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ABSTRACT

A report on the limitations of present methods of obtaining time synchronization of remote station clocks, and the inadequacy of these methods in meeting present and future Apollo time synchronization requirements.

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TIME SYNCHRONIZATION

OF REMOTE STATION CLOCKS

INTRODUCTION

The purpose of this report is to point out the limitations of present methods of obtaining time synchronization of remote station clocks, and the inadequacy of this method in meeting present and future time synchronization requirements.

Accuracy of time synchronization depends on the degree to which the comparison of an epoch as regarded by two independent clocks - a station clock and a reference clock - can be made. The accuracy of the epoch comparison depends on the limitations of the equipment and the method of sync, as illustrated in Table 1 and enumerated in Appendix A.

PRESENT METHODS OF TIME SYNCHRONIZATION

Gemini Stations

Gemini Stations utilize the method of coordinated time signals (high frequency) to synchronize station clocks. An examination of Table 1 indicates that Gemini Station clocks cannot be relied upon to be synchronized to a master clock to better than ±2 milliseconds (msec).* This implies that Gemini Station clocks cannot be relied upon to be synchronized to each other (interstation synchronization) to a relative accuracy of better than 4 msec; for example:

Gemini Clock #1 to MASTER = +2 msec
Gemini Clock #2 to MASTER = -2 msec
Gemini Clock #1 to Gemini Clock #2 = 4 msec

(See Appendix A for explanation of high frequency time synchronization limitations).

*NOTE

This value is a conservative estimate since the MFEB has not actually conducted tests to verify its validity (ref. 1).

Apollo Stations

Apollo Stations utilize the same method of time synchronizing station clocks as used at Gemini sites; therefore, the same limits of accuracies apply.

Table 1. Time Synchronization Methods

Method	Accuracy Obtainable
1. Transporting a portable clock which has been synchronized with a master clock:	
A. Crystal Oscillator for a 1 month	± 1 to 10 μsec
B. Atomic Oscillator for a 1 month	± 0.1 to 1 μsec
2. Artificial Satellite:	
A. Free running reference clock on board	± 10 to 100 μsec
B. Relay of time signals	± 10 to 100 μsec
3. Loran - C transmission of low frequency signals referenced to UT-2	
A. Ground wave	± 0.1 to 1 μsec
B. Sky wave	± 10 to 20 μsec
4. Coordinated time signals high-freq. referenced to UT-2:	
A. Ground wave	± 0.1 to 0.5 msec
B. Multi-Hop Sky wave	± 1.0 to 2 msec
5. Very low freq. signals referenced to UT-2:	
A. WWVL (20.0 to 19.9 KC) UT-2	± 1 to 10 μsec
B. VLF Navy	± 0.5 to 1 msec
C. Navy Omega Project	not operational probably ± 0.5 to 1 msec

NOTE: μsec = microseconds

TIME SYNCHRONIZATION REQUIREMENTS

Present Apollo station clock requirements for interstation synchronization have been stated as 1 msec (ref. 2). This requirement includes the near earth orbit, transfer orbit, and the lunar phase, of the Apollo project. However, it is felt that participation in tracking equipment calibration, site positioning and other geodetic programs will require interstation synchronization accuracies comparable to the requirements of the scientific satellite tracking stations (STADAN Stations) which have been stated as 100 μsec (ref. 3). Therefore, future Apollo station clock sync requirements can probably be expected to be stated as 0.1 msec (100 μsec) for interstation synchronization.

METHODS OF OBTAINING REQUIRED TIME SYNCHRONIZATION

Of the five methods listed in Table 1, only the presently used method, method no. 4 (high frequency coordinated time signals) is not capable of meeting the Apollo clock sync requirements. Of the remaining methods, two (2) seem to be most promising in offering immediate solutions to the problem of meeting both present and future time sync requirements. These methods are:

1. Transportable Clock

NASA, MFEB, does not presently have a transportable "flying clock"; however, at least two organizations do offer time sync services using a "flying clock".

