Satellite Broadcasting of WWV Signals

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Abstract

An experiment concerning the broadcasting of time and frequency information from geostationary satellites is discussed. Included are discussions on satellite motion, time delay, Doppler shift, and delay calculations. Ground station requirements, time recovery techniques, and timing resolution and accuracy are also included. Delay computation aids for the user were designed to provide free space delays between the master clock and the user. Measurements made in North and South America demonstrated a timing resolution of about 10 μs and an accuracy of 25 μs.

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I. 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 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 Eruope and Africa, a total of about 40 percent 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 transfer 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 experiment reported upon in this paper 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 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.

Examples of satellite timing systems operating in the one-way mode include 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.

Timation [6] uses synchronized clocks in the satellite and user equipment to find the range from the satellite to the user. Information provided the user on satellite position and the satellite clock allows the synchronization of the user's clock. Accuracies of better than 1 μs have been reported. GEOS [7], a similar system, 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 experience in the two-way mode and motivated by an emphasis on low cost and simplicity, also directed its efforts in 1967 to exploring 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 [8] and with the U. S. military communication satellites, LES-6 and TACSAT [9], [10]. These satellites contained transponders which operated in the frequency range between 120 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, and Colorado, and at 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 in this paper transmitted unambiguous time information, accurate to better than 25 μs 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.

II. The Experiment

Time and frequency signals were relayed by the satellite from NBS, Boulder, twice a day. The time signals were referenced as shown in Fig. 1 to the UTC (NBS) time scale and the NBS Frequency Standard, both of which are maintained at the NBS Laboratories in Boulder. 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.

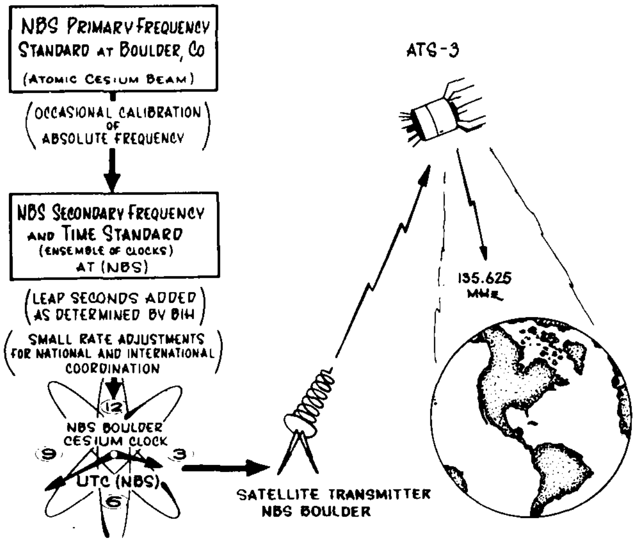

Fig. 1. Time and frequency facilities providing reference to the ATS-3 experiment.

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 ATS-3 satellite 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.

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 μV/m or − 145 dBW/m^2.

Beginning with the first satellite-relayed broadcasts of the time and frequency signals in late 1971, the broadcast format underwent periodic changes 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.[1]

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 percent of the

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[1] Because of common usage of 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).

