Modernized LORAN-C Timing Test Bed Status and Results

Tom Celano and Casey Biggs
Timing Solutions Corporation
4775 Walnut St
Boulder, CO
tpcelano@timing.com

Benjamin Peterson
Peterson Integrated Positioning
30 Pond Edge Dr
Waterford, CT 06385
benjaminpeterson@ieee.org

Lt (JG) Kevin Shmihluk
Loran Support Unit, USCG
12001 Pacific Ave
Wildwood, NJ 08260
Kevin.R.Shmihluk@uscg.mil

Abstract—**LORAN-C is being examined as a viable backup to GPS for timing and navigation. Accuracy from the LORAN-C network has always been limited by variations in the propagation delay of the 100 kHz LORAN pulse. Using common-view techniques that are commonly used in GPS, LORAN data can be corrected to improve timing accuracy. The USCG plans to transmit corrections in real time via a new pulse in the LORAN signal called the LORAN Data Channel (LDC).**

Initial testing was conducted using a 3 monitor network of Timing Solutions Corporation (TSC) in Boulder CO, NIST in Boulder CO and LORAN Station Gillette WY. This provided a short baseline between TSC and NIST and a long baseline between TSC and Gillette. This setup showed that even in the long baseline, LORAN-C could be used as a precision (sub 50 ns RMS) time recovery system in the western US.

Upon completion of the proof-of-concept test in Colorado and Wyoming, a second, more extensive experiment was initiated on the east coast where greater variations in propagation delay have been historically observed. Monitors have been configured at the LORAN Support Unit in Wildwood, NJ, the United States Naval Observatory in Washington D.C. and the Naval Research Laboratory in Washington D.C. These monitors collect data that will initially be post processed in a common-view LORAN solution between the different collection points. As the test progresses, corrections from some or all of these monitors will be transmitted via the LDC and processed in real time by the network of prototype receivers. This paper will present results to date on the east coast network and provide the schedule for the testing of real time corrections via the LDC.

I. INTRODUCTION

The United States Coast Guard's LORAN Support Unit (LSU) has been conducting a timing study over the last 3 years to determine if a modernized LORAN-C service can serve as a backup to GPS for precision timing users in the continental United States (CONUS). The study initiated with a feasibility analysis that was performed on historical LORAN data [1] to determine the applicability of common-view techniques used in GPS for LORAN timing. Upon successful results, a small 3 node network was used to collect LORAN data and post process for common-view time differences. This network, which included TSC and NIST in Boulder and LORAN Station Gillette in Wyoming provided data that showed time synchronization less than 50 nanoseconds (RMS) [2] over the long baseline between TSC and Gillette and less than 10 ns (RMS) over the short baseline between TSC and NIST.

With the viability of common view LORAN demonstrated on a best case network in the central United States (due to the minimal variations in propagation delay), a permanent test bed was established in the eastern United States to process common view LORAN data in a more challenging environment. This paper details the current status of the test bed, presents initial results and future plans.

II. LORAN AS A GPS BACKUP

A. GPS Vulnerability

The Global Positioning System (GPS) has a near monopoly on timing and navigation users in the United States and beyond. This market dominance is the understandable outcome of a superior system. GPS is an outstanding service that can provide time synchronization to UTC(USNO) at commodity prices. Combining performance and price with global availability has led to an unprecedented monopoly on timing users.

While GPS is the obvious first choice for time and frequency users, there is no obvious second choice for users who prefer redundant means for time and frequency recovery. The known vulnerabilities of receiving a low power signal from space include accidental or purposeful jamming and spoofing. It is well established that GPS can be jammed over a large area with a small, easily concealable device that would be difficult to locate and eliminate [3]. This concern has led to increased interest in fielding an alternative service that will complement GPS with different failure mechanisms and adequate performance to fill in gaps in GPS coverage.

B. LORAN-C as a GPS Backup

Legacy (existing) LORAN-C's viability as a GPS backup was examined by the LORAN Accuracy and Performance Panel (LORAPP) that is co-chaired by the USCG and the FAA. The advantages of using LORAN-C as a GPS backup include:

- Existing Transmitter and Monitor infrastructure
- Maintained by a US Government agency with an established operational budget
- LORAN-C is a high powered ground wave with different failure mechanisms than GPS. LORAN-C is extremely difficult to jam or spoof
- LORAN-C has potential for indoor reception without an exterior antenna

The disadvantages of using LORAN-C as a GPS backup include:

- Timing and Navigation performance is not sufficient to backup GPS
- Obsolete equipment at transmitter and monitor sites
- No leap second or time-of-day information in transmitted signal
- Minimal data integrity information

The advantages of an existing infrastructure and resistance to jamming make LORAN-C a worthy investment to solve the disadvantages and recast the service as a GPS backup.

