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TIME AND COORDINATE SYSTEM STUDIES

TECHNICAL DOCUMENTARY REPORT NO. ESD-TDR-64-627

MARCH 1965

R. K. Gardner

Prepared for

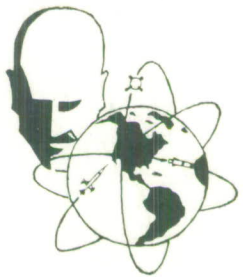
496L and 474L SPACETRACK SYSTEM

ELECTRONIC SYSTEMS DIVISION

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

L. G. Hanscom Field, Bedford, Massachusetts



Project 496. 2

Prepared by

THE MITRE CORPORATION

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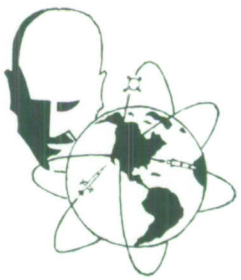

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ABSTRACT

This report describes the state of the art in the determination and dissemination of time and the coordinate systems for satellite tracking. The report also recommends methods for improving the capabilities of the Space Track system.

REVIEW AND APPROVAL

This technical documentary report has been reviewed and is approved.

THOMAS O. WEAR
Colonel, USAF
System Program Director
496L/474L System Program Office
Deputy for Surveillance and Control Systems

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SECTION I

INTRODUCTION

The problem of interest is that of establishing at the Space Track sites time standards that are traceable to some basic standard time such as UT-2. The U. S. Naval Observatory at Washington, D. C. has the task of determining and maintaining the standard time for the United States. The Royal Greenwich Observatory at Herstmonceux Castle, Sussex, performs the same service for the United Kingdom. As a result of a cooperative program involving these two observatories, the United States and British standard times are essentially identical.

In order to make standard time available for commercial and scientific use, the National Bureau of Standards (NBS) has constructed and continuously operates stations WWV and WWVH (which transmit in the HF band) and is constructing radio stations WWVB (LF band) and WWVL (VLF band). The General Post Office provides a similar service for the U. K. through radio station MSF (HF and LF bands) and GBR (VLF band). The U. S. Navy also broadcasts accurate time information over the VLF station NBA. Because of the geographical distribution of these radio stations (see Fig. 1), standard time and frequency signals are available over a wide area of the globe.

Since the radio stations are separated by great distances, it could easily happen that the time signals emitted by, say, WWVH in Hawaii and MSF in England, could differ by significant amounts. As the result of an extensive and continuing program involving the Royal Greenwich Observatory, the National Physical Laboratory, and the General Post Office in the United Kingdom plus the U. S. Naval Observatory, the Naval Research Laboratory, and the National Bureau of Standards in the United States, the signals emitted by all of the

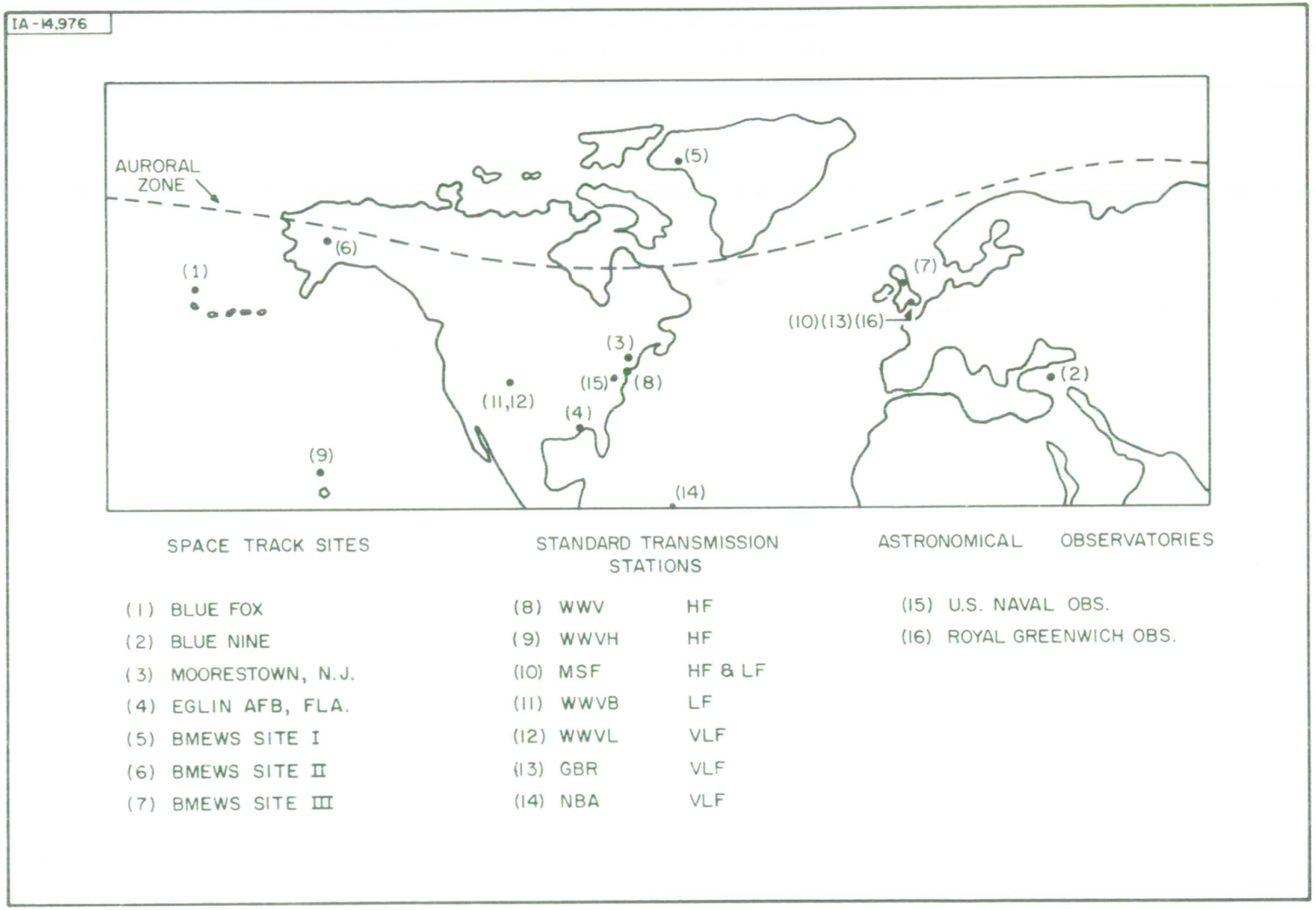

Fig. 1. Geography of Timing Network

stations listed in Fig. 1 are closely coordinated. * This is not to say that the time signals emitted by the stations agree perfectly; rather, as will be seen in Section III, the errors are the order of 1-2 milliseconds (msec). In contrast, the time signal emitted by another station may differ from those emitted by the above coordinated stations by many tens of milliseconds.

The time signals emitted by the cooperating stations are adjusted to approximate but not equal UT-2 time (UT-2 time can only be approximated since it depends on random variations in the earth's rotation rate). That is, a timing system perfectly synchronized with the time signals from WWV can be said to keep WWV time. However, WWV time can differ from UT-2 time by as much as 100 msec. The U. S. Naval Observatory continuously monitors the signal from WWV and other stations and determines the difference between the transmitted times and UT-2 time. The other national observatories provide similar services, with coordination and final determination of UT-2 time provided by the Bureau International de l'Heure. This problem is discussed more fully in Section III.

Because of the vagaries of radio-wave propagation, the establishment of an accurate time standard at a remote site is considerably more difficult than the establishment of an accurate time standard at a site located near a standard radio station. As can be seen from Fig. 1, the distance between Space Track sites and the nearest standard stations varies from 100 miles to almost 3000 miles. Further, the auroral zone affects the signals received at some of the

*Other countries, including Argentina, Australia, Canada, Japan, South Africa, and Switzerland have joined in the coordinated plan. [1]

Space Track sites. Thus we are forced to consider such items as the ionosphere, modes of HF propagation, modes of VLF propagation, and the effect of aurora on propagation. These are considered in Section IV.

The accuracy of a time standard will, of course, depend upon the equipment used in the timing system at each site and the way the equipment is operated or adjusted. Section V discusses the equipment presently used in the timing system at most of the Space Track sites and the various methods of adjusting the timing system.

SECTION II

AVAILABLE TIME AND FREQUENCY SIGNALS

INTRODUCTION

Since the signals from the standard transmission stations (listed in Fig. 1) form a basic link in the timing network, these signals are considered below in some detail. This section considers the electrical parameters such as carrier frequency, type of modulation, radiated power, schedule of transmission, etc. Section III considers the accuracy of the emitted time and frequency signals and their relation to basic standards such as UT-2 time.

Tables I, II, and III contain a tabulation of the standard transmission stations* (plus some other stations of interest) grouped according to the frequency band. In general terms, the HF stations (Table I) supply constant frequency and time signals over a large section of the world; however, the received HF signals depend strongly upon the status of the propagation path. The LF stations (Table II) also supply constant frequency and time signals; however, the coverage is limited (WWVB is expected to cover only the continental U. S.). Finally, at present, most of the VLF stations (Table III) supply constant frequency signals but not timing signals over a very large area of the globe. VLF stations NBA and GBR do supply timing signals.

*Data from References 2 through 4 and a personal communication from Edward Andrews of NBS Laboratories, Boulder, Colorado

Table I

Characteristics of HF Standard Transmission Stations

Call Signals	Operating Organizations	Location		Carrier Frequency (Mc)	Radiated Power (kw)	Seconds Tick			Operating Schedule
						Normal Tick Duration (msec)	Tick Modulation (cps)	Minute Mark	
WWV	NBS	Beltsville, Md.	38°59'33"N 76°50'52"W	2.5 5.0 10.0 15.0 20.0 25.0	1 8 9 9 1 0.1	5	1000	No tick at sec 59	Continuous except for min 45-49 each hour
WWVH	NBS	Maui, Hawaii	20°46'02"N 156°27'42"W	5.0 10.0 15.0	2 2 2	5	1200	No tick at sec 59	Continuous except for min 15-19 each hour and 1900-1934 UT each day
MSF	British Post Office	Rugby, England	52°22' N 1°11' W	2.5 5.0 10.0	0.5 0.5 0.5	5	1000	Tick for sec 00 is 100 msec long	5 min in each 15 min except min 15-20 each hour

Notes: All stations use a vertical dipole antenna.
All stations operate 24 hours a day, 7 days a week, except for scheduled down times lasting from 5 minutes to 30 minutes.
Carrier signal is modulated by seconds tick using double sideband amplitude modulation.
WWV currently transmits a special 1-minute PCM timing signal 10 times per hour.

Table II

Characteristics of LF Standard Transmission Stations

Call Signals	Operating Organizations	Location		Carrier Frequency (kc)	Radiated Power (kw)	Time Signals	Operating Schedule
WWVB	NBS	Boulder, Colorado	40°40'29"N 105°02'39"W	60	3 (approx)	Time tick every second. Pulse consists of 1-kc sine-wave.	Starting July 1, 1964 Continuous except for 8 hours on Tuesdays Starting by Jan. 1, 1965 Continuous operation
MSF	British Post Office	Rugby, England	52°21' N 1°11' W	60	10	None	Daily from 1430-1530 UT

Note: WWVB should provide reliable signals in continental United States only.

Table III

Characteristics of VLF Stations

Call Signals	Operating Organizations	Location		Freq. (kc)	Radiated Power (kw)	Operating Schedule		Notes
						Time Signals	Frequency Transmission	
WWVL	NBS	Sunset, Colorado	45°40'51"N 105°03'02"W	20.0	400	None	Starting July 1, 1964 Continuous operation except for 8 hour maintenance on Tuesday By Jan. 1, 1965, Continuous operation	Experimental sidebands will be transmitted in future. However, 20kc should always be present.
GBR	British Post Office	Rugby, England	52°20' N 1°11" W	16.0	300	4 times daily 0255-0300 UT 0855-0900 UT 1455-1500 UT 2055-2100 UT	Continuous except for daily maintenance from 1300-1500 UT	Carries Traffic
NBA	U. S. N.	Balboa, Canal Zone	9°04'30"N 79°34'30"W	18.0	20	Continuously transmitted	Continuous except between 1200-2100 on Wednesday	Carries Traffic
NAA	U. S. N.	Cutler, Maine	44°40' N 47°14' W	18.6	1000	None	Continuous except for maintenance as req'd.	Carries Traffic
NPB/NLK	U. S. N.	Jim Creek, Washington	48°05' N 121°35' W	24.0	250	None	Continuous except between 1600-2400 UT on Thursday	Carries Traffic
NPM	U. S. N.	Lualualei, Hawaii	21°24' N 158°10' W	19.8	100	None	Continuous except between 0900-1700 UT on Wednesday	Carries Traffic
NSS	U. S. N.	Annapolis, Maryland	33°59' N 76°30' W	22.3	100	None	Continuous except for maintenance as req'd.	Carries Traffic

Note: NBA provides the most precisely regulated time and frequency signals among the U. S. N. stations.

HF STANDARD TRANSMISSION STATIONS

The HF stations emit signals at discrete carrier frequencies ranging from 2.5 Mc to 25.0 Mc. The lower frequencies provide good short-range coverage, the middle to higher frequencies (10 Mc in particular) provide long-range coverage.

The carrier is amplitude modulated with a multitude of signals.[2] In particular, Fig. 2 shows the pattern of 440-cps and 600-cps tone modulation on WWV and WWVH for a typical hour period. Note that the tones last for two or three minutes starting on the hour and every 5 minutes thereafter (except for an occasional silent period). Further, these stations periodically carry voice announcements such as "National Bureau of Standards, WWV; when the tone returns, Eastern Standard Time is 9:10 AM." This announcement can be used to check the hour and minute reading of the timing system. *

Twice each hour WWV and WWVH carry radio propagation forecast messages broadcast in Morse code. The WWV forecast applies to the North Atlantic radio paths (such as New York to London) while the WWVH forecast applies to the North Pacific radio paths (such as Seattle to Tokyo). The forecast consists of a letter (W, U, or N) plus a digit (1 through 9) (see Table IV). The letter refers to the radio propagation conditions at the time the forecast is made. The digit refers to the forecast of the radio propagation quality for six or more hours after the forecast is made. Thus, for example, the message N4 means that propagation characteristics at the time that the forecast was made were normal but are expected to be only "poor-to-fair" within the next six-hour (or longer) period. The forecasts are revised twice daily for WWVH and four times daily for WWV.

*Universal time is also transmitted by International Morse Code every 5 minutes from WWV and WWVH.

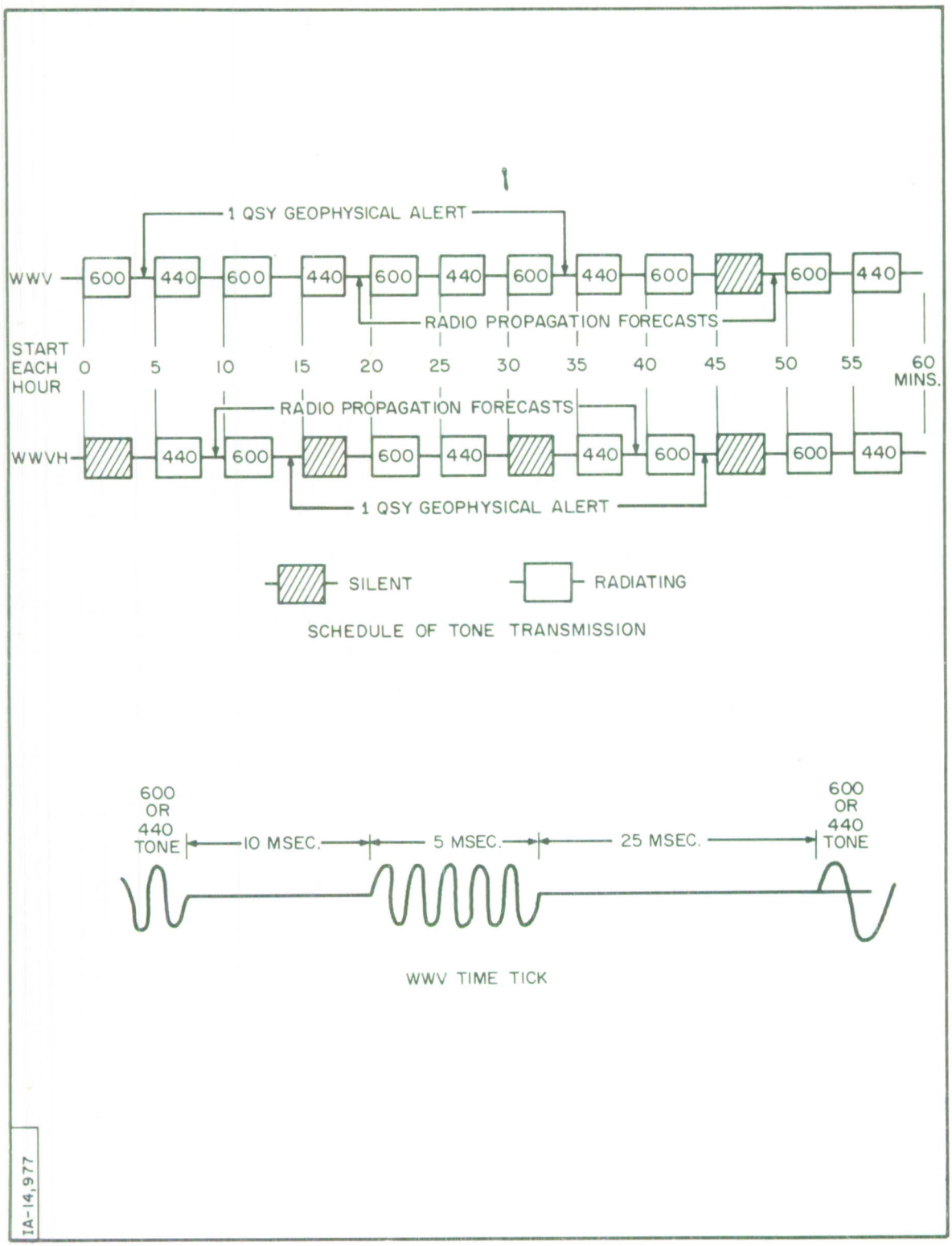

Fig. 2. Modulation Signals on WWV and WWVH

During the International Years of the Quiet Sun, 1964-1966, WWV and WWVH will carry IQSY Geophysical Alerts.[4] These alerts are made by the World Warning Agency at 0400 UT and apply to the following 24-hour period. The code symbols are transmitted by slow Morse code, twice each hour (see Table IV).

Finally, the HF stations emit "time ticks" (see Fig. 2) which are pulses of 5-msec duration* consisting of 5 cycles of a 1000-cps sinewave for WWV and MSF or 6 cycles of a 1200-cps sinewave for WWVH.[1] The start of the time tick marks the exact second. Further, for WWV and WWVH, the 59th-second time tick is omitted so that the next time tick marks the start of the minute. For MSF, the start of the minute is designated by lengthening the 00th-second time tick to 100 msec.

Table IV

Code Symbols Used by WWV and WWVH
Letters and Digits used in Radio Propagation Forecasts

Disturbed Grades (W)	Unsettled Grade (U)	Normal Grades (N)
1 - Useless	5 - Fair	6 - Fair-to-Good
2 - Very Poor		7 - Good
3 - Poor		8 - Very Good
4 - Poor-to-Fair		9 - Excellent

Symbols used in IQSY Geophysical Alerts

Symbol	Meaning
AAAAA	Magnetic storm (with K_p index of 5 or more) is expected, or has just started, or is in progress. Aurora can be expected or has been observed.
SSSSS	Solar activity is high because of the presence of one or more active centers on solar disc.
EEEEE	No alert.

*The tone signal is interrupted for 40 msec in order to transmit the seconds tick.

Thus, the HF stations transmit enough information to allow the synchronization of a timing system to the station time with an accuracy of a fraction of a millisecond, provided the timing system is located close to the transmitting station. When the timing system is located at a remote site, poor propagation conditions can degrade the synchronization accuracy.

LF STANDARD TRANSMISSION STATIONS

There are two LF stations of interest, as shown in Table II. Both stations emit a constant frequency signal at 60 kc, but only WWVB transmits time ticks.

It should be noted that the National Bureau of Standards is still constructing station WWVB; hence, its performance does not reach the goals initially set forth. [3] For example, the radiated power is now approximately 3 kw, * while the initial design goal was 7 kw. Also, the only modulation is the time-tick modulation plus station identification (by Morse code).

At present, WWVB is only transmitting for relatively short periods of time. Starting July 1, 1964, the NBS plans to be transmitting signals continuously except for an 8-hour period on Tuesdays. * By January 1, 1965, after an additional antenna has been installed, the NBS plans to have the station operating continuously. More antenna work is planned in order to increase the radiated power and the percentage of modulation.

From a systems point of view, the major drawback to the LF stations is their limited coverage. [3] In particular, WWVB should provide reliable coverage only for sites within the continental U. S. However, it is interesting

*Personal communication from Edward Andrews of NBS Laboratories, Boulder, Colorado.

to note that the timing system presently operating at the AN/FPS-85 does monitor WWVB and has successfully used this signal to adjust the local crystal oscillator.

VLF STANDARD TRANSMISSION STATIONS

Table III lists seven VLF stations. Only stations NBA and GBR now transmit time signals. The other stations transmit constant frequency signals. Furthermore, all of the stations except WWVL carry "traffic."

Station WWVL is suffering from many of the same construction problems* as WWVB. For example, the radiated power is now 200 watts while the goal was 1 kw. Also the station is presently operating only for short periods of time; however, the NBS plans to achieve continuous operation with the same schedule as station WWVB.

Station WWVL is emitting a carrier at 20 kc that is modulated to provide only station identification. The NBS has an experimental program [3] underway which may, in the future, provide accurate timing information by sideband signals added to the 20-kc carrier. Presently, however, station WWVL can only be used as a source of accurate frequency signals.

Navy stations NAA, NPG/NLK, NPM, and NSS also supply accurate frequency signals.[5] Occasionally, these stations emit timing signals; however, the signals are not extremely accurate. These Navy stations have certain drawbacks; for instance, they may change carrier frequency with little or no advance warning, they may be down for extended periods, and, in the future, use FSK modulation.

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*Op. cit.

Stations NBA and GBR supply highly precise frequency and time signals. GBR provides time signals for only four 5-minute intervals during the day.[6] However, time signals are continuously available from NBA.[5] The time signals from both stations are similar; NBA produces pulses of 300-msec duration, and GBR produces pulses of 100-msec duration. The start of the pulse marks the exact second. For NBA, the 29th-second pulse is omitted each minute and certain other pulses are omitted during the last 5 minutes of each hour in order to identify the minute. For GBR, the minute is marked by transmitting a 500-msec pulse at 00 seconds.

