WORLDWIDE CLOCK SYNCHRONIZATION USING A SYNCHRONOUS SATELLITE

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Worldwide Clock Synchronization Using a Synchronous Satellite

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Abstract—**An experiment performed in late 1967 is reported which investigated the synchronization of widely separated clocks. One-way VHF timing signals were relayed to remote clocks from a reference clock by means of a transponder on a geostationary satellite. The problem of synchronizing clocks using one-way transmission reduces to the problem of predicting the radio propagation delay. The accuracy of predicting the delay was 10 μs or 60 μs depending on the method used. This technique may offer an alternative to transporting atomic standards to geodetic and spacecraft tracking stations around the world in fulfillment of their clock synchronization requirements.**

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Introduction

CONSIDER a time dissemination system wherein time information derived from a reference clock is broadcast to users who compare the received time with that of their local clocks. The problem of measuring the time difference between a local clock and a remote reference clock reduces to predicting the propagation delay experienced by the radio wave. Station WWV is the transmitter for one such system. The accuracy of predictability of the propagation delay associated with the HF transmissions from WWV is limited to the millisecond region for most users. This limitation arises from the inability to predict the exact route a radio signal follows to the user and from the difficulty of defining the radio refractive index at all points along the path.

The principal advantage of using a geostationary satellite transponder is that the radio path is predominately a free-space line-of-sight path which is more predictable. Those portions of the path for which radio refractive index is a variable constitute only a small percentage of the total path.

Clock synchronization techniques involving two-way transmissions relayed by a satellite transponder between the reference and remote clocks have been described in the literature [1]–[4]. The technique described is of interest because in a one-way system the remote clock station would be relatively simple, cheap, and easy to operate, and the location would not have to be revealed by radio transmissions [5]. Any number of remote clocks could be synchronized simultaneously to the reference clock.

I. Description of Techniques

A. Definitions of Terms Used

Master Clock: the clock that is designated as the time reference point in comparing two or more clocks.

Slave Clock: a clock that is to be synchronized or referenced to the master clock.

Mode I: a satellite clock-synchronization technique involving a one-way communication channel from the master clock to the slave clock, similar in principal to WWV.

Round Robin: a technique for checking Mode II clock synchronization accuracies in a network of three or more stations.

Mode II: a satellite clock-synchronization technique involving a two-way communication channel between the master and slave clocks.

Clock Synchronization: (as used in this paper) the measurement of the time difference between two clocks.

B. Description of the Mode I Clock-Synchronization Technique

In the technique under investigation, Mode I, time signals are sent from the master clock to the slave clock via the satellite. The slave station measures the time difference between the slave clock and the received time signal. Consider the simplest case where the time difference between the master and slave clocks is zero (see Fig. 1). The master station transmits a one-pps signal format, and the slave station oscilloscope displays the received signal format. The sweep speed of the oscilloscope is set to 0.1 cm per second in order to display one sweep per second. Assume that all equipment delays are zero. Since the transmitted pulse train and the slave oscilloscope triggering pulse train are time coincident, the delay from the start of the sweep to the leading edge of the received pulse is equal to the radio propagation delay.

In general, there will be a time difference τ between the master and slave clocks and the equipment delays will be greater than zero. Then the measured delay on the slave oscilloscope will consist of four terms:

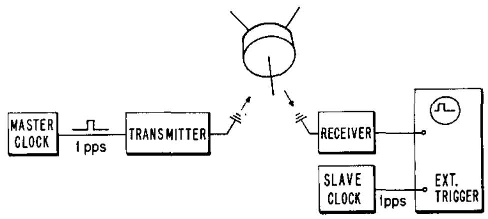

Fig. 1. Block diagram of Mode I clock-synchronization system.

$$R_s = -\tau + P + D_{ms} + D_s,\ \tau < (P + D_{ms} + D_s) \quad (1)$$

where R_s = the reading of the time difference between the slave-clock time tick and the received master-clock time tick, τ = algebraic time difference between master and slave clocks (referred to the master clock), P = radio propagation delay, D_{ms} = sum of the delays of the master transmitting equipment and the slave receiving equipment, and D_s = time delay of the transponder in the satellite.

