100ns SYNCHRONIZATION AND THE USERS OF LORAN-C

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ABSTRACT

As a result of the Airport and Airway Safety and Capacity Expansion Act of 1987, the Coast Guard is required to synchronize its master Loran-C transmitting stations to within 0.1 microseconds of Coordinated Universal Time (UTC) and to study the possible effects of synchronizing secondary Loran-C transmitting stations to UTC. There is a need to look into the benefits, costs, improvements and new procedures that will result from these new requirements. This paper will discuss some of the preliminary actions the Coast Guard is taking to meet the requirements of the new law.

INTRODUCTION

Loran-C was developed in 1952 to use cycle matching techniques to increase the accuracy of the Loran system. By using cycle matching and low frequency band (90-110 kHz), time difference measurements accuracies down to a few tenths of a microsecond. The marine navigation use of Loran-C grew quickly and became accepted as the standard radionavigation system for navigating the coastal confluence of the United States. The Loran-C system is based on a triad of transmitting stations in a chain. The master station transmits at regular intervals known as the Group Repetition Interval (GRI). After a finite delay, known as emission delay, the secondary stations transmit in sequence. The transmitting stations are usually designated by the order they transmit. Master (M) being first, then Victor (V) (five station chain), Whiskey (W) (four station chain), X-ray (X) (three station chain), Yankee (Y) and Zulu (Z) (1).

Presently, most receivers initially acquire and track the master station. Once the receiver is tracking the master station, it then seeks the secondary stations and tracks them. When the receiver is tracking the master and secondaries, it measures the interval between the reception of the master and secondary stations (2). These time differences may be displayed and used with a Loran-C chart, or the receiver may convert them into equivalent latitude and longitude or some other selected function (i.e. distance and bearing to a way point, course and speed, etc.). This method of using Loran-C is known as the hyperbolic mode and is derived from the family of hyperbolic LOPs that result from the time differences. It is the preferred mode of Loran-C navigation today. In this mode, best accuracies are obtained along the baseline (the line that connects the two stations) and worst near the baseline extensions (the line running past the stations). This is due to the direct dependence of the size of the error ellipse on the time difference (TD) gradient. The TD gradient is a minimum along the baseline and maximum near the baseline extension. This geometric limitation can be compensated for by adding stations to cover the baseline extensions (see figure 1).

Figure 1a. A single Hyperbolic Loran-C Pair Showing Baseline and Baseline Extension.

Figure 1b. A Hyperbolic Loran-C Triad with Estimated Coverage and Lines of Position.
Another way of navigating with Loran-C is to take advantage of its frequency stability and synchronization to UTC. The U. S. Naval Observatory has the responsibility of monitoring and reporting the synchronization of Coast Guard master Loran-C stations and is responsible for all precise time and time interval (PTTI) standards in the United States. In this mode the receiver predicts the time of transmission of a station's signal, then measures the time it takes for the signal to arrive. This travel time can be converted to a range to the transmitting station. Using ranges from two stations, the receiver can find its position. This method of using Loran-C is known as rho-rho. Figure 2 shows a typical rho-rho network (with an onboard clock, or alternately using a third station to obtain system timing information) with a rough estimate of the geometric coverage limits. One of the advantages of using rho-rho is in the flexibility in station selection. If the chains are closely held to UTC, the receiver is not limited to stations in one chain (of one GRI), but can select from the best available regardless of which chain they are in. However, the very stable timing reference needed to predict the transmission times can be rather expensive.

A compromise between hyperbolic and rho-rho receivers is the master-independent receiver which uses the master station of a chain only to acquire the stations and is then able to use secondary-to-secondary time differences in addition to master-secondary time differences for navigation. The master-independent receiver has the advantage over rho-rho receivers of not requiring an expensive time reference and over hyperbolic receivers of being able to use any three available stations for navigation (it will still provide a fix if the master is unusable)(3).

On December 30, 1987, the President signed public law 100-223, the "Airport and Airway Safety and Capacity Expansion Act of 1987" which required the Secretary of Transportation to synchronize master Loran-C transmitting stations, subject to the authority of the United States, to within approximately 100 nanoseconds of Universal Time (in actuality to be Coordinated Universal Time (UTC)). Included in the law was a requirement to study the possible effects on Loran-C users of also bringing the secondary stations to within about 100 nanoseconds of UTC, and to study the methods of coordinating Loran-C to within approximately 30 nanoseconds of GPS time. A goal of September 30, 1989 was established for synchronizing the master stations and reporting on the studies. The Secretary assigned the $1.35 million project to the Coast Guard and is being funded by the Federal Aviation Agency (FAA).

