THE EVOLUTION OF SYNCHRONIZATION IN THE WORLD–WIDE OMEGA NAVIGATION SYSTEM

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Abstract

If the accuracy of the Omega Navigation System were to be limited at all times solely by unpredictable propagation disturbances, the relative timing with which the signals are transmitted must be controlled to an accuracy of less than 0.5 microseconds. Tests of VLF signal transmissions over long distances have established that the timing stability of such signals will exceed one microsecond for at least some period of time. Prior to 1972 the Naval Electronic Laboratory Center (NELC) now the Naval Ocean System Center (NOSC) was the synchronization control center for Omega and made the necessary calculations and adjustments using reciprocal path measurements. However, without external measurements the mean system "walked" from Coordinated Universal Time (UTC). After the U. S. Coast Guard and the Japanese Maritime Safety Agency (JMSA) became responsible for the synchronization of the Omega system a more sophisticated technique was developed. This method still relied on a reciprocal path technique, but also included a statistical filter which tracked each cesium frequency standard at the transmitting stations and computed optimal phase adjustments based on internal path measurements. In 1977 with seven of the eight network stations on–line, external measurement source such as LORAN–C and portable clock measurements tied the Omega system to UTC time. In November 1985 Global Positioning System (GPS) data from Omega station Liberia was used for the first time as an external input to the existing Synchronization software package. By early 1987 GPS monitor receivers were installed at all the Omega Transmitting Stations. In 1988 data from the transmitting stations in the southern hemisphere was used to remove a 2–3 microsecond bias which greatly improved the synchronization throughout the Worldwide Omega Navigation System.

INTRODUCTION

Omega is a very low frequency (VLF 10–14 kHz) radio navigation system with a total of eight worldwide stations (Figure 1) transmitting phase synchronized signals at five frequencies (10.2, 11.05, 11.333, 13.6 and a station specified unique frequency) in a time–multiplexed format (Figure 2). The Omega system is designed to provide a worldwide all–weather position fix capability with 2–4 nautical miles accuracy (2dRMS). For the phase contour pattern, whose position is defined to be stationary, the timing signal of the stations must be synchronized. Operationally, the signals of each station are independently timed with cesium frequency standards and synchronization instructions are generated and issued by the Japanese Maritime Safety Agency (JMSA) in Tokyo, with the U. S. Coast Guard Omega Navigational System Center (ONSCEN) acting as the back up.

In the early to mid 1960's Omega entered the development stage, with four transmitters located in Norway, Trinidad, Hawaii and New York. Of these four original stations, Norway and Hawaii remain

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today as full power operational stations. Australia was brought on-line in 1982 to complete the eight station worldwide network. In an effort to minimize synchronization errors Loran-C timing data was introduced in the northern hemisphere stations in 1976. In 1988 GPS data from the transmitting stations in the southern hemisphere was used to remove a 2-3 microsecond bias which synchronized all Omega stations well within 0.5 microseconds relative to UTC traceable to the U. S. Naval Observatory (Figure 3). Synchronization is maintained by having each of the eight station report to JMSA and ONSCEN, the computing centers, signal phases of 10.2 and 13.6kHz of all other stations within range with respect to its own signal along with timing information from LORAN-C and GPS. The computing centers determine the deviation of each signal phase from the system mean and using this external timing information directs the stations to adjust their timing rates to minimize deviations as illustrated in Figure 4.

HISTORICAL DEVELOPMENT

Master-Slave Mode

At inception, and for many years thereafter, the developmental Omega system was operated in a master slave mode in which transmitters were designated as master or slave. The master transmitter was driven by a frequency standard of moderate stability (1 part in 1010). Master transmissions were monitored near the remote slave transmitter (10-30 km), which broadcasted on a subsequent transmission segment in phase coherence with the received master signal. Slave transmitters, therefore, approximated in-phase reflectors. This method of synchronization is traditional with many navigational systems, having originated with LORAN A and DECCA. Compared to "absolute" synchronization, slaving has the advantage of not requiring costly precision frequency standards and the disadvantage of requiring different specifications of the master-slave relationship in system design. Also, navigators may not alter the established master-slave relationship and must use the prescribed lines-of-positions (LOPs).

