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Time and Frequency Broadcast Experiments from the ATS-3 Satellite

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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TIME AND FREQUENCY BROADCAST EXPERIMENTS FROM THE ATS-3 SATELLITE

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TIME AND FREQUENCY BROADCAST EXPERIMENTS FROM THE ATS-3 SATELLITE

D. W. Hanson and W. F. Hamilton

An experiment designed to reveal the advantages and special problems associated with the broadcasting of time and frequency information from geostationary satellites is discussed. Included are discussions concerning satellite motion, time delay variation, doppler shift due to the motion, and calculation of delay. Receiver or ground station equipment requirements, time recovery techniques, timing resolution and accuracy, and special advantages of satellite broadcasts for time and frequency dissemination are also discussed. Specially equipped sites in North and South America gathered data from the experimental satellite broadcast, which in turn were used to determine the potential accuracy of satellite dissemination, the results of which are presented. Delay computation aids for the user were designed to provide a simple and inexpensive means of computing free space delays between the master clock and the user via a geostationary satellite. The aids, delay overlays on an earth map and a circular slide rule, are discussed with examples. Qualitative discussions of the signals and broadcast format are given. Final comments are made concerning the results of the experiment and how they might reflect upon a final system design for a permanent service using one or more geostationary satellites.

Key words: Dissemination; frequency; satellite; synchronization; time.

1. INTRODUCTION

During the course of two years beginning in August 1971, the familiar WWV time and frequency signals, usually heard only on the National Bureau of Standards high frequency radio stations, were transmitted from the NBS laboratories in Boulder, Colorado, and relayed by a geostationary satellite to a major portion of the earth. Those signals covered the North and South American continents, much of the Atlantic and

Pacific Oceans and parts of Europe and Africa, a total of about 40% of the earth's surface.

A standard frequency tone, seconds ticks, a time code, voice announcements of the time of day, and satellite position were transponded by the satellite to the earth twice a day for 15-minute periods. The time and frequency information was referenced to and derived from the NBS Frequency Standard (NBSFS) and the NBS Coordinated Universal Time scale, UTC (NBS), both of which are maintained at the Boulder NBS laboratories.

In general, two modes of satellite time transfers may be envisioned. A one-way mode places a listen only requirement on the user. The two-way mode requires that the user communicate information about his clock to the master clock, via the satellite, immediately after receiving a transmission from the master clock. The present experiment may be classified as being of the one-way mode.

Historically, the first satellite time experiments were conducted in August 1962 using Telstar [1]. The purpose of those experiments was to compare the clocks at the U. S. Naval Observatory (USNO) in Washington, D. C., and at the Royal Greenwich Observatory in England. Signals were relayed between these locations by Telstar's microwave transponder. A two-way exchange resolved the round trip path delay and assumed that the paths were reciprocal. If the satellite motion was negligible, which is assumed to be the case for geostationary satellites over a short period of time, the one-way path delay was one-half the round trip delay. The major advantage of the two-way exchange was that knowledge of the location of the satellite and of the ground stations was not required. The major disadvantage was that both ends of the path needed a transmitter and receiver and that only one user could be synchronized in any one exchange. Similar experiments were carried out with the Relay communications satellite in February 1965 [2] and again with ATS-1 and ATS-3 in 1971 [3]. Those experiments reported accuracies ranging from 0.01 μs to 1 μs. All of these experiments were conducted in the microwave radio region using wide signal bandwidths. Although great accuracy can be obtained under these conditions, the equipment costs are too great for many users. The need for a lower cost technique led NBS in 1967 to conduct two-way experiments using the National Aeronautics and Space Administration (NASA) ATS-1 satellite VHF transponder [4]. Accuracies of about 5 μs were achieved using inexpensive VHF receiving and transmitting equipment. It was believed that accuracies better than 1 μs were possible with better equipment and higher signal to noise ratios.

An example of a satellite timing system operating in the one-way mode is TRANSIT [5], a low altitude polar orbit satellite designed primarily for navigation. The 2-minute TRANSIT frame includes time information and updated orbital elements. With this information and a measurement of the satellite's Doppler, a user, knowing his location, can determine the range to the satellite to correct the received time information. In principle, high accuracy time synchronization is possible with TRANSIT, but the user cost is high since special equipment is required to process the orbital elements and timing information. User cost can be reduced if high accuracy is not required.

GEOS [6], a low orbit satellite, is another example of the one-way technique and was used by NASA to synchronize tracking stations. Time pulses are provided at intervals of 1 minute. Receiving station locations are accurately known with respect to satellite position and accuracies of about ± 25 μs are reported.

NBS, having had some experience in the two-way mode and motivated by an emphasis on low cost and simplicity, directed its efforts in

1967 to the one-way mode for time transfer. The first tests were conducted with geostationary satellites containing VHF transponders to relay signals from a master station to any user in common view of the satellite. Experiments were conducted with the NASA satellites ATS-1 and ATS-3 [7] and with the U. S. military communication satellites, LES-6 and TACSAT [8], [9]. These satellites contained transponders which operated in the frequency range between 130 and 300 MHz. Accuracy was limited primarily by errors in the path delay predictions since even geostationary satellites drifted in their position. Satellite time transfers were made with accuracies ranging between 10 and 150 μs. These experiments were conducted at sites in Alaska, Hawaii, Ohio, Massachusetts, Colorado, and a number of sites in South America. To check the accuracy of the time transfer, the sites were equipped with commercial, portable cesium standards which were independently synchronized to UTC to within a few microseconds.

All the experiments mentioned above fell short of providing completely unambiguous time and frequency information from a satellite. The experiment described here transmitted time information unambiguous to 1 year and in a form suitable for all levels of users. It provided the participants in the experiment with all the tools required to obtain and maintain time without bilateral contact between NBS and the user.

The experiment was conducted in the following manner. Time and frequency signals were relayed by the satellite twice a day. Four sites, two in North America and two in South America, observed the signals and recorded the apparent time delay by referencing the signals to their on-site clock. Each site had receiving equipment which had been carefully calibrated by NBS prior to its use in the field. The time references at each site consisted of, at a minimum, a commercial cesium clock previously synchronized to the NBS master clock by portable atomic clock carries. Some of the sites also monitored LORAN-C or VLF stations. The received satellite signals, referenced to on-site clocks, provided the signal delay from the master clock at NBS via the satellite to each of the sites as well as a means to test ways of computing the signal delays. Because the sites were situated at widely dispersed points about the subsatellite point and at drastically different "look" angles to the satellite, the resultant data provided a comprehensive evaluation of the system's ability to provide time information.

In addition to the NBS-sponsored sites, numerous other government agencies, industries, and private individuals, used the broadcasts. Through a special brochure offered to the public, equipment requirements, broadcast schedules, antenna pointing information, propagation delays, and other pertinent data were offered. Over 9,000 of the brochures were distributed in addition to many telephone inquiries.

For the higher accuracy user of time and frequency, a circular slide rule was designed to compute propagation delays. This slide rule, in addition to the voice announcements of satellite position relayed by the satellite, enabled the user to compute the path delays with high accuracy. The satellite's position was computed from NASA generated orbital elements in advance of each broadcast, and provided the user with the capability for immediate time recovery and synchronization.

The experiment very effectively demonstrated the potentials for satellite dissemination of time and frequency information. It also provided many users a preview of the level of performance which could be available using this space age technology.

2. BROADCAST EQUIPMENT AND FORMAT

Figure 1 shows the equipment that was used to broadcast the time and frequency signals to the satellite. The time signals were referenced as shown in figure 2 to the UTC (NBS) time scale and the NBS Frequency Standard both of which are maintained at the NBS laboratories in Boulder, Colorado. The timing format consisted of tones, ticks, a time code, and voice announcements similar to the signals heard on the NBS high frequency stations, WWV and WWVH. The signals frequency modulated a carrier, were amplified, and transmitted to NASA's ATS-3 satellite. The antenna shown in figure 3, a bifilar helix, was used to transmit the time and frequency signals to the satellite.

The signals were received by the satellite at 149.245 MHz, frequency converted to 135.625 MHz, amplified and retransmitted back to the earth. The deviation of the carrier was ± 12 kHz occupying a 30 kHz bandwidth. The ATS-3 satellite, shown in figure 4, was in geostationary orbit and "station kept" at approximately 70° west longitude. The satellite's VHF antenna provided for an earth coverage as seen from synchronous altitudes and is illustrated in figure 5.

The satellite's VHF antennas consisted of eight dipole elements. As the satellite spun on its axis, the dipole elements were electrically despun and acted as a phased array always pointing at the earth. The satellite's VHF transponder and antenna system is illustrated in the block diagram of figure 6.

The ERP of the satellite was approximately 47.6 dBm with both transmit and receive antennas being linearly polarized. The corresponding field strength at the earth's surface was about 1.2 microvolts per meter or -145 dBW per square meter.

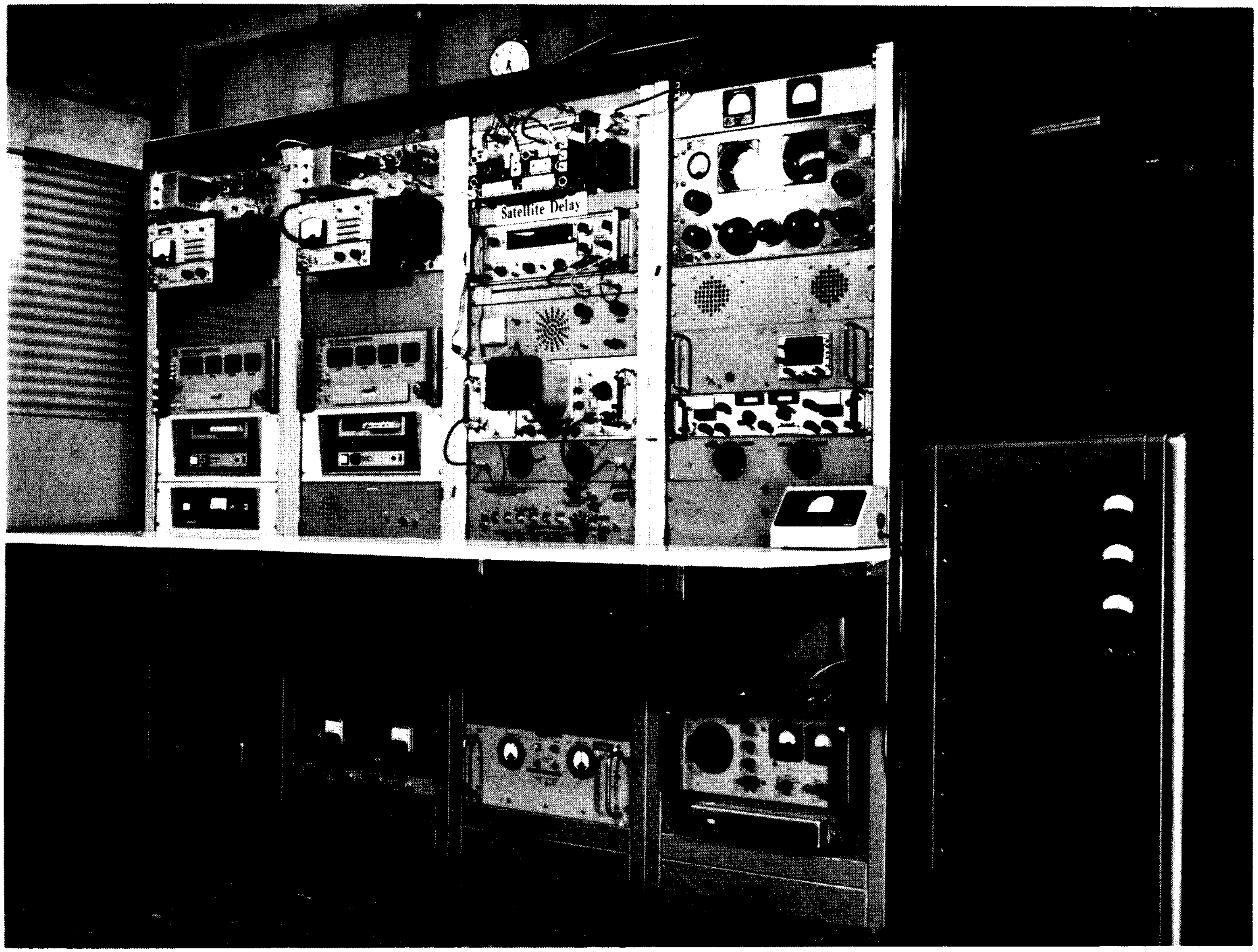


Figure 1. Transmitting equipment.

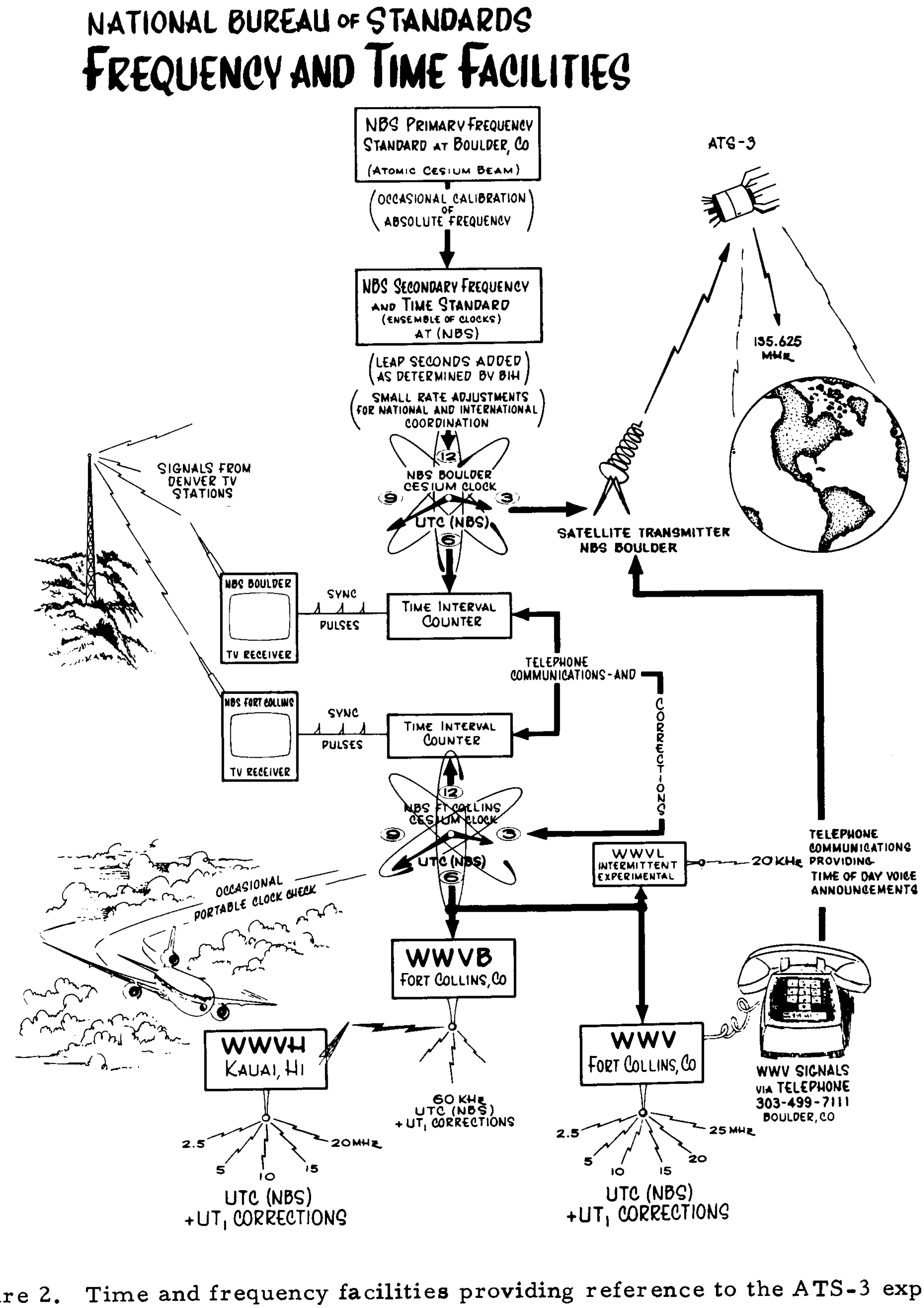


Figure 2. Time and frequency facilities providing reference to the ATS-3 experiment.

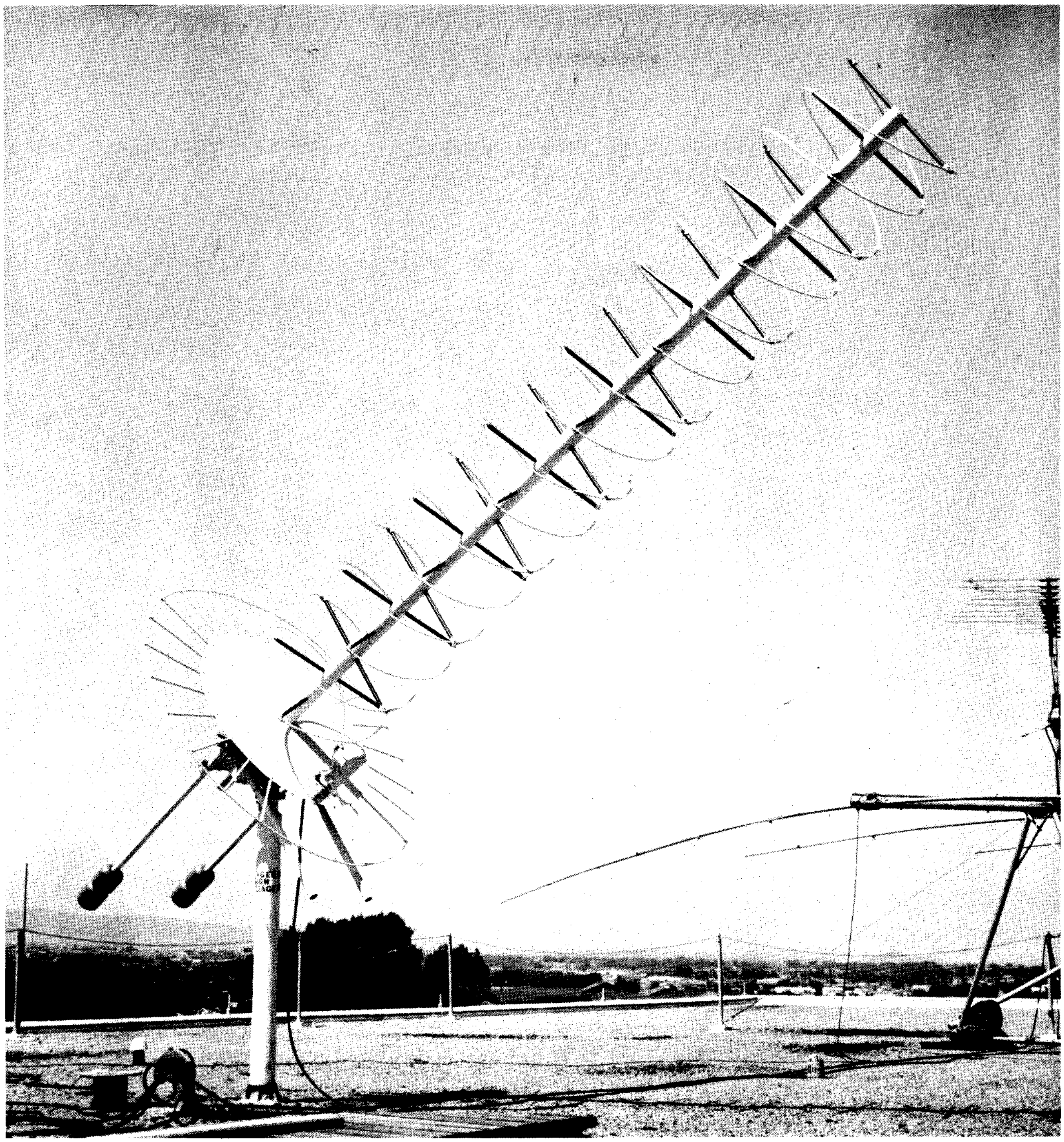


Figure 3. Transmitting antenna.

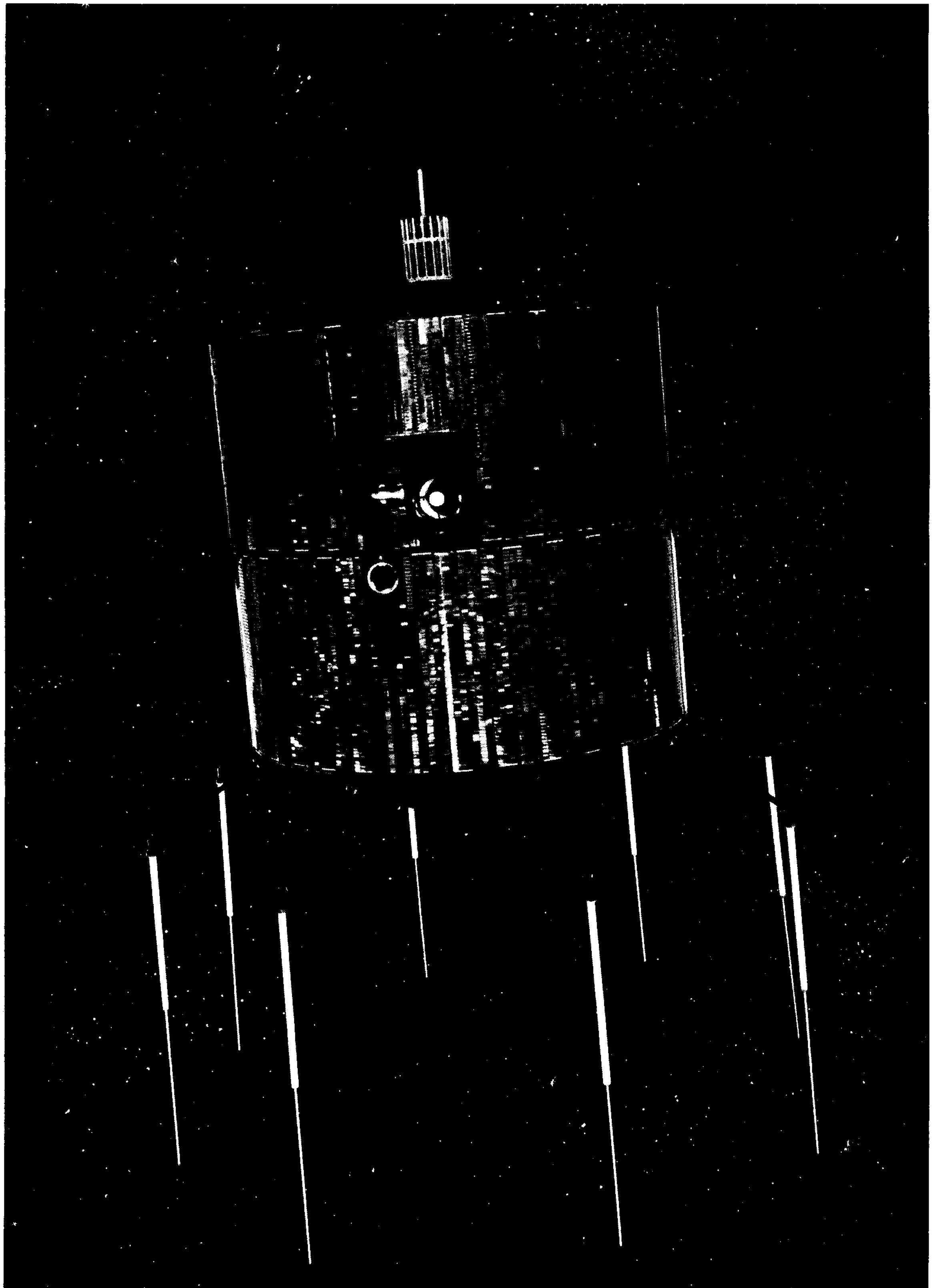


Figure 4. ATS-3 Satellite.

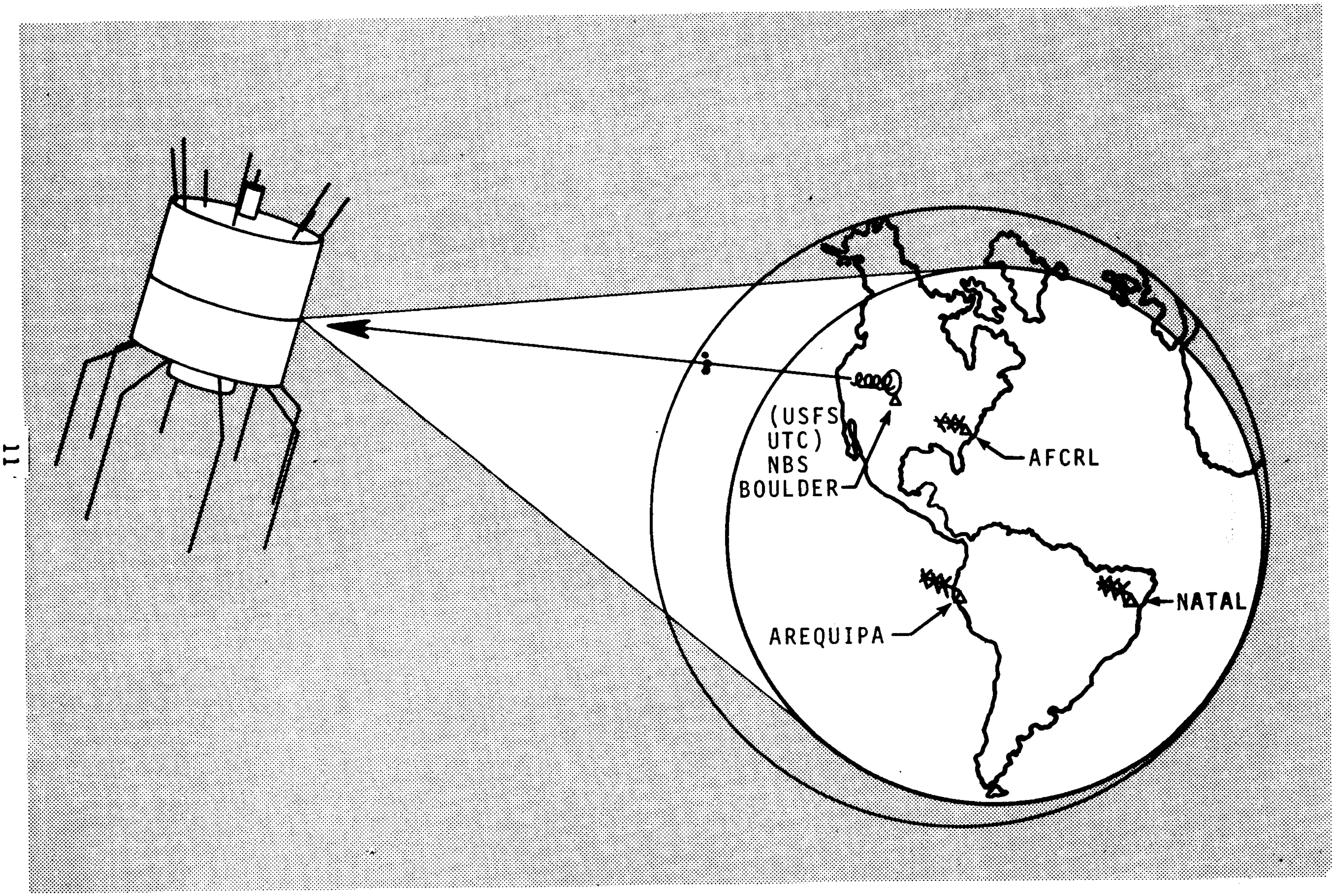


Figure 5. ATS-3 coverage at VHF.

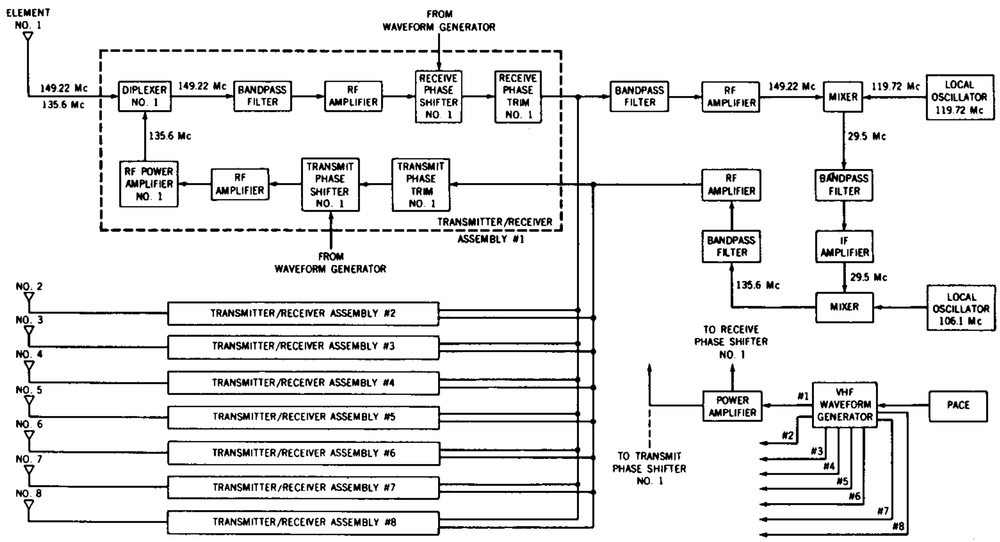


Figure 6. VHF transponder, block diagram.

Beginning with the first satellite relayed broadcasts of the time and frequency signals in late 1971, the broadcast format underwent changes in an effort to improve its performance as an experimental space to earth dissemination service.

The broadcast schedule was Monday through Friday except legal holidays at the times of 1700 to 1715 and 2330 to 2345 Greenwich Mean Time.* During those two 15-minute periods the format content generally included the following:

Voice Announcements: Once a minute the time of day in hours and minutes of Greenwich Mean Time was given. Once every five minutes, during the second, seventh and twelfth minutes of the quarter hour, the position of the satellite, in longitude, latitude and radius (normalized) was given when available.

Ticks: At the beginning of every second a tick, consisting of five cycles of 1 kHz, was transmitted to the satellite with the leading edge of the tick leaving NBS-Boulder on time.

Tones: During the first 45 seconds of every minute which had no voice announcements, a 1 kHz tone was transmitted. This tone was coherent with the tick, i. e., its zero crossings were on the half millisecond intervals between the zero crossings of the seconds ticks. The beginning of the first second of each minute was

*Because of common usage of the name Greenwich Mean Time, the time announcements from ATS-3 were referred to by this name. As noted in a resolution of Commission 31 of the International Astronomical Union, August 1970: "The terms of 'GMT' and 'Z' are accepted as the general equivalents of UTC in navigation and communications." More precisely the actual reference time scale for the ATS-3 experiment was the Coordinated Universal Time Scale, maintained by the National Bureau of Standards, UTC (NBS).

identified by a 1500 Hz tone of 770 milliseconds duration beginning 30 milliseconds after the minute. This tone, being unique to the format, was available to activate automatic equipment or reset clocks.

Time Code: A 100 Hz subcarrier was added to the format. This subcarrier was amplitude modulated 100% with a modified IRIG-H time code. The code had a 1bps rate with a one minute time frame, and was pulse duration modulated as shown in figure 7.

The schedule for the above described format is shown in figure 8. The voice, tones, and ticks frequency modulated the carrier approximately ± 12 kHz. The time code was added to the format, and amounted to about 10% of the amplitude of the other components. To prevent distortion of the tick's waveform, the ticks were gated into the format and all other components of the format were blanked during its presence. Figure 7 also shows part of the time domain of the baseband as it existed for the majority of the experiment.

