A TWO-WAY TIME TRANSFER EXPERIMENT USING A SYNCHRONOUS SATELLITE

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ABSTRACT

A time transfer experiment using the Applications Technology Satellite, ATS-1, was conducted in 1973-75 under joint sponsorship of the Goddard Space Flight Center (GSFC) and the Federal Aviation Administration (FAA). The experiment is designed with a capability to serve a large number of users and to achieve a time synchronization accuracy of 0.5 microseconds at 3 sigma values. A two-way satellite time transfer technique is used to eliminate the need for a priori knowledge of the propagation path delay. Thus, the technique is inherently capable of transferring precise time on a real-time basis from a master time station to a host of user or slave stations.

INTRODUCTION

The precision time transfer experiment reported upon in this paper was conducted under an interagency agreement between the Federal Aviation Administration of the Department of Transportation and the National Aeronautics and Space Administration.

The objective of the experiment was to demonstrate the feasibility of a system designed to disseminate a precision time reference from a master station clock to a remotely located clock via a synchronous satellite. The experiment was conducted in four phases: Phase one consisted of an RF terminal design and the modification of several pieces of available equipment. The second phase was comprised of the design and construction of the RF terminal as well as several RF link studies. Phase three consisted of the calibration of the system, and RF tests using one station, in which time transfer equipment and clocks were colocated. Phase four was conducted to demonstrate the feasibility of transferring time from a master station to a remote station and to provide the data necessary to evaluate the system accuracy. It is the phase four experimental results which we will be primarily concerned with in this paper.

The phase four tests were conducted during the period from March 14 to April 1, 1975, and consisted of a series of measurements performed during this period of time. An rms error, between the transferred (slave) reference signal and the master system reference, not exceeding 167 nanoseconds was established as the system design goal. The purpose of the measurements, of course, was to provide the data necessary to verify the accuracy of the system. In another section of this paper we will discuss the data which were collected, as well as the methods used to analyze the data in order to ascertain if the system objectives were satisfied.

In this paper our objectives are: to briefly describe the system and how precision time is disseminated, evaluate and discuss the experimental data collected during phase four test and the results achieved disseminating time from Mojave, California to Rosman, North Carolina, and finally to discuss, as appropriate, the problems encountered.

SYSTEM DESCRIPTION

The overall system consists of essentially two radio stations linked to each other by a wideband RF channel relayed by the ATS-1 synchronous satellite. The satellite simply acts as a "bent pipe" repeater, receiving on 6.3 GHz and transmitting on 4.18 GHz. Each station contains three major subsystems: a transmitter, a receiver, and a MODEM terminal. The MODEM interfaces with the transmitter and receiver at 70 MHz.

The MODEM terminal equipment complement encompasses a spread spectrum modulator/demodulator system, time interval counters and control equipment. The clocks and clock control equipment are also included as a part of the terminal. An overall block diagram of the system (excluding the satellite) is illustrated in Figure 1.

The modulator contains a pseudorandom noise (PN) code sequence generator whose repetition rate is controlled by a voltage controlled crystal oscillator (VCXO). The PN code is biphase modulated on a 70 MHz signal which serves as the IF of the C-band carrier of the uplink signal from the ground to the satellite. The demodulator serves to recover the PN coded signal by correlating the received signal with a locally generated replica of the transmitted PN sequence.

The PN code generator used in this experiment has an eleven stage shift register. The shift register clock is a VCXO

