OMEGA TIMING RECEIVER, DESIGN AND SYSTEM TEST

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ABSTRACT

Each OMEGA Navigation Station is scheduled to transmit two unique frequencies separated by 250 Hz. These signals can be used to transfer precise time to receivers all over the world.

This paper discusses the design of a two frequency OMEGA Timing Receiver being developed by the Naval Electronics Laboratory Center (NELC). The receiver tracks the arrival time of the signals by precise phase matching at the receiving antenna. Provision is made for inserting a propagation delay correction for each signal path. Time is measured as the difference between the zero crossing coincidence of the corrected signals and the local time. This number is displayed on the front panel in microseconds. The receiver can also function as a precise phase tracking receiver for collection of propagation data essential to augmenting the propagation corrections. All phase and time information is made available in a BCD format for flexibility in interfacing with other equipment.

Results of preliminary tests run at NELC (San Diego, California) using experimental transmissions from the North Dakota OMEGA Station are given. Preliminary results indicate time may be transferred by this technique to an accuracy of a few microseconds.

I. INTRODUCTION

This paper discusses a two-frequency timing receiver being designed and built by the Naval Electronics Laboratory Center (NELC). Preliminary tests conducted at NELC, receiving OMEGA North Dakota, indicate that time transfer accurate to a few microseconds is obtainable. Section II presents a background discussion of the OMEGA transmission format, timing epoch, and defines the term *pseudo-epoch*. Effects of propagation are also addressed. Section III discusses the actual receiver design, and section IV is a discussion of results of preliminary tests conducted at NELC. Section V explains proposed system tests.

II. BACKGROUND

Transmission Format

Two unique frequencies with a 250-Hz separation will be transmitted from each OMEGA station as part of the 10-second OMEGA transmission sequence. The frequency assignments listed in Table 1 have been proposed.

Table 1
Proposed Frequency Assignments.

Station Designation	Station Location	Frequencies	
		F_1	F_2
A	Norway	12.10	12.35 kHz
B	Trinidad	12.00	12.25
C	Hawaii	11.80	11.55
D	North Dakota	13.10	12.85
E	La Reunion	12.30	12.05
F	Argentina	12.90	13.15
G	Australia	13.00	17.75
H	Japan	12.80	13.05

The approximately one-second-duration pulses of 10.2 kHz, 13.6 kHz, and 11-1/3 kHz which are radiated sequentially by each station will be followed by five pulses of F_1 and F_2. See the generalized transmission format shown in Figure 1. Several uses are being considered for the F_1 and F_2 transmission. Among them is time transmission, which is the subject of the paper.

General Discussion of Timing Epoch

Merriam-Webster defines *epoch* as: "An event or a selected time marked by an event that begins a new period . . . ." The OMEGA station epoch is defined by the positive going zero crossing of a selected cycle of 10.2 kHz. F_1 and F_2 positive going-zero crossings are held to ±100 nanoseconds of this epoch, and ±20 nanoseconds with respect to each other. Since F_1 and F_2 are both multiples of 50 Hz, a "timing epoch" can be defined which will occur at a 50-Hz rate (every 20 milliseconds) and will be marked by the coincident positive going zero crossings of F_1 and F_2. Two of the stations, B and G (Table 2), have frequencies that are multiples of 250 Hz and will have coincident positive going-zero crossings every 4 milliseconds, therefore, an epoch every 4 milliseconds.

Table 2
Pseudo-Epochs for each F_1/F_2 Pair.

Station	Frequency (kHz)	T (μsec)	Epoch (No. of cycles)	Pseudo-Epochs (No. of cycles)			
C	11.55 11.80	86.58 84.75 diff=1.834	231 236	46 47	92 94	139 142	185 189
B	12.00 12.25	83.33 81.63 diff=1.700	48 49				
E	12.05 12.30	82.99 81.30 diff=1.687	241 246	48 49	96 98	145 148	193 197
A	12.10 12.35	82.64 80.97 diff=1.673	242 247	48 49	97 99	145 148	194 198
G	12.75 13.00	78.43 76.92 diff=1.508	51 52				
H	12.80 13.05	78.125 76.63 diff=1.497	256 261	51 52	102 104	154 157	205 209
D	12.85 13.10	77.82 76.34 diff=1.485	257 262	51 52	103 105	154 157	206 210
F	12.90 13.15	77.52 76.05 diff=1.474	258 263	52 53	103 105	155 158	206 210

The other frequency pairs will also have zero phase differences every 4 milliseconds, but zero crossing coincidence will not occur every 4 milliseconds. Adjacent to these zero phase points, a pair of zero crossings will come very close to coinciding. Only a few tenths of a microsecond separate the positive going zero crossings at these near-coincidence points. In practice they will show up as zero crossing coincidences because of system noise and the finite resolution possible. These are not genuine timing epochs; we have called them *pseudo-epochs*. We do not want to take time from a pseudo-epoch, because it will be in time error by some multiple of fifths of a cycle. Figure 2 illustrates the pseudo-epochs for station A, 12.1 kHz and 12.35 kHz. The first pseudo-epoch is displaced from the 4 millisecond timing by 2/5 cycle of the timing frequencies (-33.1 microseconds); the second by 1/5 cycle (+16.5 microseconds), and so on. The pseudo-epoch problem rules out using a four millisecond repetition rate for measuring time.

