SYNCHRONIZING LORAN-C MASTER STATIONS TO COORDINATED UNIVERSAL TIME

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ABSTRACT

In 1987 the Coast Guard, anticipating Public Law 100-223, began improving the synchronization of its Loran-C master stations. Two parallel approaches were begun. One was to develop a hardware addition to the master station's frequency standard rack to provide timing offsets and maintain synchronization with Coordinated Universal Time (UTC) using GPS timing receivers. The other was to examine administrative methods to improve the master station synchronization as reported by the U.S. Naval Observatory (USNO). Three such methods were studied: frequency control, time step control, and modified master station control. These methods were used at three Loran-C master stations: Seneca, NY, Dana, IN, and Malone, FL. All three methods achieved significant synchronization improvement. Key improvement factors were timely and precise time-difference offset reporting by USNO and no-notice timing corrections by the Coast Guard.

INTRODUCTION

The Coast Guard began improvements to the synchronization of its master stations in anticipation of Public Law 100-223, Section 310 (1). This law requires the Coast Guard to synchronize all Loran-C master stations in the United States to within approximately ±100 nanoseconds (ns) of Coordinated Universal Time (UTC). An accurate and timely method of time transfer from UTC, as maintained by the USNO, to the Loran-C master station's time is one of the keys to successful compliance with the law (2). In March 1987, the Coast Guard began studying two ways to improve the synchronization of its Loran-C master stations:

The first approach was a study conducted by the Coast Guard Electronics Engineering Center, Wildwood, NJ, (EECEN). The EECEN was tasked to develop an addition to the frequency standard rack to provide precise time using the GPS system to transfer time between USNO and the Loran-C station (LORSTA). The EECEN would also study and evaluate methods of coordinating Loran-C time with GPS time to within ±30 ns. Their equipment would be used to monitor and steer the local cesium oscillators, keeping them synchronized to UTC.

The second approach was a series of experiments using administrative techniques to steer the master station's clocks. The Coast Guard believed that it could approach 200-ns synchronization using the administrative method and, possibly, 100-ns synchronization as the techniques were refined.

Results

The result of these two approaches is that Loran-C offsets have been held within ±100 nanoseconds of UTC to confidence levels ranging from 67% to 78% for the four Loran-C chains in the lower 48 states (Northeast U.S. (NEUS), Southeast U.S. (SEUS), Great Lakes (GLAKES), and the U.S. West Coast (USWC)) since 1 May 1989. For the NEUS, SEUS, and GLAKES Chains, these offsets are daily averages of measurements comparing Loran-C signals received at USNO, Washington, D.C. with the USNO master clock. For the USWC chain, the signal is received at a USNO supported Precise Time Reference Station (PTRS) at the Naval Weapons Testing Center, China Lake, CA, and linked to the USNO master clock via GPS time transfer. These chains were chosen for their proximity to USNO monitoring facilities.

The remaining chains required by law to be synchronized to UTC are the Canadian East Coast (CEC) chain, the Gulf of Alaska (GOA) chain, the Central Pacific (CENPAC) chain, the North Pacific (NORPAC) chain, and the two midcontinent expansion project (MEP) chains: the North Central U.S. (NOCUS) and South Central U.S. (SOCUS) chains. Synchronizing the master stations of these chains requires adding to or upgrading USNO PTRS facilities. The Coast Guard intends to include the LABSEA chain, the Canadian West Coast (CWC) chain and the required CENPAC chain, with minimal equipment additions.

This report discusses the administrative efforts from the standpoints of performance, procedures and future recommendations.

IMPROVING THE SYNCHRONIZATION OF LORAN-C MASTER STATIONS ADMINISTRATIVELY

Improving the synchronization of Loran-C master stations using administrative techniques was one of the least expensive alternatives the Coast Guard considered feasible. It could also be implemented quickly at selected chains.

The USNO proposed one method of improving synchronization, and the Atlantic Area Regional Manager (responsible for the NEUS, SEUS, GLAKES, CEC and LABSEA Loran-C chains) proposed two methods.