The problem is to determine the value of τ. The D_{ms} and R_s are measured, D_s must be known, and P is computed. Using these values in (1), τ can be obtained.

With the master transmitting 1 pps the slave can measure τ with an accuracy of perhaps 0.01 second. If the frequency of the transmitted pulse train and the slave oscilloscope triggering train is increased by a factor of 10, the resolution of τ is increased by 10. This process can be continued until limitations are imposed by the system bandwidth. The transmitted 1 pps, 10 pps, 100 pps, etc., are derived from the master clock and they are coherent. Correspondingly, coherent oscilloscope triggering pulse trains are derived from the slave clock.

1) Corrections to Mode I Propagation Delay Calculations to Take Account of Ionospheric Effects: The propagation delay of the radio signals is increased over the free-space value when they pass through the ionospheric layer. An estimate of the increment of delay may be obtained from the relationship

$$\Delta l = \frac{b}{\omega^2}\left[\int_0^s N dh\right]. \quad (2)$$

Here, Δl is the increase in the group path due to the wave traveling through the ionosphere, $b = e^2/(2\ \epsilon_0 M) = 1.6 \times 10^3$ (e is the electronic charge, ϵ_0 is the dielectric constant of free space, M is the mass of the electron), $\omega = 2\pi f$, (f is the signal carrier frequency), and N is the "effective" electron density. The unknown to be determined in the equation is the value of N.

It is possible, in theory at least, to determine N from the measured penetration frequency at vertical incidence. However, such data may not generally be available and therefore another approach was used which seemed suitable for the time accuracies desired here.

Lawrence *et al.* [6] indicate that the value of the integral $[\int_0^s N dh]$ may vary from 10^{16} to 10^{18} electrons for vertical quasi-longitudinal propagation through a square meter column of the layer. These are the midday values encountered during a sunspot cycle, the maximum value being correlated with the maximum of the sunspot cycle and vice versa. Allowance must be made for the longer path length through the ionosphere for nonvertical propagation. Quasi-longitudinal propagation at VHF implies that the angle between the radio ray path and the earth's magnetic field is less than 89° [7]. This condition holds true for almost all locations other than the subsatellite point.

During the measurements reported here, the sunspot number was about 130 [8], which is the average maximum value for several previous sunspot cycles. Therefore, the value of the integral was chosen as 10^{18}.

Making use of this value of the integral, (2) indicates that the midday increase over the free-space value in one-way group delay of a 135-MHz radio signal traveling vertically through the ionosphere is 7 μs. The nighttime increase may be as small as 1 μs. The uncertainty due to the variability of the sunspot number at corresponding phases of several cycles is estimated to be ± 3 μs for a vertical path.

2) *Mode I Timing Error Due to Uncertainty of Receiving Site Location:* A determination of the propagation delay requires knowledge of the satellite orbit and the coordinates of both the master and slave stations. The approximate uncertainty in the time synchronization Δt of the slave clock due to the uncertainty in its location, Δd, may be calculated. The geometry is depicted in Fig. 2. It is assumed that the locations of the satellite and the master clock are accurately known so that the time at which the signal leaves the satellite is known. Assuming a spherical earth, it may be shown that

$$\Delta d = r\Delta\theta \cong \frac{c'\Delta t[r^2 + (h+r)^2 - 2r(h+r)\cos\theta]^{1/2}}{(h+r)\sin\theta}, \qquad 0 \leq \theta < \frac{\pi}{2} \tag{3}$$

where c' is the effective propagation velocity of the radio signal, r is the earth radius, h is the height of the satellite above the earth, θ is the angle subtended at the earth's center by the satellite and the slave station, and $\Delta\theta$ is the uncertainty in θ due to the uncertainty in the location of the slave station. Equation (3) contains an approximation but is in error by less than 1 percent for values of $\Delta\theta$ less than 8°.

