One-Way Time Synchronization via Geostationary Satellites at UHF

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Abstract—**This paper describes an experiment designed to evaluate the accuracy of one-way clock synchronization using geostationary satellites with the propagation delays calculated from the satellite's orbital elements. Propagation delays from a ground transmitter via satellite to each of five locations in the North and South American continents were measured and compared with the calculated values. Three months of data are presented along with descriptions of the equipment, timing signal format, and methods for delay calculation and time recovery.**

The results show that within two weeks of epoch for the orbital elements, clocks can be synchronized to 150 μs using the Tactical Communications Satellite (TACSAT). If one of the observers of the timing signals was already synchronized to the master clock, his delay measurement could improve the results for TACSAT to 75 μs. By the same method and within 12 hours of epoch, the results for the Lincoln Experimental Satellite-6 (LES-6) indicated that synchronization to 25 μs was possible.

I. INTRODUCTION

A NUMBER of time dissemination systems exist that permit remote clocks to be synchronized to a master clock by a listen-only, i.e., one-way, mode of operation. Systems such as WWV, WWVH, Loran-C, and Omega are examples. In each case, the propagation time from the transmitter to the observer must be known. The VLF and LF propagation delays can be established to an accuracy of a few microseconds. The MF and HF regions allow only millisecond accuracy in delay calibration. Delay calibration is usually a one-time requirement since the transmitter and observer are normally fixed in position and the delay remains constant.

Satellites have been used to transpond timing signals between a master clock and remote clocks. The major difficulty associated with this use of satellites is the variability in delay caused by satellite motion. The requirement of computing or measuring the delay has been avoided by a two-way exchange of time information between the master clock and remote clocks [1]–[4]. This exchange effectively eliminates the delay time from consideration but also limits the usefulness of the time dissemination system. Since only one user can be serviced at a time, there is system saturation. Also, each user must have a greater investment in equipment, i.e., a transmitter as well as a receiver.

One-way synchronization of clocks using satellites can be accomplished by either sending the information necessary to calculate path delay along with the timing signals as is done with the TRANSIT satellites [5] or by publishing satellite positions projected ahead in time from the satellite orbital elements. Orbital elements describe the satellite's orbit and position in that orbit at a given instant of time, usually referred to as its epoch. This paper describes experiments conducted by the National Bureau of Standards (NBS) to evaluate the accuracy of a one-way time dissemination system using earth synchronous satellites and path delays derived from orbital elements. Additional objectives of the experiments included the evaluation of user equipment requirements and determining the utility of certain timing signal formats. Constraints on the system design were accuracy in the 0.5-ms 10-μs region, low cost, and simplicity in the time recovery procedures.

Observations were carried out in North and South America by listening to the timing signals relayed through two Air Force experimental satellites, the Lincoln Experimental Satellite-6 (LES-6) and the Tactical Communications Satellite (TACSAT). The path delays measured during these observations were compared with the computed values obtained from the satellite's orbital elements and are presented in the results. Descriptions of the equipment used, signal format, and the method by which the delay computations were made are included.

II. MEASUREMENT

The major technical problem with one-way satellite time synchronization is the signal delay calculation. The path delay via the satellite cannot be calibrated in the normal sense because the satellite is in continuous motion relative to points on the earth's surface. Satellites are observed, however, resulting in descriptions of their orbit and position at a given time in that orbit. This information, issued approximately monthly, is in the form of six constants of motion called orbital elements. From these constants the position of the satellite, at any time, can be calculated.

The accuracy of these delay calculations can be checked by simply measuring the delay from a number of positions on the ground. In order to make the effects of cross-track, in-track, and radial calculation errors most readily apparent, the observing sites were dispersed around the subsatellite point as much as possible. Micro-

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second synchronization of the transmitter and all observers' clocks would allow an accurate measurement of delay. A signal from the ground transmitter would be initiated, for example, on the 1-pps tick and its arrival relative to the 1-pps tick of the observer's clock would be a measure of the path and equipment delay.