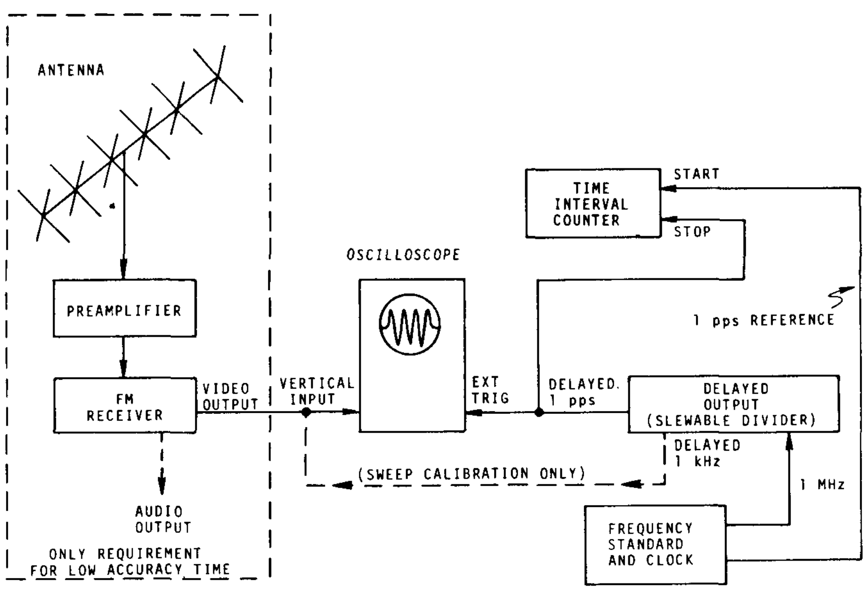


Fig. 2. Equipment for ATS-3 time comparison, including tick phasing adjustment.

amplitude of the other components. To prevent distortion of the tick's waveform, the ticks were gated into the format with all other components of the format blanked during its presence.

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 these synchronized 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 accurate time information.

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.

III. 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 Fig. 2. This configuration was used extensively by NBS at its laboratories in Boulder 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. 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-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—being received at the satellite with high signal-to-noise ratios—the return signals 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). Typical ground station characteristics used by NBS were calculated and are represented in Table I.

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

TABLE I

Downlink 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.

Obtaining time information to better than a few tenths of a second required additional equipment. As shown in Fig. 2, the receiver was connected to the vertical input of an oscilloscope. The receiver output came 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 pulse per second and 1000 pulse per second outputs, both variable in their occurrences in time. The tick was brought into phase with the pulses from the delay generator and the difference between a local clock and the tick arrival was read from the time interval counter.

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 on an oscilloscope more of these zero crossings and enhanced his ability to average the crossings, yielding a correspondingly greater precision.

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 [11] as

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

where δt is the rms error in measuring the time of the zero crossing, T is the period of the sine wave, and S/N is the signal-to-noise power ratio. For the conditions existing in this experiment a δt was obtained of 11.25 μs for an S/N of 10 dB, and 3.6 μs for an S/N of 20 dB. The increased triggering rate allowed for averaging of the zero crossings, 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 increased the resolution to 1.6 μs and 5 μs for the signal-to-noise ratios of 20 dB and 10 dB, respectively.

V. 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, and, for the approximately 76 000-km path from NBS to the user, meant a delay in the arrival of the signal of about one-fourth second. The user, to synchronize a clock to appreciably better than one-second accuracy, was required 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.

The ATS-3 satellite, like all so-called "geostationary" satellites, was moving about in a complicated manner. This

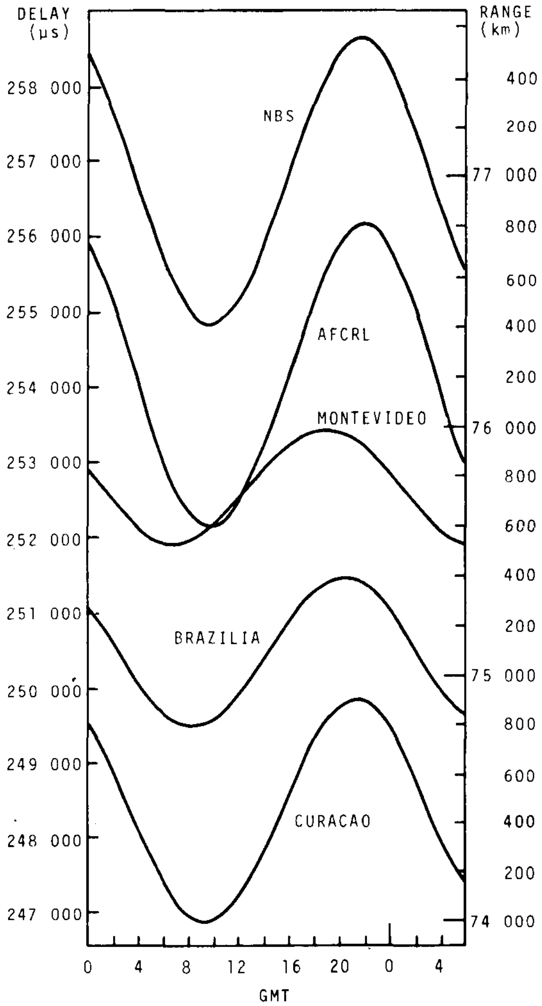


Fig. 3. Delays from NBS to five sites via ATS-3.

motion was significant when considering microsecond timing, since in 1 μs 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 5000 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 above two 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 of 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 paper. The reader is referred to [12] and [13] for a more complete treatment.