Propagation and Resolution

"OMEGA time" is indicated by a timing epoch at the transmitting station. Specifically, every 20 milliseconds F_1 and F_2 will have coincident positive going-zero crossings. To retrieve this time epoch at some receiver site, time delays introduced by propagation must be taken into account.[1,2] Dispersion complicates the process of compensating for propagation delays. Swanson and Kugel[3] develop in detail the predication accuracies to be expected, and give many examples of applicable data.

Both the cited references point out the importance of knowing the elapsed propagation time from the transmitter to the receiver. Swanson and Kugel further define the limits to which we can expect to be able to know this. This knowledge is fundamental to retrieving time at a receiver site. No matter what scheme is used, this elapsed time must be accounted for.

The OMEGA Timing Receiver looks at the positive going zero-crossings of the received signals. Timing epoch will be indicated by coincidence of these zero crossings when propagation has been properly taken into account. The propagation correction is set into the receiver via a pair of front panel thumbwheel switches. Short duration pulses with leading edges that coincide with the positive going-zero crossings are formed. These pulse trains are, in turn, examined by logic circuitry for coincidences. The duration of these pulses is important. Too short duration pulse imposes too precise requirements on knowledge of propagation, (remember, we're limited in the accuracy of our knowledge of propagation at any given time). On the other hand, too long duration pulse can result in multiple

[1] E. R. Swanson, "Use of Propagation Corrections for VLF Timing," *Proceedings of the Fourth PTTI Conference.*

[2] A. R. Chi, L. A. Fletcher, and C. J. Casselman, "OMEGA Time Transmissions and Receiving Requirements," *Proceedings of the National Electronics Conference*, 1972, pp. 268-73.

[3] E. R. Swanson and C. P. Kugel, "OMEGA VLF Timing," NELC Technical Report 1740, pp. 29ff.

coincidences. Referring to Figure 2, it can be seen (with a little thought) that the optimum pulse width is one half the difference between periods of the two frequencies. That is, it is best to make the pulse wide enough so there is always a coincidence, but narrow enough so multiple coincidences are not possible as the two pulse trains move in time with respect to one another. As implemented, the pulse widths are approximately 700 nanoseconds, which approaches the ideal for the highest frequency pair, and falls about 200 nanoseconds short for the lowest pair. This is manageable.[4]

In any time measuring system which uses two frequencies to identify epoch, the time readout will change in increments of a whole cycle of either frequency. This happens as the respective phases of the frequencies are differentially perturbed by noise or propagation. In this receiver it will be seen as steps of 76 to 86 microseconds depending upon the particular frequencies.

RECEIVER DESIGN

The OMEGA Timing Receiver performs, in brief, as follows:

- It tracks the phase of the received timing signals
- It automatically removes receiver phase effects
- It removes propagation phase effects (manual insertion of phase corrections)
- The resulting signals, which are phase equivalent to the transmitted signals, become the internal OMEGA time reference
- The time difference between OMEGA time and local time is measured and displayed
- The phase of the received signals (without manual phase corrections), with respect to local time, are provided as an output for data collection purposes.

The receiver is shown in simplified block form in Figure 3. It consists of three main groups of circuitry: the F_1 receiver, the F_2 receiver, and circuits common to both frequencies.

Each of the receiver groups contains two phase holding loops. The first holds an internally generated reference signal, F_R, in phase with the received signal as seen at the phase detector. This phase holding loop has a time constant long enough to smooth out additive noise in the received signal. The second phase holding loop holds another locally generated signal, F_S, in phase with F_R as seen at the phase detector. F_S is injected into the antenna coupler and has all the antenna and receiver circuitry in common with the

[4]OMEGA Timing Receiver Report and Instruction Manual, publication pending.

received signal. By injecting F_S like this, and holding it in phase with F_R at the phase detector, the phase of F_S at the F_S generator is compensated for any phase shifts introduced by the antenna and receiver circuitry. F_S has the true phase of the received signal; receiver phase effects have been removed.

Since F_S is a strong signal (good S/N), the F_S phase holding loop has a time constant of about one tenth that of the phase holding loop that holds F_R in phase with the received signal. F_{1S} and F_{2S} are used to measure phase with respect to local time and to generate F_{1SC} and F_{2SC} which are used to determine the time.

F_{SC} is F_S passed through a manual phase shifter to provide a means of correcting for propagation effects. The smoothed and corrected signals, F_{1SC} and F_{2SC}, are used to determine the time difference between the received OMEGA time and local time.

Front panel thumbwheel switches control the phase shifter circuits. The phase correction is entered in centicycles;* only the fractional cycle portion of the propagation delay for each frequency must be set in. The time information is conveyed by the uniqueness of the phase relationship between the two timing frequencies. This relationship will not be affected by whole cycle changes in phase of either frequency.

All the phase sensitive operations in the receiver are carried out to 0.1 cec resolution. Since all digital circuitry is used, the resolution is obtained by deriving F_R, F_S, F_{SC} (and F_L) from 1000 F_1 and 1000 F_2. In this way, step size is 0.1 cec. The 1000 F signals are generated by the frequency synthesizer. The synthesizer is a phase locked loop which may be programmed to generate any of the timing frequencies, and holds them phase stable to the one MHz input. The synthesizers and the narrow band filters required for the front end portion of the receiver are contained in one modular plug in assembly, so by changing modules all frequency sensitive circuits are changed at once. Two of the modules are mounted in the receiver, selectable by a front panel switch. Either of two (preselected) stations can thus be received by switch selecting between them.

