Results of Tests Performed with the Telstar I Satellite at the Pleumeur-Bodou Satellite Communication Station

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Tests performed at the Pleumeur-Bodou satellite communications station with Telstar I are described.

These tests have made possible an analysis of the feasibility of acquisition and tracking of a satellite by an antenna of very narrow beamwidth and of the good and bad features of the transmission channel established in this manner. These tests were completely satisfactory and have enabled us to determine the methods which will be economically and technically valid for establishing a commercially practical system for satellite communications.

Tests of communications through an active satellite began at the French station at Pleumeur-Bodou on the day the Telstar I satellite was launched—10 July 1962. They continued with this satellite until 21 February 1963, when the satellite transmissions were broken off.

These tests were performed during more than 110 revolutions and were intended to explore and analyze the feasibility of establishing and keeping in operation a communication link via satellite, in other words, the feasibility of acquiring and tracking a satellite and the good and bad features of the transmission channel established in this way.

From the first pass of the satellite, during its sixth orbit about the earth, the quality of the television pictures transmitted by the AT and T station at Andover and received at Pleumeur-Bodou showed that the entire station was operating perfectly well and the link was of very satisfactory quality. The tests described in the following pages were performed to enable us to determine the optimum characteristics and the limits of capability of each part of the equipment and to provide us with the experience which would be indispensable for future developments leading to the establishment and use of satellite communication links.

Acquisition and Tracking Tests

During the 115 passes of Telstar I utilized by the Pleumeur-Bodou station, corresponding to 40 hours of traffic across the Atlantic, the total time during which the link was interrupted or delayed by reason of a failure of the equipment or personnel of the antenna control amounts to 22 minutes, distributed over 5 passes. Three of these interruptions are related to operator error, one to misadjustment of a circuit before the pass, and one to a power failure. The percentage of time during which the tracking of the satellite was correct and permitted television and telephony demonstrations or technical tests amounts to over 99 percent. It should be noted that during these first hours of space communications, which must be considered from many points of view as part of an experimental period, there was no serious equipment failure.

Since the main purpose of the antenna drive is to assure correct pointing of the horn reflector antenna in the direction of the satellite to provide for transmission and reception of communications or any related tests, we made an effort during the various passes to determine the acquisition capability of the different kinds of tracking equipment and of their capability for maintaining contact with the satellite in the various modes of operation. In the light of the results of these observations, some modifications or additions were made to the equipment.

We call attention to the fact that, with one exception, the components which went into the command antenna were supplied by Bell Laboratories and are identical to those in operation at Andover. The exception is the 136 Mc command and telemetry equipment, referred to as the "command tracker", produced by CNET.

We shall analyze the various components successively. They are shown in block diagram form in Fig. 1.

COMMAND TRACKER TESTS

Tracking Tests

We recall that the tracking equipment receives the satellite beacon signal, which is transmitted at a frequency of about 136 Mc. In the case of Telstar I, the frequency is 136.05 Mc.

The many measurements which have been made have shown us that

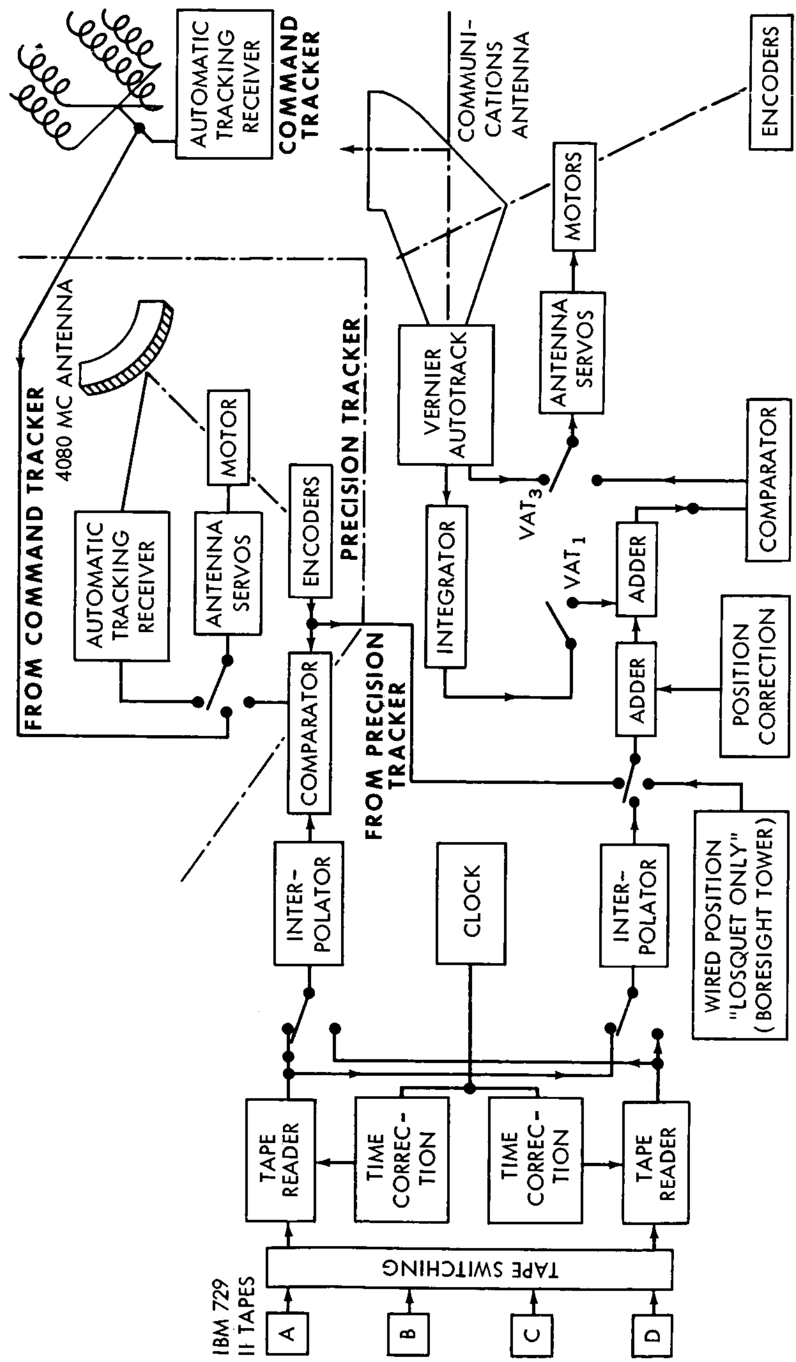

Fig. 1 — Functional block diagram of the antenna drive.

acquisition could be achieved at the time of the apparent rise of the satellite above the horizon. Taking into account the phenomena of refraction at elevations which permit reception of the first beacon signals at geometrical elevations of between −0.5 and −1 degree and of the time necessary for the receiver to achieve frequency lock, it is always possible to drive the antenna in the automatic tracking mode at elevations below 2°.

However, on account of ground reflections and the width of the antenna pattern (20° at 3 db) some important errors appear between the real positions of the satellite and the information supplied by the encoders. These differences are more evident in elevation for angles of less than 20°: the rapid fluctuations of the antenna can attain ±5° without causing the autotrack to lose lock. For higher elevations the pointing accuracy improves and attains ±1° at 40°. The azimuth data is only very slightly affected by reflections, but due to the size of the antenna and its mechanical structure, errors of about 2° can appear under the buffeting of winds over 60 kilometers per hour. Due to the exposure of the antenna site, such wind velocities were experienced fairly frequently during the winter of 1962-1963.

In Fig. 2 we have reproduced the recording of a tracking operation. During this pass the signal/noise ratio was 25 db and the wind speed 50 Km/hr.

To make this chart, we used for measuring equipment some components of the tracking encoder in the precision tracker.

With the precision tracker slaved to the command tracker, the position information given by its encoders is compared at each instant with the precomputed tape corresponding to the pass. The validity of this tape is continuously checked against the data given by the horn reflector antenna tracking the 4080 Mc beacon.

Furthermore, for the 15, 20, and 30 degree positions, a control was provided by shifting the precision tracker to autotrack.

Following the conclusions indicated above, the use of the command tracker as a means of acquisition for the communications antenna is limited to confirming the presence of the satellite as well as the time when the satellite rises above the horizon. The positions indicated by the computed tapes are more accurate, as we shall see later on, than those given by the command tracker.

Telemetry

The reception of Telstar I telemetry data is always accurate and all the recorded magnetic tapes have been easily decoded.

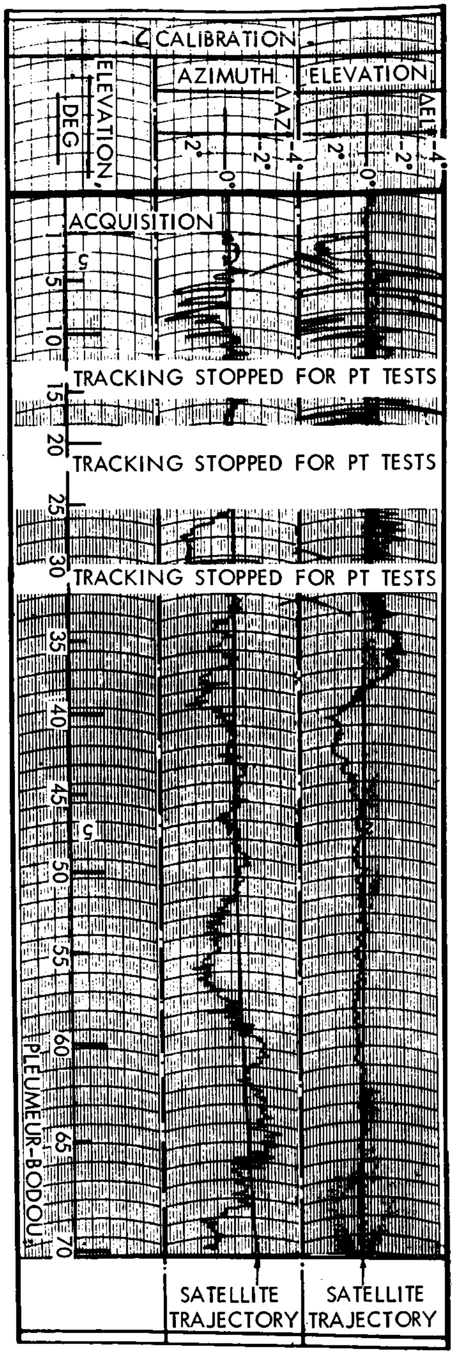

Fig. 2 — Plot from the 136 Mc tracker: S/N = +25db.

The quality of this data is such that it could have been used for monitoring the satellite during the various command operations.

After some difficulty with the reception of the Telstar II telemetry on 7 and 8 May 1963, an equipment modification (reducing the receiver bandwidth from 50 Kc to 8 Kc) allowed very satisfactory use of the data from this satellite, despite the low received level due to the range, often from 15,000 to 16,000 Km.

TESTS WITH THE 4080 MC PRECISION TRACKER

Acquisition

Acquisition by the precision tracker of the 4079.73 Mc satellite beacon takes place in two steps:

1. Acquisition in position.
2. Acquisition in frequency.

Acquisition in Position

Acquisition is considered achieved to the extent that the pointing of the antenna corresponds to the real position of the satellite within ½ degree. The 3-db beamwidth of the antenna being 2 degrees, a pointing error of 0.5 degree corresponds to an attenuation by 1 db.

Some series of tests were made with a view to adapting the method to any circumstances which might arise, and to the training of operators.

It became apparent that the problem is not the same in the case of the beacon being ON when the satellite rises above the horizon as it is for elevations other than zero.

1. In the case of the beacon being ON when the satellite comes up over the horizon, acquisition can be achieved by means of
   a. Computed magnetic tapes which, acting through the tracking encoder, operate the azimuth and elevation equipment, to the extent that the available information furnished regarding time and position can be considered accurate.
   b. Manual positioning in elevation at elevation zero, with the beacon moved slowly through a small sweep (approximately 2°) in azimuth, around the calculated position. This method has the great advantage of practically eliminating the acquisition time parameter, an accurate trajectory with a slight shift in time still permitting the solution of the problem of acquisition.

It is to be noted that acquisition by slaving to the command tracker was not used. In the event of the pointing information appearing doubtful, the presence of the satellite is confirmed by this equipment which provides sufficient indication to avoid gross errors.

2. If the beacon is not ON when the satellite rises above the horizon, acquisition is achieved by servo drive with precomputed magnetic tape, plus a search in azimuth and elevation about this position.

Series of tests were made with the antenna slaved to the command tracker. Due to the rapid variations of about ±5° (see Paragraph I.1.1) it was not possible to obtain satisfactory results for elevations below 20°. On the other hand, for elevations above about 30°, a trained operator may effect acquisition by this mode of operation.

It should be noted that the 4080 Mc beacon is practically always ON for elevations below 20°.

Frequency Acquisition

When acquisition has been effected, phase lock of the automatic frequency control oscillator* must be achieved. Depending on the received signal level, this operation either is automatic and almost instantaneous, or calls for the intervention of the operator. Taking into consideration Doppler effect, thermal drift of the beacon, or any other disturbance within the satellite, the range of frequencies within which the frequency can be located is 150 Kc around the nominal value.

The automatic method, making use of the comb filter of 300 outputs, is usable for practical purposes for received powers of −139 dbm at the level of the parametric amplifiers, corresponding to a signal/noise ratio of +2 db in the receiving circuit used.

This operational mode of acquisition was always usable for Telstar I, for which acquisition ranges varied between 9000 and 4000 km, corresponding to received powers between −137 dbm and −130 dbm.

This no longer held true for Telstar II, for which the received power is often in the vicinity of −141 dbm (range of 16.000 km). In this case we had to use manual acquisition routinely, consisting of prepositioning the 3-Kc bandwidth receiver channel on the frequency received by the equipment. Taking into account the Doppler frequency information supplied by the computing center, a small amplitude search around the predetermined frequency, together with an aural

* In the tracking receiver.

analysis of the beat signal, makes it possible to obtain acquisition for signal/noise ratios in the 3 Kc bandwidth as poor as −8 db.

Actually, for Telstar II this acquisition was achieved most of the time at a signal/noise ratio of −5 db.

As soon as acquisition has been achieved the oscillator phase-lock reduces the equivalent passband to 100 cps, which brings the noise level to −151 dbm.

It should be noted that allowing for the refraction at 4080 Mc (a systematic study of which will be found in Paragraph I.3.3), the acquisition is completed and the precision tracker turned over to autotrack almost certainly at geometrical elevations below 2°, whatever the method used, whether automatic or manual, providing of course that the beacon is ON when the satellite comes up over the horizon.

Tracking

When the satellite has been acquired, the accuracy with which it can be followed will depend upon random variations in tracking as well as on systematic errors due to mechanical imperfections of the system.

Random Errors

These errors depend both on the elevation above the horizon, and on the signal/noise ratio in the receiving channel after phase lock.

The direction of the received signal suffers far fewer disturbances than is the case with the command tracker.* As a consequence of the width of the antenna lobe, the accuracy obtained is around 0.2° for elevations less than 2°. For higher elevations, this accuracy improves rapidly until at 3° it depends solely on the signal/noise ratio.

The fluctuations due to ground reflections have been noted by recording on magnetic tape the data from the position encoder outputs and comparing it to the theoretical trajectories.

To achieve measurements of tracking characteristics at elevations above 3°, we made use of the horn-reflector antenna with its vernier autotrack as a necessary instrument.

To perform these tests we took into consideration the fact that the precision of angular measurements by this equipment is markedly superior to those of the precision tracker. This results from the dimensions of the horn reflector antenna, and the fact that the signal/noise

* In fact it is the reflections which activate the command tracker at low elevations because of the width of the antenna lobe.

ratio in the receiving channel of the vernier autotrack is always superior by 10 db to that of the precision tracker.

On the other hand, the overall response characteristics in position of the two systems are essentially comparable in the region utilized.

With the horn antenna slaved to the precision tracker antenna, via the encoders and the digital equipment, the angular deviation between the pointing of this antenna and the true position of the satellite is measured at each instant by the vernier autotrack circuits operating in open loop (Fig. 3).