Absolute Mode

The idea that Omega transmitters be operated from precision frequency standards originated with a suggestion by J. A. Pierce of Cruft Laboratory, Harvard University in 1960. The possibility of Omega becoming a global system with redundant information available would allow the navigator to select transmitters in any convenient manner so as to obtain usable signals and geometry. Absolute synchronization provides this particular advantage, as well as the following:

a. Improved accuracy from reduction of the number of active propagation paths from three to two for a single LOP.

b. Improved reliability.

c. Simplified use of the system for time and frequency dissemination, as all transmitters are an equivalent source of precise time.

These considerations and the concurrent advancement of the state of the art of cesium frequency standards rendered absolute operation both desirable and practical. Initial exploratory attempts at absolute synchronization were not made until 1965. At that time, no cesium standards had been installed and quartz oscillators were still in use at the four R & D Omega stations. The original experiments involved Canal Zone and Hawaii using an intermittent transmission schedule of approximately 12 hours per day. This procedure required that data for Hawaii observed in the Canal Zone and for Canal Zone data observed in Hawaii be transmitted to San Diego where timing/phase control information was derived. This interrupted schedule, together with a lack of redundancy in timing equipment rendered many phase/timing jumps which probably occurred during off air periods or as a result of timer power loss. Because of the poor stability of the existing standards, prompt transmission and utilization of data and control information were necessary. In practice, communications delays were substantial and technical operation was not completely successful, even though useful navigation signals were transmitted. This early operation illustrated the need for redundant precision frequency standards and emphasized the importance of communications in a reciprocal path control procedure. In early 1966 cesium standards were installed at Norway, Hawaii, New York and Trinidad (moved from Canal Zone) along with updated timing equipment. This began modern Omega in the absolute mode of operation.

Cesium Standards

The synchronization method chosen for this R & D system implementation was developed by J. A. Pierce in late 1965. This procedure was initiated in late February of 1966 with three stations and was extended to include Norway in April. Each station would measure the phase difference (10.2 and 13.6 kHz) with the other stations and then compute and make appropriate adjustments using Predicted Propagation Corrections (PPC's), weights and references. Each station would then adjust based on measurements of the other stations and all stations would therefore be adjusting on each other. During this period the original four R & D stations were transmitting and using this self-adjusting procedure in which each station made discrete daily phase changes to remove one third of the calculated errors observed on reciprocal data. By mid May a ten microseconds epoch error had developed (measured by portable cesium clock) at Norway and that station was removed from general adjustment procedure and placed under direct control of Omega New York which was able to track their signals. This modified procedure proved satisfactory for the summer of 1966. However, the mean system "walked" and administrative difficulty ensued. The administrative troubles together with degraded performance led to a change from the Pierce procedure to one involving an active control site which determined all synchronization adjustments. The new procedure necessitated a central control site which was located at the Navy Electronics Laboratory Center (NELC) now Naval Ocean System Center (NOSC) in San Diego. This method relied on the reciprocal path technique to detect synchronization disparities, but also included a statistical filter which tracked each cesium oscillator and computed optimum phase adjustments based on internal path measurements.

The four stations would send their observations on 10.2 and 13.6 kHz by message weekly to the control center where they would determine the daily phase adjustments to be applied to each station. In addition to the phase data, phase shifter positions were also sent, which enabled the control center to keep a history file of the back-up cesium frequency offsets. If the on-line cesium failed, the back-up system would be available with it's own historical offset, and continuity would be maintained.

EXTERNAL MEASUREMENTS

LORAN-C

External measurements are valuable in reducing synchronization errors resulting from biases in PPC's. Over the past 18 years Omega synchronization methods went through three major phases. In the 1970-1976 time frame "internal" synchronization via reciprocal Omega signal measurements was used. This method synchronized the stations to within 3-5 microseconds of each other. However, since this method did not tie the system to UTC or any other external timing source the system "walked." At one point the system was out by 29 microseconds with respect to U. S. Naval Observatory (USNO) Master Clock. This was promptly removed in the fall of 1975 before the new stations in Argentina, La Reunion and Liberia became operational. In an effort to reduce the timing errors and tie the system to UTC, Loran–C timing equipment was installed at four stations (Norway, Hawaii, North Dakota and Japan) during the period of 1976–79. After proper calibration of the timing paths this data was introduced to the synchronization process. In October 1977 the Japan Maritime Safety Agency was given the primary responsibility for synchronization execution and the dissemination of synchronization and frequency corrections to the stations. The Omega Navigation System Center maintains a back–up synchronization capability. With the implementation of Loran–C as an external timing source in the northern hemisphere, the system was steered to UTC within 2–3 microseconds although the individual stations in the northern hemisphere were held within one microsecond of UTC. This method was a big improvement to synchronization and the system time became traceable to the U. S. Naval Observatory as illustrated in Figure 5.