If the timing control of the secondary stations is to be changed, fundamental changes in the way the Coast Guard operates and controls Loran-C may be required. We anticipate little effect of the synchronizing of master stations on the traditional maritime user, however more drastic changes may be required if changes are made for the control of secondary stations. The Coast Guard has only started to look into these new requirements with research work being done at the Coast Guard Research and Development Center, the Coast Guard Electrical Engineering Center (ECECN) and with the Northeast U. S. Loran-C (NEUS) chain.

WHY TIGHTEN SYNCHRONIZATION?

Loran-C has been providing accurate navigation to the maritime user for more than 30 years. However, rho-rho, direct ranging and master-independent receivers would be more effective if the Loran-C
transmitters were synchronized to a common time reference. The possibility of using Loran-C in ways other than hyperbolic, prompted the creation of the law. Meeting the new requirement would enable the master-independent receivers to use cross chain time differences, increasing the number of Loran-C stations available to use. The master-independent receivers are presently limited to the stations in a single chain because the Coast Guard maintains the master stations only to within 2.5 microseconds of UTC. With the new requirement, the master to master synchronization should result in synchronization error reduction from within 6200 yards to within 70 yards.

General aviation use of Loran-C is growing rapidly. Since Loran-C has been provided primarily for the marine navigator, there are gaps in Loran-C coverage over the inland areas. The FAA is incorporating Loran-C into the National Airspace System as a radionavigation aid for enroute navigation and non-precision approaches. In addition to this synchronization project, the FAA is funding the installation of four Loran-C stations in the central U.S. to close the existing coverage gap. Even with the expanded capabilities of rho-rho receivers and master-independent receivers, will they be able to add needed coverage or redundancy to the stations in the continental United States? And if so, will the additional coverage or redundancy be worth the expense of changing the way the Coast Guard controls Loran-C?

POSSIBLE CHANGES

Synchronize only Master Stations. Synchronizing only the master transmitting stations should not have a significant affect on the present users of Loran-C. Synchronizing master more closely to UTC will not affect the control or relative timing of the secondaries to master. The present low frequency offset in the Loran-C signal to a signal with less offset, but more frequent corrections. Limiting the synchronization to master stations only will not require any change to the way the Coast Guard controls the Loran-C chain, but will add operational overhead and equipment maintenance costs to maintain the master synchronization.

The PTTI users of Loran-C should see an improvement in the precision of Loran-C. The offset of Loran-C to UTC will become more noisy in the sense that corrections to the operate oscillators will make more frequently (probably every few days). The Coast Guard would continue to use timing information from USNO and, perhaps GPS, to steer the operate cesium frequency standards to maintain synchronization to GPS, but would retain its independent frequency and time standard. The key improvement in the PTTI application will be the decreased timing offset between chains.

Rho-rho Navigation. By predicting when a transmitter transmits a signal and measuring the time the signals arrives at the receiver, the distance to the transmitting station can be determined. This method of using Loran-C does not require "chains" of transmitters to fix its position. It only needs two Loran-C transmitting stations to fix its position. This increases the flexibility in selecting transmitting stations to use for positioning. This is especially convenient when one of the stations being used is no longer available or if the master station goes off-air. In these cases the hyperbolic Loran-C receiver may become inoperable, but the rho-rho receiver user simply selects another available station and continues navigating.

One of the drawbacks of using rho-rho receivers is that rho-rho receivers require a highly stable time reference to predict the transmission times of the transmitting stations. The present 2.5 microsecond master-UTC synchronization

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1 All tolerances are assumed to be 2 sigma, or roughly 95% confidence.

2 Distance errors are calculated using the CEP-Rg5 method described in Gerald Y. Chin's "Two-Dimensional Measures of Accuracy in Navigational Systems," March 1987, Transportation Systems Center, Cambridge, MA 02141, Report number DOT-TSC-RSPA-87-1. The gradient is assumed to be the speed of light in free space. The crossing angle is assumed to be 30 degrees.
tolerance limits their accuracy to within 4100 yards because of the synchronization error. By reducing the master-UTC offset to within 0.1 microseconds, the error is reduced to about 200 yards. The main advantages for using rho-rho receivers are the flexibility in selecting transmitting stations to use and their expanded coverage area. For example, if the master station of a chain should go off-air, the hyperbolic receiver is useless, but the rho-rho receivers would continue navigating using the remaining secondary stations. This is the reason the Coast Guard no longer blinks the secondary stations when master goes off-air.

