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RECENT FIELD TEST RESULTS USING OMEGA TRANSMISSIONS FOR CLOCK SYNCHRONIZATION

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ABSTRACT

This paper presents the results of clock synchronization experiments using OMEGA transmissions from North Dakota on 13.10 kHz and 12.85 kHz. The OMEGA transmissions were monitored during April 1974 from NASA tracking sites located at Madrid, Spain; Canary Island; and Winkfield, England. The sites are located at distances between 6600 kilometers (22,100 μs) to 7300 kilometers (24,400 μs) from North Dakota.

The data shows that cycle identification of the received signals was accomplished. There are, however, discrepancies between the measured and calculated propagation delay values which have not been explained, but seem to increase with distance between the receiver and the transmitter. The data also indicates that three strategically located OMEGA transmitting stations may be adequate to provide worldwide coverage for clock synchronization to within ± two (2) microseconds.

INTRODUCTION

The field tests were conducted from April 1 through April 22, 1974. The objectives of these tests were to determine the adequacy of unique OMEGA transmissions for time determination at distances greater than 6000 km from the transmitter and to collect experimental data that would indicate the minimum number of sites, appropriately located, required for worldwide clock synchronization to within ±2 μs.

Receiving transmissions from the OMEGA North Dakota (N.D.) station, data were collected at Madrid, Spain (7185 km); Canary Island (7298 km); and Winkfield, England (6626 km). Previous test results conducted at Greenbelt, Md. (1934 km); Washington, D.C. (1922 km) and Rosman, N.C. (1794 km) were reported at the 1973 PTTI Meeting.[1] Further tests will be conducted during September-October 1975 at Hawaii and Australia.[2] Transmissions from OMEGA stations N.D. and Hawaii will be used. Transmissions from OMEGA N.D. will be monitored at Kauai, Hawaii (5926 km) and from both N.D. and Hawaii will be monitored at Orroral, Australia (14,408 km and 8443 km respectively from the transmitters).

The use of the OMEGA system for time transmission not only will augment existing systems such as Loran-C by providing an additional capability in the northern hemisphere, but would also provide coverage in the southern hemisphere where Loran-C transmitters do not exist and time synchronization is limited to within ±25 μs.

PROPAGATION DELAY MEASUREMENT

If the phase velocities for two VLF signals (f_1 and f_2) are v_1 and v_2 respectively, then the propagation delays for a path length D are:

$$t_{p_1} = \frac{D}{v_1} \tag{1}$$

and

$$t_{p_2} = \frac{D}{v_2} \tag{2}$$

Since the two signals were emitted in phase at time t_{xm} at the transmitter, the signals as received at a station at time t_{rv} relative to the station clock must satisfy the following conditions(3):

$$t_{xm} - t_{rv_1} = t_{p_1}^m = n\tau_a + (n_1 + \Delta n_1)\tau_1 \tag{3}$$

$$t_{xm} - t_{rv_2} = t_{p_2}^m = n\tau_a + (n_2 + \Delta n_2)\tau_2 \tag{4}$$

where t_{rv_1} and t_{rv_2} are the time of signal reception of f_1 and f_2 relative to the receiving station clock, and $t_{p_1}^m$ and $t_{p_2}^m$ are measured propagation delay values. The received cycle of each carrier, n_1 and n_2 is determined from the phase measurements Δn_1 and Δn_2.

The ambiguity identification of n for τ_a (20 milliseconds) is considered a priori knowledge or determined from the theoretical predicted propagation delay (see table 1) which is in error by much less than 4 milliseconds. The receiver design actually requires the ambiguity resolution to 4 milliseconds (see cycle identification p. 193 and reference 2).

Equations (3) and (4) can be used to calculate the measured propagation delay if the receiving station clock time is known relative to the transmitter clock. Having measured the propagation delays via portable clock, the received VLF signals can be used to synchronize a receiving station clock.