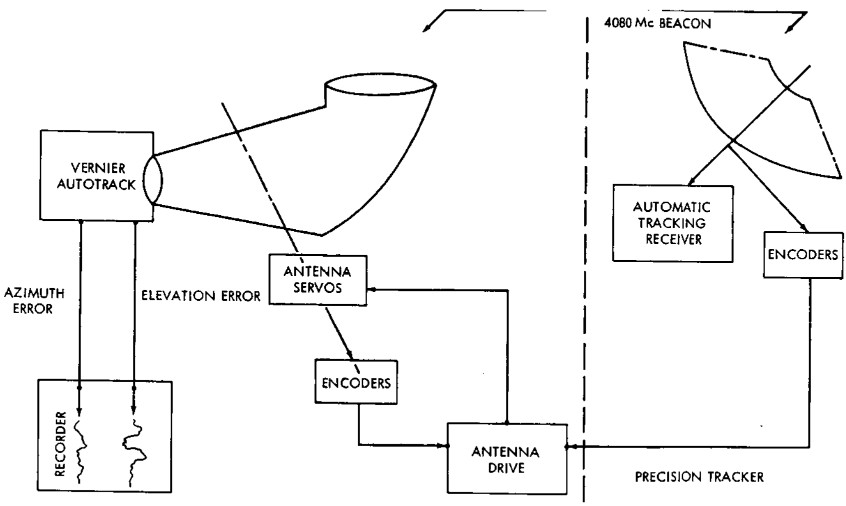

Fig. 3 — The horn reflector antenna.

In Figure 4 are shown tracings of recordings corresponding to signal/noise ratios of 27 db and 12 db for a servo noise bandwidth of 0.2 cps.

An analysis of these results brings us to an RMS noise jitter of:

$$10^{-4} \text{ radians for } \frac{\text{signal}}{\text{noise}} = 27 \text{ db}$$

$$3 \times 10^{-4} \text{ radians for } \frac{\text{signal}}{\text{noise}} = 12 \text{ db}$$

It should be noted that these measurements take into account thermal noise, and also the potential digital error (0.5×10^{-4} rad) of the encoders and the mechanical imperfections about the position used.*

* i.e., mechanical biases as a function of angular position.

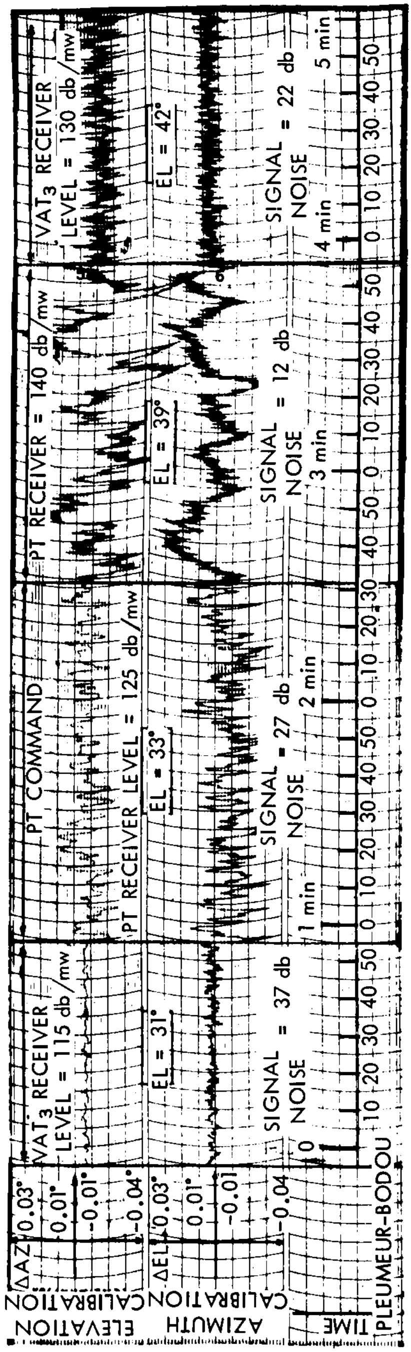

Fig. 4 — Plot from the 4080 Mc precision tracker.

We have shown in this figure the recordings, made during the same passes, of the output errors of the vernier autotrack operating in closed loop.

Systematic Errors

These errors can be the result of imperfections in fabrication or wear of the elevation and azimuth drive mechanisms of the antenna and the associated encoders, or of shifts in the position of the antenna base.

The only systematic checks were to verify that the base was level; they revealed a settling of the foundations during the first three months, resulting in an angular variation of the reference plane of 0.015°. The monthly measurements now performed do not indicate the need for any adjustments.

In any case, no noteworthy mechanical error was detected with respect to variations in elevation or azimuth in the course of the passes which were studied.

Operation

During all of the operational passes which were utilized, the precision tracker was operated. The reliability and accuracy of this equipment, together with its relatively wide practical acquisition angle (width of the antenna beam associated with the search about the computed position), led to its being considered, while not essential to the smooth running of the operations, an element of functional reliability.

The data received and recorded on magnetic tape during these passes was not utilized in any useful way for the determination of orbital parameters. It should be noted that the average duration of the passes which included the acquisition phase, is 20 minutes.

To facilitate the use of the equipment and to reduce the operating personnel of the station, the main controls of the tracking encoder were mounted on the precision tracker operator's console.

Information concerning the difference between the taped position and the antenna pointing is displayed at the central station console. This information, shown on a dial after conversion into analog form and amplification, informs the chief of operations of the difference to within 0.01°. A time correction adder identical to the one used in the antenna drive located in the lower cabin under the radome provides time corrections to the tape used for the tracking encoder. With the error indications supplied by the central console, this allows optimum adjustment of the time and position information on the tape driving the horn antenna, and helps in the establishment of the link.*

A computer unit which can be hooked up between the precision tracker and the antenna drive was designed and built so that when the horn antenna is directly slaved to the precision tracker (through the encoders) an accurate pointing of the radio beam carrying the communications information can be achieved despite deformations of the antenna.

We shall define the theory of this equipment in Paragraph 1.3.2.2.

TESTS WITH THE COMMUNICATIONS ANTENNA

The tests concerned the different possible modes of acquisition and tracking, requiring therefore the measurement of the intrinsic characteristics of the antenna in relation to the particular conditions which prevail at the time of the mission.†

For this reason we were led to an examination of the following parameters:

The radiation patterns of the horn reflector antenna in the communications receiving band, centered on the normal frequency of 4169.72 Mc, and at the vernier autotrack frequency of 4079.73 Mc.

The azimuth errors as a function of elevation.

Refraction at low elevations.

Antenna Patterns

These tests were performed with a view to learning the patterns of the secondary lobes near the antenna and verifying that when the antenna is in the vernier autotrack mode. The pointing corresponds to the maximum of the pattern for the communications receiving frequency.

These measurements were carried out by receiving the signal from the satellite for elevations included between 20° and 30°. It was not possible to take these readings using the simulator on the boresight tower because the ground effects are not negligible, the elevation at which the horn reflector antenna sees the simulator being 1.35°.

Method of Measurement

The satellite is illuminated by an auxiliary station transmitting a pure frequency. The signal is received at Pleumeur-Bodou by the com-

* Manual offsets of time and position information can be inserted in order to eliminate systematic errors.

† The schematics of the digital drive circuits of the antenna drives of the precision tracker and the communications antenna are shown in Figures 10 and 11.

munications equipment at the frequency of 4170 Mc and the autotrack equipment at 4079.73 Mc.

The frequency band of the communications receiver used for the measurement is a compromise based on the stability of the transmitter, the receiver circuits, and the level at which the pattern must be traced.

Tracking of the satellite is performed by tape, the relative deviation between the position of the satellite and the direction of the antenna being obtained by the insertion of position corrections into the antenna drive chain. The tape chosen is checked in advance to make sure that it is satisfactory; if not, fixed position and time corrections are made to make the computed trajectory and the actual trajectory coincide.

This test is a dynamic one, with the receiver level to be measured recorded continuously and position corrections applied to the constant speed of 65.76 deg/min. The receiver levels in both the VAT channels and the communication channel are determined from the previously calibrated AGC level; the zero of the VAT error corresponding to the pointing direction in automatic tracking is obtained by recording "errors" in the azimuth and elevation channels.

Relative variations in range on the order of 1 percent per minute are disregarded during the test.

The transmitter power of the satellite is assumed constant over the duration of any pointing error.

After each pattern trace the zero level at the pattern maximum is taken again.

The accuracy of the measurement, dependent both on the calibration accuracy of the recording and on the accuracy of reading the recording, is on the order of ±0.25 db.

Results

Figures 5 and 6 are pattern traces obtained on the communication channel. Pointing errors from $-10°$ to $+10°$ were measured; only those angles for which the received level is detectable are plotted. Various series of tests resulted in half-power widths.

1. Variable elevation minus zero azimuth error.

   Allowing for the accuracy of ±0.25 db, we obtain for 3 db beamwidth for 3 different pointing errors:

$$0.208 < 3 \text{ db } W° < 0.225$$

$$0.208 < 3 \text{ db } W° < 0.23$$

$$0.205 < 3 \text{ db } W° < 0.225$$

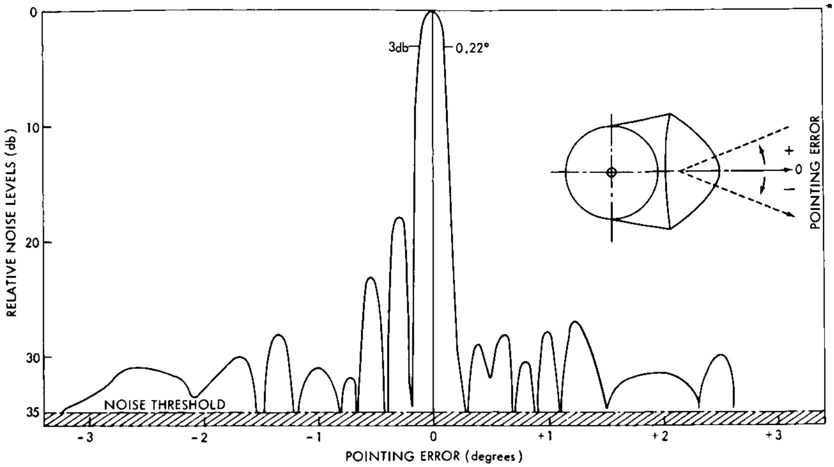

Fig. 5 — Communications antenna pattern, elevation plot.

Taking the mean value,

$$3 \text{ db beamwidth} = 0.215°$$

2. Variable azimuth. Zero elevation error.
   As above, for 3 different pointing errors we obtain:

$$0.235 < 3 \text{ db } W° < 0.25$$

$$0.235 < 3 \text{ db } W° < 0.25$$

$$0.241 < 3 \text{ db } W° < 0.26$$

Hence the mean value

$$3 \text{ db beamwidth} = 0.245°$$

Comparison of the null command of the VAT to the maximum radiation shows that within the accuracy of measurement these two points coincide.

In Fig. 7 are shown traces of the patterns seen by the X and Y channels of the VAT. Because of the sensitivity of the equipment, the measurement could only be made up to 15 db.

The patterns traced for the 4080 Mc frequency are perceptibly different from the patterns traced at 4170 Mc. This difference corresponds to a slight misadjustment of the hyperfrequency circuits resulting in insufficient decoupling of the TM 01 and TE 11 channels. The low

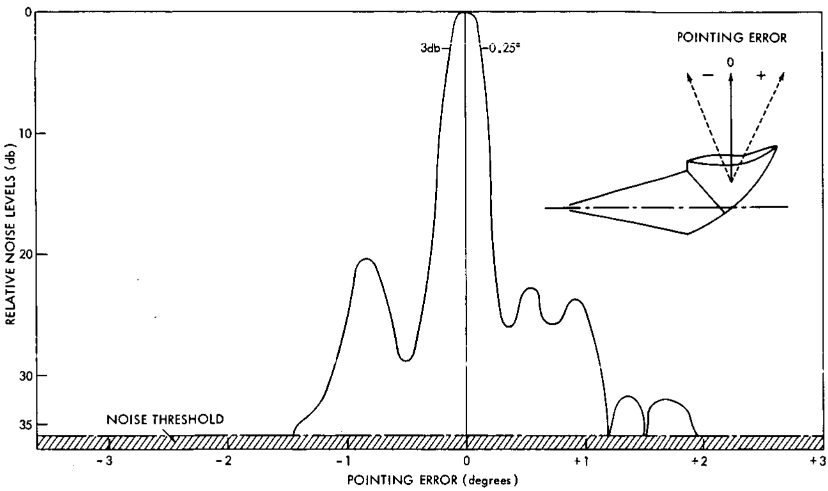

Fig. 6 — Communications antenna pattern, azimuth plot.

amplitude of this perturbation does not affect in any way the overall operation of the system.

Study of Azimuth-Elevation Coupling

After the first month of operation of the station with Telstar I, it became evident that there was a systematic error in azimuth whenever the elevation of the satellite was above the horizon. A control check performed by calibration on stars showed an error of about 0.20° for an elevation of 62°. A series of measurements was therefore undertaken to establish the curve of azimuth-elevation coupling, so that a distortion correction could be applied to the communications antenna drive tapes.

The method used consisted in tracking the satellite separately with the precision tracker and with the large antenna positioned by the vernier autotrack. The positions were recorded on magnetic tape during the entire pass and subsequently compared. The information obtained, together with the star calibration and the precomputed theoretical trajectories of the satellite, enabled us to establish a curve providing the azimuth errors as a function of elevation. The tests performed for different azimuths showed that this law of variation remains valid for any azimuth.

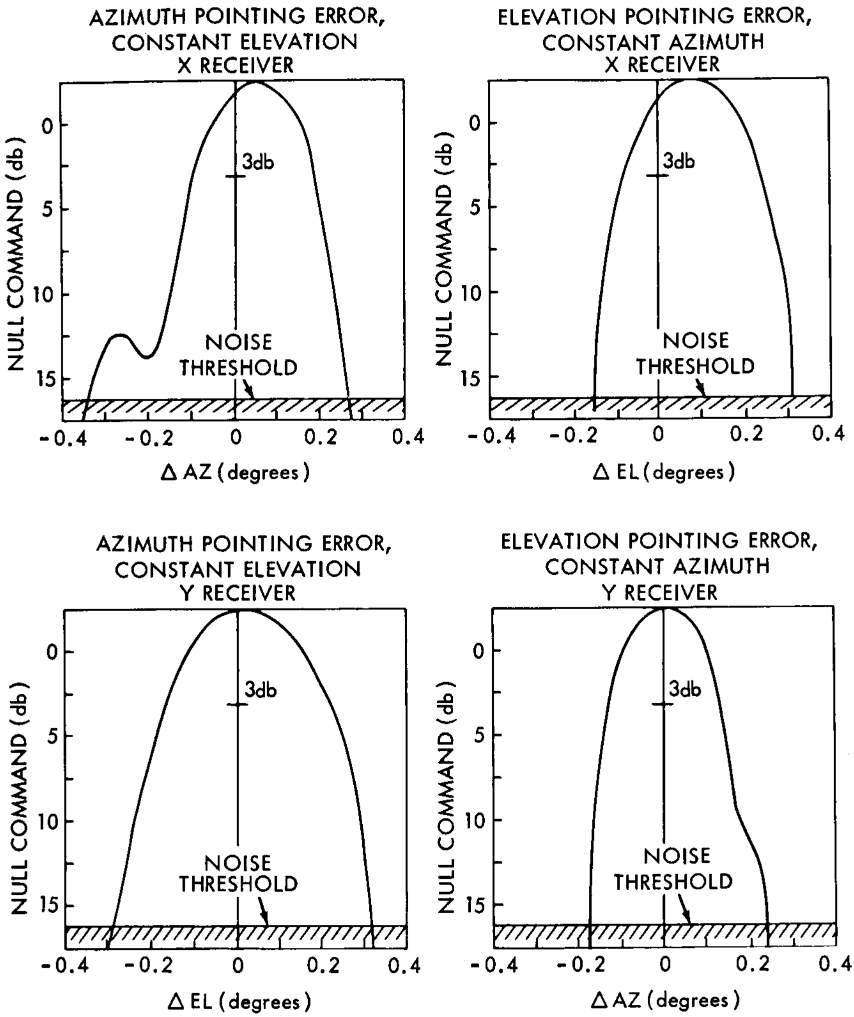

Fig. 7 — Vernier autotrack receiver levels.