Synchronize Secondary Stations. The Coast Guard has only begun looking into the affect of synchronizing the secondary stations. It is presumed that the main impact on the present users of Loran-C will be in the final control method used to keep the secondary station synchronized to UTC.

A method of synchronizing the secondary stations to UTC under investigation involves using GPS timing receivers moving the monitor point to the transmitting stations. If the monitor points change, to implement the secondary synchronization, then the distribution of the grid in the coverage area may also change significantly affecting the current users of Loran-C. Currently, the monitor points "tie down" the Loran-C grid at a fixed point.

By changing the monitor points in the coverage area, the positioning grid is "tied down" in another area. The resulting redistribution of error could change the observed reference points used in many Loran-C charts and receiver software. This could have a significant affect on the traditional marine users of Loran-C and those using the repeatable accuracy of Loran-C for positioning. The study into the affect of synchronizing the secondary stations will assess the viability of extending the 0.1 microsecond synchronization to the secondary stations.

PRESENT EFFORTS

An Experiment With NEUS. An attempt to synchronize a master Loran-C station through strictly administrative (i.e. no additional timing equipment required) means is being made at the control station for the master of the Northeast U.S. Loran-C (NEUS) chain located in Seneca, NY. This may be the most cost effective method of meeting the master synchronization requirement of the new law.

Loran-C station (LORSTA) Seneca is monitored by USNO in Washington, DC. USNO, in addition to monitoring and reporting duties, calculates a recommended daily phase microstepper correction for LORSTA Seneca's offset from USNO's reference time and are placed on an electronic bulletin board (see figure 3). The station's onboard phase microstepper is used to make a fine adjustment to the output frequency of the cesium frequency standards. The Coordinator of Chain Operations (CCO) uses the bulletin board information and, at a specified time, enters the correction recommended by USNO. The preliminary results are encouraging (See figure 4).

After more than month of testing (offsets were recorded daily), the frequency offset has improved. Before the start of the experiment, LORSTA Seneca's offset from USNO averaged 0.57 microseconds, standard deviation of .36 (using USNO Series 4 reports for the period JAN88 to MAY88). One month after the experiment was started through August 1988, the average offset was reduced to 0.14 microseconds, standard deviation of 0.092 (JUN88 through AUG88 Series 4 reports). Although the standard set by the new law has not been met, the synchronization of LORSTA Seneca has improved significantly. Perhaps as the administrative procedures are refined as the experiment proceeds, the new synchronization standard may be met and exceeded. The ability of this method to synchronize master stations may well depend on the proximity of the USNO time service station to the transmitting station.

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requirement comes to bear, then a new system of synchronization will have to be developed.

An alternative to this would be to install a GPS timing receiver in the frequency standard rack at the Loran-C stations as a time reference for the operate cesium oscillator (see figure 5). Although, this would place the monitor point for the chains at the transmitting stations, it would be one of the simplest methods to implement in hardware. The GPS receiver would measure the operate cesiums offset and automatically insert corrections to the phase microstepper. This would allow for more frequent updates to the phase microstepper and eliminate external communications circuits between USNO and the station. This method could conceivably meet the 30 nanosecond tolerance of Loran-C/GPS interoperability, but would be more expensive and involve more changes than the administrative method being tried at LORSTA Seneca.

![Figure 5. Possible GPS Timing Receiver Controller for Loran-C Synchronization.](image)

Using a GPS receiver as a part of the frequency standard rack, this method of synchronization may be installed in all of the Loran-C stations. A single operational procedure would apply to all stations. USNO would still be tasked to monitor the timing offset of the Loran-C signals, but would not have to expend the additional resources to control the offset using the administrative method described for LORSTA Seneca. This hardware solution to synchronize Loran-C to UTC would reduce the human resource burden, but would increase the implementation equipment maintenance costs for this project. GPS timing receivers, although not as expensive as cesium frequency standards, are expensive (about $10K) and new training requirements would have to be established to support the new equipment. Of greatest concern would be the loss of two independent navigation systems. Coast Guard's EECEN is working on developing a Loran-C frequency standard rack that will incorporate a GPS timing receiver and expects to field test the new rack at two stations during the summer of 1989.