Fig. 3 shows the effects on signal delay in the short term for ATS-3. The delays were 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. Fig. 4 shows the measured round-trip delay between Boulder and ATS-3 at 1700 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.

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.

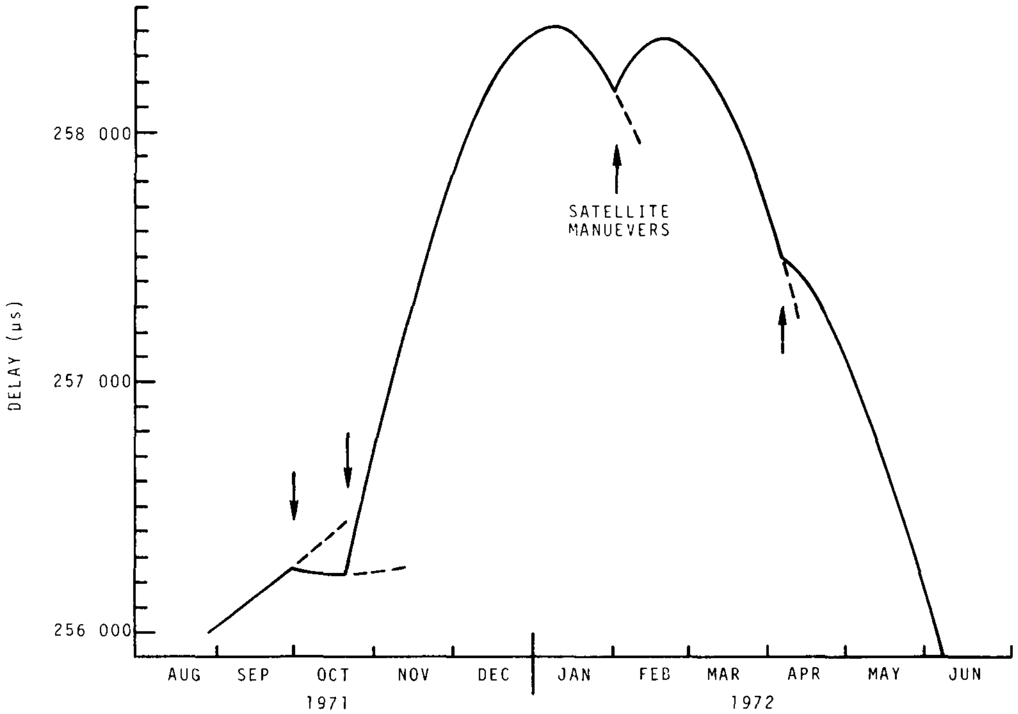


Fig. 4. Long-term, two-way delay between Boulder and ATS-3 at 1700 GMT.

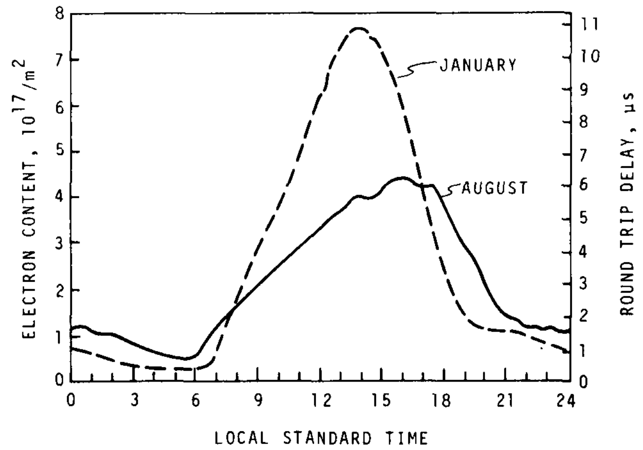
Referring again to Fig. 4, a "Δν" maneuver was performed on February 2, 1972. As shown in the figure, these maneuvers are of very great significance to a user of satellite-disseminated high-accuracy time and frequency information because of the discontinuities in the path delay and orbit prediction.

