CLOCK SYNCHRONIZATION EXPERIMENTS USING OMEGA TRANSMISSIONS

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ABSTRACT

The OMEGA transmissions from North Dakota on 13.10 and 12.85 kHz were monitored at several sites using a recently developed OMEGA timing receiver specifically designed for this purpose. The experiments were conducted at Goddard Space Flight Center (GSFC), Greenbelt, Maryland; U.S. Naval Observatory (USNO), Washington, D.C.; and at the NASA tracking station, Rosman, North Carolina.

Results show that cycle identification of the two carrier frequencies was made at each test site, thus, coarse time (76 microseconds) from the OMEGA transmitted signals to within the ambiguity period of each OMEGA frequency was extracted. The fine time determination, which was extracted from the phase difference between the received OMEGA signals and locally generated signals, was about ±2 microseconds for daytime reception and about ±5 microseconds for nighttime reception.

INTRODUCTION

Very low frequency (VLF) transmissions, which are phase controlled at the transmitter relative to a time scale such as UTC, have been successfully used for many years with relative ease for frequency control of precision oscillators. This is realized due to the inherent stability characteristics of the D-layer of the ionosphere, for propagating VLF signals. The utilization of VLF signals for synchronization of a clock, however, requires the continual phase count of the received signal relative to an oscillator which drives the clock at the receiver site. This requirement restricts the use of VLF transmissions for precise clock synchronization due to phase discontinuities or phase perturbations such as Sudden Ionospheric Disturbances (SID's). Additionally, the diurnal phase changes, which are on the order of 180°, can also introduce phase discontinuities at sunrise or sunset due to modal interferences on certain propagation paths. All these phase interruptions must be accounted for if VLF transmissions are to be used for clock synchronization.

A technique has been developed which is independent of phase perturbations or SID's. It is by the use of two unique OMEGA signals whose frequencies are closely spaced and whose phase stabilities are rigidly controlled at the transmitter with respect to a master clock. By measuring the relative phase difference of the two received signals, which is a function of the propagation path length, the integer cycle of a carrier signal for a given path length can be determined. The product of the period of the frequency of a carrier signal and the determined carrier cycle by the receiver gives the propagation delay to the nearest period integer. The remaining fraction of a period is obtained by measuring the phase differences or time interval between the coincident positive zero crossings of the received signals and the coincident positive zero crossings of locally generated signals. Thus, the two step approach using the dual frequency technique is independent of perturbations due to SID's and provides an accurate means for clock synchronization with a precision related to the phase stability of the propagated VLF signals.

Description of the Dual VLF Technique

The use of dual VLF signals for clock synchronization is not new; however, the use of OMEGA transmissions for clock synchronization is unique. The emitted VLF signals from OMEGA stations are synchronized to a time scale with reference to UTC of January 1972. Each signal after propagation over a certain path length, experiences a delay of T_p and exhibits a phase change of $n_i \phi_i + \Delta\phi_i$. It is this phase difference between the two transmitted signals that permits the establishment of the time epoch. Ideally, of course, the propagation medium should be homogeneous and isotropic to permit the use of the transmission medium properties. In practice this assumption cannot be made except for closely spaced frequencies. An additional factor for selecting closely spaced frequencies is the fact that the effects due to propagation anomalies are minimized.

OMEGA NAVIGATION SYSTEM

The OMEGA Navigation System is composed of eight VLF transmitting sites strategically located to provide worldwide coverage as shown in Figure 1. Three navigation frequencies (10.2, 13.6 and 11-1/3 kHz) are transmitted by each station in a commutation format as shown in Table 1. Two side frequencies are transmitted in the five remaining segments and may be used for other purposes such as timing. Coordination among various users of OMEGA transmissions resulted in the adoption of the present transmission format. The two frequencies which are separated by 250 Hz are transmitted by each station in duty cycle ratios of 3 and 2 in eight time segments. Thus, the five frequencies make up the total commutation transmission format. The two frequencies can be used for clock synchronization if these signals are phase controlled at the

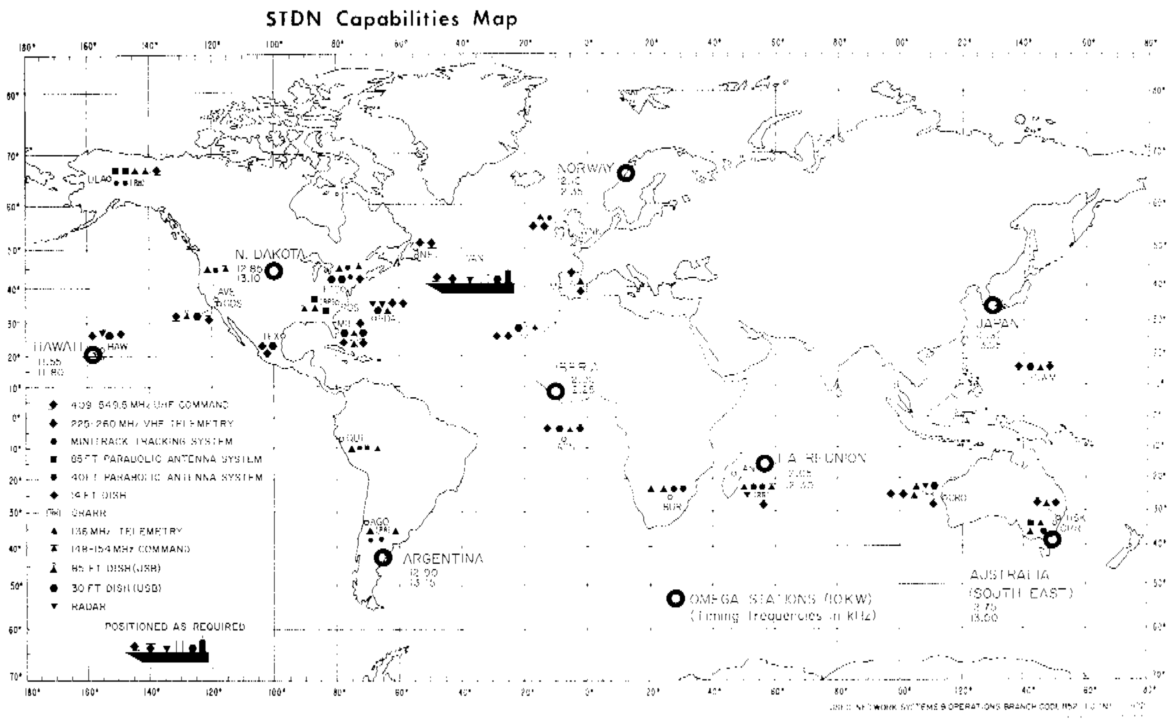
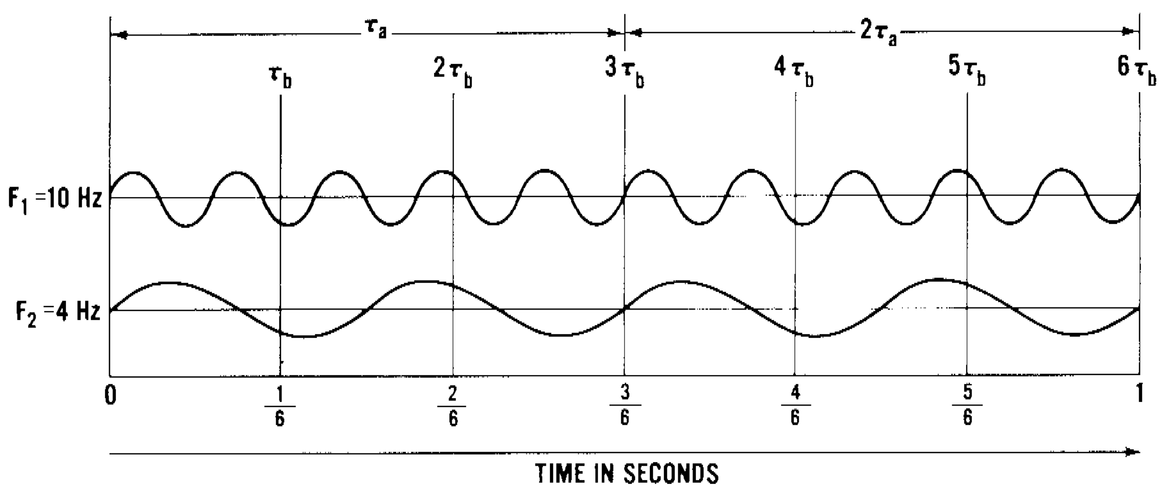


Figure 1.



$F_1 = 10$ Hz

$F_2 = 4$ Hz

$Q = \frac{F_1}{k_1} = \frac{F_2}{k_2} = 2$

$k_1 = \frac{F_1}{Q} = 5$

$k_2 = \frac{F_2}{Q} = 2$

$k = k_1 - k_2 = 3$

$\tau_b = \frac{1}{\Delta F} = \frac{1}{6}$ sec

$\tau_a = k\,\tau_b = \frac{3}{6}$ sec

Figure 2.

transmitter relative to a standard clock. They can also be used for aircraft navigation in remote areas by the same scheme as or in combination with other VLF transmissions such as NAA, NBA, NPM, etc.

Presently on the North Dakota OMEGA station transmits the two frequencies, at 13.10 and 12.85 kHz, which are phase controlled at emission coincident to the UTC time scale of January 1, 1972.

Figure 2 gives a pictorial representation of two signals emitted at time t_0 from the transmitting antenna. As the signals are propagated to the right of t_0 the phase difference of the signals increases from 0 to 2π as a function of distance or propagation time delay. One can see that the relative phase becomes zero at integer multiples of the beat frequency periods as shown at 1/6, 2/6, 3/6, 4/6, 5/6 and 6/6 seconds. At 3/6 and 6/6 seconds, the relative phase of the two signals is exactly the same as that at t_0, i.e., both signals are in phase at the positive going zero crossings. The time between coincident positive going zero crossings is called the ambiguity period. To avoid confusion, those beat periods at which the phases of the two propagated signals are the same but not at the positive going zero crossings, are called the pseudo ambiguity periods.