The commutator generates the gating pulses (commutation sequence) and all other control signals for the receiver. One of these control pulses is a 4-millisecond pulse, which is used in determining the time difference. This pulse is made to begin two milliseconds before the local one-second time pulse, and to continue for two milliseconds afterwards. The receiver searches for time during this four millisecond "window."

The leading edge of the four-millisecond pulse is used to start a counter and the F_{1SC}–F_{2SC} coincidence, the timing epoch, is used to stop it. By presetting the counter to -2000 microseconds the algebraic difference between OMEGA time and local time is read out directly (to the nearest microsecond). If the received OMEGA time is sooner than local time, the time difference readout will be minus; if received time is later than local time, the time difference readout will be plus. These readings appear on a

*Centicycle (cec) = 1 percent cycle = 3.6°.

front panel readout, and are provided in BCD form on a back panel plug. They are also made available in a low resolution analog output described in detail under Preliminary Test Results.

PRELIMINARY TEST RESULTS

The timing receiver was tested October 11-13 and October 31-November 3, 1972, at NELC, San Diego, on off-the-air signals from the North Dakota station. Since the North Dakota station is not yet radiating the timing frequencies on a regular basis, special arrangements were made for these two periods of testing. Arrangements were also made for North Dakota to radiate F_1 and F_2 the week of November 13-17 so the receiver could be demonstrated at the fourth PTTI conference at NASA/GSFC.

During the tests, time was known at NELC relative to OMEGA North Dakota to ±5 microseconds. This was established by a "flying clock" in April, with subsequent monitoring of other OMEGA transmission, and represents a "best estimate."

The need to take into account propagation delays and changes in propagation delays has already been mentioned. Using their VLF propagation model, Swanson and Kugel provided predictions of the propagation delays for October 11 to 13, to be valid at noon local time ±2 hours. The result of setting in this initial propagation correction was an indicated timing error of about 76 microseconds, or one cycle of the timing frequencies (refer to discussion of resolution). Phase measurements made on the received 13.10 and 12.85 kHz signals were examined, and based on this actual propagation information the initial propagation corrections were adjusted. This change in the propagation correction was 0.7 cec (1/2 microsecond) for each frequency. These "refined" values for propagation give time difference readings as indicated in Table 3.

The five-microsecond reading for October 13 is the time measured the last day of the first test. This number was visually observed and noticed to be very constant. The same propagation corrections were maintained for the second test and a digital printer was installed to record the time measurements. The measurement updated every ten seconds and was printed. The October 31 readings ranged from -3 to +2 microseconds. It was subsequently discovered that the receiver antenna coupler box had not been properly sealed and was admitting moisture; this in turn grossly affected the local signal injection network (up to 7 cecs of phase shift). The effect was essentially the same at both frequencies; thus it shows up as a modest translation in time, rather than a large time step to another pair of zero crossings. The last three entries of the table show the time readings with the equipment functioning properly, demonstrating excellent repeatability. As was previously stated, the best estimates of receiver site time relative to transmitter site time was ±5 microseconds. This accuracy was adequate to prove that the proper pair of signal zero crossings could be identified. To make a statement as to accuracies down to the last microsecond, would require "flying clock" trips between the transmitting and receiving sites during the tests.

Table 3
Time Difference Readings Between Local Time and Received Omega Time
During Four-Hour Midday Period.

Propagation Corrections set into Receiver			
13.1 kHz	79.5 cec		
12.85 kHz	92.4 cec		
Test	**Date**	**Time**	**Remarks**
1	Oct 13	+5 μsec	Visual Observations Only
2	Oct 31	−3 to +2	Coupler Network Disturbed by Moisture
	Nov 1	+4 to +5	
	Nov 2	+1 to +3	
	Nov 3	+1 to +3	

Figures 4 and 5 present segments of the data taken during the tests conducted October 31 to November 3. The phases of 13.10 kHz and 12.85 kHz as received (F_{1_S} and F_{2_S}) versus local time are presented. Each phase record is made of two parts. The straight line segments represent tens of centicycles, while centicycles and tenths of centicycles are given by the dispersed meandering line. The tens of cec portion of the recording has 100 cec full scale; the units and tenths portions 10 cec full scale. The two lines are summed to get the reading. By using this split presentation, the Rustrak recordings offer resolution to 0.1 cecs. The data labeled "time difference" are a low resolution analog presentation of part of the front-panel time-difference readings. The purpose of these data is to identify the reading occurring most often among several (i.e., the statistical mode). Bearing in mind that in the presence of noise the time difference readings will vary in steps of one cycle, approximately 76 microseconds, this record assists the operator in identifying the proper time difference number. This record is the analog presentation of the least significant three figures of the time difference reading, along with the sign. Full scale is ± 1000 microseconds; positive numbers are indicated from zero at the left edge, and negative numbers are indicated from zero at the right edge.

Figure 4 shows F_1 and F_2 phase through a night to day transition. The phase of F_1 and F_2 varies through 25 cec during the transition, yet cycle identification was not lost. At the right of the figure are printouts of the time difference in microseconds at 10 second intervals from 1557Z to 1603Z. These illustrate the constancy of the time measurements which occurred during daylight hours.