USNO Proposal

The USNO proposed to develop a steering algorithm to steer the master operate oscillator. This technique uses frequency changes to maintain synchronization. It was tested at LORSTA Seneca, the master station of NEUS.

Atlantic Area Proposals

The first proposal from the Atlantic Area Regional Manager was to retain the current method of controlling master stations and to reduce the offset data averaging period from 30 days to 3. This involves making a combination of time steps and frequency adjustments to the master operate oscillator to maintain synchronization. It was decided to test this technique at LORSTA Malone, the master station of SEUS.

The second proposal from the Atlantic Area Regional Manager was to use daily time steps to "zero" the master station's daily offset. The record of offsets and subsequent corrections would then be used to calculate monthly frequency adjustments to reduce the magnitude and frequency of the time steps needed to maintain synchronization.

To maximize the performance of the new techniques, the Coast Guard suspended the requirement to issue prior user notification of timing corrections being made to the master stations. The Atlantic Area Regional Manager solicited objections to removing the prior notification requirement and received no response. Therefore, the plan was implemented.

GENERAL ASSESSMENT OF SUCCESS

The Frequency Control Method used at LORSTA Seneca

The USNO is responsible for reporting the timing offset of Loran-C master stations. To do this, USNO compares the arrival time of a Loran-C master signal to the station's time of coincidence (TOC) with the universal second. A modeled propagation time and equipment delay from the station to the monitor point is subtracted from the time difference, or offset, to move the time reference to the master station. The offset data are then averaged over a day. The average offset is published daily in USNO's Series 5 report and biweekly in their Series 4 report. This process is used to monitor all Loran-C master stations under the jurisdiction of the United States. For LORSTA Seneca, USNO uses its PTRS in Washington, DC to directly monitor LORSTA Seneca's signal.

The USNO began by averaging LORSTA Seneca's offset data for 4 days and, based on the averaged data, recommended a frequency correction, if necessary. The correction was entered in a special Electronic Bulletin Board (EBB). At a predetermined time, the watchstander at LORSTA Seneca called the EBB to obtain the day's correction. If a correction was recommended, the watchstander entered the correction and confirmed its entry with the EBB.

The performance of this method is shown in Figure 1. Performance statistics from USNO's steering method are listed in Table 1.

Improved Synchronization at NEUS			
From	To	Mean usec	Sigma usec
Jan. 1, 1988	May 25, 1988	−0.26	0.65
May 25, 1988	Oct. 14, 1988	−0.045	0.139
Oct. 14, 1988	Jan. 17, 1989	−0.109	0.130
Jan. 17, 1989	May 15, 1989	−0.023	0.160
May 15, 1989	Aug. 17, 1989	−0.031	0.061

Table 1. The Synchronization Performance of Loran−C Station Seneca.

The period from 01 January 1988 through 25 May 1988 shows LORSTA Seneca's performance before 4-day averaging began. The USNO began calculating steering corrections on 03 May 1988. During the start-up period, LORSTA Seneca's offset was reduced approximately 5-fold, as shown in Figure 1. The improvement lessens during the winter of 1988, from 14 October 1988 through 17 January 1989. On 17 January 1989, USNO reduced the minimum time between corrections from four days to three, resulting in another improvement. On 15 May 1989, USNO again decreased the minimum time between corrections from three days to one. The average offset improved somewhat as a result, and the standard deviation of the offset was more than halved.

The goal of this experiment, as with the others, was to attain a zero offset average and to minimize the standard deviation. As Figure 2 shows, about 84%

(79 of the 94 offsets plotted) of the offsets from 15 May through 11 August were within the ±100-ns limit of the law.

This experiment was successful. The offest of LORSTA Seneca went from a mean of -0.26 microseconds (usec) and a standard deviation of 0.65 usec before the improvement to a mean of 0.031 usec and a standard deviation of 0.061 usec after the minimum period between corrections was reduced to one day. This is more than a 10-fold improvement.