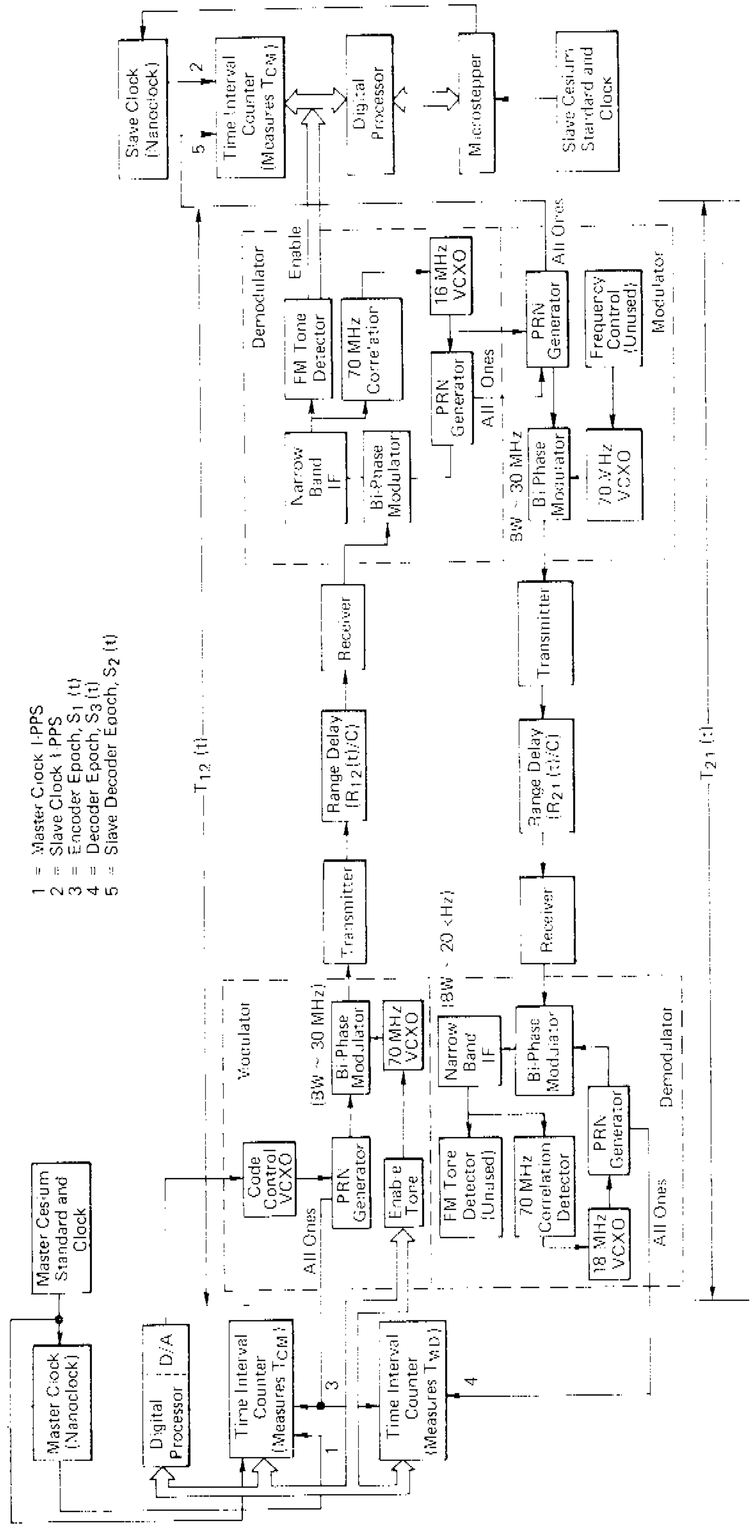

Fig. 1 Block Diagram of Precision Time Disseminating System

at 16.376 MHz. The frequency of the VCXO can be binarily divided to extend the period of the PN sequence. The period of the sequence is $(2^n-1)/f$ or 125 microseconds for n=11 and f=16.376 MHz.

When the state of every stage in the shift register is a logic "1", it marks the beginning of the PN sequence (the all 0's states are excluded). That is, the all 1's state is the reference epoch of the PN sequence, and whenever an all 1's state is detected, an output pulse is generated for time measuring purposes.

During the phase four tests, the master station was located at the NASA/STDN Goldstone Station ATS-wing (Mojave). The master station terminal system was comprised of the ATS transmitter and receiving subsystems interfaced to a MODEM terminal. The slave station equipment was housed in an RF mobile Van assembled specifically for the phase four tests. The antenna, a 10 ft. dish, was mounted external to the Van on a concrete pedestal. For the tests the Van was transferred to the NASA/STDN Rosman Station, Rosman, North Carolina. The RF characteristics of the master and slave station terminals are given in Table 1.

DESCRIPTION OF TECHNIQUE

In this section the method by which the precision time reference is transferred from a master to a slave terminal will be discussed. The precision time reference at the master will be referred to as S1(t) and at the slave as S2(t). The signal S1(t) is the all-ones epoch of a PN sequence which is phase locked to the master system clock 1-pps. The master system PN sequence is biphase modulated onto the 70 MHz IF of the MODEM, heterodyned to RF, and relayed through the satellite to the slave. At the slave terminal a similarly encoded signal is correlated with the received sequence. When correlation is achieved, a second PN signal is synchronized to the correlation epoch. The signal S2(t) is the all-ones epochs of the second PN sequence.

The slave MODEM IF is also biphase modulated, translated to RF and relayed to the master terminal where the received signal is correlated with a replica of the slave PN sequence. When correlation is achieved, the all-ones epoch S3(t) of the locally generated sequence will be synchronized to S2(t). Assuming that the correlator errors can be neglected, then for forward and return path time delays, T12(t)

TABLE 1. RF TERMINAL SYSTEM CHARACTERISTICS

OPER. MODE	CARRIER FREQ (MHz)		ANTENNA			XMT POWER (WATTS)	RCV SYSTEM	
	XMT	RCV	DIAMETER (METER)	GAINS (db) XMT	GAINS (db) RCV		C/N BW 20 KHz (db)	NOISE TEMP °K
MASTER[1]	6301.0	4178.6	12	54.6	51.0	40 — 50	15 — 19	76
SLAVE[2]	6301.0	4178.6	3	40.1	39.7	600 — 800	15 — 19	316

(1) NASA ATS TRACKING STATION TERMINAL AT MOJAVE, CALIFORNIA

(2) EXPERIMENTAL MODEL PORTABLE TERMINAL

and T21(t)*, the all-ones epoch, S2, corresponds very nearly to S1 delayed by the forward path delay, T12. Also, S3 corresponds to S2 delayed by the return path delay, T21. Once correlation between the code sequences is achieved at the master station, the time interval between S1 and the master clock 1-pps (Tmc) and the time interval between S1 and S3 (Tmd) are measured, and Tmc is compared with Tmd/2 in a feedback loop. The loop error signal, which is proportional to (Tmd-2Tmc)/2, is periodically adjusted (once per second) to minimize the loop error.

When the loop error is less than a predetermined value a command tone is frequency modulated on the master terminal 70 MHz IF, and subsequently detected at the slave terminal. The command tone signals the slave to begin measuring the error between the slave clock 1-pps signal and the locally generated precision time reference, S2(t). The time differential between the slave clock 1-pps and S2(t), say Tċm, will be proportional to T12-Tmc+ΔT, where ΔT is the error between the master and slave clock 1-pps signals, and Tmc, of course, is the time interval by which S1(t) precedes the master clock 1-pps.

