Clock Synchronization from Satellite Tracking

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Abstract

The tracking of synchronous satellites to provide propagation delays for the synchronization of clocks is described. The tracking is accomplished by range measurements to the satellite from three stations using signals transponded by the satellite. These same signals also functioned as the timing signals for the synchronization of other stations' clocks. Although the range measurements were of low resolution by usual standards, approximately 3000 meters, they provided the delays necessary to synchronize clocks to 40 microseconds or better. These results were obtained over a 4-month period using two satellites with measurements from five stations in the United States and South America.

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I. Introduction

Propagation delays are a necessary piece of information to the synchronization of clocks by radio. In most cases, the delays can be calculated or can be calibrated through clock carries. When satellites are used to transpond the timing signals, calculation or calibration of the delay becomes difficult and complicated due to the satellite motion. Calculation is possible, however, by utilizing the satellite orbital elements [1]. Orbital elements describe the satellite orbit and the satellite position in that orbit at a given instant of time, usually referred to as its epoch. From the elements, the satellite position at any other time may be calculated. The calculated position will be most accurate at epoch and will become increasingly in error with time from the epoch. The quality of the elements varies depending upon how they were generated and to what purpose they were intended. Without adequate assurance of the quality of the elements or an independent check as to their accuracy, it is wise to limit the synchronization of clocks with the delays calculated in this manner to times at or near epoch. It is usual practice to generate these elements no more than once per month. Because orbital elements are normally generated from measurements made by sophisticated tracking facilities with large computers, more frequent generation of elements solely for the purpose of clock synchronization would be, for most situations, impractical.

Development of a more simplified approach to delay calculations was the subject of experiments by the National Bureau of Standards. By simply measuring the range to the satellite from three stations during the transmission of timing signals, the satellite position was determined and the corresponding delays to any point calculated. This three-station trilateration of the satellite was accomplished simultaneously with the synchronization of clocks of other stations because the same signals provided both functions. The tracking stations were passive or listen-only and, in terms of modern tracking ranges, possessed only low-range resolution, approximately 3000 meters. The equipment required for the tracking of the satellite or synchronization of clocks was identical and included a simple FM receiver, an oscilloscope, a clock, and a special-purpose frequency divider.

Using the Lincoln Experimental Satellite-Six (LES-6) and the Tactical Communications Satellite (TACSAT), measurements were made of the delay or range[1] from five stations, two in South America and three in the United States. Three of these five measurements were selected for use in the determination of the satellite position. The remaining two measurements (in some cases only one measurement was available) were compared to the delays calculated from the satellite position. The comparisons between these measured and computed delays agreed to

[1] Delay and range are used interchangeably because they were assumed to be related by a constant, the free space velocity of light. The ionosphere and troposphere had little effect on total delays at the frequencies involved in these experiments.

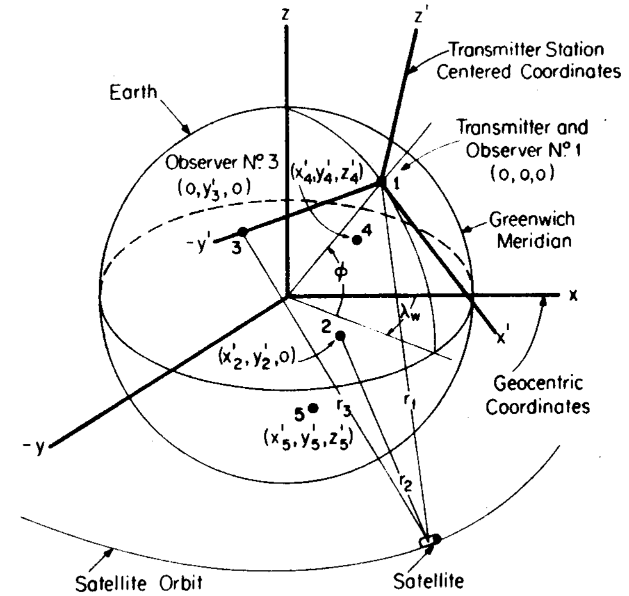

Fig. 1. Geometry of observers and satellite with respect to coordinate systems used.

within 40 microseconds. The results indicated a small bias which had a rms scatter about the mean of less than 15 microseconds.