Figure 5 shows data taken mostly at night. The period of 1055Z to 1130Z when F_1 was off the air, serves to illustrate how the time difference reading runs off in steps of 76 microseconds. The time difference printouts at the right also illustrate the step runoff.

Table 4 shows the good phase stability of the difference frequency as received during stable daytime hours. These numbers were generated by subtracting the measured arrival phase of the 13.1 kHz from that of the 12.85 kHz. This can be thought of as the arrival phase of the 250 Hz difference frequency, although this frequency never exists, nor is it generated. To the extent this difference phase will stay stable and predictable within the ± 0.95 cec limit, the proper coincidence of zero crossings can be relied upon to occur, and precise time down to a few microseconds can be obtained. As can be seen, all of the data points fall well within these limits. The starred data points occurred during the previously mentioned moisture problem with the antenna coupler. As can be seen, the phase shift effect was the same for both frequencies and therefore didn't affect the difference frequency. (A word about the distribution of the stars through the data: Two antenna systems were being used alternately during the test, a troublefree one as well as the troublesome one. By the end of the test the exact manner of the trouble had been determined and corrected.)

In summary, the receiver concept and design have been proven with off-the-air tests. These preliminary tests show good correlation between the two timing signals and good correlation to the prediction model. The OMEGA timing signals appear to afford a workable system for dissemination of microsecond timing.

SYSTEM TEST

The system test is designed to demonstrate the system capability for transmitting precise time, but also to determine the limitations and the extent to which the applications can be made in the use of the transmissions.

As demonstrated, the input requirements are: the propagation delay calculations based on the coordinates of the location where time is received; a one pulse per second output from a local clock whose time is accurately known to a reference clock; and a one megahertz output signal.

With the knowledge of the difference of the local clock time relative to a standard time, we can measure the propagation delay. The measured propagation delay can, therefore, be compared with the predicted propagation delay and is used to check the theory.

Using past experience, three days to a week is needed to conduct the test. This is the minimum amount of time required for the needed data. This length of time in a location depends, of course, on the objective of the test.

Table 4
Half-Hourly Difference-Phase Measurements
Made During Daylight Hours
ϕDiff = ϕ12.85 – ϕ13.1

Time	Oct 11	Oct 12	Oct 13	Oct 31	Nov 01	Nov 02	Nov 03
1500Z		12.9	12.8		12.8*	12.7*	12.9
1530	12.9	12.8	12.7		13.1*	12.7*	13.1
1600	—	12.8	—		12.8*	12.4*	13.1
1630	12.8	12.8	—		—	12.6*	12.9
1700	13.0	12.7	12.7		—	12.8*	13.0
1730	12.8	12.9	12.7		12.8*	12.6*	12.8
1800	12.9	13.0	12.8		12.8*	12.8*	12.9
1830	12.9	12.9	12.7		12.8*	12.8*	13.1
1900	12.9	12.8	12.7	12.9*	13.0	12.8*	—
1930	12.8	12.9	12.8	13.0*	13.1	12.8	13.1
2000	13.1	12.7	12.8	13.0*	13.1*	13.0	13.0
2030	12.9	12.7		12.5*	13.2	13.0	
2100	12.9	12.6		12.7*	—	12.6	
2130	12.9	12.9		12.6*	13.0	12.7	
2200	12.7	12.8		12.5*	12.9	12.5	
2230	12.8	12.7		12.8*	12.8	12.4	
2300	12.9	12.7		12.8*	12.9	12.9	
2330	12.9	12.7		12.6*	—	12.6	
0000	13.0	12.7		12.7*	12.4	12.9	

N = 45
ϕ_{Diff} = 12.82 cec
Std Dev = 0.11 cec
Pk Dev = +0.3, –0.1

N = 55
ϕ_{Diff} = 12.82 cec
Std Dev = 0.20 cec
Pk Dev = +0.4, –0.4

Allowable Deviation for a Workable System ±0.95 cec

The objectives of the tests are the following:

1. To determine the precision of the time reception as a function of time, such as time of day or time of year, from a single transmitter

2. To identify satisfactory signal reception for determining range from the near distance to the far distance between the transmitter and the receiver for which the precision of the received time is the same

3. To test the global coverage of the system

In order to test the global coverage, one should intercompare the results of signal reception and precision obtained from all the eight stations to determine if all or only selected OMEGA transmitting stations are needed and at the same time to determine the extent they are intercontrolled.

Figure 6 illustrates the geographical locations of the eight OMEGA stations relative to our tracking network. This figure shows that most of our tracking stations are within about 5000 miles. This distance is believed to be within the good signal reception range for VLF transmissions.

Obviously, the first thing that we shall try to do is to coordinate the time transmissions from the OMEGA stations. Next we shall try to select the locations which are the most suitable for the test, in particular, the sites from our tracking stations. There have been a number of people from the Department of Defense, the National Bureau of Standards, and so on, who have participated in this program with us and with whom we certainly shall coordinate the test program.

Comment on Units for VLF Phase Recording

We would like to make one comment in regard to the units for phase recording; that is the units of microsecond and cycle. I recall some years ago when VLF receivers were designed; there was a considerable discussion on how the phase should be recorded and in what units the phase should be expressed. The decision at the time was in favor of the unit of time and furthermore the full scale of a phase record was chosen to be 100 microseconds for phase-tracking VLF receiver.