Results

A first series of tests performed up to 15 December 1962 enabled us to determine the relation (Fig. 8):

$$\tan Az = \frac{1}{570} \tan El$$

which is equivalent to the variation contributed by the antenna pat-

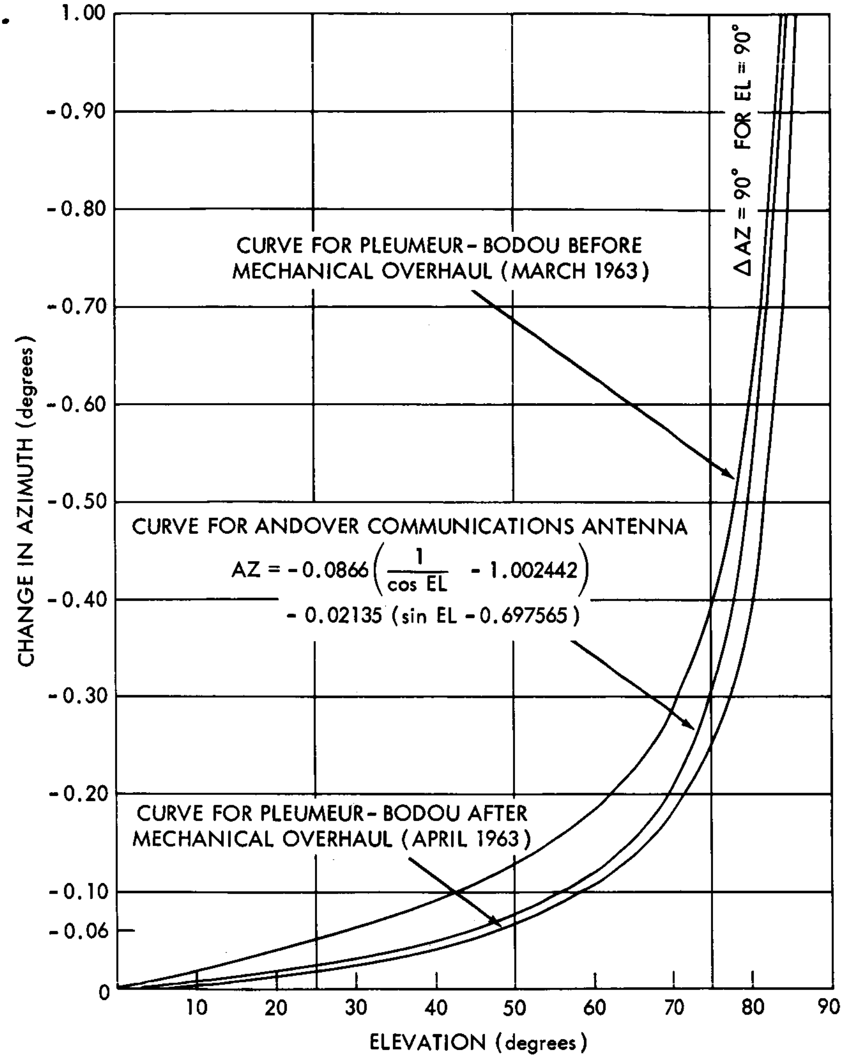

Fig. 8 — Communications antenna, azimuth error versus elevation.

tern in a plane which is not perpendicular to the axis of rotation in elevation, but in a plane shifted from that plane by 0.1°. A check of the antenna structure failed to show any systematic error of that order of magnitude, but enabled us to see that a very large percentage of the structure bolts were loose, leading to an excessive deformation as a function of variations in elevation.

A general overhaul of the structure was carried out in April, 1963.

With Telstar II, a new series of tests was undertaken, resulting in a new law of variation. A mathematical analysis of this curve, made so that it could be applied to the antenna drive tapes, led to:

$$Az = -0.06 \left(\frac{1}{\cos El} - 1 \right) - 0.05 \sin El$$

This law is to be compared to that which was provided us by BTL and which was applied to the Andover antenna (Tracking Program Document, 15 October 1962: Program Description):

$$Az = 0.0866 \left(\frac{1}{\cos El} - 1.002442 \right) - 0.02135 \; (\sin El - 0.697565)$$

Direct Slaving to the Precision Tracker

It thus appeared that because of this coupling there would be some difficulty in slaving the communications antenna directly to the precision tracker. The positions displayed by the encoders of the two antennas did not have the same value during satellite tracking. A computer unit was therefore designed and built to permit application of this correction between the encoders of the precision tracker and the antenna drive. The purpose of the unit, which is mounted in available space in the tracking encoder unit, is to effect an automatic correction by means of a wired program which determines the value to be added to the azimuth information:

$$Az = -a \left(\frac{1}{\cos El} - 1 \right) - b \sin El$$

with $a = 0.06$ and $b = 0.05$

which corresponds to the measurements made and holds for elevations up to 85°.

The computer, of the series type, computes the successive powers of the elevation expressed in radians to the seventh term, performs the modifications of these terms as a function of the coefficients a and b, and then adds the partial results, in such a way that a cycle of operation is completed in 1/64 second.

The polynomial retained is of the form

$$Az = \frac{5}{3} bx + \frac{b}{6} x^3 - \frac{b}{120} x^5 - \frac{45a}{720} x^6 + \frac{bx^7}{7040}$$

The deviations between this function and the theoretical function are always less than the noise in the data provided by the precision tracker.

Study of Refraction

Since the satellite is commanded from the Andover station, the relative positions of the Pleumeur-Bodou and Andover stations result, for the trajectory of Telstar I, in the fact that the TWT of the satellite is very often in operation when the satellite rises above the theoretical horizon at Pleumeur-Bodou. The favored location of this station, for which the theoretical horizon is in many directions the same as the actual horizon because of the proximity of the sea, led to the performance of tests of the refraction of electromagnetic waves at low elevations. These measurements were made for frequencies in the vicinity of 4000 Mc.

Many passes were used for the performance of these tests. It should be noted that no appreciable variation in the results was noted as a function of the seasons: this stability must be considered as resulting from the proximity of the sea above which the satellite rises, and from the fairly constant climatic conditions of the region.

Two methods were used:

1. For elevations above 1°, we used magnetic recordings of the antenna position in automatic tracking of the satellite. This operation requires all the attention and the skill of the operators because of the fluctuations in received signal levels at elevations up to 3°. The data obtained, corresponding to apparent elevations, is later compared with the geometrical elevations of the theoretical trajectory, reconstructed from trajectory data taken during the entire pass.
2. For elevations below 1°, the antenna is prepositioned in elevation at the value chosen for performance of the measurement, the azimuth drive being made by tape. For this condition, the desired pass is one for which the azimuth varies only slightly with respect to time, in order to eliminate any time error in pointing. When the satellite rises, the time of passage through the antenna lobe permits determination of the geometric elevation corresponding to this apparent elevation.

The two methods enabled us to plot, point by point, the curve for refraction correction as a function of geometric elevation (Fig. 9).

This law of variation enabled us, after it was applied to the program for preparation of magnetic antenna drive tapes, to acquire the satellite at apparent elevations of 0.2°, corresponding to a geometric elevation of −0.6°. We did not consider in this acquisition the quality of the communication link, which is subject to large fluctuations in level.

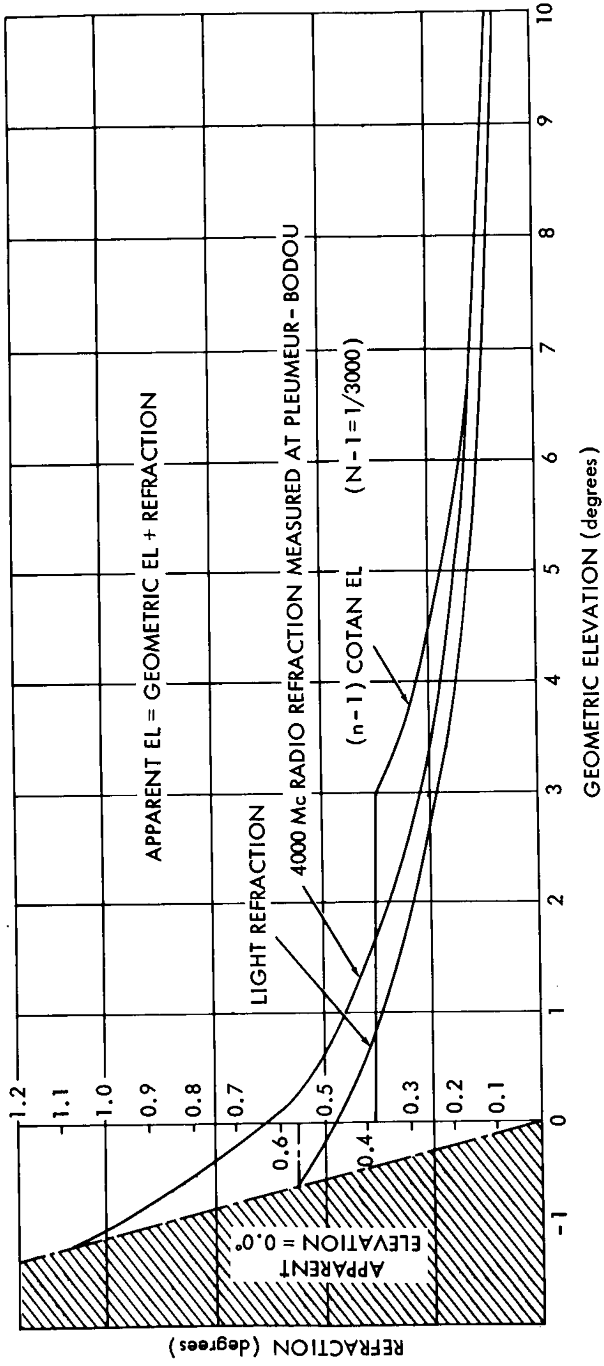

Fig. 9 — Tropospheric refraction.

We plotted on the same figure the following curves:

1. Light refraction law.
2. Law of (n−1) cot El, with $(n-1) = 3.3 \times 10^{-4}$.
3. Law derived at Pleumeur-Bodou for 4000 Mc.

Analysis of the results shows the following:

1. The refraction measured at 4000 Mc, which is slightly greater than light refraction to 3°, is clearly greater for smaller angles, with a limiting value of 1.05° for 0.55°.
2. The measured refraction law coincides with the (n−1) cot El law with $(n-1) = \frac{1}{3000}$ for angles above 7°.
3. The use of the (n−1) cot El law limited to the value of El = 3° corresponds, for the rise of the satellite, to an error of 0.6° and delays acquisition with the tapes which have been computed with allowance for this information.

Acquisition and Tracking Modes

We have summarized here the experience we acquired during 115 passes of Telstar. This experience has enabled us to define general line of operation with respect to the various circumstances which may arise.

Acquisition

During the period of waiting for the satellite to rise, or for turn-on of the beacon in the event it is not illuminated at the time the satellite appears, the antenna is nominally driven by the magnetic tape computed from the osculating orbital parameters furnished by BTL. During the 115 passes of Telstar I, the reduction of the output data from the precision tracker and from the communications antenna monitor led to a determination that there was a time error on the precomputed tapes of an average value of 5 sec, with the extreme not exceeding 12 sec. The position errors are negligible after application of the time corrections to the antenna drive chain (Figure 10).

It should be noted that the information provided for Telstar II led to errors which were appreciably greater in time and in position. The use of the uncorrected tape often corresponds to deviations greater than one degree.

The mean orbital parameters determined by NASA do not enable us, with the computer programs in our possession, to drive the antenna in a usable manner, since the results of the computations are too far

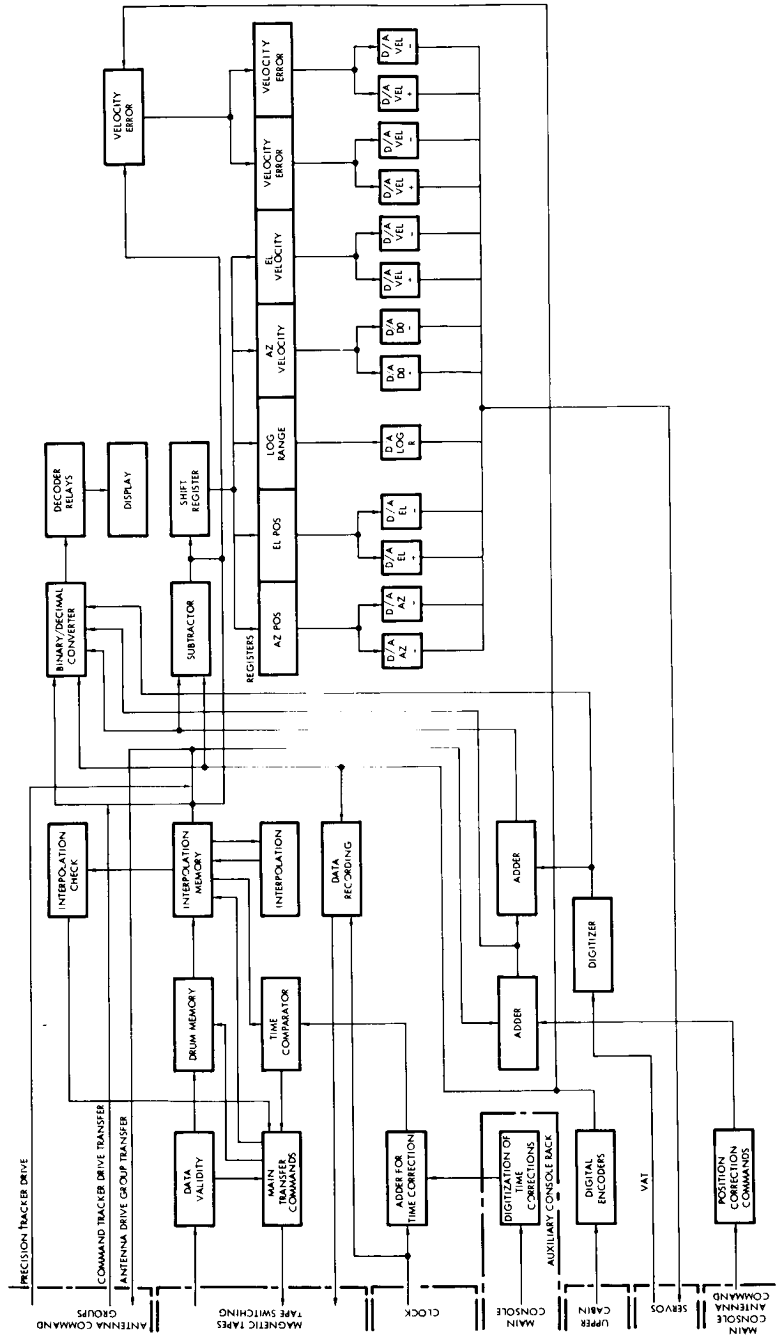

Fig. 10 — Block diagram of the antenna drive.

from the actual positions. On the other hand, the topocentric coordinates received from this agency are particularly satisfactory, giving a position error less than 0.05 during the entire pass.

The criterion of acquisition is the locking on in phase of the VCO of the VAT receiver, assuming of course satisfactory operation of all the equipment.

Two cases are possible for such acquisition:

1. The precision tracker acquires the satellite first, and goes over to automatic tracking. The acquisition delay for the horn antenna may arise either from the fact of a poor position of the frequency of the phase-lock oscillator of the VAT receiver or from the fact that the data tapes do not correspond to sufficiently accurate pointing of the antenna. In either case, phase lock of the oscillator is not achieved.

The chief of operations can, by checking the AGC level of the communications receiver displayed on the main console, determine which of these two errors is at fault.

As a result:

1. The VAT goes over to being slaved in frequency to the precision tracker.
2. The precision tracker/tape error displayed on the console is reduced to a minimum by insertion of time corrections.

If, after these two operations, the satellite has not been acquired, and if the elevation of the satellite is above 2°, the horn antenna is slaved to the precision tracker. The 2° limit results from the fact that below this value the oscillations of the precision tracker make it impossible to use it for very long to drive the horn reflector antenna.