II. Geometry

The geometry involved in the measurements is illustrated in Fig. 1. Three stations on the earth's surface at distances from the satellite of r_1, r_2, and r_3 are shown. Since the geocentric coordinates of these three stations were known, the satellite position in this coordinate frame was fixed. The station coordinates were given by geodetic longitude, latitude, and altitude. Conversion to Cartesian form was accomplished by the transformations given in (1) through (4) [2]:

$$x = (\nu + h + N) \cos \varphi \cos \lambda \tag{1}$$

$$y = (\nu + h + N) \cos \varphi \sin \lambda \tag{2}$$

$$z = [(1 - e^2)\nu + h + N] \sin \varphi \tag{3}$$

$$\nu = a/(1 - e^2 \sin^2 \varphi)^{1/2} \tag{4}$$

where

a = the earth's semimajor axis
e = the earth's eccentricity
N = the height of geoid above the spheroid
h = the height above the geoid
φ = the geodetic latitude
λ = the geodetic longitude.

These geocentric coordinates had the z axis parallel to the earth's axis of rotation with the x axis in the Greenwich meridian plane.

The solution of the three range equations involving the station coordinates and ranges r_1, r_2, and r_3, for the satellite's position, was simplified by a transformation of coordinates. The new coordinates, (x', y', z'), placed the three stations at $(0, 0, 0)$, $(x_2', y_2', 0)$, and $(0, y_3', 0)$, as shown in Fig. 1. These transformations were obtained by

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} x - x_1 \\ y - y_1 \\ z - z_1 \end{bmatrix} \tag{5}$$

where, after translation of the geocentric coordinates origin to the station coordinates (x_1, y_1, z_1), α was the angle of rotation about the x axis necessary to bring the third site into the x-y plane, β was the angle of rotation about the new z axis necessary to make the third site lie on the y axis, and θ was the angle of rotation about the resulting y axis necessary to bring site 2 into the x-y plane. Those rotations were given by

$$\alpha = \sin^{-1} \frac{z_3 - z_1}{[(y_3 - y_1)^2 + (z_3 - z_1)^2]^{1/2}} \tag{6}$$

$$\beta = -\sin^{-1} \frac{(x_3 - x_1)}{\{(x_3 - x_1)^2 + [(y_3 - y_1)\cos\alpha + (z_3 - z_1)\sin\alpha]^2\}^{1/2}} \tag{7}$$

$$\theta = -\sin^{-1} \frac{-(y_2 - y_1)\sin\alpha + (z_2 - z_1)\cos\alpha}{\{[(x_2 - x_1)\cos\beta + (y_2 - y_1)\sin\beta\cos\alpha + (z_2 - z_1)\sin\beta\sin\alpha]^2 + [(z_2 - z_1)\cos\alpha - (y_2 - y_1)\sin\alpha]^2\}^{1/2}} \tag{8}$$

where x, y, and z refer to the geocentric Cartesian coordinates.

Finally, the satellite's position in the new coordinate system was given by

$$x_s' = \frac{1}{2x_2'} \left[r_1^2 - r_2^2 + x_2'^2 + y_2'^2 + \frac{y_2'}{y_3'} (r_3^2 - r_1^2 - y_3'^2) \right] \tag{9}$$

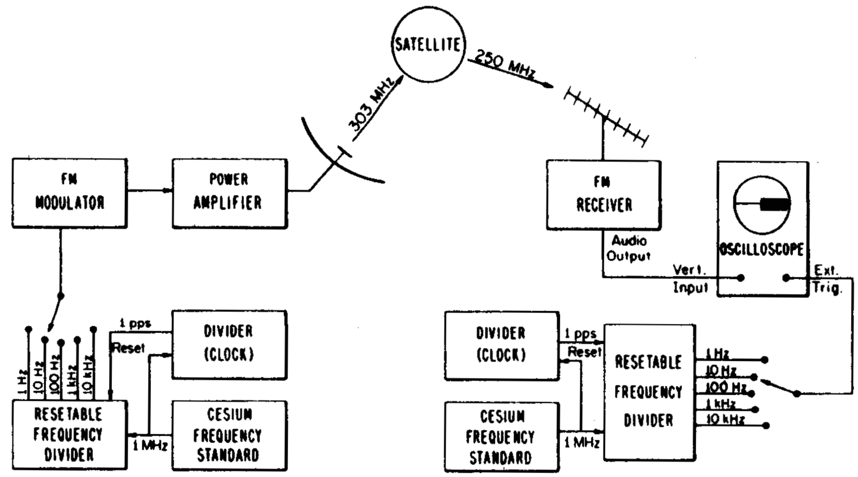

Fig. 2. Block diagram of ranging or clock synchronization equipment.