The straightforward approach would have been to use a fast rise pulse for reference. For microseconds resolution, however, such an approach would require wide bandwidth, high power, and expensive equipment. Since the ultimate objective of the time dissemination experiment was to serve the user at a minimum cost, the technique commonly used by tracking ranges known as side-tone ranging was adopted. A series of tones in the audio range was modulated onto a carrier and relayed through the satellites. Each tone was forced to maintain a fixed relationship to the 1-pps tick of the transmitter's master clock. An identical set of tones bearing the same relationship with their clock's 1-pps tick was also generated at each observing site. At the observer's site, the received tones were phase compared with corresponding locally generated tones using an oscilloscope. Those five phase comparisons when properly combined constituted the desired delay measurement. The lowest audio tone resolved the ambiguity of delay while the highest frequency tone provided the resolution. This method of delay measurement utilized only modest transmitter power and bandwidth requirements. An observer needed only a simple receiving system and the time recovery techniques were very straightforward.

The audio tones at the transmitter and at each observer's site were generated in essentially the same way. The 1-MHz standard frequency from the clock's oscillator, a cesium frequency standard, was divided down in steps of ten with outputs at 10 kHz, 1 kHz, 100 Hz, 10 Hz, and 1 Hz. The divider had a reset mechanism that, when activated by the 1-pps tick of the clock, aligned each of the outputs to have positive-going-zero crossings coincident with each 1-pps tick. The divider, constructed of digital logic, gave fast rise time square wave outputs (see Fig. 1.). Because the transmitter and observer's clocks were synchronized, all generated tones from each clock were in phase.

The transmitter carrier was modulated by these tones sequentially with each occupying 10 s of transmission time. The carrier was demodulated at the observing sites. The corresponding locally generated tone triggered an oscilloscope and the sweep rate of the scope was set to display one full cycle of the received tone. With the demodulated tone fed into the vertical input of the scope, the phase shift was determined from the point where the pulse began on the oscilloscope's face.

Photographs of the five phase-shift measurements and the resulting delay figure are shown in Figs. 2 and 3. The 1-Hz tone display shown in Fig. 2(a) was a result of a 1-kHz sine wave 100-percent amplitude modulated by the 1-Hz square wave. This in turn frequency modulated the carrier. The 10-Hz display was a combination of 1-kHz and a 10-Hz square wave. A 10-kHz sine wave was used with the 100-Hz and 1-kHz displays. The highest tone [Fig. 2(e)] was simply the 10-kHz tone without amplitude modulation. Due to a phase reversal in the baseband generating equipment, the 10-kHz tone was 180° out of phase with the square waves, and the negative-going zero crossing of the 10-kHz tone served as the reference point for the phase measurements shown in Figs. 2(d) and (e).

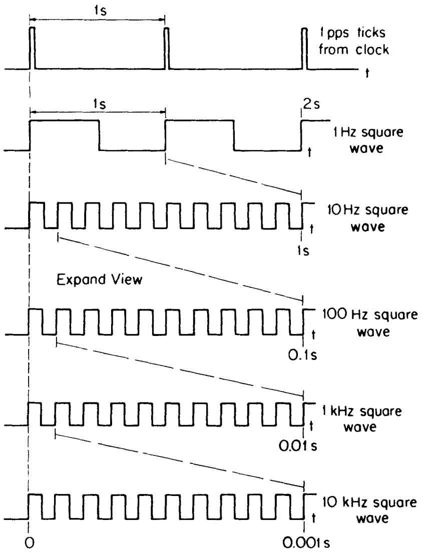


Fig. 1. Side-tone ranging signal baseband in relation to the 1-pps clock ticks.

Fig. 3 illustrates how the five phase measurements comprise the delay. Each phase measurement was estimated to two figures. The first digit was recorded above the second digit. Note that the scope face was divided into ten columns. The 1-Hz measurement was recorded in the first column of Fig. 3, the 10-Hz measurement in the second column, etc. Since the scope sweep nonlinearity limited the measurement to 5-percent accuracy, the second digit had value only as a check on the first digit in the preceding column.

Referring to Figs. 2 and 3, if the 100-Hz phase measurement had been recorded as a 79 instead of 80, the error would have been detected when the 1-kHz phase measurement was made. That phase measurement would have been recorded as 06 and this inconsistency easily noted by looking across the diagonals. In the example, a diagonal disagreement of the 9 and 0 would have necessitated a choice in favor of 80 rather than 79. After this check, the delay was obtained by reading across the top row and down the right-hand side. In Fig. 3, the delay was 258 063 μs.