Global Positioning System (GPS)

With the advent of GPS, a real–time, accurate, external timing system became available for all Omega stations in the southern hemisphere plus Liberia. Initially the test bed with the prototype GPS receiver was introduced at North Dakota and compared with existing Loran–C timing. Figure 6 is a comparison plot of the two systems for a typical month. The timing of Omega station Liberia was always suspicious as reported by various portable clock trips. A GPS timing receiver was introduced to the timing configuration of Liberia in early 1985 which confirmed earlier reports of a constant bias of about three microseconds. In November of that year, GPS data was used for the first time as an external timing source in the synchronization process which removed a long standing bias as shown in Figure 7. The GPS receivers were placed in an automatic mode of operation which selected the best geometrically suited satellite. One observation was made per day and every Monday the data was sent to the synchronization control center. By mid 1987 all Omega stations were configured with GPS timing receivers. As the confidence level grew with the GPS equipment and data the southern hemisphere stations were moved on–line one at a time.

Argentina was the first to be brought on–line in January 1988. The resulting effect it made on the synchronization process is shown in Figure 8. This was followed by Australia (Figure 9) in March and La Reunion (Figure 10) in May bringing all the southern hemisphere stations into the synchronization process with external sources. Figure 3 shows that having GPS timing available in the southern hemisphere has increased the Omega system synchronization accuracy well within 0.5 microseconds with minimum weekly corrections applied and tied to UTC which is traceable to the U. S. Naval Observatory.

The ability to synchronize the individual Omega stations to within 0.5 microseconds and ultimately the system has been achieved as envisioned by the originators. The present policy is that GPS timing data is not a substitute for the current synchronization program but rather serves as a highly weighted external input to the current program. A study is now being made to determine how we can more effectively use this highly accurate resource and at the same time continue to use current reciprocal Omega VLF measurements. Dependence on GPS solely can lead to the problem encountered in September 1988 when the Department of Defense (DOD) decided to change the satellite message format which disabled many GPS receivers.

According to the 1986 version of the U. S. Federal Radionavigation Plan (FRP) there are about 21000 known Omega users of which less than 10% are DOD users. The current thinking is that Omega will be available at least 15 years after GPS becomes fully operational. In this paper we have tried to make the Timing community aware of a very cost–effective system like Omega that can be used as a worldwide timing system. By employing special techniques one should be able to recover epoch to better than one microsecond traceable to UTC (USNO) and frequency accuracy on the order of a few parts in 10^{12}. Omega transmissions offer the following:

- Advantages:
  1. Continuous operation 24 hours per day.
  2. High reliability of the stations and repeatability of propagation.
  3. Eight stations providing worldwide coverage.
  4. Extreme range providing redundancy, if one station is off air for maintenance.
  5. Transmissions controlled by atomic standards.
  6. Time is traceable to UTC (USNO).
  7. Reception is relatively simple and inexpensive.
- Disadvantages:
  1. Occasional propagation disturbances such as Sudden Ionospheric Disturbances (SID's).
  2. Propagation complexities which can result in modal or long–path interference.
  3. Repeated measurements at various frequencies or other time disseminated methods required to initially set or periodically verify coarse epoch.

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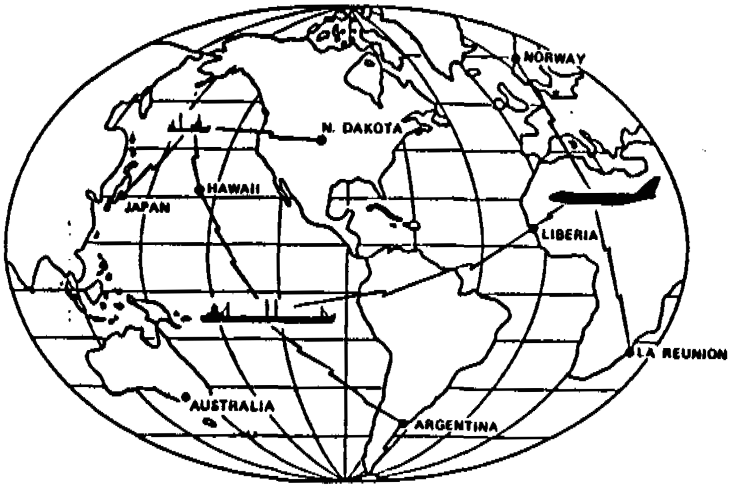
2) Swanson, E. R., Kugel, C. P., "Naval Electronic Laboratory Center Omega Synchronization and Control." R & D, 19 March 1971.