3. RECEIVING EQUIPMENT

A block diagram of a receiving ground station used by NBS for the ATS-3 time and frequency broadcast reception and time recovery is shown in figure 9. This configuration was used extensively by NBS at its laboratories in Boulder, Colorado, and at field sites. A number of antenna and receiver combinations were used during the course of the experiment to develop a familiarity with the basic requirements for the equipment and the performance to be expected. Other equipment combinations not mentioned in this report worked well for most users' timing requirements. For the majority of users, where only low accuracy time was required (a few tenths of a second), a modest antenna and inexpensive receiver provided a recognizable voice and tick reception. The high

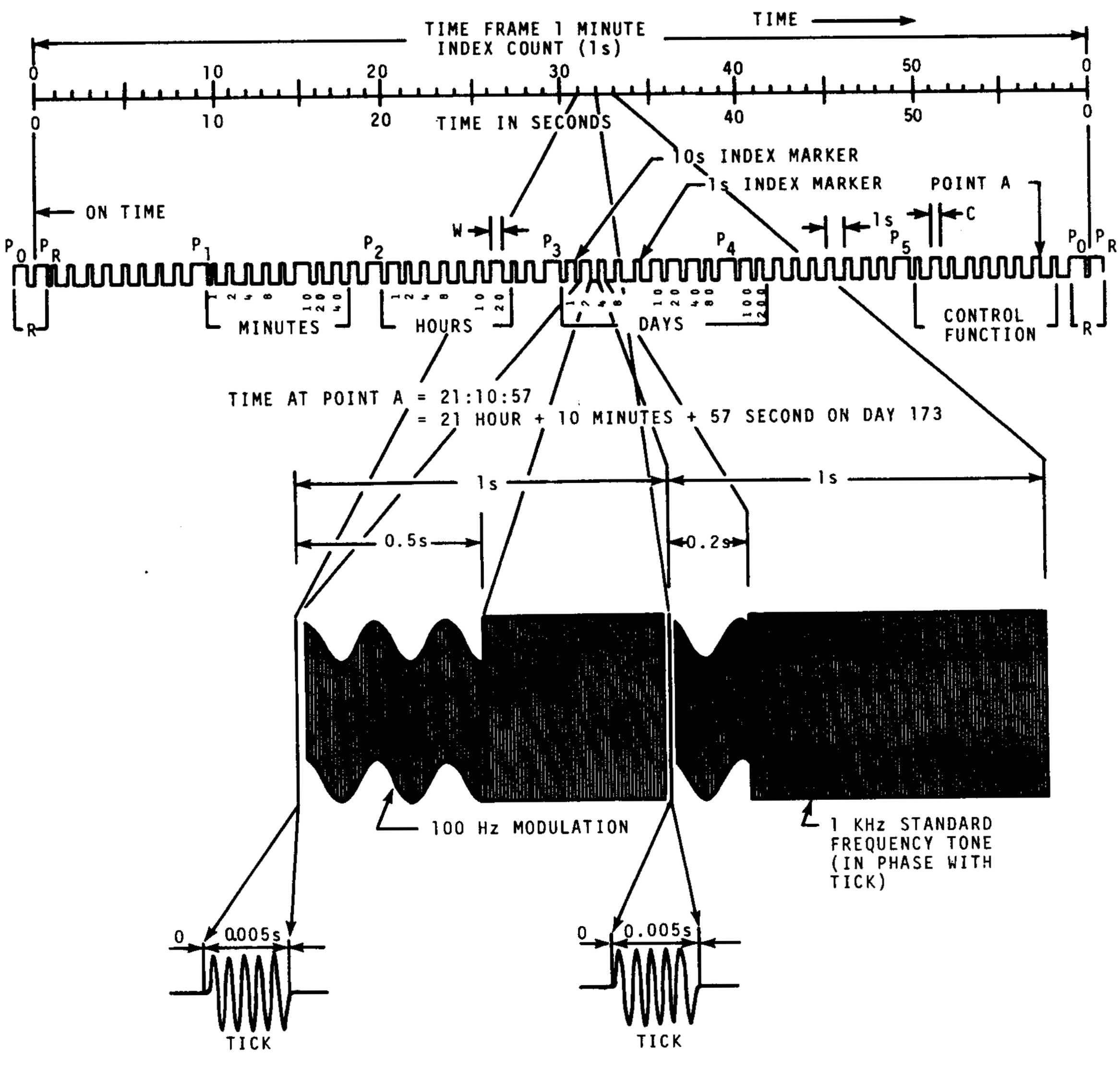
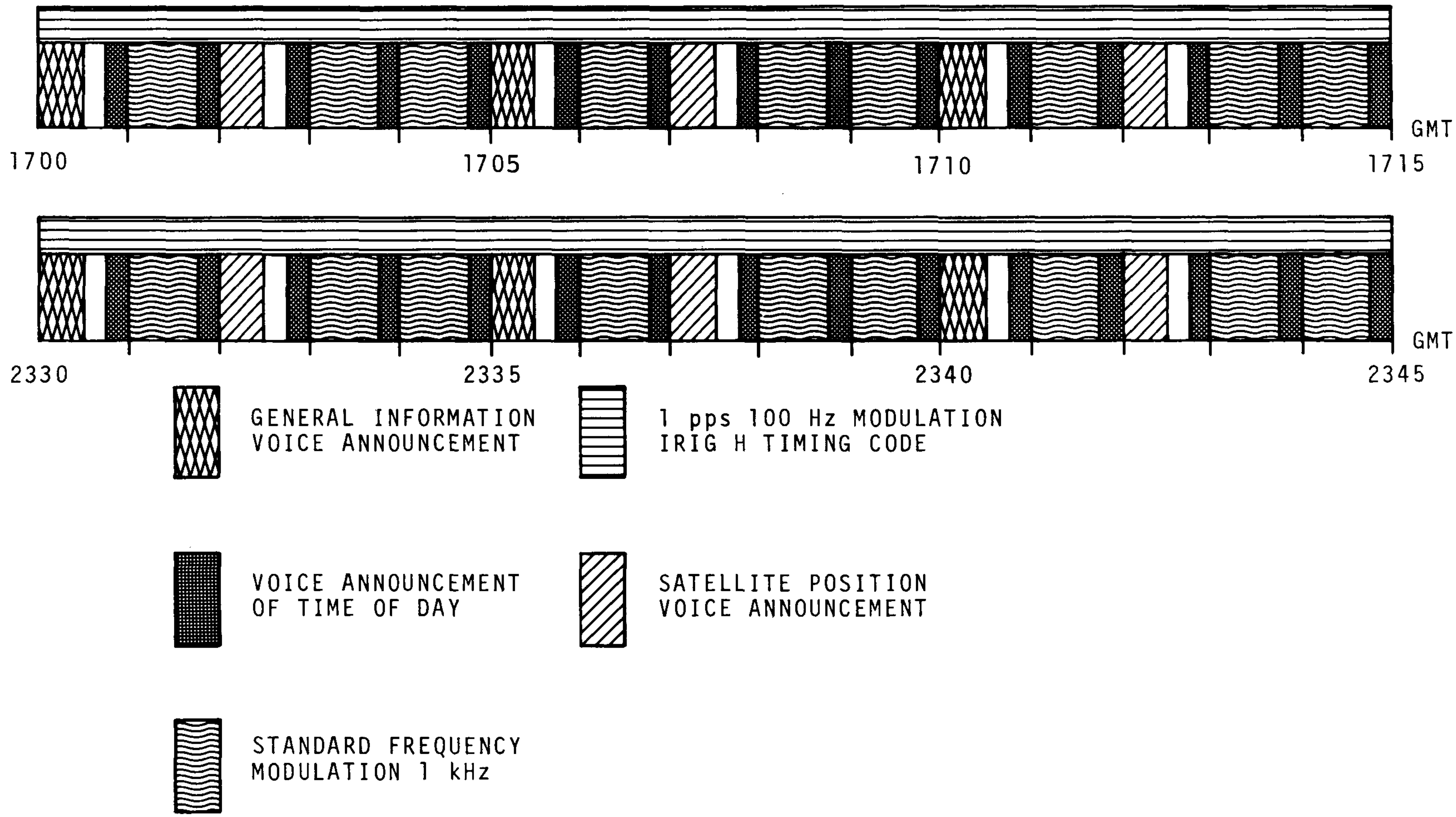


Figure 7. Time and frequency waveforms.



BEGINNING OF EACH MINUTE IDENTIFIED BY 0.77 SECOND LONG 1500 Hz TONE 30 MILLISECONDS AFTER THE MINUTE.

Figure 8. Broadcast schedule from ATS-3.

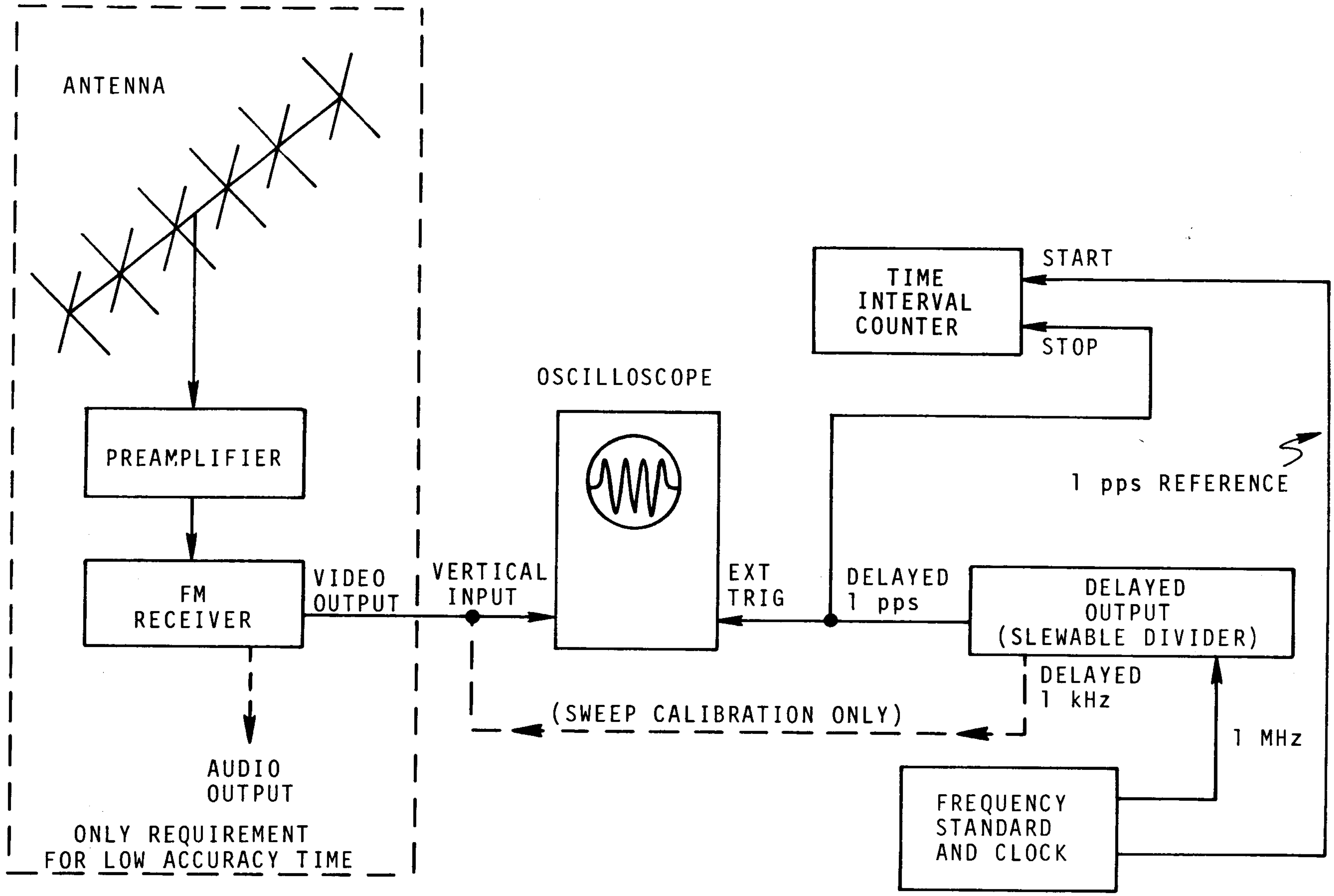


Figure 9. Equipment for ATS-3 time comparison including tick phasing adjustment, block diagram.

accuracy user, of course, leaned toward the use of the highest gain antenna and a receiver with high sensitivity and selectivity.

Because the signals were transmitted to the satellite at high power, arriving at the satellite with high signal-to-noise ratios, the signals arriving back at the ground were down-link limited; i.e., the signal-to-noise ratios were determined solely by the characteristics of the receiving ground station. As an example of that determining down-link, table 1 provides a calculation for the typical ground station used by NBS. The satellite transmitter radiated 11.4 watts into a linearly polarized array of antennas whose gain was 8 dB. A diplexer loss of 1.8 dB reduced the effective radiated power, ERP, from the satellite to 17.6 dBW. A free space loss of 167.2 dB and a circularly polarized antenna with 10 dB gain resulted in a signal input to the receiver of -142.6 dBW after a 3 dB reduction for a linearly polarized signal incident upon a circularly polarized antenna.

The antenna and receiver noise temperatures were calculated to be 700 K and 527 K, respectively. With a 30 kHz bandwidth the effective noise input power was -152.9 dBW, resulting in a carrier-to-noise ratio of 10.3 dB.

3.1. ANTENNAS

A number of antennas provided satisfactory reception quality. Because the ATS-3 satellite radiated a linearly polarized signal, these signals, after passing through the earth's ionosphere, were incident upon the earth's surface at an unpredictable polarization orientation due to the Faraday rotation. A linearly polarized receiving antenna while optimized in polarization to receive these signals required rotation about its axis to maintain maximum coupling to the incoming signals which were slowly rotating in their polarization orientation. In contrast, a circularly

Table 1

Down-link Calculations (f = 135.625 MHz)

CHARACTERISTIC	ATS-3
TRANSMITTED CARRIER POWER, dBW	11.4
DIPLEXER LOSS, dB	-1.8
TRANSMIT ANTENNA GAIN, dB	8.0
SATELLITE EIRP, dBW	17.6
PATH LOSS, dB	-167.2
POLARIZATION LOSS, dB	-3.0
RECEIVER ANTENNA GAIN, dB	10.0
P_{rs} dBw	-142.6
BOLTZMANN'S CONSTANT, dBW/K Hz	-228.6
RECEIVER NOISE FIGURE, dB	4.5
RECEIVER NOISE TEMPERATURE*, dB K	30.9
NOISE POWER DENSITY, dBw/Hz	-197.7
IF BANDWIDTH, dB Hz (30 kHz)	44.8
NOISE, dBW	-152.9
(C/N), dB	10.3

*BASED ON ANTENNA NOISE TEMPERATURE OF 700 K, AND RECEIVER NOISE TEMPERATURE OF 527 K.

polarized antenna while rejecting one-half of the available incoming signal would always accept the other half without any rotation or reorientation. The circularly polarized antenna, though not the simplest antenna, was preferred for this experiment.

Some of the antennas used by NBS are shown in figure 10. Figure 10a is a circularly polarized antenna consisting of two linearly polarized yagi antennas mounted orthogonally on the same boom and phased for circular reception. This antenna had a gain of approximately 10 dB above a circularly polarized isotropic radiator and was available commercially for less than $50.00 including impedance matched phasing cables. Figure 10b shows a 3-turn helix with approximately 10 dB gain. Figure 10c shows another circularly polarized antenna with 4-5 dB gain and a wide beamwidth. In contrast to the two previous antennas this antenna had a sufficiently broad beamwidth that it could be set upright for satellite reception whereas the other two were required to be pointed in the general direction of the satellite. Figure 10d shows a quarter-wave dipole mounted on a receiver which was capable of receiving the signal and providing good quality audio reception. The first two antennas were considered to have the gain necessary for high-accuracy time recovery using oscilloscope techniques whereas the last two provided for low-accuracy timing using voice reception only. These antennas are summarized in table 2.

Considering the wide beamwidth of these VHF antennas, pointing them at the satellite presented no particular problem. As information for users, an antenna pointing angle overlay on an earth map was prepared like the one shown in figure 11. The cross in the center of the overlay was the point on the earth directly below the satellite. An overlay such as this one was valid for the entire two-year duration of the ATS-3 time and frequency experiment. The heavy line near the

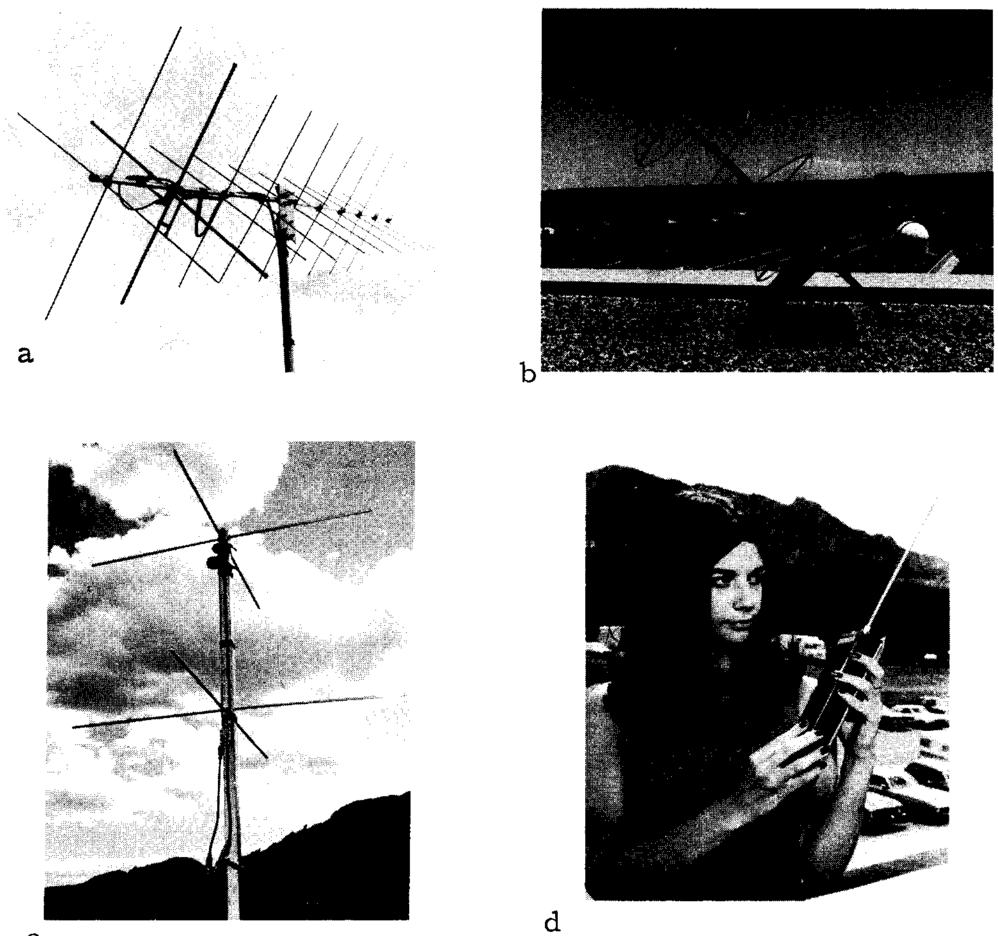


Figure 10. VHF receiving antennas, (a) crossed yagis; (b) 3 turn helix; (c) crossed dipoles with reflector; (d) grounded quarter wave dipole.

Table 2

Receiving Antenna Summary

ANTENNA TYPE	GAIN	BEAMWIDTH	POLARIZATION	COST	USE
CROSSED YAGI (8 ELEMENTS)	10 dB	60°	CIRCULAR	$50	HIGH ACCURACY TIMING
HELIX (3 TURNS)	10 dB	60°	CIRCULAR	$25	HIGH ACCURACY TIMING
CROSSED DIPOLES WITH REFLECTOR	4-5 dB	140°	CIRCULAR	$25	LOW TO INTERMEDIATE ACCURACY TIMING
GROUNDED QUARTER WAVE DIPOLE	2 dB	NEARLY ISOTROPIC	LINEAR	$10	LOW ACCURACY TIMING

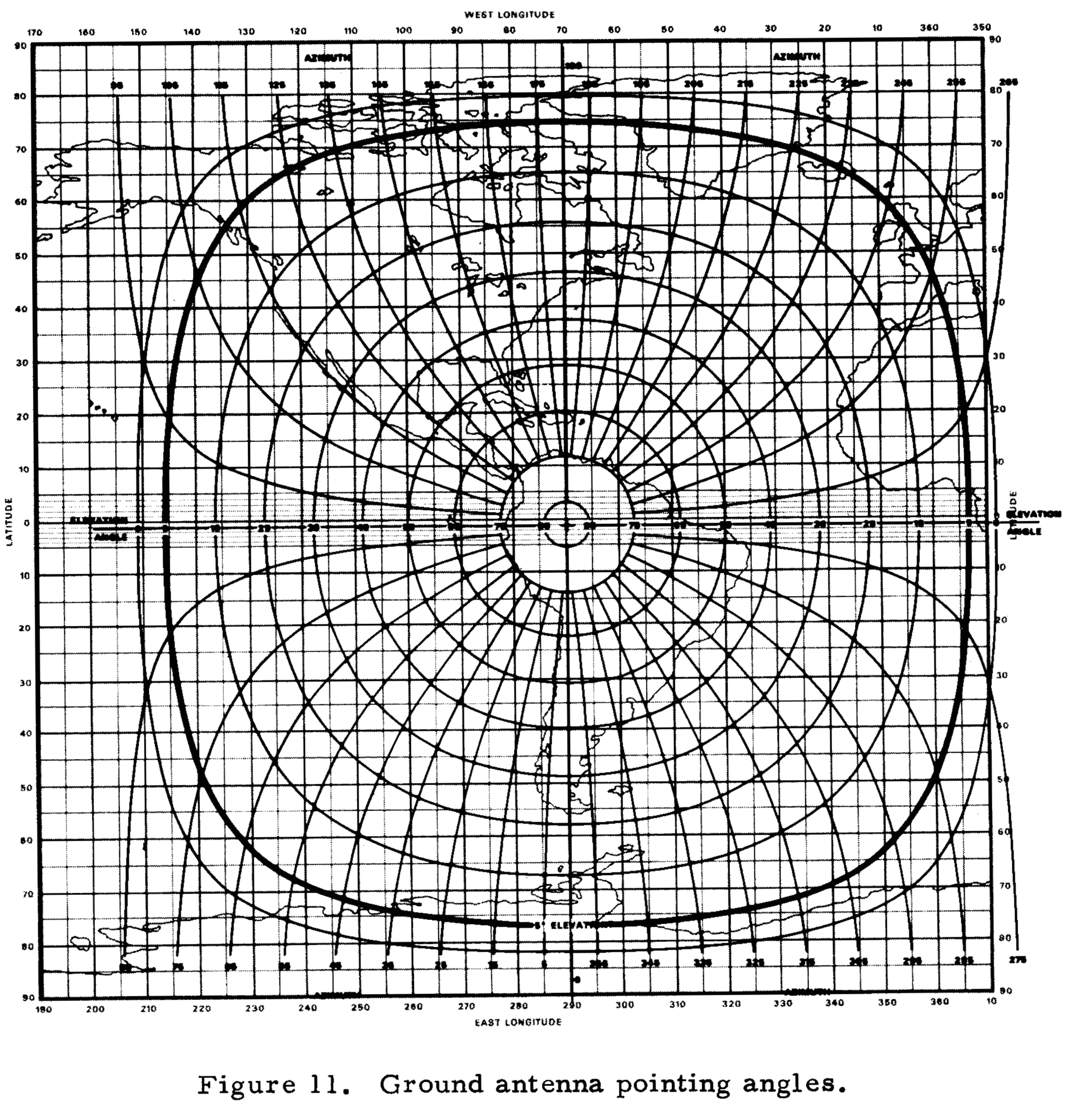


Figure 11. Ground antenna pointing angles.

periphery of the overlay was the five degree take off angle from the ground to the satellite. For example, the antenna pointing from Washington, D. C., (77° west longitude and 39° north latitude) was 170° azimuth and 42° in elevation.

3.2. PREAMPLIFIERS

In applications where a considerable amount of cable would exist between the antenna and receiver, such as in a building, a preamplifier was found necessary to overcome the cable loss. Additionally, the preamplifier in some cases provided for a better signal-to-noise ratio because of its lower noise figure. Commercial transistor preamplifiers like the one shown in figure 12 were available for less than $20.00.

3.3. RECEIVERS

A number of FM receivers were used in the experiment with good results including both older vacuum tube models and more recent transistor units. Receiver choices varied from standard telemetry receivers, communications receivers preceded if necessary with frequency converters, or the receivers could have been built from readily available parts. The quality of the equipment used with success by NBS ranged all the way from inexpensive receivers (less than $100) which had no manufacturer specifications to accompany them, to higher priced equipment with specifications of 0.5 μV for 20 dB quieting and selectivity of -80 dB.

In addition to using 30 kHz bandwidth receivers in the experiment, the carrier deviation was reduced to ± 5 kHz on occasion to test the performance of the standard narrowband receivers. The narrowband receivers performed very well with the ± 5 kHz transmission and were acceptable for voice and tick reception even when the full 30 kHz transmission was used. Conversely, the wideband units were also acceptable when receiving the narrowband transmission.

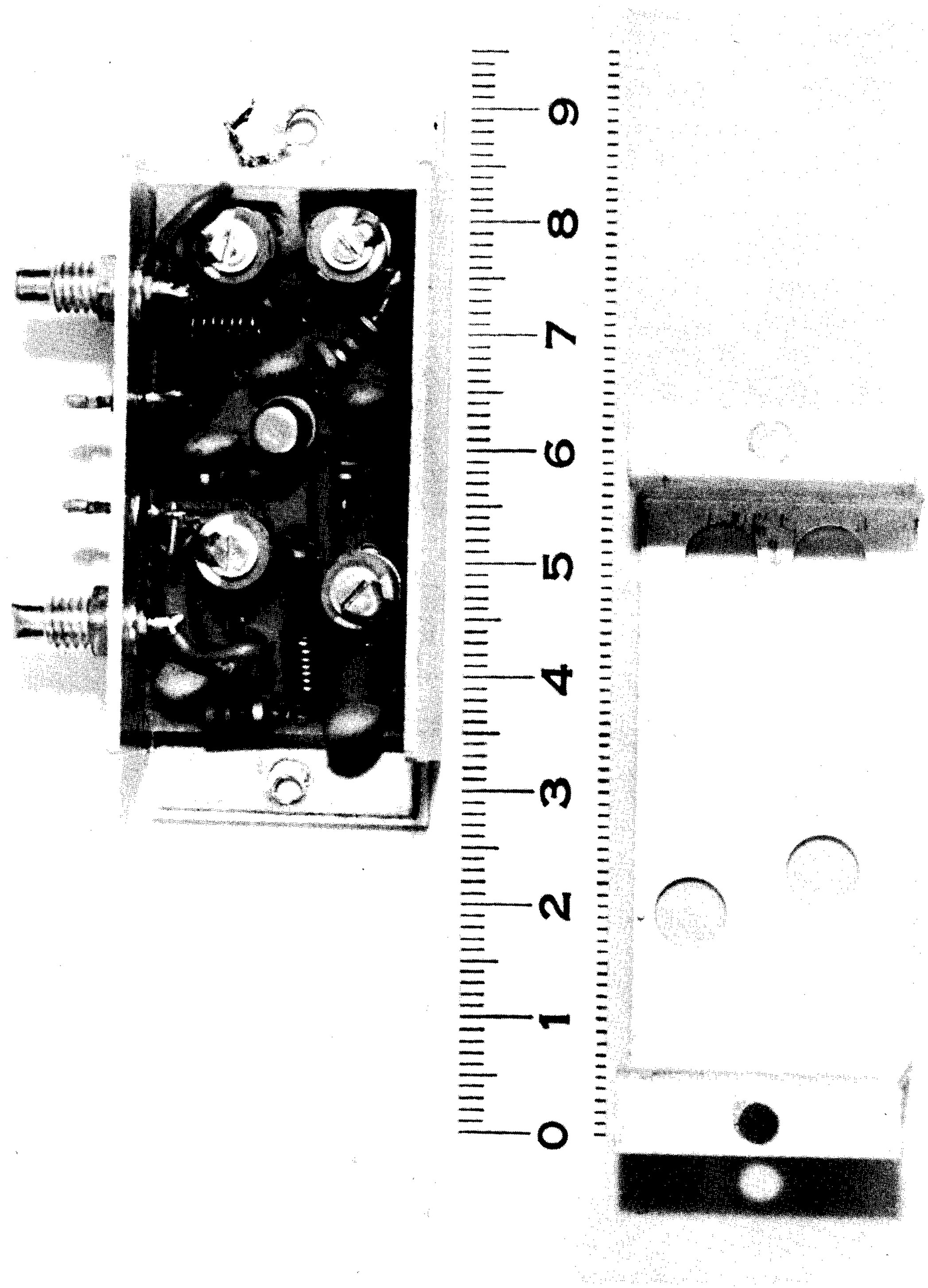


Figure 12. VHF preamplifier.

From the beginning of the experiment, it was decided to concentrate on using 30 kHz bandwidths rather than the more popular narrow bandwidths. This decision was based on the desire to obtain the highest timing resolution possible. It was also recognized, however, that a narrower bandwidth operation would generally reduce antenna requirements and allow use of the newer FM equipment being produced for general communications use.

Figure 13 shows a few of the receivers tested by NBS in this experiment. Quantitative measurements of the performance of each receiver were not made. Satisfatory performance of each unit was consistent with the desire to operate the experiment in a manner which would allow the general public the best chance to participate without undue complication or expense.

NBS also interfaced an inexpensive solid state FM receiver into a commercial time code reader for automatic clock synchronization by the satellite broadcasts. This device, shown in figure 13g, worked very well. A 100 Hz active filter followed the output of the receiver and fed into the time code reader. The reader usually was able to recognize the code frame and reset itself within two or three minutes. Once the time code reader had "locked" on to the satellite broadcast code, the unit worked flawlessly. This illustrated the satellite's potential for automatic, unattended timing applications.