This same delay measurement technique can be used by anyone wishing to synchronize a clock. If the clock were in error by some amount, a delay measurement would have that same error. Supplying the user with a computed delay would reveal the clock error and thus synchronize the clock to some assigned accuracy. The ac-

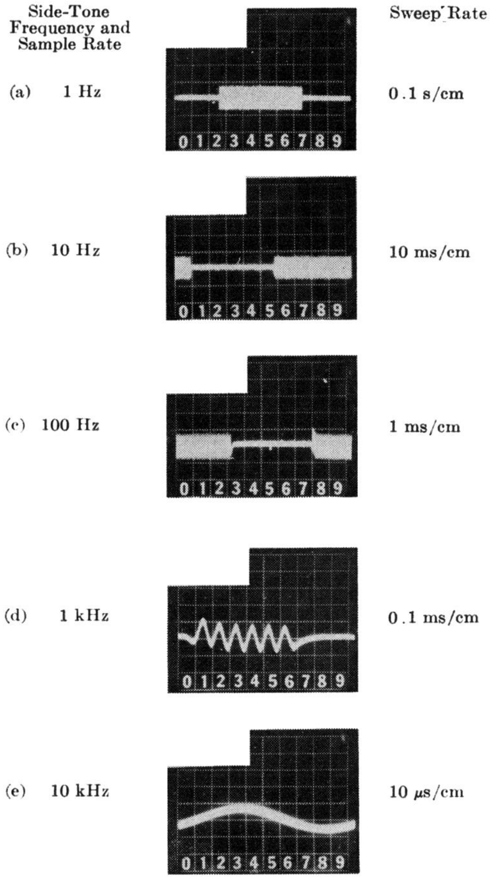


Fig. 2. Phase measurements by oscilloscope.

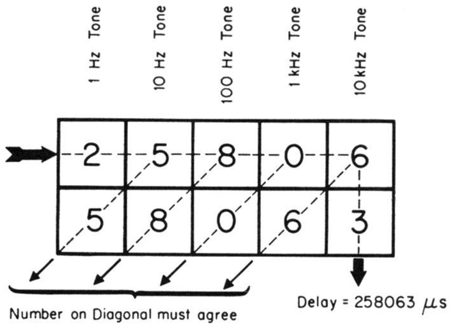


Fig. 3. Phase measurements converted into delay.

curacy depends upon the delay calculation and the frequency of the highest tone used in the timing format.

III. INSTRUMENTATION

A. Satellites

Two Air Force satellites, LES-6 and TACSAT [6]–[7], were used in the NBS experiments. LES-6 was developed by Lincoln Laboratories for an Air Force program. The UHF transponder operated at an uplink center frequency of 302.7 MHz and a downlink frequency of 249.1 MHz. For the experimental time system, the output power was approximately 40 W radiated through a circularly polarized antenna with 9.8-dB gain above isotropic. The satellite was station kept at approximately 40° west longitude providing coverage to latitudes of ±81° and longitudes of 120° west to 40° east.

TACSAT was designed for synchronous service and was located at approximately 107° west longitude through June 1970 after which it began movement to a new location. The 107° location, on the minor axis of the earth's equatorial plane, is a stationary point for a synchronous satellite. A satellite will remain in this position without station keeping [8]. The transponder operated at a 303.4-MHz uplink center frequency and at a 249.6-MHz downlink frequency. A radiated power of approximately 100 W was used with a circularly polarized 17-dB gain above isotropic antenna. The earth coverage, when the satellite was at the 107° location, extended to ±81° in latitude and 187° to 27° west longitude with a drop in antenna gain of 2.5 dB on the periphery of this coverage.

B. Master Clock and Ground Transmitter

The master clock and the transmitter were located at the M.I.T. Lincoln Laboratories. The master clock consisted of a commercial cesium frequency standard driving a frequency divider both operating from fail-safe power supplies. This clock was synchronized to Coordinated Universal Time (UTC), by periodic clock carries from the Air Force Cambridge Research Laboratories (AFCRL). AFCRL was in turn synchronized to UTC by the monitoring of the Loran-C transmissions, a relatively new technique utilizing TV synch pulses in the vertical interval [9], [10], and by clock carries from the United States Naval Observatory (USNO). Derived from the master clock's frequency standard were the group of five waveforms discussed previously. These five waveforms, transmitted sequentially, made up the basic timing signal format or baseband. The baseband frequency that modulated the 303-MHz carrier was amplified and radiated to the satellite. The deviation of the carrier was limited to restrict the energy spectrum to a 30-kHz bandwidth. The satellite received this signal, translated it to 249 MHz, amplified it, and reradiated it back toward earth.