The Accelerated Coast Guard Master Control Method Used at LORSTA Malone

For the SEUS Loran-C chain (SEUS), the Coast Guard proposed to accelerate the current technique used to maintain master synchronization. Prior to this, daily offset data collected over a 30-day period were analyzed to determine if the station required a time step or frequency adjustment. The proposed technique reduced the 30-day period to about 3 days. The experiment was coordinated by the Coordinator of Chain Operations (COCO) for the SEUS. The synchronization improvement project was started at the same time as that for NEUS.

This method provided a significant improvement in LORSTA Malone's synchronization, as shown in Figure 3. Performance statistics of the technique used at LORSTA Malone are shown in Table 2.

Improved Synchronization at SEUS			
From	To	Mean usec	Sigma usec
Jan. 1, 1988	Oct. 14, 1988	−0.32	0.86
Oct. 24, 1988	Apr. 21, 1989	−0.029	0.188
Apr. 21, 1989	Aug. 17, 1989	−0.006	0.089

Table 2. The Synchronization Performance of Loran−C Station Malone.

The period from 01 January 1988 through 14 October 1988 shows LORSTA Malone's performance before the experiment, including the start-up period beginning on 03 May 1988. LORSTA Malone's synchronization improved significantly using this technique. The average offset was reduced 15-fold, with a 4-fold reduction in the standard deviation. On 21 April 1989 LORSTA Malone's operate oscillator was replaced, and this resulted in an additional 50% reduction in both average offset and standard deviation. The overall performance is shown in Figure 4.

The Time-Step Control Method Used at LORSTA Dana

The technique applied at LORSTA Dana used small time steps to maintain synchronization and occasional frequency adjustments to reduce the number and magnitude of the time steps. The watchstander at LORSTA Dana called the USNO EBB and examined the Series 5 report for the day's offset. If the offset was greater than ±50 ns, then the offset was "zeroed" using 40-ns time steps. The time steps and offsets were plotted, and frequency adjustments were made, as needed, after 30-days of observation. This technique has the advantage of being able to collect long-term drift data that can be used to steer the cesium frequency standards.

Figure 5 is a plot of offsets for LORSTA Dana, and it shows that synchronization improvement was almost immediate. Performance statistics of the system are shown in Table 3.

Improved Synchronization at GLKS			
From	To	Mean usec	Sigma usec
Jan. 1, 1988	Feb. 24, 1989	−0.08	0.64
Feb. 24, 1989	Aug. 17, 1989	−0.013	0.099

Table 3. The Synchronization Peformance of Loran−C Station Dana.

The period from 01 January 1988 through 24 February 1989 shows LORSTA Dana's performance before time-step control was begun. After the start-up period from 12-24 February 1989, this technique produced the largest improvement in the shortest time, nearly an 8-fold decrease in the average offset and a 6-fold decrease in the standard deviation. Figure 6 shows the synchronization performance. There is a gap in the data every weekend, giving a false periodic appearance to the offset plots. The gap occurs because USNO does not issue the Series 5 report on Saturday and Sunday.

Improving Synchronization at Other Loran-C Stations

After the Coast Guard observed the successes in the Atlantic Region, the Pacific Area Regional Manager began using the time-step control technique at LORSTA Fallon, NV, the master station of the USWC chain, on 12 February 1989. This is the same method used at LORSTA Dana. The USNO was unable to furnish daily offset reports with 10-ns resolution (the resolution of the offset reports for NEUS, SEUS and GLAKES) until 17 April 1989.

The offset plot in Figure 7 shows the 100-ns resolution of the offset data used to maintain LORSTA Fallon's synchronization. Note the sinusoidal seasonal drift common to Loran-C in this plot. Once USNO increased the precision of the reported offset data to 10 ns, LORSTA Fallon settled within the ±100-ns boundaries. Table 4 lists the progress of improving the synchronization of LORSTA Fallon.

Improved Synchronization at USWC			
From	To	Mean usec	Sigma usec
Jan. 1, 1988	Feb. 24, 1989	−0.151	0.61
Feb. 24, 1989	Apr. 27, 1989	−0.113	0.141
Apr. 17, 1989	Aug. 17, 1989	0.015	0.116

Table 4. Synchronization Performance of Loran−C Station Fallon.