A. Department of Defense. As per service note #1 of December 1965, "Precise Time Synchronization Service", DOD will on a limited scale (depending on DOD requirements) sync remote clocks without service charge. It is assumed, however, NASA would not have a very high priority, as the service is primarily for use at DOD installations.[4] Further, it is felt that the service would not be rendered in any reasonable length of time, i.e., all USB station clocks would not be synchronized within 6 months, and after this period of time the station clocks would probably have to be resynchronized.

B. Hewlett Packard Company - This company has made several around the world "flying clock" synchronization experiments and intends to make future experiments as the need arises. In April, 1966, the company offered its services to sync MSFN station clocks which were located on a route compatable with their planned route. A further offer was made to sync one or two MSFN station clocks free of charge.[5] Due to the lack of operating procedures for USB timing synchronization this offer was not accepted.

2. Loran - C

Loran-C receivers may be utilized in either of the following two modes to obtain time sync of MSFN station clocks:

A. As a portable "flying clock", i.e., a substitute for an atomic "flying clock". (Carry one receiver to each site).

B. As an integral component of each MSFN timing system, i.e., each station would have a receiver to obtain time sync and a backup system for VLF phase comparisons (Loran-C provides a 100KC phase stable signal).

Note that utilizing either mode of sync requires that the site be within the Loran-C coverage area, i.e., within 8,000 - 10,000 kilometers (4,000 - 5,400 nautical miles) of a single Loran-C station. Two MSFN stations (Carnarvon and Canberra) are not within a prime coverage area, i.e., the Loran-C stations (Northwest Pacific Chain) covering this area are not time synchronized directly to the Naval Observatory Clock. However, this difficulty can be circumvented by using the Guam MSFN station as a monitoring site to determine the difference in sync between the Northwest Pacific Chain and Hawaiian Chain. The Carnarvon and Canberra station clocks can be corrected to account for this difference.[6] Thus, all MSFN station clocks can be time synchronized to the Naval Observatory clock using a Loran-C signal.

SUMMARY

The following is a brief summary of the advantages and disadvantages associated with the two methods of synchronizing station clocks considered most feasible at this time.

1. Cost

A. A cesium beam "flying clock" could be purchased for $25,000 (Hewlett Packard).

B. Using the free services offered, together with contractual services, it is felt that all MSFN Apollo station clocks could be synchronized once for $10,000. The station clock will probably need resynchronizing twice a year.

C. A Loran-C receiver used as a portable "flying clock" could be purchased for $750 (Electronic Engineering Co.).

D. Loran-C receivers for all Apollo sites - $12,000.

2. Reliability

A. "Flying Clock Method" - Reliability as considered here means the reliability of having a station clock in sync with a master clock after initial synchronization (say 6 months after initial synchronization). Utilization of the "Flying Clock" method of synchronization depends entirely on the reliability of the station being synchronized, i.e., the Flying Clock method presupposes both station clock redundancy (two or more clocks) and stable station clock oscillators. Apollo stations fulfill these two requirements; however, the weak link in the Flying Clock method of synchronizing clocks lies not in the method itself but in the method of maintaining sync which is as follows: a phase stable VLF signal is monitored continuously; an accumulated time error log is kept, in which daily time errors due to oscillator instability are recorded. Thus, one knows the time correction factor required to resynchronize to initial conditions. Unfortunately, this method is dependent on continuous operation of the VLF station being monitored, and on the continuous operation of the VLF receiver. A recent VLF station monitoring test at MSFN stations (HAW and BDA) has indicated that a continuous phase comparison record cannot be obtained over a one (1) month interval. However, modifications to the timing system could probably limit the need for resynchronization to twice yearly. This is a very conservative estimate which assumes some kind of additional reliability is built into the VLF receiver and phase comparator portions of the timing system, and that the only factor to be considered is VLF station reliability (i.e., how often does the station go off the air - estimated to be at least once every 6 months). Once the VLF station signal has been interrupted, the station clock would have to be resynchronized. This is because future performance (stability) of an atomic oscillator cannot be obtained from past performance.[7]

