TIMEKEEPING

for the

Laser Ranging Experiment at McDonald Observatory

S. K. Poultney

1 September 1969

TECHNICAL REPORT NO. 70-021

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

Department of Physics and Astronomy
University of Maryland
College Park, Maryland

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ACKNOWLEDGEMENTS

I. INTRODUCTION

A. Equipment

The basic clock consists of a Sulzer 2.5C quartz Frequency Standard and an Astrodata 7190 Time Code Generator. The Frequency Standard has outputs at 100 KHZ, 1 MHZ, 5 MHZ, and 20 MHZ. The Time Code Generator uses the 1 MHZ output and provides day, hour, minute, and second visual readout. Electronic readout to milliseconds is available at a parallel binary to decimal time-of-day output. The Time Code Generator also provides pulsed rate outputs of 1-pps to 100-kpps as well as NASA 28 bit serial time code.

Frequency calibration of the Frequency Standard is done using a Fluke 207-1 VLF Receiver, VLF Whip Antenna, and the 100KHZ output of the Frequency Standard. A permanent, continuous record of the frequency offset from the selected VLF station is kept on a built-in chart recorder.

Time synchronization is done using a Specific Products Model WVTR WWV receiver, long wire antenna, and the 1-pps output of the Time Code Generator. The Time Code Generator can be advanced or retarded manually by 0.001 to 100 milliseconds per second. Time synchronization is also possible by transporting the basic clock to NBS-Boulder or Naval Observatory-Washington although one would probably prefer to have one of their portable clocks brought on-site. Six hour battery-packs make the basic clock portable.

Frequent power failures on-site have required the installation of a three-day battery for the basic clock. Power surges will require complete isolation from the power line if the full potential of the Sulzer 2.5C is to be realized.

The choice of equipment for the clock was dictated by three criteria; adequacy and cost, and delivery time. Given a longer lead-time and more money, one may not have chosen the same equipment. A Cesium beam or rubidium frequency standard would probably have been chosen.

B. Equipment Layout

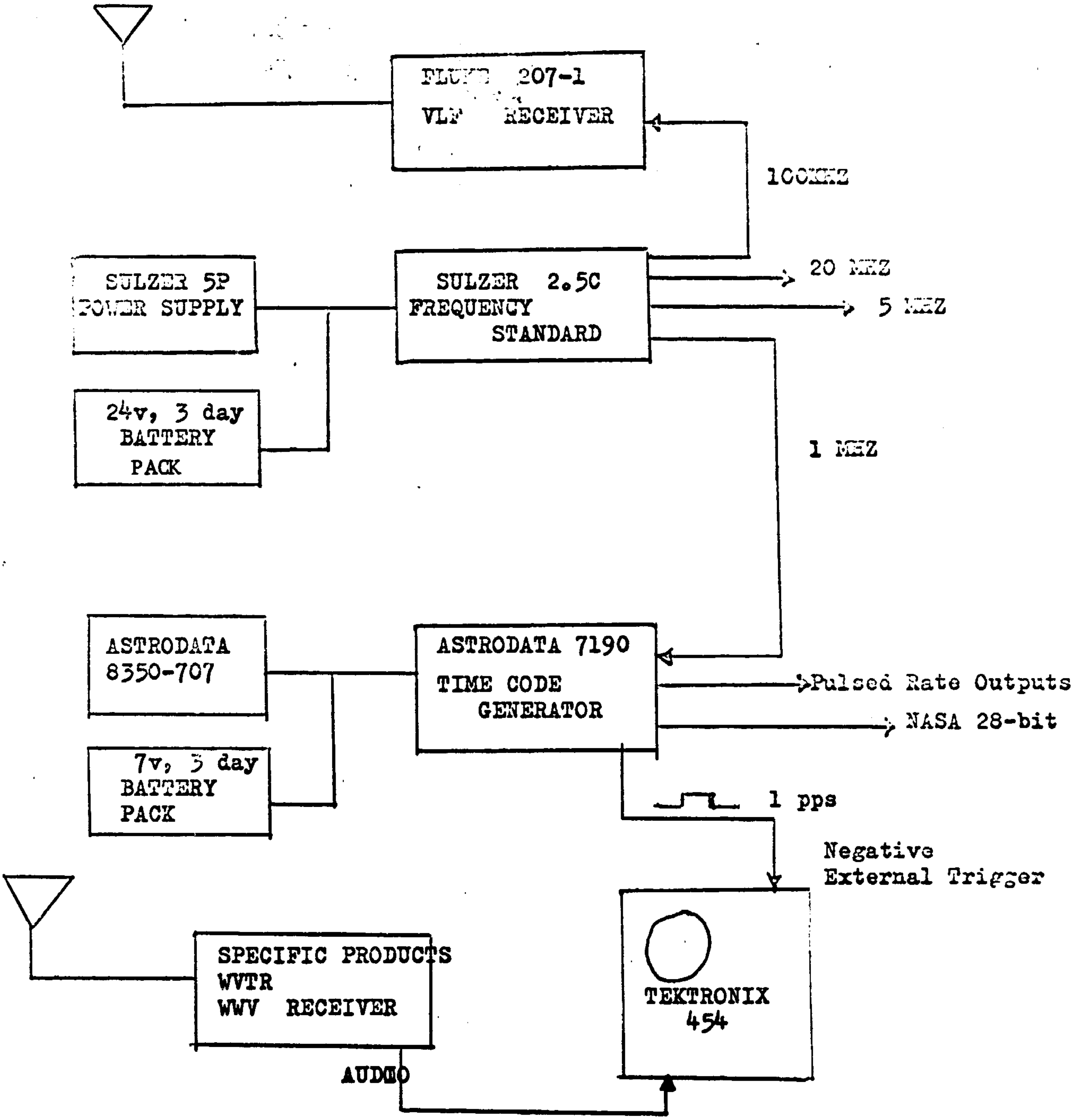
The clock and its monitoring equipment are located in a single rack to the right of the computer rack on the south wall of the laser room at the McDonald Observatory 107" telescope. Immediately to its right is the thermostat which keeps the room temperature to 68°F nominal. From top to bottom in the time-keeping rack are the WWV receiver, the VLF receiver, the Frequency Standard, the Time Code Generator, and the portable battery set for the Time Code Generator. The three-day battery packs are in the base of the rack. A separate portable rack is available for transporting the basic clock.