Synchronization improved from a mean offset of -151 ns to one of 15 ns with a 6-fold reduction in standard deviation. The short period between the beginning of the synchronization improvement project (24 February 1989) and when USNO was able to publish daily offset reports with 10-ns resolution (17 April 1989) is not considered significant, but the later synchronization improvements are. Figure 8 shows the performance of LORSTA Fallon from 17 April 1989 through 11 August 1989.

OVERALL PROGRESS AND RESULTS

As shown above, the three techniques (USNO's frequency control (NEUS), modified master control (SEUS) and time-step control (GLAKES, USWC) all provide significant reductions in the synchronization offsets as reported by USNO. Table 5 shows the

Improved Synchronization Performance May 1, 1989 through August 17, 1989				
Station	Mean	Sigma	% of Daily Averages	
			< 100 ns	< 200ns
Seneca	−0.050	0.076	73.5	96.3
Malone	−0.012	0.089	61.8	100.0
Dana	−0.007	0.073	78.4	100.0
Middletown	−0.020	0.116	75.5	89.8

Table 5. Overall Administrative Synchronization Performance.

overall performance of the four master stations involved in the preliminary administrative effort to improve master synchronization with UTC. All four experiments gave synchronization offsets within ±100 ns at least 60% of the time. The data are from the summer of 1989. The effect of increases in propagation noise during the winter months is to be determined.

CONCLUSIONS

The administrative methods for improving Loran-C master station synchronization evaluated herein have been effective. They have reduced the offsets of the four experimental master stations to within ±200 ns of UTC 97% of the time. Average offsets were reduced to near zero values and, more significantly, the standard deviations were reduced to near 100-ns.

The Coast Guard will continue testing the three methods of improving the synchronization of Loran-C master stations. The administrative techniques will be refined, and further improvements are expected. This winter season should show the full capability of the methods, including their strengths and weaknesses.

LIMITATIONS OF THE ADMINISTRATIVE CONTROL METHODS

The synchronization improvements shown for the four chains tested are at the limit of feasibility, given the facilities available. Even these significant improvements must be viewed critically, for several reasons.

First, the synchronization experiments run by the four chains were developed to determine the best methods of synchronization and to identify problems. They may have to be further refined to satisfy long-term operational requirements for using synchronized signals.

Second, these results reflect the more quiet spring/summer propagation season and may hide the fact that synchronization accuracy depends strongly on the proximity of the PTRS and the master transmitter. Changes in overland propagation will probably increase the errors in synchronization accuracy. These errors increase with distance from the transmitter. To minimize propagation error for reliable synchronization, a PTRS should be located in the service area of each Loran-C master station and, ideally, it should be relatively close to the master. The receiver site at USNO is just marginally within the service area of the three chains discussed.

SUMMARY

Significant improvements have already been made in Loran-C synchronization to USNO UTC using only administrative techniques. If additional hardware techniques such as two-way satellite time transfer and environmental chambers to increase cesium frequency standard stability are also used, it is highly probable that the requirements of Public Law 100-223 will be satisfied, independent of how that law defines the synchronization confidence limits.

REFERENCES

1. Public Law 100-223, "Airport and Airway Safety and Capacity Expansion Act of 1987."

2. Interim Report #1, "Enhanced Interchain Timing," Coast Guard Electronics Engineering Center, Wildwood, NJ, 01 May, 1989.