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. The ionospheric delay was frequency-dependent and nonisotropic. However, for frequencies in the high VHF band and above, anisotropy can be ignored.

The ionospheric 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 Fig. 5. The associated signal-delay increment for that same 24-hour period is also shown in Fig. 5 for a one-way path at 90-degree 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 the measured results presented in this paper.

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 Boulder 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 a calibration procedure. 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 per day—were used to obtain the above statistical values.

Fig. 5. Total ionospheric electron content and associated two-way delay for an average winter and summer month.



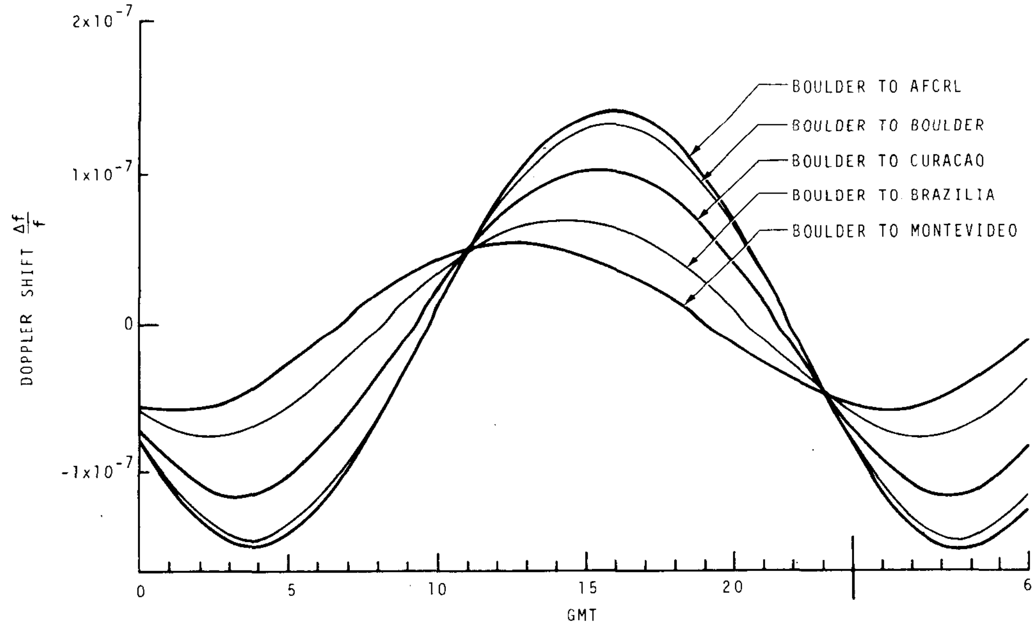


Fig. 6. Doppler from Boulder to five sites.

VI. Doppler

Because the ATS-3 satellite was in motion relative to points on the Earth's surface, frequencies of the satellite-relayed signals were Doppler shifted. Fig. 6 shows the computed Doppler as seen by an observer at widely separated 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.

The only standard frequency available from ATS-3 in this experiment was the 1-kHz tone mentioned previously. The 135.625-MHz carrier was not usable as a standard frequency because of the instabilities in the transfer oscillator.

For direct frequency comparisons, the Doppler can be predicted and taken out of the phase recordings. Future satellites will be station kept to tighter tolerances and reduce this Doppler by two orders of magnitude, making phase recordings more practical.

