (given by the orbital parameters), a cone could be determined on which the spin axis must lie. Another such observation determined a second cone, and the spin axis must then lie along one of the two intersection lines of these two cones. A third glint observation, of course, would remove the ambiguity; however, solar aspect information from solar cells on the satellite was generally available at the same time, and was sufficiently accurate to eliminate the wrong intersection line. The position of the spin axis was usually specified in terms of the right ascension and declination of the intersection of the axis with the celestial sphere.

The glint telescope itself was a 12-inch Cassegrain with a 0.5° field of view seen by a photomultiplier at the focus. Sensitivity was such that the glints could be detected out to a slant range of 3,000 miles or more, depending on viewing conditions. (Of course, the glints could only be seen at night.) The telescope was mounted on the M-33 optical tracker, and was pointed at the target by the methods described above to an accuracy well within the angular field of view. Because of the finite size of the sun, a glint event usually consisted of a train of flashes occurring at the spin rate of the satellite and lasting from ten to thirty seconds. The mid-point of the train was taken as the time of the glint. By using a precise crystal oscillator for time comparison it was also possible to determine the spin rate of the satellite by measuring the interval between successive flashes. A more detailed description of the telescope and associated electronics is given in Ref. 5.

### 2.4 *Data Recording*

A variety of recording means was provided in order to insure that no significant information during a Telstar satellite pass was lost. The areas of interest may be grouped as follows:

(a) Signal levels
(b) Glint telescope
(c) Spin rate
(d) Audio portion of the television signal
(e) Comments of operating personnel during a pass
(f) Tracking data
(g) Time synchronization of all recordings.

A block diagram of the recording system is shown in Fig. 5.

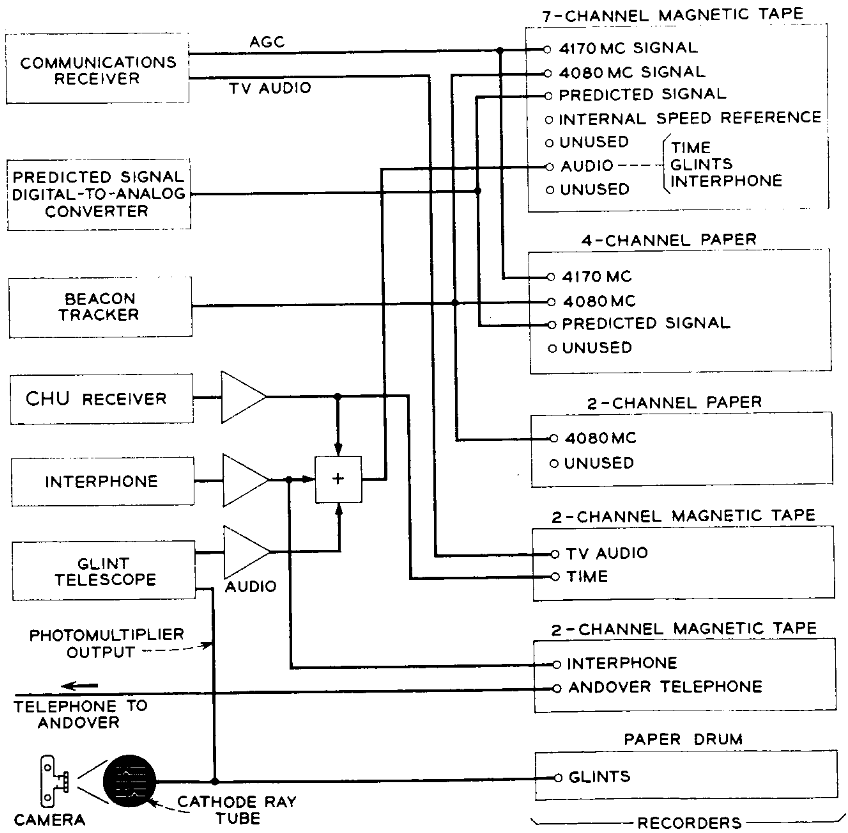



Fig. 5 — Block diagram of data recording facilities.

#### 2.4.1 *Signal Level Recording*

The AGC voltage from the beacon tracker receiver was recorded on a paper recorder at the tracker location, and also in the main control building on the 7-channel magnetic tape recorder and the 4-channel paper recorder. This voltage was calibrated in terms of signal level before and after every pass.

A voltage from the communications receiver was also recorded by the magnetic and paper recorders in the control building. This voltage was obtained either from the frequency compression demodulator AGC during video transmission, or from the phase-lock receiver when a crystal-controlled carrier was transmitted. Signal level calibrations were also made before and after every pass.