Under these conditions, acquisition should be achieved very quickly:

1. Acquisition is effected by the VAT or at the same time as the precision tracker. In this case the tracking phase is started immediately.
2. It should be noted that acquisition by spiral scan about the position given by the magnetic tapes has never been utilized. The use of this mode of operation assumes that the precision tracker has not acquired, and requires a simultaneous search in frequency and in position. Considering the rates of the spiral scan and the range of frequencies to be covered, the problem cannot practically be solved.

Tracking

As soon as the beacon has been acquired in frequency the method generally used is the tracking mode called VAT 3. In this mode of operation the antenna is directly slaved to the satellite without use of the tapes. It is thus possible to compare the pointing information given by the satellite to the information provided by the tapes and to apply time and position corrections to make the two identical. Once this is done, it is possible to maintain this tracking mode or to utilize the VAT 1 mode, which makes use of both the data tapes and the pointing errors furnished by the VAT. This mode has the advantage of greater reliability, since a break in the signal receiver by the VAT receiver does not interrupt tracking: the antenna continues to be driven by the updated tapes.

In practice, these two modes (VAT 1 and VAT 3) were used during the tests with Telstar I with no loss of the satellite directly attributable to either.

Tracking by direct slaving to the precision tracker was used for test purposes. This method gave very good results after installation of the computer for antenna distortion. The oscillations caused by the tracking noise of the precision tracker (see Fig. 4) do not lead to any fluctuation in the communications channels, since the angular deviations are comparable to the 0.23° width of the lobe at 3 db.

This tracking mode may be used if required in the event that the magnetic tapes have not been prepared and that acquisition has nonetheless been effected by the precision tracker. In order to facilitate these tests, the circuits of the antenna drive group (Fig. 10) were modified to permit insertion of position corrections between the precision tracker encoders (Fig. 11) and the horn antenna.

The tests taken as a whole prove that acquisition of the satellite is virtually certain and that subsequent tracking is accurate enough that communication links can be established and tests performed without any degradation due to pointing errors.

Trained operators who are thoroughly familiar with the equipment can, making use of various circuits for pointing the antenna in the direction of the satellite, handle any minor incidents which may occur during a pass without interrupting the link.

Transmission Tests

Transmission tests with the Telstar I satellite were performed at the Pleumeur-Bodou station during 113 passes with mutual visibility for Andover and Pleumeur-Bodou. These passes are spread over the

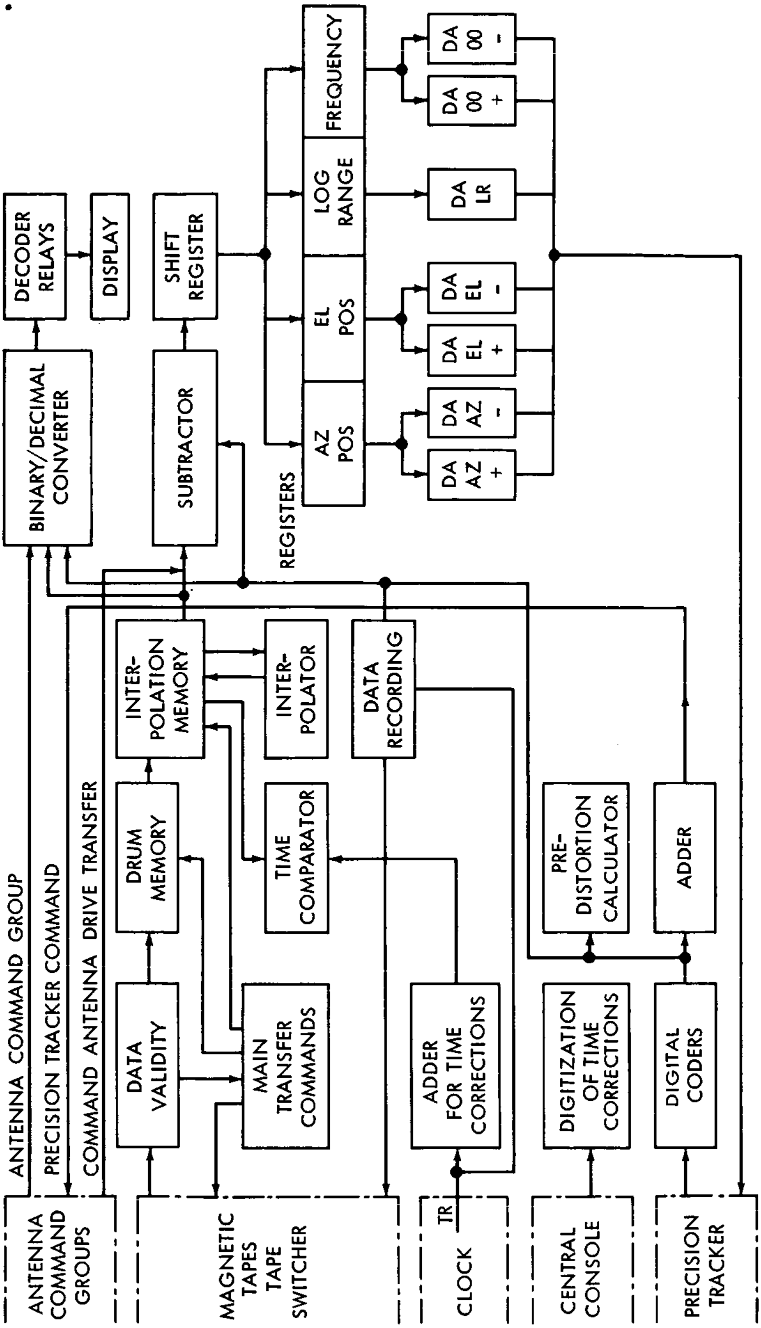

Fig. 11 — Block diagram of the tracking encoder.

periods 10 July to 2 November 1962 and 3 January to 21 February 1963. Technical tests were performed during 69 of these passes. For most of these tests the satellite was utilized in loop, with the station receiving back the signal it had transmitted. The conditions are in almost all the cases identical to those existing for a station-to-station link, and the tests are easier to perform. A few tests were, however, carried out in collaboration with the Andover station. System or demonstration tests were carried out in addition during 59 passes.*

The technical tests were concerned with measurements of the received carrier power and of the receiving equipment; these parameters define the capability of the station for receiving the transmitted information. Our studies also dealt with the noise in the transmission channel and the distortions of the transmitted signal. Studies were made of some effects which are peculiar to satellite communications and do not exist in other modes of transmission presently in use. We also describe a few of the most interesting of the system tests.

RECEIVED CARRIER POWER

We measured the power of the received carrier during each of the passes utilized, recording the variations in the AGC current of the receiver. This current is calibrated before and after each pass by sending into the receiver input a signal of known power provided by a hyperfrequency generator. These measurements can be compared to the value calculated on the basis of the distance of the satellite from the station. For these calculations we used the following mean values:

Power level of the signal transmitted by the satellite:

- 33.5 dbm for a one-way link.
- 30.5 dbm for a two-way link, assuming that the two carriers radiated by the satellite are equal.

Satellite antenna gain: 0 db.

Station antenna gain at 4170 Mc: 58 db.

Receiving system losses: 0.4 db.

We examined the mean value and the fluctuations of the received carrier power.

Mean Value of Received Carrier Power

Figure 12 shows an example of the mean value of the received carrier power as a function of the range of the satellite for a one-way link

* Some technical tests were performed at the same time as system or demonstration tests in the different telephone channels of the multiplex system.

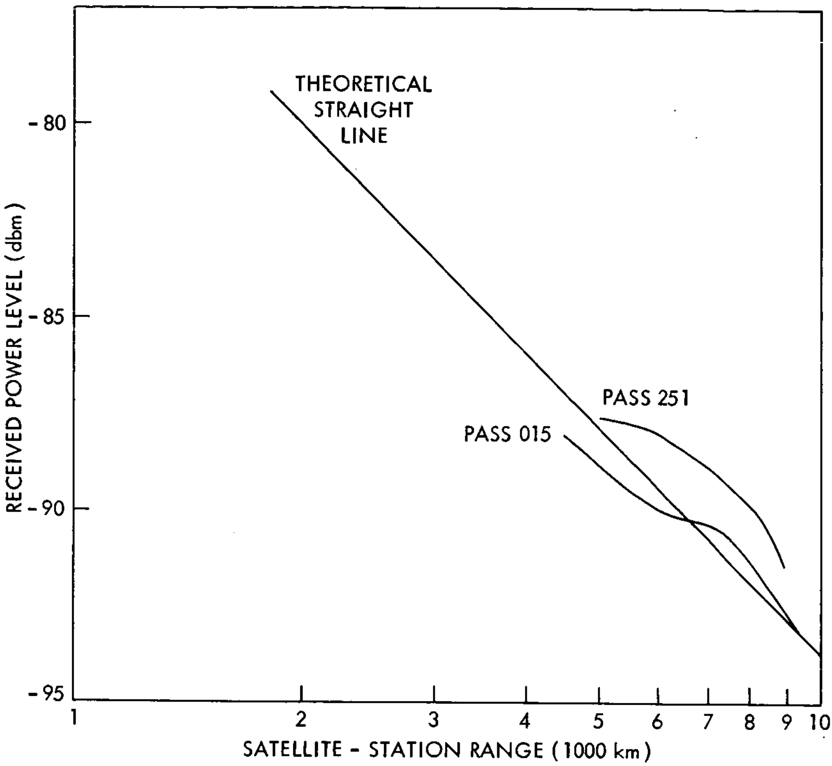

Fig. 12 — Received power at receiver input (1-way link).

for two different passes. Noting that the calculation does not take into account the satellite transmitting antenna gain, which varies with the look angle from the station, we see good agreement between the theoretical and experimental results. In Fig. 13, the same quantities are plotted for two two-way passes. For pass 1974, good agreement is seen between the theoretical and experimental values; on this pass special precautions were taken to see that the satellite received the same power from each station. On pass 33, on the other hand, where no such precautions were taken, a large difference can be seen. If the two carriers received by the satellite are at different levels, the two signals which it transmits are at different levels. This phenomenon was studied during tests performed in collaboration with the Andover station.

The radiated powers of the two stations were altered with programmed variations corresponding to the range of the satellite for each station. After it was determined that the powers of the two

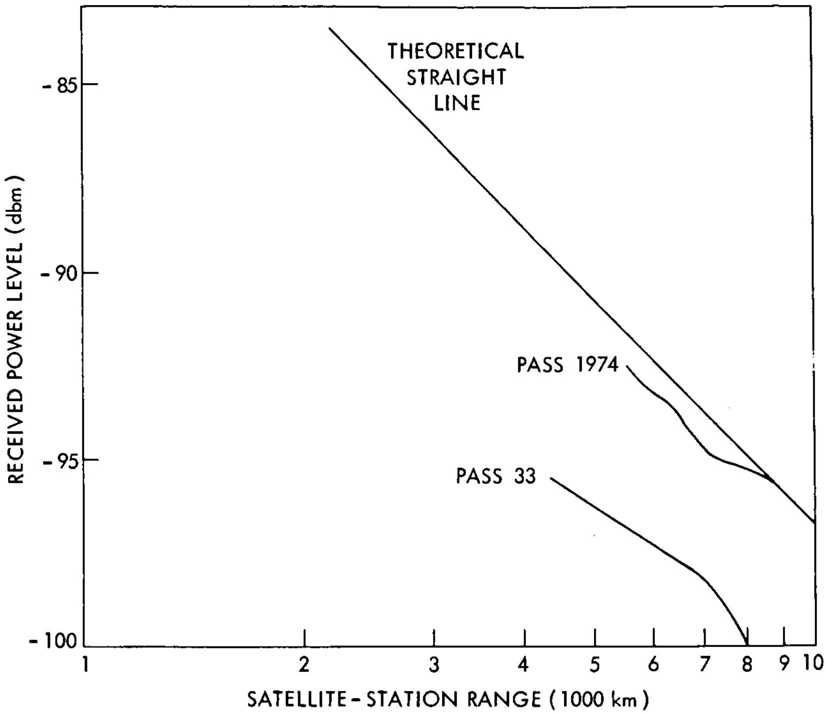

Fig. 13 — Received power at receiver input (2-way link).

carriers received by the satellite were equal, the Andover station made its radiated power vary by a known quantity from the programmed value. The variations in received power at Pleumeur-Bodou are given in Fig. 14. It can be seen that the power radiated by the satellite at the frequency of the carrier received at Pleumeur-Bodou is divided in the same ratio as the power of the corresponding carrier which it receives. The power radiated by the satellite on the other carrier, however, varies simultaneously in the inverse direction although the corresponding power it is receiving remains constant. Consequently, the ratio of radiated carrier powers at the satellite is greater than the ratio of the carrier powers it receives.

Fluctuations of Received Carrier Power

Fluctuations Due to the Receiving System

Figure 15 shows reproductions of received carrier power recordings made for a one-way link at low elevation angles, and Fig. 16, the same

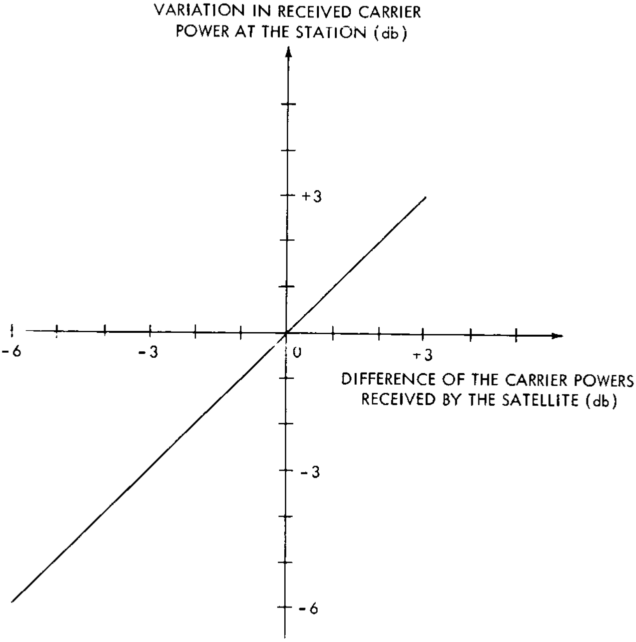

Fig. 14 — Variations in the power of a carrier radiated by the satellite (2-way link).

data for high elevation angles. The value given for elevation is the geometrical elevation of the satellite. The value of received power based on satellite orbital data is shown in a dashed line. The tracking mode used was VAT 1, which makes use simultaneously of the calculated data and corrections furnished by the VAT. It can be seen that the fluctuations were of large amplitude for elevations below 3°, but that above this value they do not exceed ±2 db and remain below 0.5 db above 10°. We saw in the first part that the pointing accuracy of the antenna is adequate even at low elevations (errors less than 2-3 tenths of a degree) to preclude a reduction in the received power. We feel that the fluctuations of received power at low elevations are due to multipath propagations and to reflection of the waves from the ground at points near the antenna where the pattern lobes are not yet closed. At elevations greater than a few degrees the only variations are those of the radiated power at the satellite, resulting from the irregularities in the satellite transmitting antenna pattern as it rotates on its axis. In any case, the tracking of the satellite, with regard to

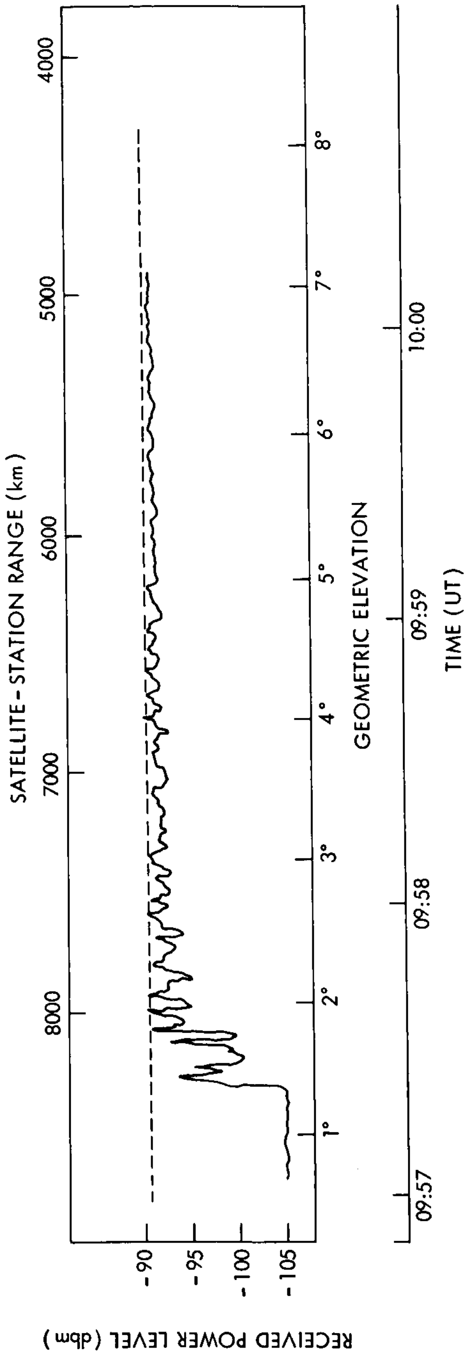

Fig. 15 — Received power at receiver input for low elevations (Pass 996).

