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Timing via the New LORAN-C System

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***Abstract*-In 1999, the United States Federal Radionavigation Plan extended the life of the U.S. LORAN-C system while the long term benefits as a GPS backup are investigated. Since 1999, U.S. Congress has continued to provide funds via the Federal Aviation Administration (FAA) to develop and recapitalize the LORAN-C infrastructure. As a result of this recapitalization, the timing systems at the LORAN-C transmitting stations are being upgraded from its 1960's technology. This paper re-introduces LORAN-C with an emphasis on the improvements that are being provided to the LORAN-C user community and the timing performance and applications of the new system. These improvements include new timing systems, new transmitters and new user equipment.**

The paper begins with an introduction to the LORAN-C Recapitalization Project (LRP). Next a comparison of the technology and performance of the new LORAN-C system and the existing systems is presented with an emphasis on timing performance. The new time and frequency equipment (TFE) suite is presented with details on the local timescale computation, UTC recovery, and transmitter timing adjustment loop. Performance of the new system will be presented from the factory acceptance testing and field trials. Additional details will be presented on the timing performance of the new transmitter. The paper concludes with a summary of the ongoing efforts and results from the LORAN-C Accuracy Panel.
Keywords: Loran, Timing transfer

I. INTRODUCTION

Long before GPS became a household name in the 1990s, another radionavigation system provided electronic navigation fixes, a form of time recovery and Stratum-1 frequency standards to the government, commerce and general public. That system is the terrestrial based network of transmitter stations known as LORAN. LOng Rang Aid to Navigation (LORAN) started in the 1940's to help guided bombers to their targets. The current form, LORAN-C, was introduced in the 1950's and made usable to the public while being operating by the US Coast Guard (USCG).

The surprise to many individuals is Loran-C is still operating today despite an early 1990's decision to shut it down after GPS became completely operational. Even more surprising, the entire Loran infrastructure is being recapitalized and studies to improve the system are being conducted by the Federal Aviation Administration (FAA) and Coast Guard. This large undertaking was started after many in the Department of Transportation realized that GPS needed a completely independent backup system especially in critical safety of life applications. The FAA and USCG partnered together to explore how Loran can be used in today's higher demand navigation environment compared to when Loran first started. The improve Loran system has demonstrated some initial great benefits as a backup to GPS for the timing and frequency users as well.

II. LRP BACKGROUND

The Loran Recapitalization Project (LRP) is composed of two separate paths. The first is upgrading the Loran-C infrastructure equipment with modern technology to mitigate shortcoming in Loran's ability to meet FAA's non-precision approach landing requirements as identified during the flights trials of the mid-1990's [1]. The FAA was looking for navigation provider to the many airports that don't have GPS backup system like ILS. Many of the shortcoming directly related to Loran transmitter equipment limitations such as timing stability of the old cesium clocks and availability of navigational signals due to old 1960's vintage tube-transmitter that are still used today.

A closely related second path of the LRP concentrates on researching methods to improve Loran and prove its ability to meet the very stringent navigation requirements of the FAA and USCG to be a backup to GPS. The reason for examining Loran as a backup was described in a Volpe GSP vulnerability report released on September 10th, 1999 that highlighted the fact that a back-up or redundant navigation and timing system is needed [2]. The report also stated that Loran has the greatest potential of being that system. The Loran evaluation has moved further to look at Loran being a GPS backup for numerous critical national infrastructure applications like providing timing and frequency standards.

The FAA desires for Loran to meet its Required Navigation Performance (RNP) 0.3 requirements for non-precision approach. These are same requirements for all electronic navigation systems including GPS. In RNP 0.3, the integrity component is the greatest challenge. The USCG desires for Loran to meet its Harbor Entrance & Approach (HEA) requirements. Here, integrity is not as big a concern as the absolute accuracy of the system.

The Loran team from FAA, USCG, many academia institutions and commercial entities started the process to redefine a Loran system usable for all transportation modes. In addition, the timing and frequency requirements have recently been included as part of the overall Loran requirements. The new system has been dubbed Enhance Loran.

III. LRP Status

The LRP is a project funded through the FAA while the USCG funds current Loran operations. The pace of the modernization is directly tied to the funding the FAA receives from Congress. Congress continues to support Loran initiatives through additional funds each year often over the amount requested for by FAA [1] (table 1).