The LORAN Recapitalization Plan (LRP) was launched in 1997 to address the deficiencies that limit LORAN-C as a GPS backup. As of 2005, all of the CONUS LORAN-C transmitting stations have been updated with new timing systems, new transmitter equipment (at the sites that still had vacuum tube transmitters) and new command/control equipment. The LRP continues to fund efforts to enhance LORAN-C's performance in the areas of timing and/or navigation. This includes changes to the LORAN service and/or signal that improve LORAN's performance by limiting or compensating for the impact of propagation delay effects.

The LORAPP established the key requirements that should be met in order for a modernized LORAN-C to serve as a GPS backup. These requirements, summarized in Fig. 1, include performance levels that the legacy LORAN-C system has never met including transmitting time-of-day information and providing time synchronization to UTC(USNO) at the sub 100 ns (RMS) level. Once the requirements were determined, it was clear that the existing LORAN-C service needed to change in order to provide these new capabilities. The primary change is the creation of the LORAN data channel (LDC) in the LORAN signal structure.

C. Differential LORAN-C and LDC

The LORAN Data Channel is a new pulse that will be added to the existing LORAN signal in order to communicate information about the LORAN signal to users [3]. The LDC pulse is pulse position modulated between 32 states to communicate 5 bits for each group repetition interval (GRI). The LDC will be used to communicate the following information to LORAN users:

- Time-of-day information
- Leap second information
- Station identifiers
- Monitor information

Performance Requirement	Value
Frequency Accuracy (target)	1 x 10^{-13} averaged over <24 hours
Frequency Accuracy (desired)	1 x 10^{-12} averaged over <6 hours
Frequency Accuracy (minimum)	1 x 10^{-11} averaged over <1 hour
Antenna	No External Antenna (desired)
Legacy Use	Backward Compatibility (desired)
Integrity Data	Minimum "Use/No Use" flag
Timing Data	Time Tag, Leap Second Info
Timing Accuracy at the user's receiver	< 50 nsec (Goal), <100 nsec (min)
Differential Data Update Rate	< once/hour

Figure 1: LORAPP Timing Requirements

Time of day and leap second information enable LORAN-C user receivers to produce time codes such as IRIG-B and to provide time information to computers using Network Time Protocol (NTP). Station identifiers are useful for all-in-view algorithms so that each LORAN station can be viewed without tracking other stations in the same LORAN chain. Monitor information allows user equipment to remove temporal variations in the received signal to improve LORAN timing and navigation performance.

The temporal variation of the velocity of propagation of the LORAN-C pulse on the Earth's surface must be removed in order to perform precision (< 100ns RMS) time recovery using LORAN-C. In the modernized LORAN system, this will be accomplished using monitor sites that compute corrections which are then transmitted to the users via LDC. Fig. 2 shows two different monitors that can be used to compute corrections. The first monitor is a USCG operated monitor site. This site has UTC via two-way time transfer or other means and tracks LORAN-C signals to determine the necessary time adjustment to put the signal on-time. This correction is sent via the USCG private network to the transmitter site where it is encoded and transmitted via LDC. User equipment demodulates and decodes the LDC message and applies the appropriate correction (initially this could be as simple as using the closest monitor site) to remove the temporal variations. The second monitor site shown in Fig. 2 is a local monitor. Local monitors will be used by LORAN users who want to optimize timing or navigation performance over a region such as a test range or city. Previous results have shown that the use of local monitors can result in time recovery performance that rivals GPS using short baselines (10-20km).

III. LORAN TIMING TEST BED

The LORAN Timing Test Bed was established in June, 2005 to support LORAN timing testing on the east coast of the United States. The test bed currently includes data collection sites at the following sites:

- LORAN Support Unit, Wildwood NJ
- USNO, Washington DC
- NRL, Washington DC
- Fort Monmouth, NJ
- Volpe Center, Boston MA

The LTTB will be used over the next year to collect LORAN timing data for that will be processed to verify and exercise the new functions in LORAN.

The network will initially be used to run tests to determine the expected performance levels for differential LORAN (using post processed data) in a geographic area that has been historically challenging for LORAN. The challenge is created by the weather patterns and mix of land and sea paths that are encountered on the east coast.