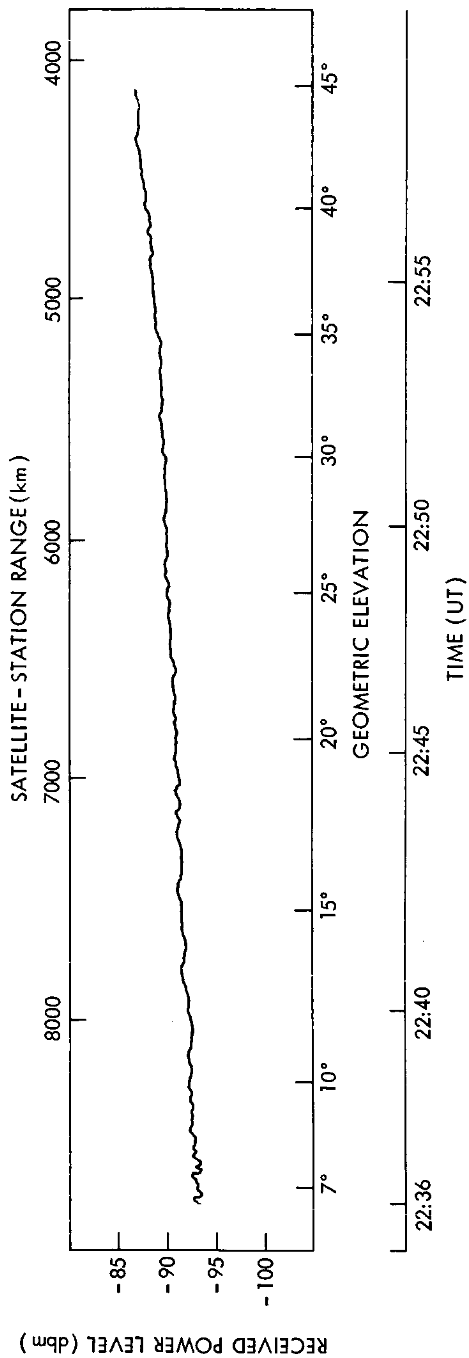

Fig. 16 — Received power at receiver input for high elevations (Pass 252).

the power of the received carrier and thus to the signal-to-noise ratio of the transmitted information, is quite satisfactory when the elevation of the satellite is above 3°.

Fluctuations Due to the Rotation of the Satellite About Its Axis

Since the radiation pattern of the transmitting antenna is not strictly constant as the satellite rotates on its axis, fluctuations of the received power are observed at the rotation rate of the satellite. For the one-way link the amplitude of the observed fluctuations is for most passes below ±0.5 db. For the two-way link this amplitude increases with the difference of the power of the two carriers received by the satellite (Fig. 17).

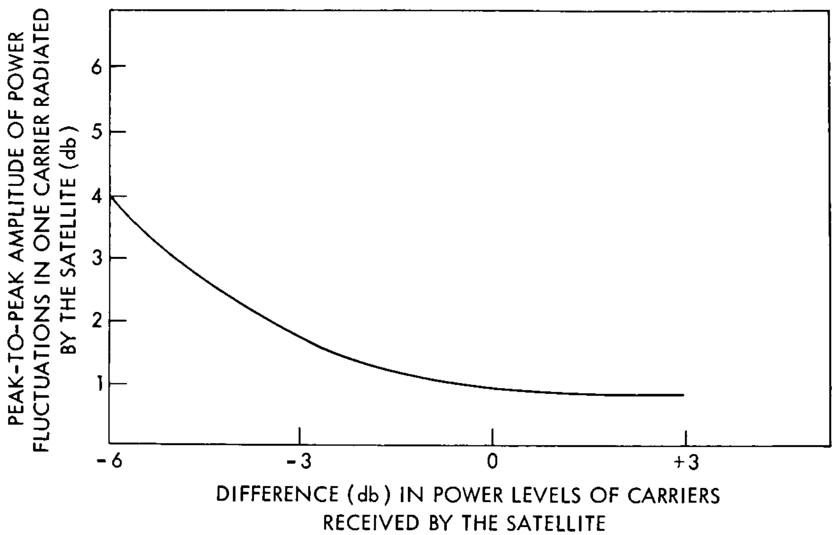

Fig. 17 — Fluctuations in received power due to illumination of the satellite (2-way link).

When the two carriers have quite different powers there are large fluctuations of the weaker carrier. It is noted that the amplitude of these fluctuations varies slightly from one pass to another because of the variation of the angle between the spin axis of the satellite and the satellite station line, with the consequent variation in the radiation from the satellite antenna. These fluctuations are probably due to irregularities in the spacecraft receiving antenna pattern as it rotates about its axis, together with the tendency of the satellite TWT to provide relatively more power to the signal which has the greater input level.

NOISE TEMPERATURE OF THE RECEIVING SYSTEM

Measurement of the noise temperature of the receiving system is performed after the maser amplifier and the first IF stages, since the noise contributed by the following components can be considered negligible. For this purpose a measurement is made of the difference in noise power level of the receiving equipment alone and the receiving equipment with a known noise power added by coupling at the maser input. The known noise power is provided by a calibrated white noise generator.

Measurement of Noise Temperature at the Zenith

Systematic measurements were made of the noise temperature with the antenna pointed at the zenith. A curve (Fig. 18) was plotted of the distribution based on 331 measurements. It is seen that for 50

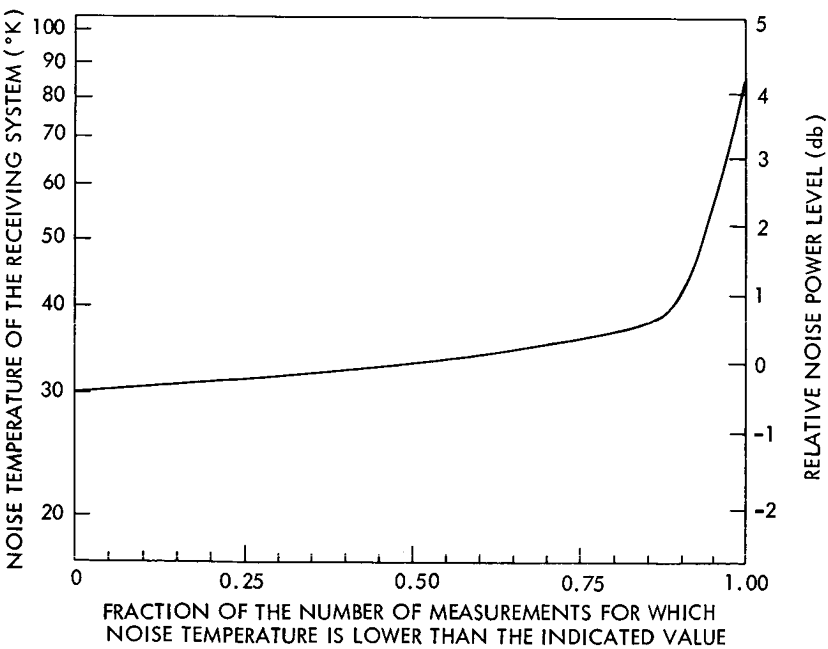

Fig. 18 — Distribution of noise temperature measured at the zenith.

percent of the measurements the noise temperature is equal to or less than 33°K. The lowest value measured was 27° K and the highest, 92°K. For 80 percent of the measurements the noise temperature was in the range of 27 to 38°K, with variation in noise power of the receiving system of less than 1 db. For 99 percent of the measurements the total variation of noise power does not exceed 4 db.

Measurement of Noise Temperature as a Function of Antenna Elevation

Figure 19 shows the variation of noise temperature as a function of elevation in dry weather. This curve is the average of a set of measurements for which the maximum deviations are less than 0.5°. Under these conditions the noise temperature at the zenith is 30.5°K, is only 44°K for an elevation of 5°, and reaches 55°K for an elevation of 3°, when the noise power is 2.5 db greater than the noise power at the zenith.

We have also shown on the same figure two examples of variations in noise temperature in the presence of perturbations. These two examples are characteristic of the two typical cases which were observed:

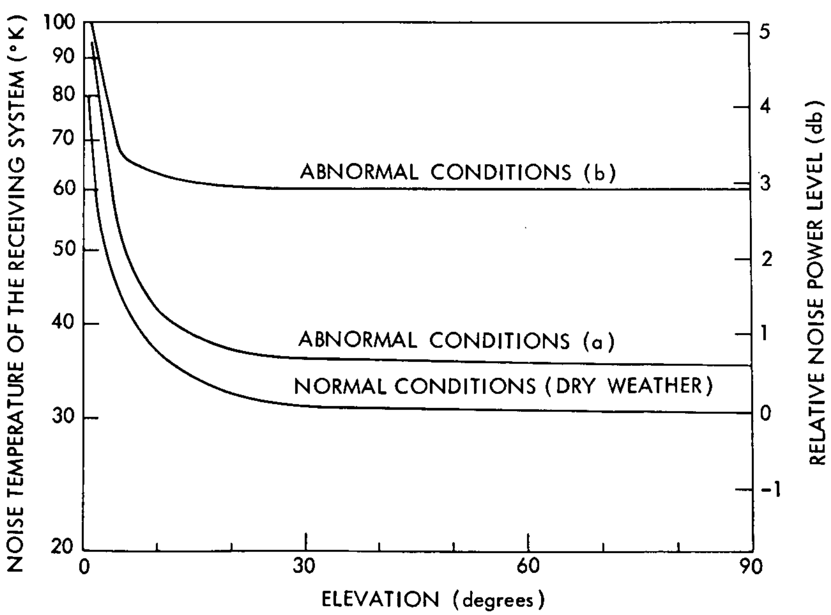

Fig. 19 — Noise temperature as a function of antenna elevation.

1. The increase in noise power level with respect to the dry-weather case is constant as a function of elevation, but small—about 0.5 db.
2. The increase in noise temperature is large, but variable with elevation. A decrease is even observed sometimes when the elevation decreases. For elevations of a few degrees, the increase in noise power level is relatively less than at the zenith (about 1 db).

NOISE IN THE TRANSMISSION CHANNEL

One measurement of the quality of the transmission channel is the amount of noise it contains. We measured this noise for each frequency and then studied its effect in the telephone channels and in the audio and video channels of the television signal.

Analysis of Noise in the Transmission Channel

The analysis of noise as a function of frequency in the transmission channel is performed with a selective analyzer having an equivalent pass band of 4 kc. We determined the curve obtained on the basis of measurements made on the wideband link (Fig. 20) and the curve for the narrowband link (Fig. 21). We plotted on these figures the signal power as a function of frequency, which enabled us to determine the pass band of the receiver. The dashed line is the curve calculated for noise power on the basis of the measured values of noise temperature and received power. The value of the measured noise power is in good agreement with the computed value for intermediate frequencies, but is higher for the lower frequencies because of the fact that the noise in the ground equipment becomes preponderant. It decreases rapidly at high frequencies because of the limiting of the RF band.

Impulsive Noise in the Transmission Channel

In order to determine the magnitude of impulsive noise which might appear in the link, we performed transmission tests with very short pulses at a rate of 875,000 bits per second, by direct modulation of the carrier. The transmission lasted for 20 minutes, which represents a billion transmitted bits. The quality of the transmission was exceptional, since only a single error was observed. It can therefore be concluded that no discernible impulsive noise appears in the link.

Noise in the Telephone Channels

Noise in the Telephone Channels on One-Way Links

When the link is one way, it is possible to equip some of the 600

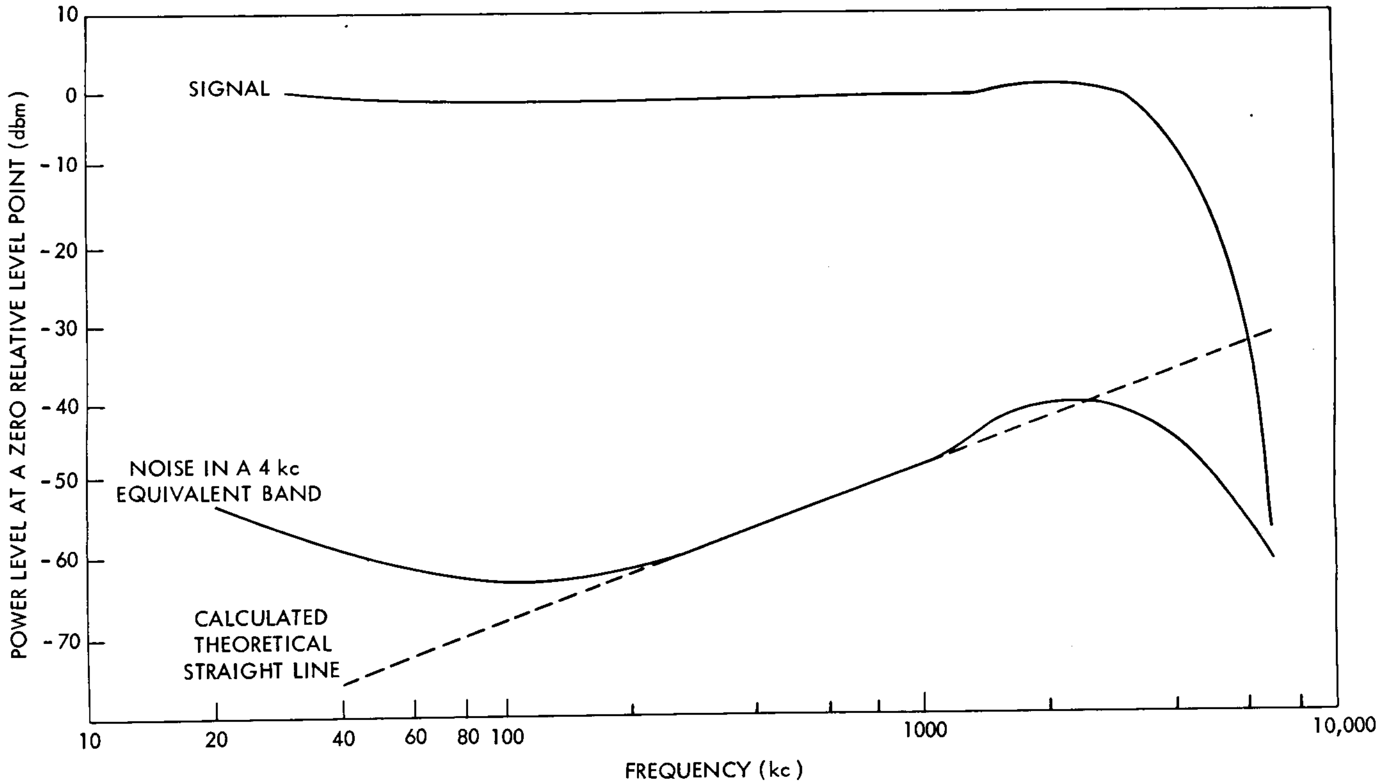

Fig. 20 — Noise analysis for the wideband link (Pass 705).