Explicit expressions relating Tmc and Tmd can be rigorously developed. It can be shown also that the time interval between S1 and S3 is approximately equal to the round trip time delay modulo To (i.e., nTo+Tmd≈T12+T21). If we assume that T12=T21 and the feedback loop error signal is negligibly small, then Tmc≈T12 and the time interval Tċm is very nearly a measure of the error between the master and slave clock 1-pps signals. The locally generated signal then, S2(t), constitutes the precision time reference available at the slave and the objectives of the system are accomplished if the difference between the clock error and the time interval Tċm can be kept negligibly small, i.e., when Tċm-ΔT→0. It is this difference which we will be primarily concerned with in the remainder of this paper. Before discussing this, however, we would like to point out some advantages of using PN sequences.

Some Advantages of Encoding the Reference Signal S1(t) As a PN Sequence

In the previous discussion, no justification for using PN encoded sequences was ventured. There are, of course,

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* The forward and return path delays vary with time because the RF carrier is relayed through the satellite which moves relative to the two stations.

several very good reasons and we would like to highlight just a few. The first of these relates to the tradeoff between resolving the ambiguity problem inherent with all periodic sequences, and the desired accuracy. Among other attributes the PN sequence satisfies both of these requirements simultaneously since the ambiguity of the precision reference is equal to the period of the sequence and the phase accuracy is a small fraction of the chip period. Another, and particularly important, advantage is that several sequences can be transmitted simultaneously through the same RF channel without significantly interfering with one another. Consequently, the forward and return path delays through the satellite repeater are identical and thereby cancel. Still another advantage is that by using a variation of the time transfer technique we discussed previously, it appears practical to transfer precise time to several remote sites simultaneously (Reference 1). Finally, the possibility of coexisting with other types of communication signals over the same RF channel with negligible interference also appears feasible (Reference 2).

System Ambiguity

In the previous section it was pointed out that one of the advantages of PN sequences was the increased ambiguity periods achievable. This is important because the absolute accuracy of a time transfer depends upon the ambiguity interval of the system. In this regard, we should like to point out that the system ambiguity is one-half the sequence period, and further emphasizes the desirability of relatively long sequences. We can discuss other aspects of the ambiguity problem, but these are not germain to our present objectives and consequently we will continue with a very brief discussion of the system controllers.

SYSTEM CONTROL PROGRAMS

There are three programs associated with the system. Two of these control the operation of the system, whereas the third is used for collecting statistical data. Each of these programs is briefly summarized below.

Master System Control Program

There are essentially two routines associated with the master system controller. The first routine comprises an automatic frequency control (AFC) loop which functions to set the VCXO frequency to 16.376 MHz ±0.0001%. Once this accuracy has been achieved, the controller tests the

MODEM status word to determine if the PN sequences are "tracking". If the demodulator indicates an in-track condition, then the AFC routine is passed over to the code epoch control routine. If the demodulator is not tracking, the entire AFC mode is repeated.

Briefly, the code-epoch control routine executes the following functions:

1. Performs the necessary measurements (by controlling various measuring equipment) to calculate the phase differences between the modulator all-ones epoch and the clock 1-pps, and the demodulator all-ones epoch and the clock 1-pps.

2. Calculates the phase error signal and controls the VCXO voltage corresponding to the phase error and filter weighting function. The filter weighting function approximates a filter characteristic associated with a second order phase lock loop. This filter characteristic was chosen because a second-order phase lock loop is capable of tracking a signal whose frequency is changing linearly with time (Doppler).

3. Calculates the mean squared phase error and activates the TONE-1 frequency generator, thereby signaling the slave system control program, when the mean squared phase error is smaller than a predetermined value, and indicates this action by setting the "loop locked" flag.

Slave System Control Program

The slave system controller is considerably simpler than the master system. Briefly, the functions this routine performs are:

1. The controller examines the MODEM status word, i.e., looks for the master system TONE-1 command.

2. Measures the time difference, Tcm, between the received PN sequence "all ones" epoch and the slave clock 1-pps.

3. Calculates the average time error over a preselected number of samples.

4. Adds a bias correction factor to the average value calculated in 3. The value of the bias depends upon the asymmetry between the forward and return path delays.

Statistical Routine

This routine performs the functions listed in items 1 through 3 for the slave system controller. In addition to the average error, however, the routine also calculates the maximum and minimum errors as well as the variance. The results of the four calculations are subsequently formatted and printed. During operation of the statistical routine the slave clock is not corrected.

TEST DATA

The tests consisted of a series of measurements designed to provide the data necessary to determine the accuracy of the system. Essentially, two types of timing data were collected. The first type of data are comprised of measurements between the primary cesium standards and are independent of the time disseminating system. The second type of data collected are comprised of the measurements relating to the system.

Primary Clock Data

Maintaining precise time between both terminal clocks is central to the problem of corroborating the accuracy of a precision time transfer. Here we will address the problem of maintaining and coordinating precise time between the clocks at the Mojave and Van sites during the test period. Briefly, time keeping at each site was maintained with primary atomic time standards. The standards used were Hewlett-Packard type 5061A cesium standards with option 004, utilizing high performance cesium beam tubes. The relative time between each standard was compared indirectly with an HP5061A Flying Clock transported via FAA and commercial aircraft.