B. Loran-C Method - Loran-C can be used to sync station clocks and automatically steer the station clock oscillators to keep them to the stability of the Loran-C oscillator (stable to 2 parts in 10^{11})which in turn is synchronized to the Naval Observatory Clock. Therefore, the time sync is always within given limits of its initial setting. Studies of Loran-C transmitter operation indicate a reliability of 97 - 99 %; and except in unusual circumstances, the transmitter operation was down for a day or less.[6] Upon re-operation of a Loran-C transmitter after an emergency breakdown, the Loran-C signal is automatically resynchronized to the Naval Observatory clock. Thus, MSFN clocks would be resynchronized to the Naval Observatory clock.

3. Accuracy of Synchronization

A. Atomic "Flying Clocks" - All MSFN station clocks could be synchronized to within ± 1 μsec by use of an atomic clock. This limit of sync corresponds to an oscillator stability of 2 parts in 10^{12} for a 3 week period, which is the time required for all MSFN station clocks to be synchronized.

B. Loran-C - MSFN station clocks within 3000 kilometers sea path or 1500 kilometers land path of a Loran-C transmitter can be synchronized to within 1 μsec. MSFN station clocks within the 2,500 kilometer to 10,000 kilometer range (land and/or water) from a Loran-C transmitter can be synchronized to within 20 μsec. Each

Loran-C clock is synchronized to the other clocks in the chain to within 0.03 μsec, and therefore, each chain is synchronized to another chain to within 0.03 μsec. The master clock of the chain is kept synchronized to the Naval Observatory clock to within ±20 μsec; therefore, the MSFN clocks can be synchronized to the Naval Observatory clocks to within ±40 μsec. This is a maximum value-corrections are made to keep the master Loran-C clocks and Naval Observatory clock within the 20 μsec range and the correction value can easily be accounted for in synchronizing MSFN station clocks.

CONCLUSION

The question of buying a cesium beam primary frequency standard for each MSFN station for timing purposes is felt to be completely uneconomical (15 X $25,000 = $375,000).

RECOMMENDATION

The most practical method of obtaining time synchronization of USB station clocks, to the stated accuracy of 1 millisecond and a probable future requirement of 0.1 millisecond seems to be through the use of Loran-C signals. It is suggested that three Loran-C receivers be purchased for field evaluation at USB sites. Two of the receivers would be implemented at distant sites, CRO and GUAM, and the the other receiver could be used to investigate the "flying clock" approach to time synchronization. Equipment cost would be $750.00 X 3 receivers = $2,250.00.

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APPENDIX A

The purpose of Appendix A is to clarify some points of confusion regarding time and time synchronization which are basic to the understanding of time synchronization problems.

EPOCH AND INTERVAL

Accurate time synchronization requires two items:

1. A means of accurately comparing an epoch

2. A precise interval between succeeding epochs.

The limitations of the sync methods listed in Table 1 are all directly related to a deficiency in one or the other of these areas. The limitations of the methods are summarized below:

Transporting a Clock

This method involves a phase comparison technique; its limitations are simply the limitations of the oscillator, i.e., oscillator stability and the limitations of the phase equipment (phase comparator) - off the shelf equipment is capable of resolving 10 KC signals to within 0.1 degree, which is equivalent to 0.03 μsec. Thus, oscillator stability becomes the important factor regarding time sync limitations.

ARTIFICIAL SATELLITE

Relay of Time Signals

An experiment utilizing this method was conducted by the Naval Observatory and the Greenwich Observatory to synchronize the two master clocks. However, the experiment involved the use of elaborate equipment at both sites and involved two way transmission of the time signals (i.e., each station had a means of transmitting a time signal). Retransmission of the time signals at the reference station is used to eliminate doppler frequency shift errors. The doppler frequency shift errors could also be eliminated by use of a synchronous satellite to relay the time signals. It is doubtful if existing WWV and WWVH time signals (2 - 25 MC range) could be used in conjunction with synchronous satellite to synchronize MSFN stations due to propagation difficulties in reflecting a 2 - 25 MC signal from a satellite at synchronous altitude. Expected accuracy of synchronization utilizing the relay of time signals is about 100 μsec.