OMEGA SYSTEM TRANSMITTING STATION LOCATIONS

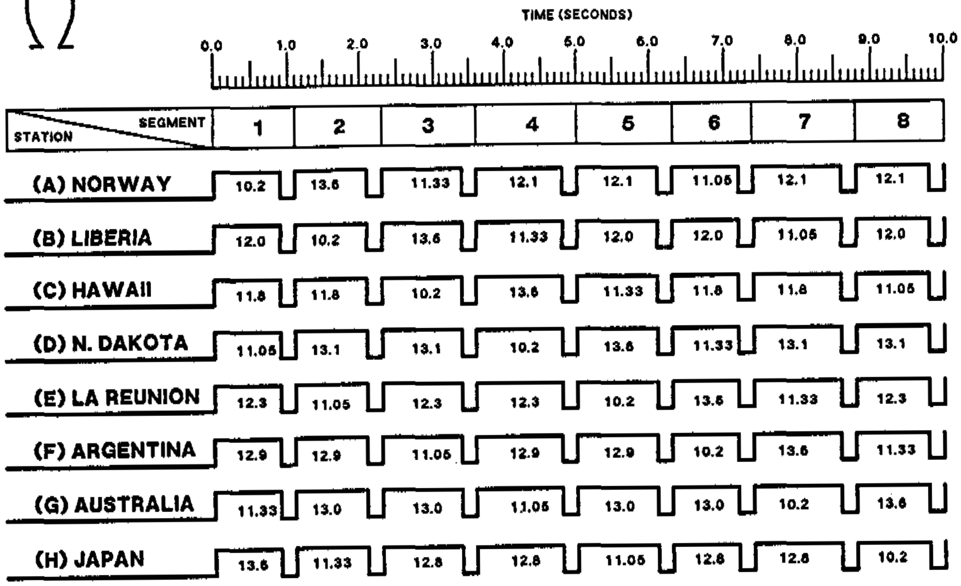


- EIGHT TRANSMITTING STATIONS (EACH AT 10 KW)
- SIGNALS RADIATED ON A TIME-SHARE BASIS WITH A REPETITION PERIOD OF 10 SECONDS
- FIVE SIGNAL FREQUENCIES — 10.2, 11.05, 11.33, 13.6, kHz PLUS A UNIQUE FREQUENCY FOR EACH STATION
- ALL WEATHER GLOBAL SIGNAL COVERAGE
- POSITION FIX ACCURACY 2 TO 4 nm (2drms)
- TIMING 0.5—1.0 MICROSECONDS TRACEABLE TO USNO (MC)

