The *Telstar* Satellite System

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This paper describes the Telstar system and discusses the over-all system design. System considerations, the orbit selection and frequency allocation considerations are covered. A general description of the Telstar satellite and Andover, Maine, ground station provides background for companion articles in this series. Finally, the transmission performance is given with some discussion of system parameters.

I. INTRODUCTION

The Telstar system consists of the active communication satellite repeater in orbit and ground facilities to work with it. The satellite was designed and built by Bell Telephone Laboratories and launched by the National Aeronautics and Space Administration (NASA) under the terms of a cooperative agreement. Bell Laboratories built the ground station at Andover, Maine, and furnished launch support equipment at Cape Canaveral. The station at Holmdel, New Jersey,[1] originally built for the Echo project, was modified to work with the Telstar system. Participating European stations were constructed at Goonhilly Downs in England, Pleumeur-Bodou in France, and Fucino in Italy by telecommunications agencies in the respective countries.

This paper gives a general description of the Telstar satellite system. It starts with a discussion of the over-all system design. This is followed by a more detailed discussion of the factors affecting the choice of the orbit and of the operating frequencies. The satellite, the Andover ground station, and the equipment at Cape Canaveral are next described and, finally, certain important transmission parameters are presented.

II. SYSTEM OBJECTIVES

The system was designed to meet the following objectives:

(1) To demonstrate broadband microwave transmission through an active satellite.

Specifically, this included the transatlantic transmission of high-quality television with sound, or the equivalent of 600 one-way telephone channels. It was also desired to test the transmission of a limited number of two-way telephone channels using a common amplifier in the satellite. A further transmission objective was to demonstrate that other services, such as data, telegraphy and telephoto, could be sent through the satellite.

(2) To test the operation of a ground station capable of transmitting to, and receiving from, the satellite while tracking it.

This involved the simultaneous operation of a high-power broadband transmitter and an ultra-low-noise receiver through a common horn-reflector antenna. An important aspect of the ground station tests was the trial of several means of acquisition and tracking of the satellite, and the steering of the antenna by both programmed and autotrack methods.

(3) To obtain data on the space environment and its effect on the satellite.

For this purpose, equipment is carried to measure particle radiation in space, as well as temperatures, voltages and other conditions in the satellite. Telemetry is provided to relay this information to the earth.

III. GENERAL SYSTEM CONSIDERATIONS AND FEATURES

A satellite communications system differs in major respects from other kinds of radio communications systems, and hence the various constraints faced by the designer differ in nature or emphasis. In this section, the major constraints which influenced the design of the Telstar system and the way in which they affected the system parameters are discussed in a general way. Major system features are given. Subsequent sections will discuss these matters in more detail.

The principal factors affecting the choice of the parameters of the Telstar system were the following:

(1) In order to provide mutual visibility across the Atlantic for periods of useful length, it was necessary to place the satellite in an orbit above 2000 miles. On the other hand, the weight which could be launched into a satisfactory orbit with available launch vehicles was limited.

(2) It was necessary to choose operating frequencies at which the sky noise and atmospheric absorption would be low and where sufficient bandwidth for television and other broadband services could be obtained. It was also necessary to consider interference between the satellite system and other radio services.

(3) Because of the long distances involved, radio path losses are very great. In addition, the effective radiated power of the satellite was limited by the primary power obtainable within the weight restrictions and because of the impracticality of using directive antennas in the satellite. The signal power received at the ground antenna, therefore, is very weak compared with levels normally received in overland radio relay systems.

(4) It was desired to design a satellite with a high probability of surviving the launch and which would last as long as possible in the space environment. This consideration affected the design and weight of the satellite in many ways, including selection of reliable components, rugged construction and protection against particle radiation.

All of these factors interact with each other and, as a result, there is no uniquely logical order in which the design choices can be developed in a step-by-step manner. Probably the choice of operating frequencies is the best starting point.

Considerations of bandwidth, propagation and radio noise narrow the choice of operating frequencies to the region between one and ten gigacycles, as will be discussed in more detail in a later section. These factors, together with hardware considerations and problems of coordination with other radio services, led to operation in the 3700–4200-mc and 5925–6425-mc common-carrier bands. The low power received at the ground led to the choice of the lower frequency band for the down path because these frequencies are better from the standpoints of radio propagation and noise.

At the operating frequencies chosen, noise from the sky is very low (as much as 20 db lower than that radiated by the earth into terrestrial microwave antennas) and thus very weak signals can be used. Advantage could be taken of this by using a low-noise ground antenna and a helium-cooled maser amplifier at the input to the ground receiver. A horn reflector was chosen because it has very low gain a few degrees off the main beam and thus would pick up very little noise from terrestrial sources. To further improve reception, it was decided to build at Andover the largest, and thus highest-gain, horn-reflector antenna that could be designed with confidence that it could be steered accurately enough to track the satellite. This antenna has a 3600-square-foot aperture.

Even with the low-noise antenna and maser, it was necessary to employ every possible technique for achieving high quality transmission with weak signals. This led to the choice of wide-swing frequency modulation for the down path, since it permits good baseband signal-to-noise ratios with poor radio-frequency carrier-to-noise ratios. The use of a frequency compression demodulator (also referred to as an FM feedback receiver) permits operation with lower carrier-to-noise ratios than is possible with a conventional FM detector. For satellite simplicity and other reasons, FM was also chosen for the up path. The satellite amplifies the signal but does not alter the modulation.

The Andover ground station provides adequate transmission performance for the down link out to a range of more than 8000 nautical miles with a satellite effective radiated power of 2 watts. A 2-kw transmitter on the same antenna provides similar performance for the up link.

If antenna gain could be used in the satellite, the actual RF power could be less than 2 watts and this could be traded for other simplifications in the satellite or ground station, or for improved transmission performance. There are a number of possible techniques for achieving this, including the use in the satellite of earth pointing attitude stabilization along with a directive antenna, steerable phased arrays or provision for switching several directive antennas. These possibilities were discarded for various reasons, including the state of the art, the time it would have taken to develop them, and the desire for a simple satellite. Instead, an antenna system which is nearly isotropic is employed. To minimize the effects of nulls on communication, the satellite is spin stabilized around the axis of symmetry of the antenna system.

A traveling-wave tube was chosen for the satellite output amplifier, since it could provide sufficient power with good efficiency and because it would provide a wide bandwidth. Prior experience with missile-borne traveling-wave tubes had demonstrated that they could be made rugged enough to withstand a rocket launch. All other circuits employ solid-state devices.

Solar cells were chosen as the only practical source of primary power for the satellite. To supply the power required for the communication equipment directly from the solar cells would mean more cells and thus more weight than was possible within the weight and size limitations on the satellite. Therefore, a nickel-cadmium storage battery charged by the solar cells supplies the communications equipment during operation. Command circuits are provided to turn off the communications equipment so the batteries can be charged and to perform a number of other functions.

Facilities for measuring trapped particle radiation and its effect on solid-state devices are provided. Telemetry provides information on the condition of the satellite and on the results of the radiation experiment. The satellite is approximately spherical, with a diameter of 34 inches, and weighs approximately 170 pounds.

The launch vehicle was a major factor in the Telstar experiment.

Very early in the planning of the project, consideration was given to possible vehicles which might be capable of putting a sufficient payload into a satisfactory orbit. For reasons of availability and reliability, the NASA Delta vehicle was chosen. Since it could not launch the payload into a high enough circular orbit, an elliptical orbit with an apogee of about 3000 nautical miles and a perigee of about 500 nautical miles was chosen. The orbit is inclined 45° to the equator. When apogee is over the North Atlantic, there are several good periods of mutual visibility between Europe and Andover daily.

Table I lists the major parameters of the Telstar system.

IV. ORBIT SELECTION

As indicated in the preceding section, it was necessary to place the satellite in a high enough orbit to give satisfactory periods of mutual visibility across the Atlantic. The problem is illustrated by Fig. 1.* It shows lunes of mutual visibility for communication between Andover, Maine, and either Goonhilly Downs in England or Pleumeur-Bodou in France, assuming minimum antenna elevation of 7.5°. For a particular height, the subsatellite point on the earth's surface must be within the corresponding lune if the satellite is to be mutually visible. As the height gets lower, the lune becomes smaller. At the same time, the orbit period becomes shorter so that the subsatellite point moves more rapidly over the earth. The net result is fewer and shorter useful passes. The lune would vanish at 475 nm height.

The inclination of the orbit also affects visibility, since the satellite never passes over regions whose latitudes are higher than the inclination. Thus, only part of the visibility lune may actually be useful for communication. The best choice of orbit inclination depends on the particular points on the earth between which communication is desired; for the points of principal interest here a high inclination is best. Thus, for the Telstar satellite, an orbit was desired with the highest altitude and inclination possible with the available launch vehicle and launch location.

The launch vehicle used is a major factor in any satellite experiment. Rockets capable of orbiting significant payloads do not exist in such variety that the problem can be approached with a set of requirements on *them* as an end result. On the contrary, it is almost inevitable that an available vehicle must be found and the experiment framed within its capability. This, in effect, limits the achievable orbits and sets weight and size limits on the satellite.

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* For a more complete discussion of satellite visibility, see Ref. 2.