4. SIGNAL PROCESSING

An antenna and FM receiver alone were sufficient for the recovery of low resolution time information. Time-of-day announcements every minute, giving hours and minutes in Greenwich Mean Time, and ticks every second could easily be heard. This method for clock synchronization was accurate to better than one-half second, remembering however,

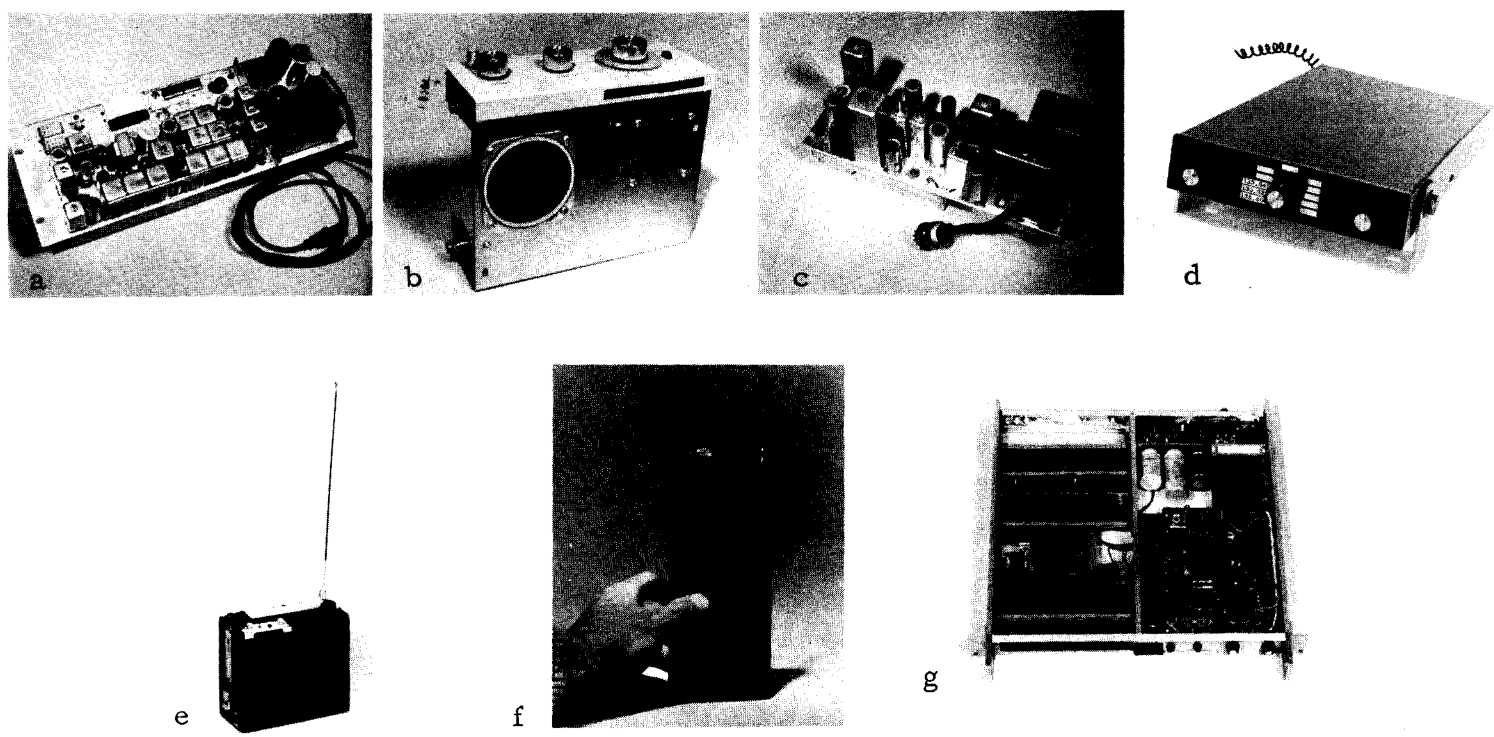


Figure 13. VHF receivers: (a) vacuum tube model; (b) solid state model; (c) vacuum tube model; (d) solid state model; (e) solid state model; (f) solid state model; (g) receiver, active filter, and time code reader.

that the ticks left the NBS Boulder latoratories on time and, after an approximately 76,000 km trip to the satellite and back to earth, were delayed by about 1/4 second. For audio reception only, simple antennas were used with good results. Whips and dipoles provided a generally satisfactory performance dependent in part upon the level of man made and natural noise and upon the receiver's selectivity.

Obtaining time information to better than a few tenths of a second required additional equipment. An example of the equipment involved for a time recovery technique is shown in figure 9. Here the receiver was connected to the vertical input of an oscilloscope. The receiver output was after the frequency discriminator and prior to the audio section to avoid possible delay variations. The oscilloscope was triggered from a digital delay generator which had 1 pps and 1 kpps outputs, both variable in their occurrences in time. A schematic of the digital delay generator is shown in figure 14. Achieving submillisecond timing resolution using this technique with the ATS-3 time signals required only a few simple steps. First the received tick had to be located on the oscilloscope and positioned at the beginning of the sweep or at the left side of the scope. This was done by setting the sweep rate to 0.1 s/cm and the trigger rate to 1 pps. The digital delay generator was then used to position the received tick to the left side of the scope as shown in figure 15a. This procedure was repeated four times. Each time the sweep rate was increased until the sweep rate was at 100 μs/cm and the tick was positioned as in figure 15c. It may be seen from the figures that the zero crossing at the center of the tick rather than the beginning of the tick served as time reference. The beginning of the tick was distorted and not easy to identify, due to the bandwidths of the transmitting and receiving equipment. Movement of 2500 μs into the center of the tick itself was found to minimize the effects of this distortion. Because

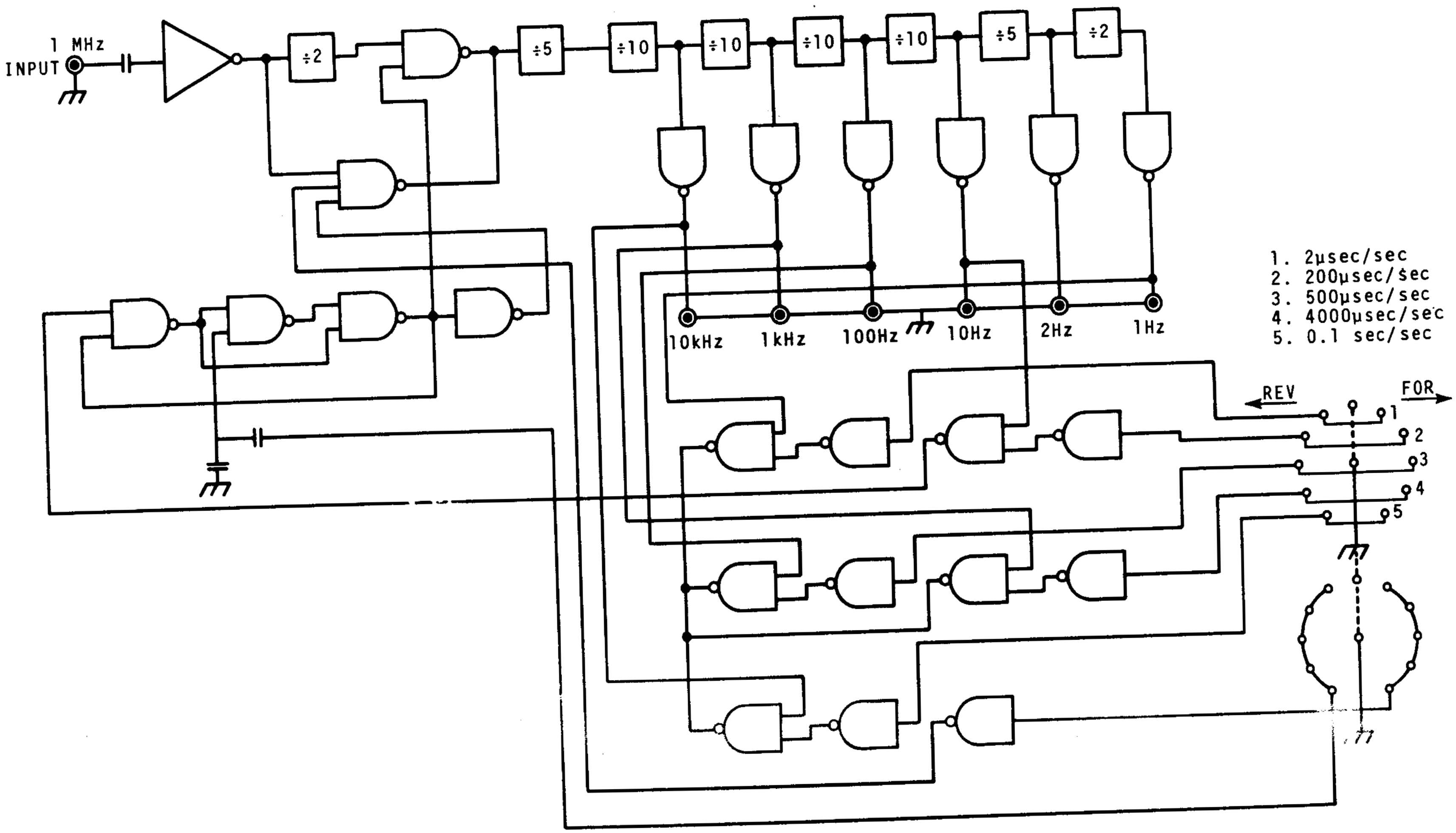


Figure 14. Digital delay generator.

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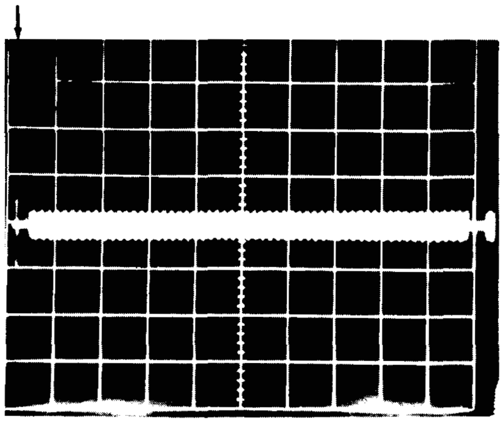
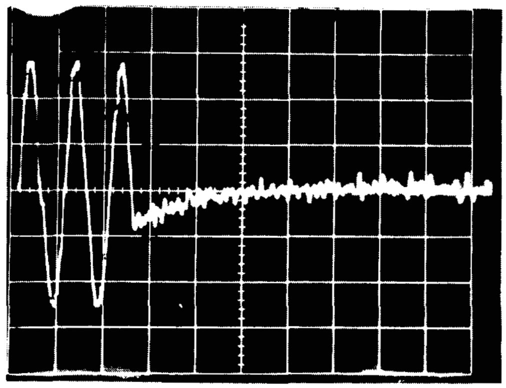
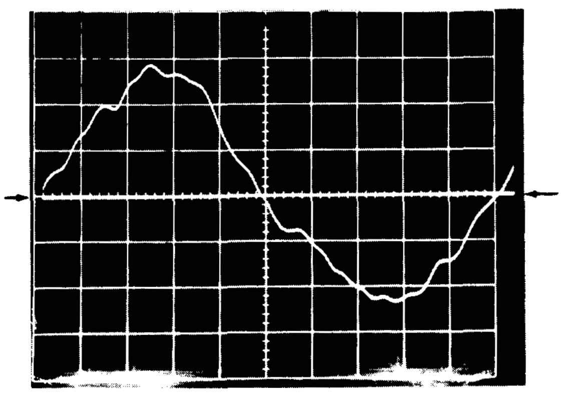


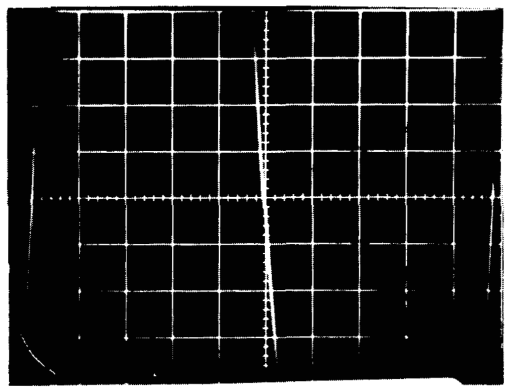
(a) Sweep: 0.1 s/cm.



(b) Sweep: 1 ms/cm.



(c) Sweep: 100 μs/cm.



(d) Sweep: 100 μs/cm.
High vertical gain.

Figure 15. Received signals from ATS-3 on an oscilloscope.

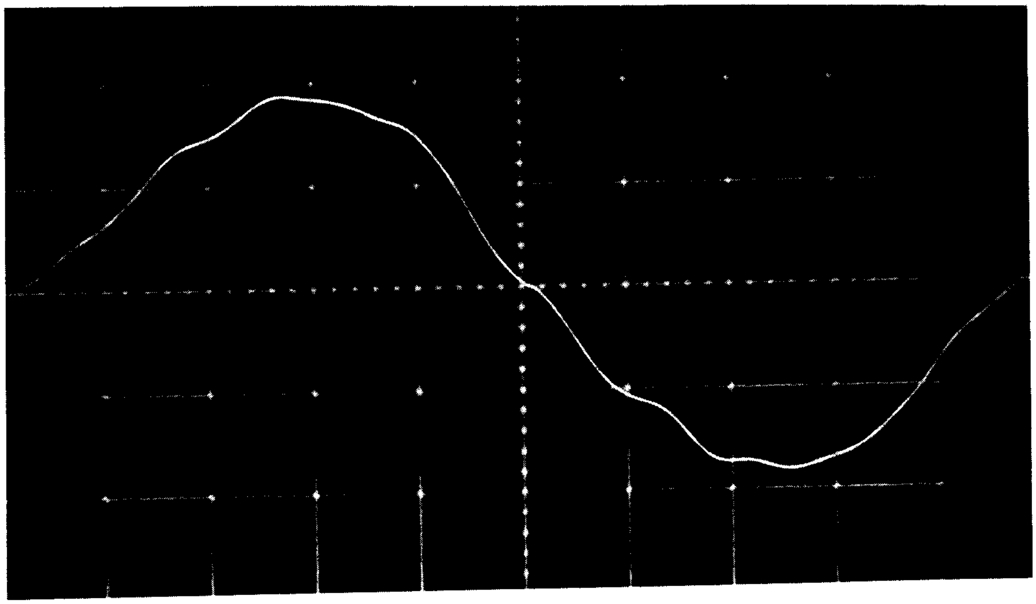
the receiver delay calibration, described in a later section, was measured in the same way using the same signals, the effects of distortion were minimized. This assumed that the path added no further distortion.

Thus far, the described recovery procedures were nearly identical to those used for WWV or WWVH. Taking advantage of the apparently excellent short term path stability, a 1 kHz tone was added between the ticks in such a manner that all its zero crossings were on the 500 μs intervals between zero crossings of the ticks. Increasing the trigger rate to 1 kHz allowed the observer to see more of these zero crossings and enhanced his ability to average the crossings, yielding a correspondingly greater precision. The effect of the higher trigger or sampling rate is shown in figure 16.

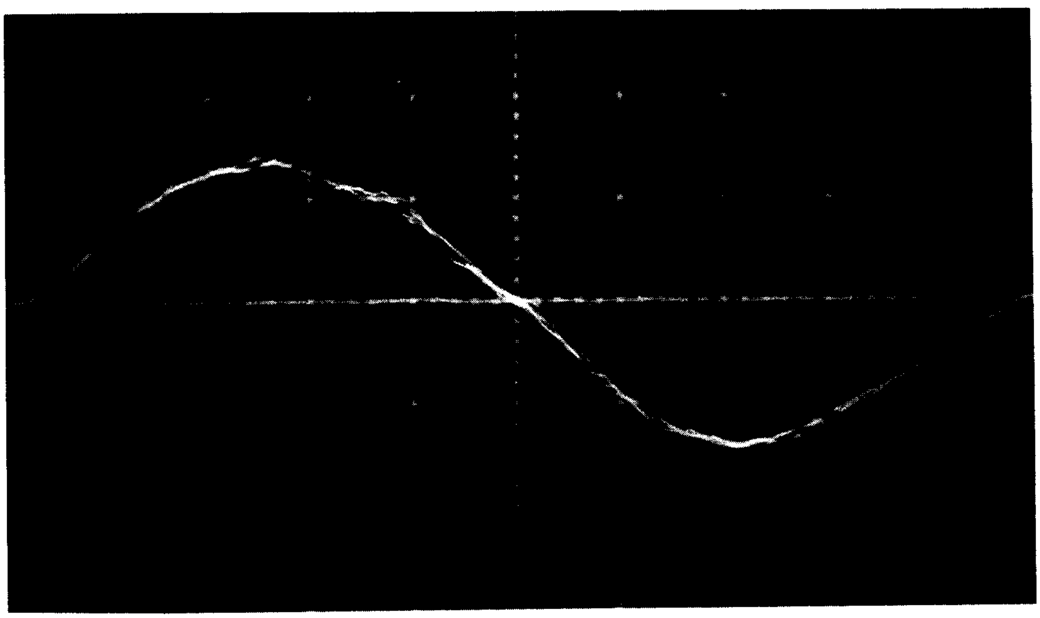
The unavoidable noise added to the received signal caused jitter in the zero crossings and limited the precision of time delay measurements. Theoretically, assuming a Gaussian distribution to the noise, the measurement of phase or time at which the waveform crosses the zero axis is given in [10] as

$$\delta t = \frac{T}{2\pi \left(2 \frac{S}{N}\right)^{1/2}} , \qquad (1)$$

where δt was the rms error in measuring the time of the zero crossing, T was the period of the sinewave, and S/N was the signal-to-noise power ratio. For the conditions existing in this experiment a δt was obtained of 11.25 μs for a S/N of 10 dB, and 3.6 μs for a S/N of 20 dB. The increased triggering rate allowed for averaging of the zero crossings with the improvement being proportional to the square root of the number of crossings averaged. It was estimated that the effective number of samples available to the eye using the oscilloscope amounted to at least 50 sweeps at the 1 kHz rate or a 50 ms averaging time. These 50 samples



(a) Trigger rate: 1 sweep/s



(b) Trigger rate: 1000 sweeps/s

Figure 16. Received signals from ATS-3 at different sampling rates.

increased the resolution to 1.6 μs and 5 μs for the signal-to-noise ratios of 20 dB and 10 dB respectively.

Prior to any measurements, the oscilloscope was calibrated and adjusted to eliminate systematic errors in the measurements. The sweep non-linearities of the oscilloscope were compensated for as follows. From the digital delay generator a 1 kHz squarewave was used for vertical input and sweep trigger. With the sweep rate at 100 μs/cm, the horizontal position of the squarewave from the delay generator was placed so its zero crossing fell at the center of the oscilloscope as referenced by the graticules on the scope face. Triggering occurred 500 μs prior to this zero crossing and, therefore, looking at the center of the oscilloscope with the 1 kHz satellite signal present insured a zero crossing at the beginning of the sweep coincident to the trigger pulses.

Misinterpretation of the zero crossings was also possible due to a direct current bias on the post detected signals or from distorted waveforms. Careful balance and alignment of the band pass filters, limiter, and discriminator circuits of the receiver eliminated large distortion effects. The zero volt reference on the oscilloscope was set by momentarily grounding the input and centering the sweep in the vertical direction.

All of the above mentioned procedures insured that the trigger pulse (1pps) was coincident with the center of the tick emerging from the receiver. As shown in figure 9, this pulse was used to stop a time interval counter for which the local clock's 1 pps reference started the counter. The counter then displayed the apparent signal delay from the NBS-Boulder reference clock to the output of the user's receiver. A difference in this apparent delay and the computed signal delay, which included equipment and path delays, indicated a clock error. The differences in apparent and computed delays will be discussed in more detail in a later section dealing with "Delay Computation and Clock Synchronization."

5. SIGNAL DELAY

The propagation of the time signals between NBS and the user via ATS-3 was, of course, not instantaneous. The free space propagation velocity of electromagnetic waves was taken to be 2.997925×10^8 m/s: which, for the approximately 76,000 km path from NBS to the user, meant a delay in the arrival of the signal of about 1/4 second. The user, to synchronize a clock to better than one second accuracy, had to know this signal delay time. The total signal delay time included the time required for the signal to pass through the intervening electronic equipment; i.e., the transmitting equipment at NBS, the satellite transponder, and the user's receiving equipment; the delay in the ionosphere, and troposphere, and the free space path delay outside the earth's atmosphere between the earth and the satellite.

To avoid becoming entangled in definitions of phase and group velocities of electromagnetic waves, the net total delay in the link between NBS-Boulder and the user was referred to as the signal delay. Signal delay was defined in this case as the time required for an identifiable point in the signal waveform to enter the transmitting equipment and reappear at the output of a user's receiver. That definable, recognizable point in the signal waveform was, in this experiment, the zero crossings of the tick and/or the 1 kHz tone. This definition of signal delay applied to the equipment where it could be argued that the equipment was dispersive and group delay through it was not well defined. For delay calibration as well as signal reception, the emerging signal was never distorted sufficiently to make identification and measurements on any particular point in the signal waveform difficult. In the earth's atmosphere the signal delays coincided with group delay. Outside the earth's atmosphere the signal velocity was the velocity of light or 2.997925×10^8 m/s.

5.1. EARTH-SATELLITE-EARTH PATH DELAY; SATELLITE MOTION

The ATS-3 satellite, like all so called "geostationary" satellites, was moving about in a complicated manner. This motion was significant when considering microsecond timing, since in one microsecond an electromagnetic wave in free space will travel approximately 300 meters. The causes for motion of a "geostationary" satellite are many. In the case of the ATS-3 satellite, its orbit plane was inclined to the earth's equatorial plane by between 2 and 3 degrees. In a period of 24 hours, the satellite moved north and south of the earth's equator by 2 to 3 degrees. At a distance of about 42,000 km from the earth's center, this meant a movement of nominally 5,000 km peak to peak in a frame of reference which was rotating with the earth. The satellite's orbit was also slightly elliptical and in a period of 24 hours it moved in and out radially with respect to the earth's center. For example, the typical eccentricity for ATS-3 of 0.0026 produced a diurnal variation in the distance to the earth's center of about 220 km. The eccentricity, e, is defined as

$$e = \sqrt{1-(b/a)^2}, \tag{2}$$

where b and a are the semi-minor and semi-major axes of the elliptical orbit of which the earth was at one focus. The radius is given by

$$r = \frac{a\,(1-e^2)}{1 + e\cos\theta}. \tag{3}$$

The geometry of an elliptical orbit is shown in figure 17.

Finally there was a general east or west drift of typically 0.05 degrees per day which moved the satellite up to 35 km/day in its mean longitudinal position. The drift was caused primarily by the asymmetrical character of the earth's equator and imperfect orbit altitudes.

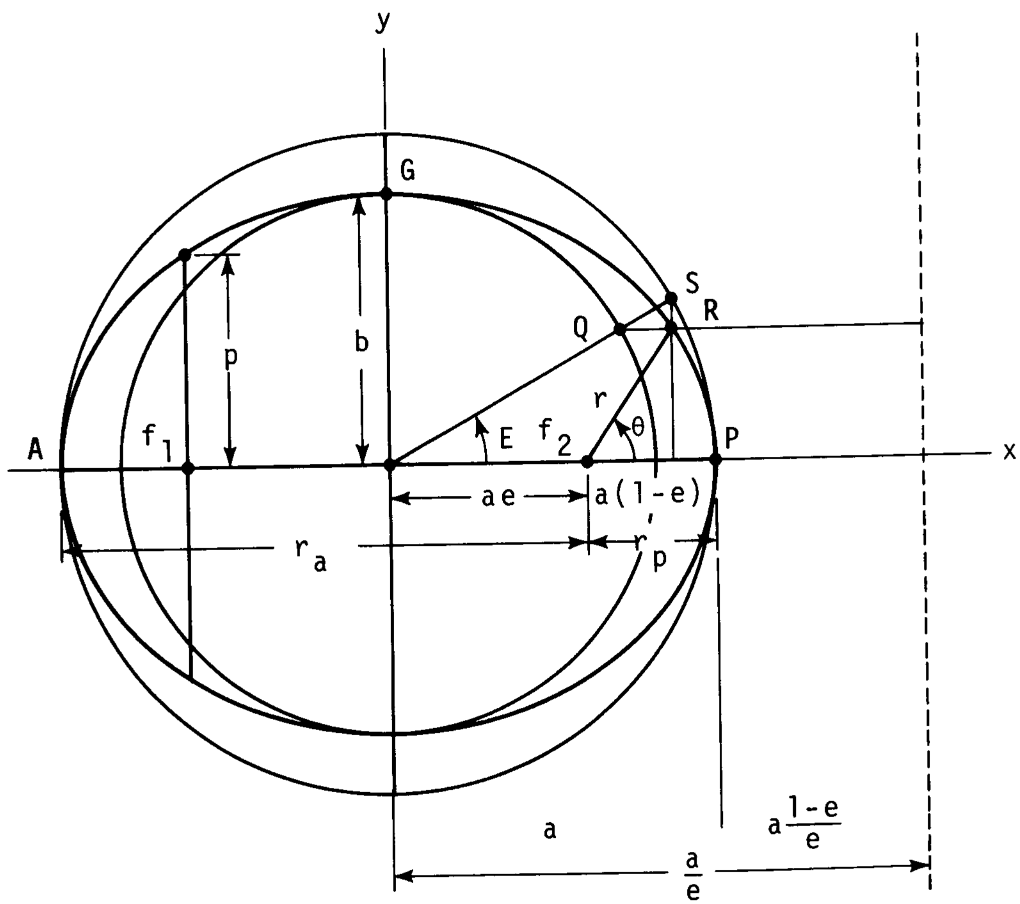


Figure 17. Geometry of an elliptical orbit.

The above three mentioned causes and effects are the most significant for ATS-3 or any geostationary satellite. Other effects important over a longer period of time were due to the fine structure to the gravitational field of the earth, the sun's and moon's gravitational fields, and solar radiation pressure. A complete understanding of the mechanics of geostationary orbits is complicated and beyond the scope of this report. The reader is referred to reference [15]-[16] for a complete treatment and to the appendices where some of these facts are expanded upon.

As a substitute for a highly theoretical explanation, a series of graphs is included in this report to provide the reader some insight into the effect these satellite motions would have upon the user interested in recovering time and frequency information.

Figure 18 shows, in exaggeration, how the effects perturb the geosynchronous orbit. The satellite moves or deviates from a perfect circular, non-inclined orbit in all directions. The resultant orbit might be best related to the edges of a clam shell. Figure 19 shows these effects on the ATS-3 satellite in terms of the total signal delay from the NBS to selected sites in both hemispheres. (These curves were computed from the satellite's position on November 28, 1972). It can be seen that the delays, which do not include electronic equipment or atmospheric effects, are diurnal and are different in magnitude depending upon the terminal site location.

Figures 20 and 21 show how these delays would be affected by variations in the eccentricity and inclination of the orbit. The orbit for November 28, 1972 was changed in its eccentricity and then in its inclination. The orbital elements for that date are given for reference.

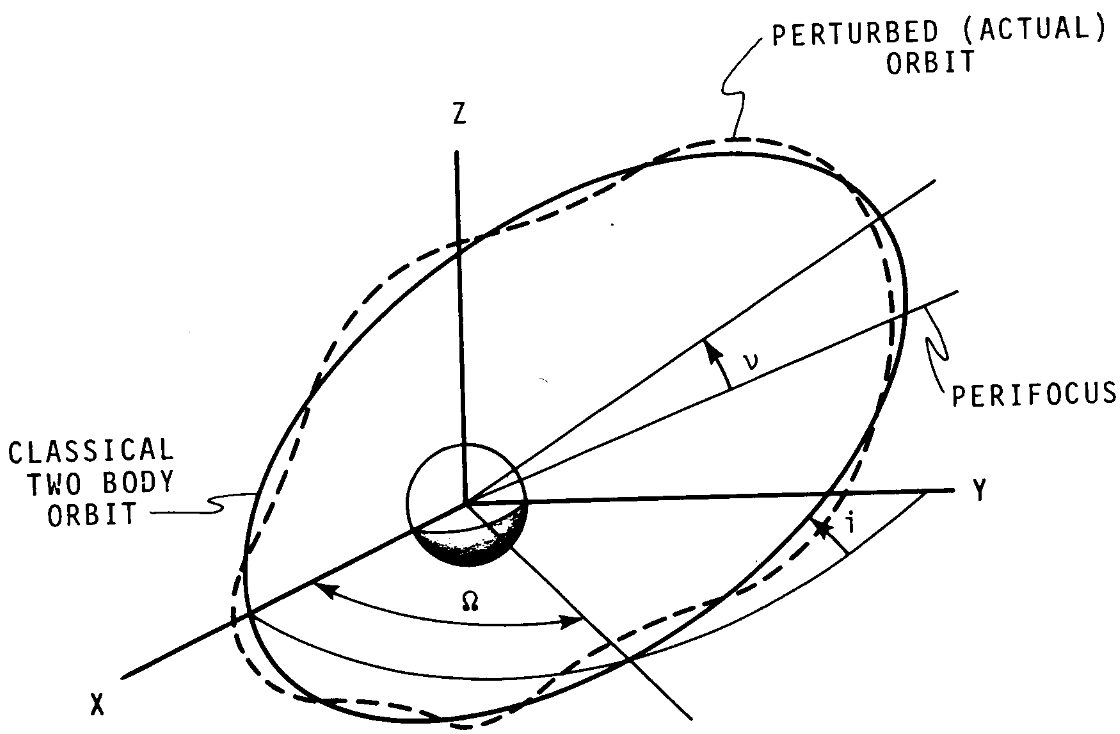


Figure 18. Classical and preturbed orbits.

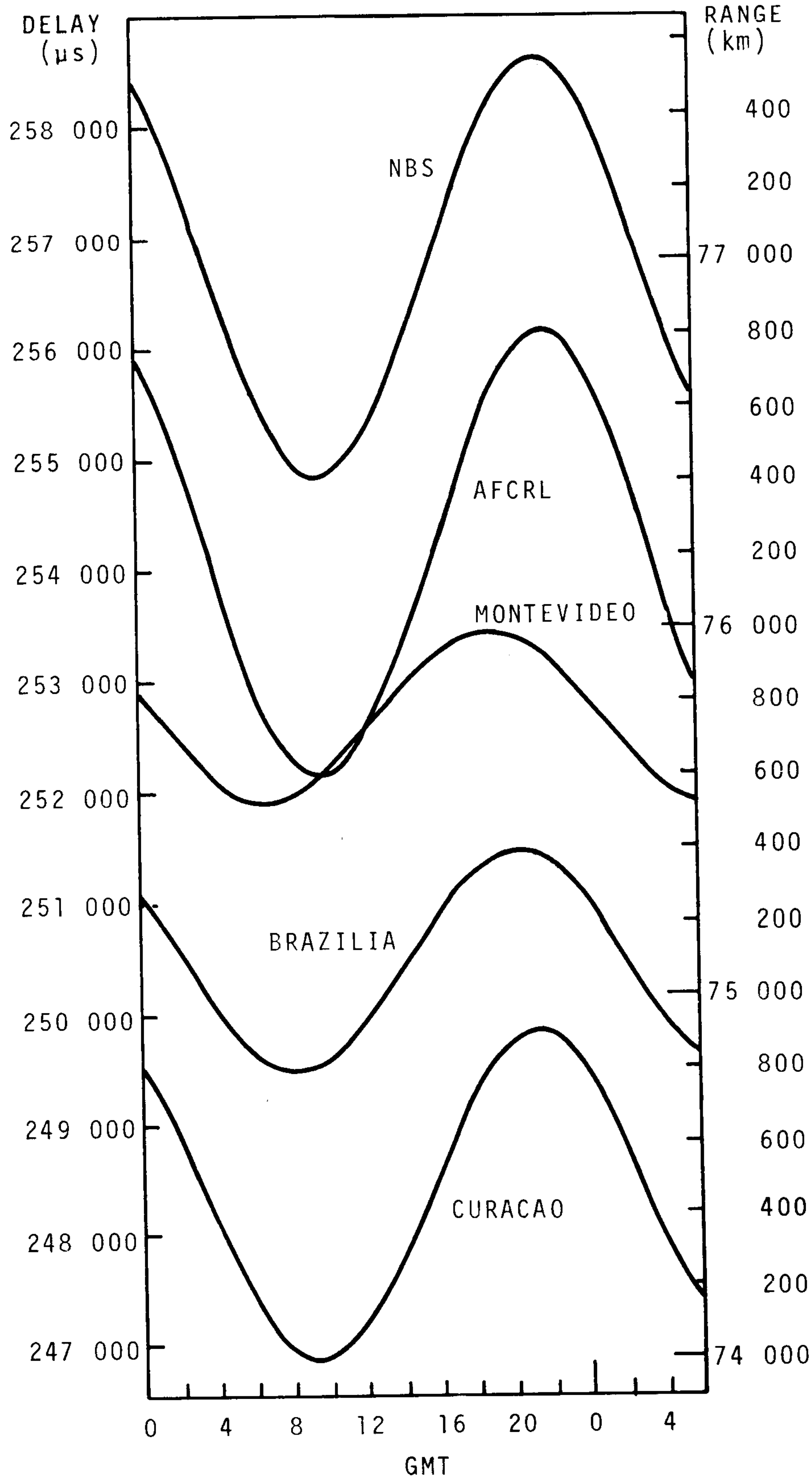


Figure 19. Delays from NBS to five sites via ATS-3.