To utilize (3), a parametric curve has been plotted. Fig. 3 illustrates the relationship for $\Delta T = 10$ and 100 μs. At $\theta = 30°$, for example, the slave-clock location must be known to 5 km in order to synchronize it to an accuracy of 10 μs using the Mode I technique.

The effect of a height error can be seen by referring to Fig. 2. At the earth tangent a change in r has no effect on the range to the satellite. At the subsatellite point, however, the range to the satellite changes linearly with the change in distance of the ground station from the center of the earth. At that point there is a timing error of 3 μs per km of height error.

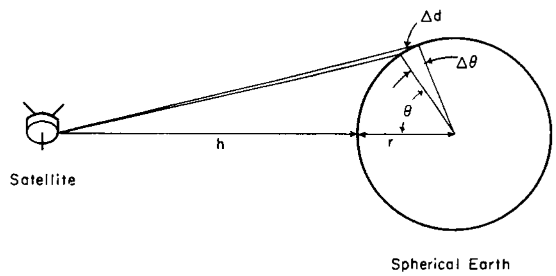

Fig. 2. Geometry of the experiment.

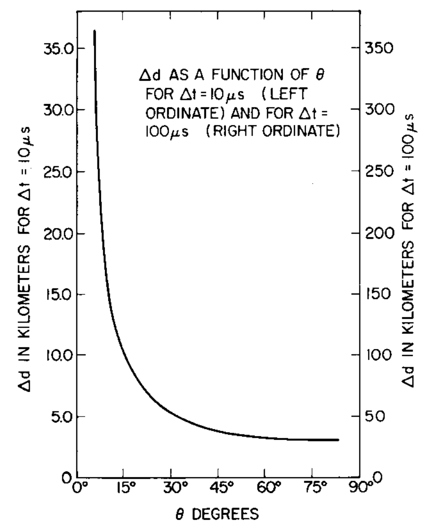

Fig. 3. Time sensitivity of station coordinates.

C. Description of Mode II Clock-Synchronization Technique

This method, which has been used and reported on before [3], was used in support of the Mode I experiment to check the time differences between the station clocks. The locations and ranges of the master and slave clocks need not be known, but both master and slave stations must have transmitters. The slave clock is synchronized as follows: From (1) the master station transmits a 1-pps time signal and the slave observes a time difference R_s:

$$R_s = -\tau + P + D_{ms} + D_s$$

as described in Mode I.

Then the slave station transmits back to the master, which will observe a time difference R_m, where

$$R_m = +\tau + P + D_{sm} + D_s; \tag{4}$$

D_{sm} is the delay associated with the slave transmitting and master receiving equipment, and the other terms are as defined in (1). If radio path reciprocity holds, one can subtract (1) from (4) and solve for τ, thus:

$$\tau = \tfrac{1}{2}[R_s - R_m] + \tfrac{1}{2}[D_{sm} - D_{ms}]. \tag{5}$$

TABLE I

Station	Latitude (°N)	Longitude (°W)	Elevation (meters)	θ (Fig. 2) (approx.)	Magnetic Dip Angle (approx.)	Satellite Range (km)	Satellite Elevation Angle Above Horizon
N	40	105.3	1659	64°	43°	39×10^3	25.26°
V	35.2	116.8	1213	53°	26°	38×10^3	36.24°
A	61.2	149.6	37	63°	43°	39.5×10^3	20.57°

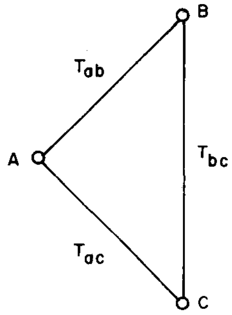

Fig. 4. Round robin check.

Equation (5) describes the case where the clock time difference is less than the sum of the propagation and equipment delays (about a fourth of a second), as in the Mode I discussion.