Table 1

Ambiguity Identification of n from Predicted Propagation Delays

NASA Tracking Sites	Predicted Delay (μs)		Ambiguity Determination	
	t_{p_1} (13.10 kHz)	t_{p_2} (12.85 kHz)	n	$n\tau_a$ (μs)
Madrid	23,974.8	23,972.1	1	20,000
Canary Island	24,346.3	24,343.5	1	20,000
Winkfield	22,113.0	22,110.5	1	20,000

EXPERIMENTAL DATA AND PROCESSING

VLF phase data at each station visited were recorded in both analog and digital form as shown in Figure 1. The analog data was replotted for the 13.1 and 12.85 kHz signals to demonstrate the diurnal phase signature for each station as shown in Figures 2, 3, and 4 (solid line). The predicted phase data furnished by C. P. Kugel of the Naval Electronics Laboratory Center (NELC) is the dotted curve. It can be seen from these figures that the agreement between the observed and predicted phase is rather good.

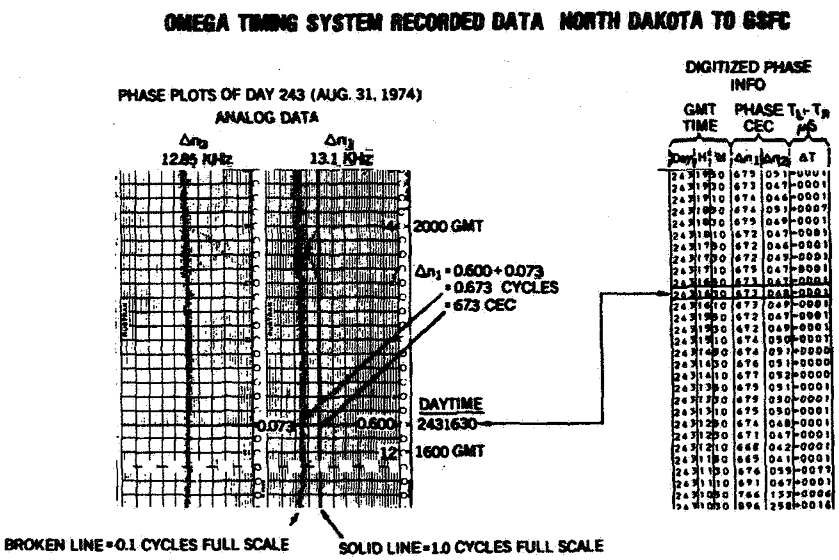
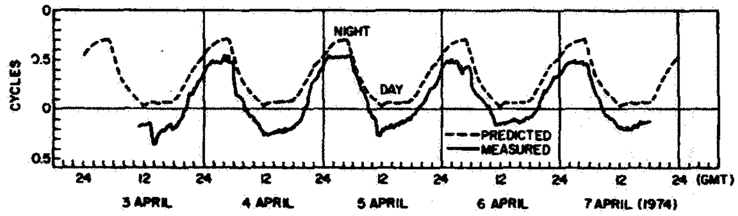
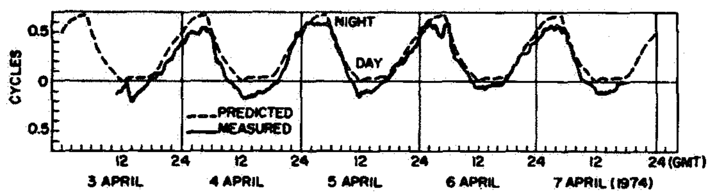


Figure 1. VLF signal phase data as recorded by the OMEGA Timing Receiver in analog (left) and digital (right) form.

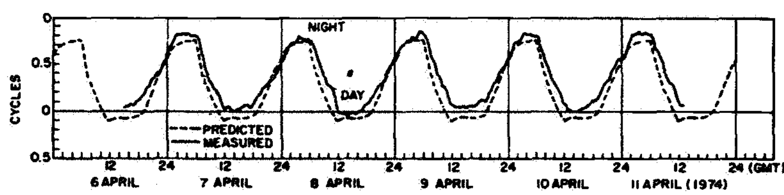


MEASURED AND PREDICTED DIURNAL PHASE OF
13.1 KHz OMEGA N. DAKOTA TO MADRID, SPAIN

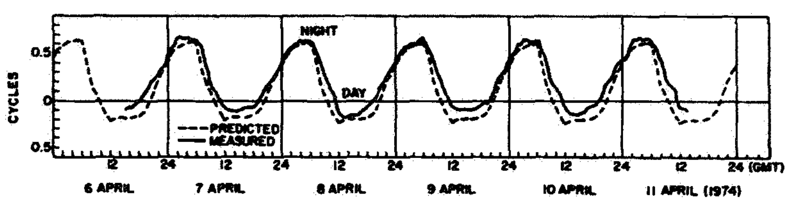


MEASURED AND PREDICTED DIURNAL PHASE OF
12.85KHz OMEGA N.DAKOTA TO MADRID, SPAIN

Figure 2. Diurnal phase records of OMEGA North Dakota transmitted signals as received at Madrid, Spain on April 3 to 7, 1974.