TABLE I — PRINCIPAL FEATURES OF THE *Telstar* SYSTEM

TRANSMISSION

- Signals handled
  - Television
  - 600 one-way telephone channels (simulated by noise)
  - 12 two-way telephone channels
- Modulation — FM
- RF bandwidth
  - Ground station — 25 mc
  - Satellite — 50 mc
- Frequencies
  - Communication up — 6389.58 mc
  - Communication down — 4169.72 mc
  - Beacon — 4079.73 mc
  - Telemetry and beacon — 136.05 mc
  - Command — about 123 mc
- Polarization
  - Microwave channels — circular
  - VHF beacon — linear
  - Command — circular

SATELLITE

- Size, shape, and weight — 34-inch sphere, 170 pounds
- Orbit
  - Perigee 514.21 nm
  - Apogee 3051.37 nm
  - Inclination 44.8°
- Launch — Delta vehicle from Cape Canaveral
- Repeater configuration — IF type: amplifies, shifts frequency, does not alter modulation
- Communications antennas — approximately isotropic, circularly polarized
- RF power output — 2 watts
- Power plant
  - Silicon n-on-p solar cells — shielded
  - Ni-Cd storage battery
- Stabilization
  - Spin with axis normal to plane of ecliptic
  - Magnetic torquing coil control
- Radiation experiments — proton and electron
  - Flux in several energy ranges
  - Radiation damage to special solid-state devices

ANDOVER GROUND STATION

- Communications antenna
  - 3600 square foot horn reflector
  - Inflated radome
  - Pointing by tape drive, autotrack, slave to precision tracker
- Communications transmitter — 2 kw
- Communications receiver — maser input, frequency compression demodulator
- Noise temperature — 32° K at zenith

The capabilities of the possible launch vehicles were analyzed. The most readily available was the Delta vehicle used by NASA for the Echo launch and planned to be the vehicle for many other space experiments. It was also believed to be reliable, as has since been borne out by a long succession of successful launches. The initial weight objective

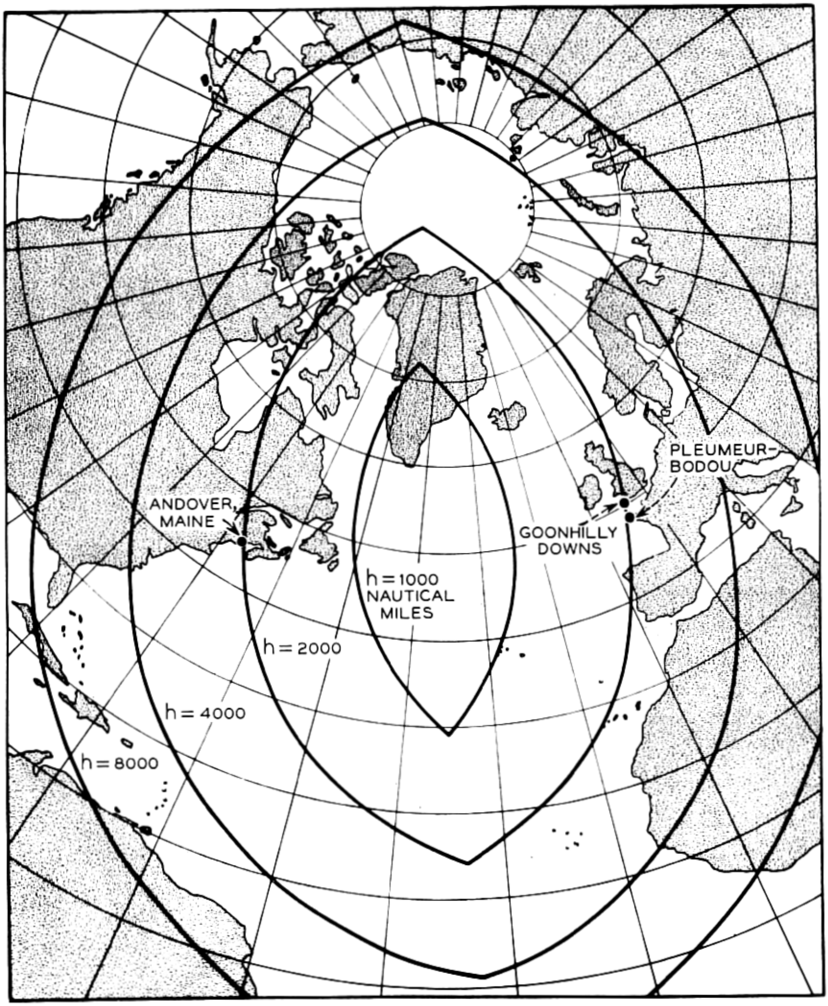


Fig. 1 — Useful regions for various heights above surface of earth.

for the Telstar spacecraft was 125 pounds, but as the real problems of design were met and solved, it became apparent that the satellite would weigh about 170 pounds. With this weight, analysis indicated that the Delta vehicle, launched from Cape Canaveral, would achieve a circular orbit only about 1000 nautical miles high with 42° inclination. This would result in only about three passes per day, typically only five minutes long, with mutual visibility across the Atlantic.

In spite of this disadvantage, the availability and reliability of the

Delta made it an attractive vehicle. Therefore, attention was turned to the possibilities of an elliptical orbit. By accepting a low perigee, an apogee much higher than 1000 miles could be achieved. If the apogee were located well north of the equator, satisfactory periods of mutual visibility could be achieved across the North Atlantic. Table II shows the orbit parameters chosen, together with those actually achieved.

Fig. 2 shows the suborbital track of the Telstar satellite for the first 24 hours after launch. With a period of 158 minutes, the satellite completes nine orbits in 23 hours, 42 minutes, accounting for the near retracing of the first track on the tenth orbit. Those periods when the satellite was mutually visible across the Atlantic are shown by heavy solid lines. Additional time when it was visible from Andover only are shown by light solid lines. Other periods are shown dashed.

It will be noted from the table that the initial apogee was south of the equator — not the best position from the standpoint of visibility. However, the line of apsides advances about 2° per day, and after launch the apogee moved in a northerly direction. It reached its northernmost point in about 50 days and then started to move southward. This gave a period of about three months during which visibility was good, followed by a period of poor visibility. Fig. 3 shows visible time per day when the satellite is at least 7.5° above the horizon. Initially, there were three or four passes per day, each lasting 10–20 minutes, during which the satellite could be used for transatlantic communication. Seven weeks later, with the apogee in its best position, there were four or five passes daily, each lasting 20–40 minutes.

Another orbit parameter is spin-axis orientation. For optimum output from the solar power plant and favorable heat balance, it was desired to have the spin axis perpendicular to the sun line. If this attitude is to be maintained as the earth carries the satellite with it around the sun, the axis must also be normal to the ecliptic plane. The desired inclination of the orbit was achieved by dog-leg maneuvers during the launch. Thus, while the orbit plane is inclined 45° to the equator, the direction

Table II — Orbit of the *Telstar* Satellite

	Proposed	Actual Orbit (NASA Minitrack)
Perigee	500 nm	511.9 nm
Apogee	3000 nm	3043.2 nm
Inclination	45.43°	44.8°
Period	156.47 min.	157.6 min.
Initial apogee latitude	8.59°S	11.92°S
Apsidal advance	2.02°/day	1.98°/day

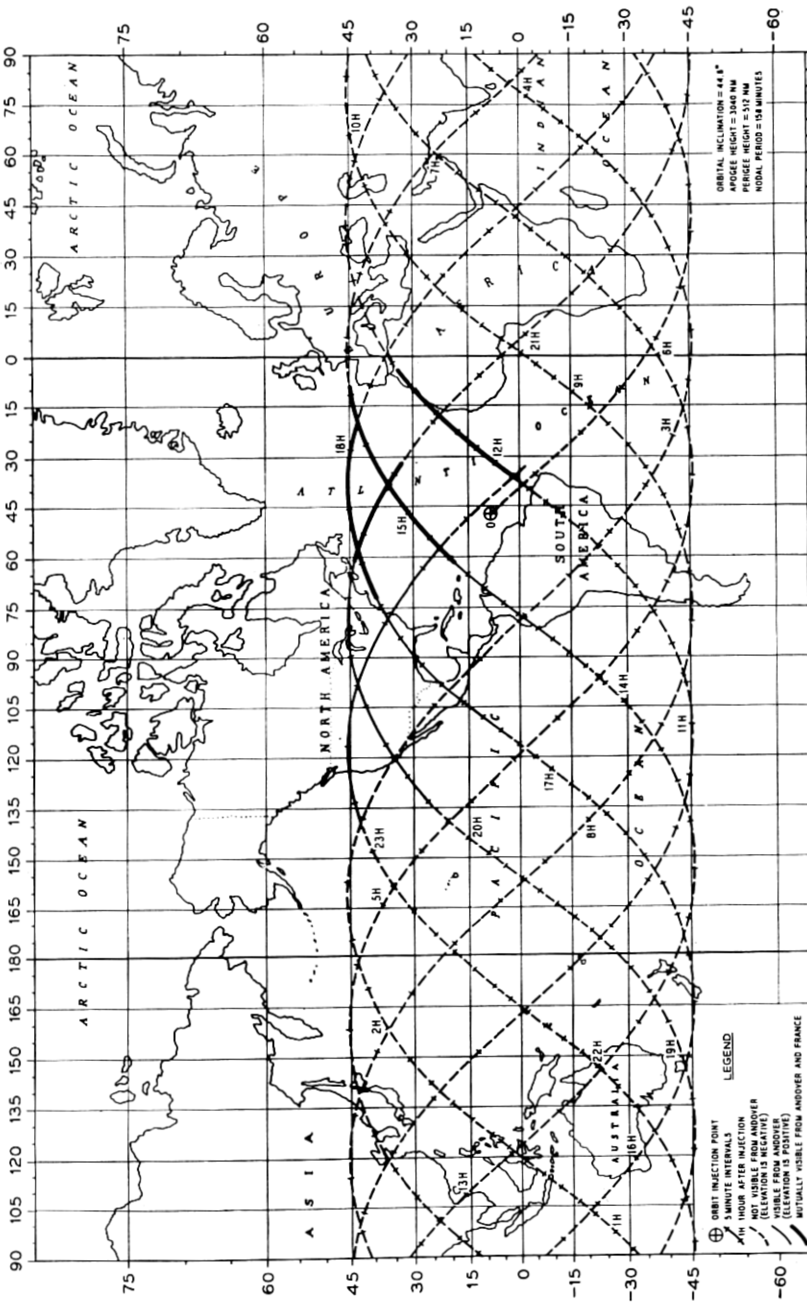


Fig. 2 — Suborbital tracks and mutual visibility for first 24 hours.