While the reason at the time was that the frequency of the VLF transmissions was not rigidly controlled and subject to change, and also that the full scale in time units would be easier for the operator to record and to read, the important reason which remains valid today is in the simplicity in receiver design and uniformity in phase records.

This decision was not made without consultation with other users. In retrospect, if one looks at the past phase records, he will find many advantages when he tries to use the phase records. Had the phase records been recorded in cycles, he would have to know the carrier frequency of the transmitter in order to know exactly what is the full scale. The disadvantage of this system is that the phase record is not continuous: unlike the cycle recordings, the phase of a signal does not come back to the same point after a perturbation due to sudden ionospheric disturbance.

Perhaps it is time to re-examine the need of standardization in the selection of units for phase recordings. We really do not see an easy solution nor a great conflict between the navigator's unit of cycles and the time user's unit of microseconds provided the unit is clearly stated.

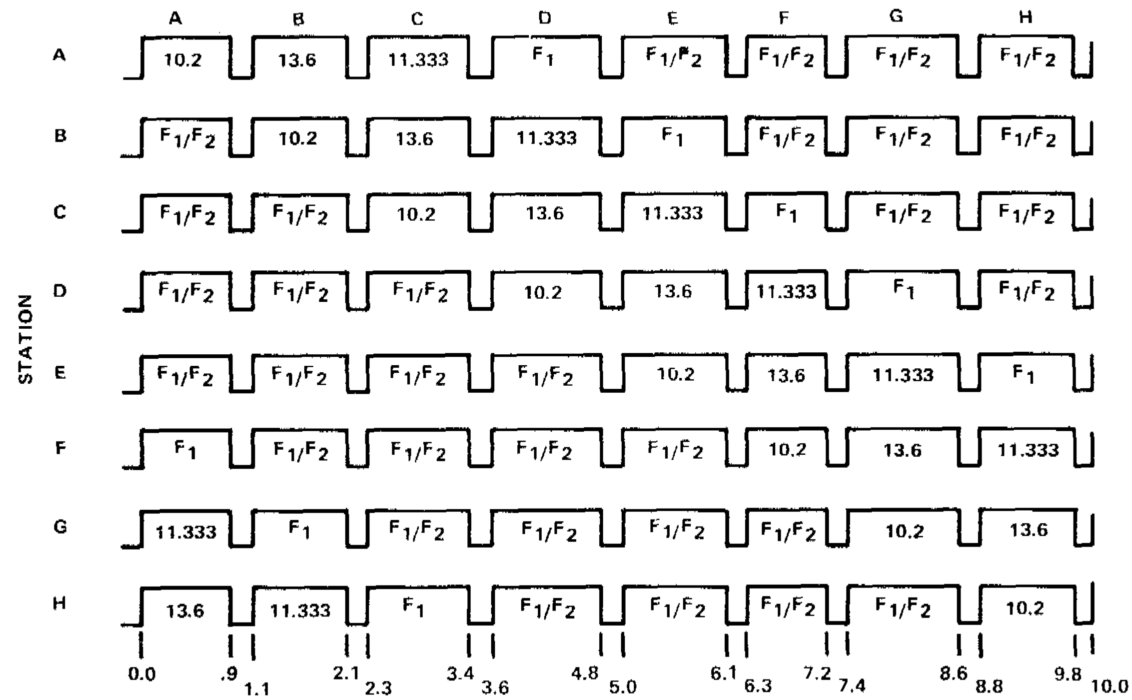

Figure 1. The ten-second OMEGA transmission sequence.

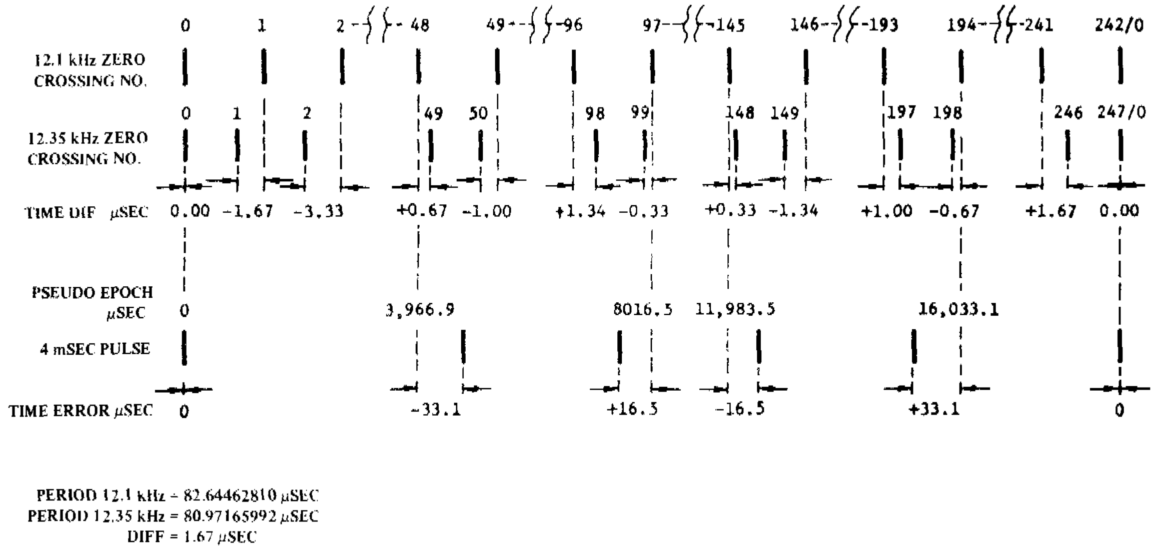

Figure 2. Example of pseudo-epochs for 12.1/12.35 kHz pair.