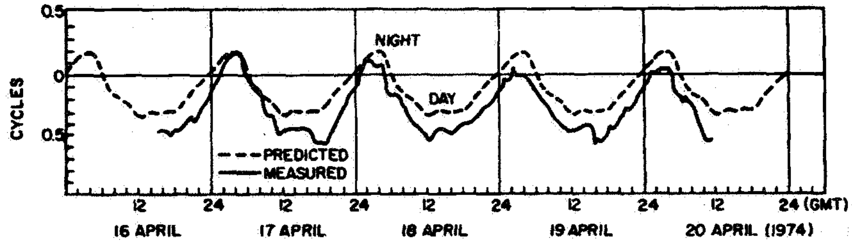


MEASURED AND PREDICTED DIURNAL PHASE OF
13.1 KHz OMEGA N.DAKOTA TO CANARY ISLAND, SPAIN

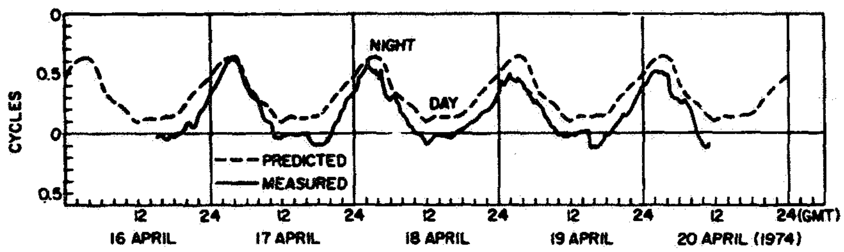


MEASURED AND PREDICTED DIURNAL PHASE OF
12.85 KHz OMEGA N. DAKOTA TO CANARY ISLAND, SPAIN

Figure 3. Diurnal phase records of OMEGA North Dakota transmitted signals as received at Canary Island, Spain on April 6 to 11, 1974.



MEASURED AND PREDICTED DIURNAL PHASE OF
13.1 KHz OMEGA N. DAKOTA TO WINKFIELD, ENGLAND



MEASURED AND PREDICTED DIURNAL PHASE OF
12.85 KHz OMEGA N. DAKOTA TO WINKFIELD, ENGLAND

Figure 4. Diurnal phase records of OMEGA North Dakota transmitted signals as received at Winkfield, England on April 16 to 20, 1974.

The digital data were grouped in time periods according to the diurnal phase record. This was done by taking the average of the data points obtained over 15 or 20 minute intervals during the periods of sunrise, daytime, sunset, and nighttime (see table 2). Due to local interference problem in Madrid, only phase record during the daytime transmission period were collected.

With reference to the results given in table 3, Δn_1 is the phase difference of the received signal (13.10 kHz) relative to the station clock and similarly for Δn_2 (12.85 kHz). The difference of the two received signal phases is given as Δn_{12} which is $\Delta n_1 - \Delta n_2$.

CYCLE DETERMINATION

Combining equations (3) and (4):

$$\Delta t_p \equiv \Delta t_p^m = t_{p_1}^m - t_{p_2}^m = (n_1 + \Delta n_1)\tau_1 - (n_2 + \Delta n_2)\tau_2 . \tag{5}$$

Let:

$$m = n_1 - n_2$$

$$\Delta\tau = \tau_1 - \tau_2$$

Table 2

Time of Day (GMT) When Data Were Collected

Time of Day	Madrid*	Canary Island**	Winkfield**
Sunrise	—	0630 - 1050	0510 - 1150
Day	1100 - 1800	1110 - 1810	1210 - 1650
Sunset	—	1830 - 0250	1710 - 2350
Night	—	0310 - 0610	0010 - 0450

*Data was collected at 15 minute intervals.
**Data was collected at 20 minute intervals.