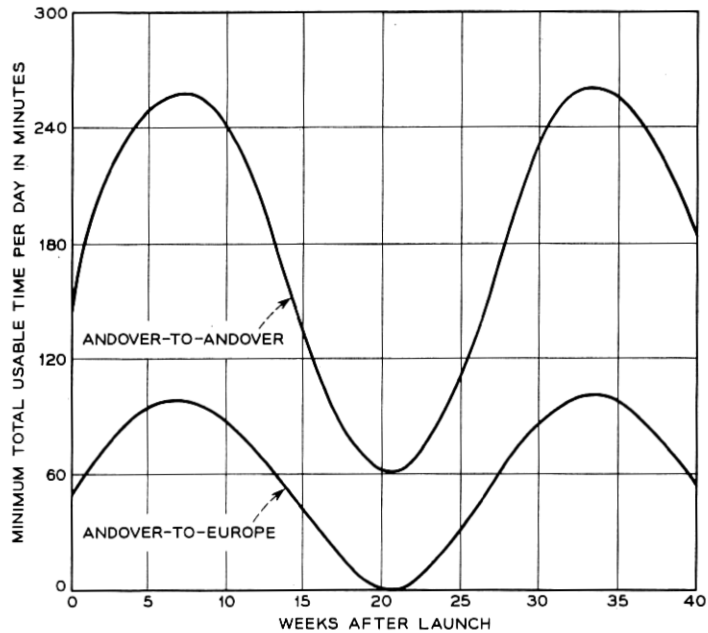


Fig. 3 — Minimum usable time per day.

of the final thrust of the third-stage rocket, and hence the orientation of the spin axis, was at a higher inclination to the equator — actually 67°. By choosing the time of launch, the 23° inclination of the earth's axis with respect to the ecliptic plane was added to this, resulting in a spin-axis attitude almost perpendicular to the ecliptic plane. The axis precesses with time because of the torque created by the residual magnetic moment of the satellite in the earth's field. To correct this precession, a magnetic torquing coil is provided in the satellite which can be turned on from time to time to control the position of the spin axis.

The elliptical orbit of the Telstar satellite is also desirable for the radiation experiment, since it covers a large part of the inner Van Allen belt and, with its apogee in northerly or southerly positions, it passes through a portion of the outer Van Allen belt.

V. CHOICE OF OPERATING FREQUENCIES

The frequencies used by the Telstar system include those required for the communications channel and for a microwave beacon used in tracking. They also include VHF channels for transmitting commands to the satellite and for the VHF beacon and telemetry. The VHF channels were chosen to fit in with the facilities of NASA Minitrack stations.

Factors in the choice of the communications frequencies included propagation, noise, and interference within the satellite system and with other services. These were considered not only with respect to the experiment, but also from the point of view of later commercial systems. These factors lead to the choice of frequencies in the region between one and ten gigacycles.

5.1 *Propagation and Noise*

The 1- to 10-gc region is the same part of the spectrum commonly used for terrestrial radio relay systems, but the critical transmission factors are different. Radio relay systems are subject to severe selective fading due to multipath effects. When enough margin is provided for fading, atmospheric absorption is unimportant except at the upper edge of the band. Radio relay antennas, since they are pointed horizontally, receive thermal noise from the earth, and this puts a floor on the effective noise temperature of the system. On the other hand, in satellite systems, selective fading is nonexistent, except at very low elevation angles of the ground antennas. Noise received from the sky in favorable parts of the spectrum is much lower than thermal noise from the earth, so that low-noise amplifiers such as the solid-state maser can be used effectively.

Receiving system noise temperatures of satellite ground stations can be made very low compared with the approximately 300°K temperature of the earth. For example, the Andover station has an effective temperature, excluding sky noise, of about 30°K. Thus, sky noise temperatures in the tens of degrees are significant.

At one gigacycle, cosmic noise can be as high as 30°K and becomes greater at lower frequencies.[3] Above one gigacycle, sky noise due to air, water vapor and rain increases as frequency increases. Noise due to air and water vapor alone is worst at low antenna elevation angles. For an elevation of 7.5°, it is about 15°K at 1 gc and 30–60°K at 10 gc. More serious is the effect of rain. Zenith measurements at 6 gc have produced values in excess of 100°K during very heavy rainfall.[4] Unpublished data indicate that, for the same rain conditions, noise will generally be higher for low antenna elevation angles. The effect is highly dependent on frequency with the lower frequencies showing less noise.

When a radome is used, as at the Andover station, there is an additional source of noise during rain due to reflection and absorption from the wet radome. Particularly with high antenna elevation angles, this may be the most important source of added noise. More data on this effect are needed, but they are not expected to alter conclusions regarding the choice of frequencies.

Not only is the noise temperature of the sky increased by rain, but the signal is attenuated because the raindrops scatter and absorb it. This effect is also strongly dependent on frequency, since it depends on the size of the raindrops measured in wavelengths. At 4 gc, a rainfall of five inches per hour causes about 0.2 db excess attenuation per mile of rainstorm traversed.[5] At 6 gc, the increase is about 1.5 db per mile of rainstorm. Although this rate of fall is very high, it does occur quite often for short periods during thunderstorms. The core of a thunderstorm may be some five miles in diameter. Thus it can be seen that excess attenuations of some 1 db at 4 gc and 7 db at 6 gc are indeed likely to occur a small fraction of the time, and lesser increases will occur more often. At frequencies higher than 6 gc, the excess attenuation will be higher — for instance, as much as 50 db at 11 gc.

5.2 *Frequency Allocation Considerations*

Frequencies in the 1- to 10-gc range are allocated internationally by the Radio Regulations resulting from the Administrative Radio Conference (Geneva, 1959) to a variety of services. Allocations differ in the three regions of the world recognized in the Geneva frequency tables, and there are numerous footnotes to the tables and reservations to the convention calling attention to national deviations from the tables. Furthermore, in the United States, there are further distinctions, particularly between government and nongovernment allocations.

It may be difficult for satellite communications systems to share frequencies with some of these services. For example, radio location and navigation services generally use very high power transmitters and very sensitive receivers, and hence may both cause interference to, and receive interference from, sharing services. Radio astronomy by its very nature uses very sensitive receivers, and would be vulnerable to interference from sharing services. The frequencies allocated to space research are scarcely wide enough to support a commercial satellite system on a world-wide basis.

Consideration of the variety of services in the 1- to 10-gc region led to the conclusion that the frequency space necessary for the Telstar satellite communications system could best be found by sharing with common-carrier radio relay systems. Specifically, these bands are 3700–4200 mc* and 5925–6425 mc. These bands are included in the October 22,

* In Europe, the band 3700–3800 mc is presently used for other services.

1962 "Draft Proposals of the United States of America for the Extraordinary Administrative Radio Conference for Space Radio Communication," to be presented at the conference scheduled by the International Telecommunications Union to be held at Geneva, Switzerland starting October 7, 1963.

5.3 *Coordination with Existing Terrestrial Systems*

When satellite systems share the same frequency bands with radio relay systems, it is necessary to consider four separate interference paths:

(1) satellite system ground transmitter to radio relay receivers,
(2) radio relay transmitters to satellite system ground receivers,
(3) radio relay transmitters to satellite receivers, and
(4) satellite transmitters to radio relay receivers.

The first two interferences are peculiar to the ground station sites and can be controlled by properly engineering the exposures between the satellite ground stations and radio relay routes.[6] The last two interferences must be considered on a world-wide basis, since they involve radio relay stations anywhere within view of the satellites with which frequencies are shared. These interferences must be kept acceptably small by agreement as to permissible parameters for both satellite and radio relay systems. Studies show that such coordination is possible with reasonable parameters of the terrestrial and satellite communications systems.[7]

Radio-frequency channel arrangements for the 4-gc and 6-gc common-carrier bands are given by C.C.I.R. Recommendations No. 278 and 280 (Los Angeles, 1959)* and are shown in Fig. 4. The microwave frequencies finally chosen for the Telstar system are indicated, with ground-to-satellite transmission at 6-gc and satellite-to-ground transmission at 4-gc. The high end of each band was chosen because, at least in the United States, it has been the custom to build up radio relay routes from the low-frequency end of the band and because, as previously mentioned, other services use the 3700–3800-mc band in Europe. While the frequency-sensitive factors favor 6-gc for the up direction and 4-gc for the down direction, the balance is not so overwhelming that the opposite choice is impractical. In the future it may be desirable to double satellite frequency usage by operating both ways simultaneously.

VI. THE *Telstar* SATELLITE

The Telstar satellite is a microwave repeater that receives signals from the earth, amplifies them and retransmits to the earth. The trans-

* These two recommendations were modified at the Plenary Meeting of the C.C.I.R. at Geneva, 1963, but the frequency arrangements are unchanged.