The VLF whip antenna is fastened on a base fixed to the outside catwalk on the east edge of the dome. Good reception of NLK, WWVB, WWVL, and Trinidad has been noted with NLK being the strongest signal. The antenna is connected to the VLF receiver by 100 ft. of 50 ohm cable. The WWV horizontally-polarized, long-wire antenna is about 50ftlong and is placed along the catwalk facing south for convenience. Good reception of WWV is obtained at various times during the day on 5, 10, and 15 MHZ.

A temperature monitor and control circuit is available to control the temperature of the clock units if the room temperature regulation proves insufficient.

Figure 1 shows a schematic of the clock and its monitoring equipment. The oscilloscope used in the time synchronization is also shown.

FIGURE 1 : Schematic Diagram of the Clock



II. Frequency Calibration

A. History

The Sulser 2.5C Frequency Standard (SN 420) was delivered live to Maryland and had been running at the factory in order to meet the long term stability specification of better than 5 parts in 10^{11} per day. The Frequency Standard was evaluated at the Naval Observatory for long term stability using their house clock. This evaluation showed that the Frequency Standard was capable of 3.6 parts in 10^{+11} per day when quieted down after transporting. The Frequency Standard was then returned to Maryland where it was compared to NSS for the two months prior to transport to McDonald. Much of the time was spent becoming familiar with the equipment and VLF stations. The best observed long term stability was 1 part in 10^{+10}.

Shipment of the clock to McDonald was to have been by air with a time synchronization made at the Naval Observatory in Washington before take-off. The time synchronization was done successfully, but an exhaustive series of telephone calls failed to uncover a responsible person who could decide whether or not the clock could indeed fly live. The clock was, therefore, taken to McDonald in an air conditioned car with power supplied by an inverter from the car battery. In transit, the 100KHZ and 1MHZ outputs of the Frequency Standard went off and, therefore, destroyed the time synchronization.

At McDonald much time was initially spent in choosing the best VLF station and in trying to get the clock stabilized. The Frequency Standard appears to be especially sensitive to the frequent overvoltages on the power line. Its standby battery should take up any undervoltage. Table 1 lists the daily time shift from noon to noon in microseconds, the calculated drift rate, the calculated aging rate, the frequency setting, and the station monitored for stable periods in July. Table 11 lists the same parameters for August. Nlk proved to be the loudest and first used station. However, it went off the air for repair on 4 August for two months. Trinidad and WWVl are now being used. The best observed long term stability at McDonald is about 4 parts in 10^{11} per day for four days.