Because of the high Q usually associated with VLF antenna systems, the pulse emitted by NBA has a 15-msec rise time as shown in Fig. 3. The point of interest is the time of the start of the pulse (time t_o in Fig. 3) which, in the presence of noise, cannot be directly determined. Instead, a line is drawn tangent to the envelope of the pulse and the intersection of the line with the

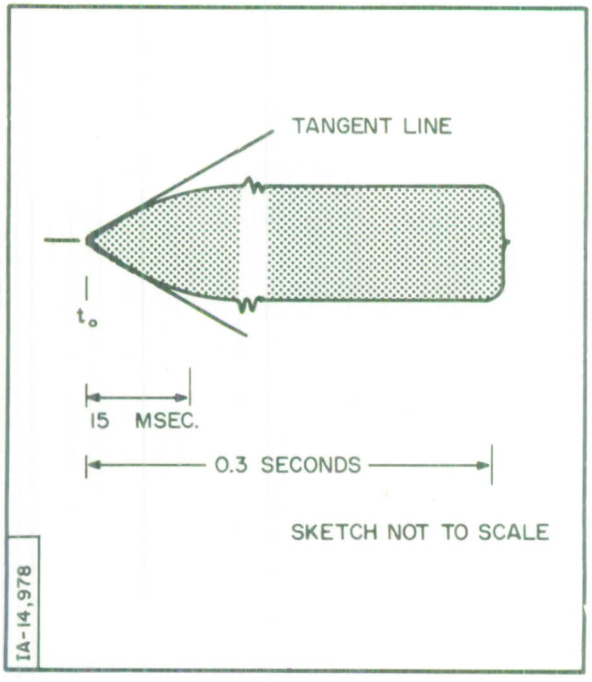

Fig. 3. Sketch of Seconds Pulse from NBA

axis determines the time of the start of the pulse. Experiments at the Naval Research Laboratory using the pulse emitted by NBA showed that the start of the pulse can be determined with an accuracy of about 0.5 msec, provided the pulse is "integrated" (by photographing the oscilloscope trace) for 2 minutes.[7] The accuracy with which the start of the pulse could be determined in more remote locations is not known.

VLF tracking receivers (see Section VI) are available which can reliably extract the carrier signal in the presence of background noise. These receivers have bandwidths on the order of 0.01 cps and should have no problem extracting the carrier signal even though they are located in remote sites. Thus VLF carrier signals are available at remote sites and can be used to accurately control the frequency of the oscillators incorporated in the timing systems.

SECTION III

ACCURACY OF AVAILABLE TIME AND FREQUENCY SIGNALS

INTRODUCTION

The previous section considered the electrical properties of the signal emitted by the standard transmission stations; this section considers the accuracy of the emitted signals and their relation to basic time and frequency standards. It is convenient to divide the discussion into two parts: the first part deals with the accuracy of the emitted carrier frequencies and their relation to the U. S. Frequency Standard; the second part considers the accuracy of the emitted time ticks and their relationship to UT-2 and atomic time.

FREQUENCY SIGNALS

The National Bureau of Standards maintains the United States Frequency Standard (USFS) at its Boulder Laboratories. [8] Since October 9, 1957, the USFS has been based upon a set of atomic standards which, in turn, are further compared with eight other standards located in North America and Europe in order to determine the final reference frequency. The quoted accuracy of the USFS with respect to the idealized atomic transition frequency is about 1 part in 10^{11}.

The carrier signals radiated by WWV, WWVH, WWVB, and WWVL are derived from stable quartz oscillators. The frequency of the radiated signal from WWVB is compared with the USFS, and the quartz oscillator frequency is periodically adjusted (approximately every 10 days) so that the radiated frequency is kept constant to better than 1 part in 10^{10}. The signal from WWVB is in turn used to calibrate and adjust the oscillators at WWV, WWVH, and WWVL.

Figure 4 is a graph of the frequency emitted by WWV for a four-year period.[9] Note that the emitted frequency F_1 differs significantly from the reference frequency F_0 (derived from the USFS). In particular, the two frequencies are related by the equation[10]

$$F_1 = F_0 \ (1 + S) \tag{1}$$

where

$$S = \text{Frequency Offset} = \begin{cases} -150 \times 10^{-10} \text{ for 1960, 1961, and 1964} \\ -130 \times 10^{-10} \text{ for 1962 and 1963} \end{cases}$$

The frequency of the emitted signal is intentionally offset* from the reference frequency so that the "second ticks," which are derived from the emitted frequency, will closely approximate UT-2 time. Thus, the carrier frequency F_1 emitted by WWV on, say, 10 Mc, can be considered to be 10×10^6 cycles per UT-2 second while the reference frequency F_0 is 10×10^6 cycles per atomic second.

The carrier frequencies emitted by all the stations listed in Tables I, II and III, and by the standard time services of all the cooperating countries listed in Section I are controlled in a manner similar to WWV. That is, the emitted frequencies are all offset from the reference frequency by the same value of S. Furthermore, the emitted frequencies are all kept constant with respect to the ideal offset frequency, by about 1 part in 10^{10}.[11]

*The frequency offset is kept constant during the year but will vary from year-to-year.

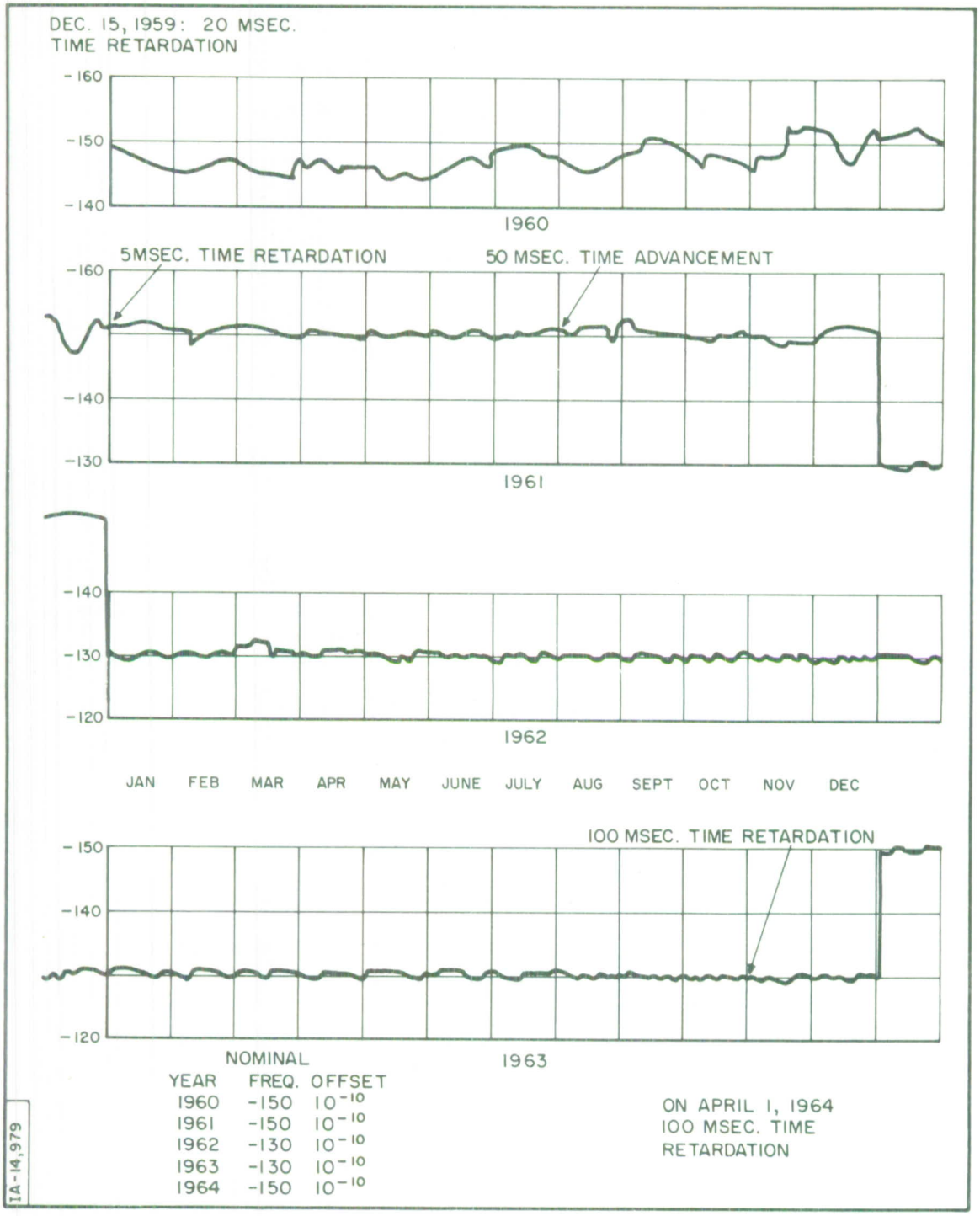

Fig. 4. WWV Frequency (in Parts in 10^{10}) with Respect to USFS

TIME SIGNALS

The United States Naval Observatory monitors the time signals from WWV in order to compare WWV time with UT-2 time which they determine from astronomical observations. The results of this comparison are plotted in Fig. 5 for the time period January 1960 through March 1963.[12]

There are three discontinuities in the curve: one at January 1, 1961; a second at August 1, 1961; and the last at January 1, 1962. This last discontinuity is caused by a change in the value of the conventional longitude of the Naval Observatory, plus changes in the fundamental star catalog used to compare the results of different observations. As a result of this change, the determination of Universal Time by the Royal Greenwich Observatory and the U. S. Naval Observatory are systematically the same.[13]*

The other discontinuities in Fig. 5 are caused by intentional time adjustments to the WWV clock made in order to keep WWV time in reasonable agreement with UT-2 time. Note in Fig. 5 that similar adjustments were also made on December 15, 1959, November 1, 1963, and April 1, 1964. The last two adjustments each retarded WWV time by 100 msec.

There is a considerable delay between the taking of observational data and the final determination of the UT-2. Presently, the Naval Observatory smooths the WWV measurements over a period of days and smooths the star observations (which determine UT-2) over several months. ** Thus, on or about March 1

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* Strictly speaking, UT-2 is defined by the Bureau International de L'Heure, which utilizes the data from 40 time service observatories. From January 1, 1962, ITH and USNO UT-2s should be in systematic agreement.

**Personal Communication from Dr. Hall, Time Service Bureau, U. S. Naval Observatory.

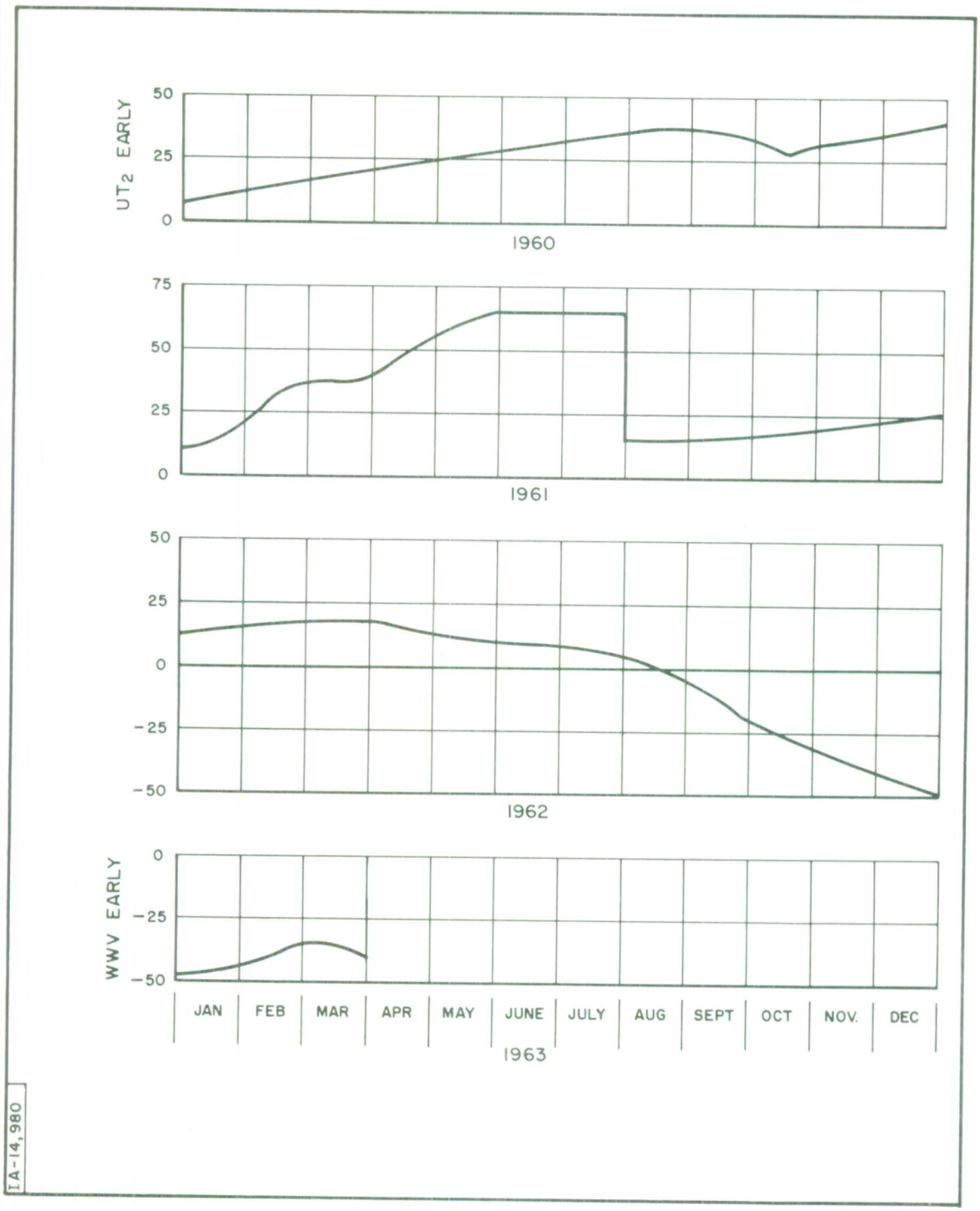

Fig. 5. Difference (in msec) Between UT-2 Time and WWV Time

of a given year, the Naval Observatory can say that WWV time and UT-2 time on January 1 of that year differed by XXX. X msec, with an accuracy of a fraction of a millisecond.

The Naval Observatory has defined an atomic time scale A-1 which is related to Ephemeris time and is provided by atomic clocks.[14] The relation between WWV time and A-1 time is also determined by the observatory, resulting in the data shown in Fig. 6. The top curve shows the difference between A-1 time and WWV time for the year 1962. Notice that the difference is approximately a linear function of time; this linear dependence is not surprising since WWV is referenced to an atomic oscillator. However, as noted in the previous section, WWV's frequency is offset by different amounts from year-to-year. Hence, it follows that the difference between A-1 time and WWV time is going to be a series of straight lines (as shown in Fig. 7) where the slope of the straight lines for each year depends upon the amount of frequency offset. In addition, there will be a jump occurring whenever step adjustments are made to WWV's clock.

The bottom curve of Fig. 6 shows the extent to which the difference between A-1 and WWV time (excluding step adjustments) deviates from a straight line whose slope is determined by the annual frequency offset. Notice that the maximum error over a 15-month period is about 0.7 msec; it is believed that the maximum errors currently do not exceed 0.5 msec. For more precise work it is possible to obtain the difference between A-1 and WWV times with a delay of less than a month. Using such information as a preliminary approximation should reduce the maximum error to 0.2 msec.

The final item to be considered is the degree to which time ticks emitted by other stations are synchronized with WWV's time tick (which has been used implicitly as the reference). Once again the data gathered by the Naval

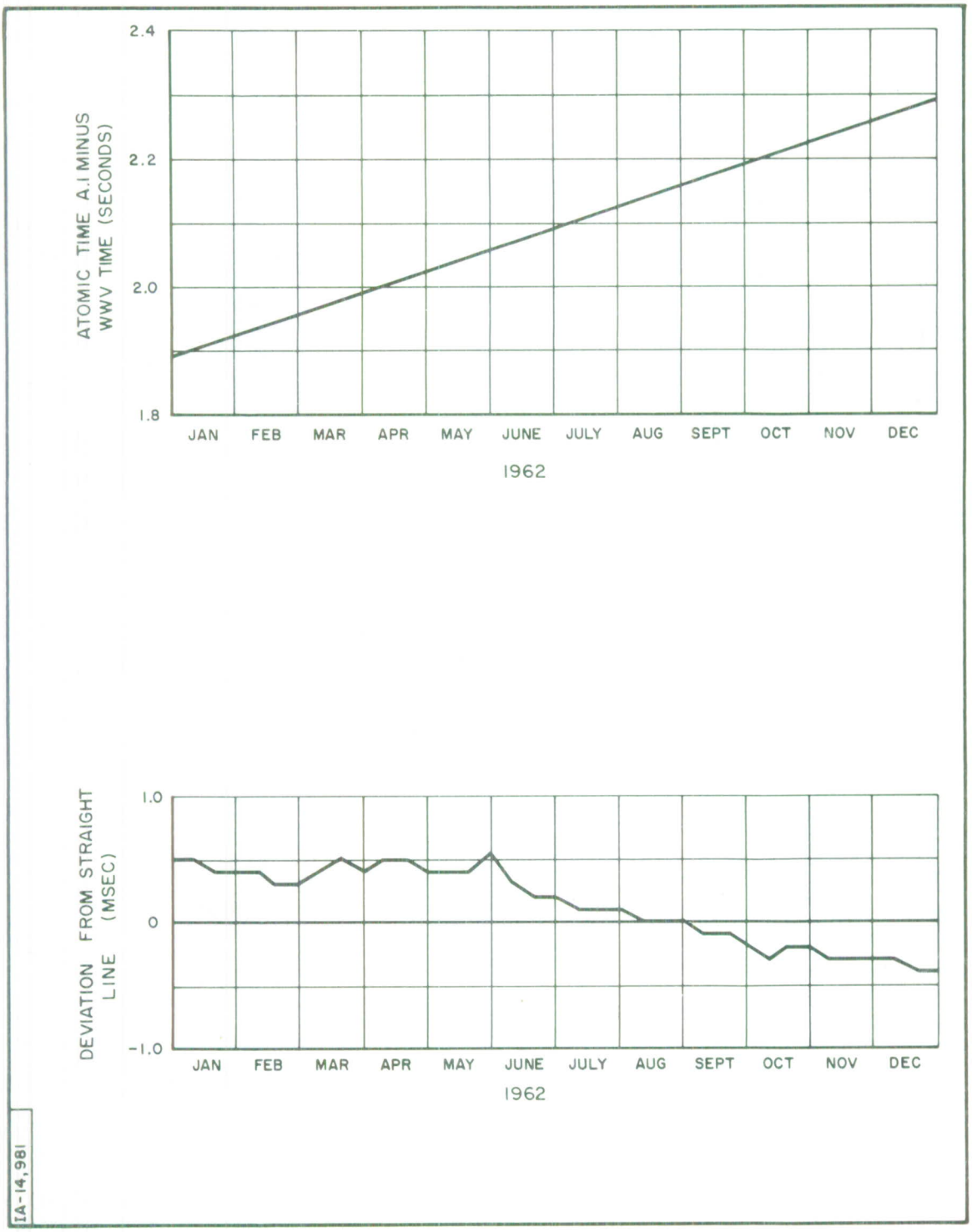

Fig. 6. Comparison of WWV Time with Atomic Time A-1

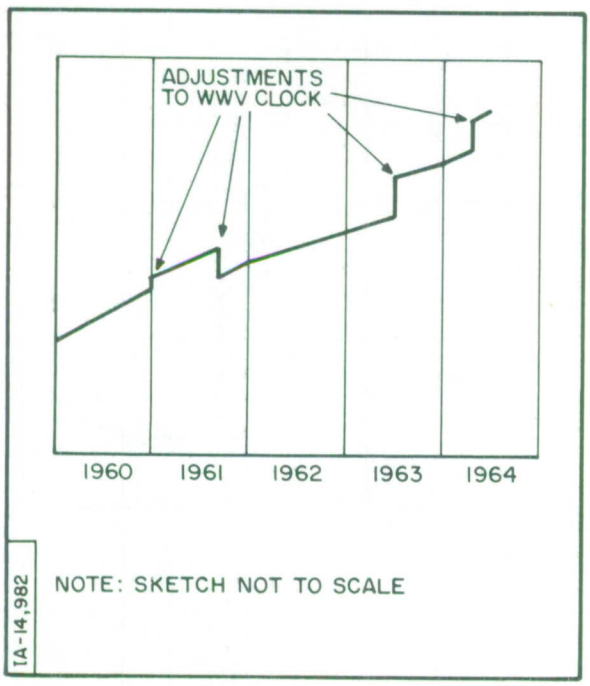

Fig. 7. Atomic Time Minus WWV Time

Observatory can be used, resulting in the set of curves given in Fig. 8. The upper set of curves relate NBA, WWVH, GBR* and WWV times. Note that all of the stations listed in the upper curve are of direct interest to Space Track and that the maximum error between these stations is about 4 msec (or an average error of about ± 2 msec). In contrast, the bottom curve shows that the difference between TQG5 (Paris, France) and WWV times can reach ± 30 msec.

*GBR and MSF keep the same time.