As mention before the projects were to modernize equipment to correct shortcoming in the FAA trails. Table 2 lists the shortcomings by requirement category and the solution to mitigate the issue [1]. Often the new equipment can help solved issues from more than one category.

One of the first projects started under LRP was the Automatic Blink System (ABS). The ABS is a Loran-C signal integrity monitor. The ABS monitors transmitted signals ensuring their timing accuracy of compared to the cesium clock, signal strength is sufficient and correct phase code. These three parameters are critical to the computation of a navigation solution and time recovery. ABS equipment was installed and operational in each of the Loran stations by 1999.

The next project was the replacement of the cesium clocks. The old HP XXX had drift rate of 200 nanoseconds per day and larger than desired frequency jitter in the 5 Mhz signal that is the timing reference for the rest of the transmit equipment. All Loran stations have installed new HP 5071 cesium clocks. The new cesium clocks have a drift rate of 7 nanoseconds per day and greater stability in the 5Mhz-timing signal.

TABLE 1
Congressional Funding of LRP

Year	Funding ($Million)
1997	4.6
1998	3.0
1999	7.0
2000	10.0
2001	25.0
2002	19.0
2003	25.0

TABLE 2
Loran-C Trials Shortcomings

	Loran-C Issue	Solution
Accuracy	Old timing clocks	New Cesium clocks
	Old timing equipment	New timing suite
	UTC Synch	New timing suite with tighter control
Availability	Brief Power loss	UPS
	Tube overloads	New SSX
Integrity	Bad timing	ABS
Continuity	Brief Off-airs	New switch cabinets/UPS
	Tube overloads	New SSX

The continuity of the Loran signal is several degraded by power outages and power bumps of even a few seconds. Uninterruptible Power Supplies (UPS) have been purchased both for the operational control equipment and for transmitter itself. A 60kV UPS by APC provides a minimum of 20 minutes of back-up power. The transmitter UPS is a 600kV UPS by APC provides a minimum of 15 minutes of back-up power. Both units condition raw power from the grid preventing power bumps from shutting down the transmit equipment and minimize timing jumps in the timing control equipment. Each Loran station has dual power generators to take the load within 5 minutes of a power outage on the commercial grid. The control equipment UPS are already installed at all solid-state transmit stations. The transmitter UPS will be completed at solid state stations (SSXs) in by June 2003. The current tube stations will receive the UPS units when they are converted over to solid-state stations. Tube stations might receive control equipment UPS depending on how quickly the tube stations can be replaced.

The 14 tube-transmit stations proved to be the biggest hurdle for the FAA trials. These stations use 1960's vacuum tube technology that requires extensive maintenance resulting in station off-air time. The tube transmitters are also extremely prone to tube overloading or heat degrading performance both causing frequent off-air that effect continuity and availability. Megapulse, Inc of Bedford, MA won the contract to upgrade the station to solid-state stations. The new SSX improves on the current Loran SSX technology from the 1980s. The signal generator cabinets are twice as powerful as the legacy SSX. However, the greatest improvements are in the transmitter control console. The console includes a signal analyzer that examines the timing between pulse, pulse shape and many more features. Digital control loops uses the analyzed data to adjust the pulses in real-time. These control loops minimizes the transmitter jitter and pulse shape variance. The USCG installed the first new SSX at the Loran Support Unit in Wildwood, NJ and first operational site at LORSTA George in Washington state. LORSTA George is receiving the rest of the equipment in May 2003 with a goal of being operational in July 2003 [3-4]. LORSTA Dana, IN and LORSTA Fallon, NV are slated to be converted in CY2003.

IV. Timing & Frequency Equipment (TFE)

Another critical project to the LRP is the upgrade of operational control equipment. Timing Solution, Inc of Boulder, CO won the bid to build a system that incorporates all the functionalities of the current equipment (added over a 4-decade time span) as well as some new functionality. The new system is called the Timing and Frequency Equipment (TFE). TFE's major capabilities are divided into UTC recovery and timescale computation, Loran-C signal generation, timing measurements of transmitted signals, closed loop control, and ABS [5].

The UTC recovery and time-scale computation is one TFE's greatest new feature. TFE time-scales the three-cesium clocks into one "local" clock increasing stability. The time-scaled clock is then steered to UTC(USNO) via a GPS receiver. The station clocks are kept to 15 nanosecond rms of UTC(USNO) when GPS is available and have the ability to flywheel for weeks using a kalman filter when GPS is not available [6]. The unit stores clock differences and timing data giving them the ability to recovery back to exact time of transmission following power outages or system failures. These functions, like all of TFE functions, are completely redundant with two separate TFE units at a Loran station. The units continuously monitor their own health and the health of the cesium clocks notifying the operator of potential problems. The two units communicate with each other allowing for auto-fail over to a fully operational, in-tolerance standby unit from the online unit in case of equipment failure or OOT conditions.