With reference to Figure 3, let t_0 be the time of emitted signals f_1 and f_2 at the transmitter site.

Let t_r be the time of reception relative to a clock at the receiving site. Then the transit time for the signals to reach from the transmitter to the receiver is

$$t_r - t_o = T_p + \Delta t_c \tag{1}$$

where

T_p = propagation delay = $t_p + \Delta t_p$
t_p = calculated propagation delay and
Δt_p = propagation delay anomaly
Δt_c = clock difference between transmit and receive site.

Rearranging terms

$$t_r - t_o = t_p + \Delta t_p + \Delta t_c$$

let

$$\Delta t = \Delta t_p + \Delta t_c$$

then

$$t_r - t_o = t_p + \Delta t \tag{2}$$

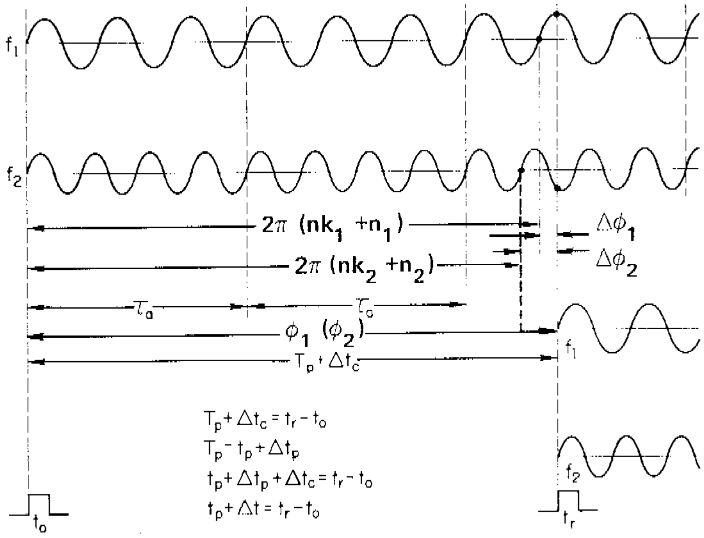


Figure 3.

Table 1

10 Second Time Frame of OMEGA Frequency Commutation Format

STATION \ SEGMENT	A	B	C	D	E	F	G	H
A NORWAY	10.2	13.6	11.33	12.1	12.1/12.35	12.1/12.35	12.1/12.35	12.35
B LIBERIA	12.25	10.2	13.6	11.33	12.0	12.0/12.25	12.0/12.25	12.0/12.25
C HAWAII	11.8/11.55	11.55	10.2	13.6	11.33	11.8	11.8/11.55	11.8/11.55
D N. DAKOTA (La Mour)	13.1/12.85	13.1/12.85	12.85	10.2	13.6	11.33	13.1	13.1/12.85
E LA REUNION	12.3/12.05	12.3/12.05	12.3/12.05	12.05	10.2	13.6	11.33	12.3
F ARGENTINA (Trelew, Chubut Prov.)	12.9	12.9/13.15	12.9/13.15	12.9/13.15	13.15	10.2	13.6	11.33
G AUSTRALIA	11.33	13.0	13.0/12.75	13.0/12.75	13.0/12.75	12.75	10.2	13.6
H JAPAN (Tsushima Is.)	13.6	11.33	12.8	12.8/13.05	12.8/13.05	12.8/13.05	13.05	10.2
	0.9 / .2	1.0 / .2	1.1 / .2	1.2 / .2	1.1 / .2	0.9 / .2	1.2 / .2	1.0 / .2
	0.0	1.1	2.3	3.6	5.0	6.3	7.4	8.8 – 10.0

The transmitted frequencies, f_1 and f_2, are phased at the transmitter such that they both pass through a positive going zero crossing at time t_0 which represents the beginning of a second of the standard time scale.

If identical frequencies are generated at the receiver at time t_r (see Fig. 3), and if the respective phase differences $\Delta\phi_1$ and $\Delta\phi_2$ between the generated frequencies at the receiver and the generated frequencies at the transmitter are measured, the time difference in delay $(t_r - t_0)$ can be calculated.

Expressed in terms of phase relationships it can be seen (Fig. 3) that the phase angle ϕ_1, generated by frequency f_1 during time $(t_r - t_0)$ is

$$\phi_1 = 2\pi n k_1 + 2\pi n_1 + \Delta\phi_1 \tag{3}$$

The ϕ's are taken as positive if measured to the right of t_r. Similarly for f_2

$$\phi_2 = 2\pi n k_2 + 2\pi n_2 + \Delta\phi_2 \tag{4}$$

where n_1 (n_2) is an integer and the number of positive going zero crossings of f_1 (f_2) between t_0 and t_r within an ambiguity period.

k_1 (k_2) is the number of integer cycles of f_1 (f_2) in τ_a (the ambiguity period). n is an integer, the number of ambiguity period between t_0 and t_r.

Let

$$\tau_1 = \frac{1}{f_1}$$

the period of frequency f_1. Also

$$\tau_2 = \frac{1}{f_2}$$

The transit time $(t_r - t_0)$ is equal to the number of cycles of either frequency multiplied by the period of the frequency time length of one cycle, hence

$$t_r - t_0 = \frac{\phi_1}{2\pi}\tau_1 = \frac{\phi_2}{2\pi}\tau_2 \tag{5}$$

or

$$t_p + \Delta t = \frac{\phi_1}{2\pi}\tau_1 \tag{6}$$

$$t_p + \Delta t = \frac{\phi_2}{2\pi}\,\tau_2 \tag{7}$$

Substitute Eq. 3 into Eq. 6:

$$t_p + \Delta t = nk_1\tau_1 + n_1\tau_1 + \frac{\Delta\phi_1}{2\pi}\,\tau_1$$

or

$$t_p + \Delta t = nk_1\tau_1 + n_1\tau_1 + \Delta n_1\tau_1 \tag{8}$$

also

$$t_p + \Delta t = nk_2\tau_2 + n_2\tau_2 + \Delta n_2\tau_2 \tag{9}$$

where

$$\frac{\Delta\phi_1}{2\pi} = \Delta\eta_1$$

Solving for n_1 and n_2

$$n_1 = \frac{1}{\tau_1}(t_p + \Delta t) - nk_1 - \Delta n_1$$

$$n_2 = \frac{1}{\tau_2}(t_p + \Delta t) - nk_2 - \Delta n_2$$

$$n_1 - n_2 = \left(\frac{1}{\tau_1} - \frac{1}{\tau_2}\right)(t_p + \Delta t) - nk_1 + nk_2 - \Delta n_1 + \Delta n_2$$

then

$$n_1 - n_2 = \frac{1}{\tau_b}(t_p + \Delta t) - nk - \Delta n_{12}$$

$$\frac{1}{\tau_b} = \frac{1}{\tau_1} - \frac{1}{\tau_2}$$

and

$$k = k_1 - k_2$$

$$\Delta n_{12} = \Delta n_1 - \Delta n_2$$

By definition k_1 is the integer number of cycles of f_1 in τ_a, k_2 is the integer number of cycles of f_2 in τ_a and k is the integer number of cycles of $(f_1 - f_2)$ in τ_a.

Thus

$$\tau_a = k_1 \tau_1 = k_2 \tau_2 = k\tau_b$$

Then

$$n_1 - n_2 = \frac{k}{\tau_a}(t_p + \Delta t) - nk - \Delta n_{12}$$

$$n_1 - n_2 = \frac{k}{\tau_a}(t_p + \Delta t - n\tau_a) - \Delta n_{12}$$

Also

$$n_1 = \frac{1}{\tau_1}(t_p + \Delta t) - n\frac{\tau_a}{\tau_1} - \Delta n_1$$

$$n_1 = \frac{1}{\tau_1}(t_p + \Delta t - n\tau_a) - \Delta n_1 \tag{10}$$

also

$$n_2 = \frac{1}{\tau_2}(t_p + \Delta t - n\tau_a) - \Delta n_2 \tag{11}$$

Substituting and rearranging terms in Eqs. 8 and 9 we have

$$t_p + \Delta t = n\tau_a + (n_1 + \Delta n_1)\tau_1 \tag{12}$$

and

$$t_p + \Delta t = n\tau_a + (n_2 + \Delta n_2)\tau_2 \tag{13}$$

Cycle Determination or Identification

Using Equations 10 and 11 the predicted propagation delay, $t_p = 6456\ \mu s$, and

$$\tau_1 = \frac{1}{f_1} = \frac{1}{13100} = 76.336\ \mu s$$

$$\tau_2 = \frac{1}{f_2} = \frac{1}{12850} = 77.821\ \mu s$$

and noting, within the first ambiguity period (τ_a), that n = 0, k = 5, τ_b = 4000 μs and $\tau_a = k\tau_b$ = 20,000 μs we obtain

$$n_1 = 84.574 - \Delta n_1 + \frac{\Delta t}{\tau_1}$$

$$n_2 = 82.960 - \Delta n_2 + \frac{\Delta t}{\tau_2}$$

If t_p cannot be calculated (predicted) it must be measured via a portable clock. Since n is assumed as a priori knowledge of the position of the local clock site (receiving site) relative to the transmitter clock site, n_1 and n_2 can be calculated from Δn_1 and Δn_2 which are measured quantities.

For Δt less than 5μs, the error contributed to cycle determination for neglecting Δt is only 0.06 cycle. In the sample calculations given in Tables 2 and 3, Δt is neglected. However, Δt can be calculated from $t_p + \Delta t$ using the carrier cycle determined by Equations 8 and 9. If the propagation delay anomaly at 1200 EDT can be considered as negligible then $\Delta t_p = 0$ and $\Delta t = \Delta t_c$. The calculated time difference between the clocks at the transmitter and the receiving site is plotted in Figure 13.