During the first part of the test period the Mojave standard (the master) was synchronized to the portable clock. The portable clock was subsequently flown to the Van (slave station) where the difference in time between the two clocks was monitored. Two types of data were recorded; the relative phase ($\Delta\phi$) between the two 5 MHz reference frequencies and the time differential between the Van and portable cesium 1-pps outputs (TVcs/Pcs).

Initially it was decided not to synchronize the Van cesium to the portable clock, however, this proved to be awkward because the Van clock was stopped while the Van was being moved from the GSFC to the Rosman STDN, and a large time difference had accrued. After several days, the Van cesium clock was synchronized to the portable clock. The portable clock remained on the Van for approximately six days during which time the TVcs/Pcs and the $\Delta\phi$ data were recorded. Following this period, the portable clock was returned to Mojave and the time difference between the Mojave and portable cesium clocks (TMcs/Pcs), along with phase data, were recorded. Immediately following the tests the portable clock was again flown to the Van and TVcs/Pcs was measured for closure. No phase data was recorded. The results of these measurements are plotted in Figure 2.

In addition to the primary clocks, each terminal maintained a secondary clock system (trade name Nanoclock). Dual clocks were included with each terminal for the tests to facilitate introducing known offsets with respect to each station without disrupting each station's reference time (the 1-pps output of the cesium clocks).

For the master terminal the Nanoclock reference signal was obtained from the cesium standard's 5 MHz output. For the slave, the reference was obtained from the microstepper which is phase locked to the 1 MHz output from the cesium standard. The clock arrangement may be clearer if we refer to Figure 1.

Time Transfer Data

We will discuss now, very briefly, the procedure used during the tests to obtain the time transfer data.

At the beginning of each test period the clock offsets between the respective Nanoclock and cesium standard at each terminal were measured and recorded, along with the time of day. Following this, the RF signal levels were adjusted until the carrier-to-noise ratio measured at each terminal was essentially equal. Once the RF levels were optimized, the master and slave system controllers were loaded with the respective clock correction program, and both the master and slave MODEM systems subsequently locked up. Upon detection of a command tone from the master, the slave Nanoclock would be adjusted by an amount equal to the average measured error between the nanoclock and precision time reference transferred to the slave. The amount by which the clock was corrected and the time of day were recorded on the system printer provided for this purpose (the time of day was annotated manually). Following a clock correction, one of the Nanoclocks (usually the Van's) would again be offset and the procedure repeated.