$$y_s' = \frac{1}{2y_3'}(r_1^2 - r_3^2 + y_3'^2) \tag{10}$$

$$z_s' = (r_1^2 - x_s'^2 - y_s'^2)^{1/2}. \tag{11}$$

The measurements made in these experiments, however, did not yield r_1, r_2, and r_3 directly. Since the tracking stations were passive, they measured the range from the transmitter to each station via the satellite and the delays in the transmitter, satellite transponder, and station receiver. To obtain r_1, r_2, and r_3 it was necessary to remove the equipment delays from the measurements and to insure that one of the three resulting range values contained r_1 only. An observing station located in close proximity to the transmitter and denoted as station 1 at (0, 0, 0) provided, for all practical purposes, $2r_1$. The other two stations provided $r_1 + r_2$ and $r_1 + r_3$. Simple algebra then gave the required r_1, r_2, and r_3. The two remaining stations not performing the tracking function provided $r_1 + r_4$ and $r_1 + r_5$.

Equipment delays were carefully measured. The satellite transponder delays were measured prior to launch by the organizations responsible for their development. The transmitter delay was measured by the M.I.T. Lincoln Laboratories. The receiver delays were measured periodically during the course of the experiments by NBS. Total equipment delay uncertainty was estimated to be less than 10 microseconds.

During the measurements of delay or range, the satellite LES-6 was located at approximately 40 degrees west longitude. The TACSAT satellite was located at 107 degrees west longitude until the first of July 1970, when it began movement to a new location.

III. Timing and Ranging Signals

The signals used for clock synchronization and ranging in these experiments are commonly referred to as side-tone ranging signals. For these measurements, five audio tones were modulated sequentially onto a carrier in 10-second intervals and transmitted to the satellite. The carrier, at 303 MHz, was translated to approximately 250 MHz by the satellite transponder and reradiated back to the earth. The tones, recovered by demodulation in the observer receiver, had acquired a phase shift proportional to the transit time between the transmitter and observer. Phase comparison of these tones with an identical set of tones generated by the observer clock determines a delay. Elaborating a little further, in each case the transmitter clock and each observer clock were periodically synchronized such that they were always within 5 microseconds of Coordinated Universal Time (UTC). As shown in Fig. 2, the 1-pps tick from each clock being fed into a resettable frequency divider forced the five coherent waveforms to have a positive-going zero crossing coincident with that 1-pps tick. Upon reception of the satellite transponded tone, the observer compared the phase of these tones with his locally generated tones by use of an oscilloscope. Beginning with the 1-Hz tone, the frequency of the tones was increased by factors of 10 in five steps, finally resolving the measured delay to 10 microseconds with the 10-kHz tone; i.e., the oscilloscope nonlinearity and post detection signal-to-noise ratio limited the phase measurement resolution to 10 percent of the highest wavelength. This same procedure for delay measurement has been used previously [3].

Fig. 3 shows the oscilloscope display of five consecutively received side-tone waveforms. Except for the 10-kHz tone, which was a sinusoid, the other four tones were composite waves, consisting of a square wave at the side-tone frequency which 100 percent amplitude modulated a subcarrier. The subcarrier frequency was 1-kHz for the 1- and 10-Hz tones and 10 kHz for the 100-Hz and 1-kHz tones. Because of a phase reversal in the format generation equipment, a negative-going crossing of the 10-kHz tone was coincident with the positive-going edge of the square waves; therefore, the point in Fig. 3(D) and (E) where the 10-kHz subcarrier first goes negative serves as the phase reference. The measured delay as read from this

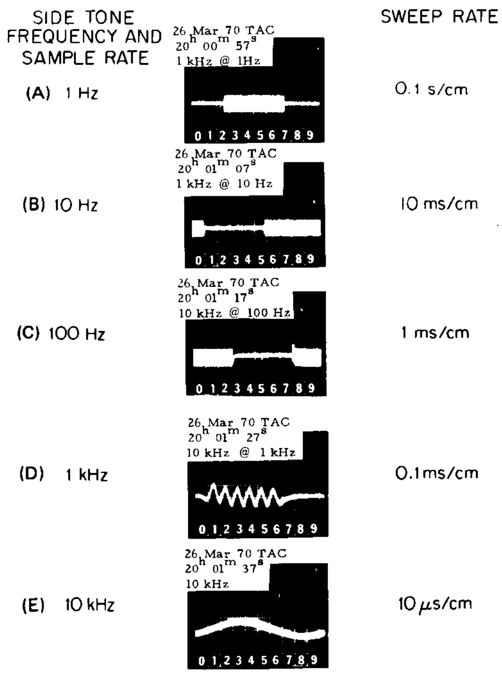

Fig. 3. Phase measurements by oscilloscope. The notations in the upper left corner give time when taken and frequency of subcarrier and tone.