1) Description of a Mode II Check—Round Robin: A useful check on the accuracy of Mode II synchronizations has been devised for a system of three or more clocks. Fig. 4 shows that

$$T_{ac} = T_{ab} + T_{bc} \tag{6}$$

where T_{ac} is the time difference between the clock at Station A and the clock at Station B referred to clock A, etc.

The time closure C is given by

$$C = \left| T_{ac} - (T_{ab} + T_{bc}) \right| \tag{7}$$

and should normally be zero.

The technique is useful in determining whether certain types of operator errors have been made at any station. For example, an oscilloscope trigger slope switch was set incorrectly on several occasions during these measurements. This gave rise to a 50-μs error which was disclosed by applying the round robin technique.

II. Description of the Experiment

A. The Satellite VHF Transponder

The NASA satellite ATS-1 was launched in December, 1966, in near stationary orbit. A part of the ATS satellite system is devoted to supporting experiments at VHF. Signals received at 149.220 MHz with frequency modulation are converted to 135.600 MHz for retransmission to earth. An eight-element phased-array antenna system operating in duplex is used for both receiving and transmitting, while simultaneous signal limiting and bandwidth filtering are employed in the satellite signal chain. Because of this, amplitude modulation is not possible at full satellite power levels and the overall system bandwidth is restricted to 100 kHz. For this experiment frequency modulation was employed. The time delay of the VHF transponder is 7 μs [9].

1) Ground Terminals: Stations were set up for this experiment at the following locations: the National Bureau of Standards Laboratory, Boulder, Colo. (Station N); Goldstone Dry Lake Venus facility (Station V); Anchorage, Alaska (Station A); and the Goldstone Dry Lake Stadan facility. The latter station, which is a command station for ATS-1, was intended to function as the master station and all other stations were to operate as slave stations. However, difficulties with the ATS ground equipment at the Stadan facility prevented its use. In view of these difficulties NASA granted permission to designate the other stations as master stations at various times during the experiment. Data for the stations used are given in Table I.

2) Equipment: All three ground terminals had similar equipment except for transmitter final amplifiers whose outputs were 1 kW, $\frac{1}{2}$ kW, and $\frac{1}{4}$ kW for stations N, V, and A, respectively. The transmitting and receiving antennas at all stations were 10-element yagis with approximately 10-dB gain. Both vertical and horizontal polarization were provided because Faraday rotation occurs at these frequencies. Commercial FM communications transceivers, optimized for 10-kHz tones, were used.

3) Timekeeping Procedures: Commercial cesium beam clocks were maintained at all three stations. These were set using the Mode II technique, and at the end of the experiment the three clocks were brought together for time and frequency comparisons. The time differences between the three clocks were regularly measured during the course of the experiment by means of the Mode II technique, and the clocks at Stations N and V were compared during the experiment using the JPL Moonbounce technique [10].

The Venus facility, Station V of this experiment, is the master terminal for the JPL Moonbounce Radar Time Synchronization System and Station N is a slave terminal. This system is similar in principle to the time dissemination technique called Mode I in this paper. The master transmits an X-band signal which is reflected by the moon to the slave. The path delay is predicted from knowledge of the lunar ephemeris and is corrected for Doppler effects introduced by rotation of the earth.

The time difference between clocks during the experiment was recovered to within 1.8 μs, peak to peak.

B. Experimental Results

Experiments were conducted on November 30, 1967, from 1940 to 2140 UT, and on December 1, 1967, from 2000 to 2300 UT. The stations took turns transmitting. All three stations, including the one transmitting, observed the signal transponded by the satellite. Each station measured the time difference between its own clock and the signal received from the satellite. The time duration for a set of three transmissions, including voice acknowledgments, did not exceed eleven minutes. Changes in path length due to satellite perturbations normally do not cause time errors greater than 1 μs during that period of time, although exceptions have been noted [11]. Such exceptions may be related to orbit correction maneuvers in which case they could be anticipated.