As new equipment becomes available to generate LDC from a LORAN transmitter and to process the LDC information in a data-capable LORAN receiver, the test bed will be used to collect real-time differential LORAN data. Initial on-air tests will involve processing differential data from LORAN transmitters in real time to evaluate and potentially refine the LDC messages and algorithms before finalizing the new LORAN signal specifications. The test

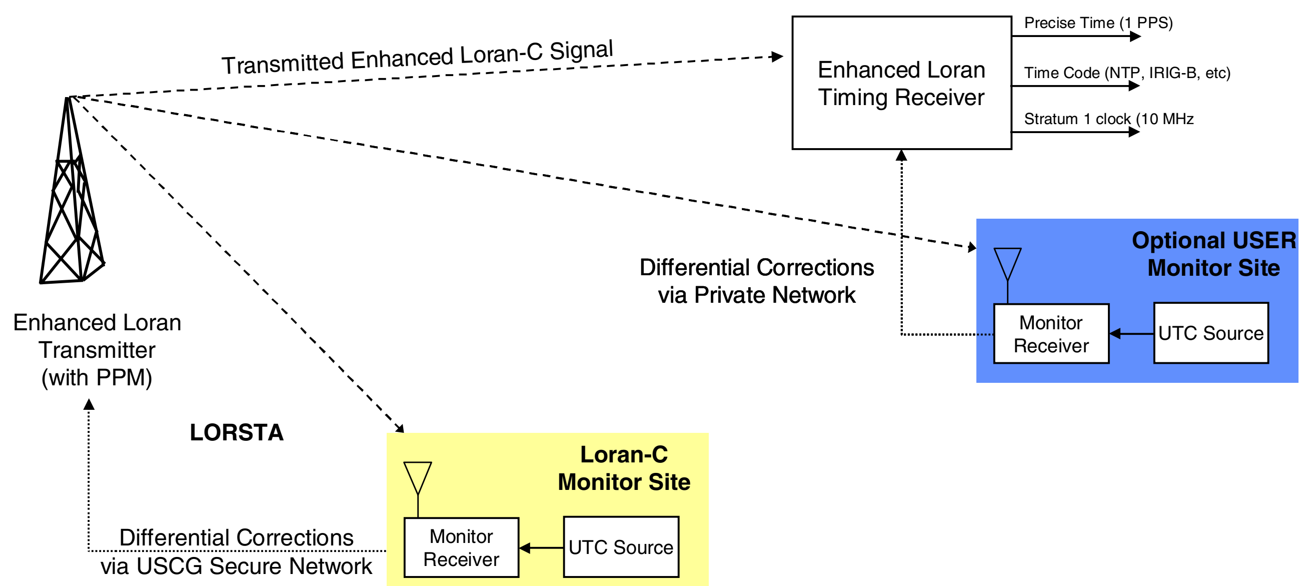

Figure 2: Monitors for Differential LORAN

bed will also be used to conduct on-air tests with new LORAN functions (such as leap second and time-of-day broadcast) in a test environment to verify new capabilities prior to transitioning to operations. Finally, the test bed will be maintained to collect long term timing data from established timing facilities such as USNO, NRL and DoD test ranges.

A. *Initial LTTB Test Data*

Continuous LORAN data has been collected at LSU and USNO for a three month period beginning in June, 2005. At each site, an independent source of UTC is used to evaluate the performance of the LORAN receiver. Fig. 3 shows the equipment setup used between USNO, NRL and LSU. At USNO, UTC is available directly without the need for a time recovery system. At LSU, a steered GPS system (called TFE) is used as the GPS source. GPS common-view data is collected between USNO and LSU for use as truth. LORAN data is collected every minute and post-processed for common-view solutions by transmitter and rate.

Fig. 4 shows the comparison of common-view (differential) LORAN and uncorrected LORAN using GPS as truth where all three data types are aligned at the beginning of the collection period. The uncorrected LORAN data in Fig 4 is a single transmitter/rate (Nantucket 9960X) received at LSU in Wildwood, NJ. The differential LORAN data in the plot is the common-view calculation between LSU and USNO. This differential solution models the scenario where the data collected at LSU is corrected using a monitor at USNO. The uncorrected LORAN timing data is impacted by the changes in propagation delay between the transmitter and the receiver. The corrected data does not exhibit these variations and compares to within 20 ns (RMS) with the GPS data used as truth. Fig 5 shows a similar comparison between common-view LORAN and common-view GPS with the same receivers at LSU and USNO tracking the Carolina Beach transmitter at 9960Y.