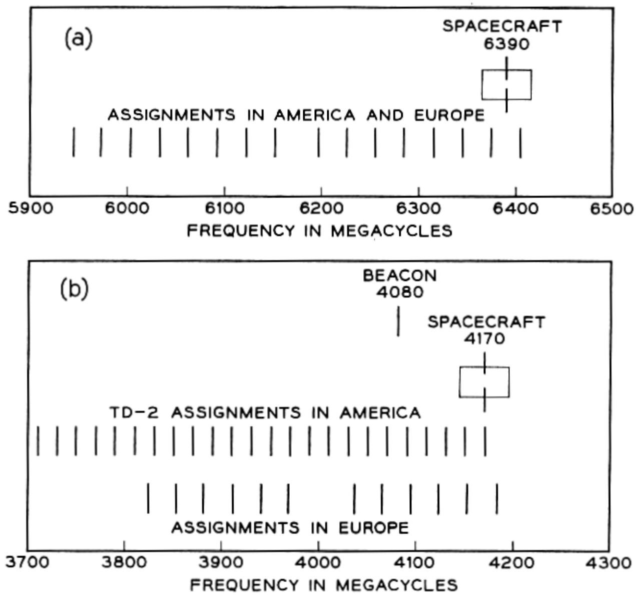


Fig. 4 — Frequency plan: (a) 6-gc common-carrier assignments, (b) 4-gc common-carrier assignments.

mission through the satellite is shown in Fig. 5. FM radio signals with a carrier at 6390 mc are received in an antenna, converted to 90 mc and amplified in an IF amplifier which supplies most of the repeater gain. The signals are then converted up to 4170 mc, amplified in a traveling-wave tube (TWT) and radiated from a separate antenna at a level of 2 watts. The beat frequency tones for the converters originate in crystal oscillators operating at about 16 mc. These frequencies are multiplied in a series of transistor and varactor doublers to the required microwave frequencies.

An interesting feature is the use of the TWT to amplify the up-converter local oscillator tone as well as the signal. This is done by combining the tone with the signal in a filter before the TWT, amplifying them together and then separating the tone from the signal in a separation filter at the TWT output. The separation filter is deliberately made "leaky" to the 4080-mc tone so that part of it is radiated as the microwave beacon for precision tracking. The 6300-mc down-converter tone is obtained by combining the 4080-mc up-converter tone with 2220 mc obtained from a separate oscillator and multiplying chain.

The primary power for the satellite is obtained from solar cells.

Silicon n-on-p cells were chosen because of their greater resistance to radiation. Radiation effects were further reduced by shielding the cells with 30 mils of synthetic sapphire. Fifty groups of cells are connected in parallel, each group containing 72 cells in series for a total of 3600 cells. The power required to operate the communication circuits, especially the TWT, is greater than the average output of the cells. A nickel-cadmium storage battery is provided to carry the peak load and also to permit operation during eclipse. The output of this battery is normally in the range of 24–27 volts. This is regulated to 16 volts, which is used directly for most of the solid-state circuits, or converted in dc-to-dc converters to the higher voltages needed for the TWT.

Since the satellite cannot be operated continuously because of power limitations, it is turned on and off by radio commands from the earth. The commands are transmitted at about 123 mc, which is received through a VHF antenna on the satellite. The command signals are amplified in command receivers, decoded, and used to operate relays which turn the communications repeater on and off. Commands are also used to turn the radiation experiment off and on, to switch between two telemetry encoders, to actuate the magnetic torquing coil and to turn the main power off and on. Duplicate command receivers and decoders are included for reliability.

The satellite transmits a continuous beacon signal at 136 mc from

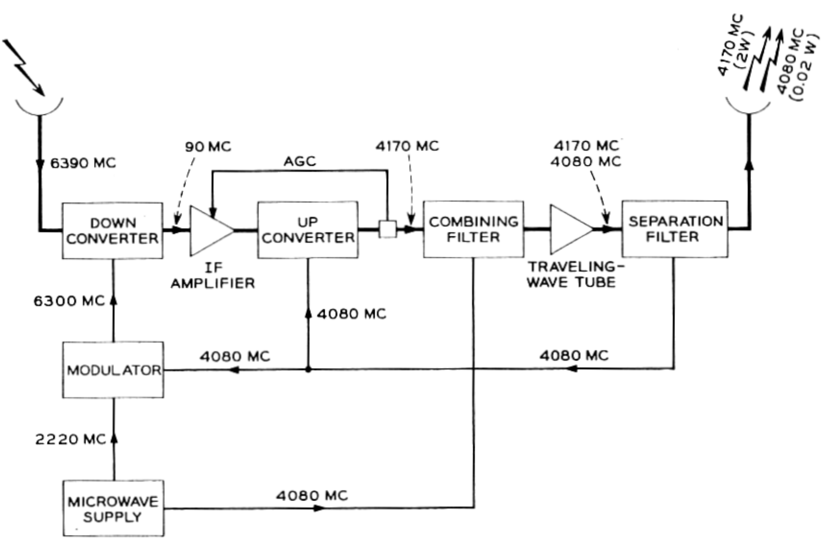


Fig. 5 — Telstar communications repeater

the same antenna used to receive commands. This is used for acquisition and coarse tracking. In addition to its use as a tracking beacon, the 136-mc signal is used as a carrier for telemetry to ground receivers. One hundred and twelve different items are measured each minute and the data transmitted to the ground by low-frequency modulations on this carrier. Measurements include information on temperatures, pressure, currents, and voltages, the state of several relays, RF power transmitted from the satellite and received signal strength at the satellite, as well as the results of the radiation experiment.

The radiation experiment is an important part of the Telstar spacecraft electronics. This experiment measures the flux of protons and electrons at several energy levels and the cumulative effect of the incident radiation on several specially designed semiconductor devices.

An external view of the satellite is shown in Fig. 6. It is a nearly spherical structure, $34\frac{1}{2}$ inches in diameter, weighing 170 pounds. It spins about an axis which is vertical in the picture. While the satellite was placed in orbit with the spin axis nearly perpendicular to the ecliptic plane, it is designed to operate, although on a reduced cycle, with the spin axis in any relation to the sun. For this reason, the solar cells are distributed approximately uniformly about the sphere.

Two equatorial bands of rectangular ports make up the microwave communications antennas. The smaller ports receive signals from the earth at 6390 mc and the larger ports transmit at 4170 mc. The design of the ports and the L-shaped diagonal probes is such that circularly polarized signals of opposite sense are received and transmitted in a nearly isotropic pattern. The pattern and circular polarization permit transmission through the satellite from all aspects without polarization tracking or loss due to cross polarization. Using opposite senses of circular polarization for the up and down paths helps to isolate the receiver from the transmitter both in the satellite and in the ground station.

The VHF command and telemetry antenna is a helical structure. It is also nearly isotropic, but is linearly polarized. Sensors for measuring solar aspect, radiation in the Van Allen belts, and the effects of this radiation, are located at several points on the outer surface. Three mirrors on the outer shell are used to reflect sunlight to the earth. Optical equipment at Holmdel, N. J., is used to observe these flashes and aid in the determination of the spin-axis orientation.

The outer structure consists of an aluminum skin on a magnesium frame. Within this outer shell and frame, a hermetically sealed cylindrical canister containing practically all the electronic circuits is suspended by nylon laces. This laced suspension provides thermal isolation from

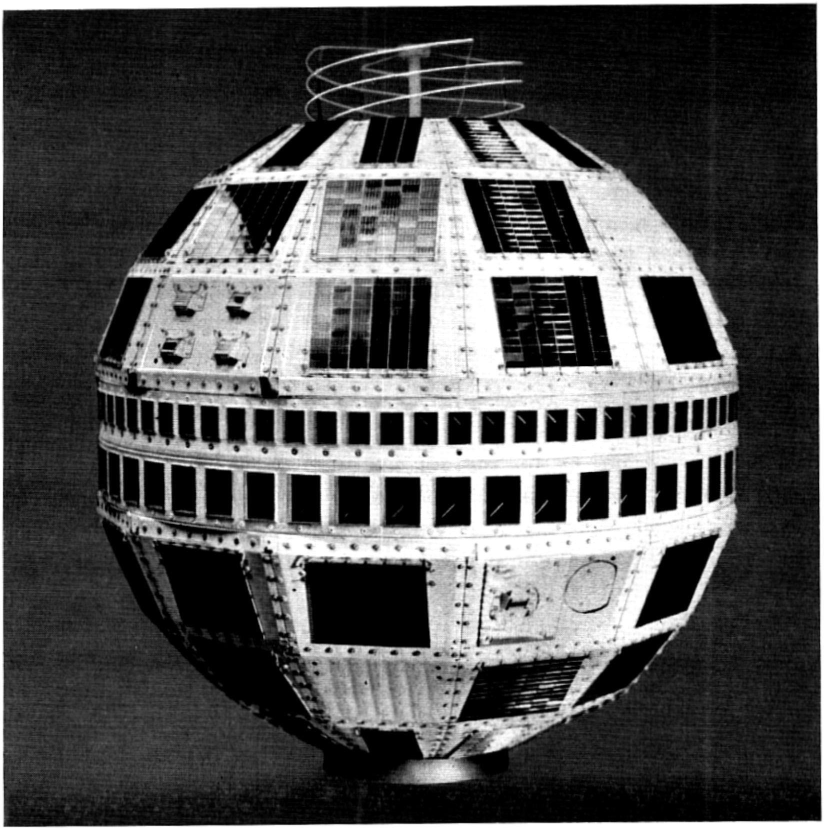


Fig. 6 — The Bell System's experimental communications satellite as it appeared before launch.

the outer shell and effectively attenuates the higher-frequency components of vibration experienced during the launch.