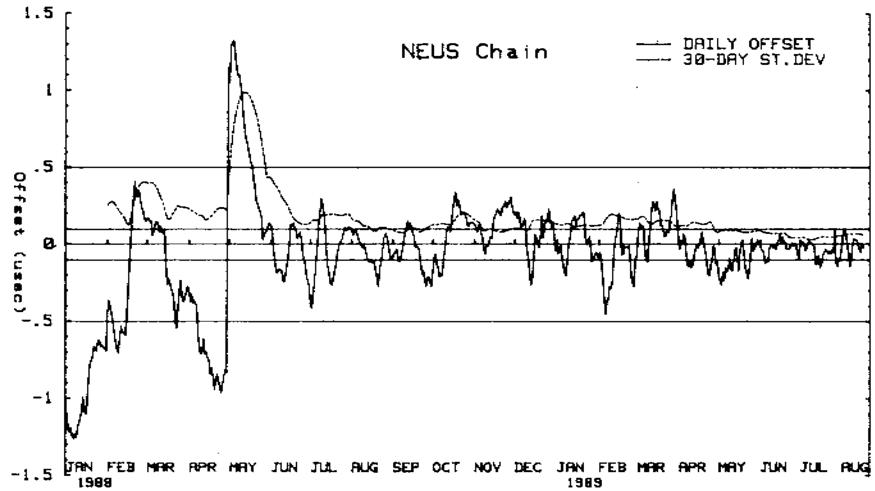

Figure 1. Offset Data for Loran-C Station Seneca, NY.

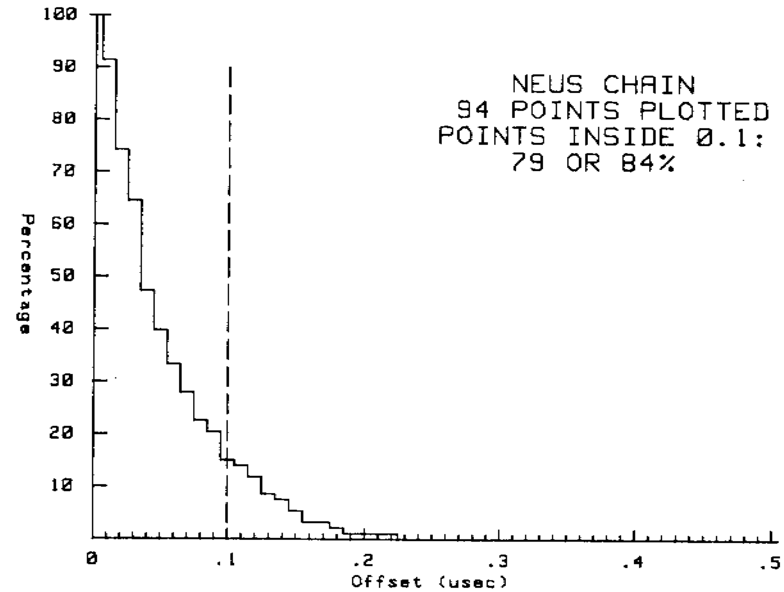

Figure 2. Percentage of Offsets Outside a Given Tolerance for LORSTA Seneca from May 15 , 1989 to August 17, 1989.

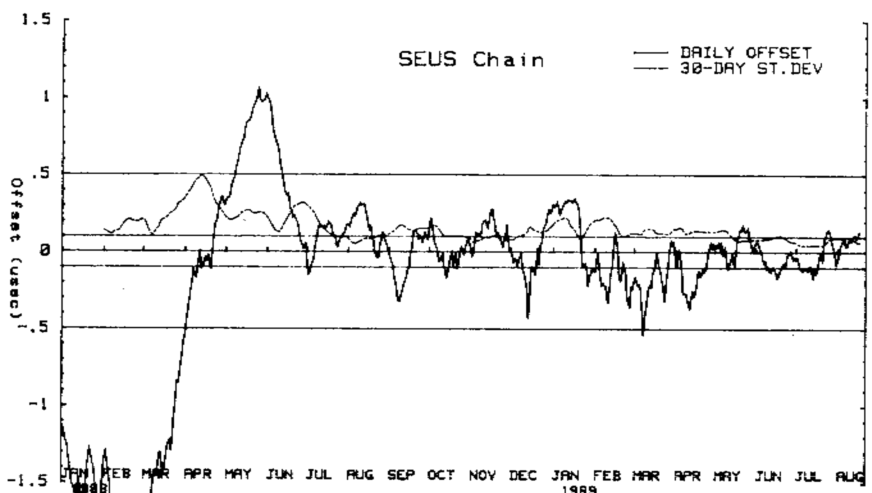

Figure 3. Offset Data for Loran-C Station Malone, FL.