Experimental Results

Using the specially designed OMEGA Timing Receiver and the predicted or measured propagation delays from North Dakota OMEGA station to the four sites where the experiments of clock synchronization had been conducted, we obtained the carrier cycle numbers for f_1 = 13.10 kHz and f_2 = 12.85 kHz given in Table 4. Δn_1 and Δn_2 are the mean of the measured phase differences in units of cycles with $\Delta t = 0$. The mean is usually taken from daily measurements at a fixed time for up to seven days except for GSFC. The mean for GSFC is obtained from 25 daily measurements as shown in Table 2.

Diurnal Phase Records

The diurnal phase of the North Dakota transmitted signals, as received at several sites, were recorded. The seasonal variation of the diurnal phase change can be observed from the series of phase records shown on the following pages.

Table 2

Cycle Identification of OMEGA Signals from North Dakota to GSFC, Greenbelt, Maryland at 1200 EDT in June and July 1973

Date	Measured			Cycle Det.			$t_p + \Delta t$ (μs)			Δt (μs)
	Δn_1	Δn_2	Δn_{12}	$n_1 - n_2$	n_1	n_2	$(n_1 + \Delta n_1)\tau_1$	$(n_2 + \Delta n_2)\tau_2$	Mean	
June 22, 1973	0.595	0.968	0.373	1.987	83.979	81.992	6458	6456	6457	1
23	0.594	0.968	0.374	1.986	83.980	81.992	6458	6456	6457	1
24	0.590	0.965	0.375	1.989	83.984	81.995	6458	6456	6457	1
25	0.588	0.960	0.372	1.986	83.986	82.000	6457	6456	6457	1
26	0.586	0.960	0.374	1.988	83.988	82.000	6457	6456	6457	1
27	0.588	0.965	0.377	1.991	83.986	81.995	6457	6456	6457	1
28	0.592	0.966	0.378	1.992	83.982	81.994	6458	6456	6457	1
29	0.587	0.958	0.371	1.985	83.987	82.002	6457	6456	6457	1
30	0.594	0.944	0.350	1.964	83.980	82.016	6458	6455	6457	1
July 1	0.590	0.952	0.372	1.986	83.984	82.008	6458	6455	6457	1
2	0.590	0.954	0.364	1.978	83.984	82.007	6458	6455	6457	1
3	0.586	0.952	0.366	1.980	83.988	82.008	6457	6455	6456	0
4	0.595	0.966	0.371	1.985	83.979	81.994	6457	6456	6457	1
5	0.614	0.932	0.318	1.932	83.960	82.028	6459	6454	6457	1
6	0.595	0.940	0.345	1.955	83.979	82.020	6458	6454	6456	0
7	0.595	0.965	0.370	1.984	83.979	81.995	6458	6456	6457	1
8	0.595	0.950	0.355	1.969	83.979	82.010	6458	6455	6457	1
9	0.586	0.963	0.377	1.991	83.978	81.997	6457	6456	6457	1
10	0.584	0.962	0.378	1.992	83.990	81.998	6457	6456	6457	1
11	0.586	0.963	0.377	1.991	83.988	81.997	6457	6456	6457	1
12	0.586	0.958	0.372	1.986	83.988	82.002	6457	6456	6457	1
13	0.582	0.958	0.376	1.990	83.992	82.002	6457	6456	6457	1
14	0.580	0.956	0.376	1.990	83.994	82.004	6457	6456	6457	1
15	0.575	0.954	0.379	1.993	83.999	82.004	6456	6455	6456	0
16	0.578	0.955	0.377	1.991	83.996	82.004	6457	6456	6457	1
Mean	0.589	0.957	0.368	1.982	83.985	82.003	6457	6456	6457	1
Cycle ID	–	–	–	2	84	82	–	–	–	–

Table 3

Cycle Determination of OMEGA Signals from North Dakota to GSFC Greenbelt, Maryland at 1200 EDT in September and October 1973

Date	Measured			Cycle Det.			$t_p + \Delta t$ (μs)			Δt (μs)
	Δn_1	Δn_2	Δn_{21}	$n_1 - n_2$	n_1	n_2	$(n_1 + \Delta n_1)\tau_1$	$(n_2 + \Delta n_2)\tau_2$	Mean	
Sept. 13, 1973	0.590	0.964	0.374	1.986	83.984	81.996	6457	6456	6457	1
14	0.595	0.972	0.377	1.991	83.979	81.988	6458	6457	6457	1
15	0.600	0.975	0.375	1.987	83.974	81.985	6458	6457	6457	1
16	0.594	0.962	0.362	1.976	83.960	81.998	6458	6457	6457	1
17	0.589	0.972	0.378	1.992	83.985	81.988	6457	6456	6457	1
18	0.590	0.966	0.377	1.991	83.984	81.994	6457	6456	6457	1
19	0.587	0.966	0.376	1.990	83.987	81.994	6457	6456	6457	1
20	0.590	0.965	0.378	1.992	83.984	81.995	6457	6456	6457	1
21	0.586	0.965	0.375	1.987	83.988	81.995	6457	6456	6457	1
22	0.590	0.966	0.380	1.994	83.984	81.994	6457	6456	6457	1
23	0.586	0.963	0.378	1.992	83.988	81.997	6457	6456	6457	1
24	0.585	0.970	0.386	2.000	83.989	81.990	6457	6457	6457	1
25	0.584	0.957	0.377	1.991	83.990	82.003	6457	6456	6456	0
26	0.580	0.956	0.376	1.990	83.994	82.004	6456	6456	6456	0
27	0.580	0.941	0.371	1.985	83.994	82.019	6456	6454	6455	-1
28	0.570	0.960	0.375	1.987	84.004	82.000	6456	6456	6456	0
29	0.585	0.957	0.375	1.987	83.989	82.003	6457	6456	6456	0
30	0.582	0.960	0.375	1.987	83.992	82.000	6457	6456	6456	0
Oct. 1, 1973	0.585	0.964	0.377	1.991	83.989	81.996	6457	6456	6456	0
2	0.587	0.955	0.375	1.991	83.987	82.005	6457	6456	6456	0
3	0.580	0.955	0.375	1.991	83.994	82.005	6456	6456	6456	0
4	0.580	0.942	0.374	1.988	83.994	82.018	6456	6455	6455	-1
5	0.568	0.953	0.375	1.991	84.006	82.007	6456	6455	6455	-1
6	0.578	0.955	0.376	1.990	83.996	82.005	6456	6456	6456	-1
7	0.579	0.952	0.376	1.990	83.995	82.008	6456	6455	6455	-1
8	0.576	0.952	0.376	1.990	83.998	82.008	6456	6455	6455	-1
Mean	0.585	0.959	0.374	1.988	83.989	82.001	6457	6456	6456	0
Cycle ID	–	–	–	2	84	82	–	–	–	–

Table 4

Preliminary Results of Propagation Delay Measurement Using OMEGA North Dakota Transmissions and Known Local Clock Time

LOCATION	MEASURED				PREDICTED
	$n_1+\Delta n_1$ (cycles)	$n_2+\Delta n_2$ (cycles)	$(n_1+\Delta n_1)\tau_1$ (μs)	$(n_2+\Delta n_2)\tau_2$ (μs)	t_p (μs)
NELC, SAN DIEGO, CA.	96.795	94.924	7388.9	7387.1	7388
GSFC, GREENBELT, MD.	84.589	82.957	6457.1	6455.8	6456
USNO, WASHINGTON DC	84.100	82.488	6419.8	6419.3	6420
STDN, ROSMAN, N.C.	78.561	77.056	5997.0	5996.6	5995

Figure 4 shows a daytime phase record of 12.85 kHz transmitted from North Dakota to Goddard Space Flight Center (GSFC) during mid June 1973. The diurnal phase change during sunrise goes from 0.33 cycles to 0.05 cycles (26.14 μs to 3.9 μs) and sunset goes from 0.05 cycles (3.9 μs) to 0.33 cycles (26. 14 μs), or a total diurnal change of 0.28 cycles (3.4 μs). The daytime phase record has a resolution of $\pm$0.001 cycles ($\pm$0.078 μs) and is stable from 1100 to 0100 GMT or for about 14 hours.

Figure 5 shows typical daytime seasonal changes of the diurnal phase records of the VLF signals for the North Dakota to GSFC path for mid-June, July, August, September, October, November through mid-December 1973. The useable daytime phase record decreases from about 14 hours in June to less than seven hours in December.