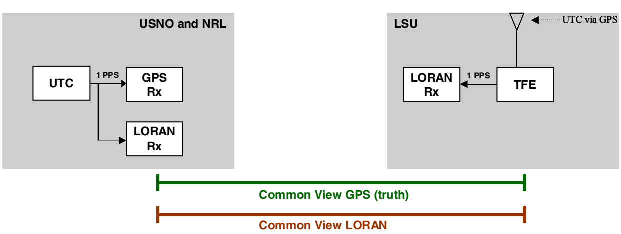

Figure 3: Equipment configuration for LTTB data collection

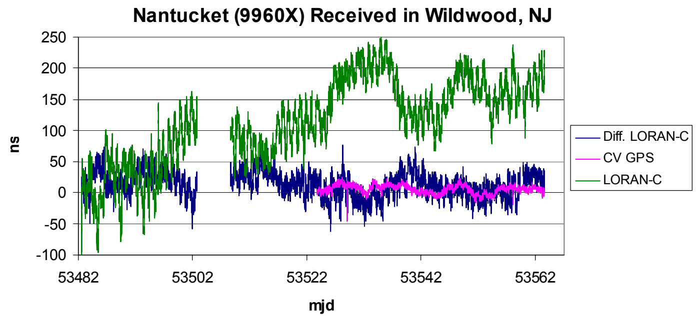

Figure 4: Legacy LORAN-C, Differential LORAN-C & GPS timing data

The data in Fig. 4 and Fig. 5 shows that a LORAN monitor for time corrections is effective over a large area with differing geography. In this case, the monitor at USNO is 120 miles away from the receiver at LSU. The signal from Nantucket has an all seawater path to LSU but has to cross land (and additional water) before reception at USNO. Similarly, the signal from Carolina Beach has path differences between the two reception sites. Even with these differences, the standard deviation is less than 25 ns (RMS) for both transmitters. As the transmitters become more distant (and SNR goes down), the performance is not as good. Fig. 6 shows the common-view data for the same collection baseline for the Jupiter, FL transmitter.

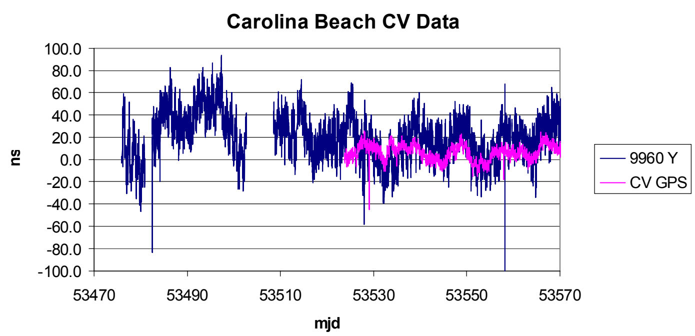

Figure 5: Differential LORAN-C data and GPS data

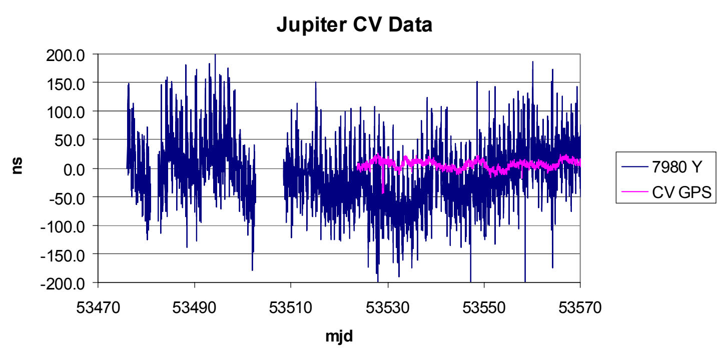

Figure 6: Differential LORAN-C and GPS data

Fortunately, for timing applications tracking 1 transmitter is sufficient and 2-3 is sufficient for a robust solution.

B. Frequency Performance

Legacy LORAN-C has been historically used for frequency recovery much more than time recovery. The slow changes in propagation delay don't affect the frequency applications as much as the time applications. The use of common-view processing for LORAN-C is not as beneficial to frequency users who are interested in achieving frequency performance with averaging times of hundreds or thousands of seconds. Fig. 7 shows a modified Allan deviation plot of the legacy LORAN-C data collected at LSU from the Nantucket transmitter. Fig. 8 shows the modified Allan deviation plot of the common-view LORAN-C data collected at LSU and corrected with USNO data for the Nantucket transmitter. The performance is comparable for averaging times less than a day but is beginning to show the benefit of the common-view correction at averaging times longer than 1 day. More data is required before any conclusions can be reached but it is expected that the common-view correction will provide better frequency performance at longer averaging times by removing the long term phase changes due to propagation effects.

C. Future Plans

The LTTB will be used extensively in 2005 and 2006 to demonstrate the new capabilities of a modernized LORAN-C system.