No check of the short term stability has yet been accomplished. The manufacturer specification states 1 part in 10^{11}. Supply voltage changes of $\pm$ 20% should cause less than 1 part in 10^{10} in frequency changes and temperature changes from 5°C to 35°C should cause less than 2 parts in 10^{10} change.

B. Procedures for Frequency Calibration

Procedures for Frequency calibration using a VLF receiver is well discussed in On Frequency, Vol. 1, #2 published by Tracor, Inc. and in Frequency and Time Standards, Application Note 52 published by Hewlett Packard Co. Station selection is also discussed. NBS Special Publication 236 and Naval Observatory Time Service Announcement, Series 3 list broadcasting stations and describe the services each provide. Occasional announcements from both organizations update these basic publications. These publications and announcements can be obtained on request.

The frequency calibration procedure used at McDonald is as follows. The VLF receiver is set up as described above and in the supplied manual. The 100KHZ from the Frequency Standard is compared to the received signal. The narrowest tracking rate possible is used commensurate with conditions. A tracking rate of 3 x 10^{-8} is typically used with the stronger stations such as NLK Trinidad, and WWVL. A wider tracking rate is only used in switching between these stations. NLK has been used the longest and satisfies the north-south criterion and the power criterion. WWVL better satisfies the north-south criterion and is thought to be a better controlled frequency. It is weaker than NLK and has not been observed with any degree of consistency on our part yet. Trinidad is thought to be quite stable due to the long water path. It is comparable in strength to WWVL, but does not satisfy the north-south criterion. Trinidad (12.0KHZ) is now being studied due to the down time of NLK for the next two months.

The time shift of the Frequency Standard with respect to the VLF signal is recorded continuously on a chart recorder with 100 microseconds full scale reading. The time shift from noon to noon is the number used in the frequency calibration. It is best to plot the time shift as a function of the day in order to interpret the shift in terms of frequency offset and frequency aging. The daily drift rate can be calculated by dividing the time shift by the number of seconds in a day (i.e. $8.64x10^4$). The daily aging rate is the difference between the daily drift rate of two adjacent days. The net daily drift rate (aging rate subtracted) is caused by a frequency offset. The Frequency Standard can be adjusted to eliminate a frequency offset by means of the Frequency Adjust Control dial on its front panel. Each minor dial division is supposed to change the frequency by 1 part in 10^{11}. It appears that the actual change is 2 to 4 times greater. Clockwise turning increases the frequency and corrects a drift on the chart to the right. The opposite is true for counterclockwise turning. Tables 1 and 11 summarize the frequency calibration in the best behaved portions of August and July. Long term stability equal to or better than 4 parts in 10^{-11} is indicated. All records are kept on the Clock Log. The Frequency Standard is never turned off.

WWVL will be studied next. Note that only stations broadcasting UT_c are used.

TABLE I : Frequency Standard Behaviour at McDonald during July 1969

Date	t(μsec)	Drift Rate	Age Rate	Remarks
19 July	-100	$- 1x10^{-9}$	-	NLK 1263.0
20 July	-100	$- 1x10^{-9}$	0	NLK 1264.0
21 July	-100	$-1x\ 10^{-9}$	0	NLK 1264.5
22 July	-40	$- 5x10^{-10}$	$+ 5x10^{-10}$	NLK 1265.0
23 July	-30	$- 3x10^{-10}$	$+ 2x10^{-10}$	NLK 1265.5
24 July	-30	$- 3x10^{-10}$	0	NLK 1265.5
25 July	-50	$-6\ x10^{-10}$	$- 3x10^{-10}$	NLK 1265.5
26 July	+17	$+ 2x10^{-10}$	$+ 8x10^{-10}$	NLK 1266.0
27 July	+30	$+ 3x10^{-10}$	$+ 1x10^{-10}$	NLK 1266.0
28 July	-5	$- 6x10^{-11}$	$- 3x10^{-10}$	NLK 1266.0
29 July	+20	$+ 2x10^{-10}$	$+\ \ x10^{-10}$	NLK 1266.0
30 July	+10	$+ 1x10^{-10}$	$- 1x10^{-10}$	NLK 1266.0
31 July	+20	$+ 2x10^{-10}$	$+ 1x10^{-10}$	NLK 1266.0