Figure 6 shows typical nighttime diurnal phase records for the 13.10 and 12.85 kHz signals transmitted from North Dakota to GSFC during mid months of June through December (excluding July and August). The nighttime phase variations are between 0.3 and 0.4 cycles and useable to within $\pm$0.05 cycles ($\pm$3.5 μs). The length of the nighttime phase record increases from about 10 hours during the summer months (minimum in June) to 15 hours during the winter months (maximum in December). The nighttime phase variations remain

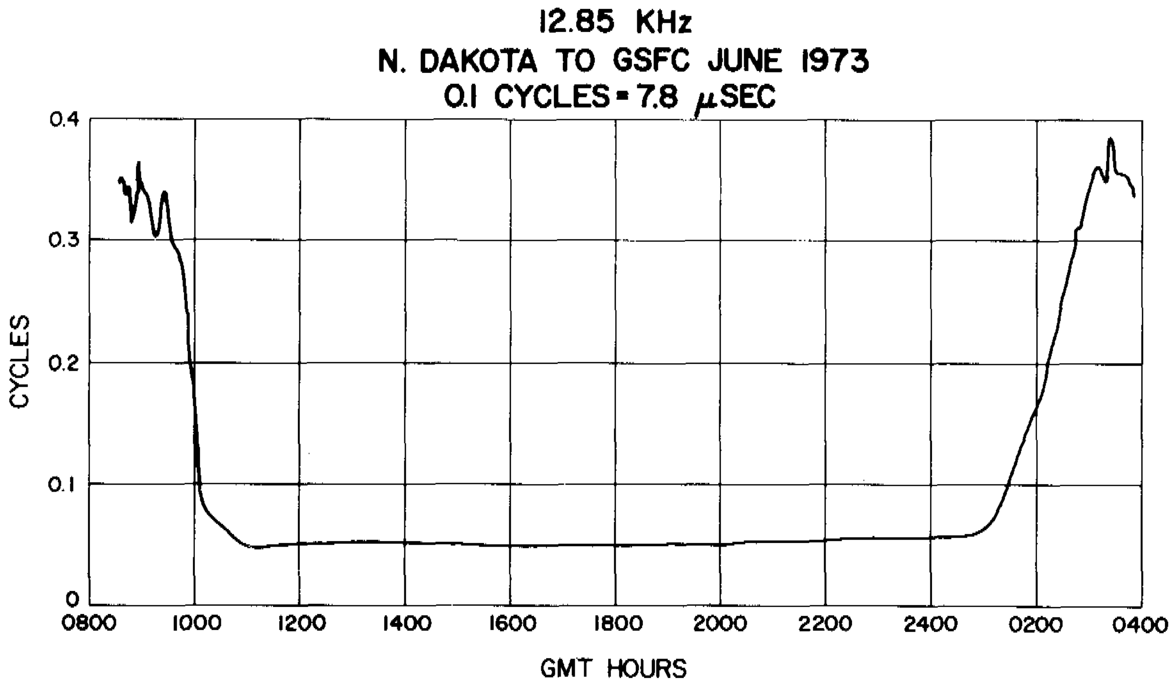


Figure 4.

fairly constant for the six months (between 0.3 and 0.4 cycles). Figure 7 is a typical phase record of the path for the 12.85 kHz signal between N. Dakota and the NASA tracking station at Rosman, N. C. for mid-November 1973. Figures 8 and 9 show the diurnal phase record for the VLF signal from North Dakota to USNO and NELC California, respectively. Typical modal interference effects during sunset for west to east propagation was observed between 2100 and 0100 GMT.

Figure 10 shows simultaneous observations of phase perturbations caused by Sudden Ionospheric Disturbances (SID's) on the 12.85 kHz and 13.1 kHz signals on September 27, 1973. The first SID occurs at about 1615 GMT and decays very slowly lasting for about five hours. The second SID occurs at 2230 and lasts into the evening diurnal. The phase record is readable to within an accuracy of about 0.025 cycles (2 μs) throughout the effects of the first SID.

Figure 11a shows a small SID occurring at 1530 GMT and lasting until 1730 GMT.

Figure 11b shows a large SID occurring at 1400 GMT and lasting beyond 1600 GMT.

Figure 12a shows two SID's occurring within three hours of each other, the first at 1600 GMT and the second at 1900 GMT. The phase record for the day is not useable to better than 0.05 cycles (4 μs).

Figure 12b shows a small SID occurring at 1650 GMT and recovering rather rapidly at 1800 GMT.

CONCLUSIONS

Based on the results obtained at GSFC (Figure 13), Rosman, and USNO, it can be said that the dual frequency time transmission technique has provided a capability of time synchronization of remote laboratory clocks to an accuracy of ± 1 microsecond if daytime transmissions are used and less than an order of magnitude of degradation if nighttime transmissions are used. It is not certain if the same results can be realized if longer propagation paths are used. Plans have been made to conduct longer path length experiments at Grand Canary Island and Canberra, Australia during 1974. These results will be given in future reports.