A second new feature of TFE improves capability over the current method for timing adjustments to the signal. The legacy timing control equipment is limited to phase adjustments of 20 nanoseconds steps. These phase steps often lead to receiver momentarily losing frequency lock on the signal and poor timing resolution for absolute accuracy. The TFE uses a digital down synthesizer (DDS) for timing adjustments. The DDS allows for controlled frequency shifts that result in the ability to adjust the Loran signal's timing slowly, a rate less than a one nanosecond per second. The difference is the two method of timing adjustments is easily seen in Fig. 1. The legacy timing system steps the phase 100 nanoseconds in an instance. Whereas, the DDS adjust the phase by slowly adjusting frequency so the timing change is spread out over 360 seconds.

TFE's Automatic Phase Adjustments (APA) control loop takes advantage of the two previous features. The APA control loop measures the time difference between when the signal should have transmitted and actual transmission. If that time difference is greater than a minimum threshold then slow timing adjustments are entered using the DDS and an adaptive steer algorithm. The adaptive steer algorithm uses selectable parameters to optimize how quickly a signal can move without large jumps. An example of the control loop curve is seen in Fig. 2.

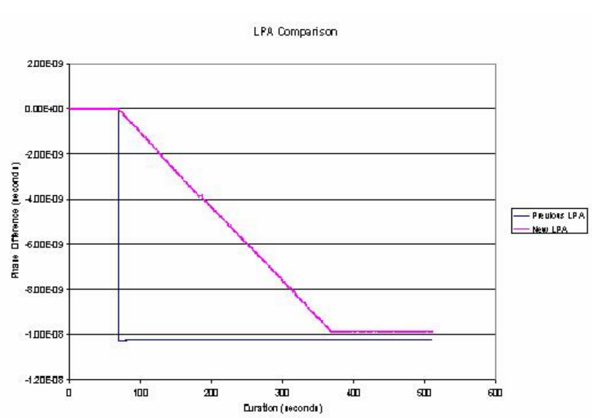

Fig. 1. Old verses new method of LPAs

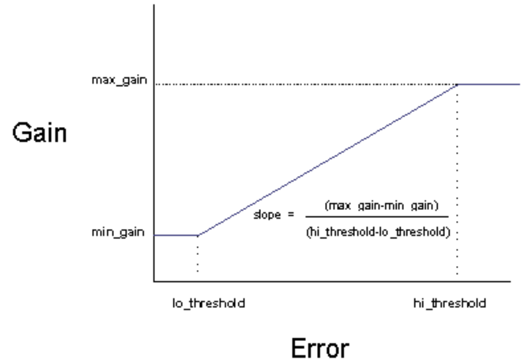

Fig. 1. Example of adaptive control loop curve

V. Enhanced Loran

As mentioned earlier, the FAA and USCG are evaluating Loran's ability to meet specific navigation, timing and frequency requirements. Two panels have been created to complete this large undertaking, the Loran Integrity Performance Panel (LORIPP) and the Loran Accuracy Performance Panel (LORAPP). The LORIPP is focused on Loran's ability to meet FAA's RNP 0.3 requirements which the integrity specification is the challenging aspect. The LORAPP is focused on the USCG's HEA and timing and frequency requirements where accuracy is the challenge category to meet. The panels work closely with each other since many of data and analysis cover both studies. There have been many papers published about their efforts [7-9].

An early conclusion of the panels, Loran will have to change in equipment, operational procedures and policies to meet the requirements as a multi-modal back up to GPS. Ideas and concepts in what the new Loran should include are examine for their impact on accuracy, availability, integrity, continuity and coverage. This group of concepts makes up Enhanced Loran.

We will focus on the key Enhanced Loran concepts that directly benefit timing transfer and frequency stability via Loran. The LORAPP put together a timing and frequency requirement list from a couple sources (figure 05).