Knowing the slant range to the satellite, frequency, and gain of the antennas, it was possible to calculate the received power as a function of time for a given transmitter power. This calculation was included in the computer program used for making the tracking tapes, making it possible to provide another punched paper tape containing the predicted received power level at four-second intervals. This tape was fed into a fairly simple digital-to-analog converter and read in real time during a Telstar satellite pass. The output voltage was proportional to the received signal in dbm, and was recorded in the control building on the magnetic and paper recorders. It was thus possible to compare predicted signal levels with those actually being observed during the pass.

#### 2.4.2 *Glint Telescope Recording*

The pulses of light incident on the glint telescope photomultiplier during a glint event were recorded in three ways:

(a) Photographs of a CR tube with the pulses on the vertical plates and a linear time raster on the horizontal plates.
(b) Pen deflections of a paper drum recorder.
(c) Tone bursts on the audio recording channel of the 7-channel magnetic recorder. Audio time signals from radio station CHU were also recorded on this channel.

This variety of methods for glint recording facilitated the determination of the exact time of the glints and the flash spacing for spin rate determination.

#### 2.4.3 *Spin Rate Recording*

The signal level voltage from the communications receiver contained a number of Fourier components due to the satellite rotation and the slight nonuniformity of the azimuthal antenna radiation pattern. The fundamental component occurred at the spin rate, approximately 3 cps, and was selectively amplified by a high-Q ($\approx$25) amplifier tuned to the actual spin frequency. The amplifier output was a close approximation to a sine wave whose period was then measured with a standard counting instrument by manually recording the time required for ten periods. An average of 500 periods was actually used to determine the spin rate, achieving an accuracy of about $\pm$0.05 rpm.

The spin rate was also independently determined on passes when the glints were observed by comparing the time between glints to the period of an accurate, crystal-controlled oscillator. An accuracy of about $\pm$0.02 rpm could be achieved.

#### 2.4.4 *Audio Recording*

The audio portion of the television signal was recorded on one channel of a 2-channel magnetic tape recorder, with time signals recorded on the other channel.

#### 2.4.5 *Personnel Comments*

All operating personnel at Holmdel were in communication with each other by a common telephone circuit. This circuit was recorded on one channel of another 2-channel magnetic recorder. The comments obtained in this way occasionally proved very helpful in subsequent data reduction, since it was impossible to keep a written log of all the last-minute changes in system performance or operation that occurred on various passes.

The Holmdel station was also in constant communication with Andover by means of a private telephone circuit for purposes of coordinating operations. This circuit was recorded on the other channel of the 2-channel recorder mentioned above, and served the same purpose as the local interphone recording.

#### 2.4.6 *Recording of Tracking Data*

During a pass the azimuth and elevation offsets required to track the satellite accurately were recorded at approximately one-minute intervals in a written log. The true azimuth and elevation could then be determined later by adding the offsets to the predicted positions during the pass. The true angles were used to make slight corrections in the orbital elements so that more accurate determination of the satellite position could be made for use in other studies concerned with the satellite.

Towards the end of the Holmdel experiments with the Telstar satellite an analog-digital converter unit was acquired which encoded the true azimuth-elevation angles into punched paper tape, along with time, at selectable intervals of 1, 2, 4, or 8 seconds. This unit made the task of improving the orbital elements considerably easier

#### 2.4.7 *Time Synchronization of Recordings*

The station clocks were generally set to the correct time by referring to the time signals broadcast by the Canadian station CHU on 3.33 mc, 7.335 mc, or 14.670 mc. As mentioned above, the magnetic tapes were time referenced by actually recording CHU on one audio channel. The 4-channel paper recorder included an auxiliary time marking pen which was actuated by a pulse every 10 seconds from the clock chain in the DAC. The paper recorder for the beacon tracker also contained a time marking pen which was supplied with 1-second and 1-minute pulses generated locally by synchronous motors. These were initially synchronized with the station clocks. The paper drum recorder for the glint telescope was manually time-tagged by referring to the station clocks.

## III. EXPERIMENTAL RESULTS

### 3.1 *Preliminary Tests*

During the period from April 11–July 6, 1962, transmissions were attempted to Andover via reflection from Echo I on 36 passes, with increasingly successful results culminating in the demonstration of satisfactory operation at Andover of all the various tracking modes. These tests helped to confirm, among other things, that it was possible to predict a satellite trajectory for Andover and have the horn properly follow the predictions, that the sense of polarization of the microwave signals was correct, and that the system thresholds at Andover were as expected. The Echo tests were challenging, since the signal levels were marginal and had large, rapid fluctuations due to the wrinkled nature of the balloon.