Table 3

Average of Measured VLF Signal Phase in April 1974

Averaging Period	Madrid (April 4-7)		Canary Island (April 6-11)		Winkfield (April 16-19)	
	Δn_1	Δn_{12}	Δn_1	Δn_{12}	Δn_1	Δn_{12}
Sunrise	—	—	—	.140	—	.557
Day	.825	.899	.063	.141	.508	.556
Sunset	—	—	—	.136	—	.554
Night	—	—	.808	.164	.999	.556

$$\tau_b = \frac{\tau_1 \tau_2}{\tau_2 - \tau_1} = -\frac{\tau_1 \tau_2}{\Delta\tau}$$

and

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

then equation (5) becomes:

$$\Delta t_p^m = (n_1 + \Delta n_1)(\tau_2 + \Delta\tau) - (n_2 + \Delta n_2)\tau_2$$

$$= (n_1 - n_2 + \Delta n_1 - \Delta n_2)\tau_2 + (n_1 + \Delta n_1)\Delta\tau$$

$$\therefore \Delta t_p^m = (m + \Delta n_{12})\tau_2 + (n_1 + \Delta n_1)\Delta\tau \tag{6}$$

Rewriting equation (6):

$$n_1 + \Delta n_1 = -(m + \Delta n_{12})\frac{\tau_2}{\Delta\tau} + \frac{\Delta t_p^m}{\Delta\tau}$$

$$= (m + \Delta n_{12})\frac{\tau_b}{\tau_1} - \frac{\Delta t_p^m}{\tau_2 - \tau_1} \tag{7}$$

Similarly:

$$n_2 + \Delta n_2 = (m + \Delta n_{12})\frac{\tau_b}{\tau_2} - \frac{\Delta t_p^m}{\tau_2 - \tau_1} \tag{8}$$

Either equation (7) or (8) can be used to determine the received carrier cycle of either f_1 or f_2 respectively. This is so because Δn_1, Δn_2 and Δn_{12} are measured quantities; m is the highest integer multiple of the beat frequency period within the propagation delay value between the transmitter and the receiving station. Values of (n) and (m) are therefore known. The values of (n) and (m) used for the stations visited in 1973 and 1974 are given in table 4.

The particular cycle of a carrier signal received at a station as calculated from equation (7) or (8) is found by assuming a parametric value for Δt_p^m, i.e., $\Delta t_p^m = 0$, 1, 2, 3, 4, etc. μs. After $n_1 + \Delta n_1$ has been calculated, the value is rounded to an integer by the following rule:

(a) Round $n_1 + \Delta n_1$ downward to n_1, if

$\Delta n_1 \leq 0.44546 \rightarrow 0.4455 \rightarrow 0.446 \rightarrow 0.45 \rightarrow 0.4 \rightarrow 0$

(b) Round $n_1 + \Delta n_1$ upward to $n_1 + 1$, if

$\Delta n_1 \geq 0.54546 \rightarrow 0.5455 \rightarrow 0.546 \rightarrow 0.55 \rightarrow 0.6 \rightarrow 1$

The 0.1 cycle difference, between the upper bound of one cycle, n_1, (0.44546) and lower bound of another cycle, $n_1 + 1$, (0.54646), is the wall thickness of the cycle well. This is the same as saying that 90% of the data is grouped correctly into a particular cycle and 10% of the data is grouped into either one cycle high or one cycle low.

Table 4

(n) and (m) Values Used for Cycle Determination
for OMEGA North Dakota and NASA Tracking Stations

Station	Predicted Propagation Delay (μs)	Ambiguity Reduction		
		n	m	Predicted Propagation Delay (μs)
Rosman, N.C.	5994	0	1	1994
USNO, Wash., D.C.	6421	0	1	2421
GSFC, Md.	5458	0	1	1458
NELC, Ca.	7388	0	1	3388
Winkfield	22113	1	0	2113
Madrid	23974	1	0	3974
Canary Island	24346	1	1	346

PROPAGATION DELAY ANOMALY, Δt_p^m

The knowledge of the propagation delay anomaly in the frequency range of 11.05 kHz and 13.15kHz is not accurate. This is because there is a lack of adequate phase velocity data in this frequency range. A more accurate method to determine the propagation delay anomaly is perhaps by the use of the time measurement. Table 5 gives a comparison of predicted and measured propagation delay values.