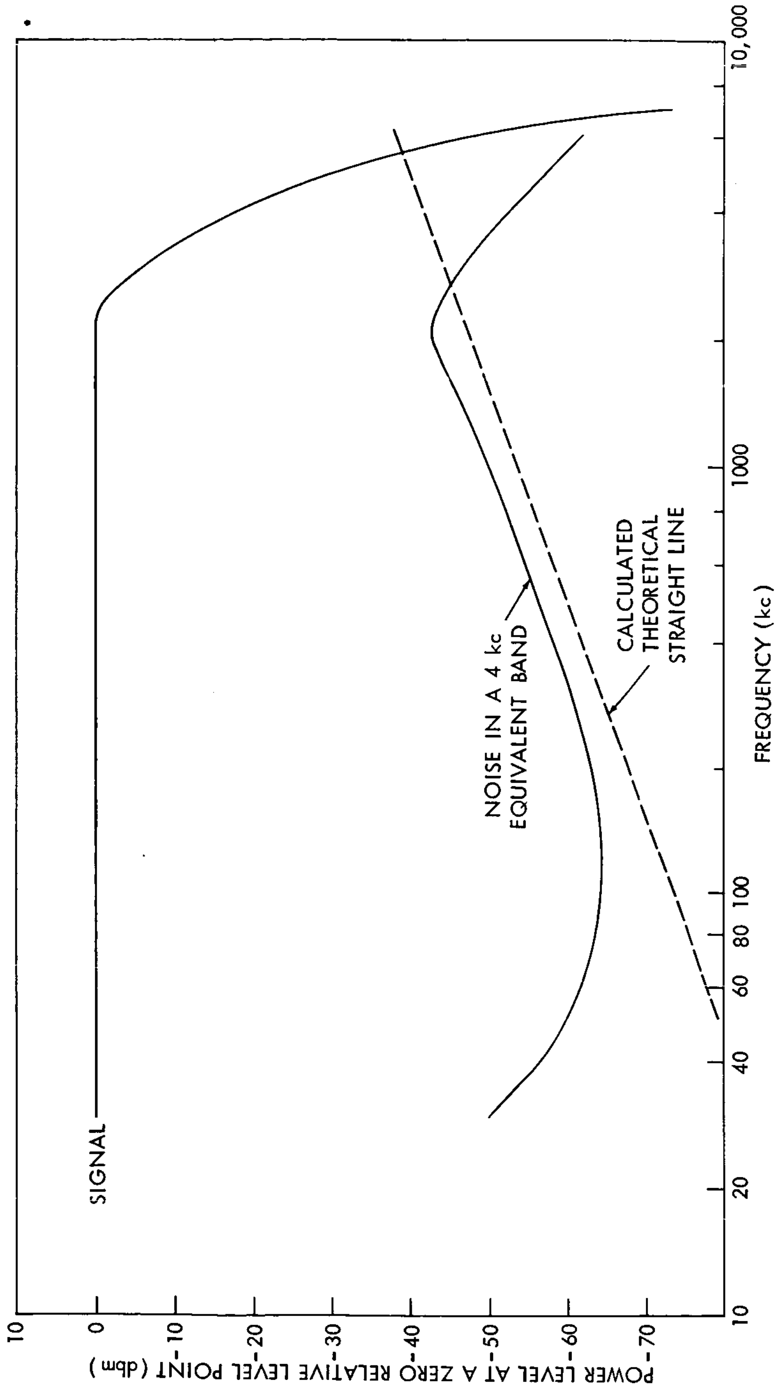

Fig. 21 — Noise analysis for the narrowband link (Pass 832).

telephone channels with a frequency-division multiplex system. After measurement of the equivalent channel a measurement is made of the psophometric noise. Figure 22 shows the results of measurements performed in loop on the satellite without pre-emphasis. The ratio of the signal to the psophometric noise, and the psophometric noise power, are plotted as functions of the frequency of the various channels measured. Corrections were made for the difference between the theoretical and measured equivalents of each channel. There is also shown the theoretical curve based on the received carrier power and the receiving system noise temperature. Very good agreement can be seen with the results of the measurements. For the pass shown here, the conditions were close to the most unfavorable conditions observed, and the noise power in the least favorable channel was on the order of 50,000 pw.

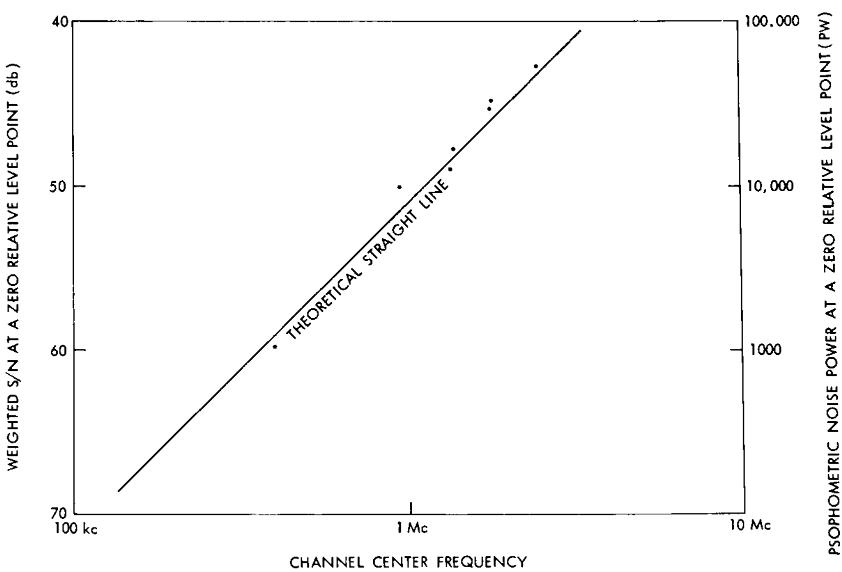

Fig. 22—Psophometric noise power in the telephone channel, one-way link without pre-emphasis.

The rapid variations of noise power in the telephone channels were also measured and recorded. Variations of less than ±0.25 db were observed. These variations are essentially due to the rotation of the satellite about its axis and to the irregularities in the pattern of its transmitting antenna.

Noise in the Telephone Channels on Two-Way Links

Psophometric thermal noise was measured for different carrier power levels received by the satellite on a 12-channel two-way link in the 60-108 kc band in collaboration with the Andover station.

Each station radiated a variable power which was adjusted automatically as a function of the satellite range, so that the satellite would receive the same power on each carrier. After checking the equality of these powers by telemetry, the Andover station varied its radiated power by a known quantity with respect to the programmed value. The Pleumeur-Bodou station continued to transmit in accordance with the planned program. For each value of the difference in received power at the satellite, a measurement was made of the psophometric noise power in channels 1 and 11 of the 12-channel multiplex telephony equipment. The nominal value for effective frequency deviation per channel (110 kc) had been used.

The results of this test are shown in Fig. 23 with respect to the received carrier power at Pleumeur-Bodou or, which amounts to the same thing, as we have already seen, with respect to the difference between the carriers received at the satellite.

It can be seen that the noise power in the telephone channels varies less rapidly than the received carrier power. This arises probably from

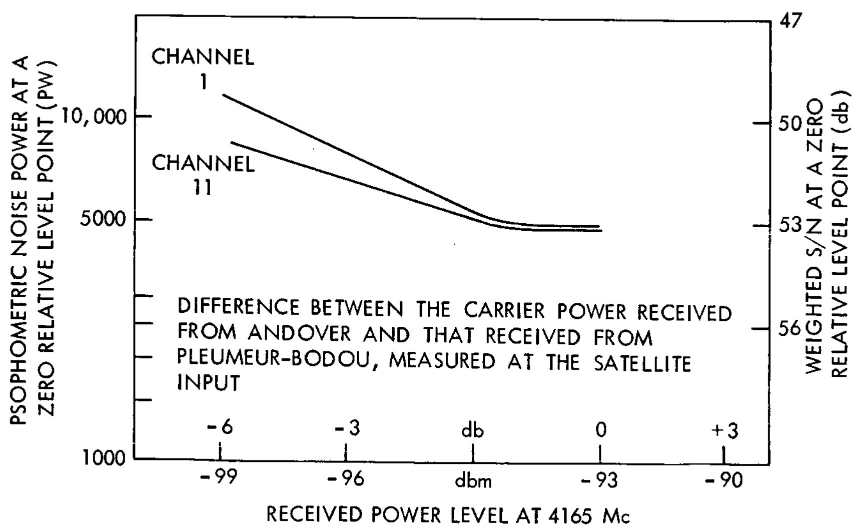

Fig. 23 — Weighted thermal noise for 12 two-way telephone channels (Pass 1014).

the noise generated in the equipment, since the measured noise power is very low. It will be noted that even for large differences of carrier powers received at the satellite, the weighted noise power is less than 10,000 pw.

Noise in the Television Channel

Noise in the Video Channel

Measurements were made of the ratio of the peak-to-peak signal to effective noise in television for received carrier powers in the range of −85 to −92 dbm. Noise temperatures in the receiving system were measured over the range 30°K to 70°K. A weighting network conforming to the network recommended by the CCIR for the 405-line standard (maximum transmitted frequency, 3 Mc) was used for certain measurements. The noise is limited between 10 kc and 3 Mc. Under these conditions the ratio of peak-to-peak signal to effective weighted noise always remained within the range 51 to 55 db. Comparison of the measured results with the values calculated theoretically from received power and receiver noise temperature was satisfactory only for the lowest measured values, corresponding to a very low received power. We were able to determine that this is due to noise in the ground equipment, which becomes preponderant when the signal-to-noise ratio reaches 55 db. For the same reason, the improvement effected by the weighting network is only about 10 db rather than the theoretical value of 12.3 db, computed for triangular noise.

The same measurements were made in two-way television, with the received carrier power lower and the frequency deviation reduced by 12 db. The ratio of peak-to-peak signal to effective weighted noise was measured for average conditions at about 41 db. No pre-emphasis was used, and the measured value is in very good agreement with the calculated value. In this case the above-mentioned noise in the ground equipment becomes negligible with respect to the noise contributed by the rest of the link.

Noise in the Sound Channel

Measurements were made of the ratio of peak-to-peak signal to effective unweighted noise in the television sound channel on a one-way link. The received carrier power was in the range of −85 to −93 dbm and the noise temperature approximately 35°K. The peak frequency deviation produced by a 1000 cps signal on the sound subcarrier at 4.5 Mc was 50 kc. A pre-emphasis network of the RC type, favoring the highs and with a time constant equal to 75 μs was used.

The peak frequency excursion produced by the subcarrier on the carrier was 1.4 Mc. The ratio of peak signal to effective unweighted noise remained in the range 50-56 db. Comparison with the calculated values indicates a slight deterioration of the signal-to-noise ratio, due probably to equipment noise. Nevertheless, the quality of the link is satisfactory.

In addition, no impulsive noise was observed.

The rapid variations of noise level are on the order of ±0.25 db. They are due mainly to the rotation of the satellite on its axis and to the irregularities of the pattern of its transmitting antenna.

DISTORTION IN THE TRANSMISSION CHANNEL

It is important not to deform the signal in the course of transmission. The most important deformation arises from variations of group propagation time in the RF band by FM signal. In telephony this produces intermodulation between channels; we also studied the deformation of television test signals.

Envelope Delay Distortion vs Intermediate Frequency

Distortions in frequency modulation are caused in particular by variations in group propagation time in the RF link of the transmission channel. The variations are measured in the following manner: At the input of the modulator a 50 cps sinusoidal signal is applied, causing a frequency deviation of ±7 Mc about the center frequency. On this signal is superimposed a 200 Kc sinusoidal wave which causes a low-amplitude (about 100 kc) frequency excursion. In the receiver the 50-cps signal is filtered out and the 200-kc signal is sent to a phase discriminator. This unit gives for each instant, and thus for a given value of the mean frequency, a voltage proportional to the deviation between its phase at that instant and the mean phase of the received signal. This error voltage is applied to the vertical deviation plates of an oscilloscope for which the horizontal sweep is synchronized to the 50-cps signal. The curve obtained on the screen thus represents the variation of group propagation time as a function of the intermediate frequency. Figure 24 reproduces the results obtained by loop tests with the satellite and the satellite simulator.

No appreciable difference can be observed between the results obtained with the simulator and with the satellite itself. The distortion is mostly parabolic. For a frequency deviation of ±7 Mc the measured value is about 25 ns. No delay equalizer was inserted in this measurement.

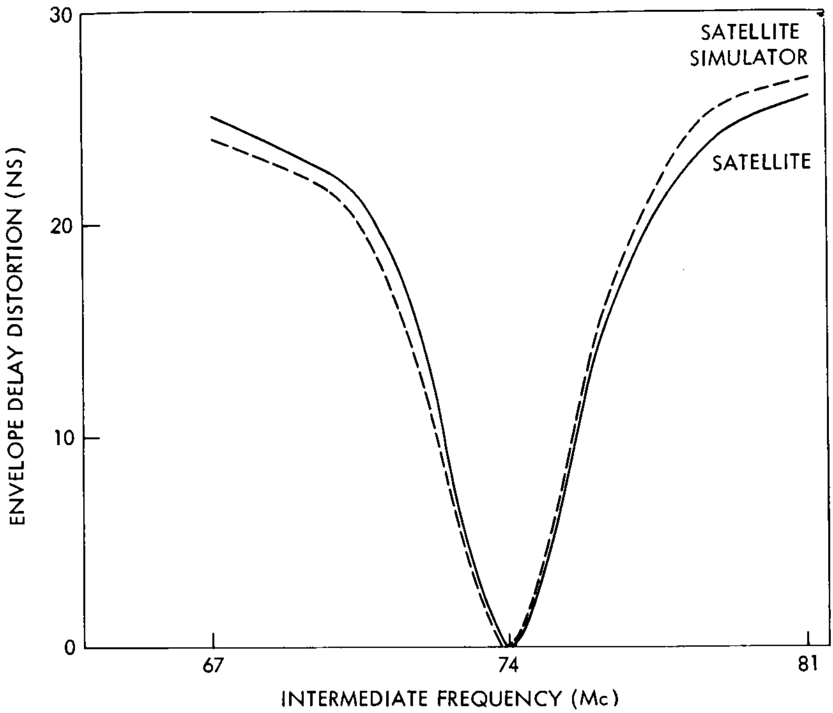

Fig. 24 — Envelope delay distortion as a function of intermediate frequency.

Intermodulation Noise in One-Way Telephony

DISTORTION IN THE TRANSMISSION CHANNEL

Intermodulation noise in one-way telephony was measured in loop on the satellite for a system of 600 telephone channels. Measurements were made for different effective frequency deviation per channel with or without the pre-emphasis network defined by the CCIR in recommendation No. 275. On Fig. 25 are plotted the values taken by the signal-to-unweighted-noise ratio in the channels centered on 70, 1248, and 2438 kc as a function of the effective frequency deviations per channel. The link was loaded by the uniform spectrum signal defined by CCIR recommendation No. 275 for 600 channels. The curves in dotted lines represent the values taken by the signal-to-unweighted-noise ratio with no modulation (thermal noise only). The solid lines represent the values taken by the signal-to-unweighted-noise ratio with modulation (thermal noise plus intermodulation noise). It can be seen that the effect of pre-emphasis is quite satisfactory and that it would be possible to increase by about 4 db the effective frequency excursion per channel, initially chosen at 512 kc, or to about 800 kc. The ratio of signal to unweighted noise would then be in all channels equal to or greater than 44 db for average conditions of received carrier power and noise temperature of the receiving system. This corresponds to a weighted noise power at a zero relative level point in the worst channel on the order of 15,000 pw.