During the same period of time mentioned above, transmissions were made to Andover via reflections from the moon at 4080 mc on a total of five separate occasions, again with increasing success. Although these tests were not as demanding as the Echo tests, they did serve a useful purpose in checking system performance. The average value of signal received from the moon indicated its scattering cross-section at this frequency to be about 20 db below a perfect sphere of the same size.

### 3.2 *Television Reception*

Starting with the first possible pass (No. 6) television was received at Holmdel on a total of 23 passes with excellent results. A brief summary of the more noteworthy demonstrations seen at Holmdel is given in Table III.

Fig. 6 shows pictures of the Holmdel monitor during scenes from the earlier passes. These are reproductions of selected frames from a 16-mm movie camera using a high-speed film, which accounts for a certain amount of graininess in the photographs. The streaks of light are reflections of room lights in the monitor glass surface. Also shown is a photograph of the picture seen at Andover after being relayed from Holmdel by land routes. The 1.0-mc filter was in the output circuit of the Holmdel receiver when these pictures were taken. The general impression was that a 1-mc bandwidth provided a picture of quite acceptable quality. On a few occasions the 2.0-mc filter was tried, and resulted in somewhat improved definition. It is evident from the photograph of the multiburst test pattern that the 1.0-mc filter had a fairly slow cutoff characteristic, which probably accounts for the qualitative appraisal of picture mentioned above.

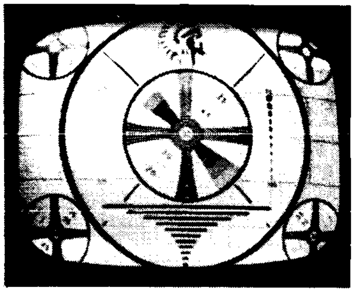
The predicted threshold of the television receiving system was verified during operations with the Telstar satellite, as the picture showed essentially no noise out to maximum range. On a few occasions, however, a signal from a nearby microwave relay transmitter operating at 4165 and 4175 mc produced interference either by direct propagation or by scatter from thunderstorms. This caused a noticeable deterioration in the S/N ratio.

The audio portion of the television signal was received with acceptable quality.

TABLE III

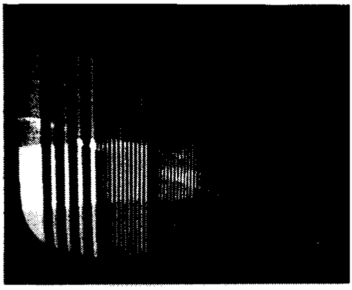
| Date | Pass | Test |
|---|---|---|
| July 10 | 6 | First transmission from satellite |
| July 11 | 15 | First television from France |
| July 12 | 16 | First television from England |
| July 23 | 123 | Special program to Europe |
| | 124 | Special program from Europe |
| July 24 | 133 | Special program from France |
| | 134 | Special program from England |
| July 31 | 196 | Special program from Sweden |

FIRST PICTURE RECEIVED AT HOLMDEL
PASS NO. 6, JULY 10, 1962

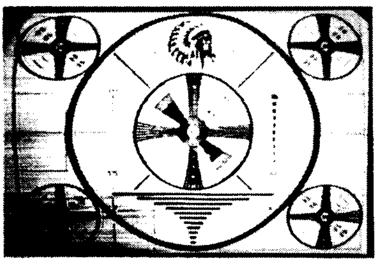


INDIAN HEAD TEST PATTERN

LIVE VIDEO ON PASS NO. 6



0.5 MC 1.5 MC 2.0 MC 3.2 MC
MULTIBURST TEST PATTERN



PICTURE SEEN AT ANDOVER AFTER
RELAY FROM HOLMDEL

Fig. 6 — Television received at Holmdel from Telstar spacecraft repeater.

### 3.3 *Data Reception*

On pass 270, August 8, 1962, transmission of high-speed data was demonstrated at Holmdel. The data were sent at a rate of approximately 40 kilobits/sec from a computer at the Murray Hill, New Jersey, location of the Bell Laboratories to Andover for transmission to the Telstar satellite. From the satellite it was relayed to the Holmdel station, and then sent by microwave relay to the computer in the new laboratory building at Holmdel, some 2 miles from Crawford Hill. The accuracy of data transmission was found to be as good as that obtained over the usual land line route from Murray Hill to Holmdel.

### 3.4 *Received Signal Levels*

Using the expression for received power given in Section 2.1.6, a comparison between predicted level and observed level was made for one point on every pass worked for both the beacon signal and communication signal. The point used on each pass was chosen to fulfill the following conditions as nearly as possible:

(a) Angle between the spin axis and observer-satellite line within $90° \pm 30°$. This insured that the gain of the spacecraft transmitting antenna could be assumed to be $0 \pm 1$ db
(b) Tracking satisfactory at the time
(c) System operation normal.