As an alternative to direct frequency calibrations, periodic clock synchronizations can identify long-term frequency differences. As shown in Section IX, "time" was available from the satellite accurate to about 25 μs. If the oscillator under examination drove a clock and that clock was synchronized by the satellite over a 24-hour interval, a frequency comparison can be made. As shown below, in 24 hours, an average frequency calibration of 3parts in 10^{10} is possible:

$$(\Delta f)/f = (\Delta t)/t = (25\ \mu s)/(0.864 \times 10^{11}\ \mu s)$$

$$\cong 3 \times 10^{10}. \qquad (2)$$

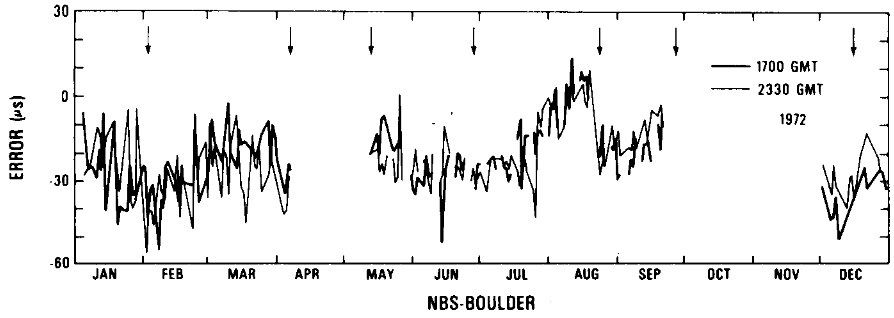
VII. Delay Computation and Clock Synchronization

For high-accuracy clock synchronization, the user has 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 earlier, 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 one-fourth 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 with its center over the subsatellite point.

Because the overlays could not provide path delays accurate to a few microseconds, a circular slide rule was designed to fulfill that need. This simple device was possible because NBS had assumed the major part of the computational burden by computing and 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



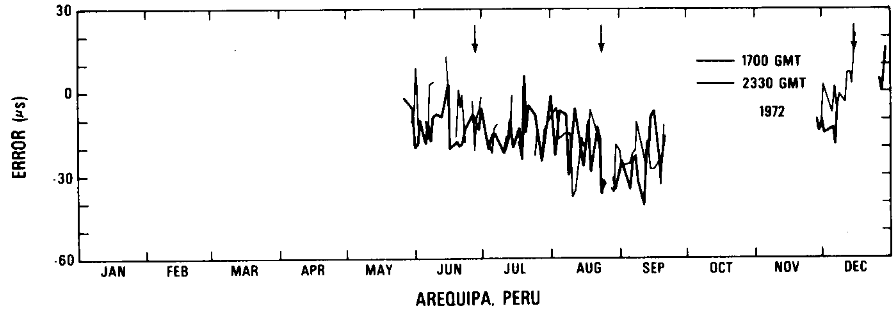


Fig. 7. Delay error at NBS-Boulder and Arequipa, Peru.

satellite. Adding in the delays due to the Earth's atmosphere and satellite and receiving equipment yields the total signal delay.

The user computed his clock error or difference as

$$\begin{aligned} \text{clock error} &= \text{apparent delay} - \text{equipment delay} \\ &\quad - \text{signal delay} - \text{cycle delay}. \end{aligned} \tag{3}$$

The apparent delay was the value of delay measured, for example, with the time-interval counter shown in Fig. 2. A cycle correction existed if tick arrival was measured relative to any other point on the tick other than its beginning.

VIII. 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 subsatellite point as possible. These sites were NBS-Boulder (which was also the location of the transmitter), Air Force Cambridge Research Laboratory (ARCRL) 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 Fig. 2. 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. AFCRL maintained its time with a commerical cesium beam clock referenced to UTC through LORAN-C monitoring and portable clock carries by the standards laboratories of the Department of Defense. 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 deirved 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. The results for one site in North America and one in South America are shown in Fig. 7. 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.

The data show 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.