C. Receiving System

The receiving system described does not represent an optimum choice in design or selection. The receivers used were available from another experimental satellite timing program that utilized the same baseband.

The receiving system shown in Fig. 4 is typical of that used at each observing site. The antenna, an 8-element linearly polarized Yagi, yielded 13-dB gain above isotropic. A 250- to 136-MHz downconverter with 30-dB gain and 2.5-dB noise figure followed the antenna. The receiver, intended for mobile communications, taxis, etc., was crystal controlled and modified for narrow-band 30-kHz FM. The video output of the receiver connected directly to the vertical input of an oscilloscope. The oscilloscope was triggered by the same five waveforms

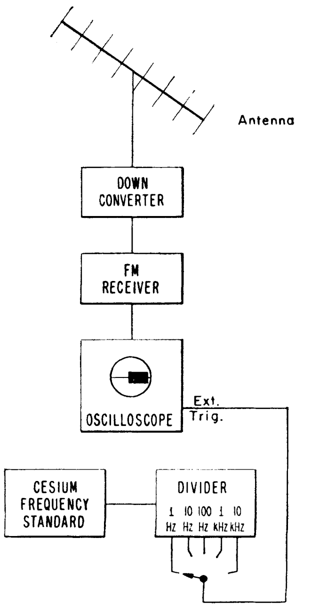


Fig. 4. Satellite time receiver with local clock for phase measurement.

used by the timing baseband and was generated by the user's clock.

Receiving systems like that just described were located at NBS in Boulder, Colo.; AFCRL in Bedford, Mass.; Newark Air Force Station (NAFS) in Columbus, Ohio; Air Force stellar camera sites in Curacao, Netherland Antilles; and Brasilia, Brazil. Fig. 5 shows locations of each receiver site. The NBS generates UTC and the NAFS maintains time to within microseconds of UTC. The AFCRL and the master clock at Lincoln Laboratories were synchronized to UTC in the manner previously discussed. The stellar camera sites synchronized their cesium clock to UTC through monthly clock carries referenced to NBS, Boulder. Each observer was therefore synchronized to UTC and to the master clock to within ±5 μs during the experiments.

D. Satellite to Ground Link

In Table I are the downlink calculations for the transmission of the timing signal between the satellite and the user located on the earth's surface. The uplink between the master clock or transmitter and the satellite involved a 30-foot (9.144-m) parabolic antenna on the ground with 50-W input power yielding a 44-dBW effective isotropic radiated power (EIRP).

E. Delay Measurement Error Budget

Table II shows the factors that contributed in establishing the error in the measurement of absolute delay from the transmitter to receiver via the satellite. Transmitter and receiver locations were assumed to be known to within a kilometer relative to each other, assuming the two points were not on the same continent. The ionosphere and troposphere contributed small errors due to the refractive index being other than free space value [11], [12]. Receiver resolution was limited by signal-to-noise ratio and by the phase measurement made with the use of an oscilloscope. The sum effect of the two causes was estimated at 10 percent of the wavelength of the highest tone or 10 μs. Equipment delay uncertainties were estimates based upon the method of measurement and might be improved with greater care.

IV. Results

Delay measurements were made using LES-6 and TACSAT from February through August 1970. LES-6 measurements were taken weekly on Tuesday mornings while TACSAT measurements were made twice a week on Tuesday and Thursday afternoons. In addition, LES-6 measurements were made once an hour for 24 hours on November 24 and 25, 1969. This was concurrent with an orbit determination on LES-6 done by Lincoln Laboratories.

At the present time, orbital data were not available on the majority of the LES-6 data but the 24-hour period will be discussed at the end of this section. Orbital elements for TACSAT were issued approximately every 30 days by the Air Force. These elements were supplied to NBS in instantaneous form.