The circuits and subassemblies in the canister are individually encased in polyurethane foam, and the entire interior of the canister assembly is foamed as a unit and the covers welded on. The foam provides a lightweight support for the electronics and greatly reduces the effects of vibration on the subassemblies. It is extremely difficult, though not impossible, to make a repair if a failure should occur after the final foaming and welding operation. The principal reliance is on achieving a reliable unit before this step is taken.

Six complete flyable models were constructed in addition to a prototype and several special-purpose development models.

VII. THE ANDOVER GROUND STATION

The Andover ground station provides means for transmitting to and receiving from the Telstar satellite. The station includes the communications antenna, associated transmitting and receiving equipment, and means for steering the antenna to follow the satellite.

A separate microwave precision tracker is used for orbit determination. A VHF command tracker is used for acquisition and coarse tracking and for transmission of commands to and reception of telemetry from the satellite. The station has computers for the data processing involved in tracking and orbit determination and to reduce experimental data.

7.1 *The Andover Site*

In selecting the site for the Andover ground station, a location was picked which would be suitable for commercial operation as well as for the experiment. Several factors were taken into consideration,[8] principal among which were proximity to Europe and freedom from interference, existing or potential. Obviously, a site in the northeastern United States would best satisfy the first criterion.

Computations indicated that if interference was to be kept to tolerable levels, TD-2 and TH stations operating close to satellite frequencies should be at least 150 miles away if their antennas are aimed directly at the ground station. Average terrain was assumed. For other orientations of the radio relay antennas, a minimum of 40 miles was used. These values are believed to be quite conservative.[6]

Using these criteria, a number of areas in the northeastern states were selected as possibilities. Of these the one in western Maine was most promising. A siting team explored this area and selected the Andover site. Profile studies were made to existing and proposed radio relay stations and showed that interference at the Andover site would be negligible. Subsequent interference measurements confirmed this conclusion.

The location of the station is shown in Fig. 7. It is situated in western Maine close to the New Hampshire border. The site is nearly as close to Europe as is possible in the United States and is well removed from existing and potential radio relay routes. On the other hand, it is close enough to existing radio relay telephone and television routes for economical interconnection.

The connecting link consists of a four-hop system with two sections of TD-2 and two sections of TJ (11 gc) to enter the site. By using TJ for the sections closest to the site, and utilizing frequencies at the low

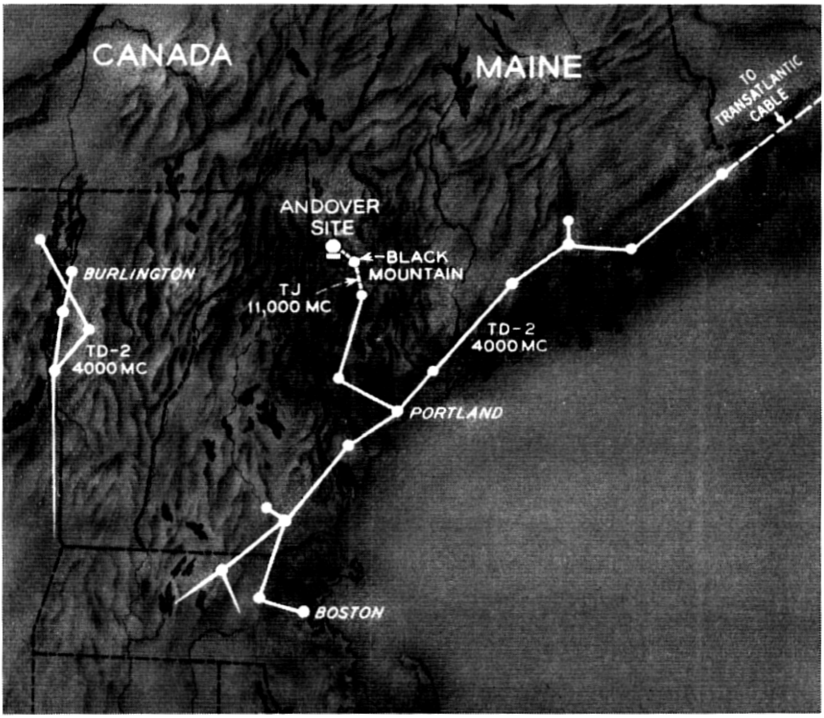


Fig. 7 — Map showing Andover site.

end of the TD-2 band, interference from the entrance link into the ground receiver has been completely avoided.

Fig. 8 is a general aerial view of the Andover site. The station is located in a wide shallow valley about 8 to 10 miles in diameter. The situation is such that additional shielding is obtained in almost all directions by surrounding hills. These are not high enough, however, to interfere significantly with the visibility of the satellite. The profile of the optical horizon from the site of the antenna is shown in Fig. 9. The tower in the foreground of Fig. 8 is for the last station of the radio entrance link. This tower houses, in addition to the TJ repeater, an electrical model of the satellite for calibrating the ground station.

A close-up aerial view of the station is shown in Fig. 10. The station is situated on a tract of about 1100 acres on top of a low rounded hill at an elevation of about 900 feet in the center of the valley. This area is large enough to permit future expansion for commercial operation. The most prominent feature of the station is the large inflated radome that

Fig. 8 — Aerial view of site

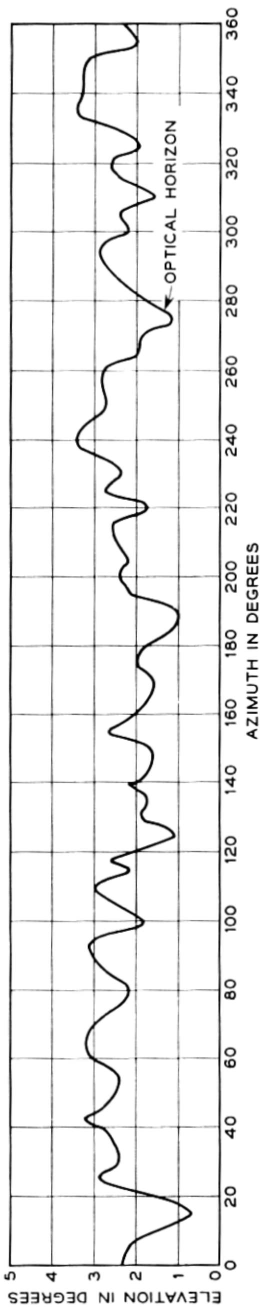
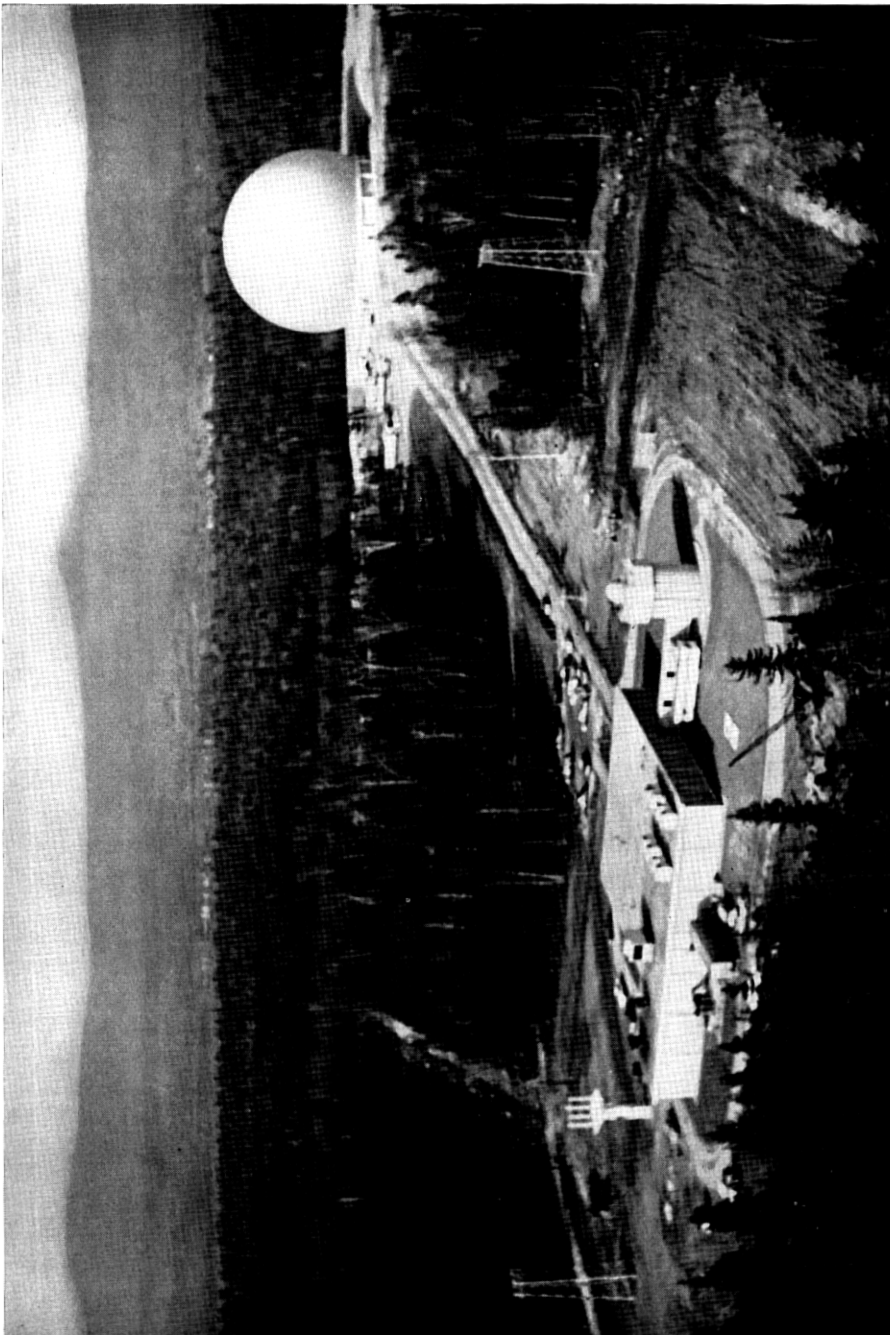


Fig. 9 — Optical horizon at Andover.



shelters the horn antenna. It is made of rubberized Dacron and is 210 feet in diameter and 165 feet high. The control building in the foreground houses the equipment for terminating the telephone and television circuits brought into the station by the entrance link. It contains the equipment for making transmission tests through the satellite, as well as the heating plant for the station and diesel generators for power. Flanking the control building on the right is the precision tracking antenna on a concrete pylon and, on the left, the quad-helix command tracker antenna.