One area in which more research needs to be done is the determination or analysis of propagation anomalies in the OMEGA frequency range where propagation predictions are not known to sufficient accuracy for microsecond clock synchronization. The propagation delays must be measured with a clock which is known relative to the clock at the transmitter. An alternate approach is to obtain an average of the measured phase differences for f_1 and f_2 for day and night time transmissions. From these average values one can calculate the propagation delay, such as shown by Table 6. Table 6 gives the sample calculation of cycle determination for data obtained from Winkfield.

Table 5

Comparison of Predicted and Measured Propagation Delay Values in Microseconds for Indicated Values of tp's

Station	Predicted				Measured		Received Carrier (f_1) Cycle Determination	
	t_{p_1}	Δt_p	n	m	Δt_p	t_{p_1}	Predicted	Measured
Winkfield	22,113.0	2.5	1	0	0 3	22,253.7 22,099.5	— 27	— 27
Madrid	23,974.8	2.7	1	0	0 3	23,644.8 23,498.1	— 52	— 45
Canary Island	24,346.3	2.8	1	1	0 3 4 5	24,585.7 24,508.6 24,432.3 24,355.9	— 57 — —	— 59 58 57
Greenbelt	6,458	—	0	1	2	6,463.8	84	84

RESULTS

The propagation delays for each station visited were measured. The results are given in Table 5. It is to be noted that for $\Delta t_p = 3\ \mu s$, the measured propagation delays for Winkfield and Madrid are lower than the predicted values; Canary Island is higher.

A sample calculation of cycle determination of n_1 for $\Delta t_p = 0, 1, 2, 3, 4\ \mu s$ is given in Table 6. The average of the measured propagation delays are 2097.5 and 2137.3 μs respectively for day- and night-time transmission paths.

It is noted that the propagation anomaly for a particular receiving station is determined only when the station clock is known relative to the transmitter clock. This information can be obtained by the use of a portable clock. During these field tests the OMEGA North Dakota station was measured relative to the U.S. Naval Observatory (USNO) Master Clock (MC) via a portable clock. It was determined by the USNO that OMEGA North Dakota was slow relative to USNO-MC by 7.4 microseconds. Also, during the tests a portable clock referenced to the USNO-MC was used. All known biases such as clock differences must be taken into account in the calculation of the propagation delay values. Once these values are established, microsecond time can be obtained since the only limitation is the phase stability of the received VLF signals.

Table 6

Sample Calculation of Cycle Determination for data Obtained from Winkfield, England.

Date		Data No	$\overline{\Delta n_1}$ Cycle	$\overline{\Delta n_{12}}$ Cycle	n_1 For Δt_p = 0	1	2	3	4	t^m_{p1} (μs) = $(27 + \overline{\Delta n_1})\ \tau_1$
1974 Apr	16	9	0.487	0.562	29	29	28	27	27	2099.2
1310 - 1750	17	13	0.510	0.548	29	28	27	27	26	2100.0
(Day Time Path)	18	15	0.508	0.556	29	28	28	27	26	2099.8
	19	15	0.498	0.560	29	29	28	27	27	2099.1
1974 Apr	16	15	1.088	0.556	29	28	28	27	26	2144.1
0110 - 0530	17	15	1.003	0.554	29	28	28	27	26	2137.6
(Night Time Path)	18	15	0.955	0.566	30	29	28	28	27	2133.9
	19	15	0.950	0.547	29	28	27	27	26	2133.6

$$t^m_{p1}\ (\text{Day}) = \overline{(27 + \Delta n_1)\ \tau_1} = 2097.5\ \mu s$$

$$t^m_{p1}\ (\text{Night}) = \overline{(27 + \Delta n_1)\ \tau_1} = 2137.3\ \mu s$$

CONCLUSIONS

Results based on the phase data collected during the field tests show that cycle determination of a received carrier signal can be determined and that the accuracy of time measurement using two VLF signals is within ±2 microseconds.

For a worldwide time transmission system the field test results indicate that a minimum of three transmission stations are needed. These stations which transmit the present dual frequency format must be selected from the OMEGA Navigation System appropriately in order to provide the coverage.

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3. Chi, A. R., Fletcher, L. A., and Casselman. C. J. "OMEGA Time Transmissions and Receiver Design," Proc. National Electronics Conference Vol. 27, 268-273 (October 1972).