TABLE 3
CURRENT TIME/FREQUENCY REQUIREMENTS

LORAPP--Timing and Frequency Requirements	
Frequency accuracy (target)	1 in 10^12 (24hr average)
Frequency accuracy (minimum)	1 in 10^11 (24hr average)
No external antenna	Desired
Backward compatibility	Desired
Integrity data	Minimum or no use of integrity flag
Higher accuracy time of day	Time Tag
Timing accuracy	100 ns (rms)
Source: DOT Task Force, T1X1 Ltr dated OCT02	

The requirements are not final and input is always welcome. One concept of Enhanced Loran is moving the control method from System Area Monitor (SAM) to Time of Transmission (TOT) [10]. TOT control has every station broadcast at a pre-arrange time with respect to UTC(USNO). The TFE suit provides the TOT capability, UTC synchronization and APA needed to change this operational procedure. A second concept is to develop a highly accurate Additional Secondary Factor (ASF) grid either by modeling or empirical measurements. ASFs are corrections to the wave propagation speed over Earth's surface much like GPS corrections for propagation through the atmosphere. The ASFs corrections for timing sites would be required for absolute timing but not frequency stability. The method to receive that correction has not been determined. One possible idea is through data modulation of the Loran signal, which is another major concept of Enhanced Loran being considered. It is know that the signal with some form of data modulation to improve integrity and accuracy for other requirements is required. The question remains of how much data and in what format. The answer determines the modulation scheme chosen. Like most Enhanced Loran concepts, the data modulation scheme affects the analysis of all the categories—accuracy, availability, integrity, etc… The time of emission and station ID will be broadcast in some form.

VI. Loran Time/Frequency Recovery

Initial data collection efforts with the purpose of determining how Enhance Loran can provide a backup to GPS have been encouraging. Time Recovery from Loran is historically done by receiving one station. The current SAM control prevents the use of more stations since they are not control to single reference. Fig 3 shows a 1-microsecond variation over a year in time recovery under the current Loran system. The large variation is due to the seasonal changes in propagation delay of the signal over Earth's surface.

The interesting observes in the high correlation of the signal from the same transmit station received at two sites approximately 400NM apart. The high degree of spatial correlation between two separate receive sites gives promise to using differential corrections to improve absolute time recovery. By "correcting" the signal received at Flagstaff, AZ with the signal received from Boulder, CO, the ability to recovery absolute time is reduce from 1 microsecond variation to 25 nanoseconds (rms) (Fig. 4). Thus, the use of differential corrections from a monitor sites could aid receivers in a large area around the monitor site.

Loran currently meets Stratum-1 frequency standards with room to spare. The seasonal variations are slow enough that they do not effect frequency recovery. The initial data illustrates Loran can almost meet the 10-12 frequency minimum established by the LORAPP (Fig. 5). A decent clock (Rubidium) is needed to average 24 hours smoothing out the frequency recovery. The installation of the TFE at transmits stations that reduce the discontinuities jumps during phase changes could reduce the averaging time and increase frequency stability.

The panels are exploring ways to maintain synchronization between Loran stations and/or UTC(USNO) should GPS be out for a period of time greater than a couple weeks. The concept is still in its infancy, and there are still many ideas on how it can be accomplished on the table. Since TOT control is a real possibility in Enhanced Loran, new receivers using all-in-view (vice signal Loran chain) and modern digital signal processing greatly enhance both navigation and timing capabilities.