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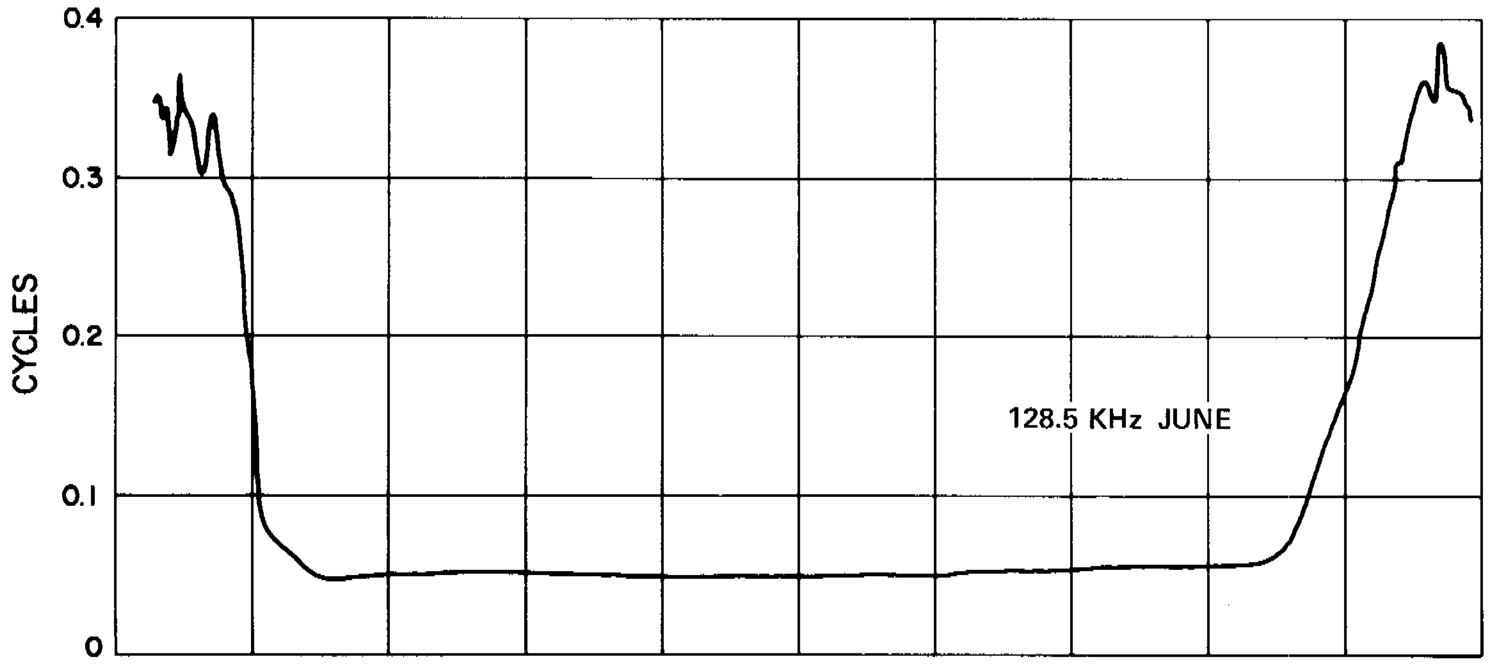
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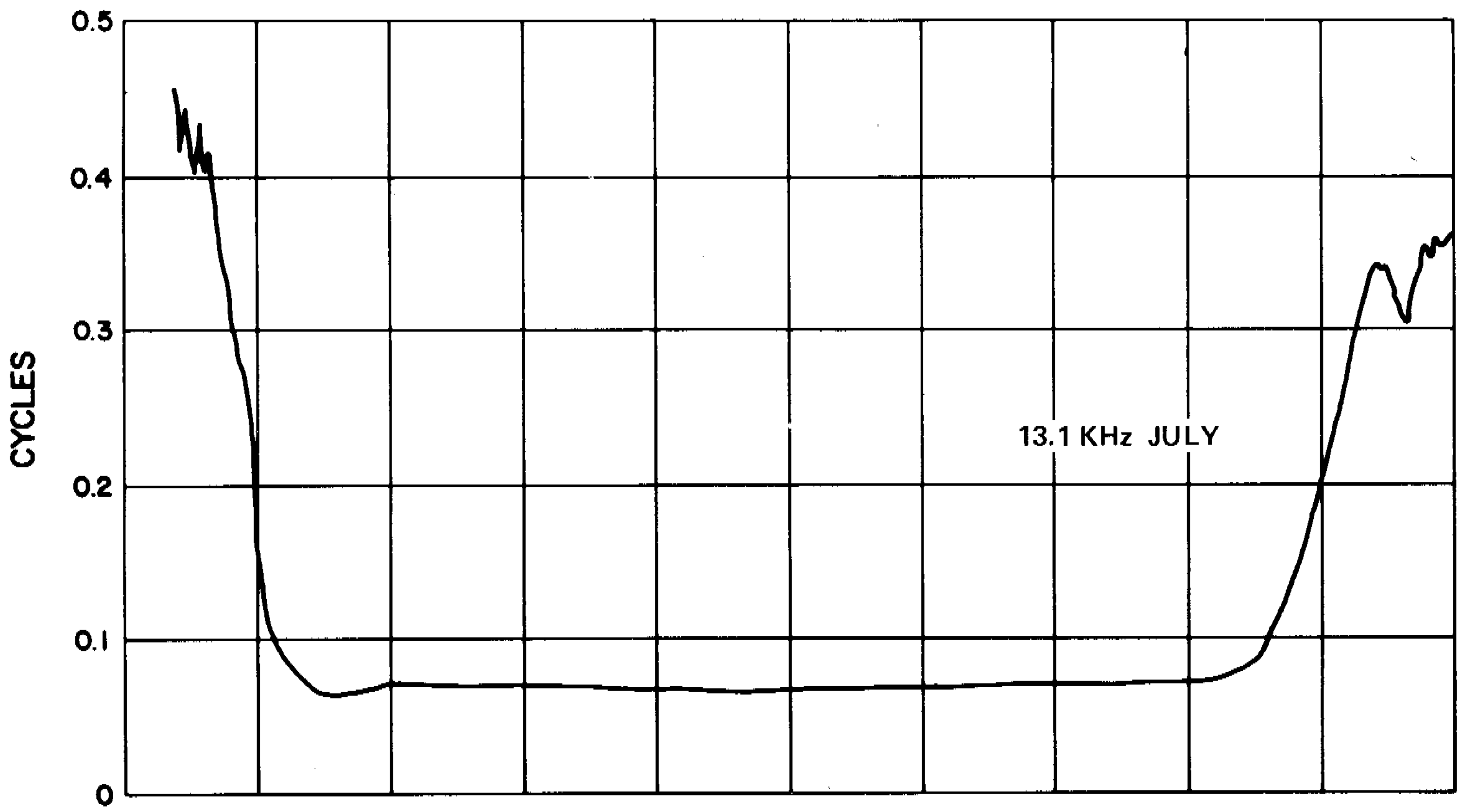
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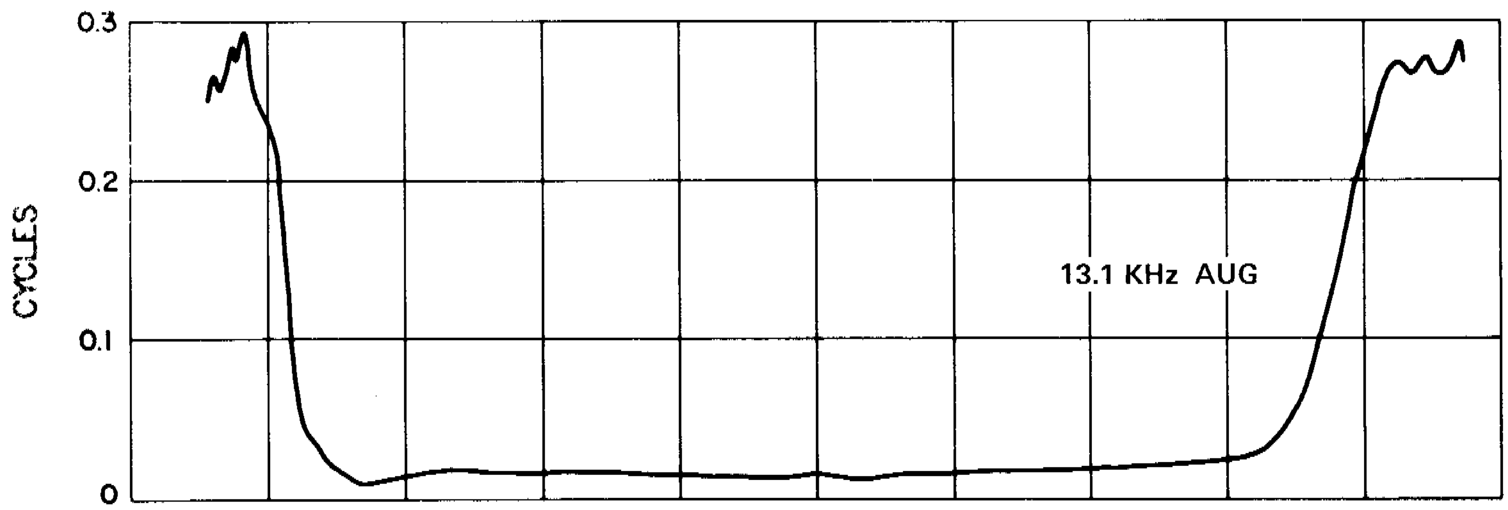
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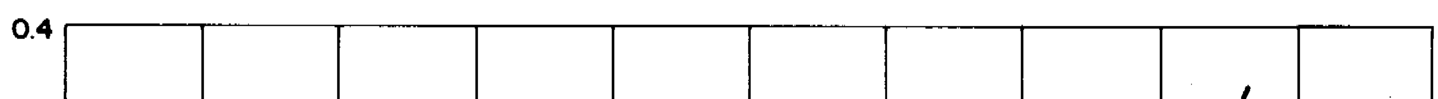
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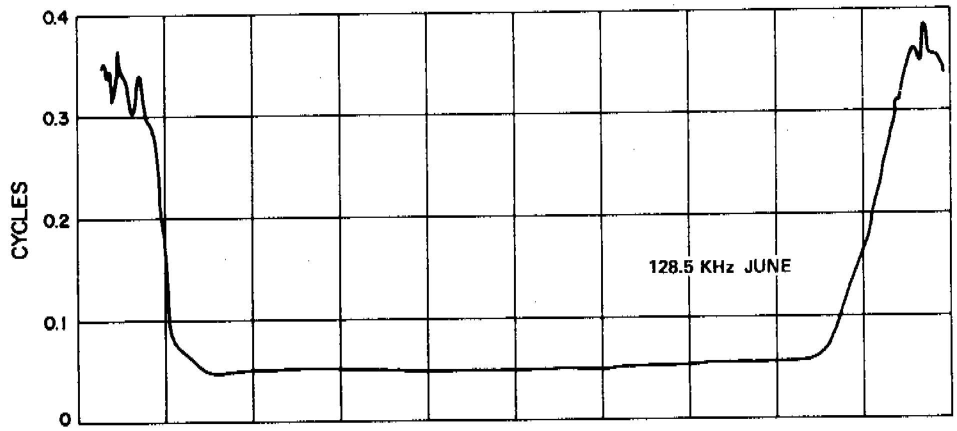
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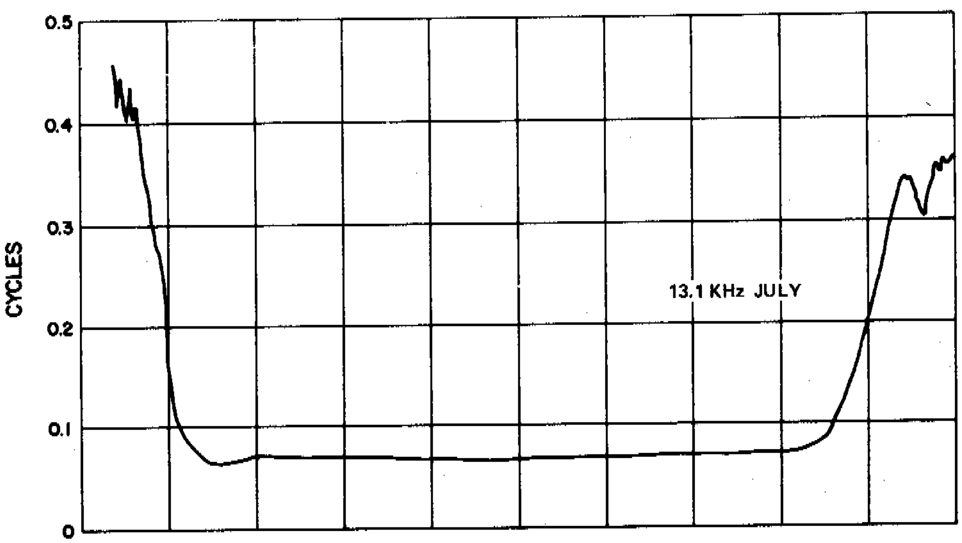
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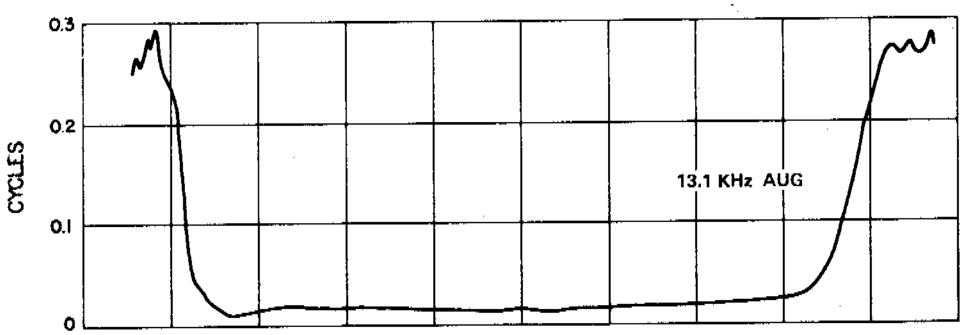
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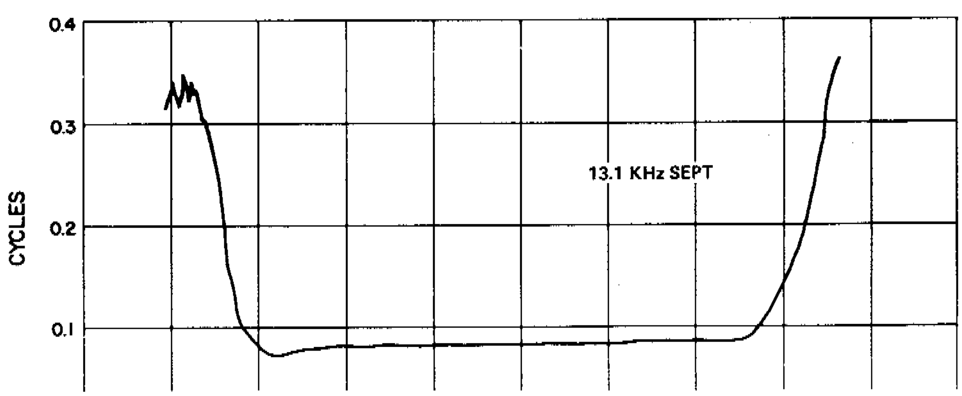
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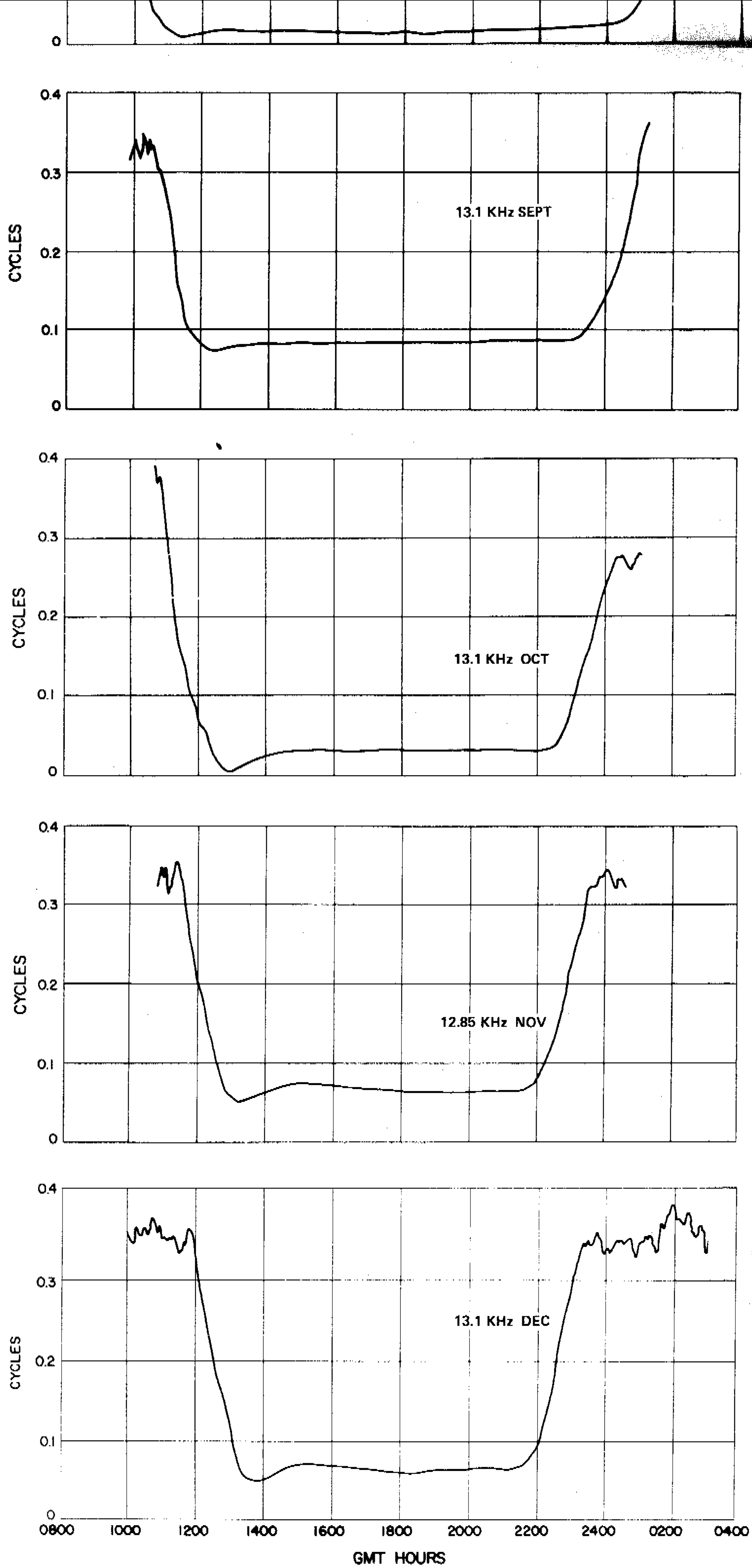