EIGHT WORLDWIDE STATIONS PROVIDING ALL WEATHER VLF RADIO NAVIGATION AND TIMING

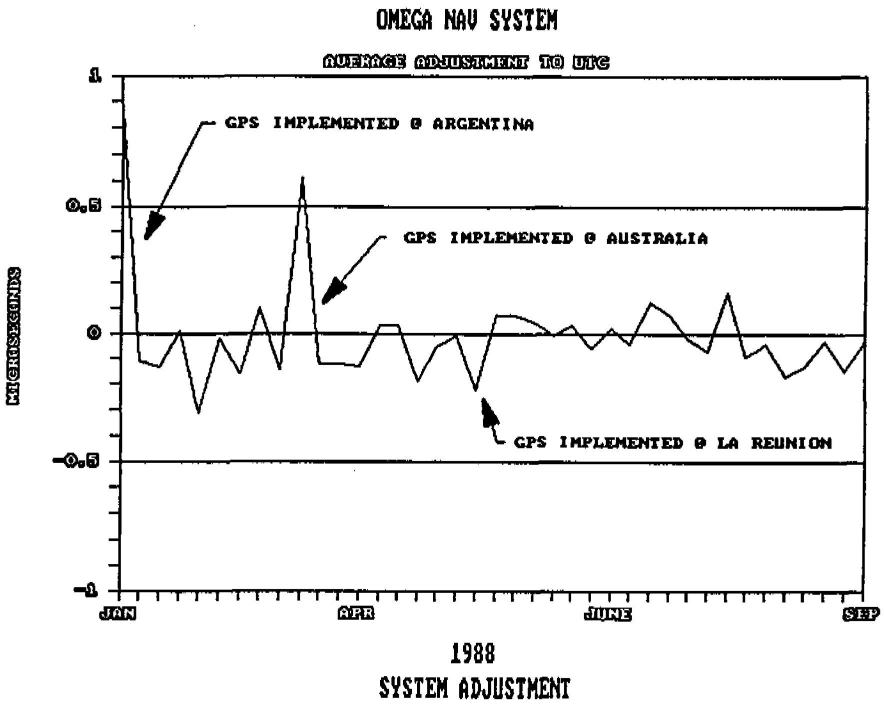
FIGURE 1

OMEGA SIGNAL TRANSMISSION FORMAT



STATION \ SEGMENT	1	2	3	4	5	6	7	8
(A) NORWAY	10.2	13.6	11.33	12.1	12.1	11.05	12.1	12.1
(B) LIBERIA	12.0	10.2	13.6	11.33	12.0	12.0	11.05	12.0
(C) HAWAII	11.8	11.8	10.2	13.6	11.33	11.8	11.8	11.05
(D) N. DAKOTA	11.05	13.1	13.1	10.2	13.6	11.33	13.1	13.1
(E) LA REUNION	12.3	11.05	12.3	12.3	10.2	13.6	11.33	12.3
(F) ARGENTINA	12.9	12.9	11.05	12.9	12.9	10.2	13.6	11.33
(G) AUSTRALIA	11.33	13.0	13.0	11.05	13.0	13.0	10.2	13.6
(H) JAPAN	13.6	11.33	12.8	12.8	11.05	12.8	12.8	10.2

FIGURE 2



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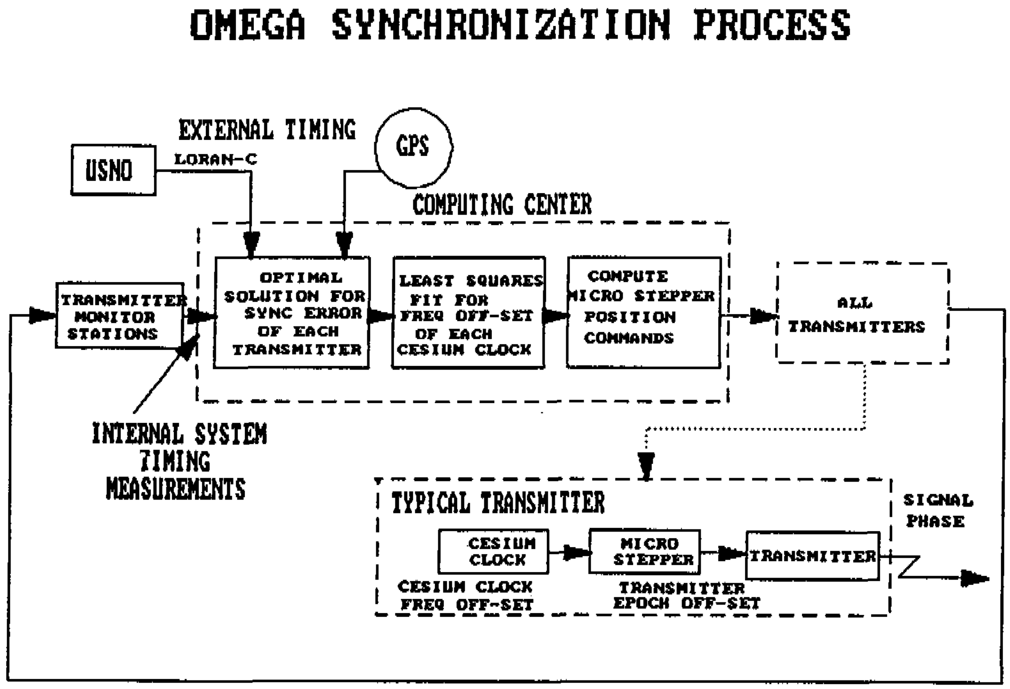