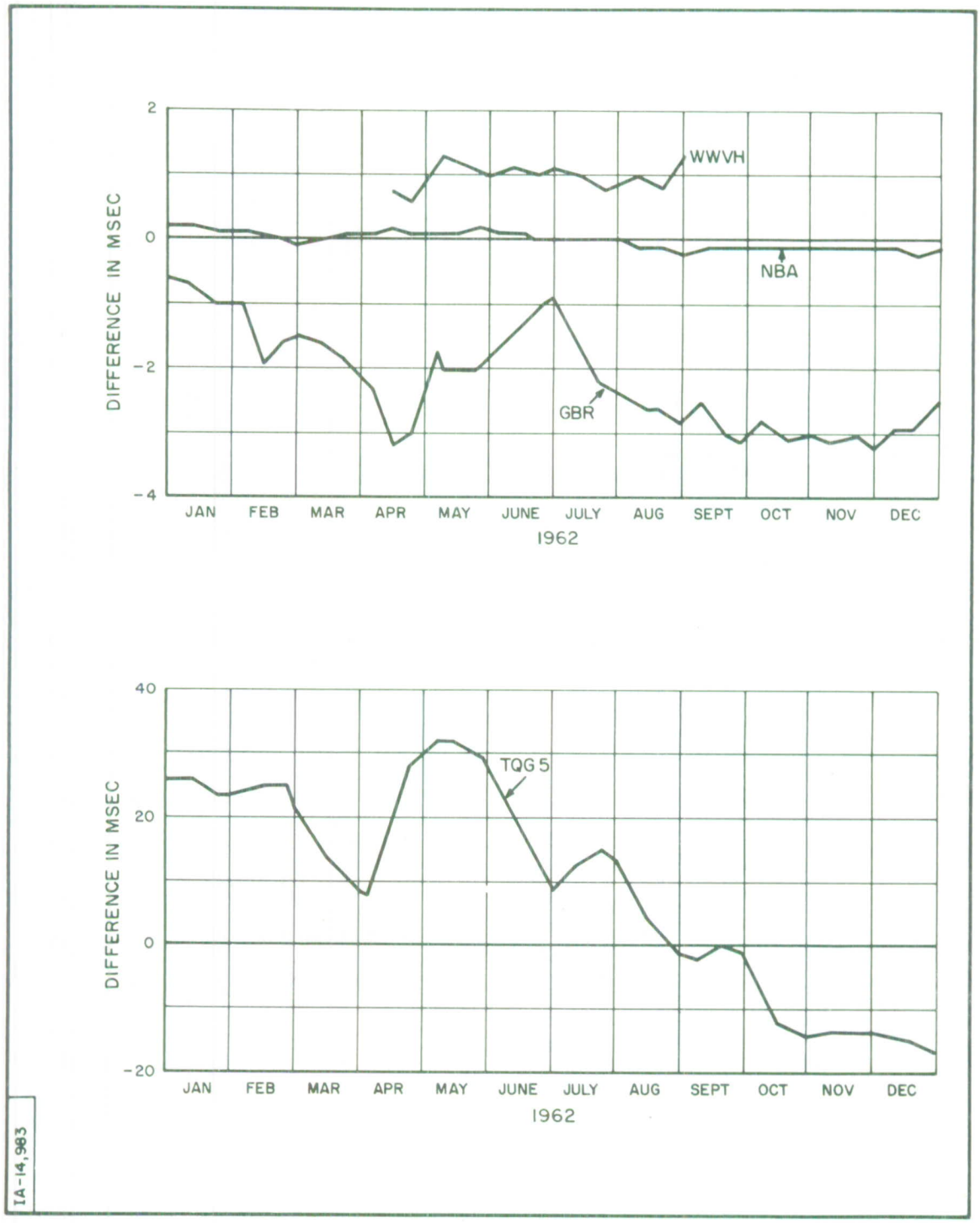

Fig. 8. Difference in Final Times of Emission WWV - Station

SECTION IV

HF, LF, AND VLF PROPAGATION

INTRODUCTION

The frequency and time signals emitted by all of the standard transmission stations are stable, accurately controlled, and relatable to primary standards. Unfortunately, the signals received at most of the Space Track sites are neither perfectly stable nor accurately relatable to the emitted signal, due to the time-varying nature of the ionosphere. The properties of the ionosphere and the effects of HF, LF, and VLF signals must be understood if Space Track is to make optimum use of available frequency and time signals.

THE IONOSPHERE AND RADIO PROPAGATION

Figure 9 shows the variation of electron density in the ionosphere with height as obtained from ionogram recordings taken at White Sands, N. M., at noon and midnight during an April day in 1961.[15] [16] [17] As can be seen, there is a considerable difference between a noontime and a midnight ionosphere; that is, the pattern of the ionosphere strongly depends upon the relative position of the sun. However, the ionosphere pattern does not repeat from day to day. Further, the ionospheric pattern varies significantly with latitude.

In spite of the variations, certain features are sufficiently important and repetitive to be given names. In particular, the heights at which the electron density reaches a relative maximum are referred to as "layers." The heights at which the layers occur vary with time, but are generally within the limits shown in Fig. 9. The number of layers that are present at any one time also

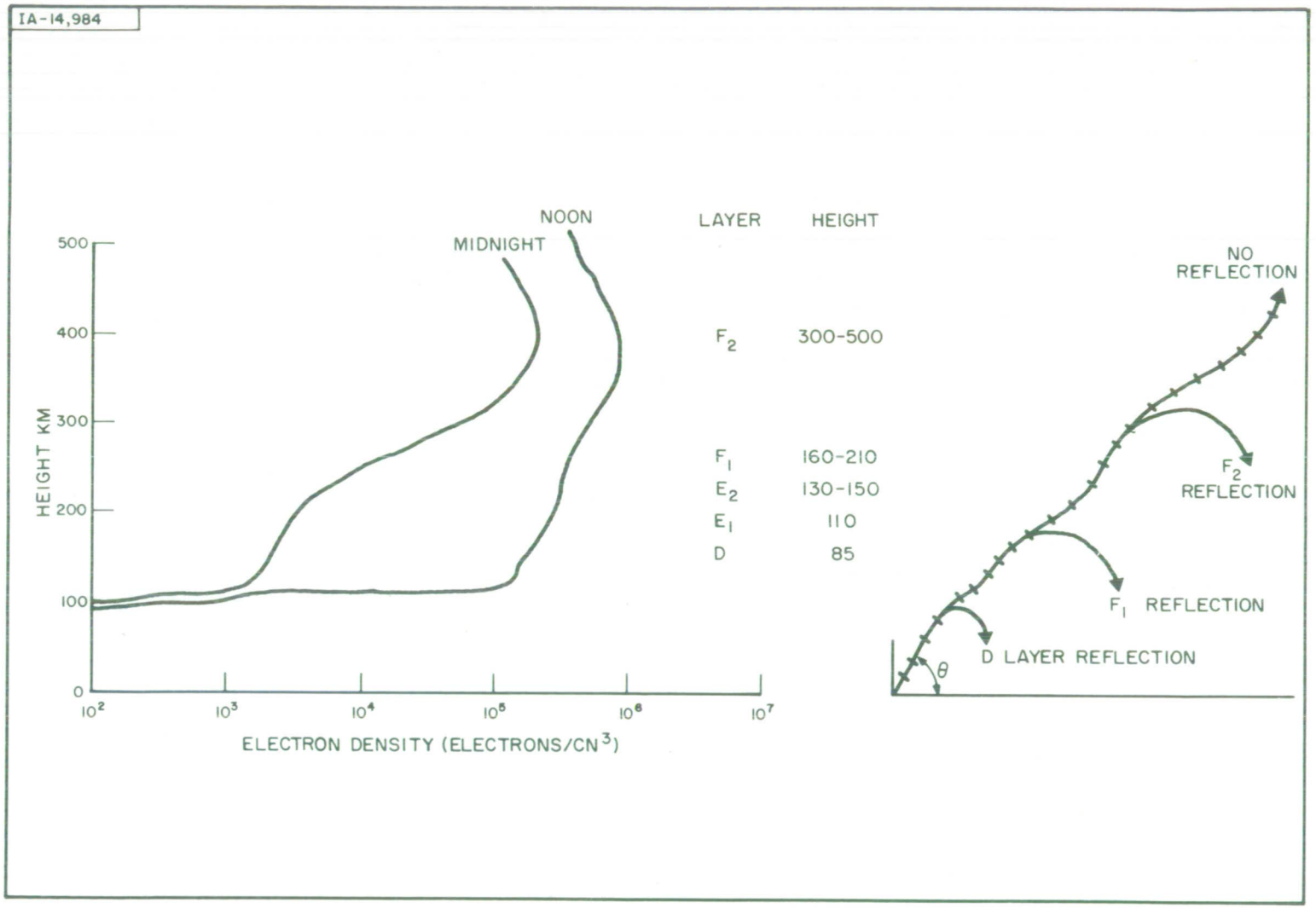

Fig. 9. The Quiet Ionosphere

varies. In general, there are more layers during daylight. During the nighttime, the F_1 and F_2 layers coalesce as do the E_1 and E_2 layers (if both existed). The density of the D and E layers drops by a factor of about 10^2 during the night; the diurnal change is significantly less for the F_2 layer.

An electromagnetic wave traveling through the ionosphere has the property that its phase velocity increases with electron density.[18] Consequently, an electromagnetic wave entering the ionosphere, as shown in the right-hand side of Fig. 9, will be bent back towards the earth when it is passing through regions where the electron density increases with height. For those regions where the electron density decreases with height, the radio wave is bent away from the earth.

The amount of bending experienced by a radio wave passing through the ionosphere depends upon the frequency and the initial angle θ. Consider the case where the angle is fixed and the frequency is varied. For frequencies at the upper end of the HF band (30 Mc) and above, the radio wave passes through the ionosphere and escapes into space (the case marked "no reflection" in Fig. 9). As the frequency is reduced, the radio wave continues to pass through the lower levels of the ionosphere but is bent more and more by the F_2 layer. Finally, a frequency will be reached where F_2 reflection occurs. Reducing the frequency even more results in the radio wave being "reflected" from lower levels of the ionosphere. Typically, reflection from the E layer occurs at the low end of the HF band (3 Mc). As the frequency is reduced to 60 kc (the frequency of WWVB) and below, the radio wave is reflected from the lowest edge of the ionosphere at heights of from 80 to 100 km.[19] [20]

Thus, the radio signals transmitted by the HF stations are affected by the complete ionosphere pattern; the reflection from the F_2 layer is of special importance. Signals from the LF and VLF stations are reflected by the lower edge of the ionosphere; hence, LF and VLF propagation is unaffected by

ionospheric variation in the upper layers. This simple example goes a long way toward "explaining" why LF and VLF time and frequency signals are orders of magnitude more stable than HF time and frequency signals.

The above discussion has dealt with the "quiet" ionosphere which can be expected to occur some 70 to 80 percent of the time at most locations. However, the occurrence of a solar flare can cause significant deviations in the ionospheric pattern that can have major effects on radio wave propagation. [17] A brief discussion of these causes and effects follows.

"A solar flare, a short duration (typically tens of minutes) bright emission from the active region of the sun usually observed in the hydrogen line (H_2), is primarily a sunspot maxima phenomena. Few, if any, important flares occur during the two to three years at the minimum of the solar cycle. On the other hand, during the peak sunspot years, it is common to observe several large flares and a great many smaller flares each month." [17]

A solar flare produces electromagnetic radiation, which takes 8 minutes to travel from the sun to the earth; cosmic-ray particles, which take several hours to reach the earth; and magnetic-storm particles, which take 20 to 40 hours to reach the earth. The electromagnetic radiation results in a great increase in the D-region electron densities, a phenomena generally referred to as a sudden ionospheric disturbance (SID). The cosmic-ray particles from large flares interact with the earth's magnetic field to produce an increase in the D-layer electron density over the poles. This phenomena is referred to as polar-cap absorption (PCA). Finally, the magnetic storm particles produce magnetic and ionospheric storms of two to five days duration or more. In addition, aurora often accompanies these storms. The principal effect of an ionospheric storm is a change in the density of the F_2 layer. In the polar region, there is a severe depression of electron density; only a mild

depression of electron density occurs in intermediate geomagnetic latitudes (30 to 45 degrees), while an increase in electron density is observed in the equatorial zone.

From a coverage point of view, SID's are limited to the sunlight portion of the earth, PCA's occur at the poles, and an ionospheric storm is a worldwide phenomena.

HF PROPAGATION

Some Properties of HF Propagation

The antenna systems of the standard broadcasting stations are all vertical dipoles. Thus the radiation pattern of the antennae is similar to the familiar donut shape of elementary theory. As a result, a portion of the radiated energy travels along the surface of the earth in a ground wave, while another portion of the radiated energy travels through the atmosphere and finally interacts with the ionosphere resulting in sky waves (see Fig. 10).

The properties of the ground wave are determined by the frequency and conductivity of the ground. Thus the ground wave is the most stable mode of propagation and would be ideal for timing purposes. In fact, the Loran-C timing schemes (at 100 kc) use the ground wave coverage and obtain synchronization accuracies in the μsec region. Unfortunately, the HF ground wave is rapidly attenuated; hence, its coverage is limited to about 150 km. Thus only Moorestown and possibly Site III could utilize this propagation mode. *

*The ground-wave seconds tick can be distinguished from the sky-wave seconds tick by its earlier time of arrival.

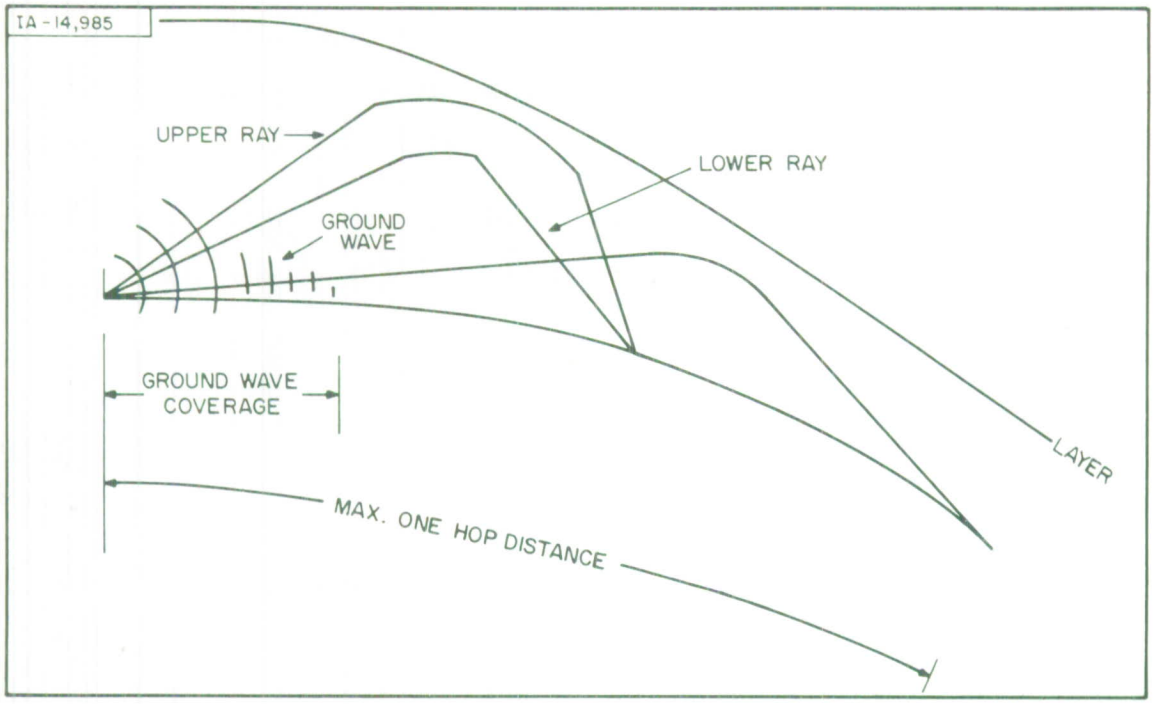

Fig. 10. Ground Wave and One Hop Coverage

Transmission of HF signals beyond the ground-wave coverage depends upon the reflection of radio waves off the ionosphere. Figure 10 shows a simplified picture of the sky-wave propagation from a transmitter to a receiver by ionospheric reflections off a single ionospheric layer. Notice that there are two paths (an upper ray and a lower ray) by which radio waves can reach the receiver. Both of these paths pertain to reflections from the same layer; however, the upper ray is usually considerably weaker than the lower ray since it spends a longer time in the ionosphere. As a result, the received signal is primarily that from the lower ray with the upper ray causing some fading.

Unfortunately, the situation is almost never as simple as that shown in Fig. 10. Depending upon the frequency in use and the status of the ionosphere, a given receiving site may receive radio waves reflected from the E layer, the

F_1 layer, and the F_2 layer. All of these signals are combined by the antenna, and the resultant signal generally shows a considerable amount of fading.

The strength of the received signal usually depends upon such factors as transmitted power and distance. Furthermore, it depends upon the electron density of the D layer. [18] Consider, for example, a situation such as that shown in Fig. 10 in which the principle mode of propagation is by reflections off the F_2 layer. Thus the frequency is high enough so that the radio wave passes through the D layer without reflection. However, the passage of the radio wave through the D layer does accelerate the D-layer electrons. Further, the height of the D layer is sufficiently low so that the atmospheric density is not negligible. As a result, the accelerated electrons collide with atmospheric particles and, hence, extract energy from the radio wave. Because of the rapid decrease in atmospheric density with altitude, almost all of the absorption suffered by a radio wave when traveling through the ionosphere occurs when it passes through the D layer.

The amount of attenuation produced by the D layer increases with the electron density of the D layer and decreases with increasing frequency. Thus the D-layer absorption is a minimum at night. Further, if a choice of frequencies is available, as it is when monitoring an HF station, the strongest signal is observed at the higher frequencies (other things being equal -- which they seldom are).

As the distance between the transmitter and receiver is increased, a point is soon reached where the radio wave cannot reach the receiver after just one reflection from the ionosphere. This distance is referred to as the maximum one-hop distance and occurs when the sky wave is tangent to the earth at the

transmitter or receiver (see Fig. 10). The maximum one-hop distance [21] for E-layer reflection is about 1500 nm and approximately 2200 nm for F_2-layer reflection.

Propagation over distances in excess of the maximum one-hop distance is achieved by multiple-hops, as illustrated in Fig. 11. Since the radio wave now

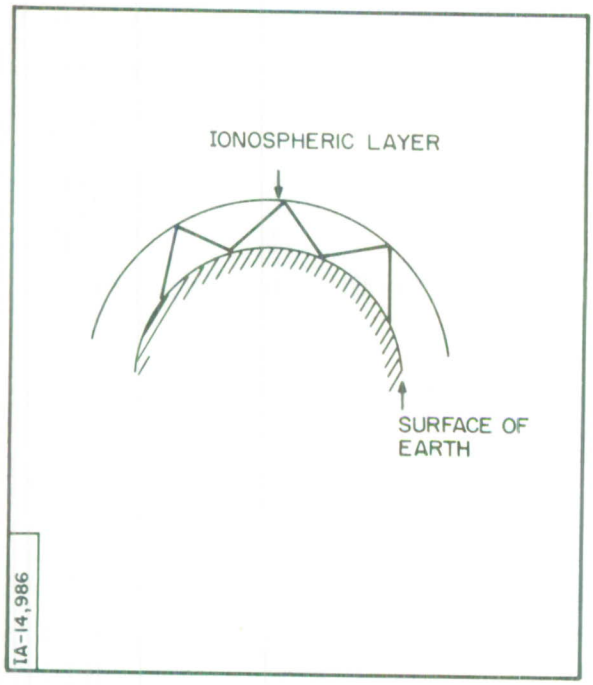

Fig. 11. Three-Hop Transmission Path

"bounces" off the ionosphere in two or more places as well as "bouncing" off the earth, the quality of the received signal is, expectedly, highly variable. Furthermore, the signal can reach the receiver along paths having two, three, or even more hops. Thus a single seconds tick emitted by the transmitter can result in a series of seconds ticks at the receiver, a phenomenon referred to as multipath.

Effects of HF Propagation upon Timing Systems

It follows from the above discussion that no single statement or group of statements can adequately describe the effects of HF propagation upon timing systems. Furthermore, there is a disturbing lack of experimental evidence dealing with the accuracy with which two remotely separated clocks can be synchronized. However, this synchronization problem is of basic importance; hence, the available experimental data is reviewed in this section. Those aspects of HF propagation that are peculiar to propagation in the Arctic will be discussed in the next section.

As pointed out in Section I, the distance between Space Track sites and the nearest HF standard-transmission station (WWV, WWVH, or MSF) varies from about 100 to 3000 nm. Furthermore, site Blue Nine (which is about 5000 nm from WWV) presently synchronizes its timing system with WWV. However, some of the sites do not take the propagation delay from the standard transmission station's transmitter to the site into account. Thus the first problem to consider is the error introduced by the finite propagation time of radio waves.

The propagation delay can be estimated in at least two ways. Morgan (of the NBS) has prepared graphs which allow one to calculate the propagation time assuming a typical value for the heights of the ionosphere layers and assuming some mode of propagation (i. e. , number of hops).[21] Alternatively, one can use experimental data gathered by the Bureau International de L'Heure.[22] This second method will be used in this report and is described below in more detail.

For many years astronomical observatories have monitored time signals emitted by other observatories. The Bureau International de L'Heure has collected this data and published equations which can be used to calculate the average propagation delay given the great circle distance. The results of this

work are plotted in Fig. 12. Note that three curves are shown for distances less than 10^3 km. The center curve applies to "average" ionospheric values; the outer curves apply to F_2-layer heights of 200 km and 350 km. For distances greater than 10^3 km, only a single curve is shown, since variations in the height of the F_2 layer introduce peak errors of only about $\pm$ 0.3 msec.

Assume that the timing system at each site is accurately synchronized with the received signal. Then the site time will differ from the standard transmission station's time by an amount which is exactly equal to the propagation delay error and varies from a minimum of about 1 msec for the Moorestown site to a maximum of about 32 msec for Blue Nine (when using WWV). As previously noted, some of the sites presently do not correct for this propagation delay error. Obviously, there is no sense in talking about timing accuracies of a few milliseconds unless the propagation delay error is corrected. The required correction can be made at each site (by properly adjusting the site timing system) or by the computer at the Space Track Center.

The previous discussions have treated the ionosphere as if its properties changed slowly with time of day. If this were so, it would be possible to measure the frequency of the received carrier and use this information to adjust the frequency of the local frequency standard. Unfortunately, this simplified model is not sufficiently accurate. The properties of the ionosphere vary so fast that measurements of the carrier frequency are useless for timing purposes. Fortunately, this situation is not true in the LF and VLF band.