Free Running Reference Clock

The limitations of this method are predominately in the instability of the oscillator and the difficulties involved in updating the satellite clock, i.e., resynchronizing with the Naval Observatory clock.

In both methods mentioned above, high frequency and very high frequency time signals are used. These signals are not phase stable and consequently the phase measuring techniques can not be utilized. Without the elaborate precautions of a laboratory experiment, these methods will not yield sync accuracies much greater than 100 μsec.

LORAN-C

Each Loran-C clock is indirectly synchronized to the Naval Observatory clock. Since the Loran time signal is a phase stable 100 KC signal, phase measurement techniques are utilized. The limitations of this method lie in the oscillator instabilities; however, the oscillator instabilities are limited to the time interval allowed before the master Loran-C clock and the Naval Observatory clock are resynchronized. At present, the accuracy of sync is kept within the ±20 μsec range, i.e., the Loran-C master clock is allowed to get out of sync with the Naval Observatory clock by up to ±20 μsec before the clocks are resynchronized to within ± 0.1 μsec.[8]

Sky Wave

At frequencies near 100 KC, the stability of the refracting medium, the ionosphere, is comparatively high. As a general rule, expected sky-wave stability is approximately ± 1 μsec per reflection; however, as cycle amplitude is reduced, actual cycle recognition becomes ambiguous, thus introducing a (1) one or (2) two cycle ambiguity. However, these uncertainties would at most introduce interstation uncertainties equal to half the interstation sync future requirements (50 μsec).

COORDINATED TIME SIGNALS

High frequency time signals are reflected by the ionosphere in a manner similar to light reflected from a plane mirror; uncertainties as to ionospheric height at the reflection points give rise to propagation time delay errors. At best, these uncertainties can be reduced to ±0.1 msec per reflection and at worst the uncertainties due to N multiple reflections would be ± 0.1 msec x N reflections.

Reception of WWV or WWVH (these two stations are kept in sync to within 5 μsec) at two MSFN stations farthest from the transmitters probably require 4 ionospheric reflections, WWVH - CRO = 4 reflections, and WWV - ASC = 4 reflections.

The uncertainties due to propagation delays at these stations are at best ±0.4 msec for each station. However, the problem is further complicated by the fact that ideal conditions do not prevail and in fact conditions exist which might cause the propagation uncertainties to become as much as ± 10 milliseconds.[9]

VLF SIGNALS

Use of dual VLF signals to determine time requires a dual VLF receiver which alternately monitors the 19.9 KC and 20.0 KC WWVL signals: One oscillator in the receiver is phase locked onto the 19.9 KC signal; another oscillator in the receiver is phase locked onto the 20.0 KC signal. A measure of the phase difference between the two receiver oscillators and an approximate transmission time of the VLF signals then allows one to determine the time to within a few μsec. (This method amounts to counting the number of beats from WWVL to the station in question between the 19.9 and 20.0 KC signal and correcting beat cycles to time). Use of this method of synchronizing clocks would require the purchase of a dual VLF receiver, cost unknown. An experimental model is made by R.M.S. Engineering. Tests to monitor various VLF stations which are now in progress indicate that the WWVL VLF signals (19.9 KC and 20.0 KC) are not received by all stations. This is probably caused by insufficient signal strength of WWVL.

APPENDIX B

TIME AND FREQUENCY

Introduction

Time concerns an epoch and frequency-the interval between epochs. It is the prime responsibility of the Naval Observatory to determine the epoch and therefore the Naval Observatory (NO) clock is the officially recognized reference or master clock. The National Bureau of Standards (NBS) has the prime responsibility of maintaining the frequency required to obtain the interval between epochs as required by the Naval Observatory. However, both the NO and NBS disseminate time and frequency.