The orbital elements described the satellite's position and velocity vectors at a given epoch. The problem, then, was to determine position and velocity at any other time from this information. The simplest approach, and the one that would yield the greatest inaccuracies, would be the classical two-body treatment. This method considered the earth to be a point mass and assumed the only other body of importance to be the satellite. There were, however, other forces that acted on the satellite. The sun and the moon's gravity fields as well as solar radiation perturbed the satellite's motion. Another, and very significant perturbing force, was caused by the nonuniformity of the earth's gravitational field.

Because the earth's gravitational potential may be asymptotically described by a harmonic series, Brouwer [13] was able to use this series to obtain a set of "mean" orbital elements. The two-body formulas then could be used to describe the average position of the satellite. Brouwer's method did not account for the other perturbations, so inaccuracies were still to be expected.

This approach was used to develop programs for a digital computer. Only the first few terms of the harmonic series were used. In the actual data analysis a Brouwer mean orbit was computed from the orbital elements at epoch. The two-body formulas were then used to generate mean orbital elements at the time at which delay measurements were made. Finally, the Brouwer process was reversed yielding osculating elements that more nearly described the satellite's actual position at the new time. The slant ranges from the satellite to the transmitter and observers were computed. The theoretical delay was then determined by computing the total range from the transmitter through the satellite

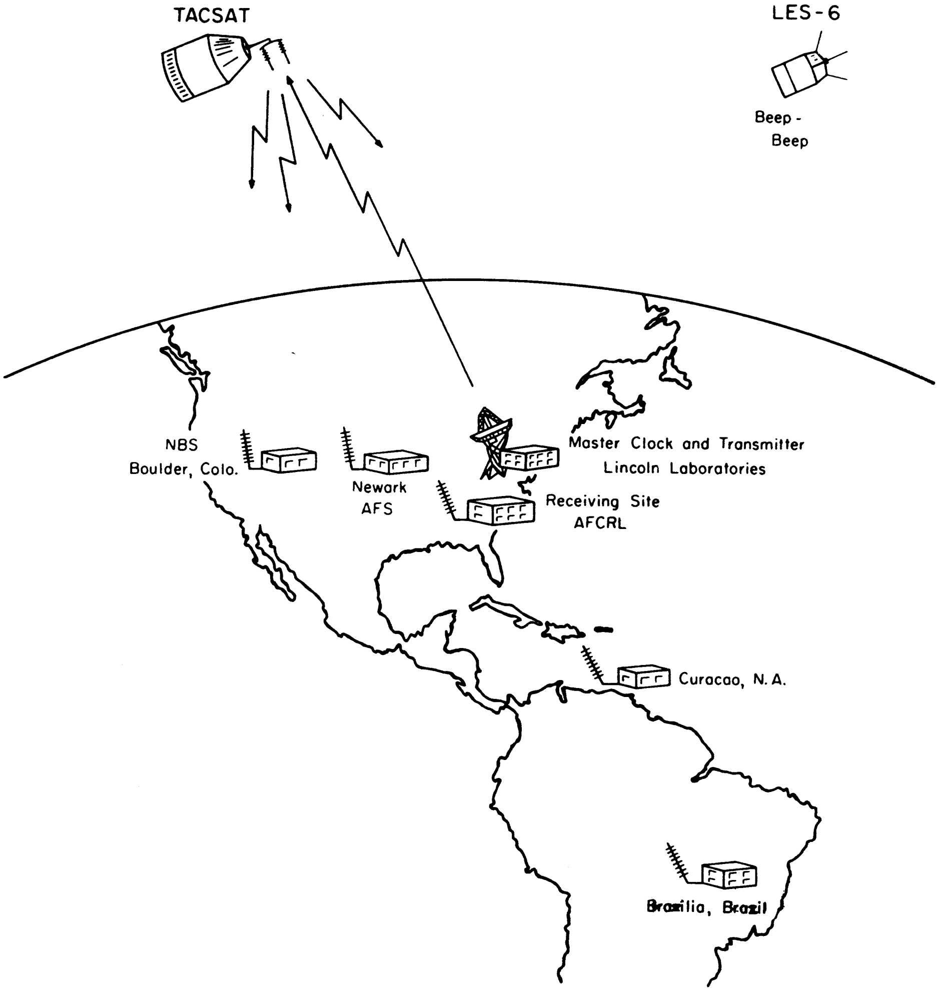


Fig. 5. Experimental satellite time relay network.