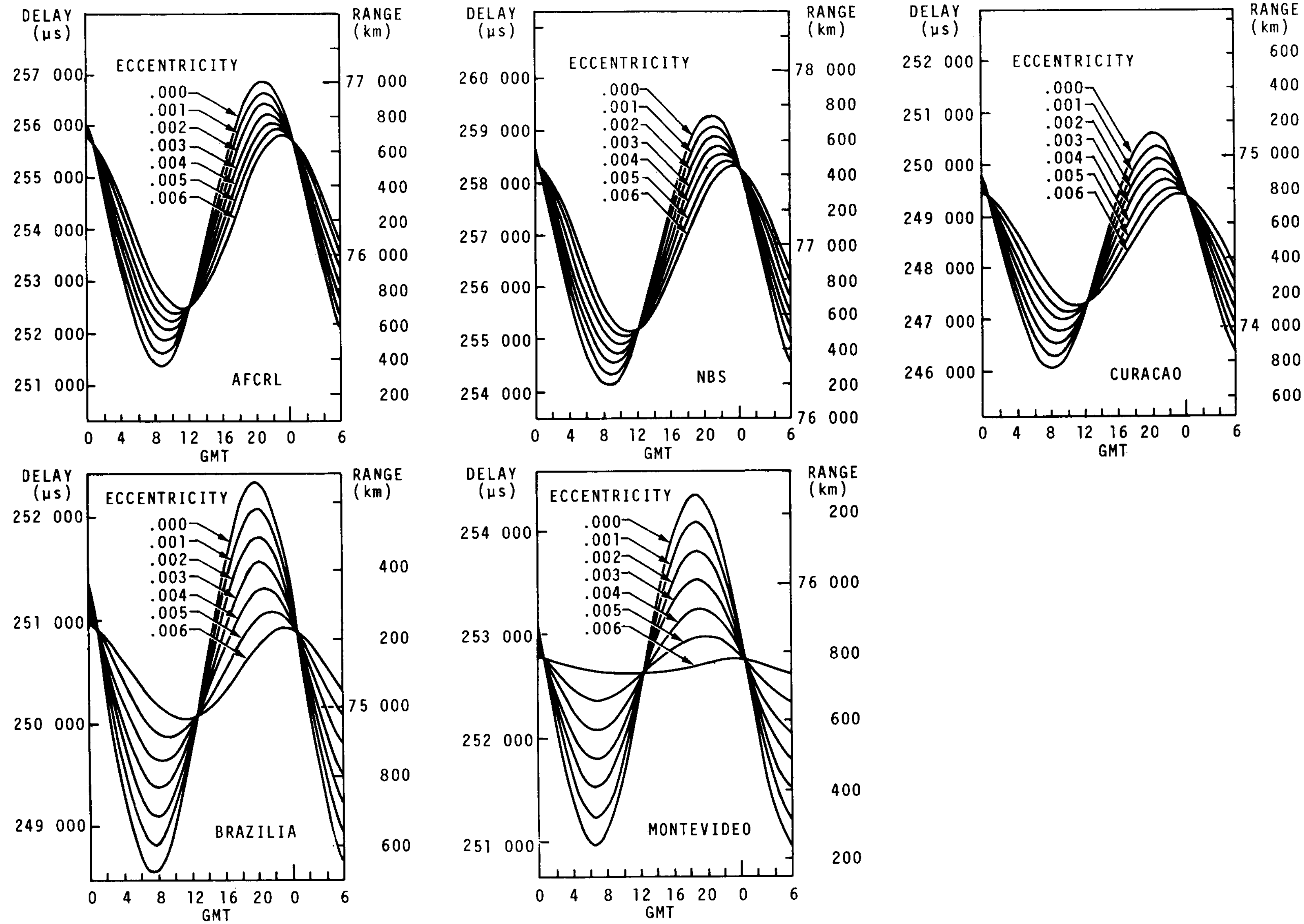


Figure 20. Delays from NBS versus eccentricity.

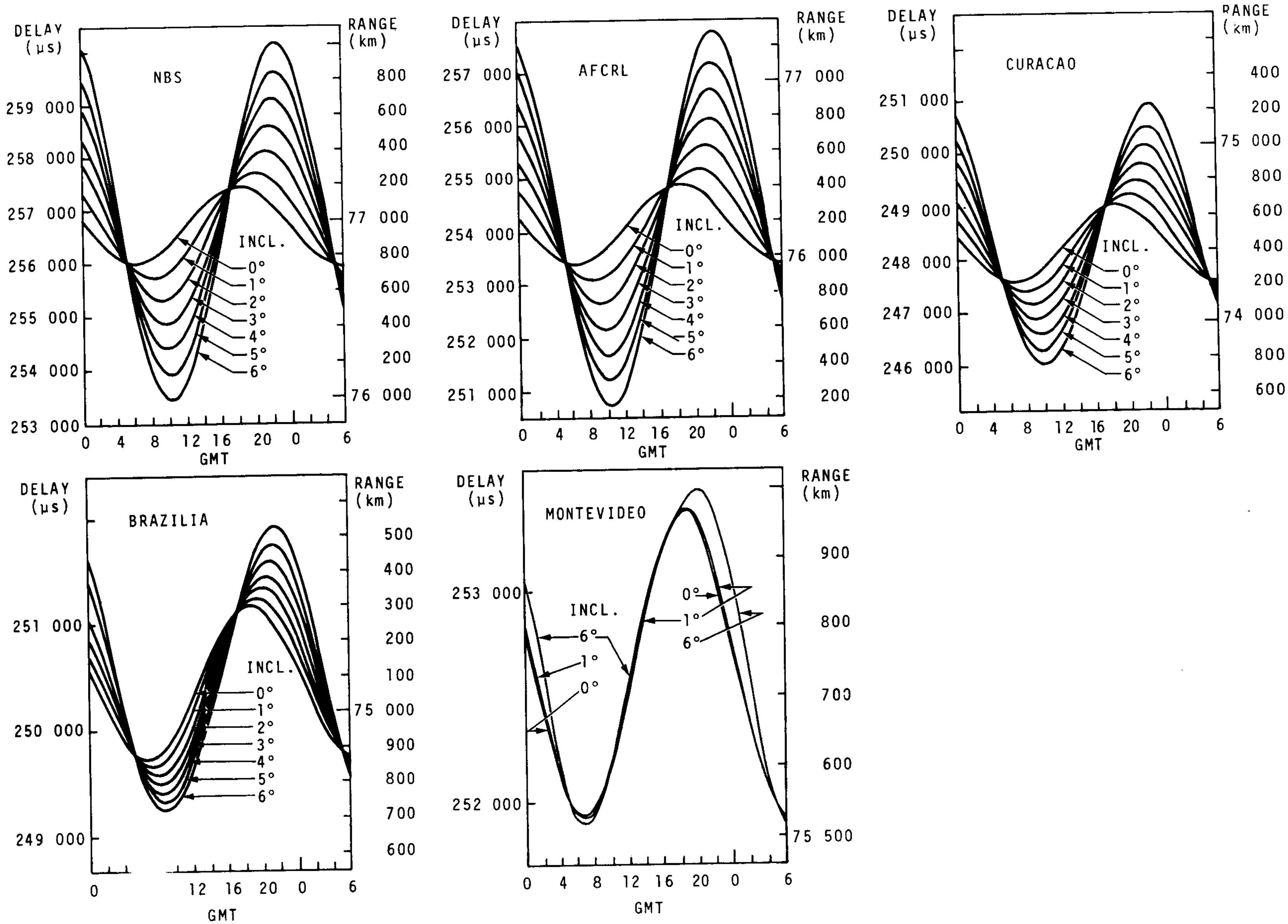


Figure 21. Delays from NBS versus inclination.

Date	November 28, 1972 00H, 00M, 00.0S
Semi-major Axis	42169.53 km
Eccentricity	0.002617
Inclination	3.0889 degrees
Argument of Perigee	23.275 degrees
Right Ascension of Ascending Node	74.632 degrees
Mean Anomaly	258.98 degrees

It is interesting to observe how the subsatellite point moved about the surface of the earth on November 28. Figures 22 and 23 show the subsatellite trace for varying inclinations and eccentricities. These curves are not directly relevant to users of satellite time and frequency signals but are further indications of the satellite's complex motion.

The figures 20 and 21 show the short-term, 24-hour satellite motion. The satellite position was nearly repeated every 24 hours. However, due to effects which become significant in the long term, the satellite drifted longitudinally and its orbit changed its shape and orientation with respect to the earth. Figures 24 and 25 show the measured round trip delay from NBS to NBS via ATS-3 at 1700 and 2330 GMT over a period of several months. It can be seen that day-to-day delay repeated to within 10 or 20 μs but exhibited considerable "drift" over a period of weeks. These two figures also represent the "view" afforded by two "narrow windows" looking at only a very small segment of the total orbit.

There was another perturbation to the satellite's orbit which was intentional. The satellite's drift in longitude, caused by natural perturbations and orbit bias required correction periodically to maintain the satellite's relatively fixed position in the sky. This man made perturbation, called either an orbit or "Δv" maneuver, was initiated by firing small rockets on the satellite for a very brief period. Referring again

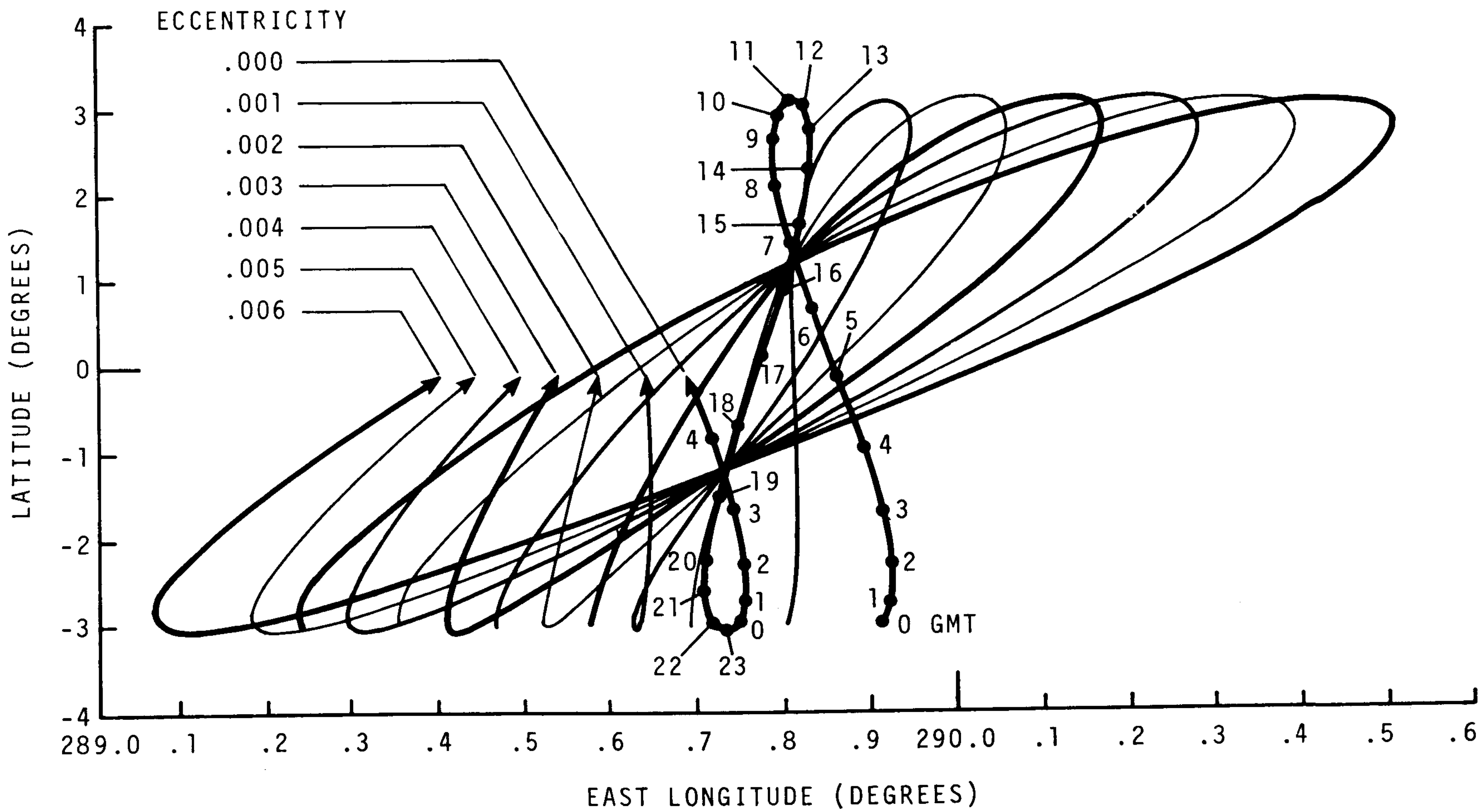


Figure 22. Subsatellite point versus eccentricity.

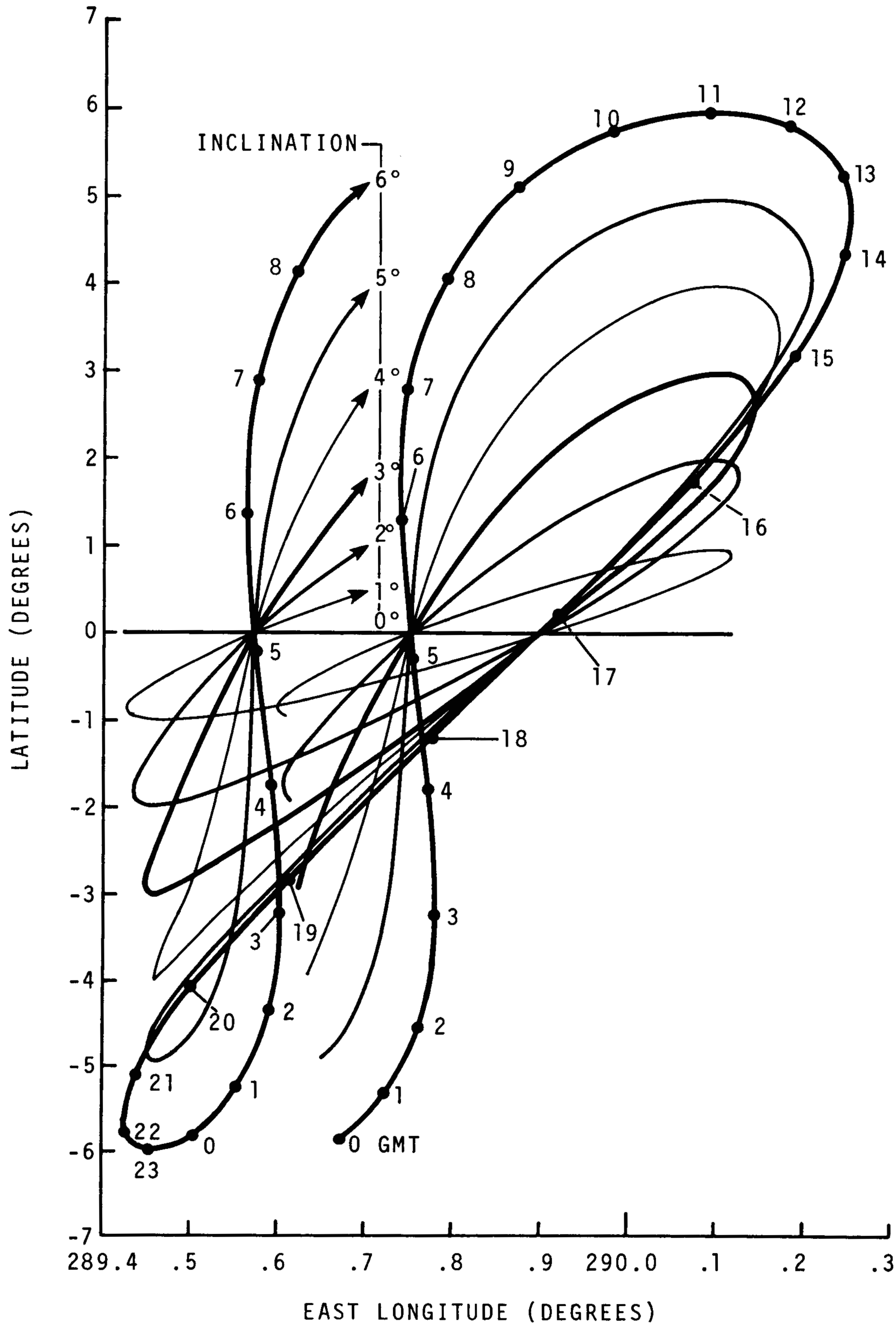


Figure 23. Subsatellite point versus inclination.

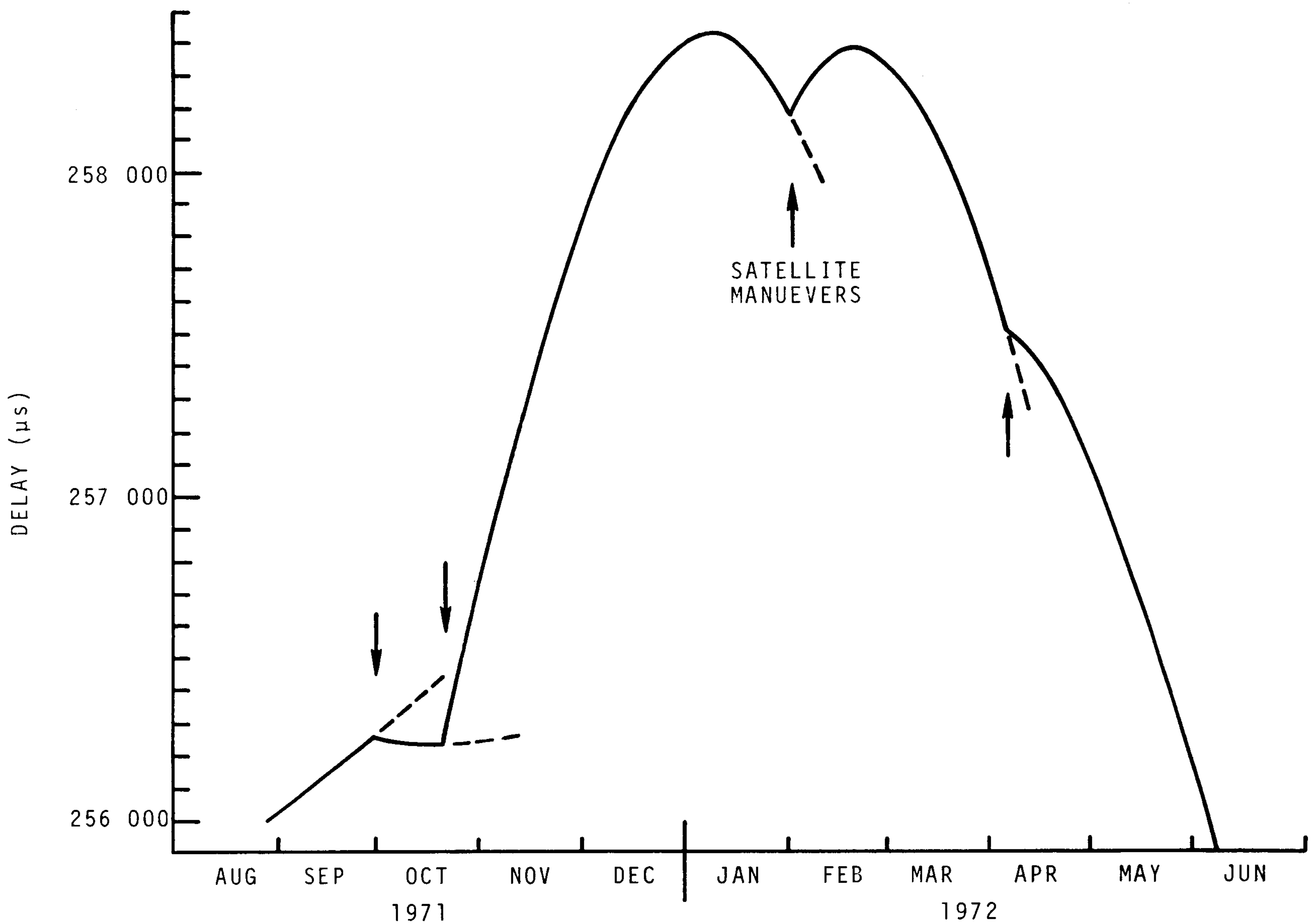


Figure 24. Long-term, two-way delay between Boulder and ATS-3 at 1700 GMT.

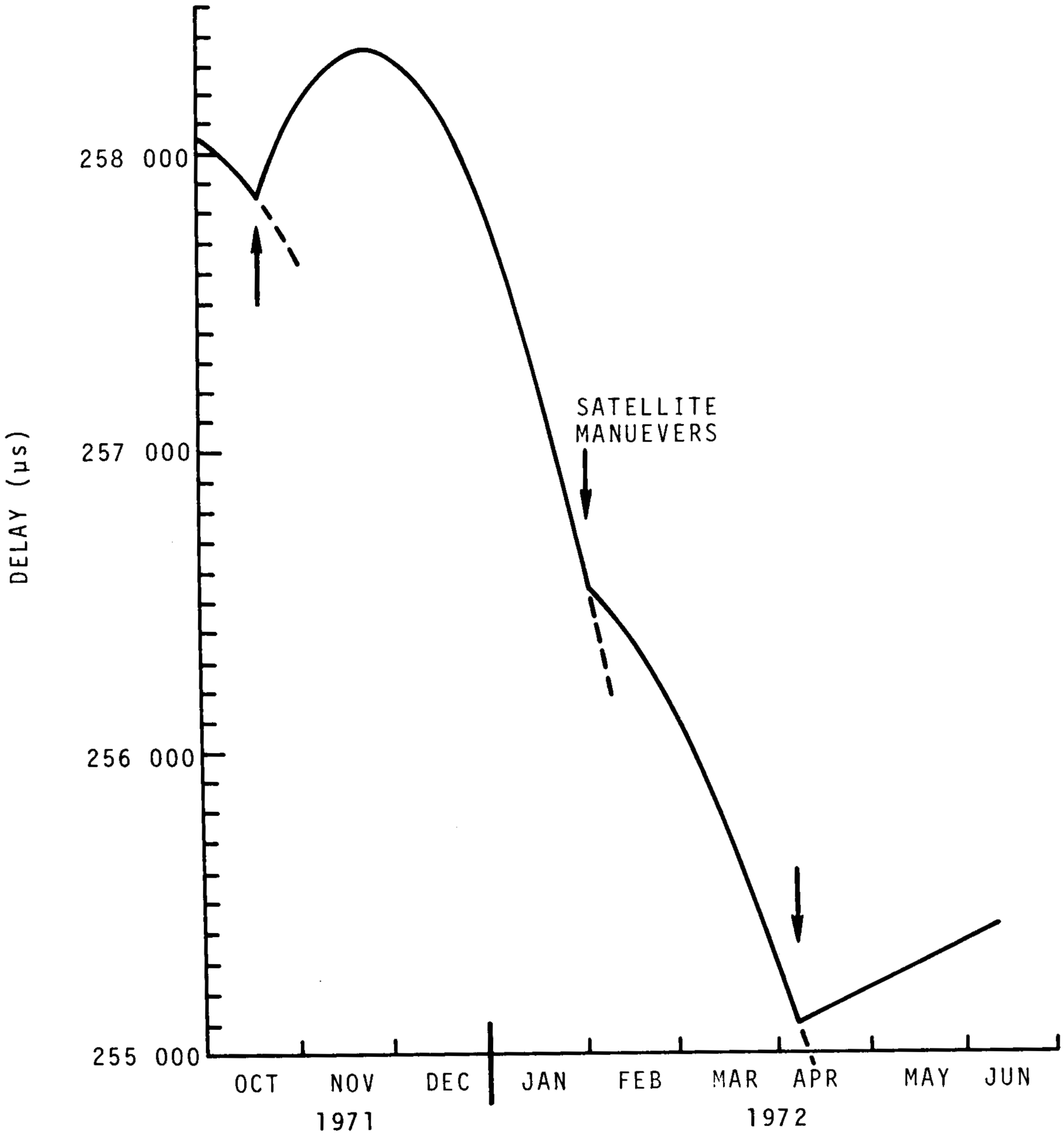


Figure 25. Long-term, two-way delay between Boulder and ATS-3 at 2330 GMT.

to figures 24 and 25 a "Δv" maneuver was performed on February 2, 1972. The results of that maneuver at 1700 and 2330 showed a pronounced change at 1700 and a relatively small change at 2330. This apparent discrepancy was the result of an incomplete picture due to the narrow windows available to the NBS experiment. The obvious point here, however, was that orbit maneuvers are of very great significance to a user of satellite disseminated high accuracy time and frequency information because of the discontinuities in the path delay and orbit prediction.

5.2. IONOSPHERIC AND TROPOSPHERIC DELAY

A small portion of the total path between the earth and the ATS-3 satellite was not in free space. The earth's ionosphere and troposphere reduced the signal velocity from that of free space, thereby adding additional time delay. The additional tropospheric delay was nearly frequency independent and is shown in figure 26. The ionospheric delay, also shown in figure 26 was frequency dependent and nonisotropic. However, for frequencies in the high VHF band and above, anisotropy could be ignored.

The ionspheric delay also varied with time and was dependent upon total ionospheric electron content which was greatest in sun light and decreased by almost a factor of 10 at night. The total ionospheric content for a 24-hour period is shown in figure 27. The associated signal delay increment for that same 24-hour period is also shown in figure 27 for a one-way path at 90° elevation angle at 135.6 MHz. A peak value for integrated electron content of 5×10^{17} electrons/cm^2, typical of the local time of 0900-1500 hours, was assumed in all the computations and results in this report.

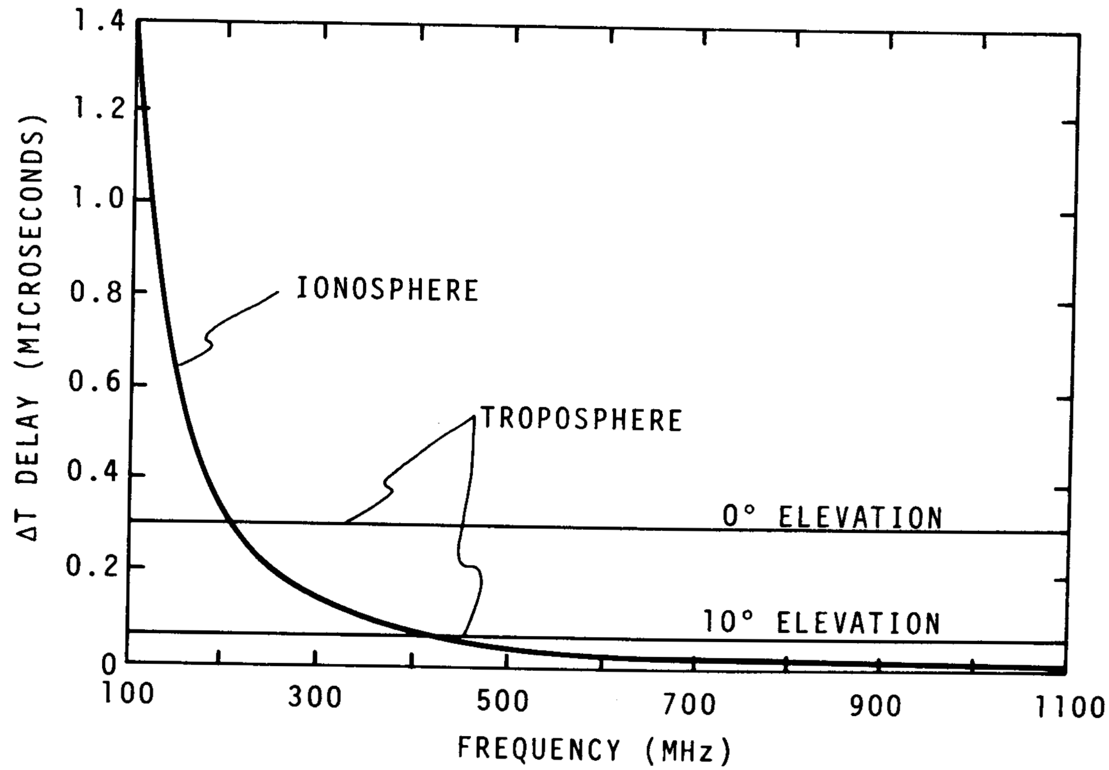


Figure 26. One-way signal delay caused by the troposphere and ionosphere.

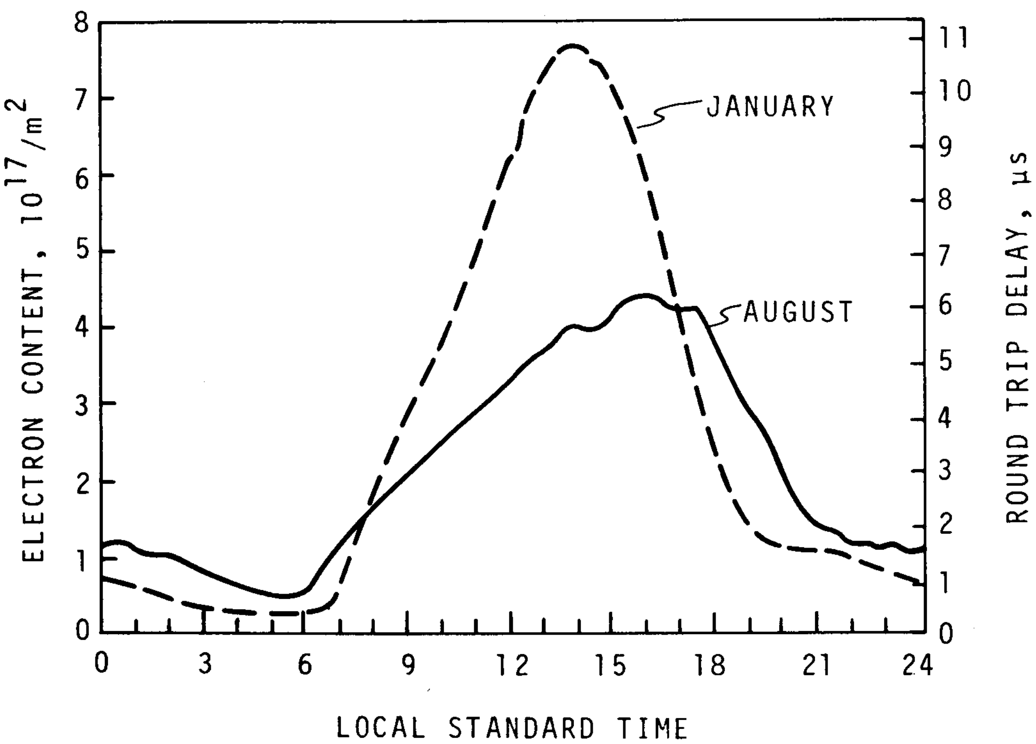


Figure 27. Total ionospheric electron content and associated two-way delay for an average winter and summer month.

5.3. EQUIPMENT DELAY

The time signals experienced added delay when passing through electronic equipment. The ATS-3 transponder, or (more properly) frequency translator, introduced a signal delay of about 7 μs. The format and transmitting equipment at NBS and the user's receiving equipment introduced additional delay. For the carefully controlled receiving equipment at the four NBS-sponsored sites, the total receiver and transmitter delay was measured as part of the calibration procedure. In this way, a more accurate equipment delay value was obtained. The block diagram of the measurement setup is shown in figure 28. The same time and frequency signals used in the broadcast were used for equipment delay measurements and minimized possible effects of distorted waveforms and varied receiver response to different signal waveforms.