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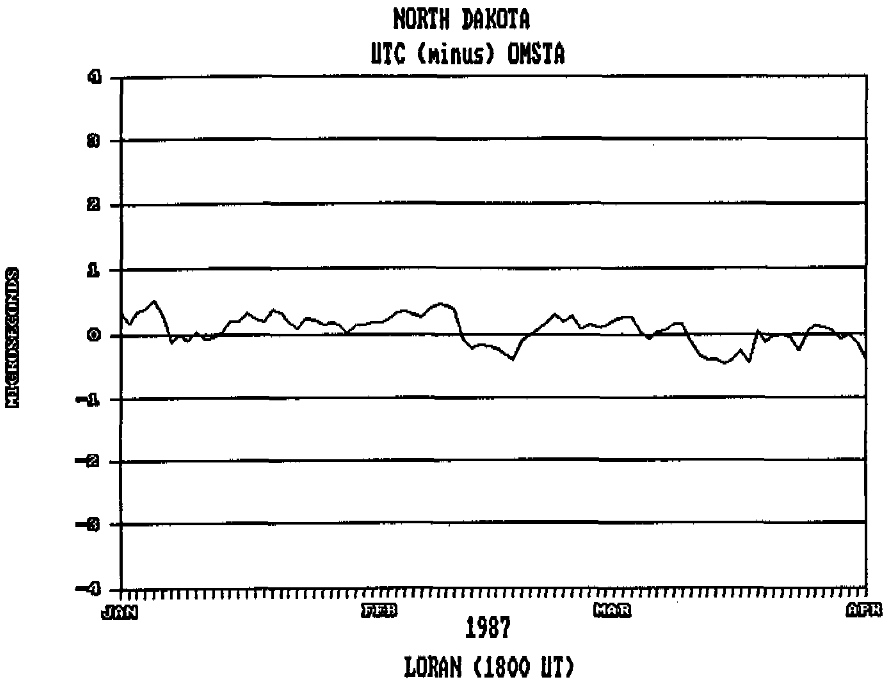

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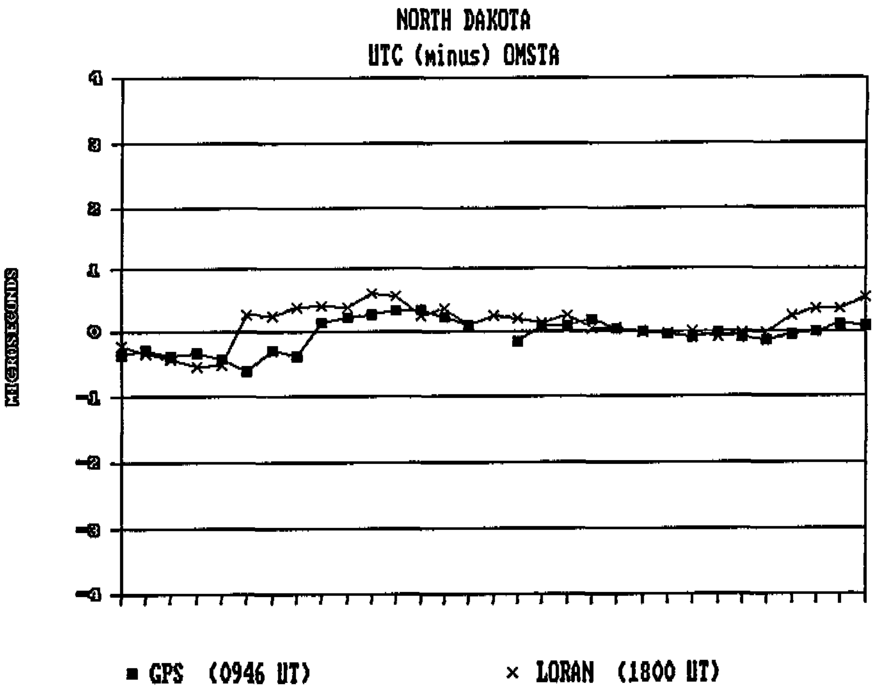