Figure 5. Daytime Seasonal Variations of the Omega Signals from North Dakota to Greenbelt, Maryland (GSFC), June through December 1973

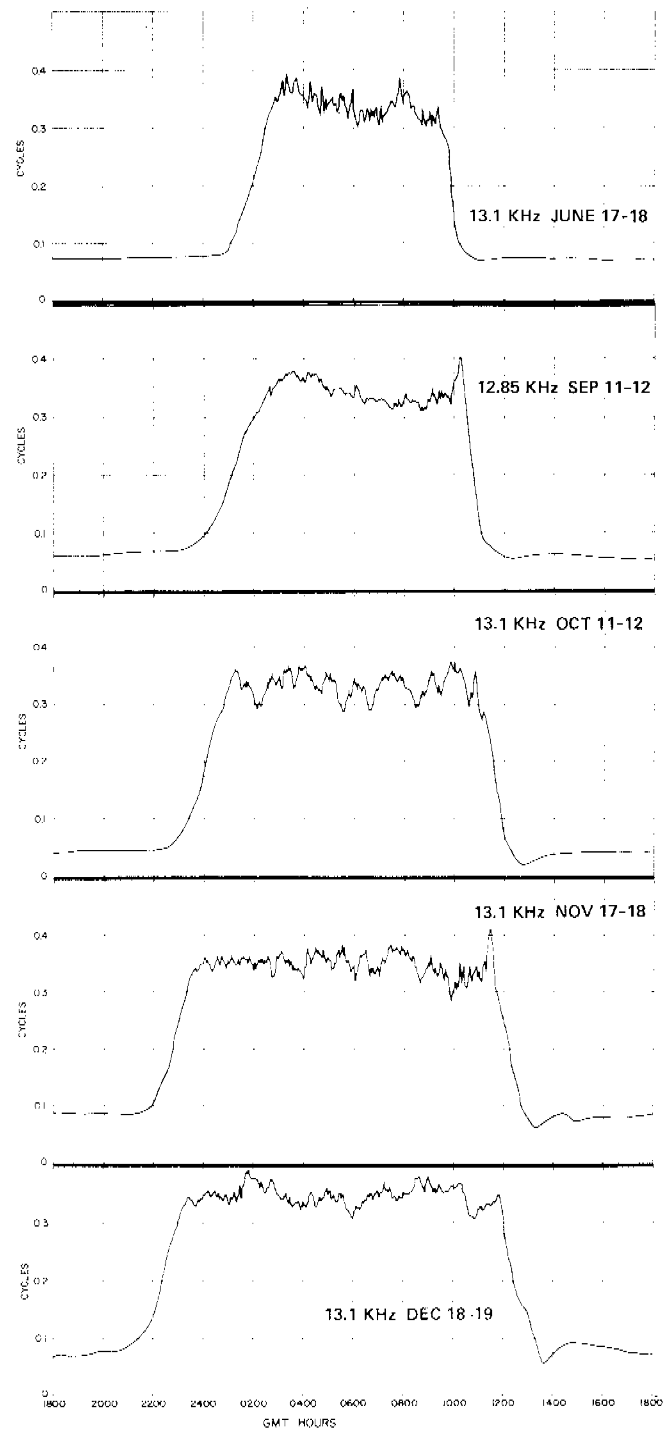
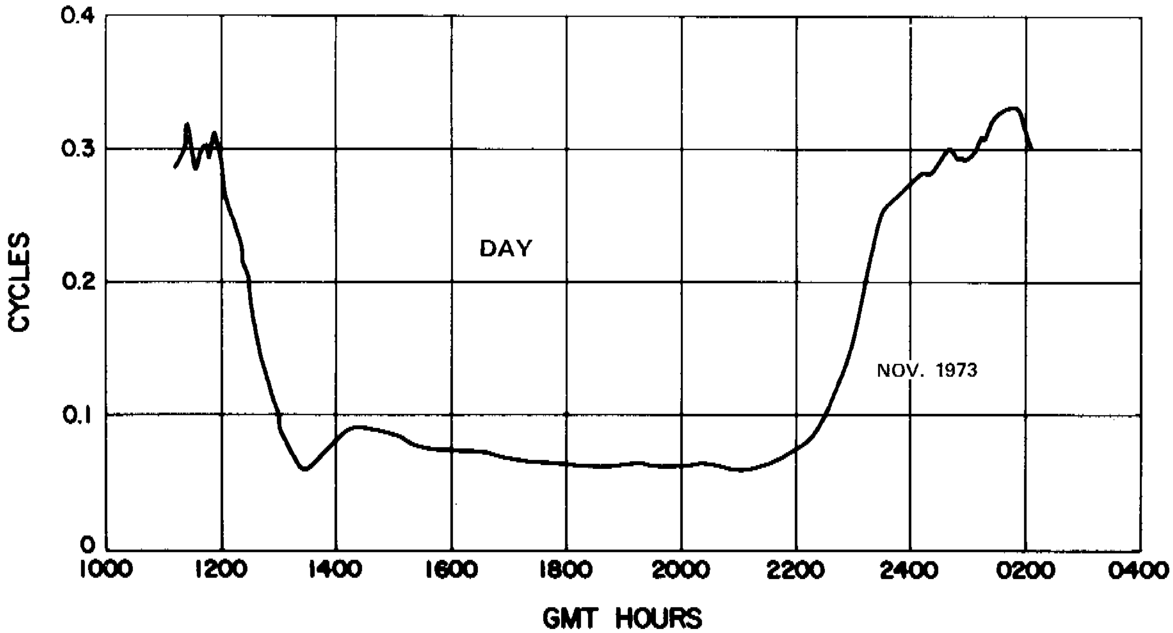


Figure 6. Nighttime Seasonal Variation of the Omega Signals from North Dakota to Greenbelt, Maryland (GSFC), June through December (July and August excluded) 1973



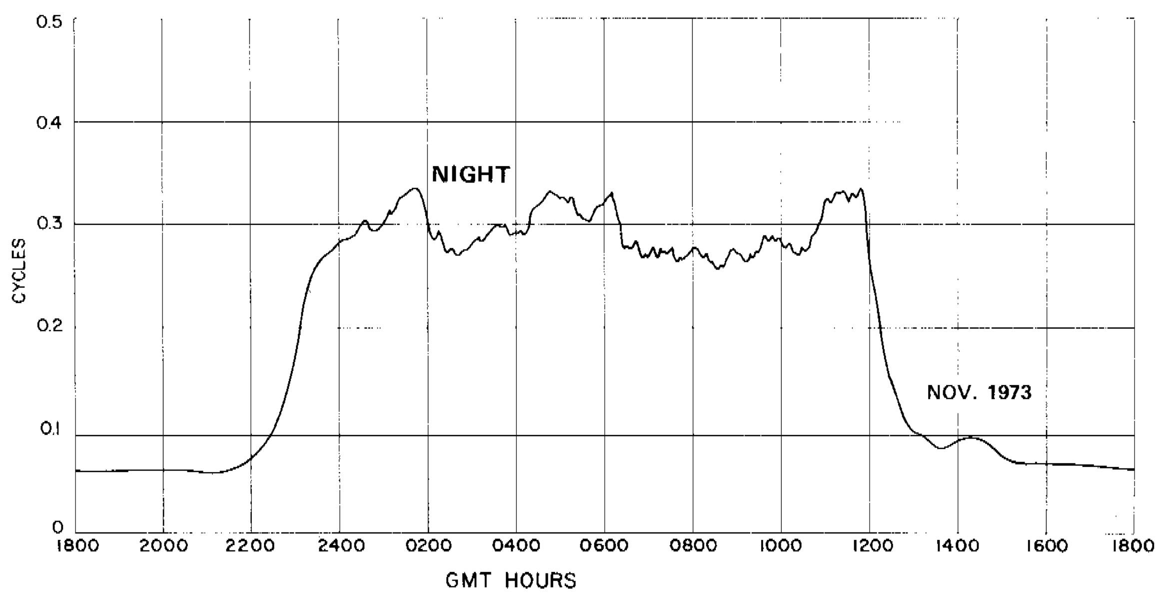


Figure 7. 12.85 KHz Signal from N. Dakota to Rosman, N.C.