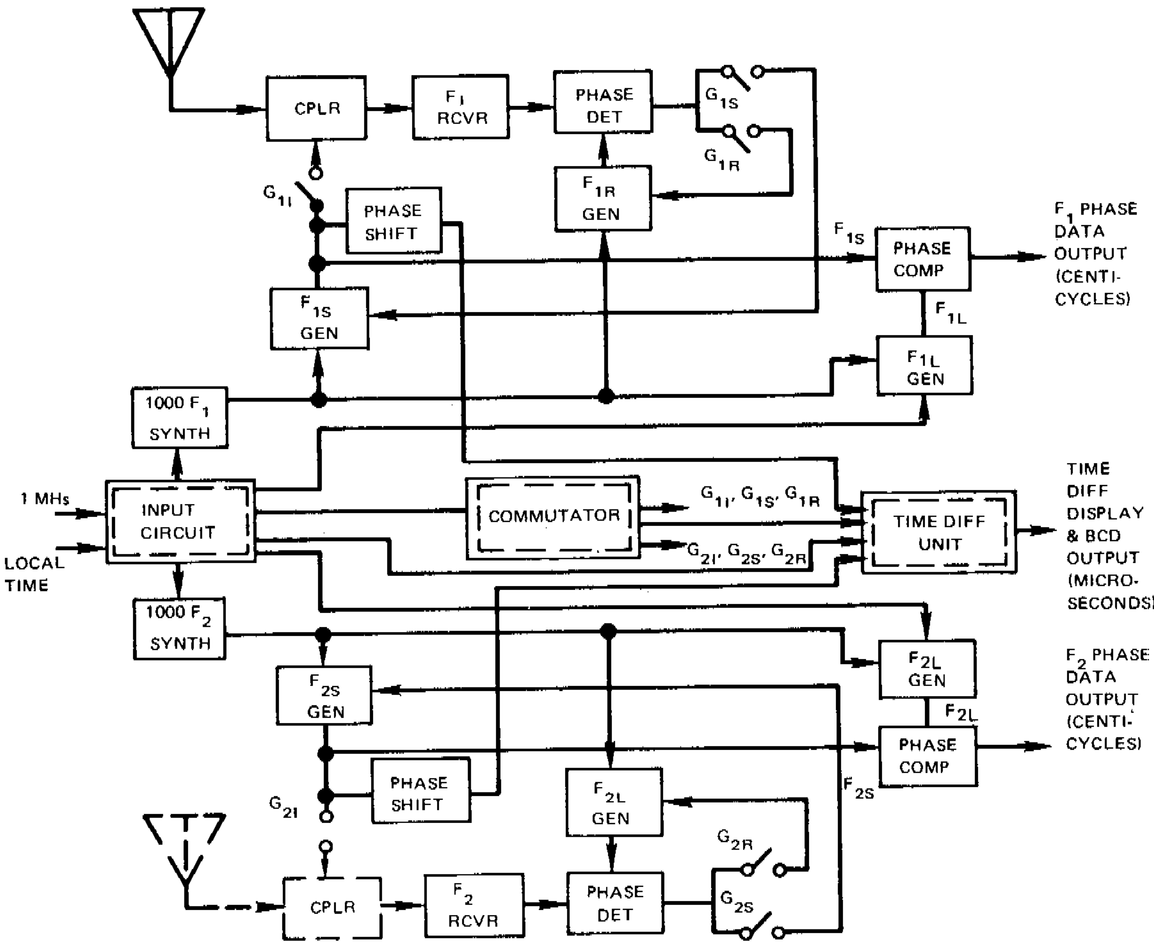

Figure 3. OMEGA Timing Receiver block diagram.