Intermodulation Noise in Two-Way Telephony

Far-end and Near-end Crosstalk

In cooperation with the Andover station, measurements were made of far-end and near-end crosstalk for a multiplex system of 60 tele-

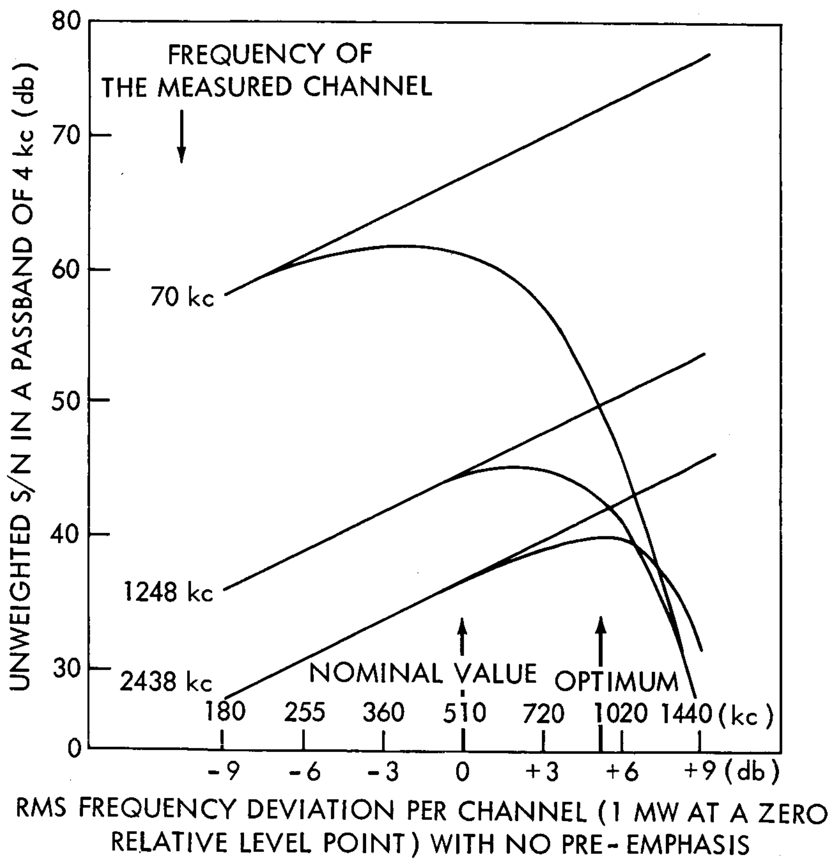

Fig. 25 — Intermodulation noise for 600 one-way channels.

phone channels in two-way link. The RF band was limited by a filter of 6 Mc bandwidth at mid power. No pre-emphasis was used.

For far-end crosstalk, the results are shown graphically as a function of effective frequency excursion per channel (Fig. 26). The curves in dotted lines represent the values taken by the signal-to-unweighted-noise ratio in the channels centered on 70 and 270 kc with no modulation (thermal noise only). The solid-line curves represent the values taken by the signal-to-unweighted-noise ratio when the link is loaded by the continuous uniform spectrum signal defined in CCIC recommendation No. 294 for 60 channels (thermal noise and intermodulation noise). It can be deduced from these measurements that the optimum effective frequency deviation per channel is 180 kc, slightly less than the 200 kc initially chosen, and that beyond this value the intermodu-

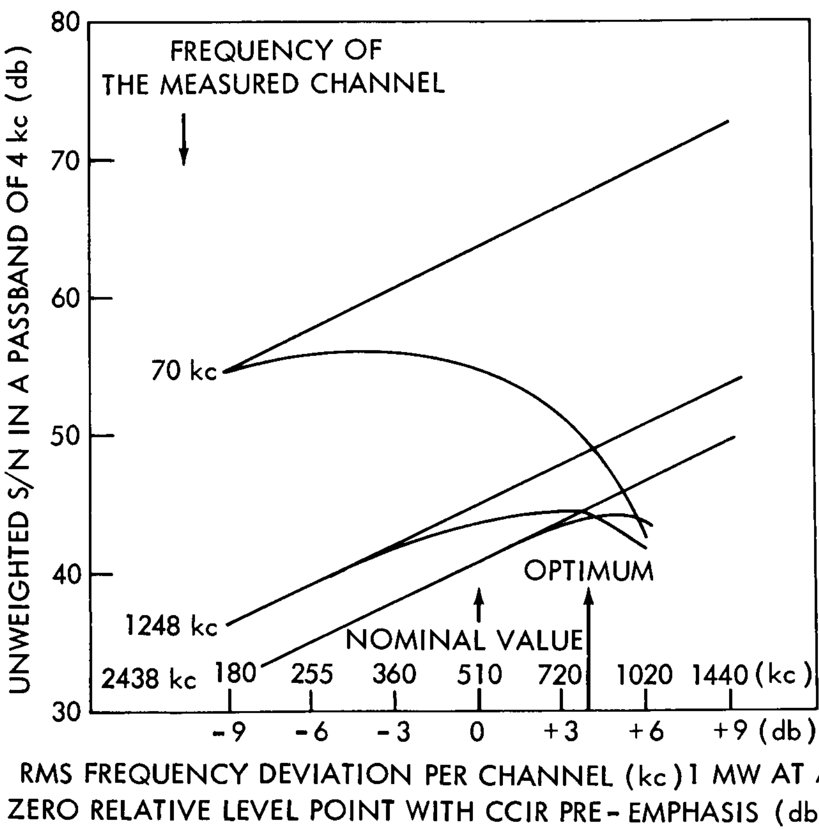

Fig. 25 (cont.) — Intermodulation noise for 600 one-way channels.

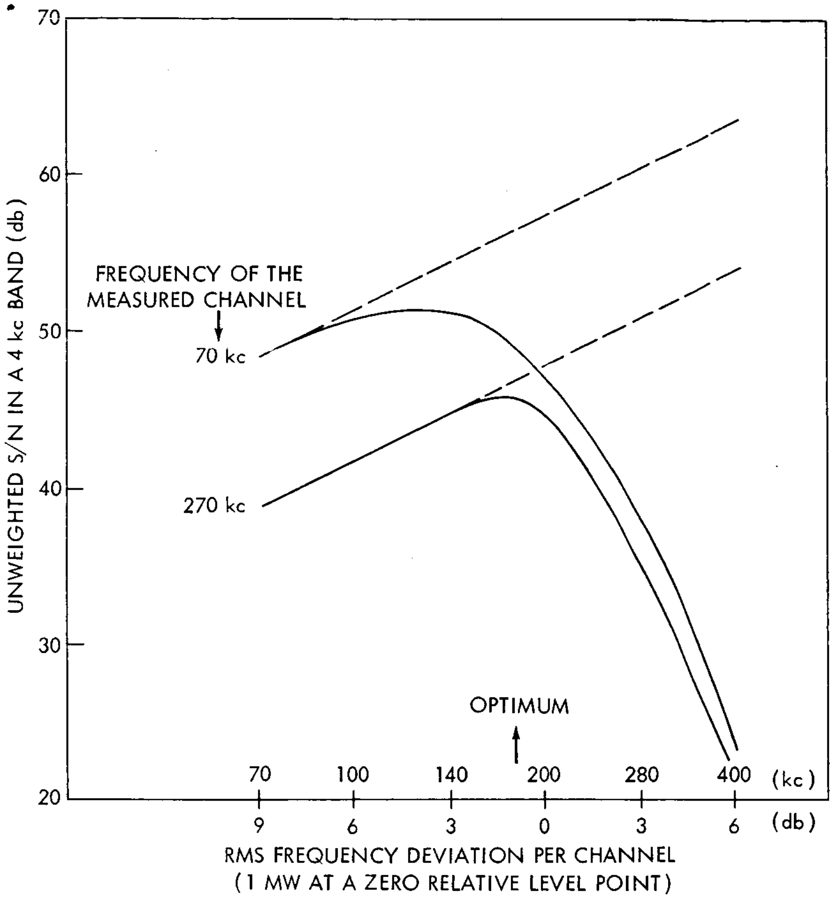

Fig. 26 — Intermodulation noise for 60 two-way channels.

lation noise increases rapidly. The ratio of the signal to unweighted noise in the worst channel is under optimum conditions, 45 db, corresponding to a psophometric noise power at a zero relative level point for each channel of less than 15,000 pw.

The near-end study shows that the signal-to-unweighted-noise ratio experiences a constant deterioration of about 2 db when the effective frequency deviation per channel varies from 100 to 400 kc.

Intelligible Crosstalk

It is possible to measure intelligible intermodulation between the two directions of transmission in two-way telephony in this way. By modulating one of the two carriers with a 100 kc sinusoidal signal, we studied the different frequency excursions produced by this signal, also with respect to the difference in power of the carriers at the satellite input.

The measurements listed in Table 1 were performed at Pleumeur-Bodou on a link with Andover.

The 100-kc signal was transmitted by the Andover station by modulation of the 6395 Mc carrier. After translation in the satellite the signal was retransmitted to the ground at 4175 Mc. The Pleumeur-Bodou station transmitted an unmodulated carrier at 6386 Mc, which was retransmitted by the satellite at 4165 Mc. The nominal values of the signal level received by selection of the 4174 Mc carrier at the measurement point for the deviations chosen (1 Mc peak-to-peak, 0.5 Mc peak-to-peak, and 0.25 Mc peak-to-peak) are shown on the first line of the table.

Table I — Intelligible Intermodulation Two-way Telephony*

Carrier		ΔF = 1 Mc P-P	ΔF = 0.25 Mc P-P	ΔF = 0.5 Mc P-P
NOMINAL VALUE	CARRIER AT 4175 Mc	−2.20 N†	−2.90 N	−3.60 N
CARRIER POWER EQUAL AT SATELLITE INPUT	CARRIER AT 4175 Mc	−2.15 N	−2.80 N	−3.50 N
	CARRIER AT 4165 Mc	−8.60 N	−9.55 N	−9.50 N
POWER AT 6395 Mc (ANDOVER) 3 db LOWER THAN AT 6385 Mc AT SATELLITE INPUT	CARRIER AT 4175 Mc	−2.15 N		−3.55 N
	CARRIER AT 4165 Mc	−9.20 N		−9.65 N

* Andover transmits at 6395 Mc a carrier modulated at 100 kc with a peak-to-peak frequency excursion ΔF. Pleumeur-Bodou transmits at 6385 Mc an unmodulated carrier.

† N = Neper.

• The power transmitted by each station is automatically adjusted for the range of the satellite and the power received from each station is determined from the telemetry and adjusted before the actual tests.

We have shown, when the power of the carriers received by the satellite are equal, the signal level received for each carrier. For the two lowest frequency deviations the parasite signal is lost in the noise. The carrier power received was −93 dbm for the two carriers and the noise temperature of the receiver was 33°K. For the greatest frequency excursion the presence of a parasite signal due to intermodulation can be observed; this increases the measured noise in a 300 cps band by about 0.9 neper.

When the power of the carrier with the signal, as measured at the satellite, is reduced by 3 db the power of the corresponding carrier received on the ground decreases by 3 db also (−96 dbm at Pleumeur-Bodou); the power of the other carrier received on the ground increases by 1 to 2 db (about −91.5 dbm at Pleumeur-Bodou). In fact, it can be seen that the 100-kc noise received after demodulation has decreased by about 0.15 N.* The parasite signal obtained by intermodulation is still lost in the noise at the smallest frequency excursion. For the greatest frequency excursion, on the other hand, the parasite signal is still present but increases the noise by only about 0.4 N.

There is thus some intermodulation occurring in the amplification equipment common to the two carriers (satellite equipment, maser amplifiers and first IF stages of the station), and it appears above the noise for the large frequency excursions (above 0.5 Mc peak-to-peak).

Distortion in the Television Channel

The study of linear and nonlinear distortion in the video channel was carried out by using the test signals recommended by the CCIR. The reconstituted signals remain within the limits defined by the CCIR for each test signal. The same tests were performed in loop on the cable link between the measurement room of the main building and the radome, without using the modulation equipment. The results were practically the same as those obtained with the satellite. From the point of view of distortion in the video channel, then, the television link is of satisfactory quality.

The total distortion of a sinusoidal signal in the sound channel was measured as a function of frequency for a sinusoidal signal at 1000 cps which produced in the 4.5 Mc subcarrier at peak frequency excursion

* Neper.

of 17.7 or 50 kc. In both cases the total distortion remained below 3 percent for all the frequencies of the useful band.

In order to examine the intermodulation of the video channel on the sound channel, the ratio of peak signal to effective noise in the sound channel was measured, with the video carrier unmodulated or modulated with the following test signals: CCIR test signals Nos. 1, 2, and 3 (Recommendation No. 267), high-frequency rectangular signal with 14 square pulses per line, test pattern, and a taped television program. It could be seen that when video and audio pre-emphasis networks are used the intermodulation can be considered negligible. Without pre-emphasis, however, the deterioration of the peak signal to effective noise ratio may reach 20 db. We feel that this deterioration comes from the ground equipment, since a similar result is observed when the transmitting equipment is looped to the receiving equipment at intermediate frequency.

SPECIAL EFFECTS ON THE LINK

Studies were made of two effects peculiar to satellite links; these do not appear in classical microwave links.

Absolute Measure of Propagation Time

The absolute measurement of propagation time is performed in loop on the satellite by measuring the interval of time which separates the leaving and the arrival of a square pulse after going through the satellite. A first series of measurements was made by transmitting the appropriate pulse in a telephone channel, the accuracy of the measurement in this case being ±0.2 ms. A second series of measurements, made by sending pulses with steeper sides in the video frequency band, enabled us to achieve an accuracy of ±0.2 μs. A comparison of measured values with those obtained by calculation based on the range of the satellite as determined by orbital data and allowing for propagation time in the equipment shows a remarkable agreement.

Influence of the Doppler Effect in Baseband

The frequency shift produced by the variation of transmission time on the frequencies transmitted in baseband is measured in loop on the satellite.

Figure 27 shows a comparison of the values measured at different times for the deviation between the received and transmitted fre-

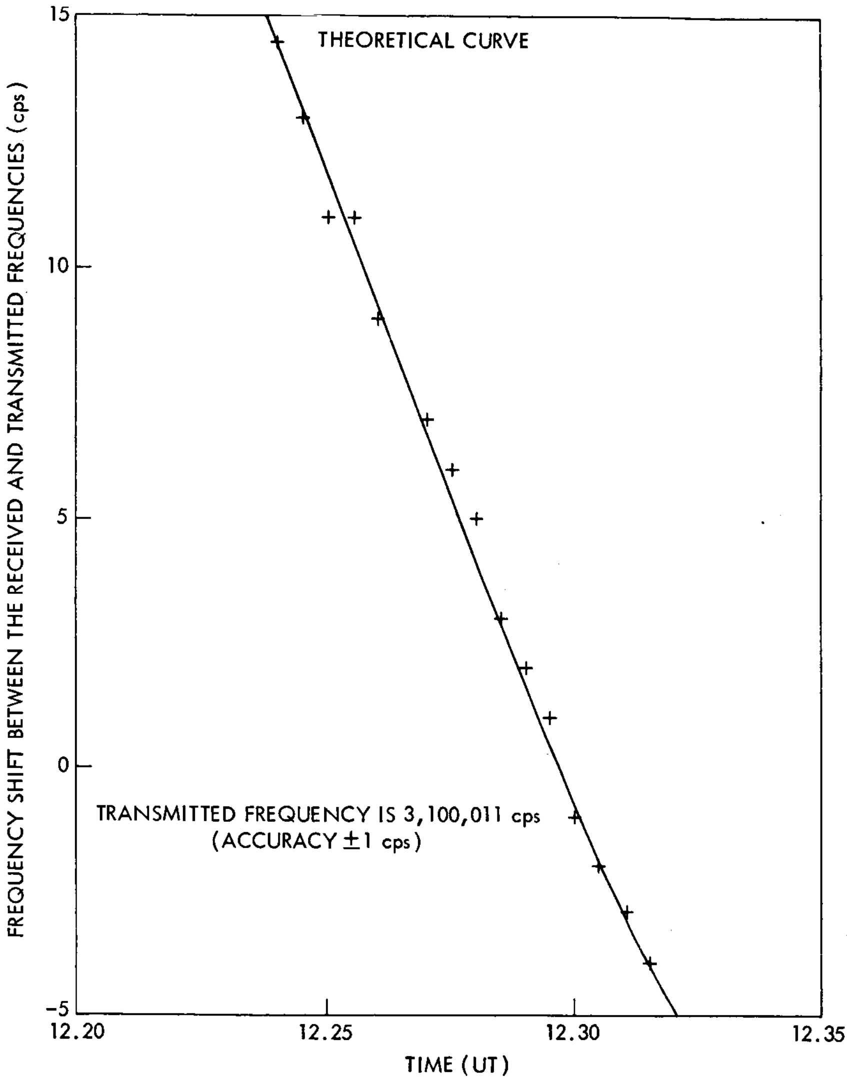

Fig. 27 — Doppler effect measurement (Pass 723).

quencies, with the transmitted frequency being 3,100,011 cps stable to 1 part in 10^8, with the theoretical curve based on orbital data. The accuracy of the measurement, made with a frequency counter, was ±1 cps.