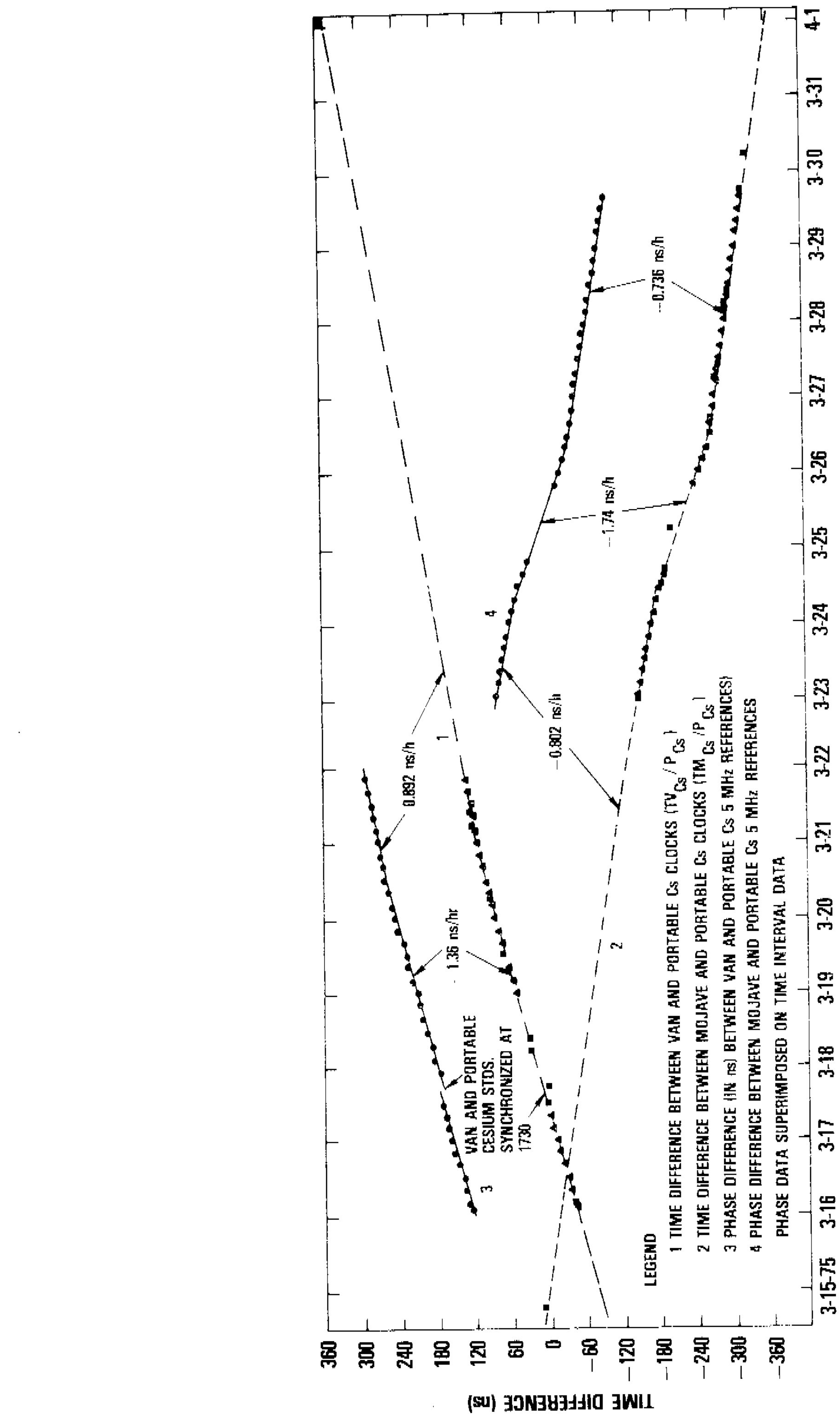

FIG. 2 MEASURED TIME DIFFERENCES BETWEEN TERMINAL AND PORTABLE CLOCKS

After several offsets and corrections, the slave system control program would be changed to the statistics routine and statistical data would be recorded for relatively long periods of time. In addition to the average error between the all 1's pulses and the Nanoclock, (T1's/Nv), the statistical routine printout also printed the maximum, minimum and variance of T1's/Nv over the averaging interval. If time allowed, the test period was usually terminated with a clock correction. In Figure 3, alternate data points taken from the statistical data recorded during the March 24 test period are plotted. We will discuss this figure shortly but first we would like to discuss briefly how we determine the accuracy of a time transfer.

DETERMINING THE SYSTEM ACCURACY

If the time between the two terminal clocks is known with sufficient precision, then the problem of verifying the system accuracy is fairly straightforward. Thus, if TMcs/Vcs is the "known" offset between the Mojave and Van cesium standards, and $\widehat{TMcs/Vcs}$ is the offset between the Mojave and Van cesium standards estimated from the time transfer data, then the system error, say ε, is

$$\varepsilon = TMcs/Vcs - \widehat{TMcs/Vcs}. \quad (1)$$

We consider now, the factors which influence the accuracy of each of the above parameters. As will be seen, the accuracy of the predicted offset between the Mojave and Van cesium clocks, TMcs/Vcs, will depend upon the reliability of the portable clock data, whereas the accuracy of $\widehat{TMcs/Vcs}$ will depend upon the capability of the system. Following the discussion of these factors, the system error is considered.

Previously we considered the procedure used for collecting the data to predict TMcs/Vcs. From the data several equations predicting TMcs/Vcs at every instant of time* were derived. These expressions are summarized in Table 2.

* "Time" implies master system time.