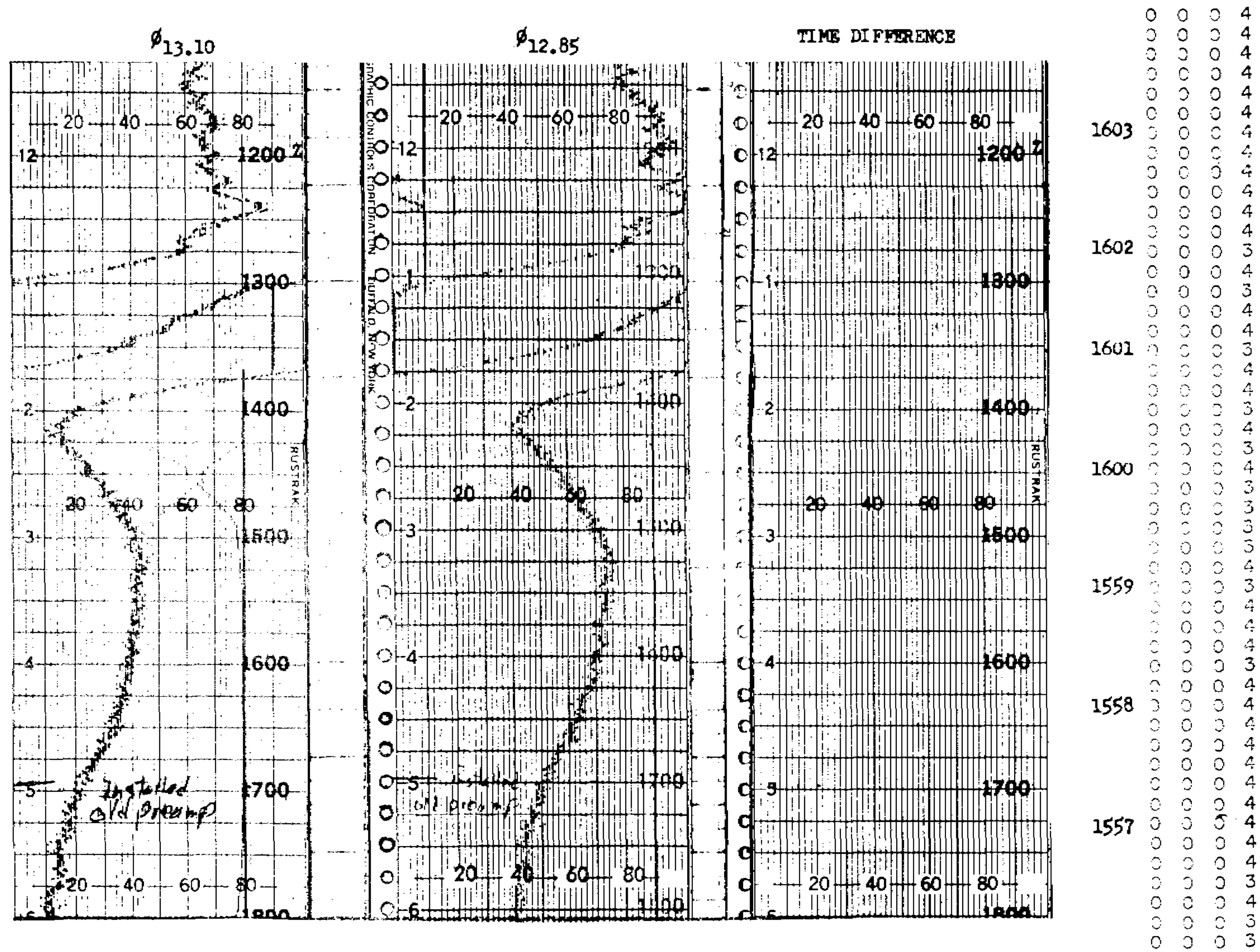

Figure 4. North Dakota received at San Diego, November 3, 1972.