A general slope to some of the results was observed which was 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 two parts of the figure indicate the date of the orbital elements where new predictions began. As an

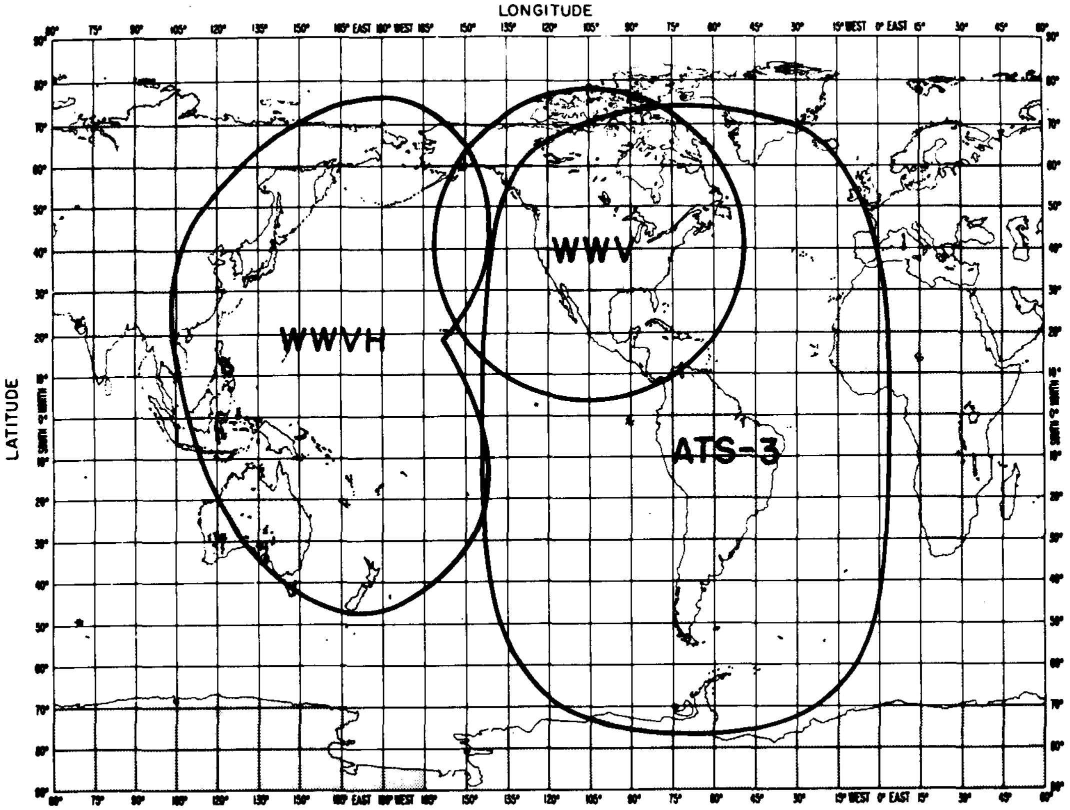


Fig. 8. Coverage showing reliability of reception (95 percent or better) for WWV, WWVH, and ATS-3.

example, in Fig. 7, 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. It should be noted also that the errors at 1700 and 2330 GMT were highly correlated and added confidence to the techniques used for measurement and orbit prediction.

IX. System Performance Comparison

This section is intended to inform the reader on how this experimental system compared with other operational modes which, at that time, were carrying time and frequency information. Primarily, the comparison was made with the NBS high-frequency stations, WWV and WWVH, the only civilian-oriented U. S. time and frequency service in operation, which the satellite experiment was attempting to imitate by virtue of its wide range of application and simplicity.

Shown in Fig. 8 are the approximate coverages of the ATS-3 satellite, WWV, and WWVH. WWV is located at Ft. Collins, Colo. and WWVH at Kauai, Hawaii. The satellite coverage has 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 delay 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 percent) and at varying levels of accuracy dependent upon conditions.

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.

One may obtain from Fig. 9 some additional feeling for the timing resolutions available from the two systems and the quality of the signals. Shown are oscilloscope photographs of the signal from the satellite anywhere in its coverage area. The top two oscilloscope displays show the ticks and tones as received from WWV and ATS-3. The varying amplitudes illustrating the fading and high noise levels associated with the WWV reception were noticeably absent from the ATS-3 signals. The lower two displays show ten ticks superimposed upon themselves, illustrating time-of-arrival for the WWV signals is about 300 μs, as compared to a few microseconds for the satellite-relayed ticks (not resolvable from this photograph).