Variations in the ionosphere also effect the seconds ticks received at a remote site. However, when measuring the seconds tick, the degradation of data is much less than when measuring frequency. In particular, Morgan [21] provides charts of the measured propagation time of a seconds tick from WWV to WWVH (a distance of about 4200 nm). From this data (see Figs. 13 and 14),

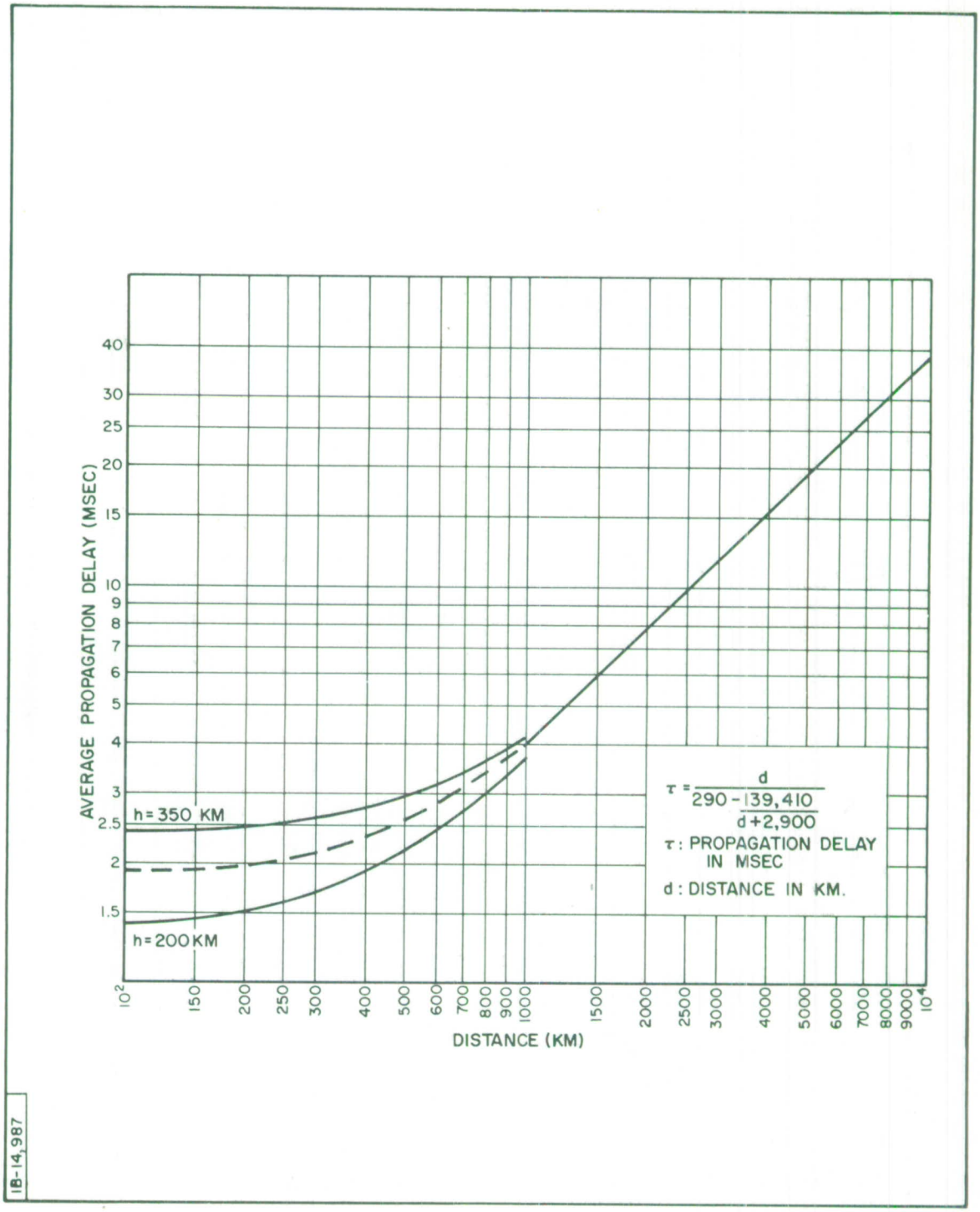

Fig. 12. Average Propagation Delay Versus Distance as Used by Bureau International de L'Heure

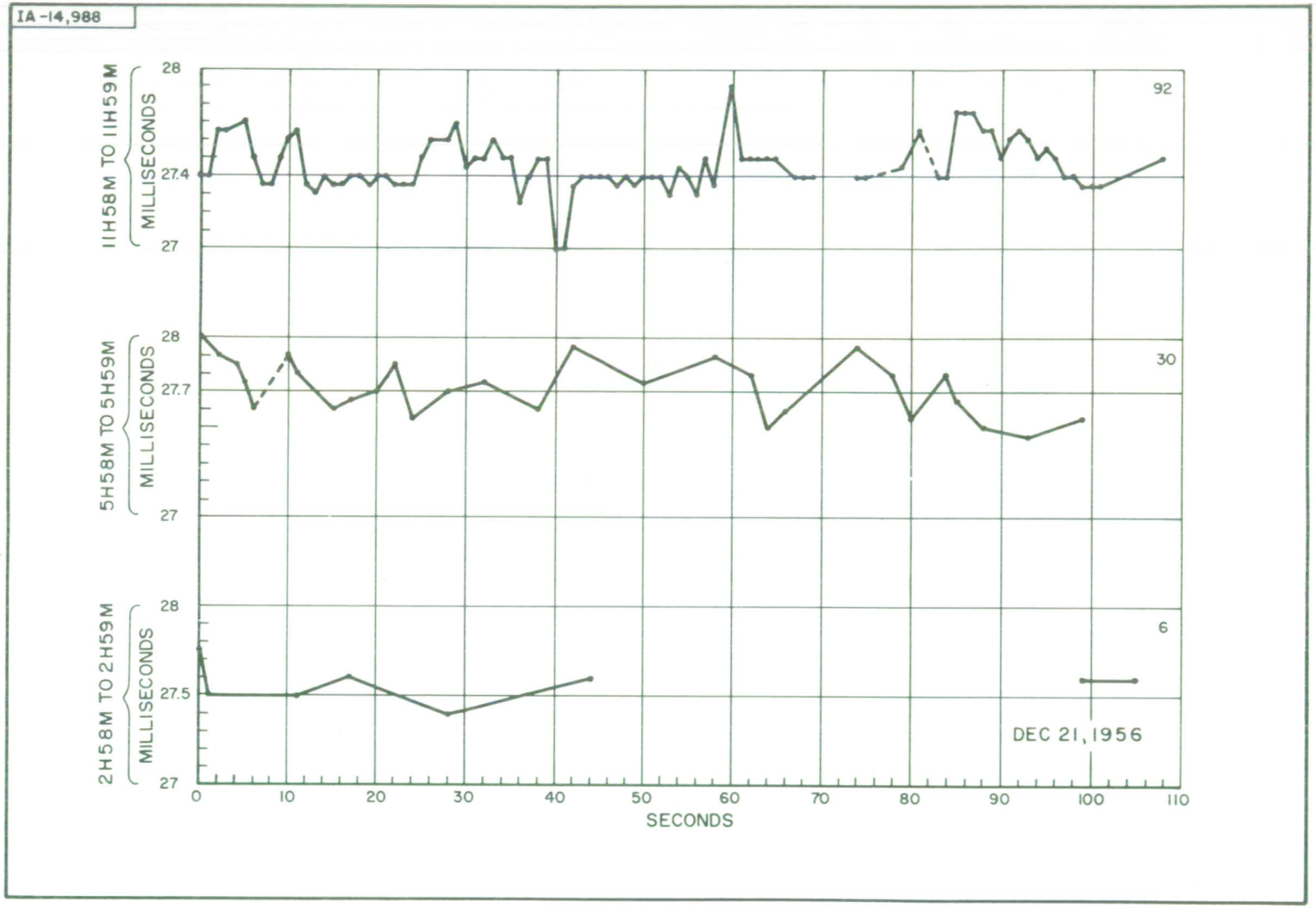

Fig. 13. Propagation Delay Variations

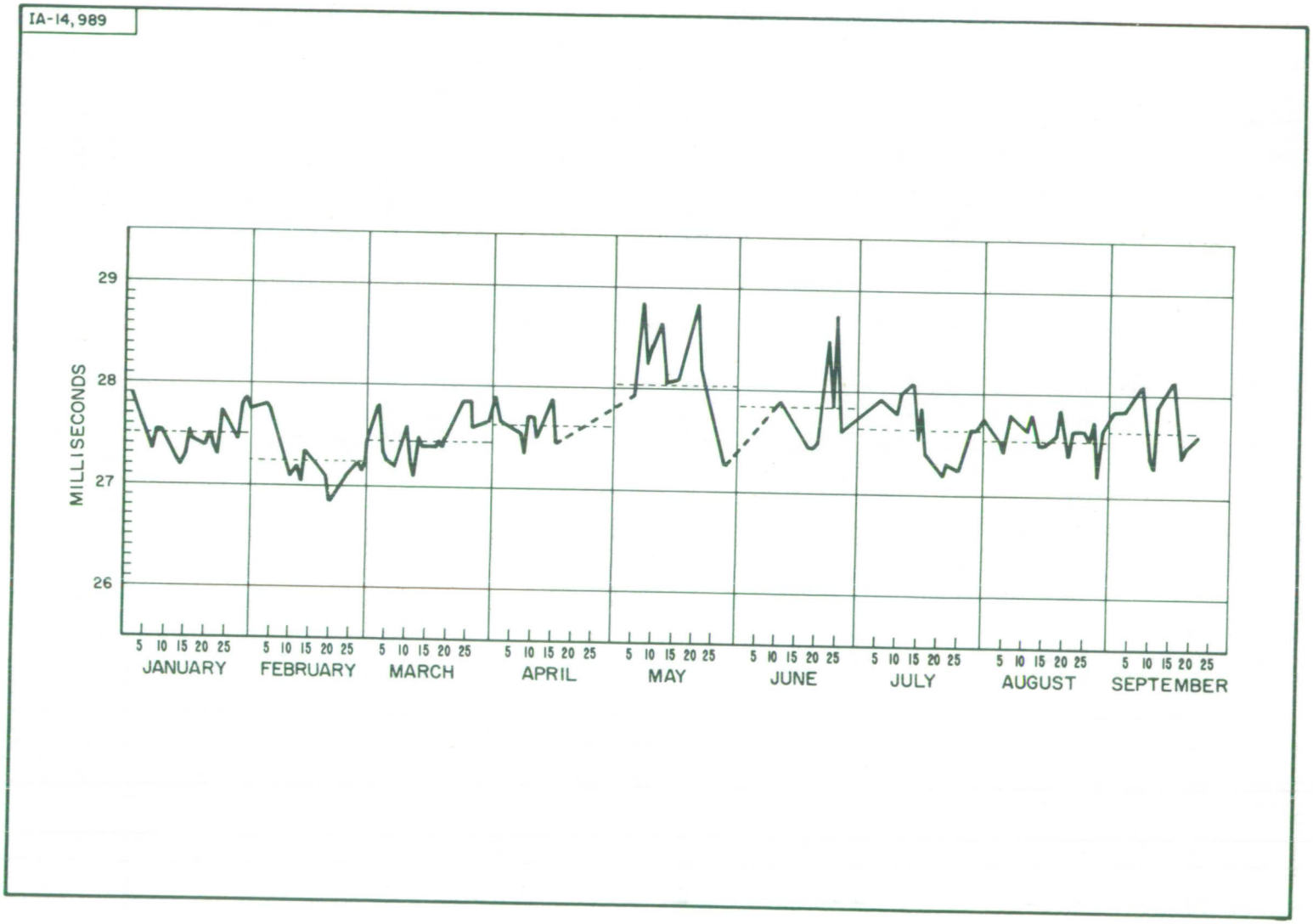

Fig. 14. Seasonal Propagation Delay Variations

it follows that there is a random variation in delay time of less than ± 0.5 msec from tick-to-tick. Further there is a seasonal variation of about ± 1 msec about the yearly average of 27.5 msec. *

In order to obtain similar results in other applications, certain precautions must be observed. Specifically, measurements should be taken when the complete path from the reference transmitter to the sensor has been in sunlight or darkness for at least two hours. If multipath occurs, the first zero-crossing of the earliest tick should be used. The highest frequency that gives consistent signal reception should be chosen in order to minimize multipath. Finally, a reference station should be chosen such that the propagation path is well away from the auroral zone.

HF Propagation in the Polar Regions

Unfortunately, some of the propagation paths of interest in Space Track pass near or through the auroral zone. Hence, the use of HF timing signals in the polar region must be given special consideration.

As noted in the discussion of the ionosphere, SID's and PCA's result in an increase in the D-layer electron density. Consequently, the attenuation suffered by HF signals propagating through this layer is greatly increased. Furthermore, magnetic storms result in a decrease in the F_2-layer electron density in the polar regions. Therefore, HF signals previously reflected by the F_2 layer may escape into space. As a result of these two effects (plus other side effects), communication personnel have suggested that the military stop using HF for communication in the Arctic.

*On the basis of this data, Morgan concludes that the propagation path from WWV to WWVH has four hops with reflection taking place off the F_2 layer at the average height of 350 km.

Fortunately, the problems of using HF for communications and for timing differ in one important respect. Specifically, a communication system must operate during most of the day while, for timing purposes, HF signals need only be periodically present, if the time gained or lost by the site clock per day is only a small fraction of a msec.

Agy[23] provides data on the propagation of HF signals in the Arctic based upon "the results of an ORTE (Ottawa) program of monitoring WWV at a number of Canadian stations." The analysis is extremely rough and depends upon hourly S-meter readings. This unsophisticated approach reveals that there was a usable signal in at least one of the WWV frequencies (2.5, 5.0, 10.0, 15.0, and 25.0 Mc) at Resolute Bay, Baker Lake, and Churchill, well over 90 percent of the time. The analysis has been carried out (for Churchill, Baker Lake, and Resolute Bay) for the sunspot minimum years 1953-1954 and for sunspot maximum 1957-1958. During 1953-1954, Churchill received WWV slightly less than 90 percent of the time, while Baker Lake and Resolute Bay had signals of sufficient strength over 98 percent and over 95 percent of time, respectively. During 1957-1958, Churchill and Baker Lake received WWV about 98 percent of the time and Resolute Bay about 95 percent of the time. The relatively low value for Churchill during 1953-1954 is due to relative lack of support by the F layer during sunspot minimum.

Other analysts of the same basic data showed that usable signals are also received at Resolute Bay and Baker Lake from WWVH (distance of 3352 and 3957 nm, respectively) during magnetically quiet days.[24]

Reference to a map shows that both Resolute Bay and Baker Lake are north of the auroral zone. Reception at these two sites should be similar to that at BMEWS Site I. Churchill is in the center of the auroral zone, so that reception at BMEWS Site II should be similar to that at Churchill.

It follows from this data that HF signals should be present at the northern sites a large percentage of the time. Unfortunately, the author has not found data on the variation in delay time from WWV to a northern site. It may happen that the received signal is strong enough to allow a measurement but that the delay time from day to day will vary by significant amounts. However, this problem can be partially overcome by having the operator note the "quality" of the signal and by monitoring the propagation characteristics as announced by WWV and WWVH. In this way, poor quality observations can be recognized and discarded.

VLF PROPAGATION

From the timing system point of view, VLF signals have two basic advantages. First, VLF signals propagate with low attenuation, and secondly, the received signals have high phase stability.

As an example of the low attenuation characteristics, the VLF signal from GBR operating at 30 kw was received* at New Zealand, [25] a distance of 12,000 miles. According to NBS calculations,[26] WWVL operating at 1 kw should cover a large portion of the globe.

Pierce [27] has shown that the phase characteristics of VLF propagation are sufficiently stable so that the frequency of an oscillator in England can be compared with the frequency of an oscillator in Cambridge, Massachusetts, with an accuracy of about one part in 10^{11} for a 24-hour measurement period.

In some respects, VLF propagation is similar to HF propagation. For example, there is a ground wave that dominates transmission for distances up to 1000 km. For distances of 1000 to 2500 km, the received signal is a

*A narrowband VLF tracking receiver was used in this experiment.

combination of the ground wave and a sky wave. However, the VLF sky wave behaves quite differently from the HF sky wave, since the VLF sky wave is reflected off the bottom edge of the ionosphere. Furthermore, the reflection coefficient is quite high, ranging from 0.1 to 0.5. Propagation over distances in excess of 2500 km could be explained in terms of a large number of sky waves. However, a better description uses the spherical wave guide approach with the earth acting as one boundary to the wave guide and the lowest portion of the ionosphere acting as the other boundary.

Measurements of the phase of the received VLF signal have shown that the phase has a rather repeatable diurnal variation with little seasonal variation. Specifically, Fig. 15 shows the monthly average of the diurnal phase variation over a 4258-km path from NBA in Panama to Boulder, Colorado. Notice that the phase shifts in a rather repeatable fashion (typically within a few μsec day to day) and has a peak-to-peak excursion of about 30 μsec. This diurnal phase variation can be explained by a motion of the lower edge of the ionosphere. Typically, the lower edge is at a height of about 70 km during the daytime. When the path goes from all sunlight to darkness, the height of the lower edge increases to about 83 km, thereby producing the observed diurnal phase shift.

The diurnal phase-shift observed in the Arctic has a different pattern from that shown in Fig. 15. Moreover, there is a larger seasonal variation in the number of daylight hours. However, the total phase shift is still relatively small; a 26-μsec phase shift was observed on a 7600-km path from NPG (Washington State) to Bodo, Norway.

VLF signals are affected by solar flares, but to a much lesser extent than HF signals. For example, a sudden ionosphere disturbance (SID) causes the phase of the received VLF signal to suddenly change; however, the amplitude of the signal is essentially unaffected. An ionospheric storm also causes

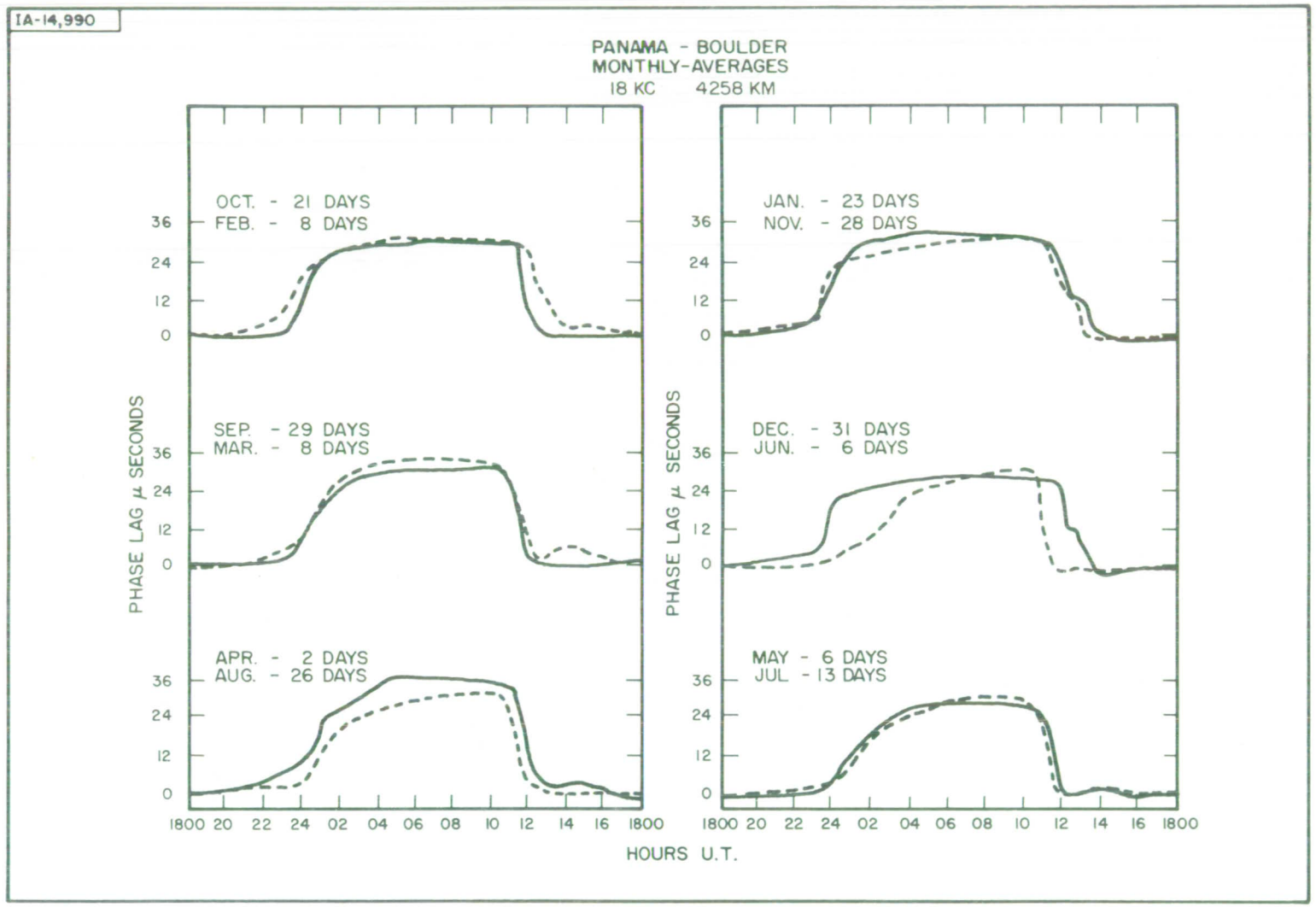

Fig. 15. Diurnal Variation in the Phase of NBA (18 kc) (Signal Observed at Boulder, Colorado)

phase variations that can be correlated with the K-index of magnetic activity. Most of the effects associated with a solar flare can also be explained by a motion of the lower edge of the ionosphere caused by the increased electron density in the D layer.

Thus solar flares can cause noticeable effects on VLF propagation, particularly in the Arctic region; however, VLF propagation does not suffer from the polar blackouts which have such a disruptive effect on HF propagation.

LF PROPAGATION

LF propagation, like VLF propagation, has good phase stability which should permit frequency comparisons within a few parts in 10^{10} or better over a short interval.[19] However, the attenuation of LF signals is significantly greater than the attenuation of VLF signals. For example, WWVB, radiating 7 kw of power at 60 kc, is expected to reliably cover only the continental U. S.

LF signals are also reflected off the lower edge of the ionosphre; since the signals penetrate into the ionosphere for a short distance, they appear to be reflected from a slightly greater height (80 to 85 km in day, 90 to 100 km at night).

The phase stability of LF propagation shows the typical diurnal phase variation discussed in the above subsection on VLF propagation. Measurement over a path from Boulder to Ottawa (2500 km) at 60 kc showed a diurnal phase shift of about 300 degrees.

Because of its limited coverage, LF time and frequency signals are of limited use in SPADATS. They could be used at BMEWS Site III, Moorestown, and the Eglin radar. However, both Moorestown and BMEWS Site III are

within 80 to 120 miles of a HF standard transmission station. The timing system presently operating at Eglin monitors the LF signal from WWVB and uses the data to adjust the oscillator frequency.

SECTION V

LOCAL FREQUENCY STANDARDS AND CLOCKS

INTRODUCTION

The heart of the timing system at each site consists of a local frequency standard plus a clock combined as shown in Fig. 16. Ideally, the local frequency standard would produce a sinewave at a known constant frequency such as 100 kc/UT-2 second. The sinewave would then advance the clock at a fixed rate. The clock mechanism displays the time to the operator and provides a means of establishing an epoch. Once the epoch has been established, the clock would keep perfect time.

To make the time available to the sensor, the clock generates electrical outputs such as a 1-kc pulse chain and a seconds tick. The 1-kc pulse chain consists of short (μsec) pulses occurring every millisecond with the leading edge of the pulse indicating the millisecond. Such a pulse chain could drive a binary counter which would indicate the time with a least significant bit of 1 msec. The seconds tick consists of a short pulse occurring every second with the leading edge indicating the exact second. Such a pulse has many uses. For example, by comparing this pulse with the WWV time tick, the epoch can be established.

The following section describes a clock unit similar to the unit used in the BMEWS and AN/FPS-85 radars. In general, the clock is a reliable unit that does not limit the performance of the timing system.