Assuming the system parameters given in Section 2.1.6, the following expressions were used to calculate signal levels:

$$\text{Beacon signal: } P_r = -116.9 - 20 \log \left(\frac{r}{1000}\right), \text{ dbm}$$

$$\text{Communications signal: } P_r = -88.0 - 20 \log \left(\frac{r}{1000}\right), \text{ dbm,}$$

where $r$ is the slant range in miles.

Any differences between calculated and observed signal levels may be interpreted in terms of departures of the satellite communications repeater transmitted power from nominal values. Points calculated on this basis are plotted in Fig. 7. The gap in the data for the beacon signal between pass 198 and 762 is due to the use of the tracker antenna in the skinny route terminal project (see Section 3.8). After pass 606 the horn antenna receiver was used for measuring the beacon signal and reception at 4170 mc was discontinued.

The data show that the power transmitted by the Telstar satellite repeater was 2 watts at 4170 mc within a measurement accuracy of $\pm 2$ db and at least 20 mw at the beacon frequency. These were the design objective values for the satellite. No significant changes with time were observed.

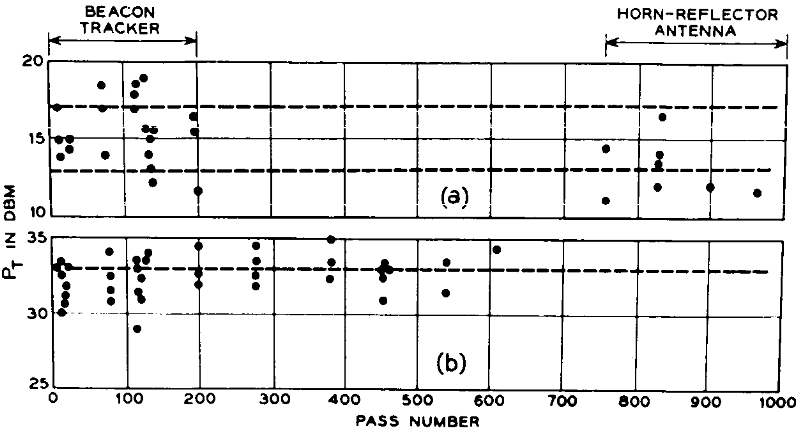



Fig. 7 — Telstar spacecraft radiated power inferred from signal level measurements at Holmdel. (a) Apparent beacon power radiated at 4080 mc. The dashed lines define the nominal tolerance of +13 to +17 dbm. (b) Apparent power radiated on the communications channel at 4170 mc. The dashed line represents the nominal power of 2 watts. Reception on horn-reflector antenna.

### 3.5 *Tracking*

The beacon tracker was operated on 29 passes of the Telstar satellite, and was able to acquire and hold the beacon signal through the Doppler shift of as much as ±100 kc with no difficulty. The achieved tracking accuracy was on the order of ±0.05°, shown by comparison with the 3-inch spotting telescope on a few passes.

The satellite was seen optically in the M-33 tracking telescope on four passes out to a maximum range of 1700 miles. With care, a tracking accuracy of about ±0.05° could be achieved.

Scanning the receiving horn antenna in azimuth and elevation proved to be a surprisingly accurate method of correcting errors in prediction, with tracking accuracies of ±0.1° being typically obtained. There were certain drawbacks to this method, however, which made a more sophisticated system desirable. For example, during the time that the antenna was being scanned the signal level data were essentially useless. A typical scanning procedure took about 15 seconds and was usually repeated every one or two minutes, depending on the accuracy of the predictions. Thus for predictions seriously in error the method would become increasingly poor due to the necessity of more frequent scanning, whereas the beacon tracker did not have this limitation. It was also essential to have a predicted drive tape to use this method, whereas the tracker could follow the satellite by manually steering the antenna to zero the error, as demonstrated on a few passes.

### 3.6 *Spin Rate*

The spin rate was measured on almost every pass worked, using either signal analysis or the optical "glints". It was found that an exponential function could be determined which agreed with the measured data to within $\pm 0.5$ rpm from pass 6 to 1114 (or 122 days after launch):

$$R = 178.2 \exp(-t/333), \text{ rpm}$$

where $t$ is the number of days since launch. The spin has a "half-life" of 333 days, which is in the range of 300–400 days estimated by a rough calculation prior to launch by E. Y. Yu of Bell Laboratories. If this expression continues to be valid, the spin will be reduced to a minimum useful value of 20 rpm in two years. A plot of the spin decay is given in Fig. 8.