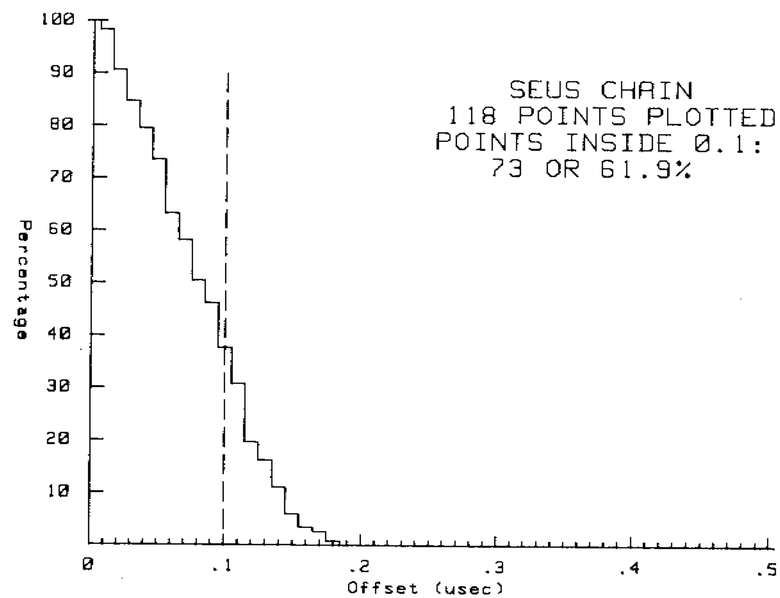

Figure 4. Percentage of Offsets Outside a Given Tolerance for LORSTA Malone from April 21 , 1989 to August 17, 1989.

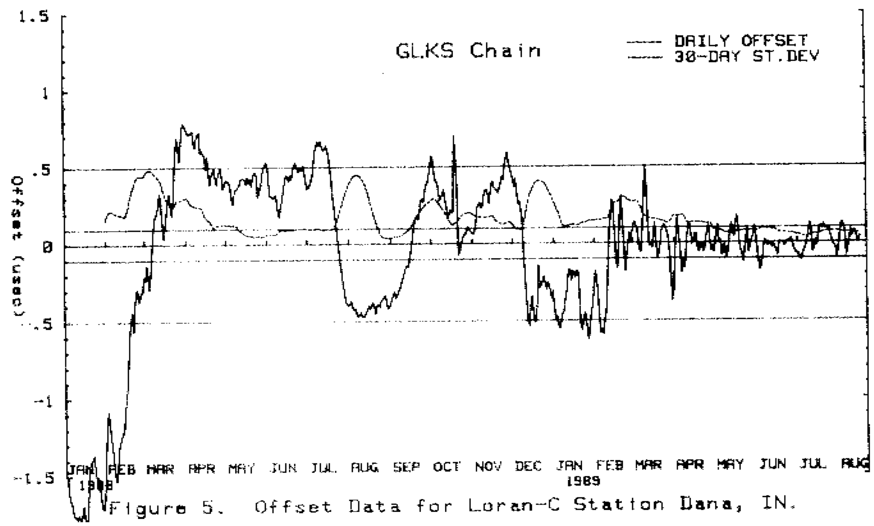

Figure 5. Offset Data for Loran-C Station Dana, IN.