Because of the changes in the rotation rate of the earth, the clock system of Fig. 16 will not keep precise UT-2 time. However, the clock system could be adjusted to keep accurate WWV time if the frequency standards at the site and at WWV were perfect. Unfortunately, neither frequency standard is

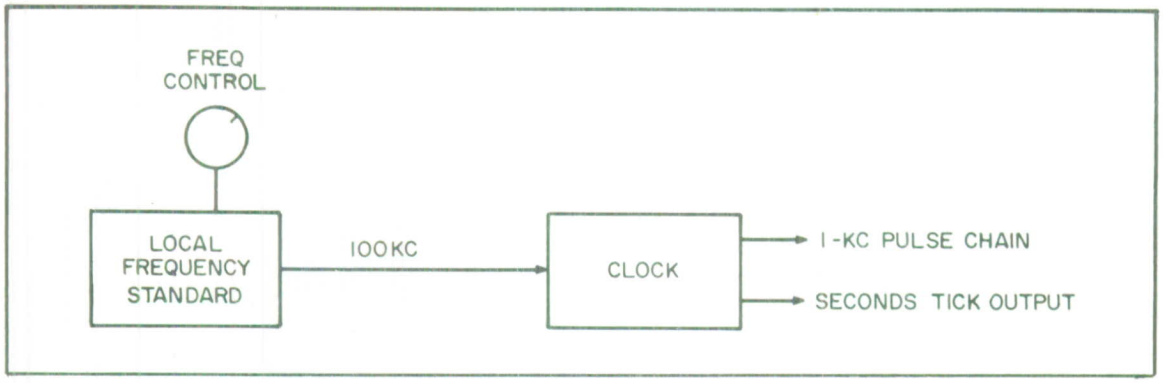

Fig. 16. Local Frequency and Clock System

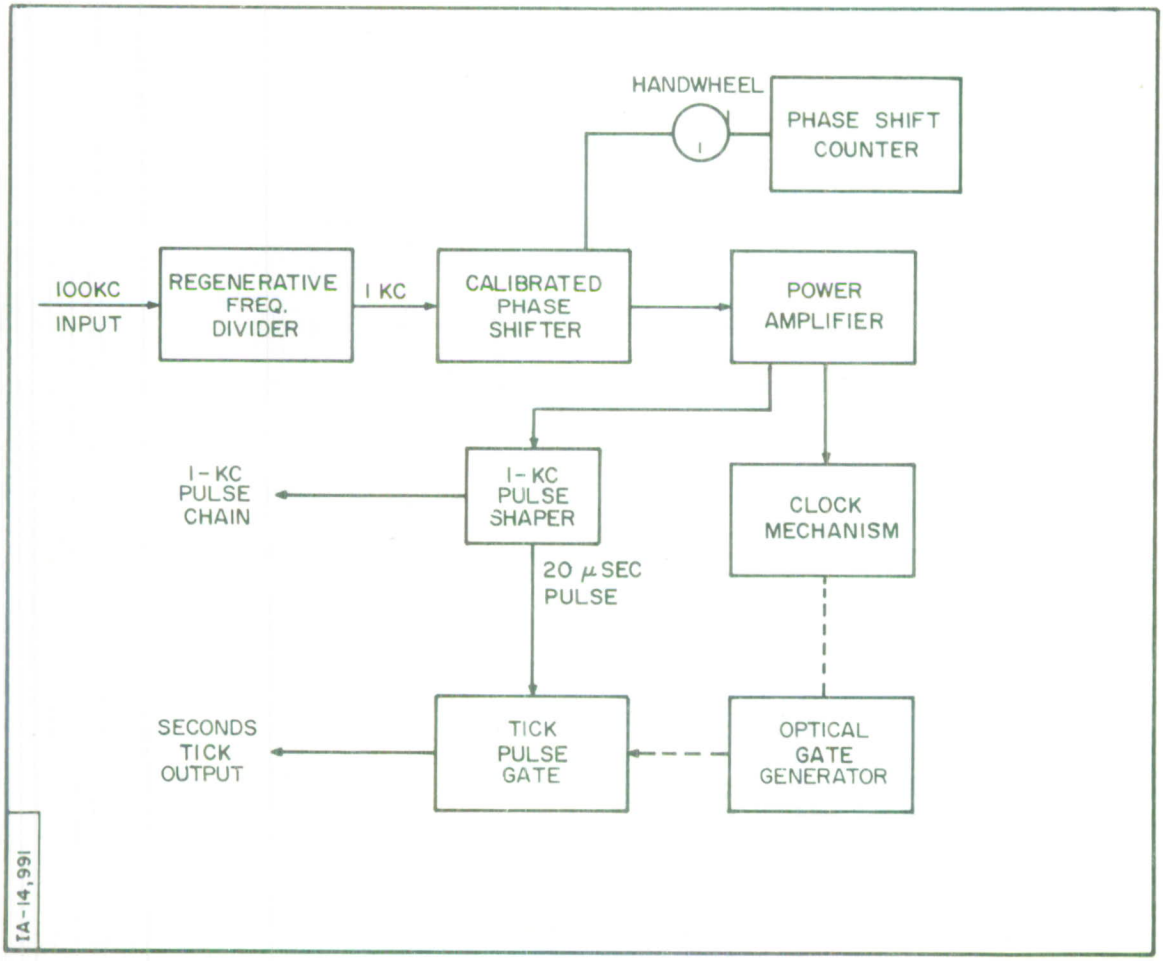

Fig. 17. Block Diagram of "Clock"

perfect, and site time will continously drift away from WWV time. The rate at which the clocks drift apart depends primarily upon the type of local frequency standard used at the site.

CLOCK

Figure 17 is the block diagram of a clock (the Hewlett-Packard Model 115BR Frequency Divider and Clock Unit[28]). The 100-kc input is first divided down to 1 kc in a regenerative frequency divider. The regenerative frequency divider is not self-starting so that a temporary loss of input stops the clock. Thus, erratic behavior of the local frequency standard is made painfully obvious to the operator.

The 1-kc signal is sent through a continuous calibrated phase shifter. By turning the hand switch, the operator can vary the phase of the output relative to the input by many milliseconds. After power amplification, the phase-shifted output is used to drive a mechanical clock mechanism which displays the time in hours, minutes and seconds. An optical gate attached to the mechanical clock unit generates a pulse every second on the second.

The 1-kc output of the power amplifier is also sent into a pulse shaper that generates a short (μsec) pulse at a given time of each cycle. This sequence of pulses is the 1-kc pulse chain. The pulse chain is also gated by the output of the optical gate in the tick pulse gate unit, to produce the seconds tick, which is thus precisely synchronized with the 1-kc pulse chain.

The clock of Fig. 17 can be adjusted to read the proper time by using the equipment shown in Fig. 18. Assume that the clock is located within the ground wave coverage of WWV so that a strong-steady signal is available at the output of a WWV receiver. The propagation time T_P from WWV to the site is known.

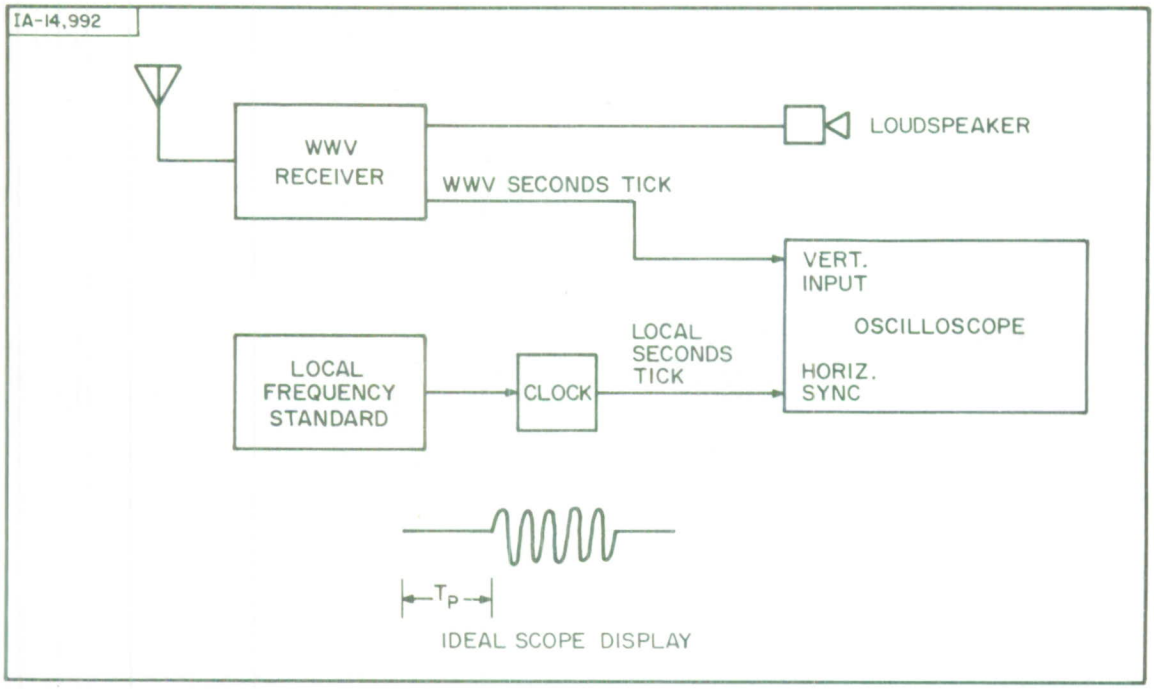

Fig. 18. Equipment Needed to Adjust Clock

As noted in the subsection on HF standard transmission stations in Section II, the 600- and 440-cps tones start at 5-minute intervals exactly on the second. Since the time is usually known to within a minute, the start of the tone can be used to adjust the clock time with an accuracy of a fraction of a second. With the HP model 115BR (shown in Fig. 17), this adjustment is performed by manually adjusting the time reading on the clock to the proper value and then manually starting the mechanical clock mechanism at the start of the tone.

To adjust the clock time with an accuracy of a millisecond, the clock seconds tick is used to trigger the horizontal sweep of an oscilloscope. The WWV signal is applied to the vertical input of the oscilloscope. When the local clock is precisely synchronized with the WWV clock, the oscilloscope trace looks like that shown in Fig. 19. That is, the WWV second tick starts

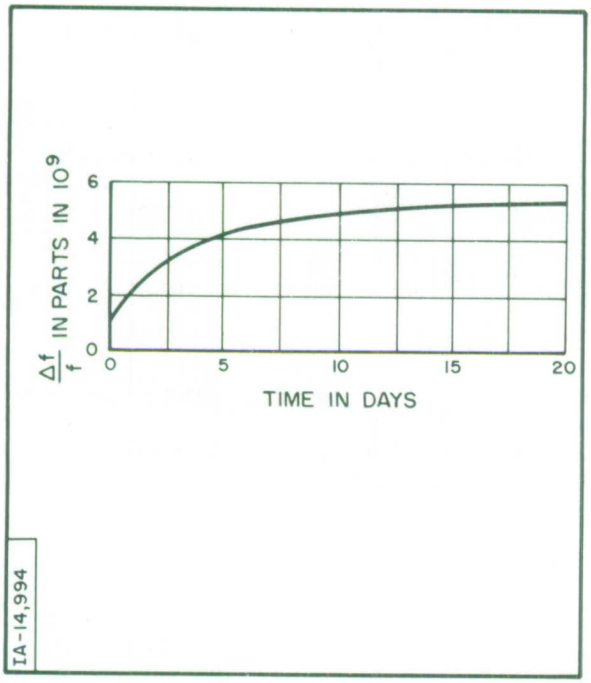

Fig. 19. An Initial Aging Curve

exactly T_P seconds after the horizontal trace. To achieve the desired result, the calibrated phase shifter is used to advance or retard the local 1-kc pulse chain, clock time, and seconds tick until the proper pattern is achieved.

The accuracy of the results depend, of course, on the precision with which the oscilloscope trace is calibrated and the ability of the operator to measure T_P on the scope face. In practice, the clock may be synchronized with received WWV and then retarted T_P seconds, using the independent millisecond counter coupled to the calibrated phase shifter.

The clocks used at sites other than BMEWS and the AN/FPS-85 differ from the clock of Fig. 18. The most common variation consists of replacing the mechanical clock mechanism and optical gate generator with an electronic counter and a Nixie tube output. Such units do not have adjustable phase shifters.

CRYSTAL OSCILLATOR

Basic Properties of Crystal Oscillator

Since all of the present Space Track timing systems use crystal oscillators, it is worth considering the characteristics of these devices.

To obtain high stability with a crystal oscillator, the crystal must be cut so as to have a low (ideally zero) temperature dependence, enclosed in a double oven, and operated at a low fixed power level. Even after all known precautions have been taken, the frequency of an oscillator is observed to vary slowly with time. Specifically, if f (d) is the oscillator frequency after d days of operation, then the fractional change in frequency

$$\frac{\Delta f}{f} = \frac{f(d) - f(0)}{f(0)}$$

is observed to vary with time in a logarithmic fashion, provided the oscillator frequency is not manually adjusted and the oscillator is continuously operating. This variation of frequency with time is referred to as the aging characteristics of the crystal. [29] [30] Figure 19 shows the aging characteristics of a precision 2.5-Mc crystal during the initial 20-day period of operation (after allowing one day of operation for oven warmup). Notice that the crystal frequency changes by about 2 parts in 10^9 during the first 2.5 days. After 20 days of continuous operation, the crystal frequency is changing much slower with time. Figure 20 shows the aging characteristics of a commercially available crystal oscillator for a period of 300 days following 100 days of continuous operation. Once again, the oscillator frequency varies with time and the rate of change of the oscillator frequency decreases with time.

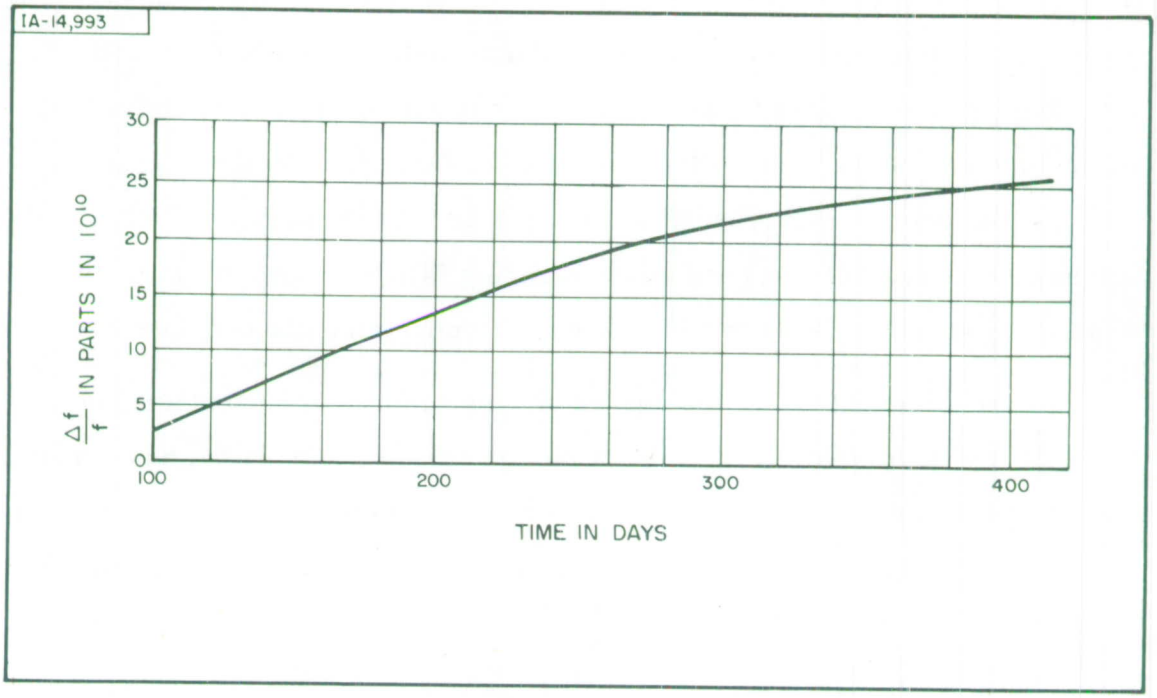

Fig. 20. An Aging Curve After 100 Days of Operation

It is customary to define the aging rate of a crystal oscillator by the slope of the aging-characteristic curve. Thus, for a period of a day to a few weeks after the initial aging period, the oscillator frequency f (d) can be approximated by the equation

$$f(d) = f_o \left[1 + \alpha \left(d - d_o \right) \right]$$

where

f (d) = oscillator frequency at time d

f_o = oscillator frequency at time d_o

d = time in units of a day

α = aging rate in units of parts per day

The aging rate is almost always positive and decreases in value with operating time. In particular, a good crystal oscillator costing about $2000 has an initial aging rate of about 5 parts in 10^{10} per day after 30 days of operation; after 6 months of operation, the aging rate has decreased to about 1 part in 10^{10}. Even better crystal osciallators [31] are now available. These oscillators cost about 3500 and have an initial aging rate of about 5 parts in 10^{11} decreasing to about 1 part in 10^{11} after six months of continuous operation.

It should be noted that the curves of Figs. 19 and 20 are obtained only when the oscillator frequency is not manually adjusted during the test period and the oscillator is continuously operated. The effect of an oven shutdown on the output frequency can be seen from the data of Fig. 21. Note that, for this

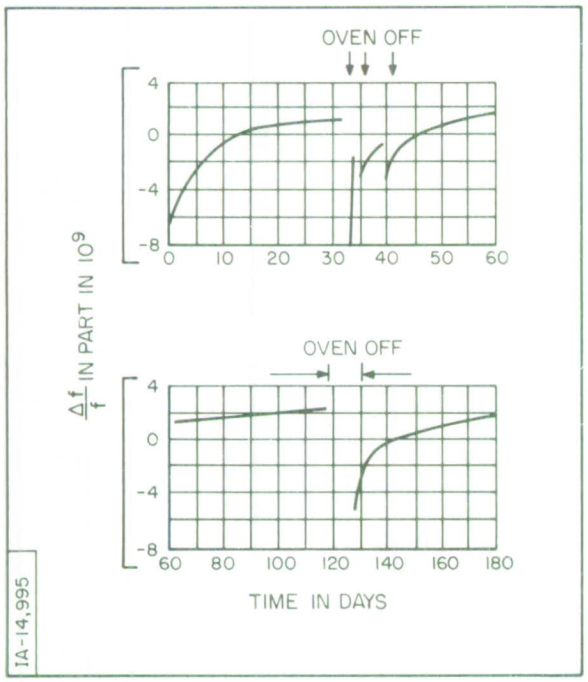

Fig. 21. Effect of Oven Shutdown on Crystal Frequency

crystal, a shutdown of the oven caused the oscillator frequency to decrease by about 1 part in 10^8. Following restoration of oven operation, the crystal frequency will approach its previous value after 5 to 40 days of continuous operation (depending upon the duration of the oven breakdown).

Crystal Oscillators in Timing Systems

As noted above, the initial output frequency of a crystal oscillator can differ from the stated value by as much as 1 part in 10^8. Thus if no correction is made to the oscillator frequency, the clock will run at an improper rate, resulting in an error of about 1 msec per day. * After a short run-in period (to stabilize the oscillator behavior), the operator is immediately faced with a problem of adjusting ** the oscillator frequency.

Unfortunately, crystal-oscillator aging normally results in a steady increase in output frequency with time. In particular, the oscillator frequency will be high by the amount $\alpha f_r d$ cps after d days of continuous unattended operation, even though the oscillator was initially adjusted to the proper value f_r. Thus the clock will run fast (at an ever-increasing rate) resulting in a parabolic time error*** as shown in Fig. 22. Note that, for an aging rate of 1 part in 10^{10} per day, the clock will be in error by 1 msec after 15 days of unattended operation. After 26 days of unattended operation, the error is 3 msec, while after 34 days, the error is 5 msec.

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* The relation between frequency errors and time errors is derived in Appendix IV.

** Precision oscillators have an external control which allows the operator to change the frequency. The control dial is usually marked in parts in 10^{10} or 10^{11}. A rough (screwdriver) adjustment is also provided.

***Equation 8 of Appendix IV with $E_o = 0$, $f_o = f_r$, $\alpha = 10^{-10}$.

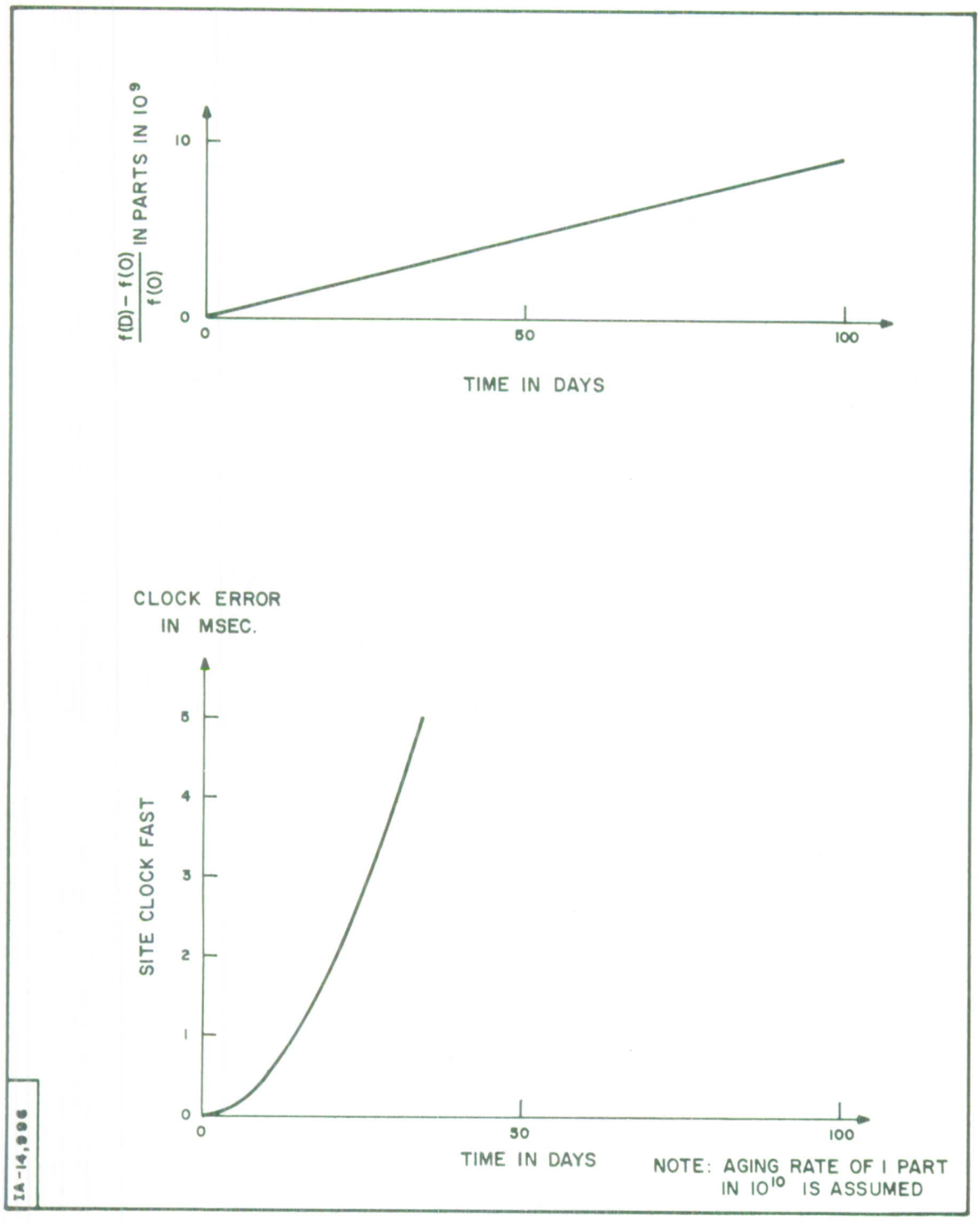

Fig. 22. Oscillator Frequency and Clock Error Using Crystal Oscillator

If the timing system is to have an accuracy of 1 msec, the operator must continuously monitor the performance of the timing system and make periodic corrections to the oscillator frequency and/or clock reading. The optimum procedure depends upon the standard time signals that are available; a more detailed discussion of this problem appears in Section VII.