7.2 *Ground Station Transmission Plan*

A general transmission plan of the station is shown in Fig. 11. Tests or demonstrations that originate at other locations are received at 11 gc and demodulated to baseband in the control building. The link from the control building to the large horn is by video pairs. This is carried to equipment rooms on the antenna structure through slip rings. The baseband signals are used to frequency modulate the 6390-mc ground transmitter, which is connected to the horn through diplexing equipment. Incoming signals from the satellite at 4170 mc are connected to the radio receiver through the diplexer and demodulated to baseband in the equipment room and then transmitted to the control building by video pairs.

7.3 *Horn-Reflector Antenna*

The communications antenna at Andover is a much enlarged version of similar antennas widely used on Bell System microwave relay routes. A horn reflector of this type with a 20 × 20 foot aperture was used at Holmdel in the Echo experiments. Fig. 12 shows a model of the Andover antenna.* For structural reasons, the horn at Andover is conical rather than pyramidal, as was the case in the smaller versions. The antenna rotates in azimuth on two concentric rails and in elevation about the axis of the conical feed horn on two large bearings. Two equipment rooms are carried on the structure. The maser is in the upper room near the apex of the horn.

This configuration has several advantages over other possible forms. It is very broadband, presents an excellent impedance to the transmitter, and the parabolic surface is efficiently illuminated. Most im-

* Since the antenna was built under the radome and has never been exposed, it has not been possible to obtain a really satisfactory picture of the actual hardware.

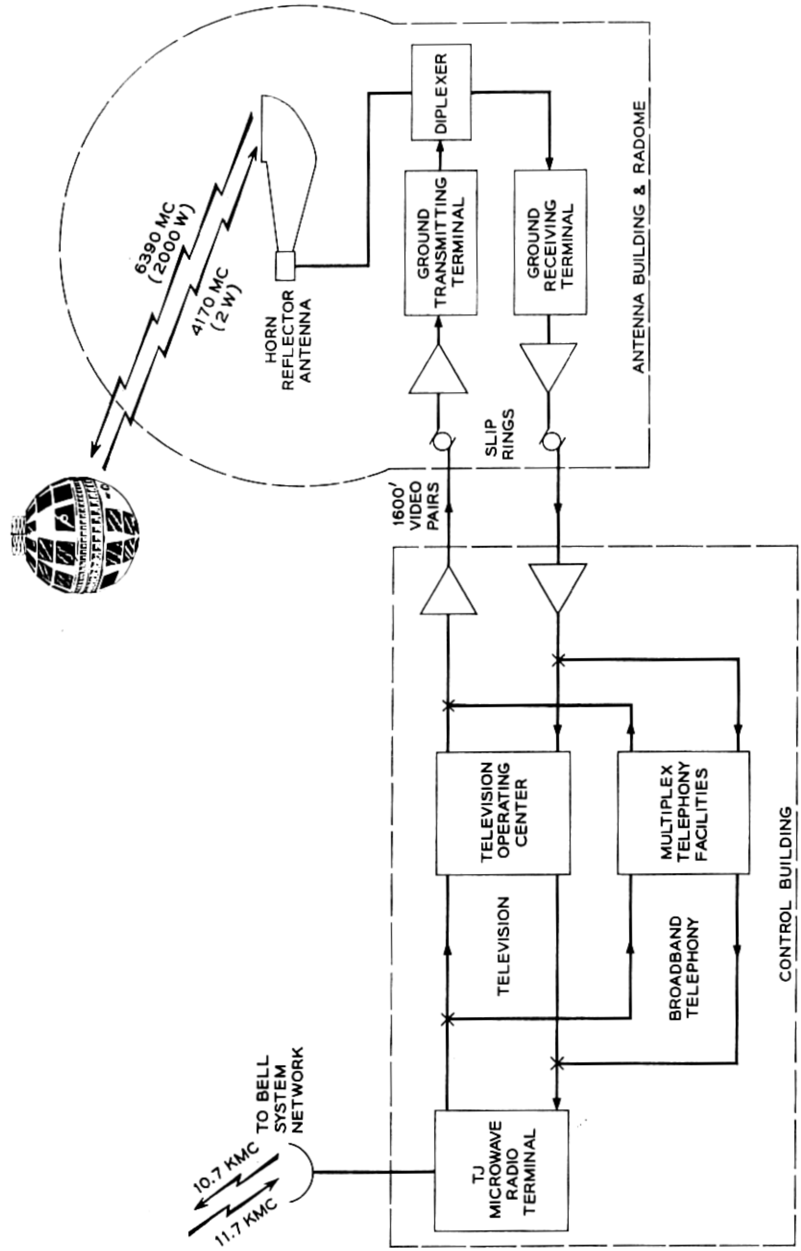


Fig. 11 — General transmission plan — Andover.

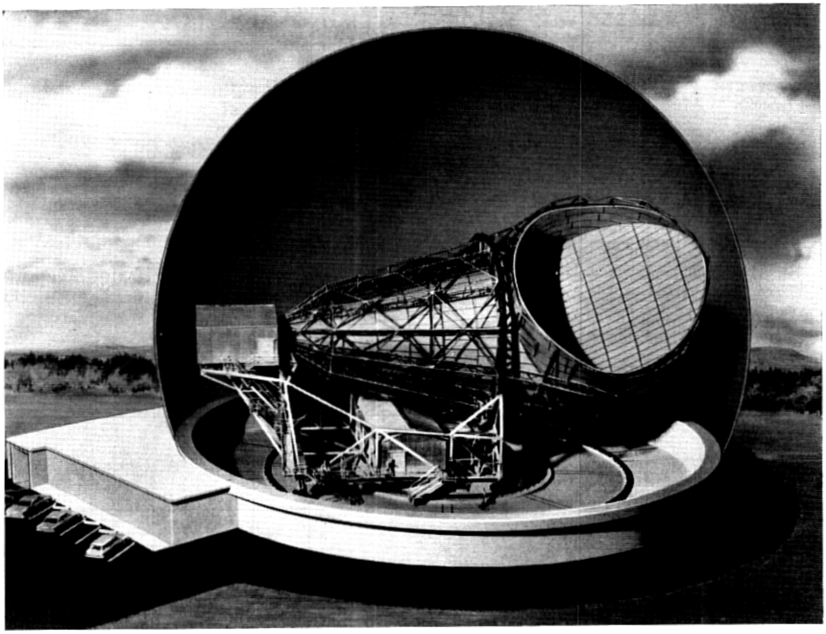


Fig. 12 — Model of Andover, Maine, antenna.

portant, however, for the present application, the antenna has very low side and back lobes and may be connected to the receiver with short, low-loss connections resulting in a low system noise temperature.

Table III gives the principal physical and performance characteristics of the Andover horn. The details of performance are covered in later papers in this series. The precision achieved on the critical parabolic surfaces is such that operation at frequencies considerably higher than 6000 mc is possible. Pointing calibration was made by tracking radio stars. The structural distortions indicated by these calibrations are corrected for in the electronic antenna direction system. The corrections are known with sufficient accuracy that, with good ephemeris data, the antenna beam may be pointed at the satellite within a small fraction of a beamwidth.

All connections to the antenna are made through slip rings located around a pintle bearing at the azimuth axis. This permits free rotation of the antenna. Cooling water, power and control leads are also carried through rotating joints and slip rings in the pintle bearing.

TABLE III — HORN-REFLECTOR ANTENNA

Structural Characteristics		
Aperture	3600 square feet	
Length	177 feet	
Weight	380 tons	
Reflector accuracy	0.060 inch (1 sigma)	
	Azimuth	Elevation
Tracking and Slewing		
Maximum tracking velocity	1.5 deg/sec	1.5 deg/sec
Maximum slewing velocity	1.5 deg/sec	1.5 deg/sec
Maximum acceleration	1.3 deg/sec²	3.0 deg/sec²
Error during acceleration	0.26° per deg per sec²	
	4170 mc	6390 mc
Performance		
Gain	58 db	61 db
Beamwidth (3-db points)	0.23 degree	0.16 degree

7.4 *Transmitter and Receiver*

The ground transmitter, shown in Fig. 13, provides an FM signal of 2000 watts maximum with a peak deviation of ±10 mc. The FM deviator and modulator amplifier stages are modified versions of TH radio transmitting equipment. The output stage is a power amplifier using a high-power traveling-wave tube.