Although the problem of time sync is interrelated with the problem of obtaining a precise interval, i.e., stable frequency source, we will not be concerned with frequency sources nor in the utilization of a standard frequency transmission to keep an already synchronized clock in sync.

TIME SCALES

The Naval Observatory determines and maintains seven (7) time scales, namely: Atomic, Ephemeris, true sidereal, mean sidereal, Universal or Greenwich, i.e., UT0, UT1, and UT2. The Atomic time scale is generated by the quantum transition of a Cesium atom, whereas the astronomical time scales (Ephemeris, sidereal and universal) are generated by the motions of the celestial bodies. Although the atomic and astronomical time scales are independent, the Naval Observatory determines the relationship between them. Three time scales are of immediate importance to the MSFN: universal time, ephemeris time, and atomic time.

DEFINITIONS

Universal Time (UT)

A time scale based on the rotation of the earth with respect to the sun (one revolution of the earth) is called Universal Time; the average of the revolutions is mean solar time. The second of mean solar time, defined as 1/86,400 of a mean solar day, is not a constant unit of time because of the variance of speed of the earths rotation. The following standard notations have been adopted:

UT-0	uncorrected universal time, i.e., universal time as determined by a particular observatory.
UT-1	universal time corrected for observed polar motion (P.M.)
UT-2	universal time corrected for observed polar motion and for extrapolated seasonal variation in the speed of rotation of the earth (S. V.)
UT-C	universal time emitted by coordinated radio stations (HF time signals from WWV, WWVH, JJY, etc.)

Ephemeris Time (E.T.)

The fundamental unit of time interval, the Ephemeris Second, is defined as a fraction 1/31, 556,925.9747 of the tropical year for 1900 January 0 at 1200 hours (December 31, 1899 - noon). This unit of time is based on the orbital motion of the earth about the sun (one revolution of the earth about the sun equals one (1) tropical year). The epoch (T = 0) is by definition 12 hours Ephemeris Time of January 0, 1900. The time unit T is one (1) Julian Ephemeris Century.

Atomic Time A.1

The atomic time scale A.1 is defined as follows:

1. A clock which keeps time A.1 advances one second in the interval required for 9,192,631,770 oscillations of cesium at zero field (interval).

2. At $0^h\ 0^m\ 0^s$ UT-2 on January 1, 1958, the value of A.1 was $0^h\ 0^m\ 0^s$ (epoch)

Time Equations

Two equations of time and the definition of A.1 time in terms of E. T. completely relate the time scales discussed above.

1. UT - 0 + P.M. corr. + S.V. corr + UT C offset = UT-C

2. $\Delta T = E.T. - UT\text{-}2$

These equations are explained as follows:

T is found from astronomical observations; it relates the non-uniform time based on the mean of one earth rotation UT-2 to the more uniform time based on revolution of the earth about the sun E.T. Equation 1 relates coordinated time signals to UT-2. Coordinated time is based on the atomic time scale; however, the coordinated time signals are offset from the A.1 time scale to more closely agree with the UT-2 time scale. UT-C time is kept within 100 milliseconds of UT-2 time by adjustment of the UT-C offset correction in equation (1).

SUMMARY

Universal Time as determined by various observatories is not the same. The principle reason for this is that the adopted conventional longitudes from Greenwich are based on erroneous values.[10] This in turn means that UT-C time as broadcast by various countries is not synchronized very accurately (1 or 2 milliseconds sync accuracies), thus the requirement that only WWV or WWVH be used to sync Mercury/ Gemini time standards. International cooperation between various countries and additional "Flying Clocks" experiments will eliminate this difficulty.

The question of which time scale to use has already been determined. For events associated with the rotating earth, navigation satellite tracking, etc., Universal time, which is most closely related to earth rotation, is required. For physical measurements atomic time is required. Coordinated time, which is presently used to sync widely separated clocks, is based on atomic time A.1 offset to be closely related to Universal Time UT-2. Thus, we see that convenience will dictate the time scale used.