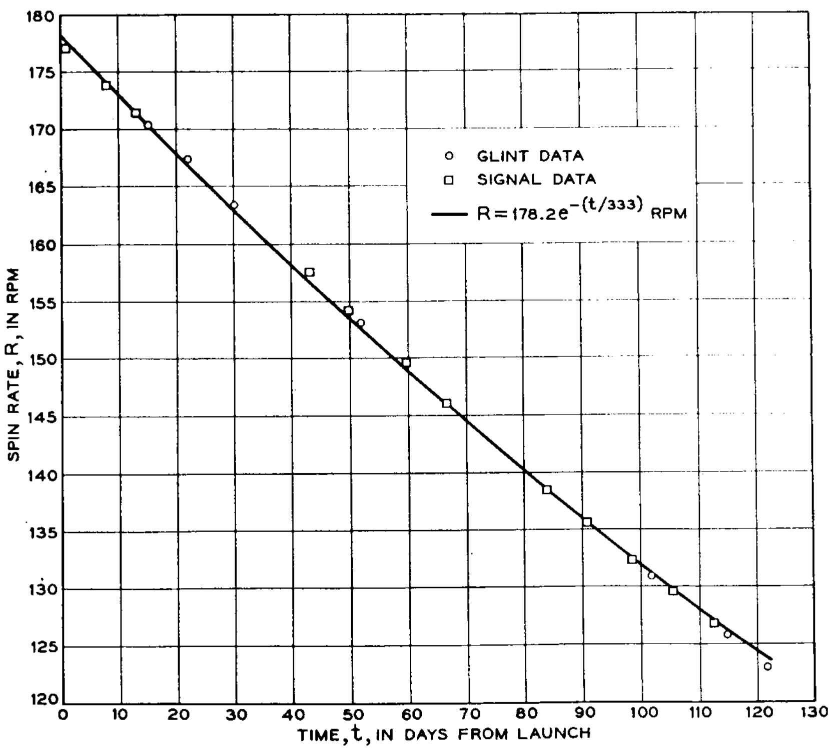



Fig. 8 — Change of satellite spin rate with time.

### 3.7 *Spin Axis Orientation*

#### 3.7.1 *Determination of the Axis Using Glint Data*

During the period from the launch on July 10, 1962, to November 9, 1962, a total of 17 separate glint events were observed at Holmdel. These made it possible* to determine 11 different locations of the spin axis, as summarized in Table IV.

These points are plotted in Fig. 9, along with a theoretical curve derived by L. C. Thomas for an assumed satellite magnetic dipole moment of $-1.0$ ampere-turn-meter$^2$. From pass 16 to 472 the agreement is quite good, but pass 931 falls more closely on a $-1.1$ ampere-turn-meter$^2$ curve. Some discrepancies were expected, of course, due to lack of complete knowledge of the earth's magnetic field and to the elliptical shape of the satellite orbit. In order to test the effectiveness of the torque coil in the satellite it was turned on in the positive sense for 18 hours between passes 1052 and 1069, and in the negative sense for about the same length of time between passes 1069 and 1114. The changes caused by these tests were apparent, and demonstrated the ability to take corrective action whenever necessary.

Also shown in Fig. 9 is the design objective location of the spin axis, corresponding to a line normal to the ecliptic plane. The achieved orientation was well within tolerance.

TABLE IV

| Pass | Date | Mirror Observed | Right Ascension | Declination |
|---|---|---|---|---|
| 7 | 7/11 | 68° | | |
| 7 | 7/11 | 68° | | |
| 8 | 7/11 | 68° | These passes were averaged | |
| 8 | 7/11 | 68° | together to give one fix: | |
| 9 | 7/11 | 68° | 81.96° | −65.57° |
| 9 | 7/11 | 95° | | |
| 16 | 7/12 | 68° | 84.39° | −65.81° |
| 72 | 7/18 | 68° | 86.86° | −66.10° |
| 135 | 7/25 | 68° | 91.22° | −65.86° |
| 136 | 7/25 | 68° | | |
| 199 | 8/1 | 68° | 95.4° | −65.4° |
| 272 | 8/9 | 68° | 100.08° | −64.51° |
| 472 | 8/31 | 68° | 104.44° | −59.92° |
| 931 | 10/20 | 95° | 98.04° | −50.69° |
| 1051 | 11/2 | 95° | 95.8° | −50.3° |
| 1069 | 11/4 | 95° | 98.48° | −49.36° |
| 1114 | 11/9 | 95° | 94.05° | −51.91° |

* The data reduction was carried out by D. W. Hill[6] and L. C. Thomas of Bell Laboratories along lines laid out by the former.