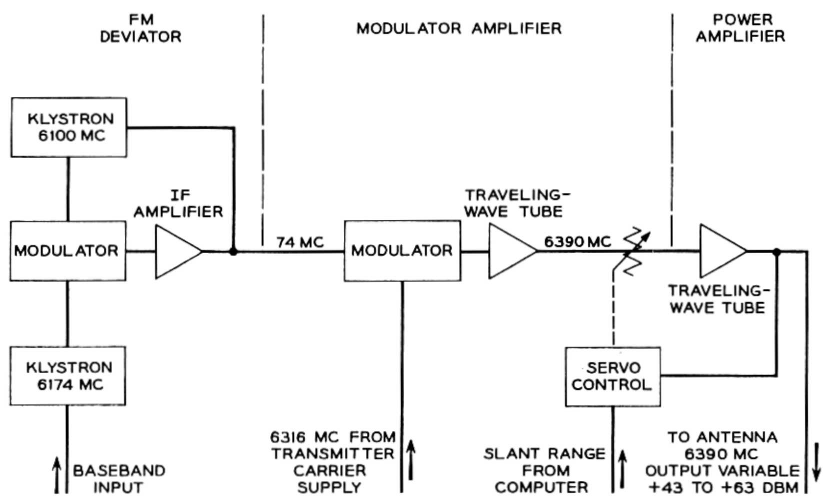


Fig. 13 — Block diagram — ground transmitter.

The center frequency is 6390 mc when the transmitter is used for television or other straight-away tests. It can be shifted ±5 mc for two-way message experiments. The servo control shown can be used to vary the output power to maintain a prescribed received power at the satellite. This is used in two-way telephone tests, where approximately equal carrier levels at the satellite are desired.

A block diagram of the receiver is shown in Fig. 14. Signals received through the antenna are first amplified 40 db by a traveling-wave ruby maser. They are then converted to a 74-mc IF frequency, where most of the receiver gain is obtained. The signals are then shifted back to the 6-gc band for demodulation in a frequency compression detector. This detector permits the baseband signal-to-noise advantage of wide-deviation FM to be realized without the loss in threshold level that would be suffered in a conventional detector of the same bandwidth. An effective compression of the noise band is achieved by feeding back part of the baseband output to a voltage-controlled local oscillator. The local oscillator follows the deviations of the incoming signal, and in this way the IF frequency deviations applied to the discriminator are reduced by the feedback factor. An improvement in threshold of 4–5 db is obtained by the feedback receiver. A standard FM detector operating at 74 mc may also be used.

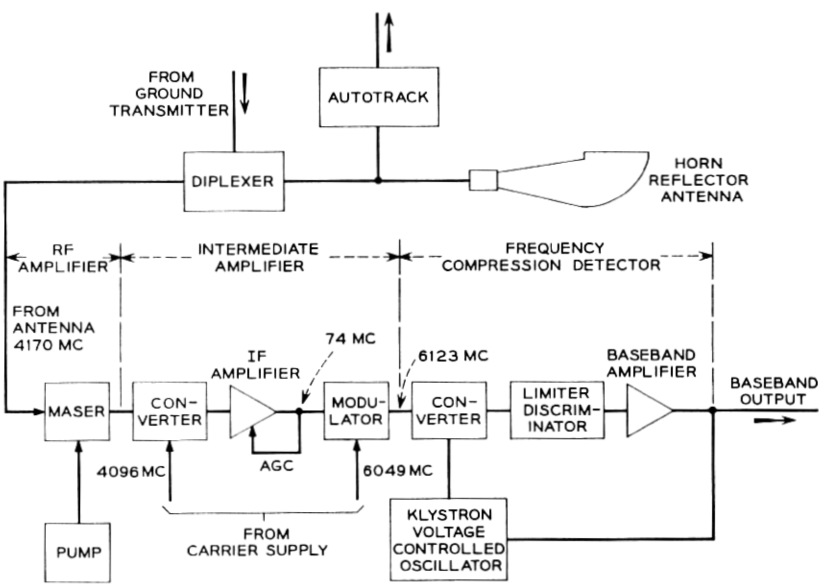


Fig. 14 — Block diagram — ground receiver.

The transmitter and receiver are located physically in the upper equipment room of the antenna structure. Unlike a conventional center-fed parabolic dish, the horn antenna allows for considerable equipment to be mounted at the feed. This has been used to good advantage at Andover, where feeder losses are kept to a minimum by locating the transmitter power stage and the maser close to the antenna feed.

7.5 *Tracking Equipment*

The tracking system at Andover consists of four parts. These are the: (1) command tracker and its control, (2) precision tracker and control, (3) horn-reflector antenna and control, and (4) computers. This is more elaborate than would be required for a commercial system. However, the flexibility that this arrangement provides is very useful in evaluating methods for future systems. Fig. 15 shows the four parts of the system and their interrelation.

The computer (IBM 1620) is programmed to derive drive tapes from any one of three different sources of information: (1) azimuth, elevation and time data from previous passes, (2) orbital elements, (3) X-Y-Z topocentric coordinates obtained from NASA. The drive tapes can be used to position all three antennas to the predicted position of the satellite. A different mode of operation which does not depend on accurate drive tapes is as follows.

The command tracker, with its wide beam of 20°, picks up the 136-mc beacon as the satellite rises above the horizon. When autotrack has been obtained with this antenna, the satellite is located to within 1°. If the telemetry indicates that the satellite is in satisfactory condition, the command sequence is started. By means of the three sequenced commands at 123 mc, the repeater in the satellite is turned on. At this time, the satellite transmits the 4080-mc beacon. With the precision tracker slaved to the command tracker, it can now acquire the microwave beacon with its 2° beam and autotrack. In this mode the precision tracker locates the satellite to within 0.02°. The horn antenna can then be slaved to the precision tracker and acquire the microwave beacon with its 0.2° beam and autotrack. Once this is accomplished, the horn can continue to autotrack without further aid.

The step-by-step procedure as outlined above is just one of many possible modes of operation. With good pointing information, the horn can be directed to acquire and then autotrack the satellite without going through the steps outlined above. This has been done on many occasions at Andover, and it is expected that a commercial system would be operated on this basis.

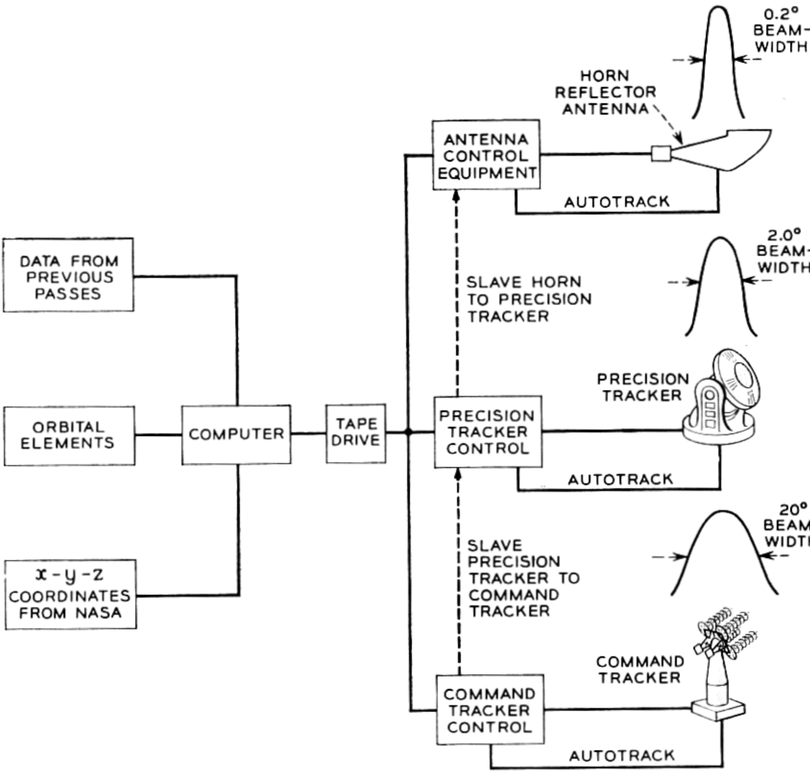


Fig. 15 — Block diagram of tracking system.

VIII. FACILITIES AT CAPE CANAVERAL

Special facilities were provided at Cape Canaveral for testing the satellite. Test equipment was located in three vans adjacent to Bell Laboratories' guidance facility and on the gantry. A command tracker like the one at Andover was provided. Compatibility of the radio frequency systems in a prototype model of the satellite with other systems involved in launching was verified about two weeks before launch. The flyable model was tested daily from the time of its arrival at the Cape and after mating with the third stage of the rocket, after spin balancing and on the gantry up to the time of launch. From lift-off, the satellite was tracked and telemetry monitored. During the following months, the facilities were used to augment Andover by receiving telemetry and, in some cases, by sending commands.

IX. TRANSMISSION PERFORMANCE

The broadband signals transmitted through the Telstar satellite were television and 600 telephone channels simulated by noise loading. In addition, the performance with 12 two-way voice channels was evaluated as well as performance with data and other special signals. Performance objectives for signals of these types have been established by the Bell System and the CCIR. Because of limitations imposed by the rocket on weight and, therefore, power, some compromise was necessary and the objectives were not met in all cases. However, the quality of these signals, when transmitted through the satellite link, is reasonably close to the objective for commercial service.