The comparisons between WWV or WWVH and ATS-3 are summarized in Table II. Finally, a comparison of all

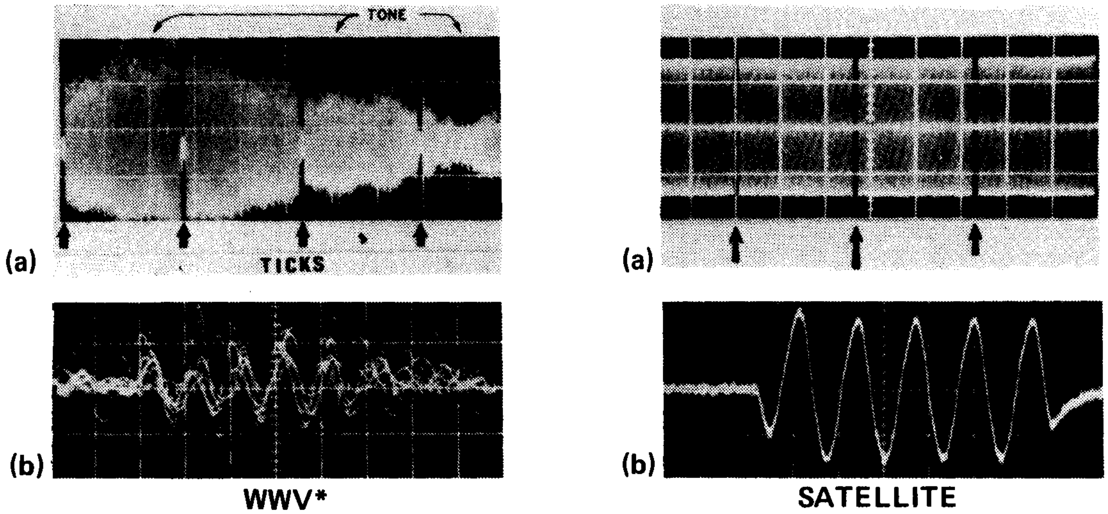


Fig. 9. Oscilloscope photographs of WWV and ATS-3 signals. (A) Ticks and tone shown together at a sweep speed of 0.3 s/cm. (B) Ten sweeps of tick superimposed. (Photographs of WWV reception reproduced from Hewlett-Packard Application Note 52 by permission.)

TABLE II

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

existing and proposed dissemination systems is shown in Table III. Some of these systems were operational and some experimental at the time this comparison was made.

X. Conclusions

This paper has described an experiment which revealed many of the potentials for broadcasting time and frequency information from geostationary satellites. A broadcast format very similar to the WWV format was used with effectiveness. The format for a permanent satellite time and frequency broadcast service shall require modifications over the format used in this experiment by virtue of its fundamental advantages over high-frequency broadcasts. Those advantages are higher signal-to-noise ratios, excellent short-term propagation path stability, wider available bandwidths, and freedom from fading and other propagation anomalies.

A fundamental characteristic of satellite-relayed signals is the long-term changing propagation path due to satellite motion. This difference is of significance to the intermediate- and high-accuracy time and frequency user, but can be handled effectively with simple and inexpensive user aids like the slide rule and delay overlays. Also, future satellites will have improved station-keeping capabilities which will reduce delay variations to less than 0.5 ms peak-to-peak and Doppler frequency shifts to only a few parts in 10^9 peak-to-peak.

Although the level of operation obtained in the experiment was not satisfactory for a national service, such as provided by WWV, it is obvious that satellites offer a means of meeting the growing needs for higher accuracy and more reliable time and frequency signals. The availability of satellite-relayed time and frequency information will expand the known applications for these signals. The high signal-to-noise ratios and freedom from fading will lend themselves to automatic equipment uses. Applications are projected in the electric industry where timing signals are required for fault monitoring and system regulation. Airports and environmental and geophysical monitoring sites will make use of the signals for automatic recording of time in parallel with the recording of designated events. The time and frequency needs in the transportation industry will benefit. Also, digital communications systems are moving to higher data rates and require increased synchronization capabilities.