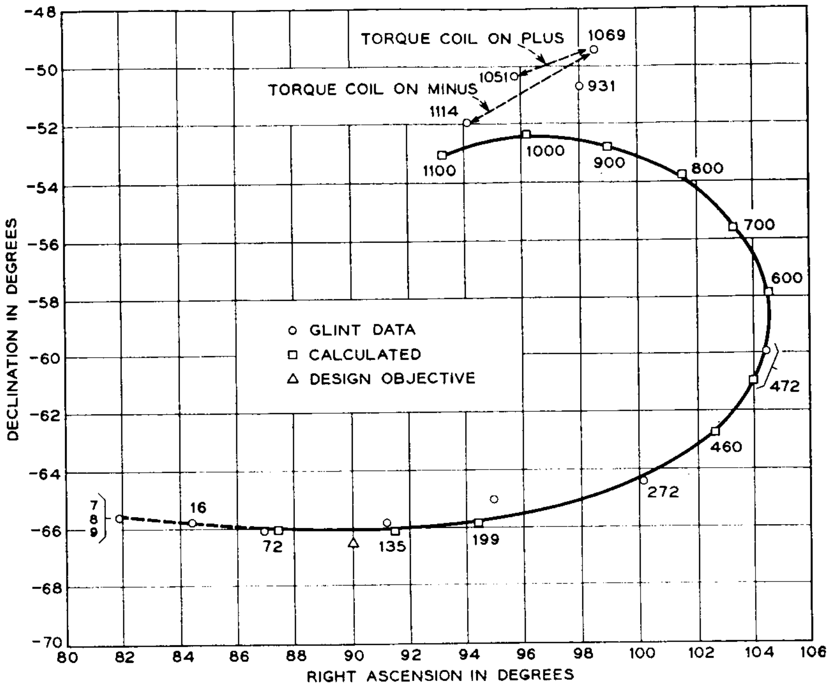



Fig. 9 — Change of spin axis location as determined by glint data; numbers refer to pass number.

### 3.7.2 *Determination of the Axis Using Signal Level Data*

The transmitting antenna pattern of the satellite at 4 gc was very nearly uniform in longitude,* and also in latitude* for angles within $\pm 30°$ of the equator. (The satellite transmitting antenna belt was approximately on the equator, and the satellite spun about an axis normal to its equatorial plane.) For values of latitude progressively nearer the poles, however, the pattern contained maxima and minima of increasing range. Thus during a pass when the observer-satellite line made an angle of about 45° or less with respect to the spin axis the received signal level showed corresponding fluctuations with time. If the angular location of the maxima and minima of the satellite latitude pattern were known with respect to the spin axis, it would be possible to determine values of the spin angle (defined as the latitude of the observer, measured in the satellite co-ordinates) as a function of time during a pass. Two such values

* These are satellite-centered coordinates.

would then be enough to determine a "fix" on the spin axis location. In order to determine the satellite pattern, the process was reversed on one or two passes for which the spin axis location had been determined from the glint data. Knowing the axis orientation it was a simple matter to compute the spin angle for a number of times during the pass corresponding to the observed maxima and minima, and thus obtain a pattern calibration. Curves obtained by this method are shown in Fig. 10 for the two frequencies of measurement, 4080 mc and 4170 mc. As one would expect, the minima are somewhat closer together in angle at the higher frequency. In the plots the maxima have all been set to the same level, revealing that all minima have different values so that there is the possibility of unambiguously determining spin angles from the received signal level variations. An expanded replica of the signals received during pass 117 is shown in Fig. 11, including both the 4170-mc and 4080-mc signals. By measuring the depth of a minimum referred to the midpoint of a line joining two adjacent maxima for all minima, a list of minima depths was determined. This list was then compared to that given by the appropriate reference pattern calibration (Fig. 10) and correspondence of minima and maxima thereby established. Knowing the times associated with the minima and maxima it was then possible to determine the apparent variation of spin angle with time during the pass. Such a plot for pass 117 is shown in Fig. 12, where data determined from both frequencies are included. It can be seen that the points for both frequencies lie on the same curve, as they should.

In order to determine the orientation of the spin axis from the spin

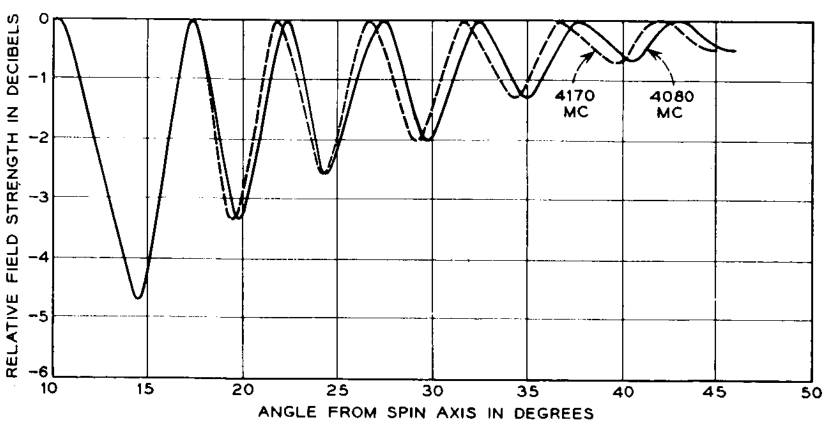



Fig. 10 — Measured latitude radiation patterns of spacecraft while in orbit.