1) Mode I Results: Since the time differences between the three station clocks were known, the measurement of the time difference between a received signal and a local clock, corrected for equipment delays, was actually a measurement of propagation delay. The comparison between the measured VHF propagation delay and that computed from the satellite range predictions was the measurement of accuracy of the Mode I technique.

The range predictions were provided by NASA from an existing computer program. Two sets of range values were provided: the first was based on orbital elements of the satellite projected from the past history of the satellite and predicted one week in advance of the experiment; the second set was based on orbital elements which were updated by NASA at the time of these experiments. Results are given in Table II. The Mode I accuracy is given as the average difference between the measured and the computed values of the propagation delay; a positive sign indicates that the latter is larger. The standard deviation follows the accuracy.

2) Mode II Results: By using paired measurements from a given set of measurements, Mode II clock synchronizations were effected. For example, the delay measurements made at Station *V* while Station *N* was transmitting were paired with that made at *N* while *V* transmitted. Results are given in Table III. The accuracy of Mode II is given as the absolute value of the disagreement between the measured (by Mode II) and the known time difference between the clocks. The standard deviation follows the accuracy.

3) Round Robin Closures: The results of the Mode II synchronizations were summed according to (7). The closure for eleven sets of measurements checked by the round robin technique varied from 0.5 μs to 8.4 μs.

4) Moonbounce Results: On November 29, 1967, the Moonbounce radar timing link between Stations *N* and *V* was operated. Ten measurements made between 1925 and 1935 UT were averaged to obtain a clock comparison. This average value differed from the known value by 2.3 μs with a standard deviation of 1.16 μs.

TABLE II

Master Station	Slave Station	Accuracy Using Predicted Values (μs)	Accuracy Using Updated Values (μs)	Number of Observations
November 30, 1967				
N	*V*	-56 ± 1.2	-3.8 ± 2.2	5
N	*A*	-53 ± 5.6	6.6 ± 4.1	5
V	*A*	-33 ± 3.7	16.8 ± 3.7	5
December 1, 1967				
N	*V*	-57 ± 0.1	-8.5 ± 1.6	7
N	*A*	-54 ± 2.1	4.7 ± 3.2	7
V	*A*	-47 ± 4.4	7.4 ± 7.1	7

TABLE III

Master Station	Slave Station	November 30, 1967		December 1, 1967	
		Accuracy (μs)	Number of Observations	Accuracy (μs)	Number of Observations
N	*A*	-5.4 ± 2.9	5	-6.0 ± 3.66	6
N	*V*	-8.8 ± 1.3	5	-7.7 ± 1.98	6
V	*A*	7.9 ± 1.0	5	2.7 ± 2.17	6

C. Error Analysis

1) Mode I Error Analysis: The following sources of error have been considered in connection with the Mode I technique (see Table IV):

a) The ground equipment delay (about 150 μs) was measured frequently during the experiment and was considered to be known to ±2 μs.

b) The satellite transponder delay (7.0 μs) was measured during construction at Hughes Aircraft Company in 1966. The accuracy of measurement was ±1.0 μs [9].

c) The locations of the stations were known to within ±200 meters corresponding to a propagation time uncertainty of ±0.5 μs [from (3)].

Range values provided for Station *V* were inconsistent, apparently because of a programming error. The range values provided for the nearby Stadan terminal were used in computing the propagation delay to Station *V*. It is believed that the range to Station *V* was greater than that to Stadan by 3 km or less. This corresponds to an increase in propagation delay of 9 μs or less.

d) Satellite range values provided by NASA were rounded to the nearest kilometer, corresponding to a propagation delay uncertainty of ±1.5 μs.

e) The up-link frequency is about 150 MHz while the down-link frequency is about 135 MHz. The ionospheric uncertainties discussed earlier in the paper are greater at lower frequencies and so were computed at 135 MHz.