TABLE II: Frequency Standard Behaviour at McDonald during August 1969

Date	t(μsec)	Drift Rate	Age Rate	Remabks
13 Aug	-	-	-	TRI 1266.0
14 Aug	+18	$+2.1x10^{-10}$	*	TRI 1266.0
15 Aug	+24	$+2.8x10^{-10}$	$+0.7x10^{-10}$	TRI 1266.0
16 Aug	-28	$-3.2x10^{-10}$	$-6.0x10^{-10}$	TRI 1264.0
17 Aug	-40	$-4.6x10^{-10}$	$-1.4x10^{-10}$	TRI 1264.0
18 Aug	0	0	$+4.6x10^{-10}$	TRI 1264.0
19 Aug	+13	$+1.5x10^{-10}$	$+1.5x10^{-10}$	TRI 1264.0
20 Aug	+15	$+1.7x10^{-10}$	$+0.2x10^{-10}$	TRI 1264.0
21 Aug	+19	$+2.2x10^{-10}$	$+0.5x10^{-10}$	TRI 1264.0
22 Aug	+26	$+3.0x10^{-10}$	$+0.8x10^{-10}$	TRI 1264.0
23 Aug	+31	$+3.6X10^{-10}$	$+0.6x10^{-10}$	TRI 1264.0
24 Aug	-128	$-1.5x10^{-9}$	$-1.9x10^{-9}$	TRI 1260.0
25 Aug	-96	$-1.1x10^{-9}$	$+4.0x10^{-10}$	TRI 1260.0
26 Aug	-86	$-1.0x10^{-9}$	$+1.0x10^{-10}$	TRI 1260.0
27 Aug	-56	$-7.0x10^{-10}$	$+3.0x10^{-10}$	TRI 1260.0 NO SIG
28 Aug	-78	$-9.0x10^{-10}$	$+2.0x10^{-10}$	WWVL 1260.0
29 Aug	-76	$-8.8x10^{-10}$	$+0.2x10^{-10}$	WWVL 1260.0
30 Aug	-70	$-8.1x10^{-10}$	$+0.7x10^{-10}$	WWVL 1260.0
31 Aug	-70	$-8.1x10^{-10}$	0	WWVL 1260.0

Frequency changes should be made as infrequently as possible and every attempt should be made to over-correct in order to reduce the number of changes. During the acquisition phase, frequency stability better than 1 part in 10^{+9} per day was not needed. However, during routine operations short term stability must be better than 1 part in 10^{10} per sec for range accuracy and long term stability must be better than 1 part in 10^{10} per day so that time will be known to 0.1 millisec without too frequent changes in frequency. These requirements make it mandatory that the problems discussed in Section V be solved.

III. Time Synchronization

A. History

The clock has been synchronized with the Naval Observatory clock, but that synchronization was not maintained as described in IIA. All other time synchronizations have been done using the WWV receiver. Under the best of conditions, the Time Code Generator has been set to a precision of about 0.1 milliseconds. The accuracy is somewhat more uncertain. During the first month of acquisition, a delay of 6.0 milliseconds was used for the transit time between McDonald and Ft. Collins, Colorado. Tick phasing time synchronization as described in the Hewlett Packard Application Note 52 was used in conjunction with a Tektronix 454 oscilloscope. No deviation from the set delay not attributable to outside causes was seen using this method.

The day is set for 1969 using the fact that 1 July is day 181. It is necessary to change both the day and hour at times in order to allow a range tape, computer, or ranging system check. This change is not advisable, but, if it is necessary, careful records should be kept. Mistakes have been made in the past in resetting the day; especially near change of GMT day.