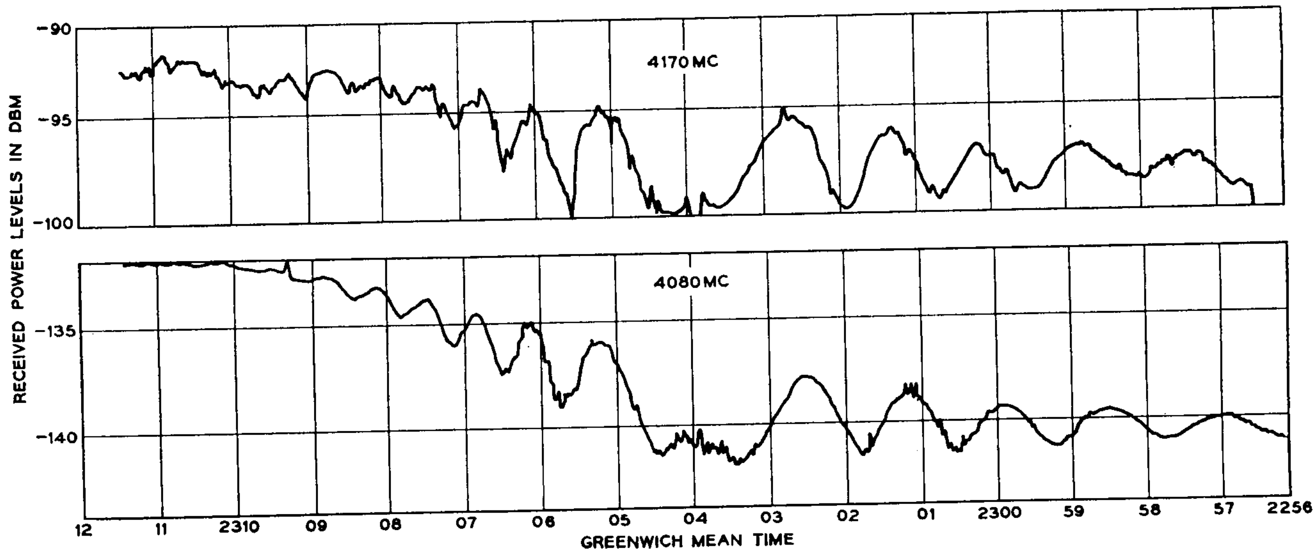



Fig. 11 — Expanded replica of received signal recordings at 4080 mc and 4170 mc showing variations caused by Telstar spacecraft antenna pattern lobes on pass 117, July 23, 1962.

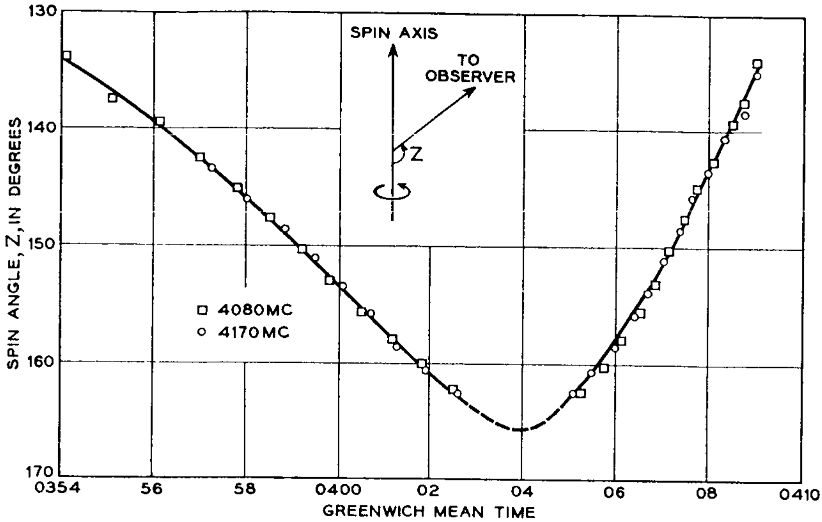



Fig. 12 — Measured variation of spin angle with time for pass 117 on July 23, 1962.

angle information, a computer program was prepared which computed the axis location from two selected data points from the set of given spin angles and corresponding times, and then computed spin angles from this value of spin axis location and compared them to the remaining given data points. Examination of the differences then revealed any gross errors, such as a slip of one adjacent minimum in achieving a correspondence between the pattern calibration and measured signal variations. Generally the spin angle differences did not exceed 1°. It was found that in choosing the two points from which to compute the axis, it was better to use two with the largest difference in spin angle, rather than the largest difference in time.