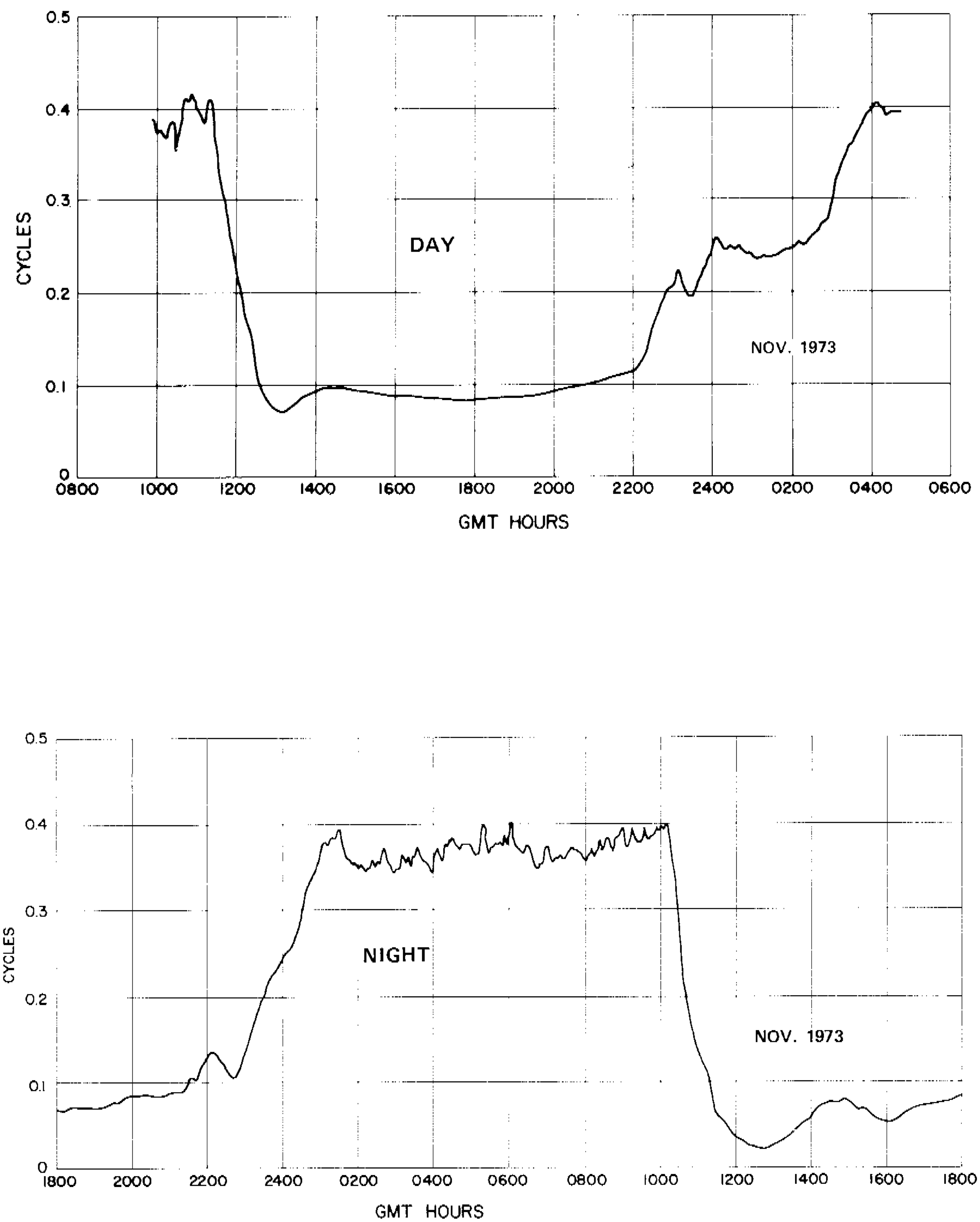


Figure 8. 12.85 KHz Signal from N. Dakota to USNO, Washington, D.C.

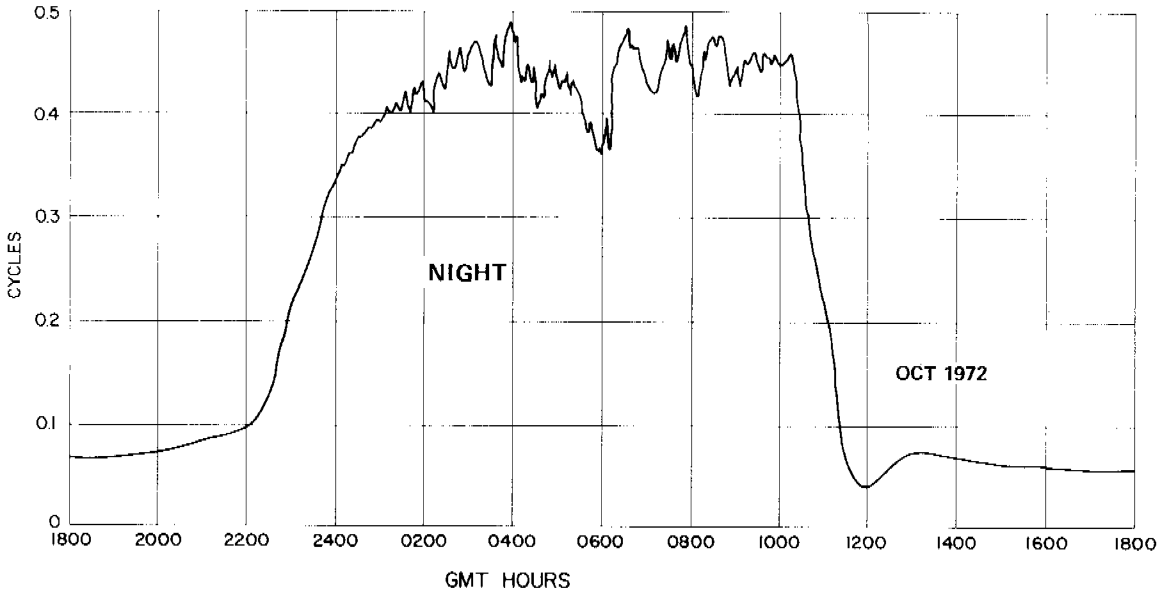


Figure 9. 13.1 KHz Signal from N. Dakota to NELC, San Diego, Ca.