B. Procedure for Time Synchronization

The Time Code Generator is synchronized using the falling edge of its 1-pps pulse to trigger a Tektronix 454 oscilloscope and the displayed audio output of the Specific Products WWV receiver. The Tick Phasing Method is used. The WWV tick is a 5 ms pulse of a 1KHZ signal. The oscilloscope may initially show the Time Code Generator pulse to be up to a half a second out of synchronization. It is, therefore, best to start with a long sweep speed on the oscilloscope (0.2 sec/cm). The Time Code Generator is now unlocked by removing the pin as described in its manual. The necessary ADV/RET rate is selected and the correct ADV/RET button held down to bring the WWV tick to the origin of the trace. This procedure is repeated as described in both the instruction manual and the application note until the first tick appears the correct number of milliseconds after the Time Code Generator tick. A calculation of the propagation delay is done in Appendix 1. The correct delay is 3.7 or 4.4 msec (±0.4) depending on whether the synchronization is done at day or at night. Schedule the observation for an all-daylight or all-night transmission path between McDonald and Ft. Collins. Choose the highest reception frequency which provides consistent reception. Set the clock on days when the WWV signal shows little jitter or fading. Make time comparisons using the WWV ticks with the earliest consistent arrival time. The day-night change in delay was observed at McDonald during August so care should be taken that the correct delay is used for the prevailing HF conditions. A scan through all the received HF frequencies serves as a guide to the prevailing conditions.

The seconds, minutes, hours, and days can now be set using the WWV voice transmission by pressing the Set buttons under each display tube. An independently calculated calendar should be located nearby in order that the day is set correctly. This procedure is especially necessary if the clock must be changed frequently for system checks. It should be noted that a change of day, hour, minute, or second does not destroy the WWV tick synchronization. After synchronizing the Time Code Generator, one should always make sure that the locking pin is replaced in its correct position.

At times, reset of the hours appears to be a delicate operation in that several hour jumps have been noticed soon after the Time Code Generator is reset.

When the final station configuration is in operation obtaining ranges to nanoseconds, time synchronization must be made at and maintained to 0.1 milliseconds or less. This accuracy requires that one of the traveling stomic clocks from the Naval Observatory be brought in to do the time synchronization. Periodic synchronizations will probably be required also. The frequency offset of the Frequency Standard is at present about 20 microseconds per day. Thus the Frequency Standard must be adjusted about every six days using the over-correction method. Inaccuracies in adjusting the frequency will probably require time synchronization with an atomic clock each month. If the Frequency Standard can be operated so as to realize its basic long term stability, then these time periods can be lengthened by a factor of six. A discussion of this basic problem with the Frequency Standard is contained in Section V.

IV. STANDBY POWER PROVISIONS

In order to keep the Frequency Standard in continuous operation and to make the basic clock portable, several battery packs have been provided. It would have been most efficient to have a standard battery pack for all clock units, but this was not possible. To allow transportation of the basic clock in operation, a Sulzer Power Supply Model 5P providing six hours time was purchased for the Frequency Standard and an Astrodata Battery Pack Model 8350-707 providing six hours time was purchased for the Time Code Generator. Both of these battery packs have automatic turn-on if power fails and an automatic cutoff if the battery lifetime is reached. One should refer to the manuals provided with the battery packs before using the batteries or recharging them. Both of the above units are very flexible in their power source requirements.

For power outages of greater than six hours at McDonald, three day battery packs have been supplied. The Frequency Standard has a 24 volt storage battery pack and the Time Code Generator has a 7 volt battery pack. Both of these battery packs are provided with automatic turn-on when the power fails. Neither the VLF receiver nor the WWV receiver have yet been provided emergency power. This system of emergency power may soon be replaced by the system described below in V.

V. PROBLEMS

The main problem with the timekeeping system is that the basic stability of the Frequency Standard has not yet been consistently realized The probable cause of this non-realization is power surges on the power line. Recall that standby power provisions keep the voltage above a certain minimum. These surges are most often related to thunderstorm activity in the vicinity. The Frequency Standard often takes off at a new offset some tens of microseconds different from the previous one immediately after a surge. A Sorenson line regulator did not help to alleviate this problem. Possible solutions are to isolate the clock completely from the power line using a motor-generator set or to isolate it using a battery pack and inverter. The latter method will be tried in the near future. In fact, all of the ranging electronics will be so isolated from the power line because of the power outages and surges. Fortunately, these power problems are a seasonal problem occuring only in July and August. Related to the power surge problem is a possible problem in switchover to the standby supply. If the standby supply is different by 20% from the regular supply, an offset of about 1 part in 10^{10} can be produced. However, unless something is wrong in the Sulzer 5P Power Supply, this switchover is not expected to be the cause.