ATOMIC OSCILLATORS

Introduction

Since the frequency and time ticks emitted by the standard transmission stations are based upon atomic standards, it would appear that the use of atomic oscillators as local frequency standards would offer many advantages. The following discussion first describes a typical atomic oscillator and then considers its use in a time standard.

Basic Properties of Atomic Oscillators

Figure 23 is a block diagram of an Atomichron Model NC-1001 Cesium Beam Frequency Standard.[32] The operation of the Atomichron starts with a crystal oscillator* operating at 5.0 Mc. The output frequency of the crystal oscillator is multiplied up to a frequency near 9192.631840 Mc which is the cesium transition frequency in a magnetic field of 57 milligauss. The frequency generated by the crystal is compared with the cesium transition frequency in the beam tube, resulting in an error voltage. The error voltage drives a servo device that adjusts the frequency of the crystal oscillator to the proper value. In this way the crystal frequency is slaved to the frequency of the cesium transition.

*Most atomic oscillators use crystal oscillators in this manner.

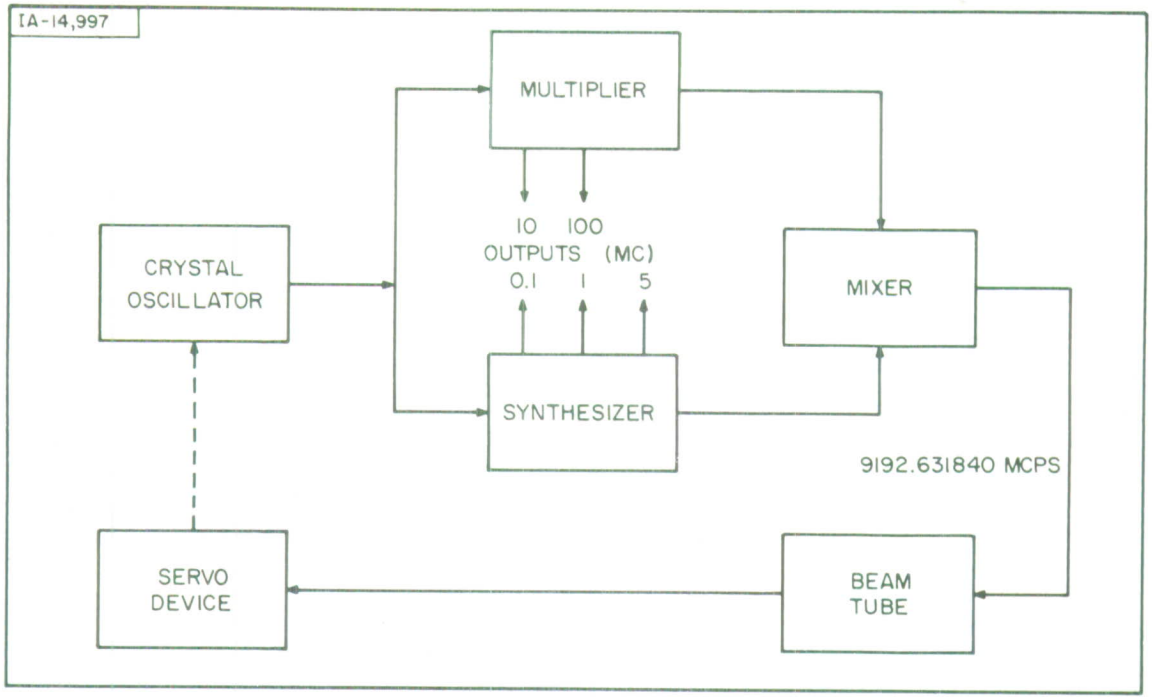

Fig. 23. Block Diagram of Atomichron Model NC-1001

It should be noted that the output frequency of an atomic oscillator is not perfectly stable, due to spectrum broadening in the beam tube, and to servo errors (see Fig. 24). The rms deviation about the average value is referred to as the oscillator stability. Typically, atomic oscillators have long-term stabilities ranging from 2 parts in 10^{11} to 5 parts in 10^{10}. (The short-term stability is usually poorer.)

Another parameter of interest is the accuracy, defined as the degree to which the frequency of any single standard agrees with that of a specified standard (excluding any fixed or variable frequency offsets designed into the oscillator). Commercially available atomic oscillators have quoted accuracies ranging from 6 parts in 10^{11} to 5 parts in 10^{10}.

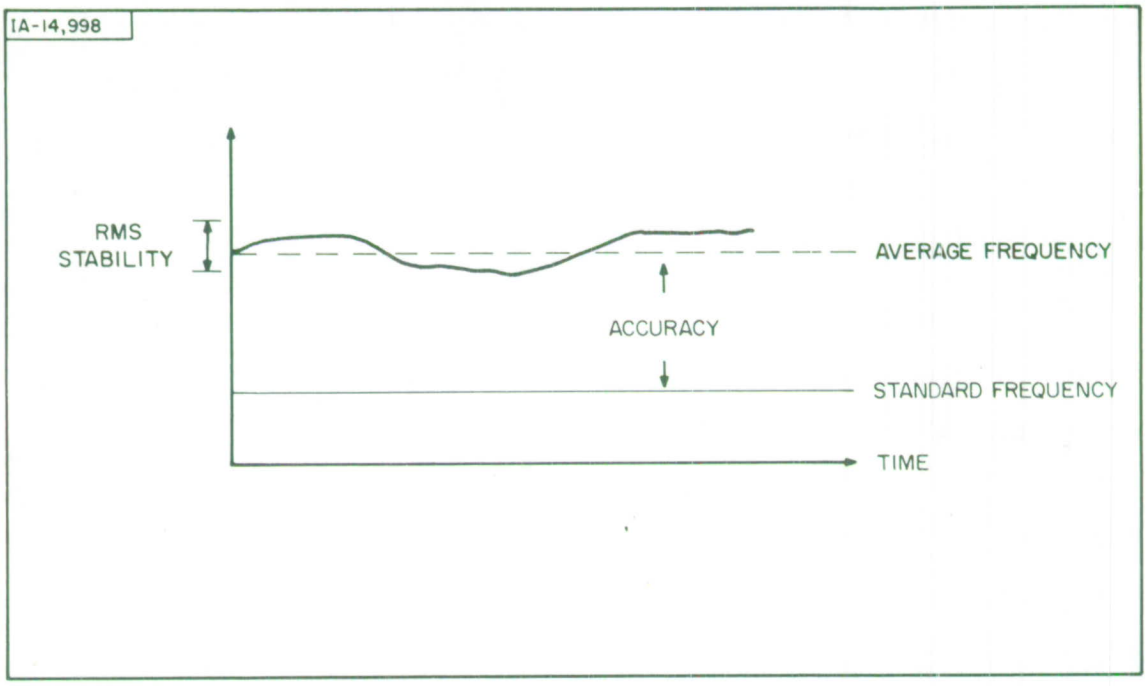

Fig. 24. Stability and Accuracy Definitions

In recent years, an atomic time A-1 has been defined. The frequency defining A-1 time is a weighted average frequency of nine cesium resonators located in nine different laboratories. An analysis of results obtained over a two-year period from 1960 to 1962 showed that the probable deviation of a single resonator from its mean frequency is 1 part in 10^{10}, the stability of a single resonator from month to month is 5 parts in 10^{11} and that the system A-1 is stable from month to month to 2 parts in 10^{11}.

Atomic Oscillators in Timing Systems

An atomic oscillator is an absolute frequency standard, since the output frequencies (normally 100 kc, 1 Mc, and 5 Mc) are controlled by the resonance of the cesium atom. However, the 100-kc output of most atomic oscillators must be considered to be 100-kc/atomic second. Thus, if the

100-kc output of an atomic oscillator is used to drive a clock (as in Fig. 16), the clock will keep atomic time. As noted in the subsection on time signals in Section III, atomic time gains approximately 1.2 msec per day with respect to UT-2 or WWV time. Thus a true atomic oscillator cannot be used to drive a clock that is to keep accurate UT-2 or WWV time.

It is possible to use an atomic oscillator which, in turn, drives the clock. This procedure is basically the method used at the WWVB and the U. S. Naval Observatory. However, this method of operation has no advantages over the VLF method discussed in the subsection on VLF/HF timing systems in Section VII; indeed, the VLF method is used to control the oscillators at almost all standard transmission stations. *

The Hewlett-Packard Company announced the availability, by late 1964, of a cesium beam standard (model 5060A)[33] in which the output frequency f_o differs from the atomic frequency f_1 (in cycles per atomic seconds) by the relation

$$f_o = \frac{f_1}{1 + S}$$

where S is a constant. Referring to Eq. (1) of Section III, note that the frequency f_o is the frequency used by the standard transmission stations if S is the standard offset for the year. Thus, the output frequency f_o can be used to drive a clock on WWV time provided S has the proper value. According to Hewlett-Packard, a simple change of one component in this atomic oscillator (taking

*The oscillators of most VLF stations are remotely controlled; i.e., VLF reception gear is located at one of the nine laboratories whose resonators define the atomic frequency.

15 to 20 minutes) is all that is required to change the value of the constant S. As noted in Section III, S is fixed for each year and has been changed twice in the last four years. *

By using the above atomic oscillator, the output frequency of the local frequency standard can be kept within 1 part in 10^{10} of the frequency of the standard transmission stations. Since the difference in frequency between the site atomic oscillator and standard transmission station will not be constant but will oscillate about some average value, the time error will also be of an oscillatory nature with a small linear component.

If we consider a worst case in which the output frequencies of the two oscillators differ by a constant value of 1 part in 10^{10}, the error between the site clock and WWV would grow linearly** with time as shown in Fig. 25. Note that it takes approximately 120 days for the time error to reach 1 msec; for the crystal-oscillator case shown in Fig. 22, an error of 1 msec occurred after 15 days of unattended operation. This example is, of course, quite crude; however, it does display the two advantages of the properly chosen atomic oscillator over a crystal oscillator in a timing system. First, an atomic oscillator does not require any initial or periodic adjustment of its output frequency. Second, the time required to accumulate 1 msec timing error in an unattended atomic-oscillator timing system is much greater than in an unattended crystal timing system.

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* Some of the National Company's Atomichrons produce an offset frequency output signal. However, a factory adjustment is needed in order to change the amount of frequency offset.

**Equation 8 of Appendix IV, with $E_o = \alpha = 0$, $\frac{f_o - f_r}{f_r} = 10^{-10}$.

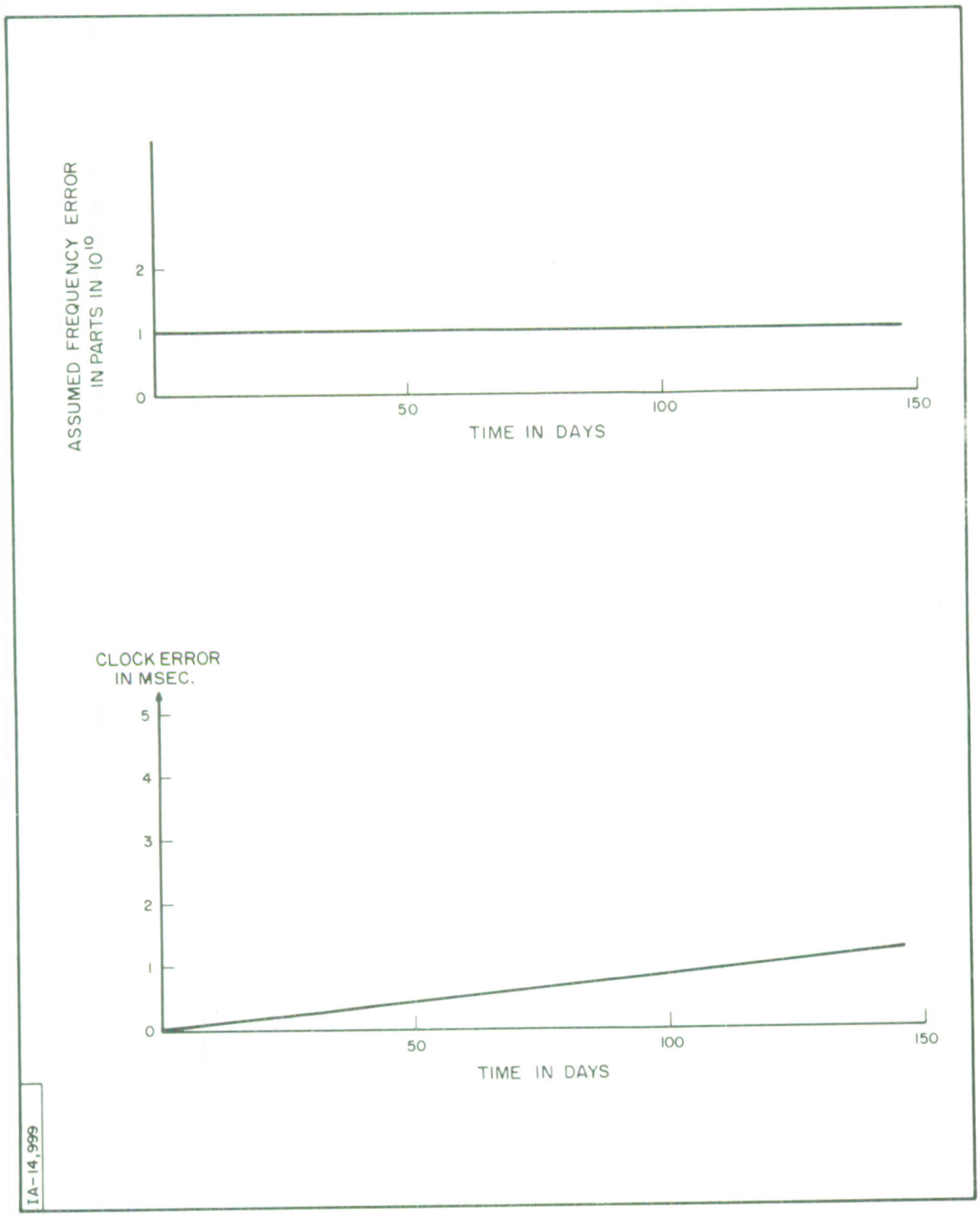

Fig. 25. Assumed Frequency Error and Resultant Clock Error Using an Atomic Oscillator

There are some disadvantages to an atomic oscillator as compared to a crystal oscillator. First of all, atomic oscillators are more expensive than crystal oscillators. The exact price of the Hewlett-Packard oscillator described above is not known; it is estimated that the price will be less than $20,000. Good crystal oscillators (with an aging rate of 1 part in 10^{10} after 6 months of operation) cost about $2000. Better crystal oscillators (with an aging rate of 1 part in 10^{11}) cost about $3500. Second, the mean-time-between-failure of a crystal oscillator typically exceeds 10,000 hours. The MTBF for atomic oscillator is less (but is improving with time).

SECTION VI

RECEIVERS

HF-BAND RECEIVERS

Since the seconds tick and other signals of interest* are carried by double-side-band modulation, the design and construction of a standards receiver for the HF band is straightforward. The receiver is of the superheterodyne variety with single or double conversion. The IF bandwidth is approximately 5 kc.

A commercially available HF receiver which can operate at 2.5, 5, 10, and 25 Mc can be purchased for $300 to $600 (depending upon power supply options, antenna included, and whether transistors or tubes are used).

VLF RECEIVERS

A VLF receiver is quite different from an HF receiver, since the signal of primary interest is the carrier (VLF signals are used primarily because of the excellent phase and frequency stability of the received signal). The phase stability allows the overall bandwidth of the receiver to be on the order of 0.005 cps (approximately 10^{-6} times the bandwidth of HF receivers). There are two types of VLF receiver of interest, a VLF tracking receiver and a VLF phase comparison receiver.

A simplified block diagram of a VLF tracking receiver is shown in Fig. 26. The received signal is first amplified in a TRF front-end which has

*Although the carrier of the emitted signal is a stable calibrated signal, motion of the ionosphere makes the carrier signal useless for timing purposes.

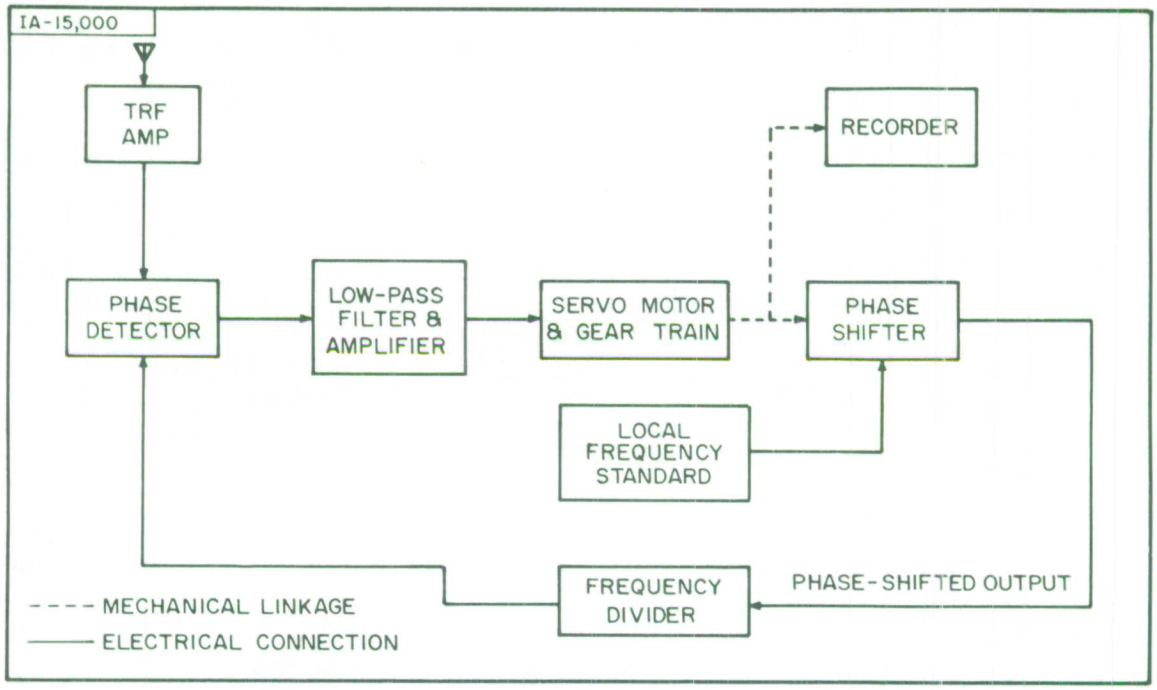

Fig. 26. Simplified Block Diagram of VLF Tracking Receiver

a bandwidth of approximately 500 cps centered at the VLF carrier frequency. The amplified output is phase compared with a CW signal derived from the local frequency standard. The phase detector output is amplified and, after passing through a low-pass filter, is used to drive a servo motor which, in turn, drives a phase shifter through a gear chain.

The output from the local frequency standard is first phase-shifted and is then divided down to the frequency of the VLF signal. The resulting signal is used as a reference in the phase detector.

Note that the block diagram of Fig. 26 is basically that of a servo system which makes the phase of the phase-shifted local frequency standard signal track the phase of the incoming VLF signal. Thus the frequency of the phase-shifted output is made to track the frequency of the VLF station.

If the local frequency standard uses a crystal oscillator, its output frequency will change because of the aging phenomena. However, the frequency error due to the aging effect is corrected by the phase shifter in a VLF tracking receiver, so that the phase-shifted output can be used to drive the clock in the timing system. Once the local clock is synchronized with the clock at the VLF transmitter, the two clocks will keep the same time.

The recorder in Fig. 26 records the amount that the phase is shifted by the phase shifter. This data can be used to adjust the local frequency standard. Such an adjustment should be performed periodically to keep within the operating range of the VLF receiver and servo, and to minimize any time errors caused by a temporary loss of the VLF signal. (This error can be compensated for by extrapolating the phase shift and manually correcting the clock.)

A VLF comparison receiver is similar to a VLF tracking receiver without the phase-shifted output. That is, the output of the local frequency standard is sent directly into the clock. Thus a VLF comparison receiver does not remove any aging effects in the local frequency standard, but the recorded phase-shift data can be used to accurately adjust the frequency of the local frequency standard and to compute any accumulated timing errors.

Practical VLF receivers have a more complicated block diagram than the one shown in Fig. 26. Such receivers incorporate AGC's, noise suppressors, and electronic circuits which prevent the servo loop from operating when the VLF signal is absent. A further complication is introduced by the presence of "traffic" on some VLF signals of interest.

Many of the VLF transmitters are operated by the U. S. Navy and are actually used for fleet communications. Such stations may shift the carrier frequency with little or no advance warning. Further, such stations may be

"down" for extended periods of time so that signals from other VLF stations must be monitored. As a result, the U. S. Naval Observatory has recommended that users of their VLF signals have receivers that can be rapidly tuned to frequencies in the range of 14.0 to 30.0 kc, in 0.1-kc steps.

LF RECEIVERS

The LF signals of interest are the carrier signal plus the double-sideband modulation. Thus, a portion of an LF receiver is similar to both HF and VLF receivers. In fact, there are commercially available receivers which are designed to receive either WWVB (LF) or WWVL (VLF) signals.

The block diagram of an LF phase comparitor receiver is shown in Fig. 27. The front end is a 60-kc amplifier. The 60-kc amplified signal is detected and amplified, thereby producing the seconds ticks and other modulation signals. The 60-kc amplified signal is multiplied up to 300 kc (for ease of handling) and compared in phase with a 300-kc signal derived from the local frequency standard. The phase difference between the two 300-kc signals is recorded on a strip chart. Once again, an examination of the strip chart allows the operator to determine the frequency error between the local frequency standard and the 60-kc signal, and to determine the necessary adjustments to the timing system.

Except for a difference in center frequencies, the block diagram of Fig. 27 would apply to a VLF phase-comparator receiver. LF tracking receivers are also available and have a block diagram essentially the same as Fig. 26. Since the phase-shifted signal is coherent with the incoming signal, the modulation can be easily obtained in such receivers by coherently detecting the LF signal.