figure was 258063 ± 10 microseconds. This delay measurement included the path and all intervening equipment delays.

The mechanics for clock synchronization by an observer are as follows. The observer would measure an apparent delay from the transmitter to his position via the satellite using his clock to generate the appropriate waveforms for reference. If his 1-pps ticks were not in time coincidence with the 1-pps ticks of the master clock located at the transmitter, the difference would be included in the delay measured. The delay calculated from the satellite's position when compared against the measured delay would then reveal the time differences in the 1-pps ticks.

IV. Results

Between April and August 1970, the timing-ranging signals were transponded by two satellites from a transmitter and master clock located at the M.I.T. Lincoln Laboratories. Path delays were measured to five observers during these transmissions. These observers included the Air Force Cambridge Research Laboratories (AFCRL), Bedford, Mass.; Newark Air Force Station (NAFS), Boulder, Colo.; and Air Force stellar camera sites in Curacao, Netherland Antilles, and Brasilia, Brazil. The AFCRL was located only a few thousand feet from the transmitter at Lincoln Laboratories, close enough to assume the delay measured corresponded to the range of $2r_1$.

The three observers selected to perform the satellite tracking function were AFCRL, Curacao, and NBS-Boulder. This choice of sites for tracking was made because they provided the most dispersed triangle for fixing the satellite position and the greatest available amount of data. After fully accounting for clock differences and equipment delays, the satellite position was calculated based upon (1) through (11). The delays corresponding to $r_1 + r_4$ and $r_1 + r_5$ were then computed from the satellite's position determined by trilateration and compared with the measured delays. The differences, measured minus computed, were tabulated and are shown in Tables I and II.

TABLE I

Measured Minus Computed Delay. Tracking Stations: AFCRL-NBS-Curacao; Satellite: TACSAT

Date	Delay: Measured–Computed (microseconds)	
	NAFS	Brasilia
April 23		-44
May 7		2
May 14		-32
May 19	20	-18
May 21	19	-9
May 28	25	
June 4	29	
June 9	34	
June 23	25	
July 14	9	
July 21	31	
July 23	14	

TABLE II

Measured Minus Computed Delay. Tracking Stations: AFCRL-NBS-Curacao; Satellite: LES-6

Date	Delay: Measured–Computed (microseconds)
	NAFS
May 5	-10
May 19	-42
June 2	-7
June 9	1
June 23	-21
July 14	-27
July 21	-2
Aug. 5	3

The results appeared to have some bias or systematic error. Although not enough data was available to justify a statistical analysis, it is worthwhile to note that the standard deviation about the bias was less than 15 microseconds. This deviation was about equal to the estimated delay measurement resolution. The bias when using TACSAT amounted to 20 microseconds at NAFS and −20 microseconds at Brasilia. The bias was −13 microseconds at NAFS when using LES-6. The source of this apparent bias was not determined. There was not sufficient data or observing stations to deduce its source. A check was attempted, however, by using the tracking stations, AFCRL-NBS-Brasilia. The results were, in effect, identical. Other triangles like AFCRL-NAFS-NBS were too weak or obtuse to yield consistent results. The most likely sources to produce a bias were clock errors and measurement errors at the tracking or observing sites. Another source for error, but of a smaller magnitude, would arise from errors in the positions of observers relative to the geocentric coordinate system.

V. Conclusions

The potential for simultaneous satellite tracking and synchronization of clocks other than the tracking site clocks was successfully demonstrated in these experiments. The results showed that clocks could be synchronized to approximately 40 microseconds. If the systematic errors are removed and the delay measurement resolution improved, a 1- to 10-microsecond synchronization should be realized. The system used was quite inexpensive to implement and operate. For special applications, a system similar to that described should prove operationally and economically superior to the existing approaches to clock synchronization, such as the flying clock.

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