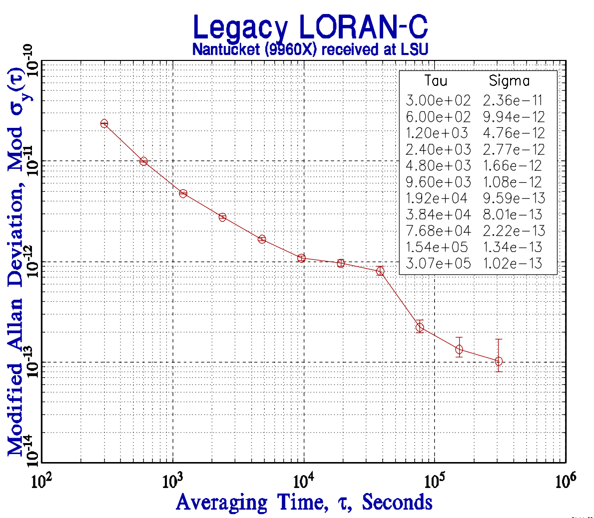

Figure 7: Frequency Recovery with Legacy LORAN-C

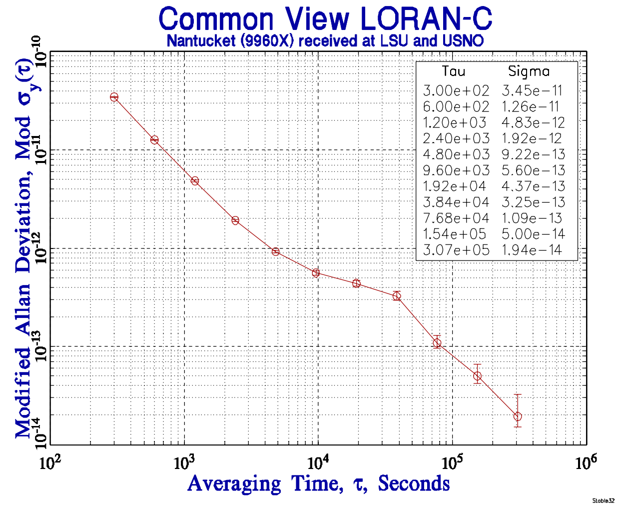

Figure 8: Frequency Recovery with Common-View LORAN-C

Testing will be conducted in the following areas:

- Time of day Recovery: Ability to set IRIG-B and NTP using the modulated information in the LORAN-C signal.
- Leap Second Testing: Ability to recover leap second prediction data and track time through a leap second.
- GPS Jamming Testing: Ability to continue to track LORAN-C and recover time and time-of-day while GPS is denied.
- Real-time common view: Ability to steer a 1 PPS in real time to within 100 ns (RMS) of UTC(USNO) using monitor correction data that is transmitted via LDC.

The LTTB testing will be supported by a combination of national laboratories, academic institutions and military organizations and contractors. Results will be published in timing and LORAN forums as they are completed.

IV. SUMMARY

Testing with a modernized LORAN-C system and signal continues with the goal of establishing LORAN-C as the primary backup to GPS for time and frequency users in the continental United States. Data has been collected on the east coast that demonstrates LORAN-C's ability to recover time at the 20 ns (RMS) level using a common-view solution over a 120 mile baseline. This initial data points to a differential LORAN-C service that will enable precision time and frequency recovery in the United States with different failure mechanisms than GPS. A LORAN timing test bed has been established and will be used over the next year to demonstrate a series of new capabilities for the modernized LORAN-C system. These new capabilities include recovering time of day, administering a leap second and real time precision time recovery.

REFERENCES

[1] K.M. Carroll, T.P. Celano, “Timing Via the New LORAN-C System” in Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibit Jointly with the 17th European Frequency and Time Forum, 5-8 May 2003, Tampa, Florida, USA, pp. 245-249.

[2] T. Celano, K. Carroll, “Common view LORAN-C as a backup to GPS for precise time recovery”, in Proceedings of the 35th Annual Precise Time and Time Interval Systems and Applications Meeting, December 2003, Mission Bay, San Diego

[3] D. van Willigen, “The challenge in finding your position in a world hostile to radionavigation”, *Proceedings of the ILA-32 Convention and Technical Symposium*, Boulder, CO 3-7 November 2003.

[4] B. Peterson, K. Dykstra, P. Swaszek, K. Carroll, ”Differential LORAN”, *Proceedings of the ILA-32 Convention and Technical Symposium*, Boulder, CO 3-7 November 2003.