9.1 *Over-all Performance*

Table IV shows the performance with the satellite at a range of 5000 nm for the three main types of service considered: TV, 600-channel one-way telephony, and twelve-channel two-way telephony.

For TV transmission the audio signal is transmitted by frequency modulating a subcarrier located at 4.5 mc. This limits the bandwidth available for picture transmission to 3 mc. Other techniques for transmitting the sound would remove this limitation.

Two-way telephony is achieved by transmitting two carriers from two ground stations through the satellite simultaneously. These carriers are separated by ten megacycles with the carrier from Andover 5 mc above the normal center frequency and the carrier from Europe 5 mc below. Because of the lack of isotropy in the satellite antenna pattern, the two carriers may be received by the satellite with a 6-db level difference. Under this condition, compression in the TWT will cause the

TABLE IV — PERFORMANCE OF *Telstar* SYSTEM

Television	
Bandwidth	3 mc
Peak-to-peak signal to rms noise (unweighted)	41 db
Peak audio signal to rms noise	56 db
600-Channel One-Way Message	
Top telephone channel noise	49 dbrn 0*
Improvement with pre-emphasis	3 db
Noise in top telephone channel with pre-emphasis	46 dbrn 0
Twelve-Channel Two-Way Message	
Noise in top channel	45 dbrn 0

* Measured with 3A noise meter with C message weighting. 0 dbrn equals 1 picowatt at 1000 cycles.[9]

weaker carrier to be transmitted 10 db below maximum output power. The 45 dbrn 0 given in Table IV is based upon this weaker carrier power.

At 5000 nm, the quality achieved for TV transmission would be judged to be a slight picture impairment. Also under these conditions, the amount of noise in the poorest telephone channel would be 6 db more than the tentative CCIR objectives for a commercial grade circuit. For an experimental system, this performance is considered reasonable. The important consideration is that measured performance was consistent with actual parameters of the system, and that no unexplained degradations occurred.

9.2 *Fluctuation Noise*

The controlling parameter in a system such as this is noise. Table V shows the fluctuation noise performance for the ground-to-satellite and satellite-to-ground paths.

It will be noted from the Table V that the carrier-to-noise ratio in the down path is 15 db. Even with this low carrier-to-noise ratio, high quality performance is obtained by means of wide deviation FM. How-

TABLE V — FLUCTUATION NOISE

Up Path: Andover to satellite	
Maximum transmitted power (2 kw)	63 dbm
Ground waveguide losses	1 db
Ground antenna gain	61 db
Path loss (5000 nm)	187 db
Satellite antenna gain	0 db
Received carrier power	−64 dbm
Satellite antenna feed loss	2 db
Satellite receiver noise figure*	16.5 db
Noise power in 25-mc band	−83.5 dbm
Carrier-to-noise ratio in 25-mc band	17.5 db
Down Path: Satellite to Andover	
Satellite power (2 watts)	33 dbm
Path loss (5000 nm)	184 db
Satellite antenna gain	0 db
Ground antenna gain	58 db
Received carrier power	−93 dbm
System noise (50°K, 25-mc bandwidth)	−108 dbm
Carrier-to-noise ratio in 25-mc band	15 db

* The noise figure of the satellite as measured by a noise lamp is 13.5 db ±1 db. However, the noise does not have a flat spectrum over the band of interest and this number applies in the region where the noise is flat. Measurements made of the system noise spectrum using narrow-band analyzers indicate a satellite noise figure in the flat region of 15 db ±2 db. If the noise spectrum around the carrier is integrated over a 20-mc band, then an equivalent noise figure of 16.5 db ±2 db is obtained.

ever, at 10 db carrier-to-noise ratio a conventional FM receiver will start to rapidly degrade the demodulated signal. The carrier-to-noise ratio in the down path, being 15 db, is only 5 db above this threshold. Therefore, a frequency compression demodulator has been used in the Telstar system. This technique improves the threshold by about 5 db, allowing adequate margin against the onset of breaking. At 5000 nm range and with 50°K system noise temperature, the breaking margin due to the down link is 10 db. The ground to satellite path also contributes to the over-all system noise and reduces the breaking margin. With 2 kw radiated from the ground at 5000-nm range, the carrier to noise ratio at the satellite is 17.5 db. At this range for both the up and down path, the effect of the up path is to reduce the over-all carrier-to-noise ratio and the breaking margin by about 2 db. Most of the time the range is shorter and the performance is better.

A number of other factors may reduce the carrier-to-noise ratio and degrade the breaking margin. These are noncircular polarization, satellite antenna pattern, ground antenna mispointing and rain.

To the extent that the antennas at both ends of the link do not have circular polarization but are somewhat elliptic, i.e., have an axial ratio other than unity, there will be some loss of signal. The axial ratio of the Andover ground antenna system is in the order of 0.5 db and that of the satellite is 2 db in the equatorial plane. Maximum loss due to these axial ratios is about 0.1 db. When the satellite is viewed at angles 30° or more from the spin axis, the axial ratio may be as much as 4 db, but even under these conditions, the loss due to this effect is only 0.25 db.

The satellite antenna has essentially 0-db gain in the equatorial plane. It is down about 6 db at an angle ±60° from the equator. The pattern is quite smooth around the spin axis with a ripple of about ±1 db. This is adequate to maintain the signal above the FM threshold, especially since an unfavorable aspect and maximum range will rarely coincide.

The signal loss due to antenna mispointing is less than 0.1 db. This is due to the use of the vernier autotrack, which is capable of maintaining the antenna beam to within 0.005° of the satellite's position.

It has been observed that system noise temperature can increase to 130°K in the presence of heavy rain. This can be ascribed to the increase in sky noise and the effect of the wet radome. The degradation of carrier-to-noise ratio under these conditions is 4 db compared to conditions on a clear day with the antenna at zenith. With the system parameters described and the margin available, operation above threshold is still possible.

TABLE VI — FM DEVIATIONS

Video	
TV bandwidth	3 mc
Peak-to-peak frequency deviation (picture)	14 mc
Peak-to-peak frequency deviation (picture + aural subcarrier)	16.8 mc
Bandwidth of audio channel	8 kc
Peak-to-peak frequency deviation (audio on 4.5-mc aural subcarrier)	100 kc
600-Channel Noise Loading	
Peak frequency deviation due to noise loading signal	10 mc
RMS frequency deviation due to noise loading signal	1.77 mc
RMS frequency deviation per telephone channel	72 kc
Twelve-Channel Two-Way Message	
Baseband signal	60–108 kc
Peak frequency deviation for twelve channels	1 mc
RMS frequency deviation per channel	16 kc

9.3 *FM Deviations*

Based upon the fluctuation noise indicated in Table V, the required modulation indices were determined. These are given in Table VI.

9.4 *Amplitude and Phase Distortion*

The presence of amplitude and phase distortion causes transmission degradation which adds to that caused by thermal noise. This form of distortion does not affect the breaking margin, but adds to the noise at baseband. The most important forms of nonlinear distortions are envelope delay distortions[10] and differential gain. In a two-link radio relay system such as Telstar, this distortion can be made small compared to thermal noise. In the allocation of system impairments, the total for intermodulation noise is 36 dbrn at the 0-db transmission level. Fig. 16

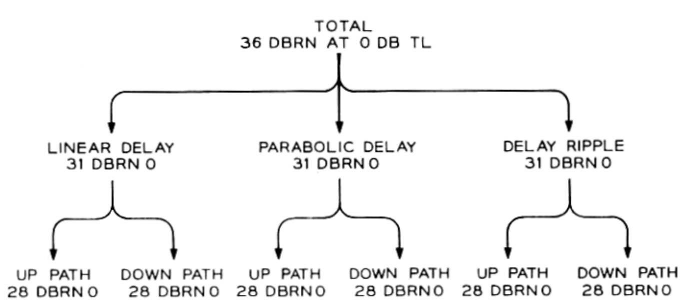


Fig. 16 — Allocation of intermodulation noise.

TABLE VII — DELAY DISTORTION OBJECTIVES

Frequency with respect to carrier — mc	±2	±4	±6	±8	±10
Linear delay distortion — nanoseconds	1.2	2.4	3.6	4.8	6
Parabolic delay distortion — nanoseconds	1.1	4.5	10	18	28

Delay Ripple

Ripple periodicity — mc	0.3	0.6	1.5	3.0	6	15
Peak delay ripple — nanoseconds	30	15	6	3	1.5	1.5

indicates how this total is divided among the various sources. Assuming the parameters indicated previously for the 600-channel noise loading signal and the use of pre-emphasis,* Table VII indicates the delay distortion objectives. The figures indicated in Table VII apply to both the up-path and down-path equally.

The differential phase would be 4.2° if the objectives in Table VII are met. For N.T.S.C. color the requirement is 5°, so that this set of performance objectives is consistent. The performance measured for television and the 600 telephone channel simulated noise load indicates that these objectives have been met.

X. CONCLUSIONS

The Telstar system has demonstrated that wideband communications by means of an active satellite is feasible and that performance is predictable on the basis of system parameters. A ground station system has been tested and shown to be operable under a wide range of weather conditions and with a variety of tracking techniques. A large amount of data on the space environment has been gathered and analyzed and has added valuable information concerning the conditions which a satellite must withstand. The satellite, the Andover ground station, and the radiation experiment are discussed in more detail in companion papers.

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* The pre-emphasis assumed starts at 3 mc with 6 db per octave slope and continues until a total of 10 db of pre-emphasis is reached.

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