Referring again to figure 28, the dashed lines enclose the equipment whose delays were measured. The mixer was substituted in place of the paths between the satellite and earth and the satellite itself. The mixer was broadband and contributed an insignificant amount of delay. The measurement of delay was made at approximately the same signal levels as experienced when receiving the satellite signals; (however, the receiver delay was not very dependent upon signal level).

The measurement's precision was discussed previously. The accuracy of the measurement was dependent upon delay variations in the equipment. Prior to each measurement of the satellite signals at NBS, the equipment delay was measured. These measurements showed the equipment to have acceptably small variations in delay. Statistically, the equipment delays had a 133 μs mean value with an rms deviation from the mean of 2.6 μs. Peak deviations from the mean were less than 10 μs in all cases. A total of 100 consecutive measurements, two a day, were used to obtain the above statistical values.

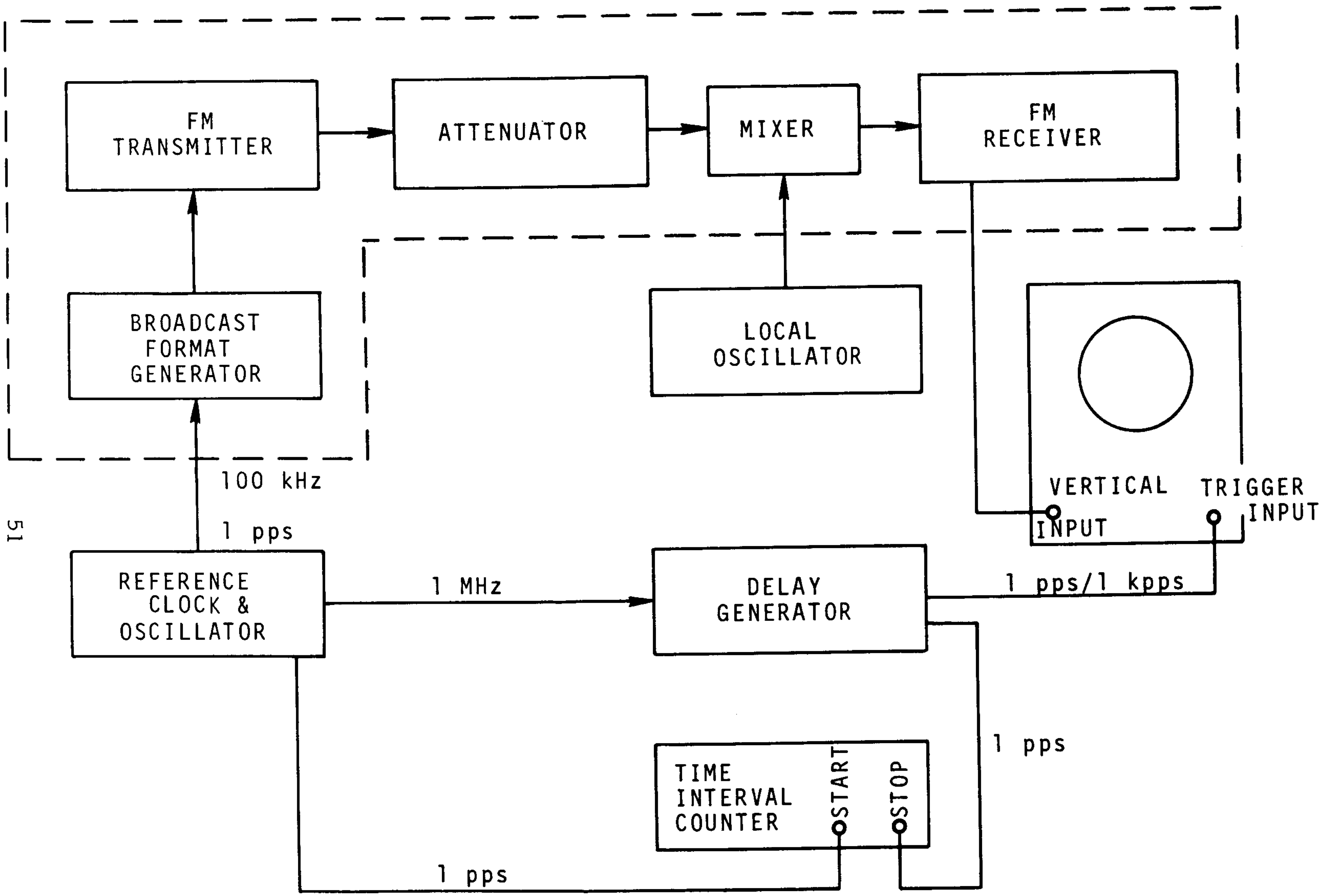


Figure 28. Closed loop system delay measurement, block diagram.

Careful attention to tuning and alignment of the receiver reduced the scatter in the measurements of receiver-transmitter delay. The receivers used in this experiment had their AGC removed and the video inputs to the oscilloscope by-passed iron core transformers. This reduced the receiver delay variation due to signal level changes. All band-pass filters were carefully aligned and the receivers were crystal controlled to reduce delay variations. This was a necessity since signals off frequency were found to have different delays than those on frequency. The limiter was adjusted for symmetrical limiting and the discriminator was carefully aligned.

The receivers used by NBS were not designed to minimize delay variations. Obviously, great improvement can be made in the receiver's performance as related to timing if some relatively simple design details are emphasized.

To enhance the usefulness of any time and frequency broadcast system, the user should be able to measure or compute in his laboratory his receiver's signal delay without great expense or effort. Two methods of achieving this goal were thought to have merit. The first was: If a large number of inexpensive transmitters could be built following one design and if the scatter in the signal delays for these transmitters were small, then they could be used as "standard" transmitters with a uniform delay and used to calibrate the user's receiver delay. The second approach was: Given any FM signal generator and a wideband frequency discriminator, a reference can be established with this discriminator and the receiver delay measured relative to it. If the frequency discriminator was simple to construct and its delay properties were repeatable, it could serve as a "standard" discriminator. Also if the discriminator was broadband, its delay would be small and possibly it could be ignored. Both philosophies were adopted with the understanding that the signals from the "standard" transmitter or FM signal generator would be of the same general character and level as that used for the time and frequency broadcast. In the case of this experiment, the prescribed modulation would be 1 kHz deviated ± 12 kHz.

NBS conducted limited tests on the standard transmitter and broadband discriminator approach with good results. The transmitter was simple in design and no reason was apparent why it could not be specified and built by users with low scatter in its resulting delay properties. Two broadband discriminator designs were tried, also with encouraging results. The combined transmitter-broadband discriminator delays as measured by NBS, amounted to only a few microseconds and indicated its applicability for the user's evaluation of his own equipment. Much of what has been verified at NBS for wideband discriminators was substantiated by a parallel investigation at the Metrology Laboratory of the Naval Avionics Facility at Indianapolis, Indiana.

Although there needs to be more work in this area the solutions do not appear to be difficult.

6. DOPPLER

Because the satellite was in motion relative to points on the earth's surface, frequencies of the satellite relayed signals were Doppler shifted. The carrier frequency of 135.625 MHz was not usable as a standard frequency because the instabilities of the transfer oscillator in the satellite could not be compensated for and the Doppler shift of the carrier was therefore indiscernible from the total frequency shift of the carrier. The only standard frequency tone used in these experiments was the 1 kHz modulation, which was also effected by the Doppler shift.

In general, the Doppler shift for electromagnetic waves in free space may be written as

$$\omega_D = \frac{\omega}{c} \frac{dr}{dt}, \tag{4}$$

where ω_D is the Doppler shift of the oscillator frequency ω. The oscillator is moving towards the observer at the rate of $\frac{dr}{dt}$, and c is the free space velocity of light. This equation applied to the NBS experiment if the oscillator, located at NBS-Boulder, was thought to be moving relative to the observer by virtue of the motion of the satellite. The influence of the Doppler shift on the carrier was to produce frequency modulation. For a frequency modulated signal, v(t), radiated from NBS,

$$v(t) = A \cos (\omega_C t + \frac{\Delta f}{f_M} \sin \omega_M t). \tag{5}$$

where ω_C is the radian frequency of the carrier, Δf is the maximum frequency deviation away from the carrier and is called the frequency deviation, and $\omega_M = 2\pi f_M$ is the radian frequency of the modulating sinusoid. The receiver "sees"

$$v'(t) = B \cos [\omega_C t + \frac{\omega_C}{c} r + \frac{\Delta f}{f_M} (\sin \omega_M t + \frac{\omega_M}{c} r)]. \tag{6}$$

The instantaneous frequency or demodulated signal was

$$s(t) = \omega_C + \frac{\omega_C}{c} \frac{dr}{dt} + 2\pi \Delta f (\cos \omega_M t + \frac{\omega_M}{c} r). \tag{7}$$

After the carrier frequency was filtered out, the post detected signal was

$$s'(t) = \Delta\omega (\cos \omega_M t + \frac{\omega_M}{c} r). \tag{8}$$

The Doppler shift of the modulated signal was then

$$\omega_{DM} = \frac{\omega_M}{c} \frac{dr}{dt} . \tag{9}$$

An expression for $\frac{dr}{dt}$ in the case of the ATS-3 satellite was possible but would not particularly contribute to the scope of this report. It was obvious, however, that since the satellite's position could be predicted with good results on a continuous basis, as will be shown later in the report, the derivative could also be predicted everywhere except at discontinuities such as those which existed with orbit maneuvers.

Figure 29 shows the computed Doppler as seen by an observer at widely selected locations in view of the satellite. The Doppler values were diurnal, as expected, amounting to a few parts in 10^7 in peak values, a significant correction for most frequency measurements.

An alternative method for direct frequency calibrations using the satellite signals was possible from clock synchronizations. As will be shown in this report, time was available from the satellite accurate to about 10 μs. If the oscillator under examination drove a clock and that clock was synchronized by the satellite at an interval of 24 hours, a frequency comparison was in effect, made. The resolution was 10 μs out of a total of $.864 \times 10^{11}$ μs (24 hours) or

$$\frac{\Delta f}{f} = \frac{\Delta t}{t} = \frac{10\ \mu s}{.864 \times 10^{11}\ \mu s} = 1.15 \times 10^{-10}. \tag{10}$$

Figures 30 and 31 provide further information on how variations in eccentricity and inclination affect the Doppler values. All the Doppler curves were again obtained from the ATS-3 orbit of November 28, 1972.

Some data was gathered from a direct frequency comparison of a standard frequency returned by the satellite at NBS. In special tests, a 10 kHz continuous tone, derived from a commercial cesium frequency standard, frequency modulated the transmitted carrier at NBS-Boulder. The frequency deviation of the 10 kHz tone was held low to avoid interfering with the other signals in the format. The satellite-returned 10 kHz

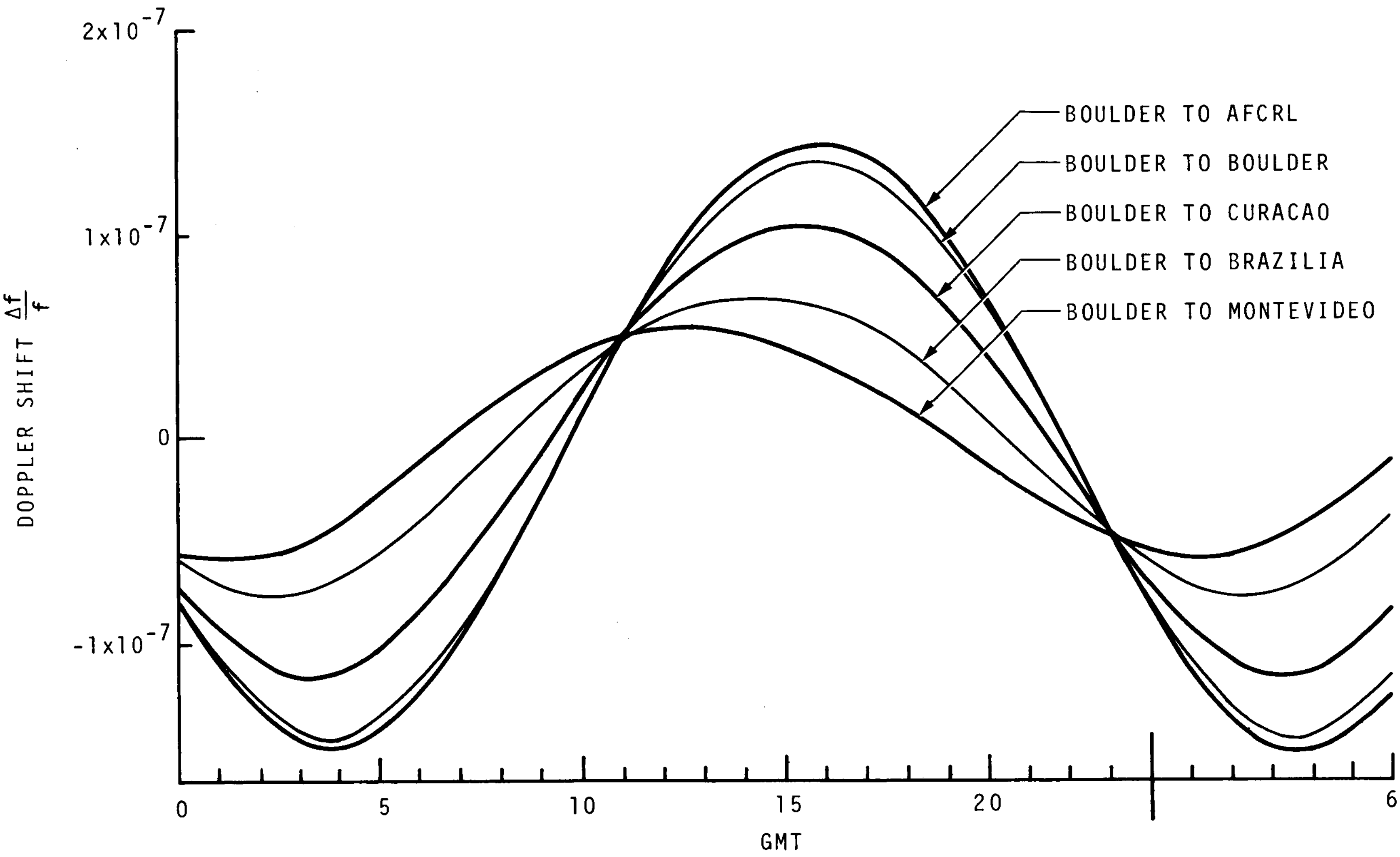


Figure 29. Doppler from Boulder to five sites.

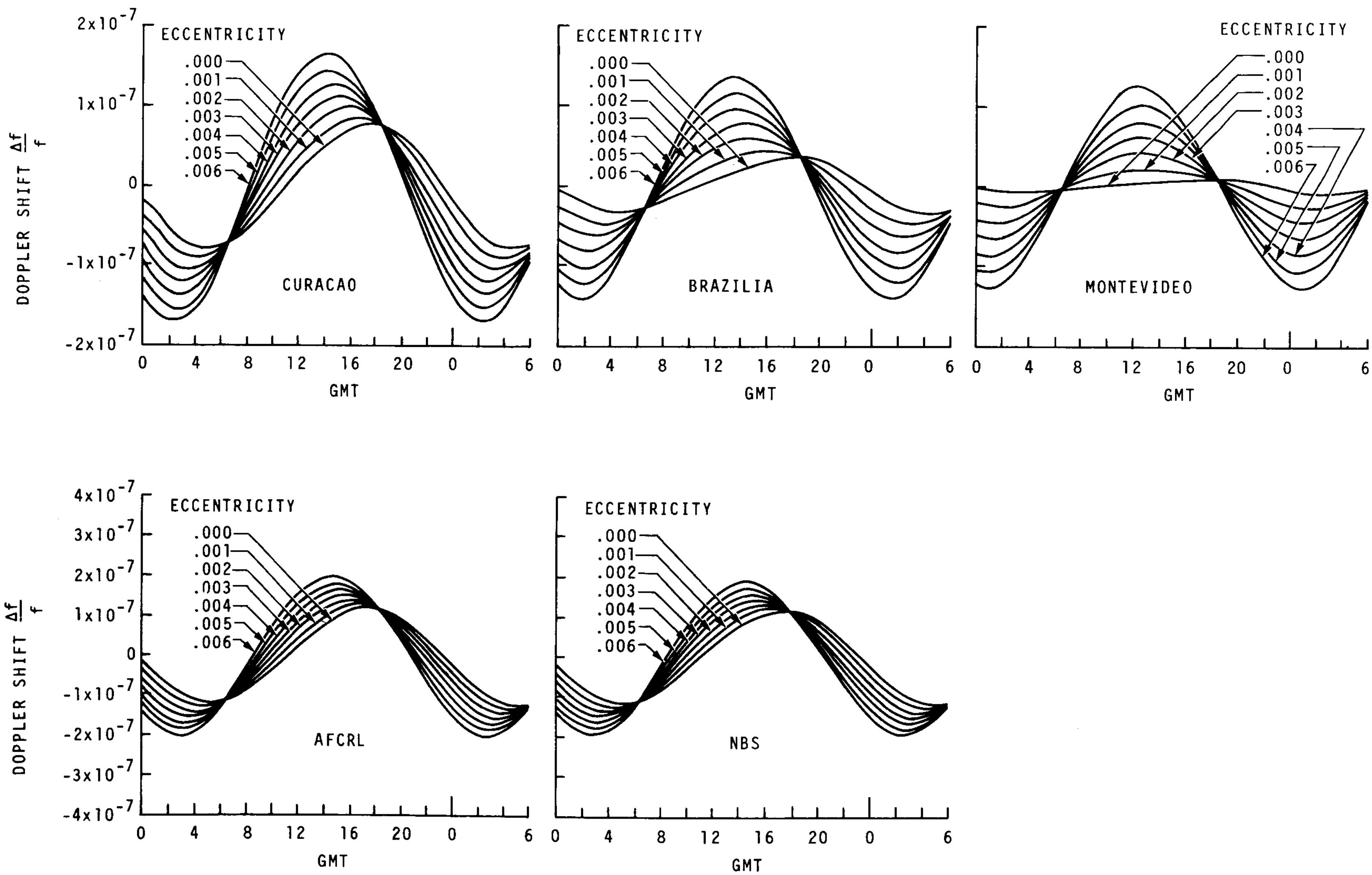


Figure 30. Doppler for signals from NBS via ATS-3 versus eccentricity.

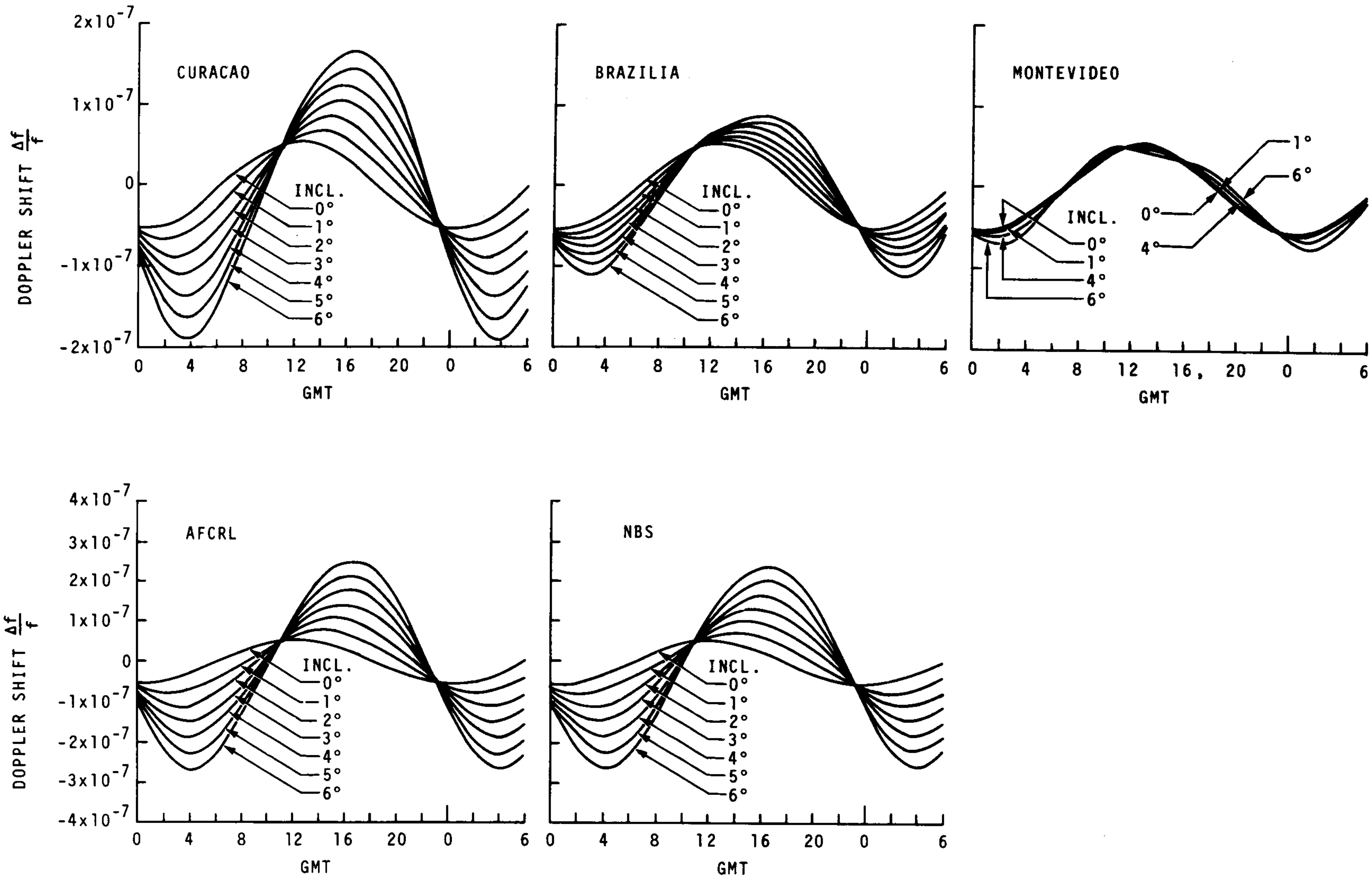


Figure 31. Doppler for signals from NBS via ATS-3 versus inclination.

at Boulder was fed into a phase comparator together with the 10 kHz from the cesium frequency standard and recorded on a paper chart. Because the broadcasts were only for 15-minute periods, the results were essentially linear on the chart representing apparent frequency differences of a few parts in ten million (1×10^{-7}). The results however agreed with predicted Doppler offsets and if a 24-hour record was available, it would no doubt look much like those in figure 29.

7. DELAY COMPUTATION AND CLOCK SYNCHRONIZATION

For high accuracy synchronization of the user's clock, the user had to compute the total signal delay from the master clock at NBS through the transmitting equipment to ATS-3, through its equipment, to his position, and through his equipment. As was shown in previous sections, the propagation path delay was variable. With the satellite moving about and dependent upon many complex forces, a complicated calculation of path delay was necessary, assuming the user began with the fundamental orbital elements. If the user was only interested in time to the nearest second, no calculation was needed other than a mental note to remember that the signals arrived at the earth's surface approximately 1/4 second later.

Even for the higher accuracy, sophisticated, time user, dealing with orbital elements to calculate path delay was deemed to be intolerable. Consequently, NBS developed two computational aids and reduced this burden to an acceptable level which would be available to the user at very little or no cost.

The first of these computational aids was intended for the user who needed intermediate accuracy time or no better than a few milliseconds. This would be the same user who finds the services, in terms of accuracy, from WWV or WWVH adequate. This aid consisted of a transparent delay grid which was placed over an earth map as directed in the ATS-3 satellite time broadcast.

During the experiments, NBS broadcast in voice the satellite's position updated every five minutes, in terms of its longitude and latitude of the subsatellite point and its distance from the earth's center in microseconds relative to a value 119,300 μs. For example, if the radius were 39,827.54 km or 119,400 μs, the "radius correction" was given as + 100 μs. Requiring time, or equivalently the path delay, to only a few milliseconds meant the delay values could be taken from the delay overlay on the earth map with its center superimposed at the subsatellite position. The "radius correction" was not required in using the delay overlays. Figure 32 shows a photograph of the overlay and earth map with the subsatellite point at 71° west longitude and 2.8° south latitude. Because the satellite's position repeated itself every 24 hours to within 10 or 20 μs (see figs. 24 and 25), the positions of the overlays were valid for a particular time of day for several weeks provided only millisecond accuracy was required. Two of these overlays, one for the 1700 GMT broadcast and one for the 2330 GMT broadcast, were published monthly in the NBS Time and Frequency Services Bulletin. Also published was the antenna pointing information shown in figure 11, which provided the user with the proper azimuth and elevation for pointing an antenna at the ATS-3 satellite. These overlays were updated for each monthly publication and provided users a simple means for obtaining path delay values. As an example, assume that the user was in Washington, D. C. From figure 32, it may be seen that the delay from NBS-Boulder to ATS-3, represented by the cross at 71° west longitude and 3.2° south latitude, was 128.9 ms. (NBS-Boulder is at 105° west longitude and 40° north latitude.) The delay from ATS-3 to Washington, D. C., 77° west longitude and 39° north latitude, was 126.1 ms. The total delay from NBS-Boulder to Washington, D. C., was the sum of these two delays or 255.0 ms.

Because the overlays could not provide path delays accurate to a few microseconds, a circular slide rule was designed to fulfill that need.

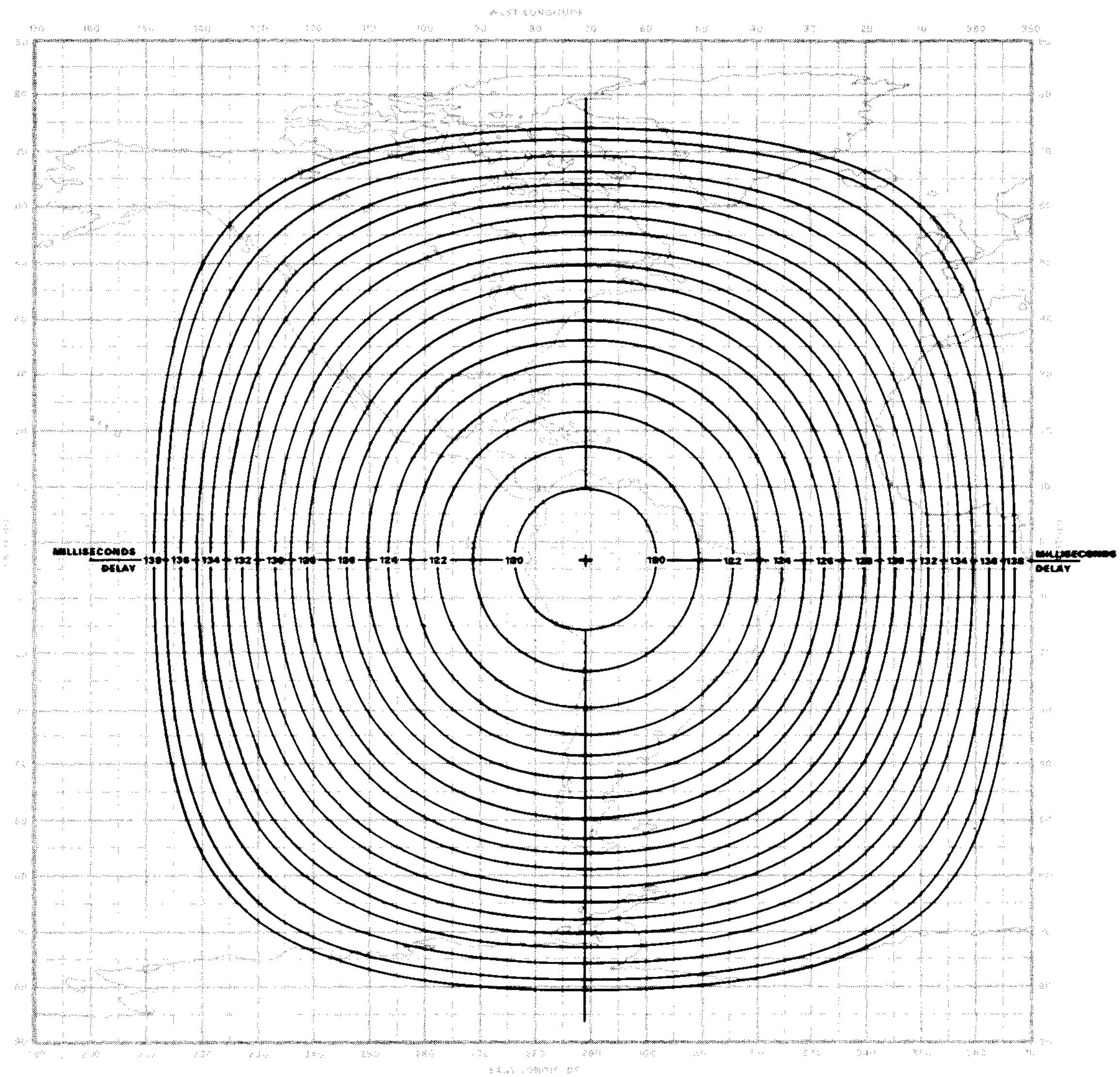


Figure 32. Propagation delay overlay at 2330 GMT.

The slide rule along with the experiment brochure is shown in figure 33. A cut-out version of the slide rule is provided in the appendix. A simple device such as this one was possible because NBS had assumed the major part of the computational burden by announcing the satellite's position. Only a simple geometric calculation, designed into the slide rule, remained to be performed by the user. The user, knowing his position, (easily obtained from maps to the desired accuracy), the satellite's location, and the location of the NBS transmitter, computed values of longitude and latitude relative to the subsatellite point. He then computed the initial path delay to which he added an oblateness and radius correction to obtain the free space path delay from NBS-Boulder to his location via the ATS-3 satellite. Adding in the delays due to the earth's atmosphere, satellite and receiving equipment yield the total signal delay.

The user computed his clock error or difference as,

$$\text{Clock error} = \text{Apparent delay} - \text{Equipment delay} - \text{Signal delay} - \text{Cycle correction.} \qquad (11)$$

The apparent delay was the value of delay measured, for example, with the time interval counter shown in figure 9 and explained in Section 4. As with the overlays, two computations were required with the slide rule, one for the up-link from NBS-Boulder to the satellite and the other the down-link or the satellite to the user. To illustrate the use of the slide rule and equation (11) the following example is included with an additional example in Appendix I. The reader may cut out the slide rule in the appendix to follow the examples.

The following are the locations of the transmitter, satellite, and user. The transmitter location was fixed. The satellite position was made known to the user via the satellite broadcast. The user found his longitude and latitude from a map.

Figure 33. Slide rule and experiment brochure.

	Longitude	Latitude	Radius Correction
NBS-Boulder	105.26°W	40.00°N	NA
Satellite	70.37°W	2.25°N	135 μs
User	56.11°W	47.85°N	NA

The user during or adjacent to the satellite position announcement measured the arrival of the ATS-3 transmitted tick relative to his clock in the manner similar to that described in Section 4. From the time interval counter he read an apparent delay of 257716 μs.

The user then performed the free space path delay calculation instructions on the slide rule as shown in table 3.

Substituting into eq (11) the previously determined transmitter-receiver delay of 133 μs and a cycle correction of 2500 μs caused by measuring at the center of the tick the clock error was found to be 62 μs, or equivalently,

NBS (UTC) - User Clock = 62 μs.

The user's clock lagged or was late relative to the NBS (UTC) master clock by 62 μs. The expected precision of this measurement was dealt with in Section 4. The same calculation, including the slide rule function, was developed into a simple computer program in the BASIC language which could be used in small computer facilities. That program is listed in Appendix III.