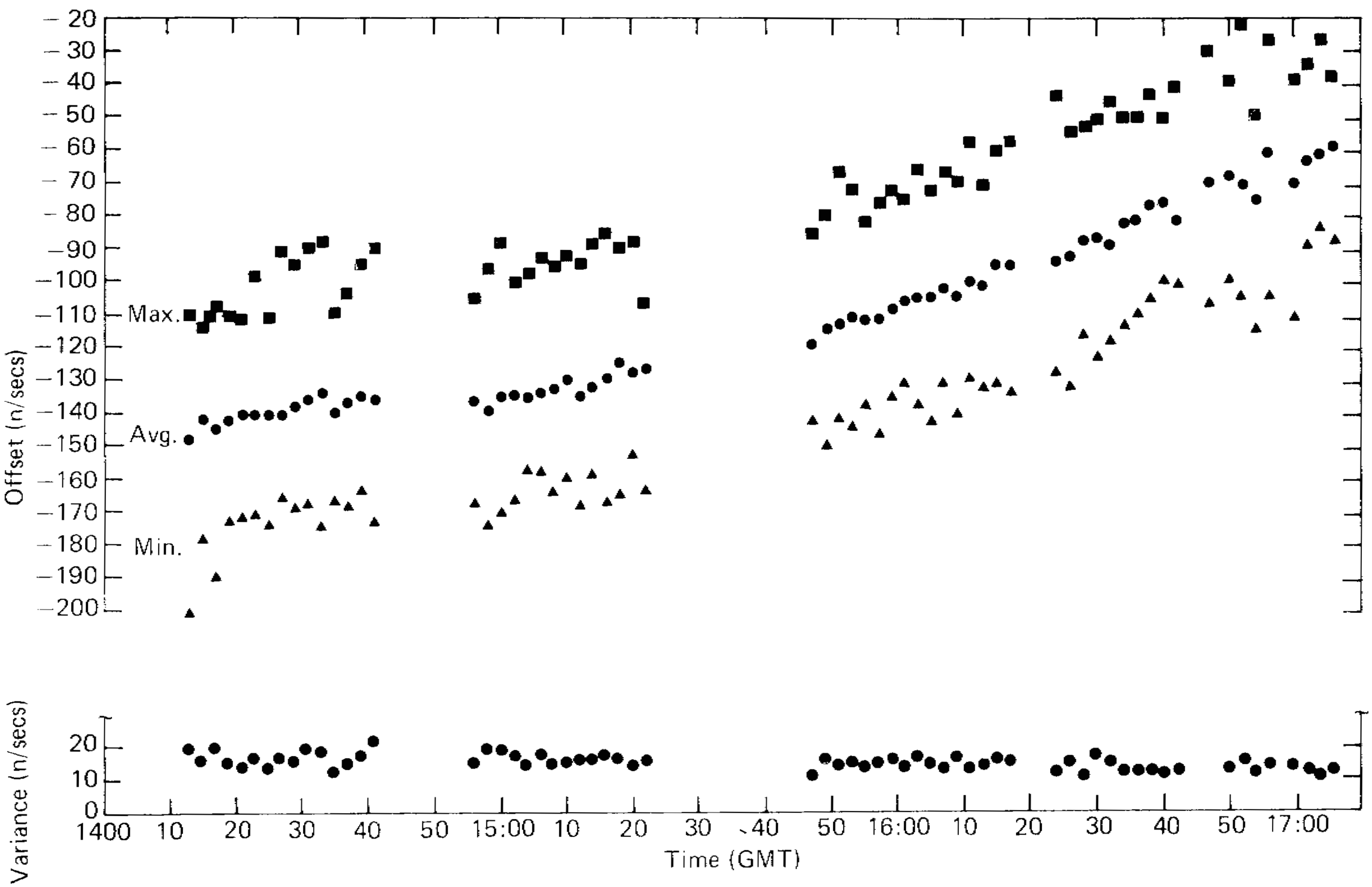

Fig. 3 Statistics Data for Mar. 24, 1975 (4 MHz PN Clock)

TABLE 2

PREDICTED TIME DIFFERENCES BETWEEN THE MOJAVE AND VAN CESIUM STANDARDS

Time differential (nsecs) between the Mojave and Van cesium clocks

$$TMcs/Vcs = \begin{cases} 2.162\tau-482,845,563 ; & t \le 17:30/3/17/75 \\ 2.162\tau+42 ; & 17:30 < t \le 16:00/3/20/75 \\ 1.694\tau+79 ; & 16:00 < t \le 0400/3/24/75 \\ 2.632\tau-73 ; & 0400 < t \le 10:00/3/26/75 \\ 1.628\tau+144 ; & 10:00 < t \end{cases}$$

τ=t-10:00/3/17/75 GMT-Hours

The reliability of these predictions, of course, depend upon the validity of the measured data but we cannot prove its accuracy, we can only hypothesize. However, the data appears valid for two reasons: First, slopes of curves 1 and 2 in Figure 2 were derived primarily from the phase data (curves 3 and 4) and were not chosen to intersect with the extreme data points as might be expected from looking at the illustration. The second reason is that, if the portable clock changed significantly while it was being transferred from one site to the other, then the slopes of curves 1 and 2 extrapolated over the time intervals for which no measured data were available would be incorrect, and this would be reflected through Eq. (1), to the system error. Since the extrapolation would tend to smooth out any change, however, transport errors would not necessarily be immediately noticeable. Gradually, though, a significant change would become evident as an unexplainable bias on the system error. As we will soon show, no such bias was detected.

We consider now, the factors influencing the determination of the estimated offset between the Mojave and Van cesium clocks ($\hat{T}$Mcs/Vcs). Briefly, $\hat{T}$Mcs/Vcs is comprised of two factors, i.e.,

$$\hat{T}Mcs/Vcs = \tilde{T}Mcs/Vcs + \Delta\hat{T}. \qquad (2)$$

The first term, $\tilde{T}$Mcs/Vcs, is the apparent cesium clock offset and is determined from the system data as follows:

$$\tilde{T}Mcs/Vcs = T1's/Nv + TNv/Vcs - TNm/Mcs \qquad (3)$$

where:

$T1's/Nv$, is the average time interval (Modulo $To/2$) between the all 1's epoch and the Van nanoclock. This is the quantity calculated in the slave control program.

TNv/Vcs, is the offset, in nanoseconds, between the Van nanoclock and cesium clock 1-pps signals.

TNm/Mcs, is the offset, in nanoseconds, between the Mojave nanoclock and ceisum clock 1-pps signals.

The second term in Eq. (2), $\Delta\hat{T}$, is a correction factor consisting of a fixed bias plus a variable component proportional to the doppler rates ($\dot{R}vs$ and $\dot{R}ms$) between the Mojave and Van terminals and the satellite. Thus,

$$\Delta\hat{T} = k(\dot{R}vs + \dot{R}ms) + B \ , \qquad (4)$$

where:

$k = 3.6$ nsecs/mtr/sec

$$B = \begin{cases} 210 \text{ nsecs for the 4 MHz PN Clock rate} \\ 187 \text{ nsecs for the 8 MHz PN Clock rate} \\ 176 \text{ nsecs for the 16 MHz PN Clock rate.} \end{cases}$$

The expression for $\Delta\hat{T}$ has been derived analytically and it can be shown that the bias term, B, is equal to one-half the difference between the forward and return path terminal time delays. Although B can be determined experimentally, sufficient time was not available for making the necessary measurements prior to the test; and, consequently, B was derived empirically from the test data.

Prior to the tests, the component proportional to doppler was not well understood. Indeed it was unexpected because the closed loop transfer function of the master system control algorithm is equivalent to a second order phase-lock loop and consequently, the doppler error should be negligible. Subsequent to the tests, however, we found that the error term proportional to doppler arises predominantly through a peculiarity in the system instrumentation. The system error has been analyzed in considerable detail and we can show that most of the error due to doppler arises becausé the time intervals Tmd and Tcm are not measured at the same instants of time. That is, the time interval, Tcm, is measured, as it should be, at precisely the one-second time marks, but the time interval, Tmd, is measured almost one second early. If we had been aware of this peculiarity prior to the tests, then the correction factor, ΔT, would have been incorporated into the system control programs and thereby reflected into the system measurement T1's/Nv. The advantage of doing this, of course, would be to preserve the real time capability of the system. Nevertheless, the achievable precision of a time transfer is unaffected by whether or not the correction is made in real time.