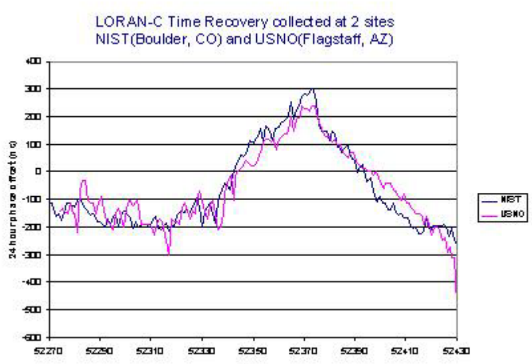

Fig. 2. Time recovery of LORSTA Boise City at Flagstaff, AZ and Boulder, CO

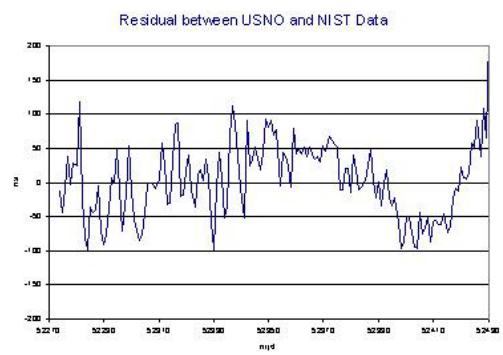

Fig. 3. Residue of correcting one site using the other site

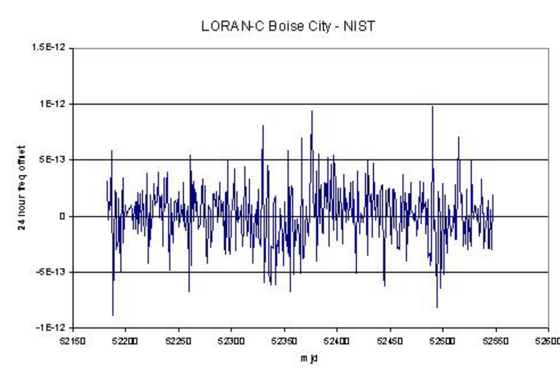

Fig. 4. Current frequency recovery peformance

Knowledge gained in time-of-arrival solutions from GPS receivers have been proven to work is an equivalent way with Loran navigation. Can the GPS timing techniques be used with Loran with positive results? It is a question that the LORAPP is looking at right now. A research test is underway to develop a timing algorithm to compute absolute time. We hope to present data and analysis of the test this fall.

CONCLUSION

- The LRP proceeds on schedule. The equipment is being designed with the flexibility to meet Enhanced Loran requirements with minimal change. This fact helps the business model for Enhanced Loran.
- The panels continue to move forward in the evaluation of Loran with amazing results. Papers are often presentation at each of the navigation conferences.
- If Loran stays around in the long-term it will not be the same Loran-C you know today. Every aspect of Loran will have some changes for Enhanced Loran to meet the requirements lay out before the panels.
- The panels are required to have their recommendations into the DOT's Navigation board by May 2004. This includes a near complete system design for Enhanced Loran.
- The LORIPP and LORAPP are open panels and any person or company may participate to the level they feel needed. If you are interested to be part of the Loran of the future, please contact us.
- A test to determine if GPS techniques can be used with Loran is underway with results published this fall.

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REFERENCES

1. "An Analysis of Loran-C Performance, Its Suitability for Aviation Use, And Potential System Enhancements", Federal Aviation Administration, Navigation Integrated Product Team AND-700, July 2002

2. "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System", John A. Volpe National Transportation System Center, August 20, 2001

3. G.K. Weeks, Jr. and K.M. Carroll, "Loran Modernization - The Roadmap to the Future", **Proceedings of the ION-NTM**, Anaheim, CA, January, 2003.

4. G. K. Weeks, Jr and J. M. Boyer, "Riding Down The Dusty Trail With The Four Horsemen", **Proceedings of the ILA-31 Convention & Technical Symposium**, Washington D.C, October, 2002.

5. T. Celano and K. M. Carroll, "TFE: The New Heartbeat of Loran", **Proceedings of the ILA-31 Convention & Technical Symposium**, Washington D.C, October, 2002.

6. S. R. Stein, "The New Loran C Time Scale & Possibilities for Future Enhancements", **Proceedings of the ILA-31 Convention & Technical Symposium**, Washington D.C, October, 2002.

7. Ben Peterson, Per Enge, Todd Walter, Sherman Lo Lee Boyce, Robert Wenzel, and Mitchell Narins, 'Hazardously Misleading Information Analysis for Loran LNAV,' **Proceedings of the 3rd International Symposium on Integration of Loran-C/Eurofix and Egnos/Galileo**, Munich, Germany, June 2002.

8. Sherman Lo, Per Enge, Lee Boyce, Ben Peterson, Tom Gunther, Bob Wenzel, Kevin Carroll, Kevin Bridges, and Mitch Narins, Certifying Loran for Aviation and The Loran Integrity Performance Panel, **Proceedings of the ION-GPS 2002**, Portland, OR, September, 2002.

9. Sherman Lo, Lee Boyce, Per Enge, Ben Peterson, and Bob Wenzel, "Loran for Required Navigation Performance 0.3: The Current Work of Loran Integrity Performance Panel (LORIPP)", **GNSS 2003**, Graz, Austria, April, 2003.

10. B. Peterson, K. Dykstra, K. Carroll and Mitch Narins, "The Development and Deployment of Receiver Technology to Evaluate Enhanced Loran Performance", **GNSS 2003**, Graz, Austria, April, 2003.