8. RESULTS

As a means of evaluating the performance of the ATS-3 time and frequency dissemination experiment, NBS set up four observation sites. These sites were selected to be as widely dispersed about the

Table 3

Signal Delay Calculations

	Down-link	Up-link
1. Satellite Longitude	70.37°W	70.37°W
2. Earth Station Longitude	56.11°W	105.26°W
3. Relative Longitude (absolute value of 1 minus 2)	14.26°	34.89°
4. Corrected Satellite Latitude (step 1)	2.32°N	2.75°N
5. Earth Station Latitude	47.85°N	40.00°N
6. Relative Latitude (line 5 minus line 4)	45.53°	37.25°
7. Uncorrected Relay (step 2)	127030 μs	127670 μs
8. Oblateness Correction (step 3)	22 μs	15 μs
9. Radius Correction (step 4)	135 μs	135 μs
10. Free Space Path Delay (sum of lines 7, 8, and 9)	127187 μs	127820 μs
11. Total Free Space Path Delay (sum of up-link and down-link on line 10; step 5)	255007 μs	
12. Ionosphere and Troposphere Delay	14 μs	
13. Total Path Delay (sums of lines 11 and 12)	255021 μs	

subsatellite point as possible. These sites were NBS-Boulder (which was also the location of the transmitter), Air Force Cambridge Research Laboratory (AFCRL) in Massachusetts, and the Smithsonian Astrophysical Observatory (SAO) sites in Arequipa, Peru, and Natal, Brazil. Each site was equipped with a receiving system similar to that illustrated in figure 9. Each site had a high accuracy time reference to UTC. NBS generated UTC and acted as the master clock with all signals sent to the satellite being derived from the NBS Frequency Standard and UTC (NBS) time scale. See figure 2 for illustration of this relationship. AFCRL maintained its time with a commercial cesium beam clock referenced to UTC through LORAN-C monitoring and portable clock carries by standards laboratories of DoD. Arequipa, and Natal, also had cesium clocks for reference and were synchronized by portable clock carries from NBS with frequency "steering" from VLF monitoring of the Navy station, NBA at Balboa, Canal Zone.

Each site measured the arrival of the time signals from ATS-3 relative to its local clock. Because each site's clock was previously synchronized to the master clock at NBS, the measured arrival time was equal to the total signal delay between the transmitter and the site. These measured signal delays were compared to computed values derived from orbital elements and complete descriptions of perturbative forces. The results of these comparisons represented, in part, the merit of the system or how well equipment delays could be measured and signal delays predicted. These results are shown in figures 34 through 37. There are gaps in the data resulting from weekends, holidays, poor orbital elements caused by reduced tracking capabilities when the NASA tracking sites were being modified, clock failures at the sites, and cancelled broadcasts to allow for satellite participation in APOLLO recovery operations.

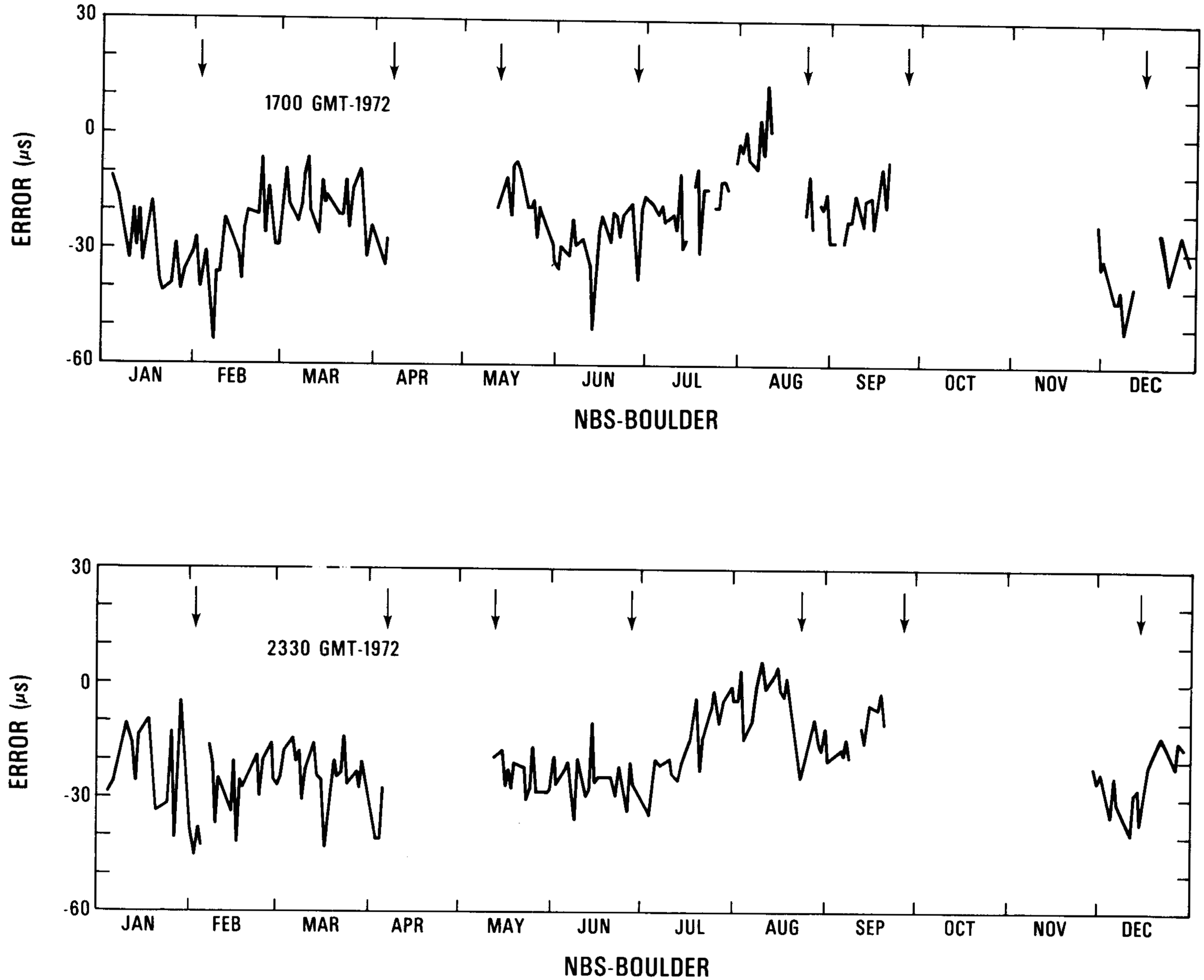


Figure 34. Delay error at NBS-Boulder.

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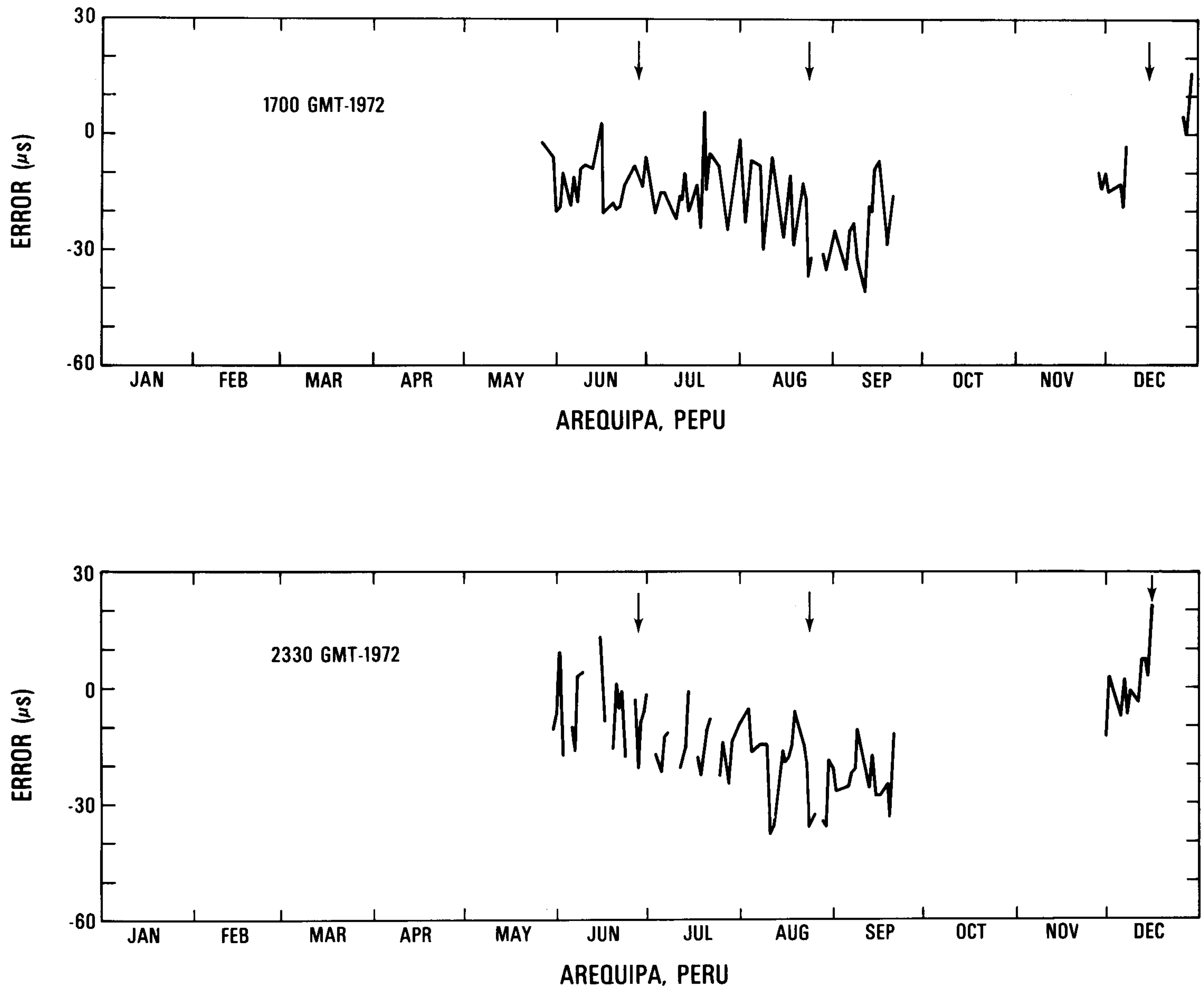

Figure 35. Delay error at Arequipa, Peru.

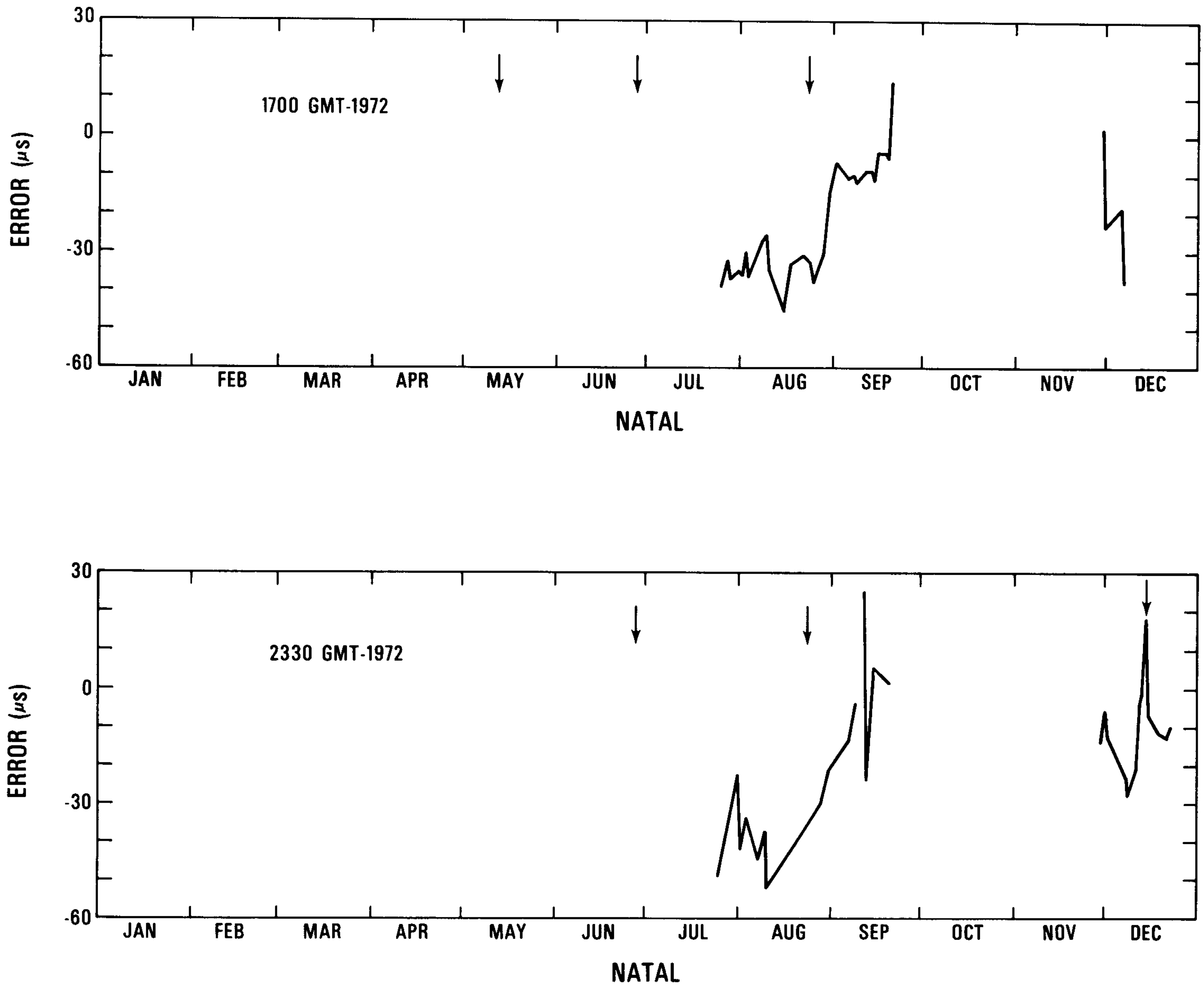

Figure 36. Delay error at Natal, Brazil.

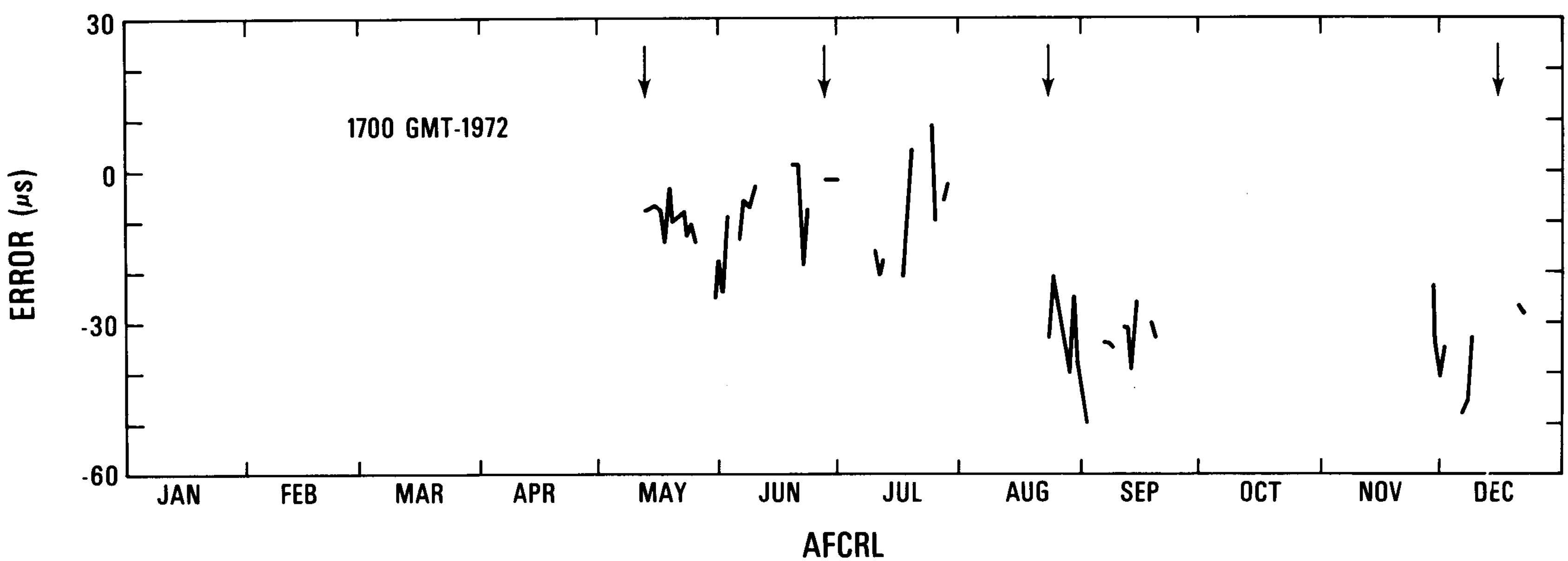

Figure 37. Delay error at AFCRL.

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The data shows a resolution of approximately ± 10 μs. There were also some apparent systematic errors which appeared as offsets to the data from the zero error line. These systematic errors were thought to be due to errors in the orbital elements or in the program which includes perturbative effects. An error in the values used for equipment delay in the receiver or transmitter was also a possibility.

There was also seen a general slope to some of the results which was also believed to be caused by the orbital elements. This belief was substantiated by the fact that discontinuities existed in the results when the orbital elements used for prediction were changed. The arrows at the top of the figures indicate the date of the orbital elements where new predictions began. As an example, in figure 34, the orbital elements for the later part of June were used for prediction until new elements were generated in late August. It was natural not to see the same error magnitudes at all sites since the errors in the satellite's orbit were not manifested in the same direction or magnitude at all points on the earth's surface.

9. SYSTEM PERFORMANCE COMPARISON

It has already been indicated how the satellite experiment performed in terms of accuracy. The purpose of this section is to inform the reader how this experimental system compared with other systems which, at that time, were carrying time and frequency information. Primarily the comparison was made with the NBS high frequency stations, WWV and WWVH. It could be said that such a comparison was unfair or out of order because of fundamental differences in the two systems. For instance, the WWV broadcasts use high frequency propagation at 2.5, 5.0, 10.0, 15.0, 20.0, and 25.0 MHz with the earth and ionosphere acting as guiding or reflecting boundaries, whereas the satellite operated at 135 MHz in line-of-sight paths. There were similarities between the two systems, however.

Both used a similar format and WWV and WWVH were the only complete, civilian oriented, time and frequency service in operation for what the satellite experiment was attempting to duplicate by virtue of its wide range of application and simplicity.

9.1. COVERAGE

Shown in figure 38 are the approximate coverages of the ATS-3 satellite, WWV and WWVH. WWV was located at Fort Collins, Colorado, and WWVH was at Kauai, Hawaii. The satellite coverage had very definite boundaries as shown. Inside the boundary the signal was always available at about the same signal levels without noticeable signal fades and with the same available accuracy. The boundaries shown for WWV and WWVH were not as well defined. The signal strength and accuracy available from these two stations were variable. Factors involved included the sunspot cycle, the radio path and whether or not the path was in darkness or daylight, the number of hops involved in the propagation of the signal, the choice of frequency, and the accuracy for which the propagation path length was known. The only really definitive comment which could be made was that the signal was available within those boundaries most of the time (95%) and at varying levels of accuracy dependent upon conditions.

9.2. RESOLUTION AND ACCURACY

It can be estimated from the results that the accuracy and precision for the satellite time signals were approximately 25 μs and 10 μs respectively. It has been generally accepted that WWV and WWVH can offer timing accuracies and resolution of 1 ms and 0.3 ms respectively. With all conditions ideal, those figures may be somewhat improved upon; however, a user would be faced with a difficult task recognizing when conditions were ideal.

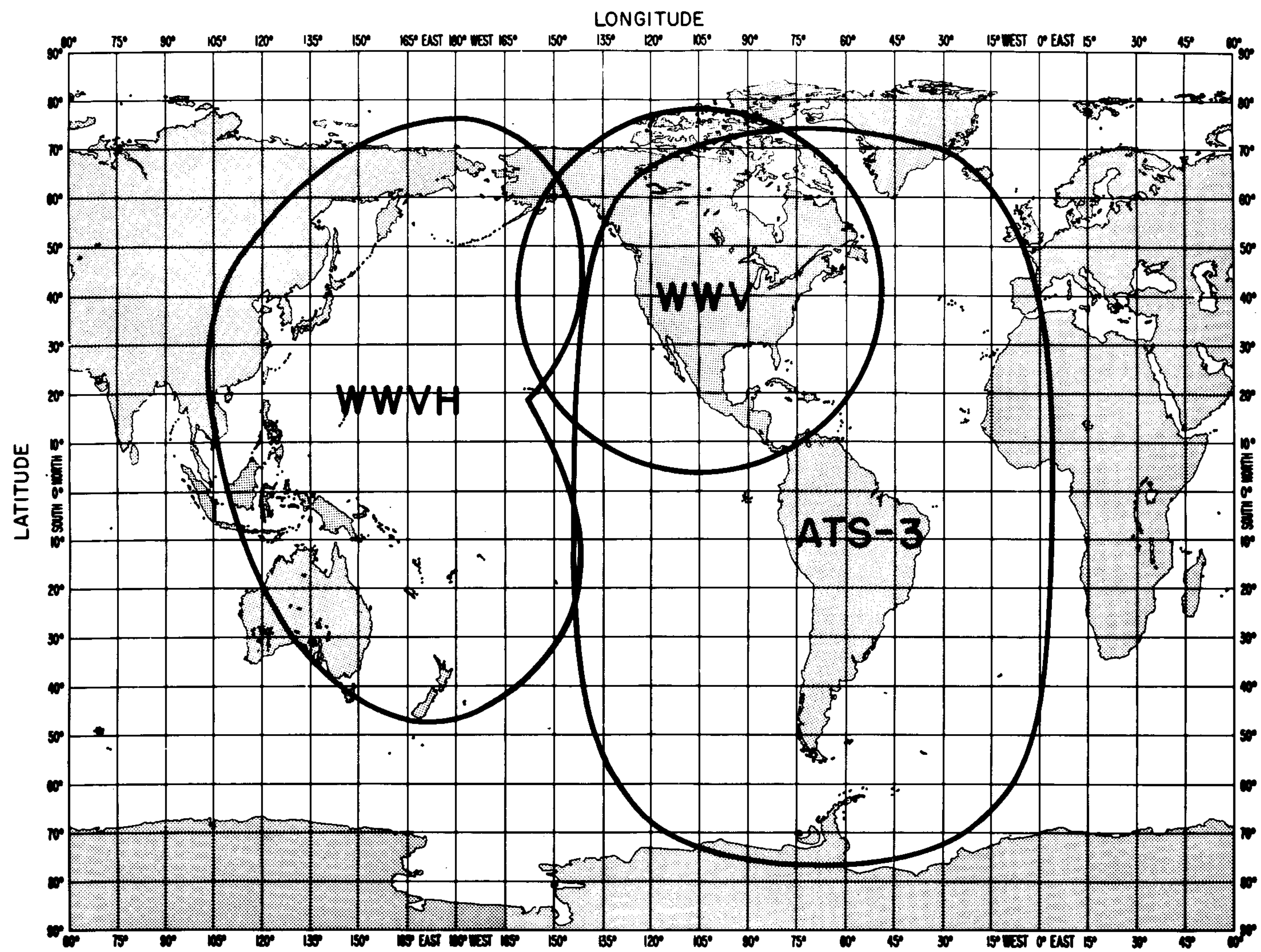

Figure 38. Coverage showing reliability of reception (95% or better) for WWV, WWVH, and ATS-3.

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One may obtain from figure 39 some additional feeling for the timing resolutions available from the two systems. Shown are 5 and 10 sweeps, of the WWV and ATS-3 ticks. The resolution for WWV appeared to be poorer than 100 μs and was limited by noise and path delay variations. The resolution for ATS-3 was estimated to be approximately 10 μs. A major limiting factor to timing accuracy from WWV was path delay variations and is shown in figure 40, see reference [13]. Here the delays for nearly nine consecutive months between WWVH and Greenbelt, Maryland, are shown. Monthly means are shown, all different with peak-to-peak variations during the nine-month period of more than 2 ms.

The comparisons between WWV or WWVH and ATS-3 are summarized in table 4.

Some of the difficulties of time recovery can be appreciated from the photos in figure 41. Shown are oscilloscope displays of the tick at different sweep speeds. The sequence of these photographs are in the order usually taken to acquire and measure the time of arrival of ticks with high time resolution. The ATS-3 tick was easier to distinguish from the noise and the signals as well as being much less distorted.

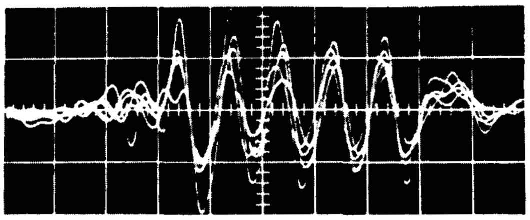
Finally, a comparison of all existing and proposed dissemination systems is shown in table 5. Some of these systems were operational, some experimental, at the time this comparison was made.

10. CONCLUDING REMARKS

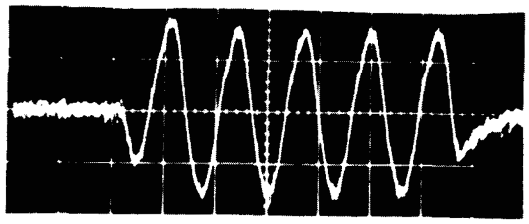
This report has described an experiment which revealed many of the potentials of and problem areas associated with the broadcasting of time and frequency information from geostationary satellites. A broadcast format very similar to the WWV format was used with effectiveness. Assuming that this format was ideal and optimum for terrestrial HF broadcasts, satellite-VHF broadcasts demand changes or modifications

WWV *

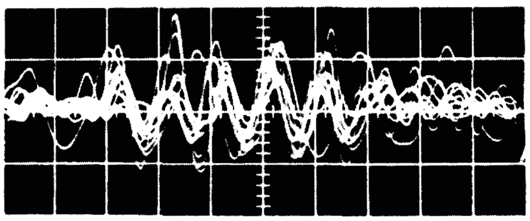
ATS-3



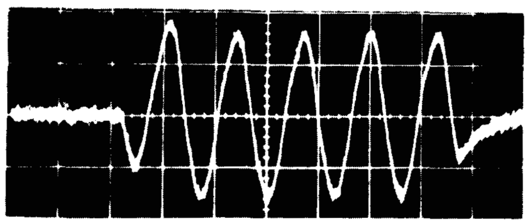
five sweeps



five sweeps



ten sweeps



ten sweeps

*Reproduced from Hewlett-Packard Applications Note 52 by permission.

Figure 39. Multiple oscilloscope sweeps of the WWV and ATS-3 ticks.

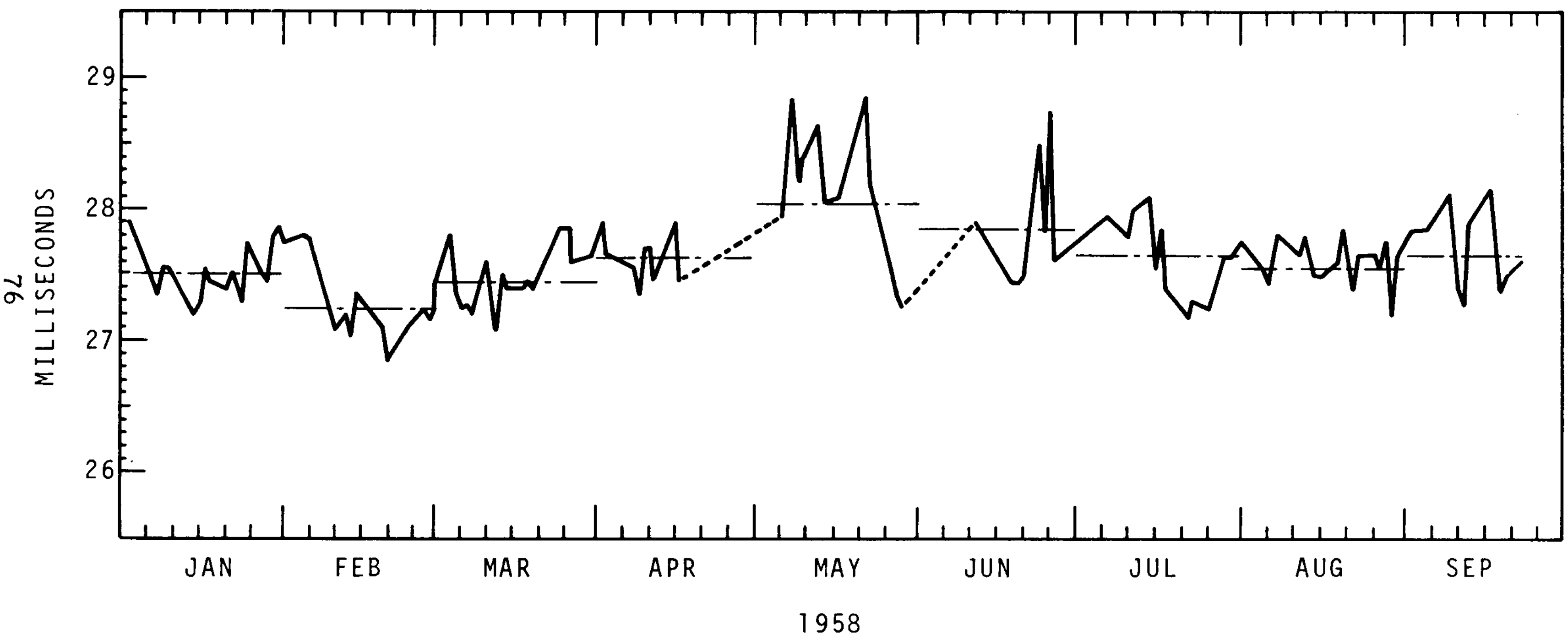


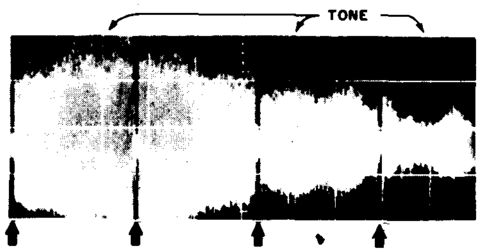
Figure 40. Measured HF delay path from WWVH Maui, Hawaii, to Greenbelt, Maryland.