TABLE IV
MODE I ERROR BUDGET

Source	Error (μs)
Equipment	
Uncertainty in measurement of ground equipment delay	± 2
Uncertainty in knowledge of satellite transponder delay	± 1
Geometry	
Uncertainty in propagation delay related to ± 200-meter uncertainty of ground station at $\phi = 65°$ (Stations N and A)	
up link	± 0.7
down link	± 0.7
Uncertainty in propagation delay due to ± 0.5-km uncertainty in satellite range	
up link	± 1.5
down link	± 1.5
Propagation Effects	
Uncertainty in correction to propagation delay due to ionosphere (including difference in up-link and down-link frequencies)	
up link	± 6
down link	± 6
Uncertainty in propagation delay due to troposphere	
up link	0.3
down link	0.3
Rms noise jitter	± 5
Mode I rms error between stations	10.4

For the oblique ionospheric path associated with Stations N, A, and V, the error was estimated to be about ± 6 μs.

f) Noise jitter observed on the slave oscilloscope trace obscured the exact location of the time reference point in the received timing signal. An accuracy of ± 5 μs was assigned to the oscilloscope readings.

g) Other propagation effects associated with VHF ionospheric propagation include Faraday rotation, amplitude and phase scintillation, and ionospheric absorption. These phenomena have negligible effect on the propagation delay [3].

h) The increase in propagation delay (over the free-space value), due to the radio path through the troposphere, was not included in the corrections. The maximum increase under any circumstances would be about 0.3 μs [12].

The Mode I rms error of 10.4 μs is the clock synchronization accuracy to be expected using the equipment of this experiment at stations whose locations are known to 200 meters, using correct satellite range predictions, and computing propagation delays by the methods discussed. The Mode I measurements between Stations N and A, using the updated satellite range values, fall within the predicted error. Using the less accurate projected range values, the discrepancy was about 60 μs.

When the 9-μs allowance is made for the greater uncertainty in the Venus range data, similar results follow from measurements between Stations V and A, and between V and N.

2) *Mode II Accuracy:* The accuracy associated with the Mode II technique (using the equipment and procedures of this experiment), has been shown to be about 5 μs [3]. The least accurate Mode II synchronizations during this experiment were between Stations N and V (average values were 7.7 and 8.8 μs). It is interesting to note that the clock at Station A, which had not been running prior to arrival at the station, was set using the Mode II technique. At the end of the experiment it was transported to Station N where it was found to be 6 μs from clock N.

3) *Moonbounce Accuracy:* The accuracy of the Moonbounce Radar Timing System is given as 5 μs [10]. The average accuracy of the measurements made in this experiment was 2.3 μs.

III. CONCLUSIONS

A technique for synchronizing widely separated clocks to a reference clock has been investigated. The technique involves the one-way transmission of a radio time signal from the reference clock, relayed by a geostationary satellite VHF transponder to the remote clocks. The problem reduces to predicting the radio propagation delay from the reference clock, by way of the satellite, to the remote clocks. The propagation delay predictability on two days has been studied between three stations. The accuracy of predictability, and hence of clock synchronization, was found to be 60 μs if the propagation delay was computed using a satellite orbit predicted one week in advance of the experiment. The accuracy was 10 μs when the orbit used had been updated to the time of the measurements.

A clock synchronization system using the technique could offer two levels of accuracy. Tables of predictions of propagation delay at future times to specific locations or areas could be distributed or published in advance. Users would observe the radio timing signals when desired, refer to the tables, and compute their time difference from the reference clocks. Those users needing more accurate synchronization would be given after-the-fact propagation delay predictions based on an updated satellite orbit. As a check on the system, key stations could be equipped with transmitters for occasional two-way operations with the reference station or with each other.

If the location of a station were uncertain, the propagation delay could be calibrated by means of a two-way synchronization or a transported clock. Thus, the technique could be applied to navigation problems.

A system based on the technique could provide an alternative to transporting atomic clocks to geodetic and spacecraft tracking stations around the world in satisfying their clock synchronization requirements.

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