As a final comment, it should be mentioned that satellite-relayed time signals can be adjusted to be of more usefulness than demonstrated in this experiment. The tick arriving at the Earth approximately one-fourth second late is not as convenient for the user as it would be if it were advanced at the transmitter by one-fourth second, thereby forcing it to arrive at all points on the ground nearly on time. The signal throughout the entire satellite coverage areas need never be more than a few milliseconds in error. No correction for delay would be needed by the low- or intermediate-accuracy user, thereby greatly simplifying the system for 90 percent 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 high-accuracy user. The transmitter-to-satellite link would, in effect, have a fixed delay.

TABLE III

Comparison 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	O	1×10^{11} (3)	■	PHASE ~50 µs	GLOBAL	□	□	▨	□	□	□
	NAVIGATION SYSTEM OMEGA	O/P	$< 1 \times 10^{11}$ (3)	≤ 10 µs■	PROPOSED CODE 1 YR PHASE ~100 µs	GLOBAL	□	□	▨	■	□	■
LF RADIO	STANDARD FREQ. BROADCAST (WWVB)	O	1×10^{11} (PHASE 24h) (3)	■	1 YR	■	□	□	■	■	■	□
	NAVIGATION SYSTEM LORAN C	O	1×10^{12} GND (3)	~1 µs(GND) 50 µs(SKY)	50ms PHASE 10 µs	■	□	□	■	□	■	▨
HF/MF RADIO	STANDARD FREQ. BROADCASTS (WWV)	O	■	■	1 DAY 0.5 min	HEMISPHERE	□	■	□	□	□	□
	NAVIGATION SYSTEM LORAN A	O	■	2.5 µs NOT UTC	■	■	□	■	■	□	▨	▨
TELEVISION (VHF/SHF RADIO)	PASSIVE LINE 10	O	1×10^{11} (24h)	~1 µs	1 DAY ~33ms	■	■	■	□	□	USA FOR EXAMPLE	□
	ACTIVE LINE 1 (NBS TV TIME SYSTEM)	E	1×10^{11} (< 30 min)	< 100ns▲	1 DAY ~33ms	■	□	■	□	□	USA FOR EXAMPLE	□
SATELLITES (VHF/UHF/SHF RADIO)	STATIONARY SATELLITES (TRANSPONDER) ONE WAY	E/O	■	■	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	O	■	0.5 50 µs	DEPENDS ON FORMAT	WORLD	■	■	■	■	□	▨
SHF RADIO	MICROWAVE	E/O	$\sim 1 \times 10^{13}$ (PER WEEK)	≤ 100ns	PHASE COMPARISON	■	□	□	■	□	■	▨
	VLBI	P	5×10^{14}	~1ns	DEPENDS ON FORMAT	HEMISPHERE	■	□	■	■	■	▨
PORTABLE CLOCKS	PHYSICAL TRANSFER	O	1×10^{12}	100ns●	1 DAY	■	AS NEEDED	□	NONE	■	■	□
	AIRCRAFT FLYOVER 2 WAY	E	1×10^{12}	≤ 100ns	DEPENDS ON FORMAT	■	■	□	■	■	■	▨
PULSARS	OPTICAL SIGNAL → NP 0532	P	1×10^{10}	~10 µs	~33ms	HEMISPHERE	▨	□	■	■	■	▨
AC POWER LINE	POWER NETWORK SYSTEM	P	■	■	16.7ms	▨	□	□	MINIMAL	MINIMAL	▨	□

GOOD □ FAIR ▨ POOR ■

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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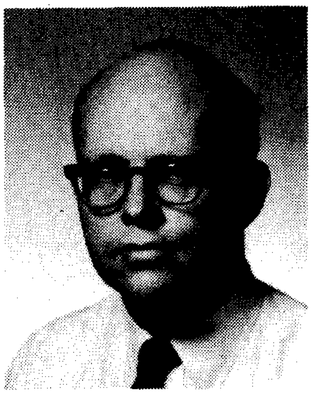

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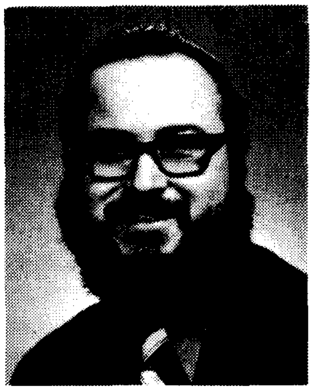

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