Table 4

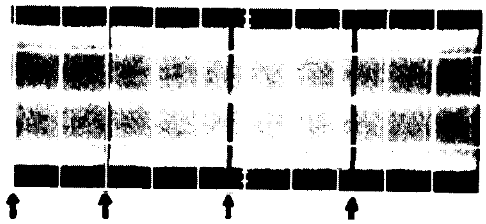
WWV and ATS-3 Performance Summary

	WWV or WWVH	ATS-3
Coverage (continuous non-interrupted)	10-15%	40% of earth
Cost to user (receiver and antenna)	$100-500	$100-500
Resolution	0.3 ms	10 μs
Accuracy	1 ms	25 μs
Path delay computations	Complex	Simple
Time recovery technique	Medium Complexity	Simple

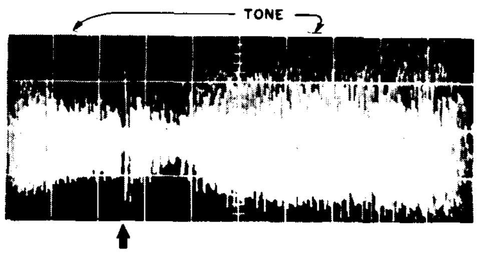
WWV * | ATS-3



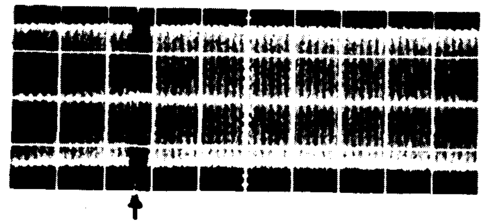
sweep speed ≈ 0.3 s/cm



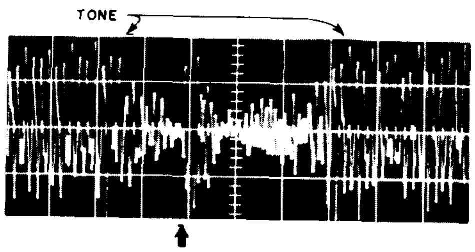
sweep speed 0.3 s/cm



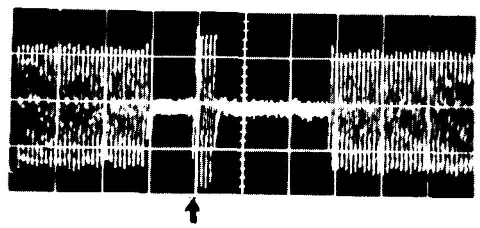
sweep speed 0.1 s/cm



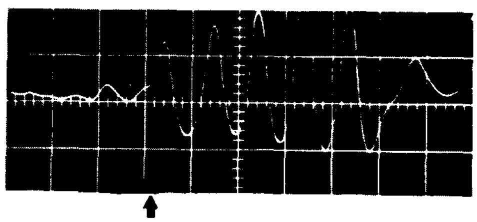
sweep speed 0.1 s/cm



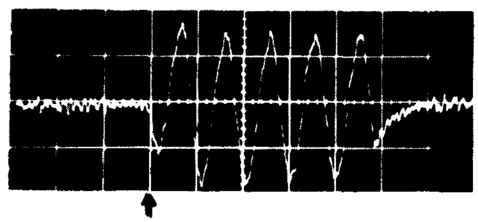
sweep speed 10 ms/cm



sweep speed 10 ms/cm



sweep speed 1 ms/cm



sweep speed 1 ms/cm

Note: Arrow points to leading edge of tick.

*Reproduced from Hewlett-Packard Applications Note 52-by permission.

Figure 41. Acquiring the ticks from WWV and ATS-3.

Table 5

Comparisons of Dissemination Systems

DISSEMINATION	TECHNIQUES	STATUS(1)	ACCURACY-FREQUENCY SYNCHRONIZATION	ACCURACY FOR DATE TRANSFER	AMBIGUITY(4)	COVERAGE FOR STATED ACCURACY	% OF TIME AVAILABLE	RELIABILITY	RECEIVER COST FOR STATED ACCURACY	COST PER CALIBRATION	NUMBER OF USERS THAT CAN BE SERVED	OPERATOR SKILL REQUIRED FOR STATED ACCURACY
VLF RADIO	COMMUNICATION/SFB GBR, NBA, WWVL	0	1×10^{11} (3)	[illegible]	PHASE ~50 μs	GLOBAL						
	NAVIGATION SYSTEM OMEGA	O/P	$<1\times10^{11}$ (3)	≤ 10 μs■	PROPOSED CODE 1 YR / PHASE ~100 μs	GLOBAL			MODERATE			TIME CODE
LF RADIO	STANDARD FREQ. BROADCAST (WWVB)	0	1×10^{11} (PHASE 24h) (3)	[illegible]	1 YR	[illegible]			[illegible]		[illegible]	
	NAVIGATION SYSTEM LORAN-C	0	1×10^{12} GND (3)	~1 μs(GND) 50 μs(SKY)	50ms / PHASE 10 μs	[illegible] ◆ AREAS					[illegible]	
HF/MF RADIO	STANDARD FREQ. BROADCASTS (WWV)	0	[illegible]	1000 μs	1 DAY / 0.5 min	HEMISPHERE		[illegible]				
	NAVIGATION SYSTEM LORAN A	0		2.5 μs NOT UTC		LIMITED AREAS		[illegible]			SPECIAL AREAS	
TELEVISION (VHF/SHF RADIO)	PASSIVE LINE 10	0	1×10^{11} (24h)	~1 μs	1 DAY / ~33ms	NETWORK COVERAGE	"LIVE" PROGRAMS				USA FOR EXAMPLE	
	ACTIVE LINE 1 (NBS TV TIME SYSTEM)	E	1×10^{11} (< 30 min)	< 100ns▲	1 DAY / ~33ms	NETWORK COVERAGE					USA FOR EXAMPLE	
SATELLITES (VHF/UHF/SHF RADIO)	STATIONARY SATELLITES (TRANSPONDER) ONE WAY	E/O	[illegible]	[illegible]	DEPENDS ON FORMAT	HEMISPHERE	STATIONARY					
	STATIONARY SATELLITES (TRANSPONDER) TWO WAY	E/O	1×10^{12} (24h)	~100ns	DEPENDS ON FORMAT	HEMISPHERE				MODERATE		
	ON BOARD CLOCK (ACTIVE) ONE WAY LOW ALTITUDE	0	[illegible]	0.5-50 μs	DEPENDS ON FORMAT	WORLD	10-15 min PER PASS 2-4 PER DAY	[illegible]				
SHF RADIO	MICROWAVE	E/O	~1×10^{13} (PER WEEK)	≤ 100ns	PHASE COMPARISON	LOCAL LINKS						
	VLBI	P	5×10^{14}	~1ns	DEPENDS ON FORMAT	HEMISPHERE	AS NEEDED					
PORTABLE CLOCKS	PHYSICAL TRANSFER	0	1×10^{12}	100ns●	1 DAY	LIMITED BY TRANSPORTATION	AS NEEDED		NONE			
	AIRCRAFT FLYOVER 2 WAY	E	1×10^{12}	≤ 100ns	DEPENDS ON FORMAT	LIMITED BY TRANSPORTATION	AS NEEDED					
PULSARS	OPTICAL SIGNAL → NP 0532	P	1×10^{10}	~10 μs	~33ms	HEMISPHERE	NIGHTTIME					
AC POWER LINE	POWER NETWORK SYSTEM	P	[illegible]	~1ms	16.7ms	CONTINENTAL USA			MINIMAL	MINIMAL	[illegible]	

GOOD (white) FAIR (grey) POOR (black)

NOTES: (1) Status of technique indicated as follows: O–Operational; P–Proposed; E/O–Experimental operational. (2) Estimates of day-to-day measurements within 2000 km(1250 mi) of Loran-A stations. These emissions not coordinated with UTC and manually operated crystal clocks drift. (3) From day-to-day phase measurements e.g., 1 μs per day phase change approximates 1 pt. in 10^{11} in frequency difference. (4) Left-hand designation gives the shortest time interval that cannot be resolved; Right-hand number gives basic ambiguity. ◆, by ground wave 1600 km; by sky wave thousands of kilometers depending upon conditions. ■, with proposed time code. ●, closure after 1 day. ▲, within local service area of TV transmitter and path delay known.

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to that format to maintain an optimum design by virtue of one or more of the satellite's fundamental differences with HF broadcasts. Those differences were higher signal-to-noise ratios, excellent short-term propagation path stability, wider available rf bandwidths, and freedom from fading and other propagation anomalies. These were characteristics observed in the experiment but not capitalized upon by changes in format during the experiment. The experiment only noted and documented these differences for consideration in later studies which may be directed towards establishing a satellite time and frequency service.

Another fundamental difference with HF broadcasts noted in this experiment was the long-term changing propagation path due to satellite motion. This difference was found to be of real significance to the intermediate and high accuracy time and frequency user. It was demonstrated, however, that satellite movement could be dealt with in a simple and inexpensive manner using special purpose user aids like the slide rule and delay overlays.

Although the level of operation obtained in the experiment was not fully satisfactory for a national service such as provided by WWV, it was indeed obvious that satellites are a very real candidate to meet the growing needs for higher accuracy and more reliable time and frequency signals. The experiment provided much of the insight necessary to specify and direct further work to develop the level of competence required for such a service.

Specifically, the experiment demonstrated the superiority and suitability of satellite broadcasts through the following areas:

1. Using a moderate receiving bandwidth and power, a potential accuracy of 10 μs or better was indicated and, in some periods of the experiment, achieved.

2. The signals were highly reliable in that they were available to 40% of the earth's surface without interruption due to fading or other propagation anomalies. This implied a continuous uninterrupted performance to the full coverage area of a permanent service.

3. The cost of user equipment was inexpensive and not substantially different from the equipment required for the reception of the NBS stations WWV and WWVH.

4. To realize the high-accuracy timing potential, only very simple delay calculations were required and were readily satisfied by the simple and inexpensive circular slide rule.

5. Considerable interest existed in the time and frequency community for a satellite service as evidenced by the over 9000 inquiries about the experiment.

6. The time recovery techniques were basically identical to those used with WWV or WWVH except that greater path predictability and higher sampling rates enhanced the user's ability for time recovery and reduced his involvement to obtain the highest accuracy.

7. The signal quality was in every respect superior to the WWV/WWVH broadcasts and resulted in a clearer voice channel.

Satellites could easily satisfy the growing needs of the nation for a higher quality, more reliable, and more flexible time and frequency information source. The availability of satellite-relayed time and frequency information would expand the applications for these signals. The high signal-to-noise ratios and freedom from fading would lend themselves to automatic equipment uses. Applications can be projected in the power industry where timing signals are required for fault monitoring and power system regulation. Airports, environmental, and geophysical monitoring sites also require automatic recording of time in parallel with the recording of designated events. The time and frequency needs in the transportation industry are growing beyond the capabilities of present systems to serve them. Areas include vehicle location, vehicle surveillance, traffic management, and collision avoidance. Digital communications systems are moving to higher data rates requiring increased synchronization capability. All these mentioned applications and many more can benefit directly from a reliable satellite time and frequency service.

The experiment also revealed a number of obvious improvements which could have been made to its operation. The improvements were not implemented, however, due to their possible interaction to other lines of investigation. For example, the tick arriving at the earth approximately 1/4 of a second late was not as convenient for the user as it could have been if it had been advanced at the transmitter by 1/4 of a second, thereby causing it to arrive at the earth nearly on time. In fact, the signal in the entire satellite coverage area would never have to be more than a few milliseconds off in the arrival of the tick. No correction for delay would be needed by the low to intermediate accuracy user, thereby greatly simplifying the system for 90% of its users. Also, the tick could be adjusted in time so only the link between the satellite and ground would need to be calculated for delay correction by the user. The transmitter to satellite link would "in effect" have a fixed delay.

A problem area in the ATS-3 experiments was evident whenever an orbit maneuver was experienced. The maneuver created an entirely new orbit for the satellite which required new orbital elements for satellite position prediction. Operationally, NASA would track the satellite immediately after the maneuver. The tracking process required a day or two after which an orbit was fitted to the data. Consequently, it was a week or two before NBS had the information necessary to broadcast satellite position to the user for delay calculations. For an operational service, this delay in orbit determination would be unacceptable. NBS is now investigating the feasibility of using the timing signals themselves as continuous low resolution range measurements and computing orbits from the resulting data. A small on-line computer could handle this computation, thus eliminating the need for high quality orbital elements which allowed for the prediction of satellite position weeks in advance. The on-line computer need only consider the general shape of the orbit and a few hours of data from the immediate past to predict into the near future of, for example, the next 15 minutes. This would be, in effect, continuous tracking at low resolution in place of high resolution short duration tracking. Development of this continuous tracking concept with somewhat higher resolution than what was available for ATS-3 should also allow for more accurate prediction of satellite position, which is believed capable of supporting 1 μs timing.

The time code was incorporated into the format in the easiest manner possible for the existing generating equipment. The code format and the method of modulation should definitely be reviewed for optimum usefulness to customers and digital processing. The satellite position information, not being of use to anyone but the high accuracy, sophisticated user, should appear in a form much like the time code. In fact, it could be interlaced into the time code in a way which would not produce interference to equipment designed for operation with the time code. Since the satellite position data would require updating approximately every 5 minutes, interlacing seems very practical. If the code were slow enough, it could be "read out" on a paper chart recorder for easy reduction.

Fundamental to this entire topic on the potential of satellites for time and frequency dissemination was the newly allocated channel for space-to-earth time and frequency broadcasts. In June 1971, the Space Telecommunications World Administration Radio Conference (WARC), held in Geneva, allocated 400.1 ± 0.05 MHz to the purpose of time and frequency dissemination from satellites. This allocation was exclusive, international, and placed no practical limitations on the flux density allowed on the face of the earth. Contained in this allocation were 25 kHz guard bands making the effective information bandwidth 50 kHz. Such an allocation opens the way for much-improved time and frequency systems over those available today. The additional 20 kHz bandwidth available over the ATS-3 experiment could be used in a number of ways. The information useful to the low and intermediate accuracy time user could be restrained to a sufficiently narrow bandwidth to be workable with conventional narrowband FM equipment which is readily available. Outside of this bandwidth, not seen by the typical user, may be placed all information of interest to only the high accuracy user. A 10 kHz continuous tone could serve for high accuracy timing just as the 1 kHz tone was used with ATS-3. It would also serve users who wish to compare frequency directly with the satellite broadcast. Doppler would still present some problems but would be predicted simply as a frequency offset as shown in figure 38. A wideband, 50 kHz bandwidth, receiver for this service would be a more expensive special purpose receiver. It would be designed to be delay stable and nondistorting. The wider bandwidth would make it more tolerant to temperature and aging effects which cause waveform distortion.

Finally, a satellite system which offers a continuous time and frequency broadcast, as dependable as the local commercial AM or FM stations, not subject to propagation anomalies, and available to 40% of the earth's surface (assuming only one satellite; three would provide global coverage) will satisfy many of today's requirements not being met economically by present services. Additionally, these high quality services will generate more uses of time and frequency technology, with new products and markets being developed. Satellites will obviously not satisfy everyone's needs--no one system ever will. Other systems will be needed to complement this service such as the NBS TvTime System which has been experiencing a parallel development to the ATS-3 experiment [14]. A satellite service, however, should be a welcome advancement since its added advantages do not cost the user more than for reception of WWV or WWVH.

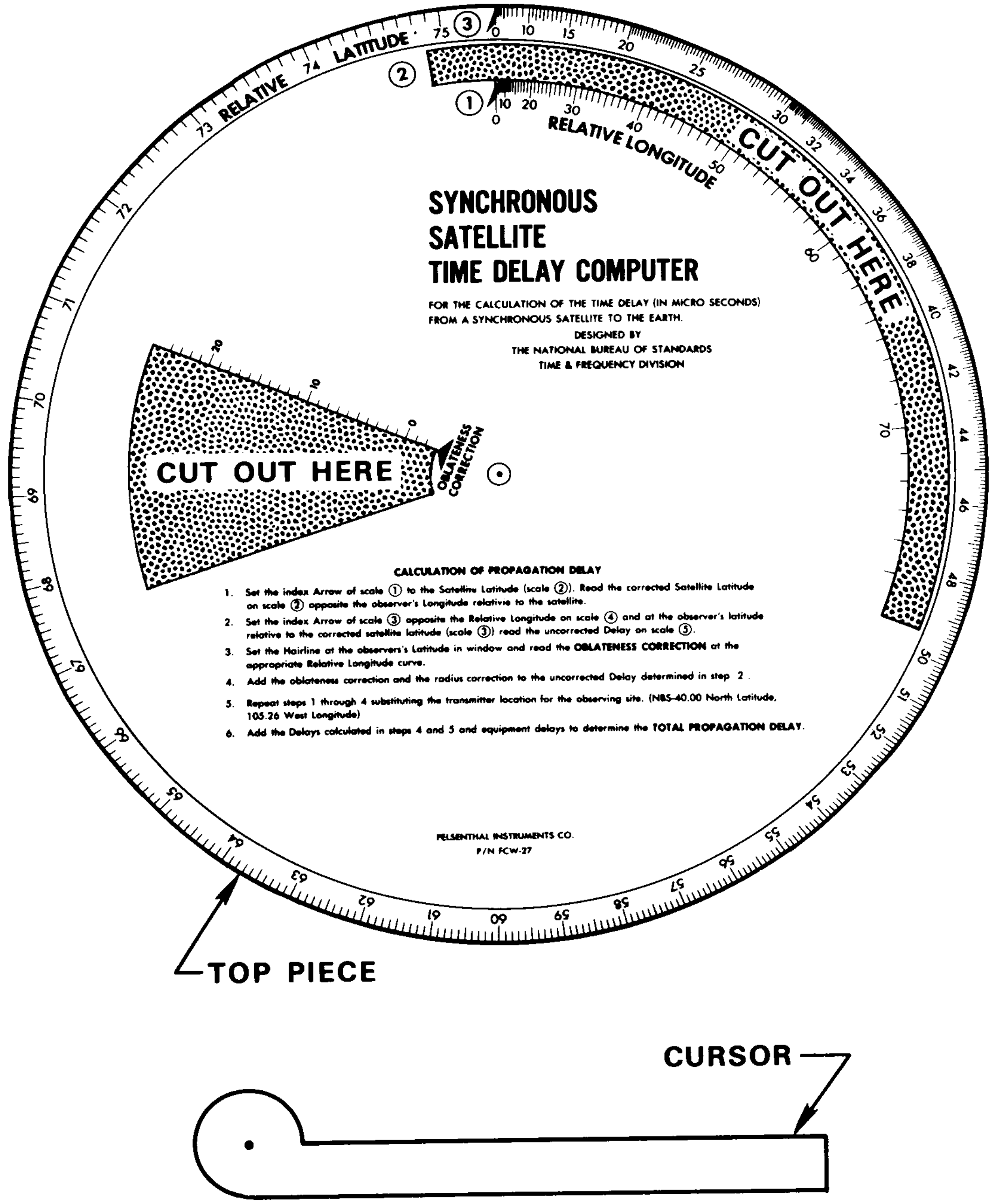
APPENDIX I

SLIDE RULE AND PERFORMANCE

A slide rule has been provided in this report which may be cut out and assembled. Figure I-1 is the top and figure I-2 is the base. Assembly instructions are included in figure I-1. The center of the slide rule is marked and the two sections must be joined carefully to assure that they are concentric. Positioning of either section off center will produce errors in the computed delays.

The only real measure of slide rule performance comes from comparing its computed delay with the delay derived from orbital elements, a digital computer, and complete descriptions of perturbating forces. Figure I-3 shows how the computations were obtained. NASA generated tracking data on the satellite from their two tracking stations at Rosman, North Carolina, and Mojave, California. This data then produced orbital elements. Using a digital computer and a model of orbit perturbations, the satellite's position during broadcast times was determined and was relayed to the user via the satellite in terms of longitude, latitude, and a radius correction. Inputing the user's position, two delay values were derived. One value came from the slide rule and the other from the digital computer which went directly from orbit prediction to delays.

If the two delays were equal then the slide rule process would have accomplished its intended task perfectly. However, this was not the case as can be seen in figures I-4 - I-7. Figure I-4 shows the difference (digital computer minus slide rule) versus user longitude relative to the subsatellite longitude for various user latitudes and selected subsatellite points in both hemispheres. Figure I-5 shows the distribution of the points for each subsatellite point and for the total of all differences. The obvious bias in the results was caused primarily by a longitudinal error



Assembly Instructions (figs. I-1 and I-2).

1. Cut out top piece, cursor, and base of the slide rule.
2. Cut out the two windows on the top piece.
3. Using a straight pin or other suitable fastner, assemble the cursor, top piece, and base at the central point, indicated with a dot in the middle of a small circle.

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Figure I-1. Sample slide rule top and cursor.

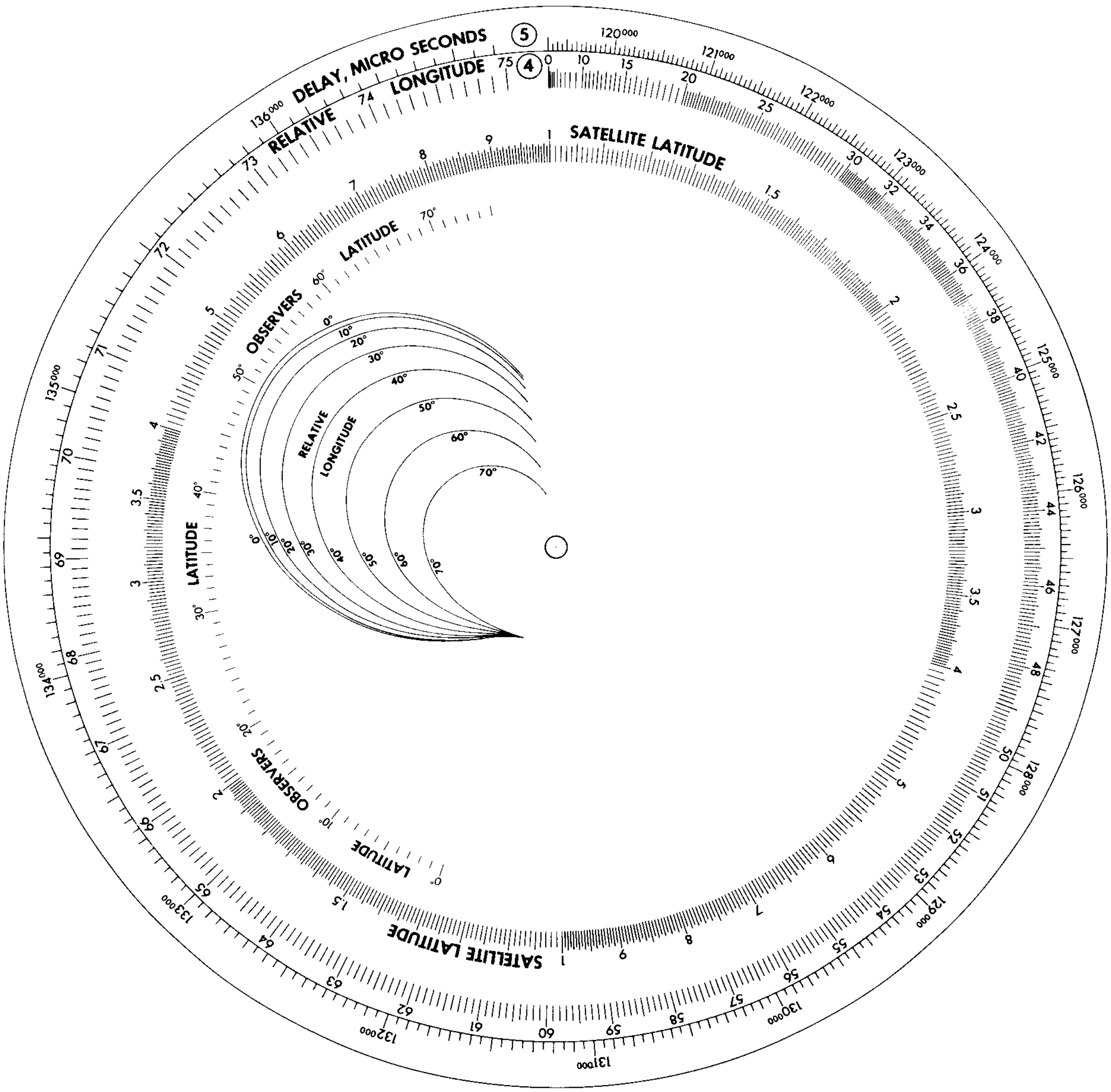

Figure I-2. Sample slide rule base.

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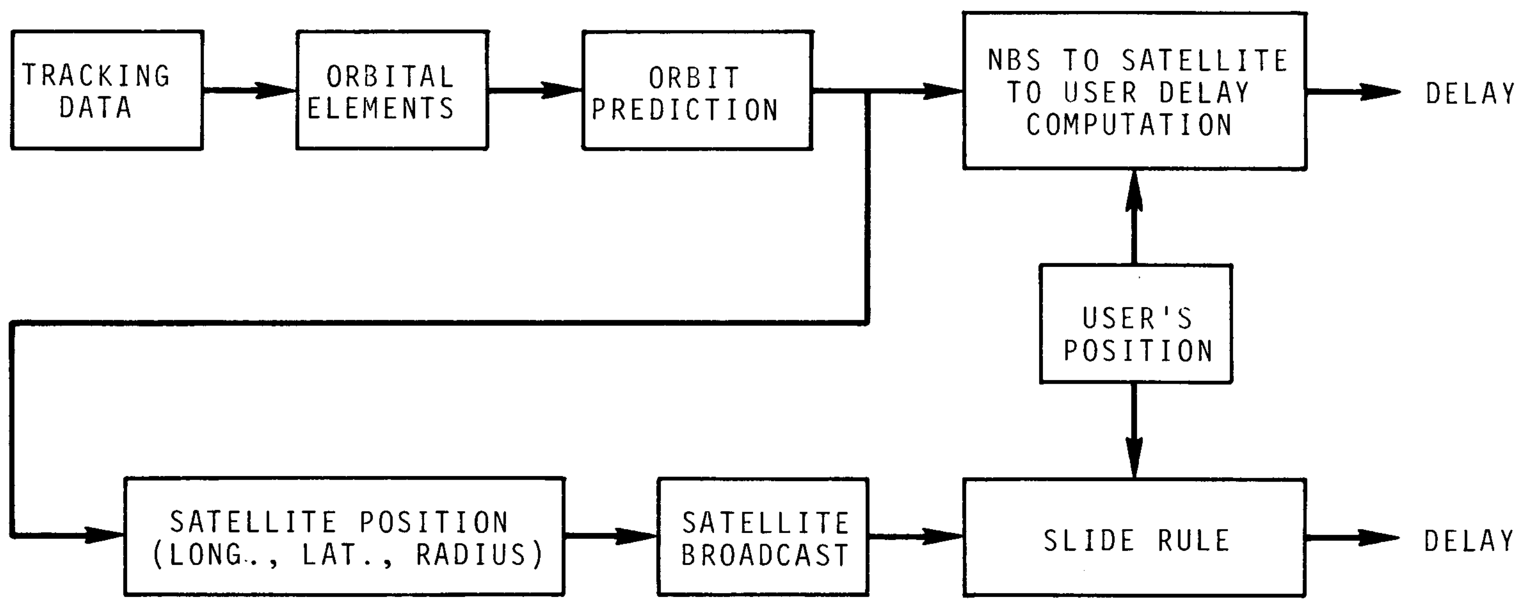


Figure I-3. Block diagram of the delay computation procedure.

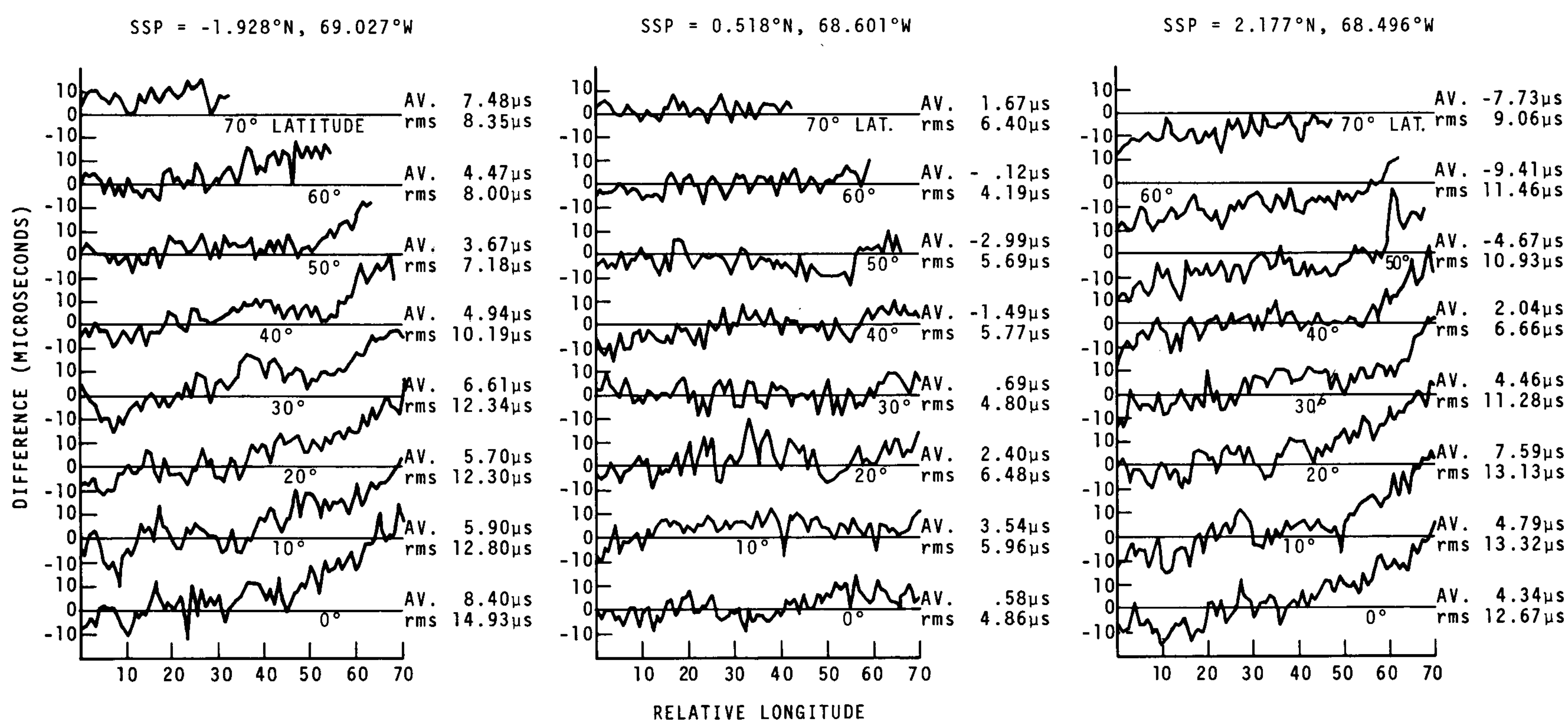
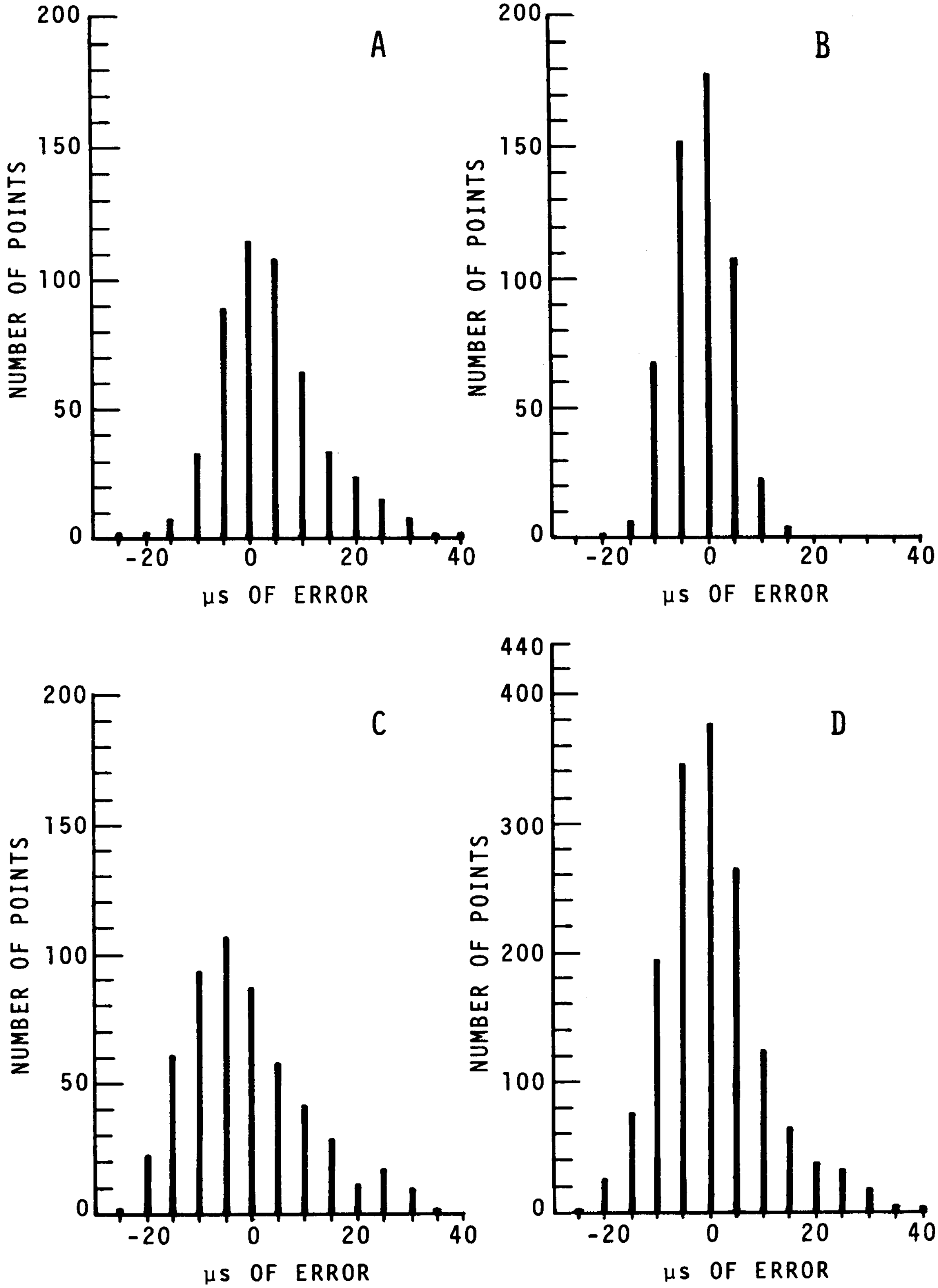


Figure I-4. Slide rule delay error. Theoretical delay minus slide rule delay.