Other causes of the main problem could be temperature fluctuations, bias battery drift, behaviour of the VLF receiver, or the VLF reception. The temperature of the clock environment is controlled to a few degrees by the room air conditioner and so fluctuations are not expected to affect the clock at the observed rates. The room air conditioner does, however, go off with the power. The Frequency Standard came with a provision for electrically changing the frequency. This provision was not noticed until the Naval Observatory tests when it was discovered that the necessary d.c. bias battery was left out by the manufacturer. Addition of the battery changed the frequency offset and necessitated a frequency change. Slow drifts in the bias battery voltage could cause the clock drift, but such is not expected; especially since the observed drift is usually correlated with thunderstorm activity. The VLF receiver is supposed to be capable of better than ± 1 microsecond per day, but it is conceivable that something is wrong with it or it is being used incorrectly. Propagation conditions and station frequency error are expected to produce an uncertainty of at most a few microseconds per day.

APPENDIX I: Calculation of HF Propagation Delay

A. Locations

WWV, Ft. Collins, Colorado

Longitude 105° 02' 27" W

Latitude 40° 40' 49" N

McDonald Observatory, Ft. Davis, Texas

Longitude 104° 01' 18"

Latitude 30° 40' 18"

B. Great Circle Distance

The haversine of the great circle distance, in degrees of arc, is given by

$$\text{hav } D = (\cos L_A)\ (\cos L_B)\ (\text{hav } Lo_{AB}) + \text{hav } L_{AB}$$

where

L_A = latitude of point A , L_B = latitude of point B,

$L_{AB} = L_A - L_B$,

$Lo_{AB} = Lo_A - Lo_B$,

Lo_A = longitude of point A, and Lo_B = longitude of point B

For the above locations,

L_A = 40° 40' 49" , $\log \cos L_A = 9.8811 - 10$

L_B = 30° 40' 18" , $\log \cos L_B = 9.9346 - 10$

Lo_{AB} = 1° 1' 9" , L_{AB} = 10' 31"

From a table of haversines,

$\log \text{hav } Lo_{AB} = 5.8750 - 10$ and $\text{hav } L_{AB} = 0.0076$

Therefore

$$\text{hav } D = \text{antilog } (5.6907 - 10) + 0.0076$$

$$= 0.0001 + 0.0076 = 0.0077$$

and

$$D = \text{arc hav } 0.0077 = 10^\circ\, 3' = 603'$$

Since

$$1' \text{ of arc} = 1.852 \text{ Km} \quad ,$$

$$D = 603' = 1060 \text{ Km} \quad (700 \text{ miles})$$

C. HF Propagation Delay

1. Ground Wave Delay = 3.5 milliseconds.

   However, ground wave is not expected at this distance.

2. Single Hop Day-Time off the E Layer

   E Layer virtual height = 125 Km

   Delay = 3.7 milliseconds

3. Single Hop off the F2 Layer

   F2 layer average virtual height 350 Km

   Delay = 4.4 milliseconds

   Delay Uncertainty = ± 0.3 milliseconds due to level height uncertainty

D. References

Frequency and Time Standards, Application Note 52

Hewlett-Packard Co., Palo Alto, Cal. 1965.

APPENDIX II: Bibliography

1. On Frequency, Vol 1, No 2, March 1969, Tracor, Inc Austin, Texas
2. Frequency and Time Standards, Application Note 52, Hewlett Packard Co, Palo Alto, Cal 1965
3. NBS Frequency and Time Broadcast Services, Special Publication 236, 1969 Edition.
4. Naval Observatory Time Service Announcement, Series 3
5. NBS and Naval Observatory Periodic Bulletins.
6. The American Ephemeris and Nautical Almanac, Naval Observatory, Washington, D.C. 1969

APPENDIX III: Daily Check Sheet for the CLOCK

Power and Batteries OK ______________________

Noon VLF Reading ACCUM ______________________

Noon VLF Reading CHART SHIFT ______________________

Record made on Graph and Table ______________________

WWV Sync Check at Noon (3.7 millisec) ______________________

WWV Sync Check before Run (hrs., min., sec.) etc. ______________________

Astrodata Day Check vs. Calendar ______________________

Astrodata Day Check before run against Mulholland Comp printouts ______________________

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Jean L'Avanceau of the Naval Observatory gave advice on timekeeping and did the initial evaluation of the Frequency Standard. John Mullendore installed the VLF antenna and the 3-day battery packs. John Caruso of McDonald installed the HF antenna.