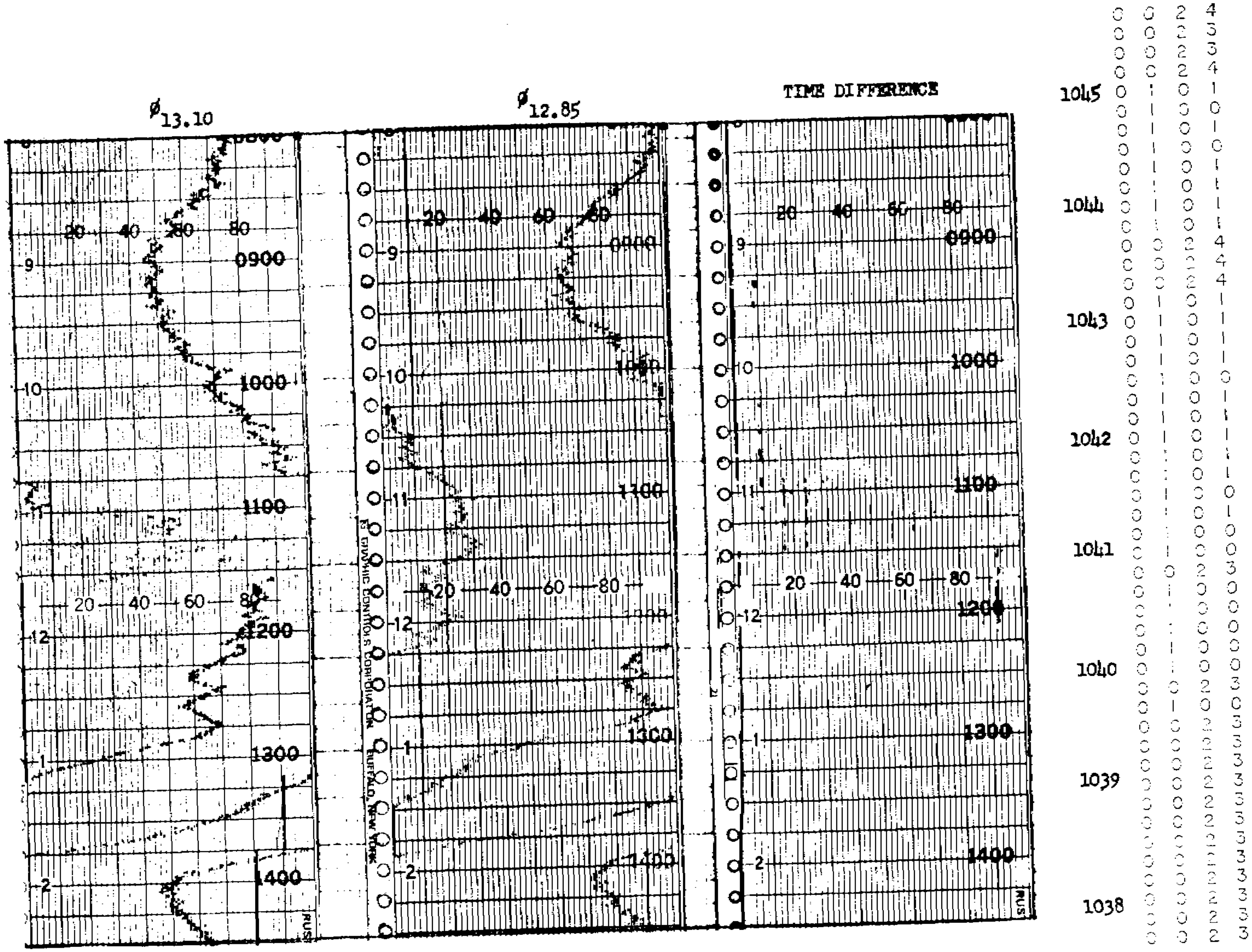

Figure 5. North Dakota received at San Diego, November 2, 1972.

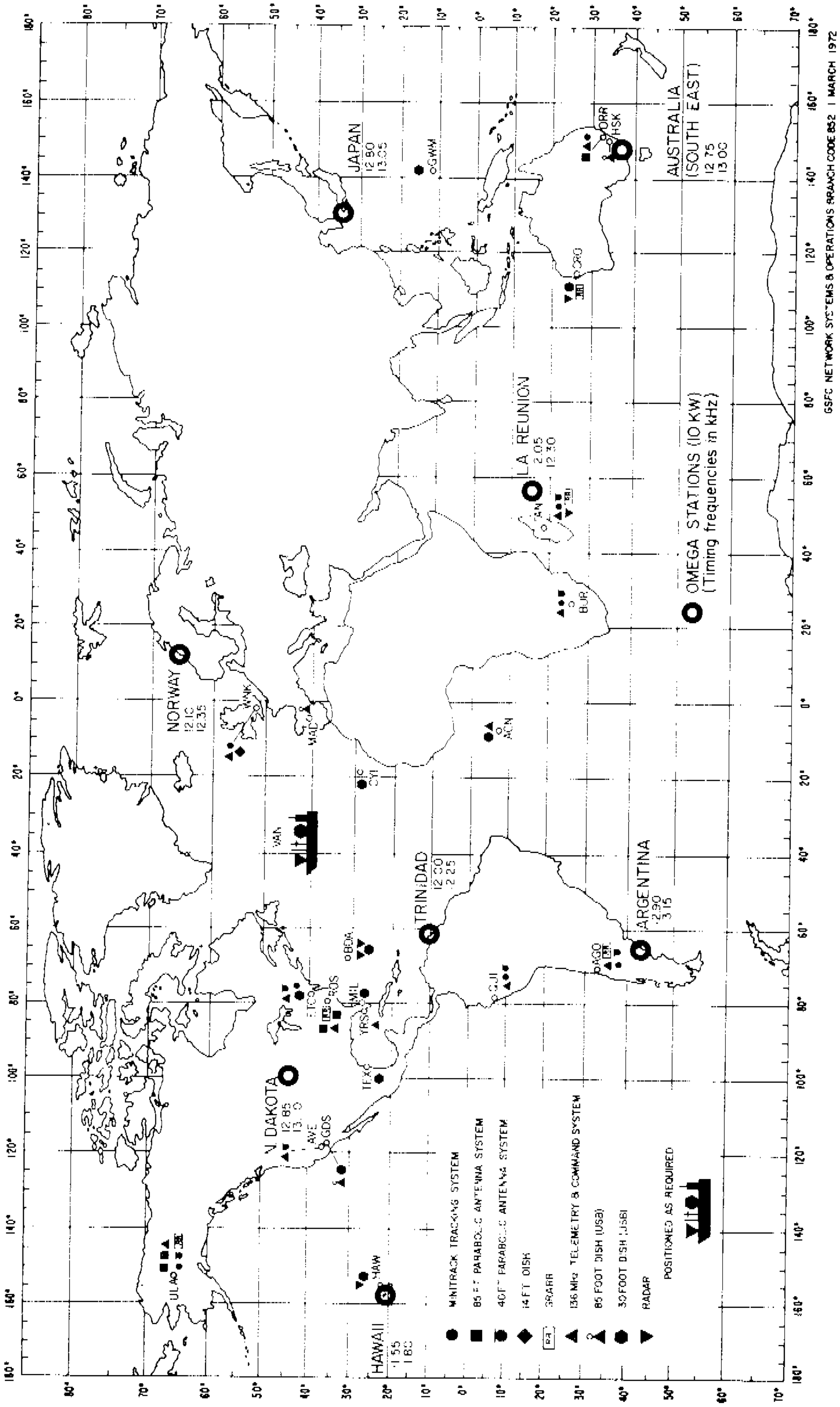

Figure 6. STDN capabilities map.