In the previous paragraphs the factors involved in the determination of the system error were discussed. In Figure 3 we showed the clock offsets prior to making any corrections and the effects of doppler are clearly evident. In Figure 4, we have plotted the system error for several days. As can be seen from these figures, the average daily error is not zero, but nevertheless, is usually small. The reason the average daily error is not zero is not clear, but it is believed to be a peculiarity of the system MODEM spread spectrum correlators.

If all systematic errors can be predicted, and thereby removed, then ideally the residual error should be randomly distributed with zero mean and negligibly* small variance. In Figure 4 the average daily error ($\bar{\varepsilon}$) is indicated by the dashed lines, and it should be apparent that the variance about the average is relatively small. This is, of course, a desirable condition. To show the trend for the entire test period the average daily error, as well as the extreme errors for each test day are replotted in Figure 5. Notice that there does not appear to be any consistent bias associated with the system error, and this seems to lend credence to our earlier hypothesis regarding the portable clock measurements.

If we list $\bar{\varepsilon}$ for each test day (Table 3 below):

TABLE 3

AVERAGE DAILY ERROR FOR PTDE TIME TRANSFERS

	DATE:									
MAR.	15	18	19	20	21	24	25	26	27	28	29/30
$\bar{\varepsilon}$(n·s)	20	-2	-19	-17	-6	16	7	-13	17	8	-7

* Statistically, of course, it is not necessary that the variance be negligibly small; however, practically, this is a system requirement.