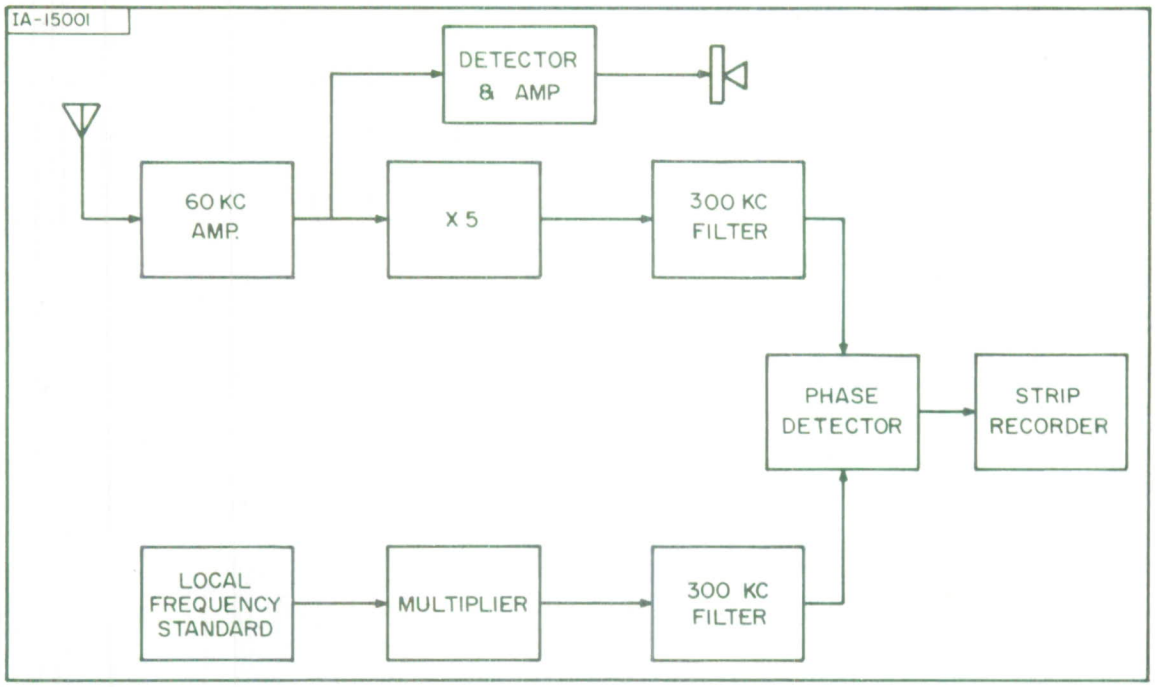

Fig. 27. LF Phase Comparison Receiver

VLF - FREQUENCY CONTROLLED RECEIVER

The conventional phase-tracking receiver eliminates a frequency error in the local frequency standard by continuously shifting the phase of the standard output signal. However, one unit, the Motorola VLF Receiver Frequency Standard, also automatically adjusts the frequency of its internal frequency standard.

The oscillator unit of the Motorola VLF Receiver Frequency Standard has a quartz crystal* plus a mechanically driven AFC capacitor. If the AFC capacitor is kept fixed, the unit acts like a phase-tracking receiver. However,

*The aging rate is less than 5 parts in 10^{10} per day.

the continuous phase shifter incorporated in the unit can be used to drive the AFC capacitor thereby adjusting the frequency of the oscillator and eliminating the crystal-aging effects. An absolute frequency accuracy* of 5 parts in 10^{10} is claimed to be "typical" with a guaranteed accuracy of 2 parts in 10^{9}.

The Motorola VLF Receiver Frequency Standard Model S1055BH has a two-channel receiver that can receive any two of the VLF or LF stations. However, reception of an alternate station requires the interchanging of front ends and a synthesizer module.

*Relative to the VLF standard transmission station.

SECTION VII

SITE TIME SYSTEMS

INTRODUCTION

This section discusses various equipment configurations for timing systems that could be used at a remote Space Track site. The objective of these systems is the establishment of a time scale at the site that is relatable to the time scale at the standard transmission station with an accuracy of ± 1 msec.

As often happens, more than one timing system can meet the required performance specification. However, one system may be considerably easier to adjust and need less frequent adjustments than other systems. Finally, there is the necessary consideration of cost.

HF CRYSTAL-OSCILLATOR SYSTEM

An HF crystal-oscillator system, as shown in Fig. 28, uses a crystal oscillator as the local frequency source and relies upon HF signals for both frequency and time calibrations. Note that the block diagram of Fig. 28 is different from that of Fig. 18 only by the addition of a time comparator.* A time comparator consists of an adjustable digital delay generator which merely delays the seconds tick by a manually controlled amount, thereby simplifying the taking of data (since the basic oscillator and clock need not be disturbed).

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*A backup power supply is also added to prevent a temporary loss in prime power from upsetting the operation and synchronization of the timing system.

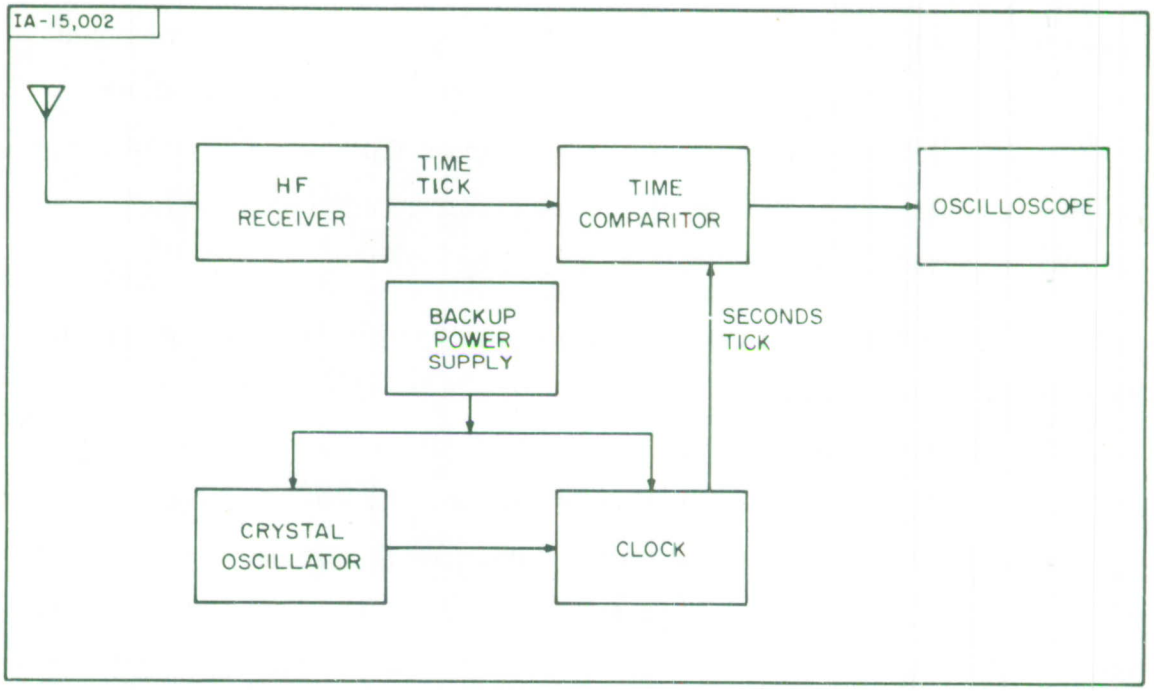

Fig. 28. HF Crystal-Oscillator Timing System

As noted in Section V, the frequency of a crystal oscillator changes, so that a timing system using such oscillators will need frequent adjustments. In principle, there are three different approaches to the problem.

The first approach to the problem is to allow the error in the timing system and to correct the error later in the system. This is the technique used by the Smithsonian in reducing their Baker-Nunn data. The time recorded on the photograph is allowed to be in error, but the accumulated timing error is measured and recorded at regular intervals. When the photographs are reduced, the timing data is corrected. This initial time determination is based on reception of WWV signals which are an approximation to UT-2 time. Since the motion of a satellite must be measured in uniform ephemeris time (which atomic time adequately approximates) while the motion of the earth is

measured in nonuniform universal time, further processing of the time data to correct WWV errors is required before precisely reduced data can be issued. In effect, the Smithsonian does not care if the time data recorded on the photographs is in error, so long as the error is known, because a correction must be made in any case. ((See Fig. 29(a).))

The second approach is to let the oscillator frequency age, but correct the output time by adding (or subtracting) time in the clock unit. In this approach, the oscillator frequency and clock error vary with time as shown in Fig. 29(b). Note that frequent adjustments must be made to the clock or eventually the clock will gain more than 1 msec per day; a coarse adjustment of the oscillator frequency should then be made. Most high quality oscillators age at a lower rate than 5×10^{-10} per day, so that the frequency need not be adjusted as often as is implied by the figure.

The third approach is to periodically adjust the oscillator frequency so that the oscillator frequency and time error curves appear as shown in Fig. 29(c). This maximizes the time between adjustments, but considerable care must be used in making the adjustments. This is the method used by WWV, since the radiated frequency must be kept as close to the nominal value as possible and step adjustments in the time signals must also be minimized. (WWV, WWVH, and MSF attempt to emit a uniform time offset from atomic time by an amount that closely approximates the mean departure of universal time from atomic time; step adjustments are made only when the departure exceeds some fixed value, e.g., 100 msec.)

The first approach discussed above could be used in Space Track, but it would not be a convenient system. The second approach requires frequent adjustments to the clock and periodic coarse adjustment to the oscillator frequency. The procedure is quite feasible for a site which has a good

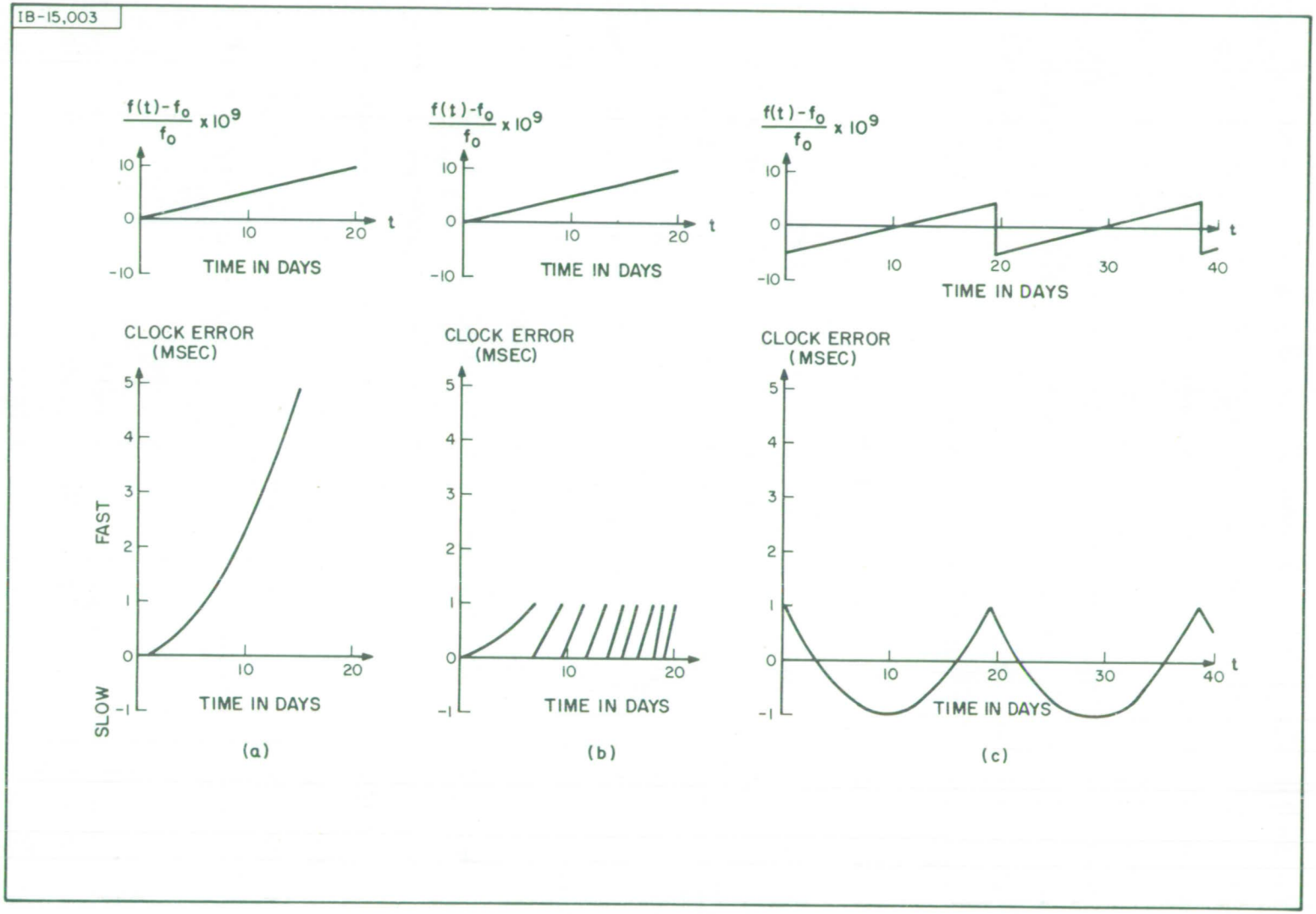

Fig. 29. Oscillator Frequency and Clock Error Patterns

oscillator and receives reliably accurate time ticks from one of the HF standard stations. If the oscillator has a high aging rate and the site is so remote (or in the Arctic region) that the received time ticks are neither reliable nor accurate, the performance of the timing system is degraded. Finally, the third method requires a precise adjustment of the oscillator frequency. This implies that the received time ticks are reliable and accurate. Once again, the performance of a timing system at a remote site using this technique will be degraded by inaccurate, unreliable time ticks.

HF ATOMIC OSCILLATOR TIMING SYSTEM

The block diagram of an HF atomic-oscillator timing system is identical to that in Fig. 28 with, of course, the crystal oscillator replaced by an atomic oscillator. As noted in the subsection on atomic oscillators in timing systems in Section V, one cannot use just any atomic oscillator. Rather, the atomic oscillator must be capable of producing an output frequency which is offset from the atomic frequency by a fixed (but adjustable) amount. * When such an atomic oscillator is used, the timing system should be capable of performing within specifications even though it is located at a remote site or in the Arctic.

The only adjustments required by an HF atomic oscillator timing system are periodic adjustments to the clock reading and changes to the frequency offset of the atomic oscillator (which can change only at the beginning of each year). As can be seen from Fig. 25, clock adjustments are not frequently required. Further, data collected for a period of over 100 days can be used

*Or one can use a separate crystal oscillator calibrated with the atomic oscillator and an electronic counter. This approach offers greater reliability but at a higher cost.

to make the adjustment. Thus, a loss of the HF signal for a period of a day or more does not seriously affect the accuracy.

VLF/HF TIMING SYSTEMS

Introduction

A VLF/HF timing system uses HF signals to adjust the clock reading and VLF signals to adjust the oscillator frequency. From the Space Track point of view, there is no advantage to using an atomic oscillator in a VLF system, so only crystal oscillators are considered. There are three types of VLF/HF timing systems, depending upon the type of VLF receivers.

VLF Tracking Receiver

The block diagram of a VLF/HF timing system using a VLF tracking receiver is shown in Fig. 30. Note that the clock is driven by the stabilized frequency output of the VLF tracking receiver. Hence, once the epoch is established by using the HF signals, the clock should keep the same time as the standard transmission station's clock.

The timing system of Fig. 30 requires a few periodic adjustments. Although the tracking receiver eliminates the aging effect of the crystal oscillator, the frequency of the crystal oscillator should be periodically adjusted using data obtained from the phase-error recorder. This adjustment is desirable, since it minimizes any timing errors that would result from a temporary loss of the VLF signal.

The HF time signals are used in three ways. First, they allow the operator to adjust the epoch of the timing system. Second, they provide a way of monitoring the performance of the VLF tracking receiver so that timing errors introduced by an extended loss of the VLF signal are readily apparent

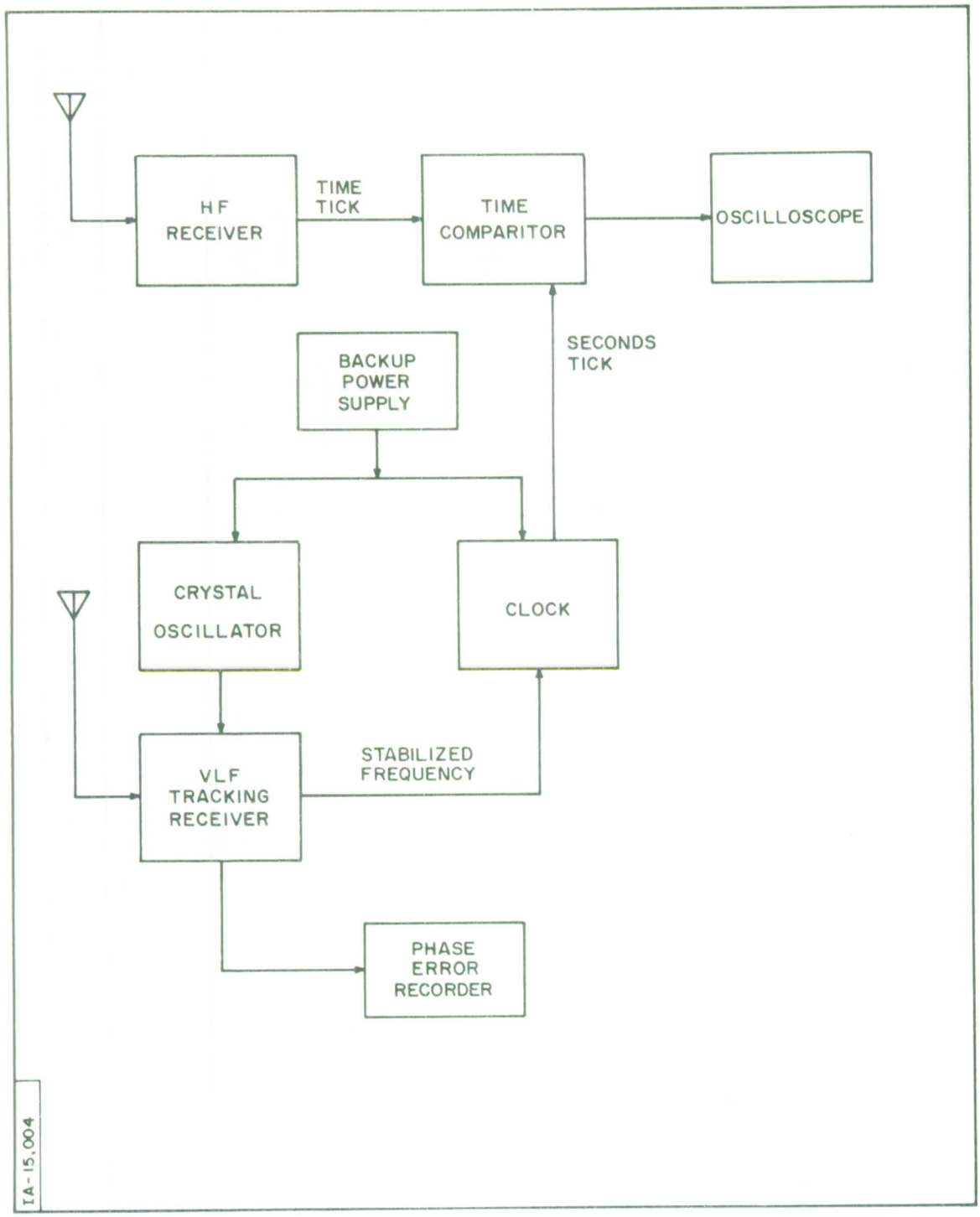

Fig. 30. VLF/HF Timing System Using VLF Tracking Receiver

and can be corrected. Finally, they allow the operator to make the occasional step corrections introduced in the transmitter time scale.

If the VLF signals used in the VLF/HF system are derived from a standard station other than the HF station, then the site clock may slowly drift way from or (more probably) oscillate about the HF station clock. The time error curve will be similar to that of an HF atomic oscillator timing system.

VLF Phase-Comparison Receiver

The block diagram of a VLF/HF timing system using a VLF phase-comparison receiver is shown in Fig. 31. Note that the clock is driven by the uncorrected output of the crystal oscillator; hence, the time error will behave in the same way as in an HF crystal oscillator timing system. However, the present system has the advantage that the oscillator error can be directly obtained from the data on the phase-error recorder. Consequently, the oscillator frequency can be adjusted to provide the frequency and time error pattern of Fig. 29(c). Furthermore, VLF signals can be received in the Arctic region even during time of HF blackout. Thus there should be no degradation in timing performance when this system is used in a remote site.

VLF Frequency-Controlled Timing System

A VLF frequency-controlled timing system has the same block diagram as shown in Fig. 30 except that the crystal oscillator and VLF tracking receiver are combined into one unit (the VLF receiver frequency standard). This unit is designed such that the frequency output is automatically stabilized to the received VLF signal with a typical accuracy of 5 parts in 10^{10}. Thus, in principle, there is no need to periodically adjust the frequency of the VLF receiver frequency standard.

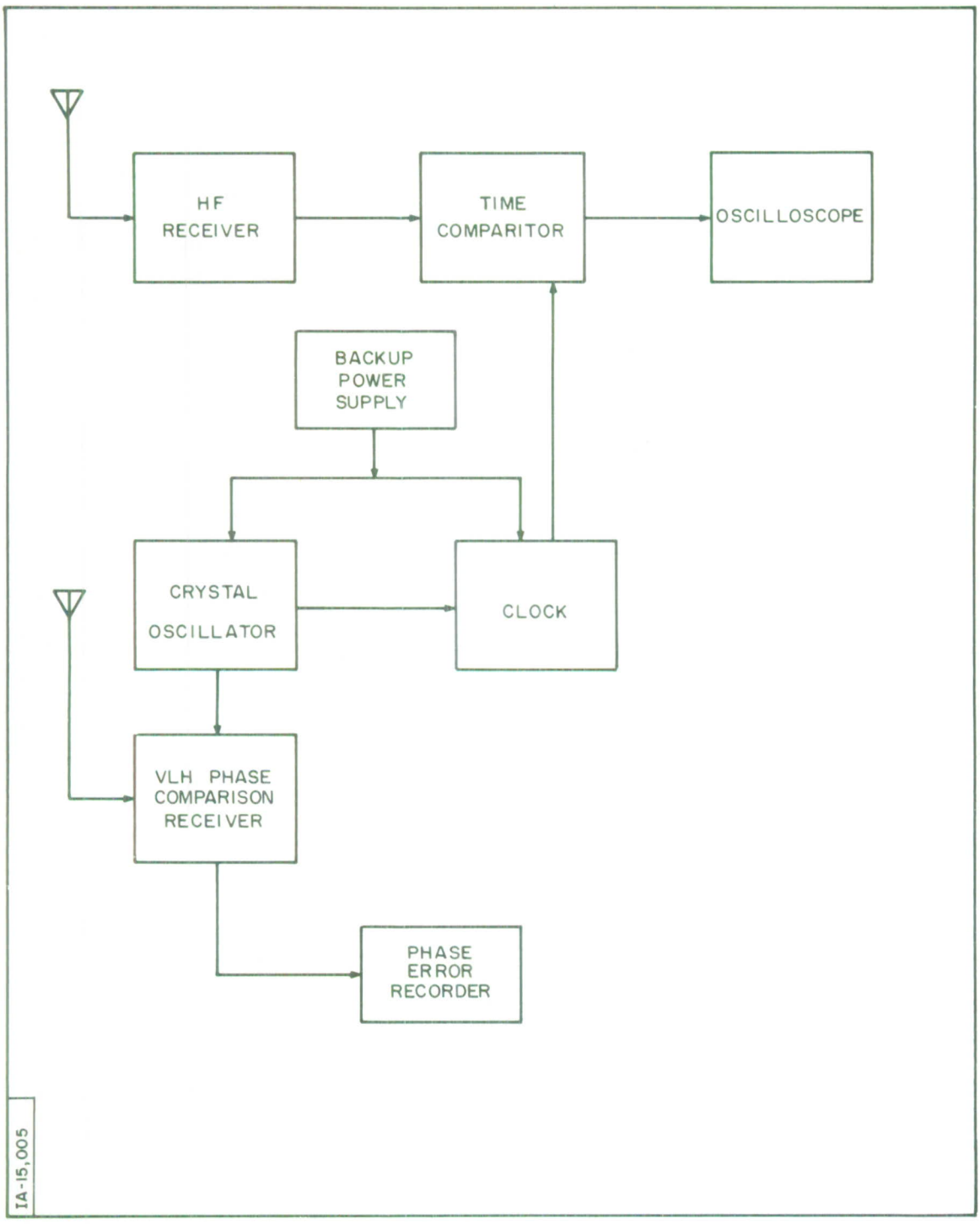

Fig. 31. VLF/HF Timing System Using VLF Phase-Comparison Receiver

Since the frequency of the VLF receiver frequency standard can differ from the ideal value, a timing error can occur. The problem here is similar to that in an atomic oscillator system in that a frequency error can occur, but the frequency oscillates about the ideal value. A crude estimate of the time required for a timing error of 1 msec to accumulate can be obtained by assuming that the frequency error has the constant value of 5 parts in 10^{10}. From Eq. (8) of Appendix IV, with $E_o = 0$, $f_o = f_r$, and $\alpha = 5 \times 10^{-10}$, one finds that 23 days are required. As in the other system, the HF signal is used to make the required timing correction.