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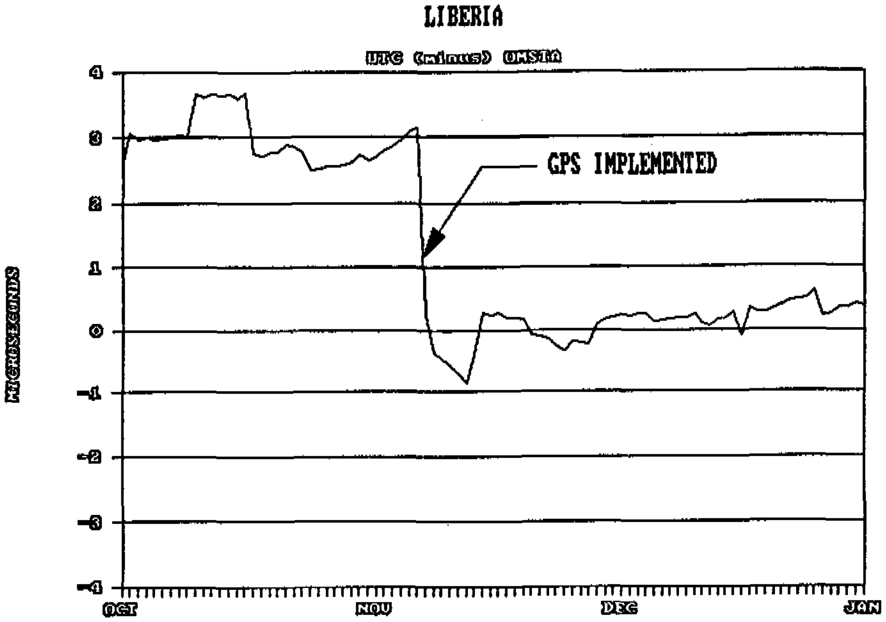
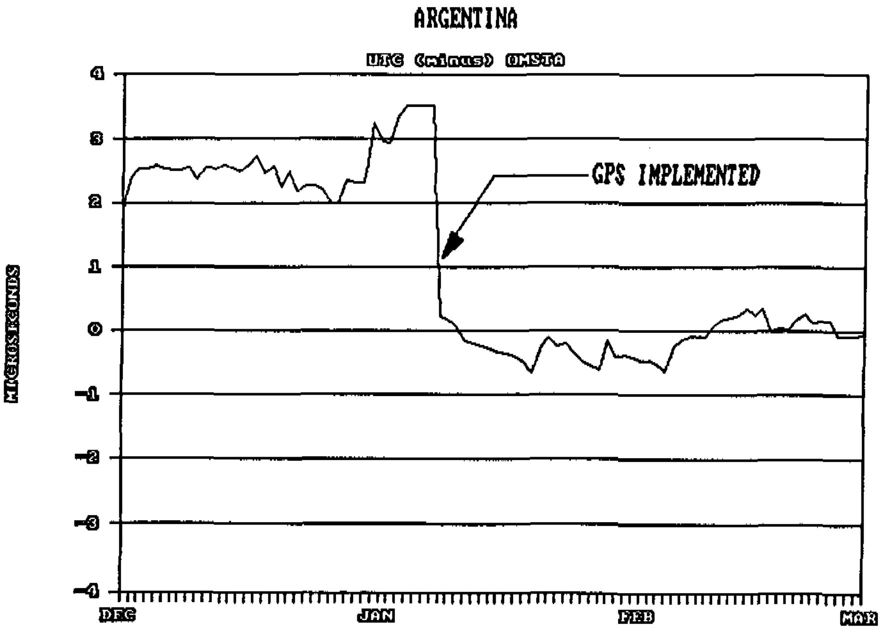