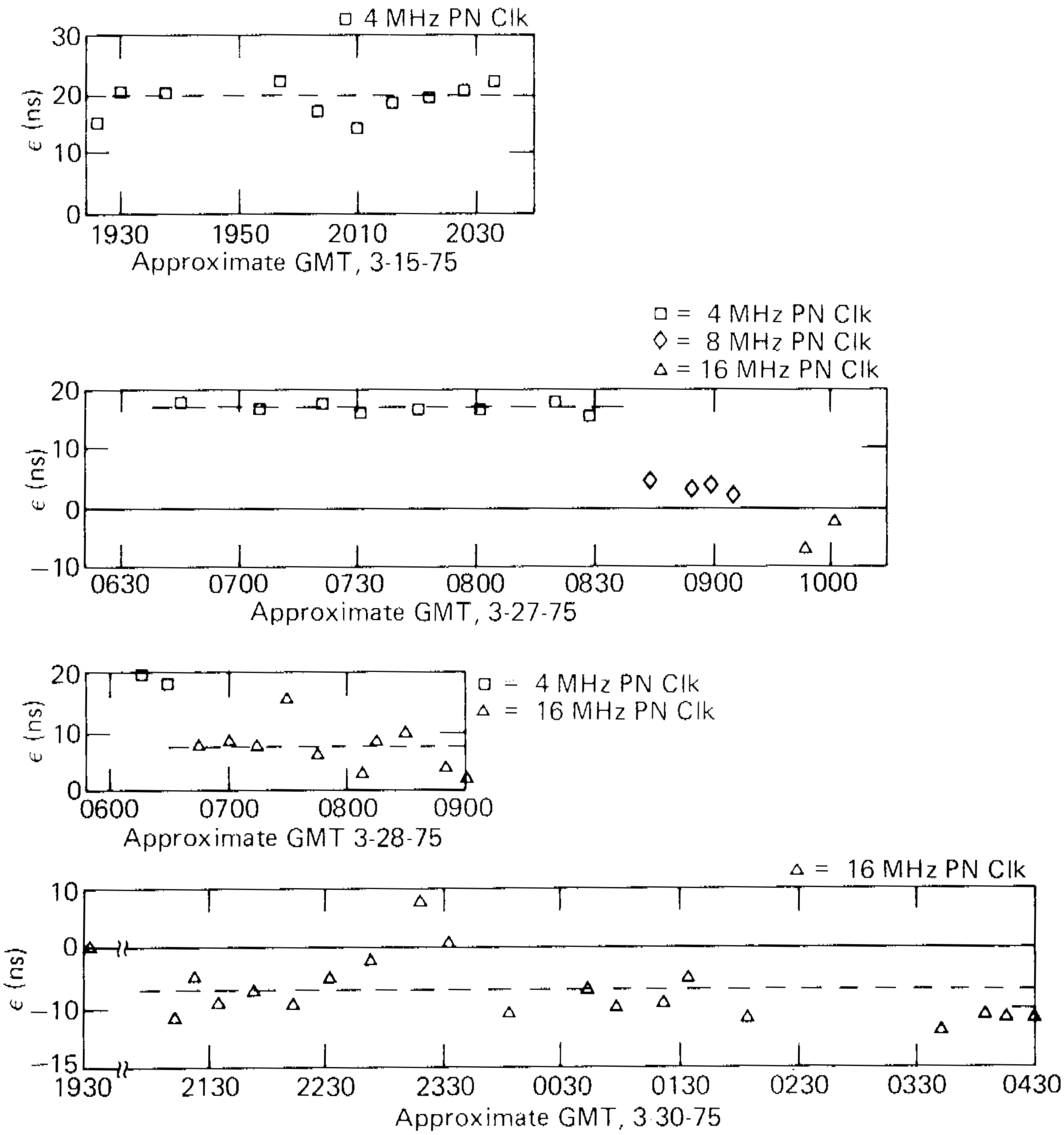

Fig. 4 PTDS Residual Error for March 15, 27, 28, 29/30

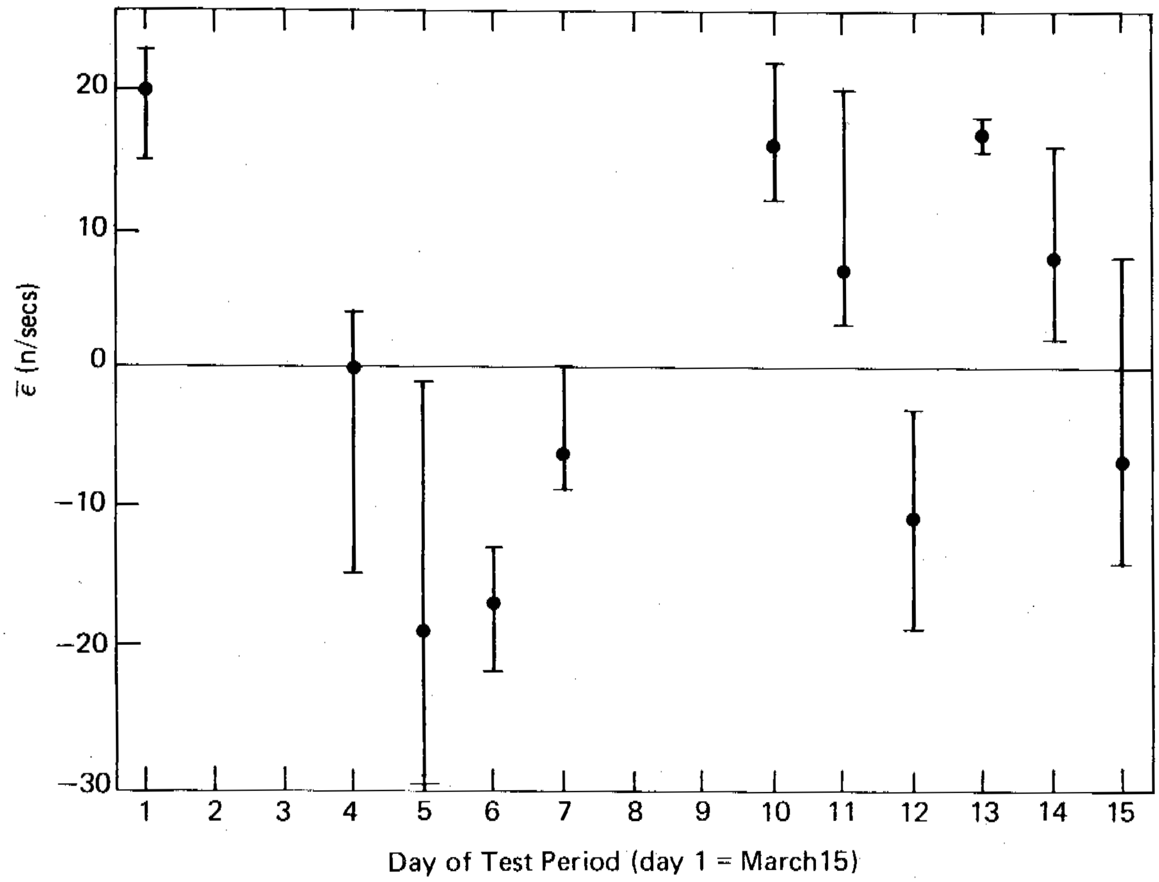

Fig. 5 Average Error, $\bar{\epsilon}$, for Each Test Day. The Maximum and Minimum Errors for Each Day Are Also Shown

then we can easily calculate the average error over the entire test period. Accordingly,

$$\langle \varepsilon \rangle = \frac{1}{N} \sum_{i=1}^{N} \bar{\varepsilon}_i \approx 0.2 \text{ nsecs},$$

and the variance of $\bar{\varepsilon}$ is

$$\sigma_{\bar{\varepsilon}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\bar{\varepsilon}_i - \langle \varepsilon \rangle)^2} \approx 11 \text{ nsecs}.$$

It can be seen (Table 3) that the average error, $\bar{\varepsilon}$ is less than $2\sigma_{\bar{\varepsilon}}$. Furthermore, from Figure 5 it can be seen that

$$|\bar{\varepsilon}| < 3\sigma_{\bar{\varepsilon}} \; (\approx 33 \text{ nsecs}) \ll 0.5 \; \mu\text{secs}.$$

and therefore, it can be reasonably concluded that the experiment objectives were achieved.

ACKNOWLEDGEMENT

The authors would like to acknowledge the many people who contributed to making the experiment a success. We would like to particularly single out Messers. J. Brannan and O. McIntyre of the FAA, Mr. G. Whitworth of the APL, Mr. L. Fleishman from Westinghouse, Messers T. Keating, P. Mitchell and W. Mazur from GSFC, Mr. J. Beatty of NAFEC, and last but certainly not least, personnel from the ATS Project Office and NASA Mojave and Rosman tracking stations, without whose contributions the experiment could not have succeeded.

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QUESTION AND ANSWER PERIOD

NO DISCUSSION