TABLE I
Down Link Signal-to-Noise Calculations

	TACSAT	LES-6
Satellite transmitter power	20 dBW	16 dBW
Satellite antenna gain	17 dB	10 dB
EIRP	37 dBW	26 dBW
Free space attenuation	173 dB	173 dB
Receiver antenna gain	13 dB	13 dB
Polarization coupling loss	3 dB	3 dB
Carrier power	−126 dBW	−137 dBW
Sky temperature	620 K	620 K
Receiver noise temperature	230 K	230 K
Receiver noise power per hertz	−200 dBW	−200 dBW
Receiver noise bandwidth	30 kHz	30 kHz
Receiver noise power	−155 dBW	−155 dBW
C/N ratio	29 dB	18 dB
FM improvement factor	3 dB	3 dB
S/N output	32 dB	21 dB

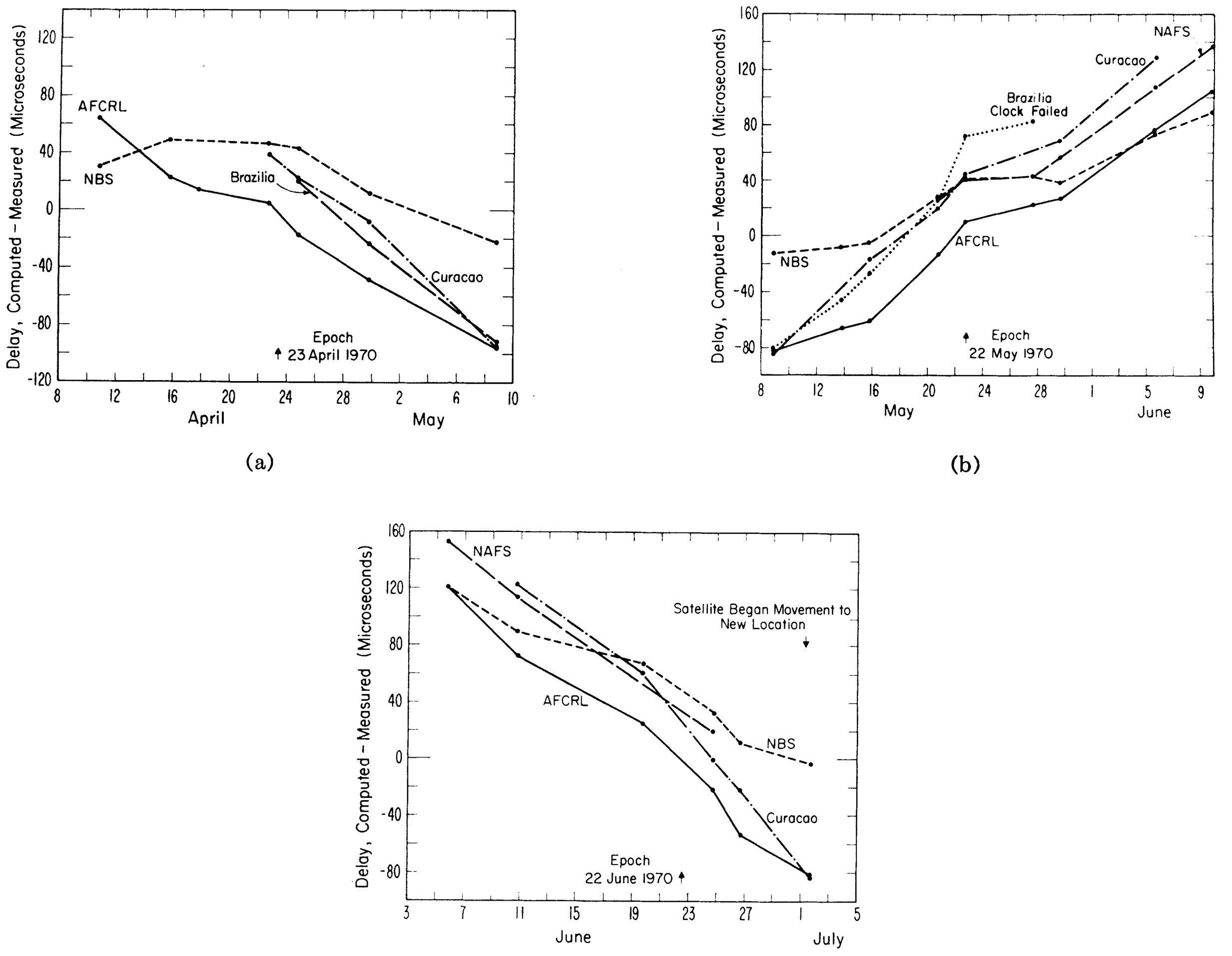
TABLE II
Delay Measurement Error Budget

Source	Maximum Error (μs)
Equipment	
Transmitter	±5
Satellite transponder	±1
Receiver	±10
Transmitter clock error	±5
Receiver clock error	±5
Receiver resolution	±10
Geometry	
Transmitter location	±2
Receiver location	±2
Propagation	
Ionosphere	±0.5
Troposphere	±0.3
rms total	±17

to the receiver site, assuming free space propagation velocity.

The measured delay was subtracted from this theoretical delay and the result graphed. Three of seven months' results appear in Fig. 6. The results show that for a four-week period centered about the epoch, the theoretical and measured delays agreed to within ±150 μs. Furthermore, the graphs have a decided linear trend. This slope is assumed to be primarily due to neglecting other perturbing forces in computing the satellite's position.

Since the curves in Fig. 6 always fell within ±75 μs of each other, the accuracy could be further improved as follows. An observer that was known to be on time, say



(a)

(b)

(c)

Fig. 6. Absolute delay measurements compared against calculations from orbital elements using TACSAT.

NBS, could communicate its theoretical minus measured delay. This additional correction would allow synchronization to within 75 μs of the master clock.

The only orbital elements available for LES-6 covered the 24 hours of measurement in November 1969. The master clock, however, had not yet been synchronized so a differential method of analysis was used. By subtracting the computed minus measured value for NBS from the same quantity for AFCRL, the only observers in operation at that time, any offset in the master clock was canceled. This