A. Satellite at -1.928°N, 69.027°W
B. Satellite at 0.518°N, 68.601°W
C. Satellite at 2.177°N, 68.496°W
D. Total of A, B, and C.

Figure I-5. Distribution of slide rule delay errors.

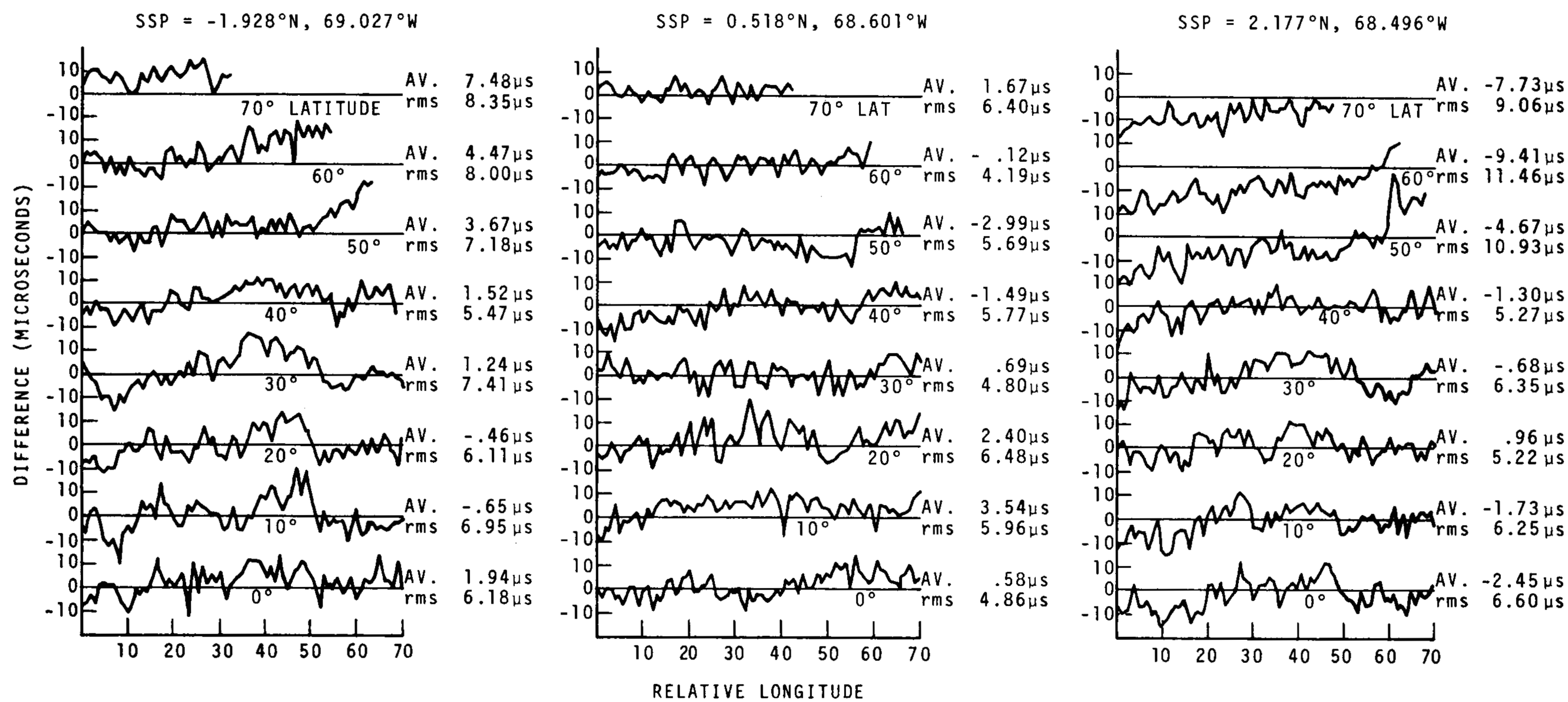
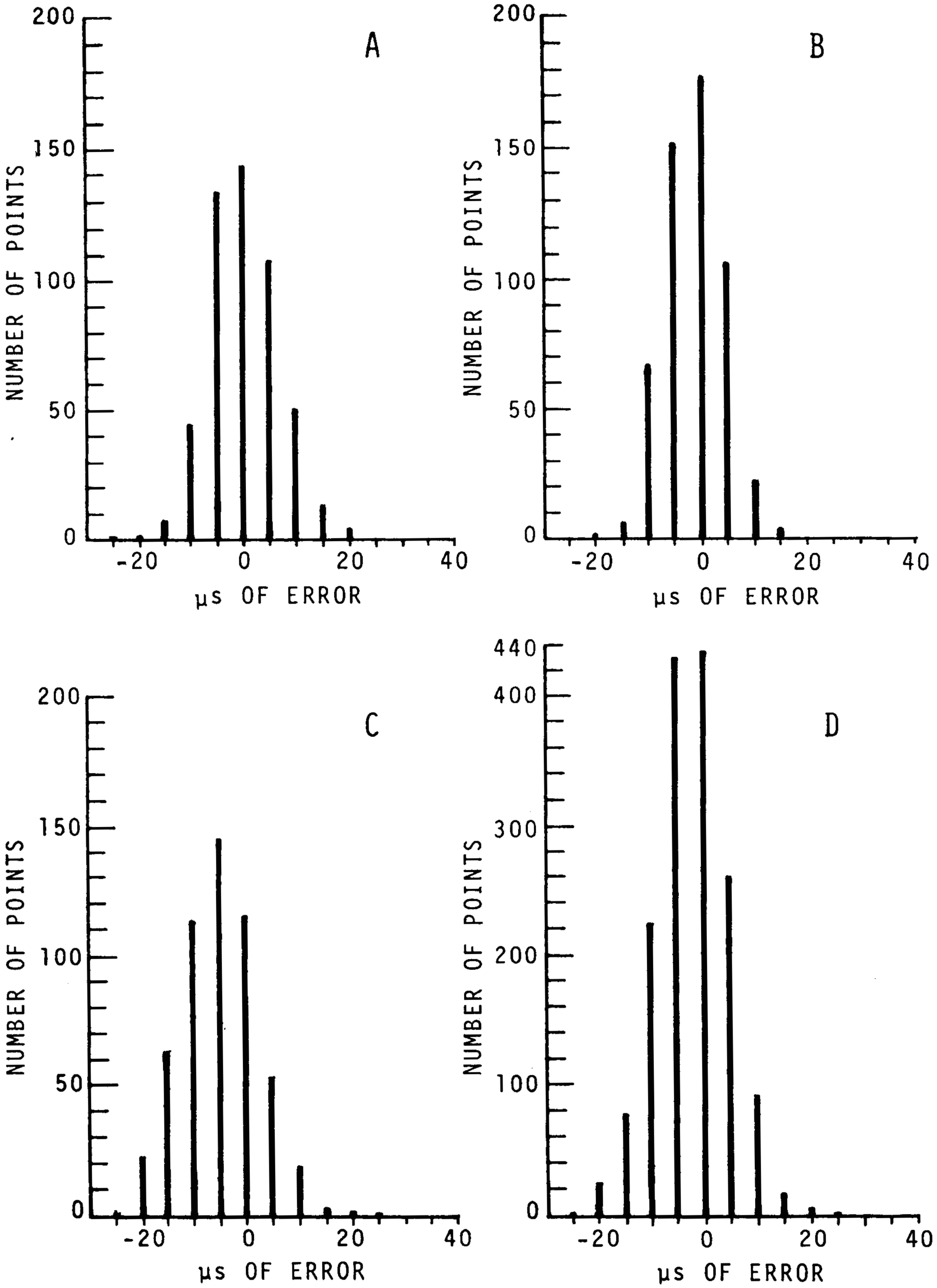


Figure I-6. Slide rule delay error with the longitudinal error removed. Theoretical delay minus slide rule delay.



A. Satellite at -1.928°N, 69,027°W
B. Satellite at 0.518°N, 68.601°W
C. Satellite at 2.177°N, 68.496°W
D. Total of A, B, and C.

gure I-7. Distribution of the slide rule delay errors with the longitudinal error removed.

which is discussed fully in another report [15]. This longitudinal error became significant whenever the relative longitude and satellite latitude fell into the shaded area in table I-1 . As an additional example of slide rule operation and removal of error, consider the following.

	Longitude	Latitude	Radius Correction
NBS Boulder	105.26°W	40.00°N	NA
Satellite	74.67°W	2.50°N	-176 μs
User (Tristan da Cunha)	12.30°W	37.15°S	NA

Slide Rule Calculation

	Down-link	Up-link
1. Satellite Longitude	74.67°W	74.67°W
2. Earth Station Longitude	12.30°W	105.26°W
3. Relative Longitude (absolute value of step 1 minus step 2)	62.37°	30.59°
4. Corrected Satellite Latitude	5.40°N	2.90°N
5. Earth Station Latitude	37.15°S	40.00°N
6. Relative Latitude (absolute value of step 4 minus step 5)	42.55°	37.10°
7. Uncorrected Delay	134765 μs	126880 μs
8. Oblateness Correction	6 μs	17 μs
9. Radius Correction	-176 μs	-176 μs
10. Free Space Path Delay (sum of steps 7, 8, and 9)	134595 μs	126721 μs

Table I-1. Values of δ for various values of φ_s and $|\lambda_s - \lambda_r|$ showing $\delta \approx |\lambda_s - \lambda_r|$.

Relative Longitude $\|\lambda_s - \lambda_r\|$	Satellite Latitude φ_s: 0	.5	1.0	1.5	2.0	2.5	3.0
0	0	0	0	0	0	0	0
5	5.000	5.000	4.999	4.998	4.997	4.995	4.993
10	10.000	10.000	9.999	9.997	9.994	9.991	9.986
15	15.000	14.999	14.998	14.995	14.991	14.985	14.979
20	20.000	19.999	19.997	19.993	19.987	19.980	19.972
25	25.000	24.999	24.996	24.991	24.984	24.975	24.963
30	30.000	29.999	29.995	29.989	29.980	29.969	29.955
35	35.000	34.999	34.994	34.986	34.976	34.962	34.945
40	40.000	39.998	39.993	39.984	39.971	39.954	39.934
45	45.000	44.998	44.991	44.980	44.965	44.946	44.922
50	50.000	49.997	49.990	49.977	49.958	49.935	49.907
55	55.000	54.997	54.988	54.972	54.950	54.922	54.888
60	60.000	59.996	59.985	59.966	59.940	59.906	59.864
65	65.000	64.995	64.981	64.958	64.925	64.883	64.832
70	70.000	69.994	69.976	69.946	69.904	69.851	69.785
75	75.000	74.992	74.968	74.927	74.870	74.798	74.710

Before determining the round-trip delay, the down-link should be corrected for the longitudinal error since the relative longitude and satellite latitude combinations fall into the shaded area of table I-1. Interpolating from this table we find that δ should be 62.26^{o}. Using this value in the table instead of 62.37^{o}, as in step 3 above, to compute the down-link delay yields an uncorrected delay of 134740 μs, a one-way delay of 134570 μs, and a round-trip delay of 261291 μs.

After this longitudinal error was removed the performance was improved as shown in figures I-6 and I-7. These results were obtained from more than 500 manual computations with the slide rule and it was obvious that this tool was capable of providing delay calculations for the user simply and inexpensively and accurate to 10 μs rms. This translated into a 10 μs accuracy for timing provided the satellite position information was perfect.

APPENDIX II

ORBITAL ELEMENTS AND ORBIT PREDICTION

This appendix briefly describes factors relating to the description of an earth satellite's orbit and prediction of that orbit. The discussion progresses from a simple two-body orbit and its orbital elements, to an n-body orbit and concludes with perturbations to an orbit.

From the universal law of gravitation the force vector between two bodies is given by

$$\bar{f}_{12} = \frac{k^2 m_1 m_2}{r_{12}^3} \bar{r}_{12}, \tag{II-1}$$

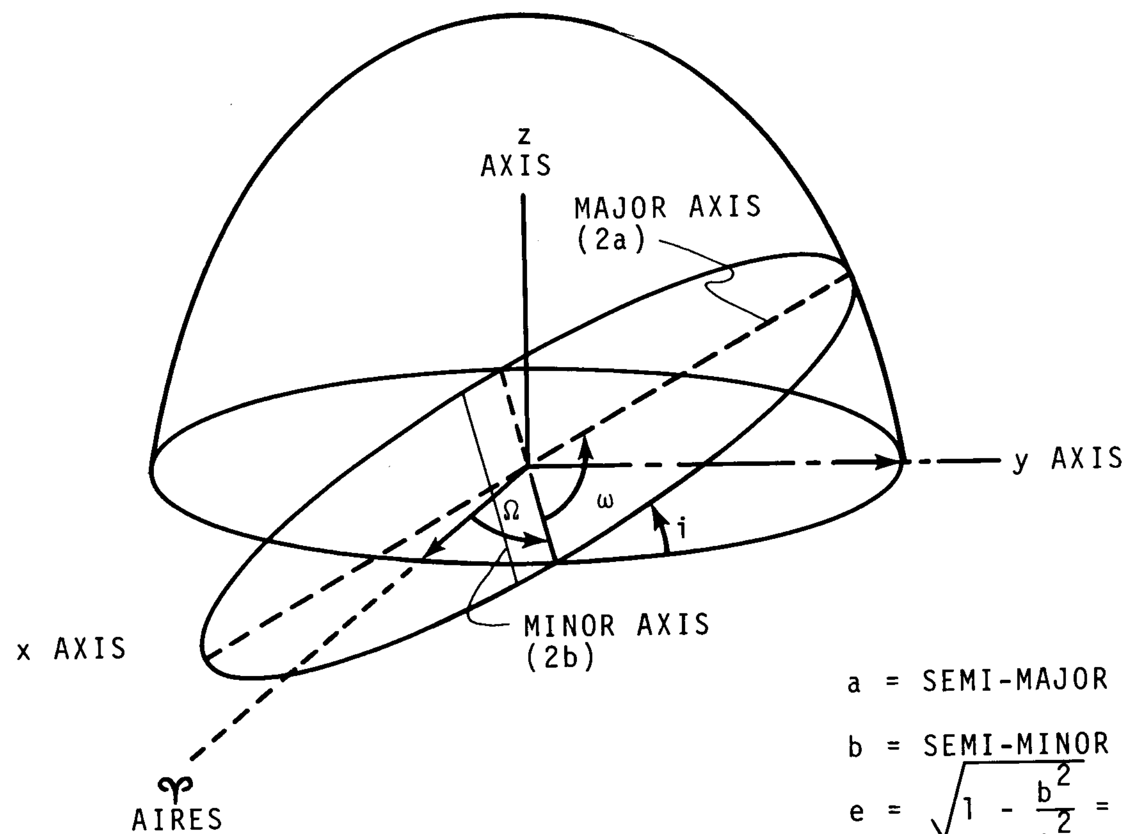
where m_1 and m_2 are the masses of the two bodies, $\bar{r}_{12}$ is the vector from the first body to the second, k is the gravitational constant. It is assumed that the two bodies are spheres with homogeneous mass distribution and that the only force acting on either body is the gravitational attraction of the other body. Dividing this force by the mass of the second body yields the acceleration of the second body

$$\frac{d^2 \bar{r}_2}{d t^2} = \frac{k^2 m_1 \bar{r}_{12}}{r_{12}^3}, \tag{II-2}$$

Double integration of this equation gives the position vector.

Because the force vector has three component parts, six constants of integration are required. These constants are called the satellite's orbital elements. The choice of the reference coordinate system determines the form of the elements. The six "classical" elements, five of which are illustrated in figure II-1, are:

1) The semi-major axis, a, of the ellipse which the satellite traces



a = SEMI-MAJOR AXIS

b = SEMI-MINOR AXIS

$e = \sqrt{1 - \frac{b^2}{a^2}}$ = ECCENTRICITY

i = INCLINATION

Ω = LONGITUDE OF ASCENDING NODE

ω = ARGUMENT OF PERIFOCUS

Figure II-1. Classical orbital elements.

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out as a function of time.

2) The eccentricity, e, of this ellipse.

3) The inclination, i, or the angle of intersection between the orbit plane and the reference plane (the equatorial plane is usually used as the reference plane for an earth-centered system.)

4) The longitude of the ascending node, Ω, or the angle between the line pointing from the geocenter to the constellation Aries and the line of intersection of the orbit plane and the reference plane.

5) The argument of perifocus, ω, the angle between the line of nodes and the perifocal direction, measured in the orbit plane.

6) The time of perifocal passage, T.

It is interesting and instructive to examine the relationship of these various parameters to a geostationary satellite. An "ideal" geostationary satellite would not appear to have any motion relative to points on the earth. This implies a circular orbit which lies in the equatorial plane. Consequently, for this "ideal" orbit, three of the classical elements, Ω, ω, and T, are degenerate. The position of the semi-major axis, a, is also indeterminate, but one may talk about the length of the axis which would be approximately 6.61 earth radii. The other two elements, e and i, are both zero. The effects of small deviations from the ideal value for these last three elements point out the types of fluctuations one might expect from a real geostationary satellite.

Small changes in the length of the semi-major axis will cause the satellite's period to differ slightly from equality with the earth's period of rotation. Thus, the satellite would drift longitudinally from the desired subsatellite point. An increase of 0.01 earth radii or 0.15% will cause a westward drift rate of approximately 0.8 degrees per day.

Small deviations from the ideal eccentricity will have three major effects. First, an additional orbital element, the time of perifocal passage T, will become defined, as will the major axis. Next, the distance from the earth will change as a function of time. Since the earth is at one of the focii of the ellipse rather than at the center, this effect is amplified above what one might expect. Finally, because of the changing distance from the earth, the velocity of the satellite also fluctuates periodically and causes a daily east-west periodic motion. For an otherwise ideal geostationary orbit, an eccentricity of 0.001 will cause a peak-to-peak variation of distance from the earth of 85 km and peak-to-peak longitudinal motion of approximately 0.2 degrees.

Similarly, small deviations from the ideal zero degrees inclination will have three major effects. An additional element, Ω, the longitude of the ascending node, becomes defined. Also, the satellite will experience daily north-south movement in latitude. The maximum north or south latitude of the subsatellite point is equal to the inclination angle. Finally, a non-zero inclination will cause longitudinal motion with a period of twice a day. The periodicity of longitude and latitude caused by inclination combines in a manner similar to a lissajous pattern on an oscilloscope to form a "figure eight" trace of the subsatellite point. An inclination of 1 degree will cause peak-to-peak latitude and longitude fluctuations of 2 degrees and 0.08 degrees respectively.

When there are more than two attracting bodies and when there are other perturbing forces, the equation of motion takes on a new form. For n bodies with perturbations then, the force vector on the $i^{\underline{th}}$ body is given by

$$m_i \frac{d^2 \bar{r}_i}{d t^2} = k^2 \sum_{j=1}^{n} m_i m_j \frac{\bar{r}_{ij}}{r_{ij}^3} + m_i p_i \quad j \neq i. \tag{II-3}$$

Here p_i represents accelerations which cause deviation from an ideal n-body orbit. These might be caused by thrust, drag, non-uniform gravitational fields, solar radiation pressure or other forces.

The non-homogeneity of the earth's mass distribution may be explicitly incorporated into eq (3) by substituting the gradient of the gravitational potential for the term in the summation which deals with the acceleration due to the earth. The gravitational potential of the earth may be expressed as:

$$\Phi = \frac{k^2 m_e}{r}\left[1 + \sum_{k=2}^{\infty}\left\{\sum_{m=0}^{k}\left(\frac{p_k^{(m)}[\sin\delta]}{r^k}\right)\left(C_{k,m}\cos[m\lambda_E] + S_{k,m}\sin[m\lambda_E]\right)\right\}\right], \quad \text{(II-4)}$$

where m_e is the mass of the earth, $p_k^{(m)}$ is the Legendre function, δ is the declination of the satellite, $C_{k,m}$ and $S_{k,m}$ are the harmonic coefficients, and λ_E is east longitude. The harmonic coefficients are related to the shape of the earth. For example, the term $C_{2,0}$ is directly related to the flattening of the earth. The term $C_{3,0}$ represents the "pear-shaped" nature of the earth with the stem at the north pole. The terms $C_{2,2}$ and $S_{2,2}$ together may be interpreted as arising from an elliptical equator. This ellipse has its major axis at about 18^o west longitude with a difference of approximately 70 meters between the lengths of the semi-major and semi-minor axes. A synchronous satellite at the major axis will be in unstable equilibrium (likened to balancing a cone on its apex). A satellite at the minor axis will be in stable equilibrium (a cone balanced on its base). At any other longitude a synchronous satellite will be slightly accelerated towards the nearest minor axis. For a synchronous satellite, δ and λ_E of eq (4) are very nearly constant. Consequently, the gravitational force will be relatively constant even though it may be significantly different than for a uniform sphere with homogeneous mass distribution.

The forces due to bodies other than the earth will cause significant perturbations to the orbit of a "geosynchronous" satellite. The two bodies which have the greatest perturbing effect on an artificial earth satellite are the sun and the moon. The force vector acting on the satellite from such a body may be resolved into two component vectors, one in the orbit plane and one normal to the orbit. The normal component imparts a rotation of the orbit plane around the earth. Since this component is periodic, however, the net effect is a trend for the orbit plane to move towards containing the force vector. The coplanar component may be further broken down into components parallel to and normal to the major axis. This normal component will cause the axis to rotate towards the coplanar component, while the coaxial component will cause a lengthening of the semi-major axis and increase the eccentricity of the orbit. Fisher [16] gives the following estimation formula for the short term effects of the moon on the semi-major axis of an artificial earth satellite:

$$da \approx 1.1 \times 10^{-7} a^3 \qquad \text{(II-5)}$$

where a is the semi-major axis expressed in earth radius units. Evaluating this formula for a synchronous satellite yields a change of 1.4 km or 0.003%. This agrees with measurements shown in the same report which gives a detailed analysis of sun and moon effects as perturbations to a two-body orbit.

The problem of accurately determining a satellite's position as a function of time may be seen to be very complex. Herrick [11] has summarized the processes necessary to the development of perturbation theory.

1) Initial conditions such as orbital elements for all of the included bodies must be known.

2) A mathematical model of the force field must be developed.

3) Physical constants such as the harmonic coefficients of eq (4) must be known.

4) A reference framework, i.e., an origin and axes, must be selected.

5) The integrands must be selected. Three choices exist. One may integrate the total acceleration, or the perturbing acceleration, or selected functions of the perturbing acceleration.

6) The mode of integration, either numerical or analytical, must be selected. Also, if numerical integration is chosen, there are various formulas or processes from which one must choose.

For more detail the reader is referred to Brouwer and Clemence [12] or Herrick [11].

APPENDIX III

COMPUTER PROGRAM FOR FREE SPACE PROPAGATION DELAY

The computer program listed below may be used to calculate the free space propagation delay to a satellite. This program, written in the computer language BASIC, uses essentially the same procedure as the special purpose slide rule described earlier, although the approximations have been removed. The input parameters are the satellite's position (latitude, longitude and radius correction) and the receiving site location (latitude and longitude) along with an identifying date. The up-link is computed assuming NBS Boulder to be the transmitting site.

```
  5  LET A = 6378.21
 10  LET B = 6356.58
 15  LET C = .2997925
 20  LET D = 1.74533E-2
 40  FOR I = 1 TO 5 STEP 1
 41    PRINT
 42  NEXT I
 50  PRINT "INPUT OF TRANSMITTER SITE LOCATION"
 55  PRINT "WEST LONGITUDE = ";
 60  INPUT L1
 61  PRINT
 65  PRINT "NORTH LATITUDE = ";
 70  INPUT L2
 71  PRINT
 75  PRINT "ELEVATION ABOVE SEA LEVEL IN METERS = ";
 80  INPUT L3
 81  PRINT
 82  PRINT
 83  PRINT
 85  PRINT "INPUT OF RECEIVER SITE LOCATION"
 90  PRINT "WEST LONGITUDE = ";
 95  INPUT M1
 96  PRINT
100  PRINT "NORTH LATITUDE = ";
105  INPUT M2
106  PRINT
110  PRINT "ELEVATION ABOVE SEA LEVEL IN METERS = ";
115  INPUT M3
116  PRINT
117  PRINT
118  PRINT
```

```
120  PRINT "INPUT OF SATELLITE POSITION AND DATE OF POSITION"
125  PRINT "MONTH, DAY, AND YEAR = ";
130  INPUT Y1, Y2, Y3
131  PRINT
135  PRINT "TIME = ";
140  INPUT T
141  PRINT
145  PRINT "WEST LONGITUDE = ";
150  INPUT N1
151  PRINT
155  PRINT "NORTH LATITUDE = ";
160  INPUT N2
161  PRINT
165  PRINT "RADIUS CORRECTION = ";
170  INPUT N3
171  PRINT
200  LET L4 = L1*D
205  LET L5 = L2*D
210  LET M4 = M1*D
215  LET M5 = M2*D
220  LET N4 = N1*D
225  LET N5 = N2*D
230  LET B1 = (B*B)/(A*A)
235  LET B2 = B1*B1
240  LET H1 = SQR((1+B2*TAN(L5)*TAN(L5))/(1+B1*TAN(L5)*TAN(L5)))
245  LET H1 = H1*A+.001*L3
250  LET H2 = SQR((1+B2*TAN(M5)*TAN(M5))/(1+B1*TAN(M5)*TAN(M5)))
255  LET H2 = H2*A+.001*M3
260  LET H3 = 42143.4+N3*C
265  LET L5 = ATN(B1*TAN(L5))
270  LET M5 = ATN(B1*TAN(M5))
275  LET C1 = COS(L5)*COS(N5)*COS(ABS(L4-N4))
280  LET C1 = C1+SIN(L5)*SIN(N5)
285  LET C2 = COS(M5)*COS(N5)*COS(ABS(M4-N4))
290  LET C2 = C2+SIN(M5)*SIN(N5)
300  LET R1 = SQR(H3*H3+H1*H1-2*H3*H1*C1)
305  LET R2 = SQR(H3*H3+H2*H2-2*H3*H2*C2)
310  LET R3 = R1+R2
315  LET T1 = R1/C
320  LET T2 = R2/C
325  LET T3 = R3/C
350  FOR I = 1 TO 5 STEP 1
355    PRINT
360  NEXT I
365  PRINT Y1;"/";Y2;"/";Y3
370  PRINT
375  PRINT T;"GMT"
380  PRINT
385  PRINT "UPLINK - RANGE = ";R1;"KM"
390  PRINT "       - DELAY = ";T1;"MICROSECONDS"
```

```
395  PRINT
400  PRINT "DOWNLINK - RANGE = ";R2;"KM"
405  PRINT "          - DELAY = ";T2;"MICROSECONDS"
410  PRINT
415  PRINT "ROUNDTRIP - RANGE = ";R3;"KM"
420  PRINT "           - DELAY = ";T3;"MICROSECONDS"
425  PRINT
430  PRINT "NOTE - EQUIPMENT DELAYS MUST BE COMPENSATED FOR"
435  PRINT "       BEFORE COMPARING THEORETICAL AND EXPERIMENTAL"
440  PRINT "       DELAYS."
```

11. REFERENCES

[1] Steele, J. McA., Markowitz, W., and Lidback, C. A., "Telstar Time Synchronization," IEEE Trans. Instrum. and Meas., IM-13, No. 4, pp. 164-170 (December 1964).

[2] Markowitz, W., Lidback, C. A., Uyeda, H., and Muramatsu, K., "Clock Synchronization Via Relay II Satellite," IEEE Trans. Instrum. and Meas., IM-15, No. 4, pp. 177-184 (December 1966).

[3] Ramasastry, J., Rosenbaum, B., Michelini, R. D., and Kuegler, G. K., "Clock Synchronization Experiments Performed Via the ATS-1 and ATS-3 Satellites," IEEE Trans. Instrum. and Meas., IM-22, No. 1, pp. 9-12 (March 1973).

[4] Jespersen, J. L., Kamas, G., Gatterer, L. E., and MacDoran, P. F., "Satellite VHF Transponder Time Synchronization," Proc. IEEE, 56, No. 7, pp. 1202-1206 (July 1968).

[5] Kershner, R. B., "Transit Program Results," Astronautics, 6, No. 5, pp. 30-38 (May 1961).

[6] Goddard Space Flight Center, "Tracking Intercomparison Tests With GEOS-1," Proc. of the GEOS Program Review Meeting, 12-14 December 1967, III, (February 1968).

[7] Gatterer, L. E., Bottone, P. W., and Morgan, A. H., "Worldwide Clock Synchronization Using a Synchronous Satellite," IEEE Trans. Instrum. and Meas., IM-17, No. 4, pp. 372-378 (December 1968).

[8] Hanson, D. W., and Hamilton, W. F., "One-Way Time Synchronization Via Geostationary Satellites at UHF," IEEE. Trans. Instrum. and Meas., IM-20, No. 3, pp. 147-153 (August 1971).

[9] Hanson, D. W., and Hamilton, W. F., "Clock Synchronization from Satellite Tracking," IEEE Trans. Aerospace and Electronic Systems, AES-7, No. 5, pp. 895-899 (September 1971).

[10] Skolnik, M.J., Introduction to Radar Systems. New York: McGraw Hill Book Co., Inc., 1962, p. 413.

[11] Herrick, S., Astrodynamics. London: Van Nostrand Reinhold Co., 1971, p. 540.

[12] Brouwer, D., and Clemence, G.M., Methods of Celestial Mechanics. New York: Academic Press, 1961, p. 598.

[13] Morgan, A. H., "Precise Time Synchronization of Widely Separated Clocks," NBS Technical Note 22 (July 1959).

[14] Howe, D.A., "Nationwide Precise Time and Frequency Distribution Utilizing an Active Code Within Network Television Broadcasts," IEEE Trans. Instrum. and Meas., IM-21, No. 3, pp. 263-276 (August 1972).

[15] Hamilton, W. F., and Hanson, D.W., "A Synchronous Satellite Time Delay Computer," NBS Technical Note 638 (July 1973).

[16] Fisher, D., "Analytic Short Period Lunar and Solar Perturbations of Artificial Satellites," Celest. Mech., 6, No. 4, pp. 447-458 (December 1972).

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