A more elegant approach, of course, would be to utilize all of the data points (spin angles with their corresponding times) and make a least-squares fit to determine the best value of spin axis orientation. It was felt, however, that the accuracy of measurement was insufficient to warrant this approach.

The coordinates of the spin axis determined from the pattern data are plotted in Fig. 13 for passes 7-271 and the agreement is seen to be within ±1° of the values determined from the glint data. After pass 271 the line-of-sight to the satellite did not come close enough to the spin axis to yield any more data, due to a combination of orbital precessions and movement of the spin axis.

### 3.8 *Skinny Route Terminal*

After the Telstar spacecraft was successfully launched and proved to be operating as planned, it seemed desirable to demonstrate a minimal-type ground station that would provide one voice channel over the satellite. An inexpensive, compact station would be useful for remote locations in the world. It was decided to adapt the 18-foot tracker antenna at Holmdel for both transmission and reception, and modify the tracking mode to make it independent of a predicted drive tape. The effort was started on a crash basis in late July, 1962, by members of the Military Research Laboratory at Whippany, and culminated in successful demonstrations of a two-way voice circuit to Andover less than three weeks later. A description of the system and tests conducted may be found in Ref. 7.

## IV. CONCLUSIONS

The general objectives outlined in Section 1.1 were accomplished during the Telstar experiments. In addition, it was clearly demonstrated that a relatively modest ground station utilizing a 20-foot horn-reflector antenna can do a creditable job of receiving a television picture across the Atlantic Ocean from an active satellite.

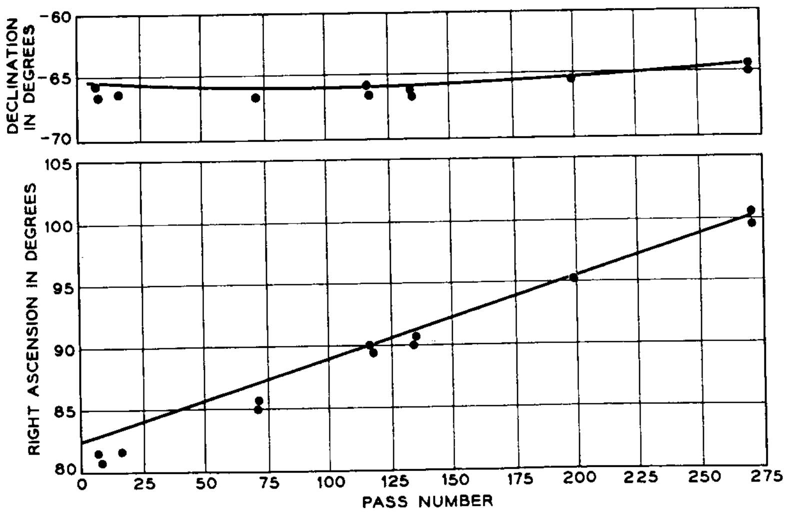



Fig. 13 — Plotted points: spin axis determination from signal level analysis. Solid curve: average of glint data.

V. ACKNOWLEDGMENTS

The Holmdel station could not have taken a successful part in the Telstar experiments without the efforts of a great many individuals. In particular, the author wishes to acknowledge the work of D. C. Hogg, R. A. Semplak, and R. A. Desmond in carrying out the conversion of the horn antenna to 4 gc and installing, testing, and operating the low-noise amplifiers; C. L. Ruthroff, W. F. Bodtmann, J. P. Schafer, and H. E. Keller for providing and operating the frequency compression demodulator; R. H. Turrin, H. A. Gorenflo, and R. H. Brandt for their part in the phase-lock receiver program and other areas; O. E. DeLange, J. T. Ruscio, and H. E. Groener for conversion of the tracker system to 4 gc and operational help; L. R. Lowry for his help with operations management and in providing many of the necessary communication facilities; E. L. Frantsvog, J. W. Barto, W. E. Legg and F. W. Radcliffe for their assistance with many of the details of conducting operations and reducing data. J. S. Courtney-Pratt and his associates planned the glint experiments, and provided and operated the equipment.

The work was carried out under the general direction of C. C. Cutler, and his continued guidance and active participation are gratefully acknowledged.

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