SYSTEM TESTS

System tests of the link are for the most part qualitative tests of the transmission of a certain number of different types of information.

System Tests of the Telephone Channels

In addition to qualitative tests of telephony between talkers, the telephone channels were used for the transmission of certain information.

System Tests of Facsimile Transmission

When the satellite communication link was used for a system of multiplex telephone channels, some channels were used for the transmission of facsimile.

The first facsimile received from the United States at Pleumeur-Bodou on pass 97 was on a two-way link is reproduced in Fig. 28. A slight deformation of the corners can be observed due to the Doppler effect.

The link could also be one way. Under this condition, in loop on the satellite, we tested a system for Doppler effect correction, using a pure frequency linked with the rotational velocity of the transmitter drum and transmitted by frequency modulation of a subcarrier in the same telephone channel as the picture. Two photographs are reproduced (Figs. 29 and 30), one received with the use of the correction equipment designed for this purpose and the other received on an ordinary facsimile apparatus. The correction system, which requires very little change of normal equipment, corrects completely for the Doppler effect. The quality of the resulting photograph is excellent.

System Tests of Data Transmission

It is possible to use the telephone channels of the telephone multiplex system of a two-way link for the transmission of data at medium speeds.

The first system test, which took place during pass 97, consisted in transmitting some text from Pleumeur-Bodou to Andover and then from Andover to Pleumeur-Bodou at the rate of 1200 bands. The error-correction system of the machines used for the test did not operate during this test and errors were noted.

A measurement was also made of the quality of transmission at 2400 bands in different channels of a 600-channel multiplex system used on a one-way link in loop on the satellite. In the first test a channel in the lower part of the frequency band was utilized. No error was observed to 2.5 million bits transmitted. During a second test, the channel which

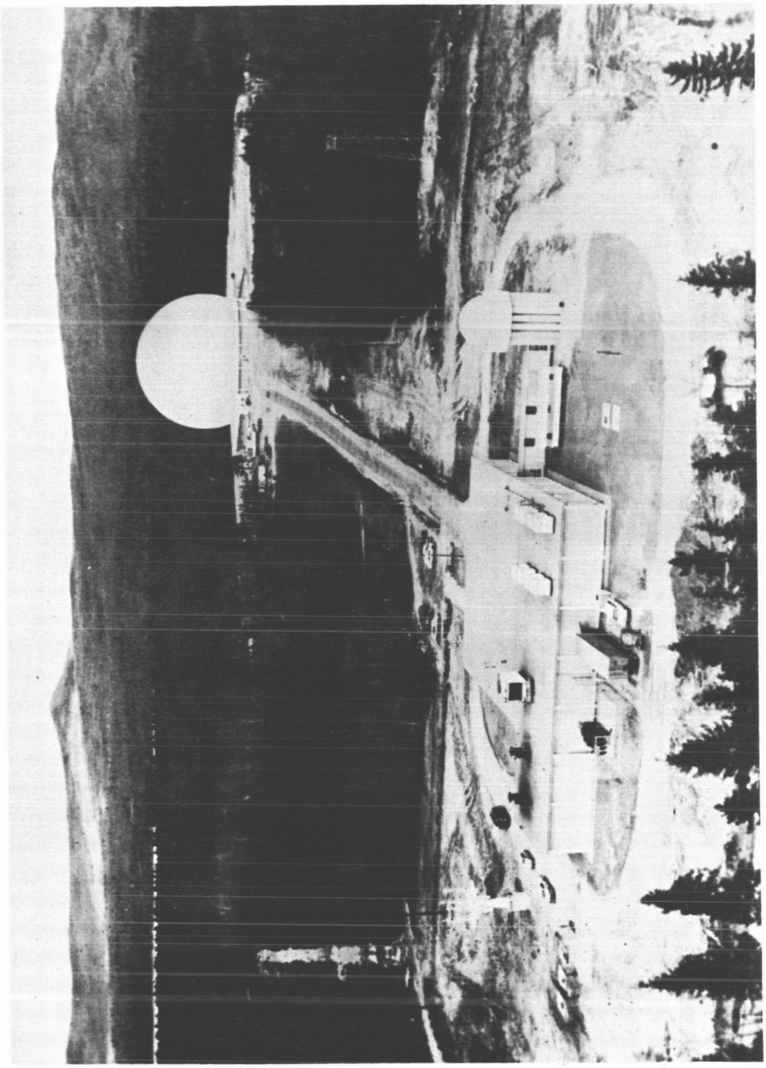

Fig. 28 — First facsimile photograph transmitted at New York and received at Paris via satellite.

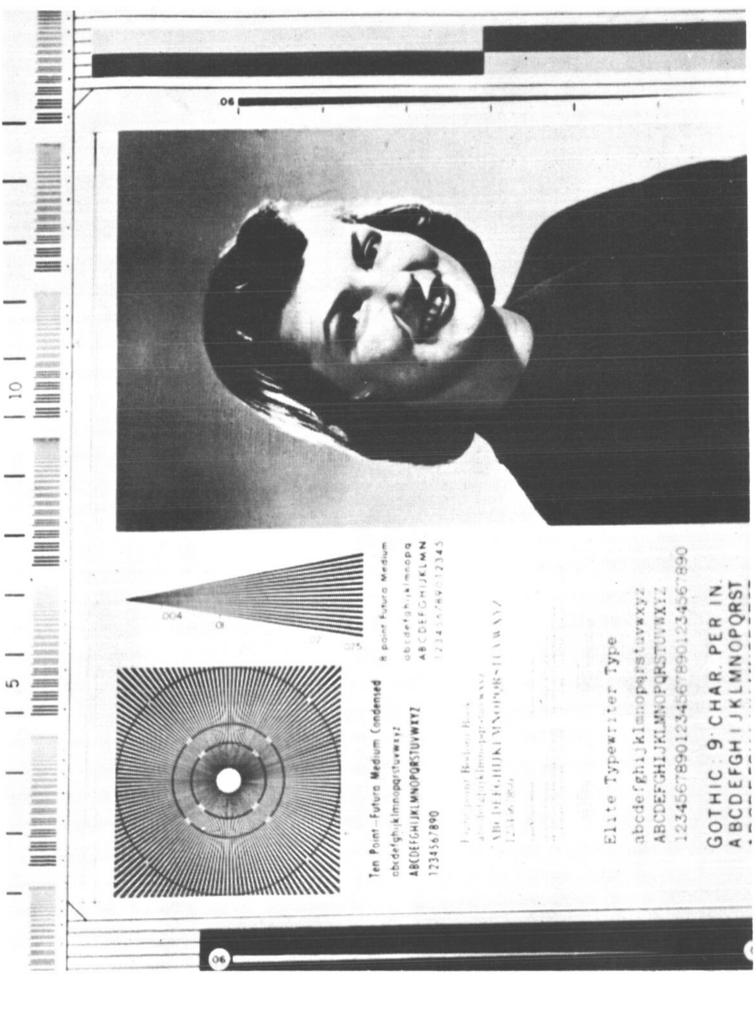

Fig. 29 — Facsimile photograph transmitted and received at Paris after round trip through Telstar I (No correction for Doppler effect).

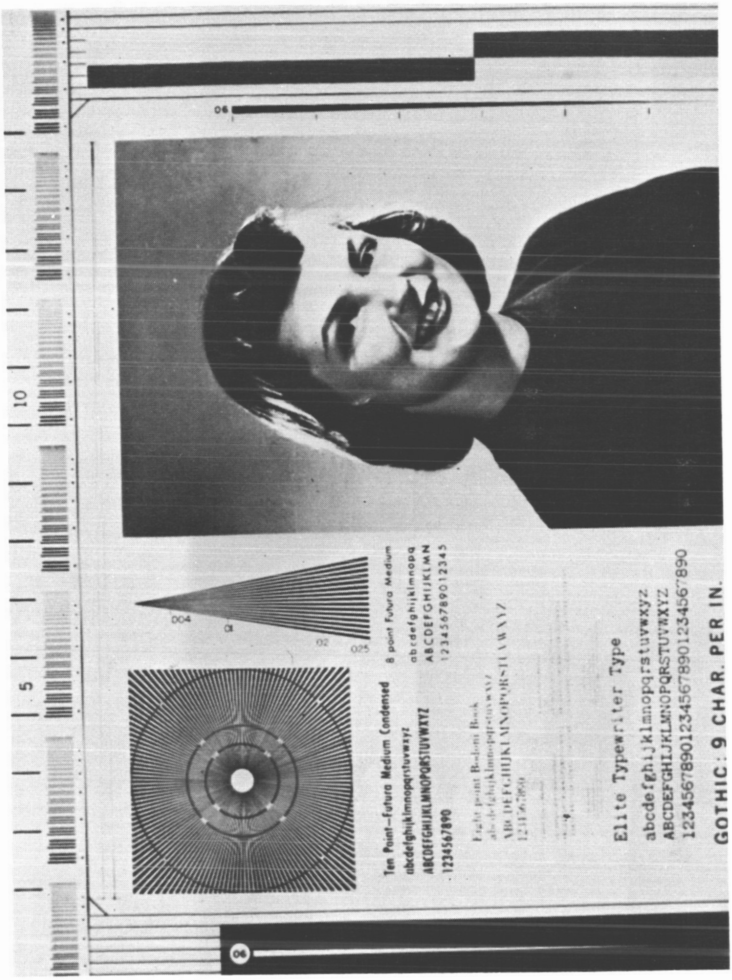

Fig. 30 — Facsimile photograph transmitted and received at Paris after round trip through Telstar I (With Doppler correction).

is transmitted at the highest frequency was used. The deviation, due to Doppler effect, between the frequency transmitted and the frequency received reached a maximum of 28 cps. No error were observed. During a third test, the ratio of signal to white noise at the input of the data transmission receiver was deliberately reduced by 13 db and set at 20 db. The frequency deviation due to Doppler effect was 13 cps maximum and an error rate of 2.5 in 10^6 was noted.

These tests show that the quality of the telephone channels for data transmission is excellent. The Doppler effect, which is nevertheless much greater in these tests than in a station-to-station link, is not troublesome in any of the 600 channels transmitted. A very wide margin over the signal-to-noise ratio exists before the error rate becomes significant.

System Tests of the Television Link

Certain passes of the satellite were reserved for the transmission of television pictures on a one-way link between the Andover station, the Goonhilly station, and the Pleumeur-Bodou station.

Especially during passes 6 and 7 (the first two with mutual visibility), pictures transmitted by Andover were received at Pleumeur-Bodou. In Fig. 31 is reproduced the photograph of the first picture received at the beginning of pass 6. During pass 16, the Pleumeur-Bodou station transmitted pictures which were received at Pleumeur-Bodou and Andover.

Later, a large number of passes were reserved for television demonstrations. Passes 123 and 124 in particular were reserved for inaugural demonstrations. Figure 32 is a reproduction of one of the pictures received from the United States at Pleumeur-Bodou on pass 123 and retransmitted directly on the Eurovision network.

All together, the Pleumeur-Bodou station participated in 20 system tests or demonstrations of one-way television in the America-Europe or Europe-America directions, from 10 July to 2 November 1962.

System tests of two-way television between the Andover and Pleumeur-Bodou stations were also performed.

The same norms were adopted as for one-way television, with the exception of the peak-to-peak frequency excursion of the signal, which was reduced by 12 db, or 3.75 Mc. The RF pass band was limited by a pass-band filter of 6 Mc at 3 db.

Figures 33 and 34 are reproductions of a picture received from Andover on one of the transmission channels and of a picture trans-

Fig. 31 — First picture received at Pleumeur-Bodou during Inaugural Program of Mondovision.

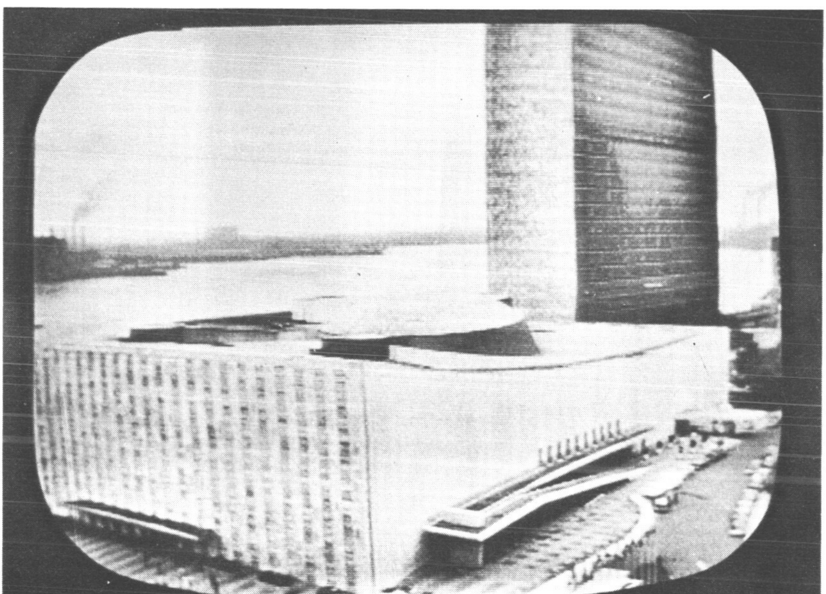

Fig. 32 — Picture received at Pleumeur-Bodou during Inaugural Program of Mondovision.

Fig. 33 — Two-way television picture transmitted at Andover and received at Pleumeur-Bodou.

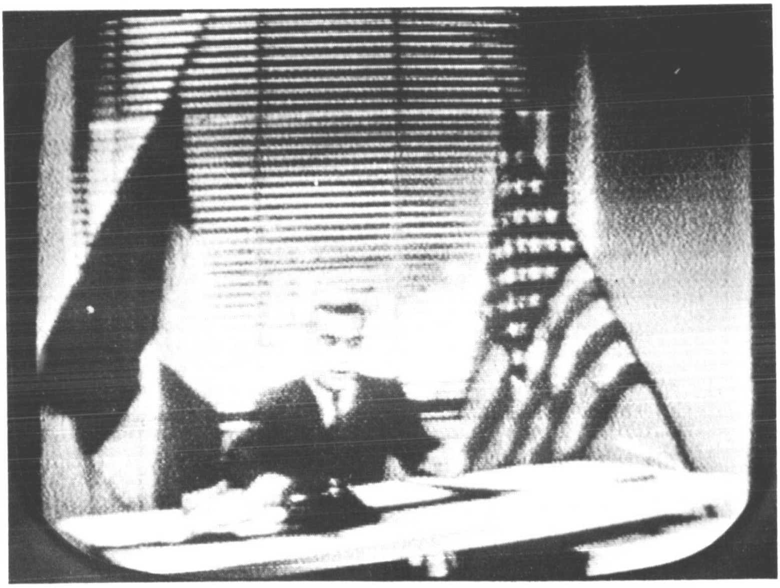

Fig. 34 — Two-way television picture transmitted and received at Pleumeur-Bodou after round trip via Andover.

mitted to Andover and retransmitted immediately to Pleumeur-Bodou on the other channel.

The quality of the pictures, although lower than that obtained on one-way television because of the reduced frequency excursion, is nevertheless acceptable.

CONCLUSION

The tests which we performed at the Pleumeur-Bodou station with the Telstar I satellite are fully satisfactory. They confirmed our hopes of being able to establish a wideband communications link between continents by the use of a satellite.

We were able to verify that the solutions which had been adopted for the solution of the problems of pointing a highly directive antenna with sufficient accuracy in the direction of a satellite at the moment it appears and then keeping it pointed at the moving satellite, and the problems of transmitting a wideband signal between two widely separated points on the earth without appreciable deterioration were technically valid. We were able to study some of these problems in greater detail and to examine the most adequate solutions for them. Thanks to the experimental facilities we have available, we were able to find the methods which were technically and economically most suitable and which will be usable for the development of a commercially useful system of communications by satellite.