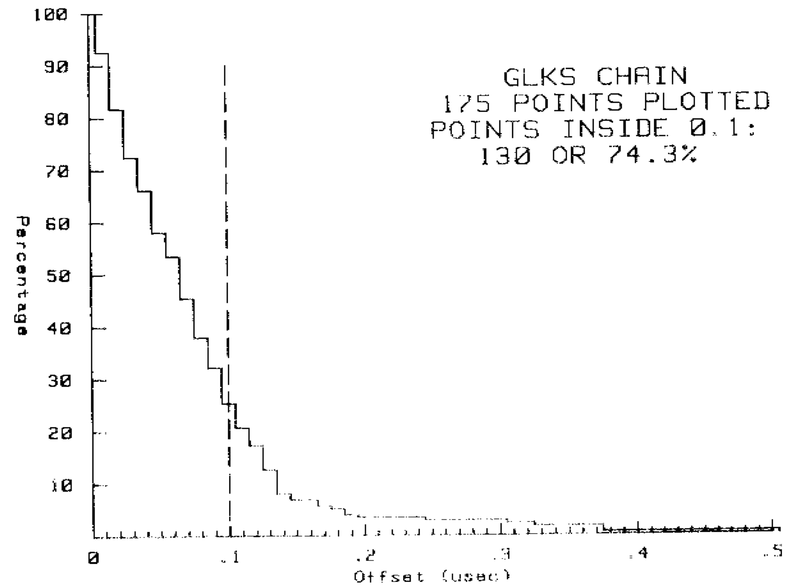

Figure 6. Percentage of Offsets Outside a Given Tolerance for LORSTA Dana from February 24 , 1989 to August 17, 1989.

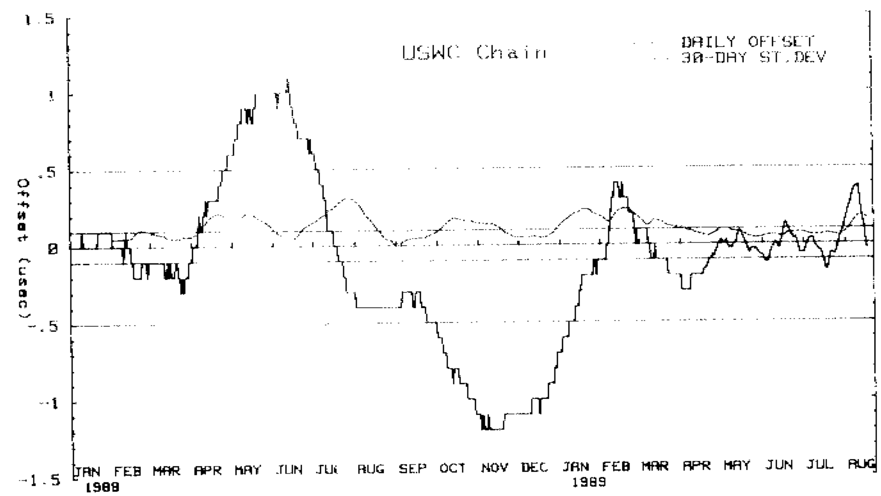

Figure 7. Offset Data for Loran-C Station Fallon, NV.

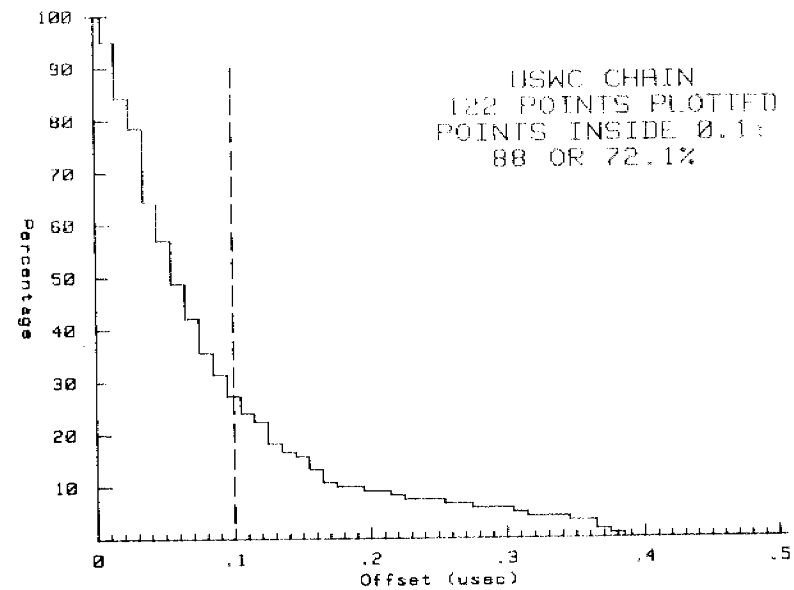

Figure 8. Percentage of Offsets Outside a Given Tolerance for LORSTA Fallon from April 17 , 1989 to August 17, 1989.