LF TIMING SYSTEMS

Since the LF signals emitted by WWVB provide both constant frequency and time data, a single LF receiver can play the role of the HF receiver and the VLF receiver. Once again, one can get LF tracking receivers and LF phase-comparison receivers. Thus there are LF timing systems whose block diagrams are the same as those shown in Figs. 30 and 31.

The coverage provided by the present LF standard stations is limited; in particular, an LF timing system cannot presently be used in the Arctic, Alaska, or in Turkey. Also, there should be no problem in receiving HF signals at those sites which could use an LF timing system and, hence, an LF system does not appear to offer any performance advantages over a VLF/HF timing system.

OTHER TIMING SYSTEMS

Timing systems can be conceived which make use of different combinations of the available HF, LF and VLF signals. For example, the Eglin radar uses time signals from the HF station WWV, while it monitors the LF station

WWVB using an LF phase-comparison receiver. However, the performance of such systems should be essentially identical to one of the above systems (such as the VLF/HF system using a VLF phase-comparison receiver).

It is also possible to design and build timing systems operating upon different signals or techniques from those previously discussed. For example, the Loran-C system (Appendix I) can be used over a limited portion of the U. S. East Coast. Atomic clocks or very stable crystal oscillators can be flown from site to site (Appendix II). Finally, the Transit navigation satellite timing signals could be used. All of these systems should allow clocks to be synchronized with an accuracy in the μ sec region. However, the systems are expensive and Space Track does not need μ sec synchronization. Hence, these systems are not considered.

COMPARISON OF SITE TIMING SYSTEMS

Table V compares the performance, cost, and operating ease of the different possible site timing systems. All of the timing systems shown in the table can provide time information with an accuracy of $\pm$ 1 msec or better, relative to the standards transmission station clock, when the system is located close to the standards station. The LF systems can provide the same performance at any location within the continental U. S. (using WWVB) or within Great Britain (using MSF). The performance of HF crystal-oscillator systems located at remote sites will be degraded by variations in the HF propagation time resulting in an accuracy of about $\pm$ 2 to $\pm$ 3 msec. Performance of these systems in arctic regions will be further degraded by HF blackouts and additional variations in HF propagation time. The VLF/HF systems and the HF atomic-oscillator system will provide the required accuracy at any Space Track site shown in Fig. 1.

The cost shown in Table V only includes the price of the basic, commercially available units. There has been no attempt to optimize the cost or to choose the best set of units. The only reason for choosing any given unit was the immediate availability of the price data. Thus, the price data of Table V is only approximate; however, it does show the relative costs of the different systems.

Also, the costs given in Table V do not include the cost of equipment needed to supply the proper timing signals to the sensor. The cost of such equipment depends on the type of timing signals required by the particular sensor and would be an additional fixed cost regardless of the type of timing system chosen for the site.

All of the timing systems have to be periodically adjusted. For example, the time reading of the reference clock has been changed four times in the last 4-1/3 years (see Fig. 4). Thus, all of the site clocks would have to be adjusted at these times. Furthermore, the frequency offset has been changed twice in the last 4-1/3 years, thereby requiring that the frequency offset of the atomic oscillator in an HF atomic oscillator be changed at the same time. Finally, small frequency errors between atomic oscillators and aging effects in quartz crystals require additional frequent adjustments.

The LF and VLF systems using phase-comparison receivers suffer from quartz crystal aging effects. However, these systems have the advantage of directly measuring the frequency error between the local oscillator and the standards station. Consequently, the oscillator frequency and clock error patterns of Fig. 29(c) can be achieved. Thus, ideally, the clock never needs adjustments (except as noted above) while the oscillator frequency has to be adjusted every 40 days. *

*Assuming an aging rate of 1 part in 10^{10}.

The LF and VLF systems using tracking receivers ideally keep perfect time (provided the proper LF or VLF station is monitored) except for the effect of a temporary loss of the LF or VLF signal. Whenever the LF or VLF signal is lost, the resultant timing error depends upon the frequency error of its crystal oscillator and the duration of the loss of signal. Thus the crystal oscillator should be periodically adjusted in order to limit this timing error. Specifically, if an 8-hour loss in LF or VLF signal is to produce a timing error of less than 0.2 msec, then a crystal oscillator with an aging rate of 1 part in 10^{10} should be adjusted ((to the frequency pattern of Fig. 29(c)) every 120 days.

If the proper LF or VLF station is not used to monitor the local frequency, then a maximum frequency error of about 1 part in 10^{10} can exist, resulting in a 1-msec clock error after 120 days.

Table V contains a summary of the cost, performance, and operating requirements of the systems of interest. As previously noted, the numbers given in the table are only approximately accurate. Specifically, choosing a different crystal oscillator could change costs by $1000 and the time between adjustments by a factor of 3. However, the table does set forth the relative advantages and disadvantages of the seven systems. Further, with the single exception of the HF crystal-oscillator case, all systems can provide timing signals accurate to ± 1 msec at all Space Track sites. The HF crystal-oscillator system should provide timing accuracies of ± 1 msec or better at sites such as Moorestown and BMEWS Site III, approximately ± 2 msec or better at sites such as Blue Fox, and probably ± 5 msec or better at BMEWS Site I.

Table V

Comparison of Timing Systems

System	Approx. Cost ($)	Time Between Frequency Adjustments	Time Between Clock Adjustments	Time & Frequency Error Curve	Available Data	Comments
HF crystal oscillator	8,400	15 days	15 days	Fig. 22	Time error	1-msec accuracy only for sites near standard transmission stations
HF atomic oscillator	25,700	Once every year	>120 days	Fig. 25	Time error	Provides required accuracy at any Space Track site
LF system with tracking receiver	10,000	120 days	Once a year	Osc. freq. error as in Fig. 29(c); no time error	Time and freq. error	Coverage limited to continental U. S. and Great Britain
LF system with phase-comparison receiver	9,000	40 days	Once a year	Fig. 29(c) (with aging rate of 1 part in 10^{10})	Time and freq. error	Coverage limited to continental U. S. and Great Britain
VLF/HF system with tracking receiver	12,800	120 days	Once a year --- >120 days	Osc. freq. error as in Fig. 29(c); no time error Osc. freq error as in Fig. 29(c); time error of Fig. 25	Time and freq. error	Assuming HF & VLF stations are synchronized --- Assuming HF & VLF stations are not synchronized
VLF/HF system with phase-comparison receiver	12,800	40 days	Once a year --- >120 days	Fig. 29(c) (with aging rate of 1 part in 10^{10})	Time and freq. error	Assuming HF & VLF stations are synchronized --- Assuming HF & VLF stations are not synchronized
VLF/HF system with frequency-controlled receiver	12,400	Never	>23 days	Fig. 25 with ordinate scale increased by factor of 5	Time and freq. error	Provides required accuracy at any Space Track site

The desired ± 1-msec accuracy in timing information is not easily achieved. The quality of the crystal oscillator used in the HF crystal-oscillator system and the LF or VLF systems using tracking or comparison receivers becomes more important as the site is more remotely located. The performance of a crystal-oscillator system will improve with time (as the aging rate of the crystal stabilizes and decreases) so that a backup power supply is desirable. Finally, the performance of any timing system should be measured at least once a day. The quality of the data should be rated and all of the data should be used when determining when and how great an adjustment should be made.

R. K. Gardner

APPENDIX I

LORAN-C

Loran-C is a pulse navigation system operating at 100 kc. The transmitted signal consists of a group of eight phase-coded pulses, separated by 1 msec with groups separated by 1/20 sec. Experiments have shown that the Loran-C signals can be used to synchronize remote clocks with an accuracy of about 1 μsec if the remote clock is within ground wave coverage of the transmitter (2000 n. m. over sea; 1500 n. m. over land). [1] [34] [35] During darkness, the skywave can be used to establish synchronization with an accuracy better than 5 μ sec for distances up to 5000 km.

The signals from the U. S. East Coast Loran-C chain (with transmitters at Martha's Vineyard, Mass., Cape Fear, N. C., and Jupiter Inlet, Fla.) are presently adjusted to keep the pulses synchronized with the master clock at the Naval Observatory. Thus the Loran-C could be used to establish an accurate time scale at the Moorestown and Eglin sites.

There are other Loran-C chains in the North Atlantic, the Mediterranean, Alaska, and Hawaii. However, signals from these chains are not synchronized to any of the standard time scales; hence, they cannot be used for timing purposes in Space Track. If these chains were synchronized to a standard time scale (the Coast Guard, National Bureau of Standards, and Navy are considering the possibility), then Loran-C could be used to establish a time scale with μ sec accuracy throughout a large portion of the world.

Finally, it should be noted that a Loran-C timing system would still require an HF system in order to eliminate time ambiguities introduced by the 20-cps repetition rate presently used in Loran-C.

APPENDIX II

SYNCHRONIZATION BY TRANSPORTING CLOCKS

One method of synchronizing clocks located at widely separated sites is simply to carry a test clock between the sites and make direct comparisons between the clock times. Typically, the test clock would first be synchronized (in frequency and time) with one of the clocks. The test clock would then be flown to the second site where the site clock would be synchronized to the test clock. The test clock can then be flown back to the first site where its time would be compared with that of the first clock. The time error between the first clock and the test clock (after the round-trip flight) is a measure of the synchronization accuracy achieved by the technique.

Two experiments of this type have been performed in recent years. The first experiment* involved two atomic clocks, one clock located at the Air Force Missile Test Center, Patrick Air Force Base, and the second clock at the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey. The test clock was also an atomic clock mounted in a C-46 airplane. The test clock was first synchronized to the atomic clock at Patrick AFB and then flown to Fort Monmouth (a flight time of 7 hours). The clock at Fort Monmouth was compared with the test clock, then the test clock was turned off for the night. The next morning the test clock was synchronized with the Fort Monmouth clock and then flown back to Patrick AFB. Upon arrival at Patrick (after a round-trip time of 32 hours), the time difference between the test clock and the Patrick atomic clock was less than 0. 2μsec.

*"Results of a Long-Range Clock Synchronization Experiment," E. Rider, M. Winkler, and C. Bickart., Proc. of IRE, Vol. 49, p. 1028-1032, 1961.

The second experiment* was performed with a high-precision crystal clock which was transported from Boulder, Colorado, to the WWV transmitter in Greenbelt, Maryland. Upon returning to Boulder, the error between the test clock and the reference (atomic) clock was 5 μsec.

Thus, if desired, all of the Space Track clocks would be initially synchronized with μsec accuracy by transporting an atomic clock or high-precision crystal clock between the sites. However, after a few months** of operation, the Space Track clocks would no longer be synchronized with μsec accuracy. Hence, this approach requires that the atomic clock be periodically flown to each site - an expensive procedure.

* "Synchronization of Two Remote Atomic Time Scales," J. Barnes and R. Fey, Proc. of IEEE, Vol. 51, p. 1663, November 1963.

**The exact time period depends upon the type of timing system.

APPENDIX III

COST ESTIMATES OF SITE TIMING SYSTEMS

The cost of the different site timing systems has been estimated by obtaining the stated price of commercial units that could be used to assemble any given timing system. No attempt has been made to either minimize the overall cost of a system or to optimize, in any sense of the word, the compatibility of the units. No allowance has been included for assembly and transportation costs or for the costs of racks, cables, etc.

The following items should also be noted:

(1) The crystal oscillator has a specified initial aging rate of 1 part in 10^{10} at a cost of $2600. Oscillators with an initial aging rate of 5 parts in 10^{10} cost about $2000, those with an aging rate of about 5 parts in 10^{10} (decreasing to 1 part in 10^{11} after six months) cost about $3500.

(2) The atomic oscillator will not be available until the latter part of 1964. Its exact cost is not known, but is claimed to be less than $20,000 (the value used in this comparison).

(3) The clock only supplies a 1-second tick and a 100-cps pulse chain. More expensive clocks will also provide time-of-day in a BCD output.

(4) The backup power supply provides 48 hours of operation for a clock and crystal oscillator after a prime power failure. It is assumed that this power supply can also handle the atomic oscillator.

(5) The LF receiver can receive either WWVB or WWVL. It also supplies the time-tick signal.

(6) The VLF tracking receivers cover the required frequency band in steps of 0.1 kc. Somewhat cheaper units (about $3500) can be obtained which can cover only a few fixed frequencies.

(7) Available price data shows that VLF phase-comparison receivers are just as expensive as VLF tracking receivers. The Gertsch Phase-Comparison Receiver can only receive four frequencies in the range 10 to 100 kc. To receive other frequencies, additional plug-in units are needed.

(8) The Motorola VLF Receiver Frequency Standard can receive any two frequencies in the range 14 to 30 kc or 60 kc. Frequencies can be changed by inserting new RF deck and synthesizer boards into the receiver.

HF Crystal-Oscillator System

Item	Unit	Cost
Crystal oscillator	Sulzer Laboratories Model 2.5	$2600
Clock	Hewlett-Packard Model 115BR	2750
Backup power supply	Hewlett-Packard Model 724BR	950
HF receiver	Specific Products Model SR-7	345
Time comparator	Hewlett-Packard Model 114BR	1200
Oscilloscope	Hewlett-Packard Model 120BR	475
HF antenna	Specific Products Model AK-8	50
		$8370

HF Atomic-Oscillator System

Atomic Oscillator	Hewlett-Packard Model 5060A	$20,000
Clock	Hewlett-Packard Model 115BR	2,750
Backup power supply	Hewlett-Packard Model 724BR	950
HF receiver	Specific Products Model SR-7	345
Time comparator	Hewlett-Packard Model 114BR	1,200
Oscilloscope	Hewlett-Packard Model 120BR	475
HF antenna	Specific Products Model AK-8	50
		$25,770

LF System with Tracking Receiver

Item	Unit	Cost
Crystal Oscillator	Sulzer Laboratories Model 2.5	$2600
Clock	Hewlett-Packard Model 115BR	2750
Backup power supply	Hewlett-Packard Model 724BR	950
LF tracking receiver, recorder and antennae	Tracor, Inc., VLF/LF Tracking Receiver Model 891	1995
Time comparator	Hewlett-Packard Model 114BR	1200
Oscilloscope	Hewlett-Packard Model 120BR	475
		$9970

LF System with Phase-Comparison Receiver

Crystal oscillator	Sulzer Laboratories Model 2.5	$2600
Clock	Hewlett-Packard Model 115BR	2750
Backup power supply	Hewlett-Packard Model 724BR	950
LF comparison receiver	Specific Products Model SR-60	850
Time comparator	Hewlett-Packard Model 114BR	1200
Oscilloscope	Hewlett-Packard Model 120BR	475
LF antenna	Specific Products Model AK-10	78
Recorder	Rustrak Model 88	100
		$9003

VLF/HF System with Tracking Receiver

Item	Unit	Cost
Crystal oscillator	Sulzer Laboratories Model 2.5	$ 2,600
Clock	Hewlett-Packard Model 115BR	2,750
Backup power supply	Hewlett-Packard Model 724BR	950
HF receiver	Specific Products Model SR-7	345
Time comparator	Hewlett-Packard Model 114BR	1,200
Oscilloscope	Hewlett-Packard Model 120BR	475
VLF tracking receiver and recorder	Tracor, Inc., Model 599H	4,300
HF antenna	Specific Products Model AK-8	50
VLF antenna	Tracor, Inc.	175
		$12,845

VLF/HF System with Phase-Comparison Receiver

Crystal oscillator	Sulzer Laboratories Model 2.5	$ 2,600
Clock	Hewlett-Packard Model 115BR	2,750
Backup power supply	Hewlett-Packard Model 724BR	950
HF receiver	Specific Products Model SR-7	345
Time comparator	Hewlett-Packard Model 114BR	1,200
Oscilloscope	Hewlett-Packard Model 120BR	475
VLF receiver and recorder	Gertsch Phase-Comparison Receiver PCR-1 (plus 2 plug-in units)	4,400
HF antenna	Specific Products Model AK-8	50
VLF antenna	Electronic Engineering Co. of Calif.	75
		$12,845

VLF/HF System with VLF Frequency-Controlled Receiver

Item	Unit	Cost
VLF receiver frequency standard	Motorola Comm. and Electronics Model S1055BH	$ 6,450
Clock	Hewlett-Packard Model 115BR	2,750
Backup power supply	Hewlett-Packard Model 724BR	950
HF receiver	Specific Products Model SR-7	345
Time comparator	Hewlett-Packard Model 114BR	1,200
Oscilloscope	Hewlett-Packard Model 120BR	475
HF antenna	Specific Products Model AK-8	50
VLF antenna	Specific Products Model AK-10	78
Recorder	Rustrak Model 88	100
		$12,398

APPENDIX IV

FREQUENCY-TIME ERROR RELATIONS

The relationship between time error and frequency error is derived in this appendix. As shown in Section V, an ideal timing system would consist of a perfectly stable oscillator operating at a frequency of f_r cps. The clock is simply a counter whose count is increased by one for every cycle of the oscillator output. Thus the units of the clock reading and the oscillator frequency are related by:

$$(\text{one clock unit}) = \frac{1}{f_r} \text{ (seconds)} \qquad (1)$$

In practice, the frequency of the frequency-determining device in an oscillator is on the order of megacycles for crystal oscillators and ~ 9192 Mc for atomic oscillators. However, electronic circuits in the oscillator are used to produce an output signal whose frequency is typically 100 kc or 1.0 Mc. Many clocks do some additional frequency division in order to produce a signal at 1.0 kc which is used to drive the clock.

For simplicity and convenience, we shall define the frequency f_r to be the frequency of that (ideal) signal which drives the counter. Note that the time scale is determined by the frequency f_r. If f_r is 1000 cycles per atomic second, then the timing system keeps atomic time; if f_r is 1000 cycles per UT-2 second, then the timing system keeps UT-2 time. In either case, the clock reading would be in units of 1 msec.

In practice, the frequency of the signal driving the clock is not f_r; furthermore, the frequency may change with time. Thus we define f(t) as the frequency of the signal actually driving the clock. Further, for the purpose of the document, it is sufficient to let

$$f(t) = f_o (1 + \alpha' t) \tag{2}$$

where

f_o = frequency in cps

t = time in seconds

α' = aging rate in parts/second.

Note that the units must be consistent. Thus if the timing system is to keep atomic time, the f_o must be in cycles per atomic second, t must be in measured atomic seconds, and α' must be in parts/atomic second.

Suppose an ideal timing system could be built and was operating side-by-side with a timing system whose counter was driven by a signal having the frequency given by Eq. (2). Let the time error between the two timing systems be given by E (t); i. e.,

$$E(t) = \begin{pmatrix}\text{time reading}\\ \text{of real}\\ \text{timing system}\end{pmatrix} - \begin{pmatrix}\text{time reading}\\ \text{of ideal}\\ \text{timing system}\end{pmatrix} \tag{3}$$

We know that the frequency error between the two systems is given by

$$\begin{Bmatrix}\text{frequency}\\ \text{error}\end{Bmatrix} = f_o (1 + \alpha t) - f_r \tag{4}$$

If the frequency error is assumed to be given, and the time error at time T_o (as determined by the ideal timing system) is known to be E_o, then we can ask for the value of the time error at any time T.

To solve this problem, we note that the time integral of the frequency of a sinewave from time T_o to time T is just the number of cycles of the sinewave which have occurred during this time interval. Since the clock readings are increased by one for every cycle in the drive signal, we have

$$\begin{pmatrix}\text{count increase}\\ \text{in a clock}\end{pmatrix} = \begin{pmatrix}\text{integral of}\\ \text{frequency}\end{pmatrix} \tag{5}$$

However, from Eq. (1), a clock unit is $1/f_r$ seconds; hence

$$\begin{pmatrix}\text{time reading of}\\ \text{clock in}\\ \text{seconds}\end{pmatrix} = \frac{1}{f_r}\begin{pmatrix}\text{integral}\\ \text{of}\\ \text{frequency}\end{pmatrix} + \begin{pmatrix}\text{initial}\\ \text{clock}\\ \text{reading}\end{pmatrix} \tag{6}$$

Combining these results, we get

$$E(t) = \frac{1}{f_r}\int_0^t \left[f_o(1 + \alpha'\tau) - f_r\right] d\tau + E_o$$

$$= E_o + \frac{f_o - f_r}{f_r}\, t + \frac{f_o}{f_r}\,\alpha' t^2 \tag{7}$$

In the equation, E(t), E_o, and t are in units of seconds. A more practical set of units would be E(t) and E_o in milliseconds with t days. The term $(f_o - f_r/f_r)$ is the normalized frequency error between the two oscillator signals at $t = 0$. Typically, this ratio is considerably less than 1 part in 10^8. The aging rate α' is in units of 1/sec; thus if α is the aging rate in parts per day (the typical units), then

$$\alpha' = \frac{\alpha}{(24)\ (60)\ (60)}$$

Finally, for all practical purposes, (f_o/f_r) can be set equal to unity.

Thus in practical units

$$E(t) = E_o + 8.64 \times 10^{+7} \left(\frac{f_o - f_r}{f_r} D + \alpha D^2/2 \right) \qquad (8)$$

where

$E(t)$	=	error in units of millisecond
D	=	time in units of a day
α	=	aging rate in parts per day
$(f_o - f_r/f_r)$	=	normalized initial frequency error.

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