left only the difference between the NBS and AFCRL clocks and some measure of the inaccuracies in delay calculations. Fig. 7 shows that the differential delays were in agreement to within plus or minus 25 μs, approximately the resolution of the measurements. It must be noted that simultaneously with our 24-hour measurements, Lincoln Laboratories was collecting the data necessary to calculate orbital elements. This allowed very accurate calculation of the satellite's position and accounts for the quality of the results.

V. CONCLUSIONS

The delay measurements made with TACSAT have established that within a two-week period of epoch, clocks can be synchronized to 150 μs. With additional input from observers already synchronized to the master clock, an appreciable improvement was realized. These results are especially significant considering the extent of geographic coverage, modest user equipment costs, and the simplicity of equipment operation and time recovery.

The results of the measurements cannot be assumed to apply to all satellites. The quality of orbital elements will certainly vary, depending upon how they were obtained and to what use they were intended. We were also limited by the accuracy of our delay measurements, and the full potential of these orbital elements for delay calculations may not have been revealed.

When higher accuracy delay measurements are available, it will probably be advantageous to include more of the perturbating forces in the calculation of satellite position. For these measurements, the inclusion of more perturbation forces probably would have removed the

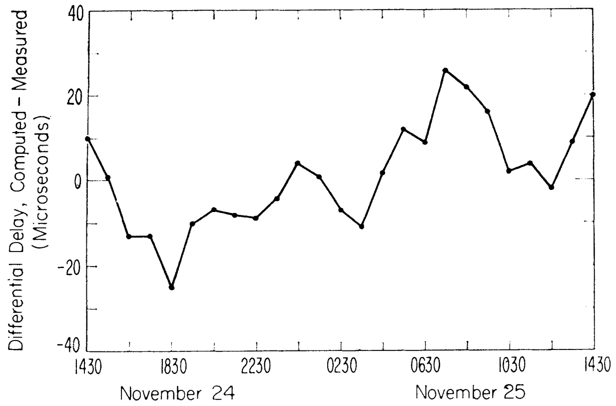


Fig. 7. Differential delay: computed minus measured for AFCRL and NBS using LES-6.

slope from the results. It is doubtful that the results would have been brought closer together. This is indicated by the fact that the curves have approximately the same scatter at epoch as at any other time. At epoch, the orbital elements contain the effects of all perturbations and the resulting calculated satellite position would be most accurate here. In other words, the quality of the orbital elements was indicated by the measurements made at epoch.

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