1985

GPS

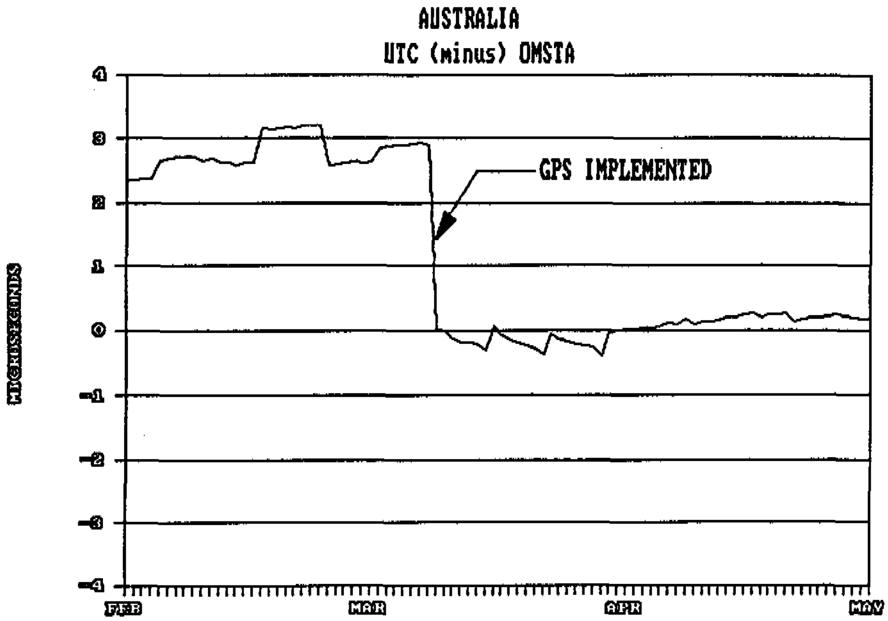
FIGURE 7



1987/88

GPS

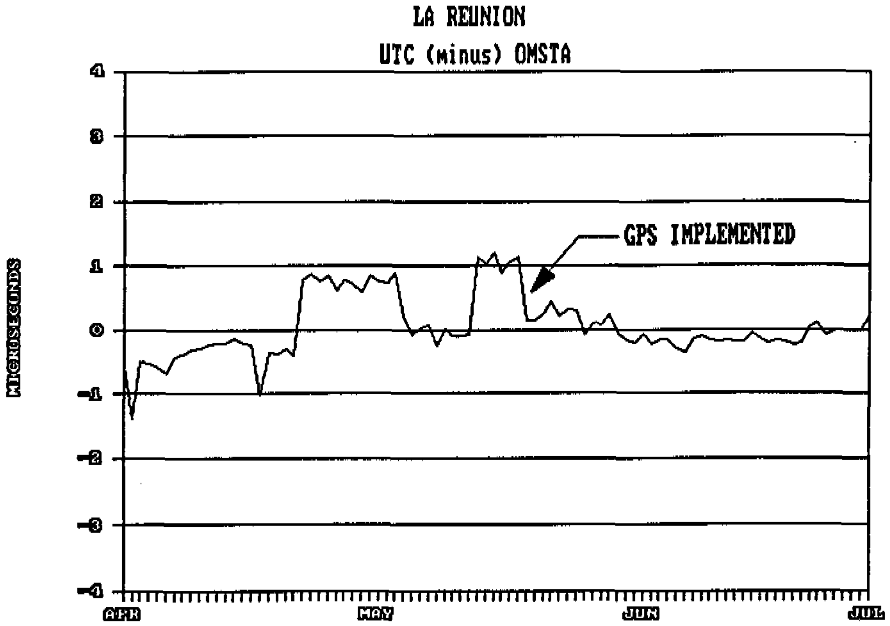
FIGURE 8



1988

GPS

FIGURE 9



1988

GPS

FIGURE 10

QUESTIONS AND ANSWERS

DR. GERARD LAPACHELLE, UNIVERSITY OF CALGARY: Could you summarize for us the improvement in accuracy for Omega due to GPS timing. Both for the absolute mode and also confirm or not confirm as to whether a gain in accuracy is obtained when operating in a differential mode.

MR. VANNICOLA: The accuracy is proven by the plots. We can maintain the stations to well within a half microsecond of UTC. Right now we are going through a process of improving our PPC's (Propagation Prediction Correction) for the diurnal change which are hard to predict because about 50% of them are going through some sort of diurnal change all the time. We are going to try to make available to the public better PPC's.

DR. LAPACHELLE: Did the two–dimensional accuracy improve for the typical ship–borne or air–borne user due to the improvement in GPS timing?

MR. VANNICOLA: I don't think that you would have noticed that. The errors in navigation are mostly propagation. Timing has improved, but not navigation. I will say this–we are not going to GPS as an external timing system solely. This was proven in September, when GPS decided that they were going to change the format. Our receivers were not able to receive the timing signals. We plan to correct the PPC's on a baseline, then pull out the external input and see how close we maintain it.