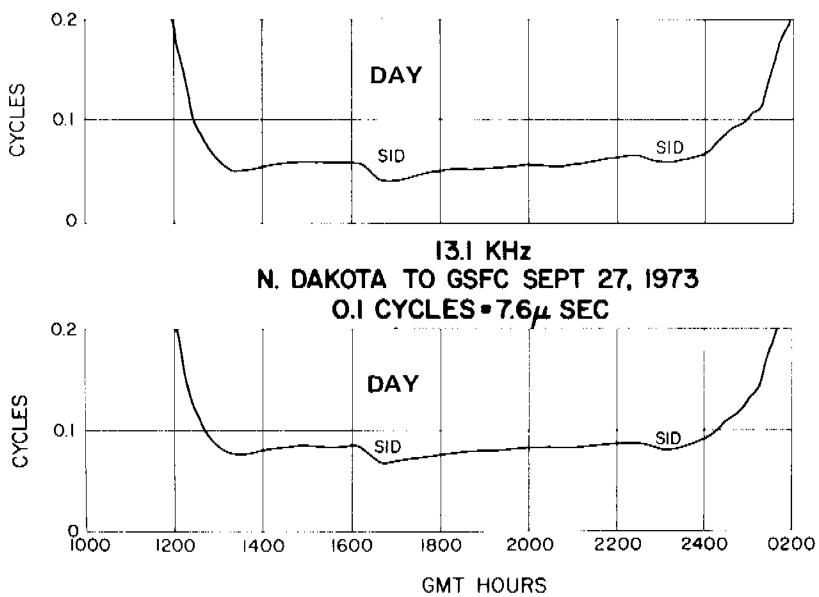


Figure 10. 12.85 KHz Signal from N. Dakota to GSFC, Greenbelt, Maryland

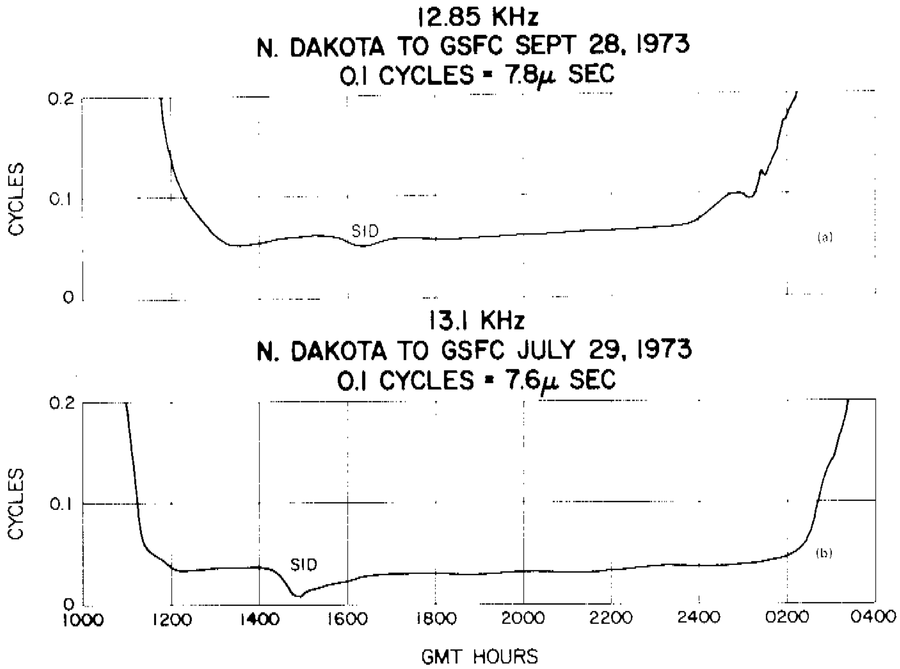


Figure 11.

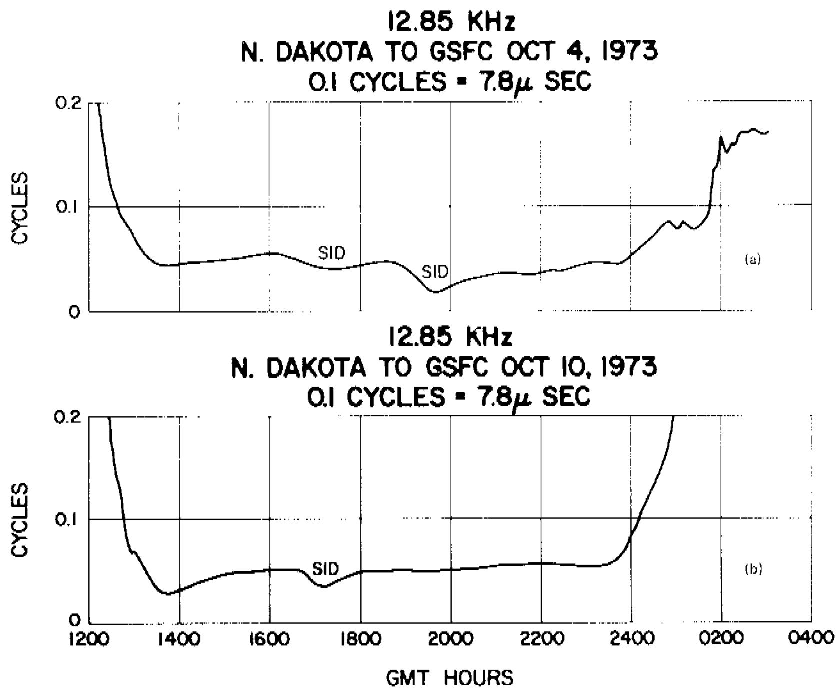
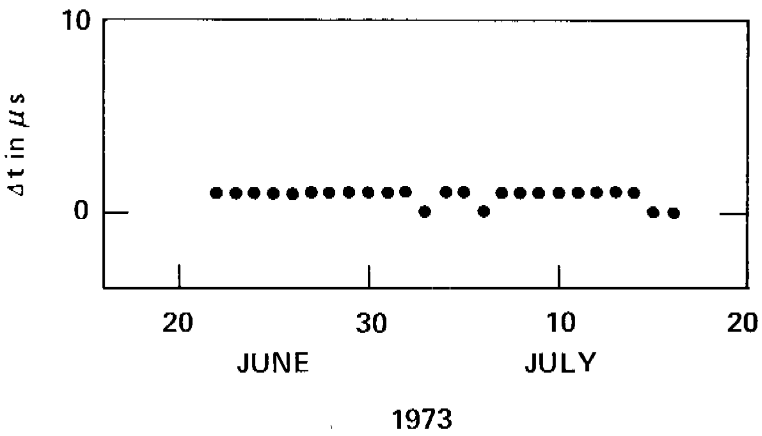


Figure 12.



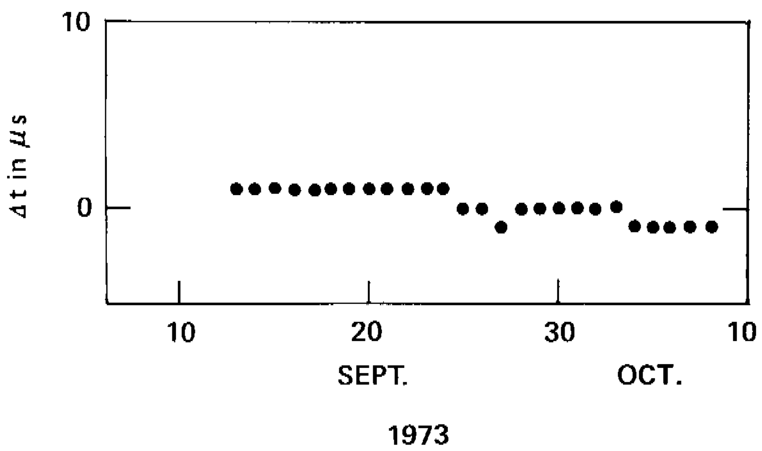


Figure 13. Time Comparison Made at 1200 EDT Between Received Omega North Dakota Time Transmission and GSFC Clock at Greenbelt, Maryland, ($t_p = 6456\ \mu s$)

QUESTION AND ANSWER PERIOD

DR. REDER:

Any questions, please? Dr. Winkler.

DR. WINKLER:

I wonder about an apparent discrepancy. You first said that we didn't have any propagation delay problem between the Observatory and North Dakota, but I have seen in your last slide a comparison between the predicted delay and measured. Could you elaborate on that?

MR. CHI:

Well, first, in the absence of a known clock difference, there could be a fixed bias. All our clocks are referenced to your clocks.

DR. WINKLER:

Okay. That brings me exactly to the main point that I am going to make.

Yesterday, and this morning, I did not share Dr. Smith's concern about the problems in using the Loran system for absolute measurements, because I feel that one can live with a relative system which is checked every half year, maybe, by portable clock measurement.

Today, however, in the Omega system, the problems are about ten times larger.

What we are concerned with is the difference between relative day to day, or week to week measurements, and the possibility to recover your epoch if you have lost it, with some confidence.

I think for that, the system is probably good enough to one or two microseconds, or maybe three, if you are careful in taking seasonal effects into account.

But when it comes to starting from scratch, and to come to a new location and to use a precomputed propagation delay, I think you will find you will often have discrepancies in the order of 20 and more microseconds, particularly in distances across the Continental United States, where you cannot ignore higher mode propagation and where you really have a very hard time to predict, without prior calibration with portable clock visits, a propagation delay.

At the moment, we do have discrepancy. I have received predictions from NELC, and they do not at all check with our measurements. We will have to send a portable clock to resolve it.

So, again, we have the difference between relative measurements and epoch recovery capability, versus absolute timing.

MR. CHI:

Well, I would like to make a few comments. One is that so far as the relative time, clock time of North Dakota relative to the U.S.N.O., is concerned, we have made the request to send a portable clock to North Dakota. As a matter of fact, my request was to measure that at an interval of six months, so we will know what it is.

The second comment I have is this, the system is not in any way competing with Loran-C, in that this is a system which will be good for microsecond, up to maybe 100 microseconds.

Certainly, it will be better once you determine the cycle. It is much better than one period, which is 77 microseconds.

So, most likely, if you use 24 hour time to determine, to recapture the time difference, you can do it to 10 microseconds. If you do it with care using the daytime phase record, you should be able to achieve or obtain one microsecond.

Now, the advantage of this is the fact that it is a VLF signal — the signal propagates much further than Loran-C, and stability of the phase record is well known that I do not have to impress on you how good it is.

Anyone who has used VLF will know that the distance coverage is much greater than Loran-C. In that respect, you have some gain, perhaps maybe for your coarse time for one microsecond, and use Loran-C to obtain the 10th of a microsecond or better.

So, they are complimentary systems.

DR. REDER:

Before I ask for the next question, I have one comment to Dr. Winkler's remarks. I would be more concerned with the short distances than with the long distances. There is no second order mode on Omega over long distances, but over short distances, from Washington to North Dakota, for instance, there is a possibility.

DR. WINKLER:

Exactly.

DR. REDER:

Another remark. I will come to you in a moment, I was thinking of you, Eric. One more remark to Andy's paper, and that is there are no SIDs at night. However, particularly North Dakota is quite susceptible to electron precipitation because of its location. Therefore, what you see at night is partially mode interference and the effects of electrons.

MR. SWANSON:

First, I should state that some of these more recent numbers I personally haven't looked into in detail since the measurements have been made. So, it is possible there is some, perhaps, epoch bias at the present time in North Dakota.

Ordinarily, one wouldn't expect this to happen. It might easily be off by a few microseconds, but anything much beyond that, I suspect not.

In any event, the predictions made here do include allowance for model structure, as well as our general estimate for the phase.

I will certainly admit, and I believe Andy has made it clear, too, that these are just four preliminary checks. They are certainly not exhaustive test programs.

Nonetheless, the four checks that have been made so far, show that the system is working, and in fact, it works on an absolute basis to a matter of a few microseconds.

DR. REDER:

Any other questions?