

COMMON-VIEW LORAN-C AS A BACKUP TO GPS FOR PRECISE TIME RECOVERY

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Abstract

The LORAN-C network is being recapitalized to serve as a backup to GPS for navigation and timing. LORAN-C is being investigated as a precision (sub 100 ns) time recovery system for use in the continental United States. Traditionally, LORAN-C time recovery has been limited by propagation effects (both spatial and temporal) to provide time recovery in the microsecond range. By employing common-view techniques long used in GPS, the potential exists to enhance time recovery performance by over an order of magnitude using LORAN-C. The LORAN-C Accuracy Panel (run by the US Coast Guard) has sponsored a research project to collect data and determine the performance level for time recovery using common-view LORAN-C. This paper presents the results of that work.

This paper begins with a short overview of the LORAN-C recapitalization project, with an emphasis on timing enhancements at the transmitting stations. A description of the common-view LORAN-C test network follows. Data collected in Boulder will be corrected via common-view using a near field station and a far field station. Results will be analyzed to determine the dependence of time recovery precision on distance.

1.0 INTRODUCTION

For the last 5 years, the United States LORAN-C network has received funding for a significant recapitalization of equipment, operating procedures, and technology. Upgrades to the system include transmitter equipment, cesium standards, time and frequency equipment (TFE), facility improvements, and control equipment. In response to the increase in performance enabled by the new equipment and technology, the U.S. Coast Guard formed the LORAN Accuracy and Performance Panel (LORAPP). The LORAPP is chaired by the USCG with the primary goal of defining the significant components and capabilities of an enhanced LORAN-C service. Enhanced LORAN-C is enabled by the technology infusion that is underway and will include broadcast differential corrections by modulating the ninth LORAN-C pulse [1]. These corrections will provide the opportunity for timing users to improve time recovery performance by computing a common-view LORAN-C solution.

The LORAPP has initiated a three-phase timing study to determine the projected performance of common-view LORAN-C. Phase I, which is complete, included the processing of existing (legacy) LORAN-C data to determine if common-view LORAN-C should be investigated as a backup to GPS. Data were evaluated from existing NIST and USNO archives and it was determined that common-view LORAN-C had the potential to provide precision time recovery (< 50 ns RMS) [2]. Phase II involves the

implementation of an experimental common-view LORAN-C network to determine performance using current-generation LORAN-C receivers over different baselines. The preliminary results of Phase II are presented in this paper. Phase III is an architecture definition that will result in a set of the requirements, necessary technology, and a candidate architecture for the implementation of common-view LORAN-C time recovery in the enhanced LORAN-C era.

This paper reintroduces the concept of common-view LORAN-C timing. The concept is not new; prior to 1981 common-view, LORAN-C and television measurements were the primary links used for the computation of International Atomic Time (TAI) [2]. Furthermore, as early as 1963 NIST and the United States Naval Observatory (USNO) made common-view LORAN-C comparisons using signals from Cape Fear [3]. However, the technique was largely replaced by common-view GPS in the early 1980s [4].

This paper presents some preliminary results based on the initial data collected from an experimental common-view LORAN-C network. Section 2 describes the common-view technique for the LORAN-C application. Section 3 details the experimental setup and hardware configuration. Section 4 presents initial data collected during the first month of the experiment. Section 5 includes initial conclusions and a summary of continuing work.

2.0 COMMON-VIEW LORAN-C

Common-view time transfer techniques have been used extensively in the GPS community for over 20 years [4]. The approach involves subtracting data collected at different sites but from a common source in order to cancel errors that are common to each user. The common-view calculation is a simple subtraction of data collected at two sites from a common source. This technique has been used for many years in the timing community, and GPS common-view time transfer is routinely performed at the 5 to 10 ns level [5]. It should be noted that common-view processing results in a relative measurement between the two clocks. That is, unless one of the clocks has a known relationship to UTC, absolute time knowledge is lost in the common-view calculation.

For LORAN-C, common-view techniques can be used to reduce the seasonal effect that limits time recovery performance to the microsecond level. The seasonal effect is the change in propagation from a LORAN transmitter that results from changes in ground conductivity (due primarily to temperature and weather). The effectiveness of the common-view technique will be related to how well seasonal effects correlate over paths traversing different terrain and distances. Previous papers have shown a significant correlation of the propagation delays from a LORAN transmitter as received by stations in Boulder, CO and Flagstaff, AZ [6]. This correlation over a baseline of > 600 km prompted the LORAPP to initiate a common-view LORAN-C timing experiment.

3.0 COMMON-VIEW LORAN-C EXPERIMENT

In order to evaluate the performance of common-view LORAN-C for timing applications, an experimental common-view baseline has been installed between Colorado and Wyoming. Figure 1 shows the high-level hardware configuration of the three experimental sites. At each site (NIST, TSC, and LORSTA Gillette), a clock is measured using a GPS receiver and a LORAN-C receiver. The output of the clock represents the local estimate of Coordinated Universal Time (UTC). For NIST, this is UTC (NIST), and for the other two locations it is the output of a cesium oscillator steered using GPS. The detailed hardware configuration for each site is depicted in Figure 2. The clock provides a 1 pulse per second (pps) output to both a standard GPS receiver and a custom LORAN-C TOA receiver. The GPS

receiver at NIST and TSC is an AOA TTR5† (part of the NIST common-view service) and the GPS receiver at Gillette is a Motorola Oncore†. There is also a Motorola Oncore† operated at TSC used for common-view comparisons with Gillette.

The LORAN-C receiver is a combination of a standard LOCUS Satmate 1020† and external hardware and processing software. The external hardware and processing software are used to compute the ASF of the signal from each transmitter. The ASF is calculated in the processing software by computing the difference between the received TOA (the value reported by the LOCUS receiver) and the expected time difference (TD), computed using the coordinates of the receiver, the coordinates of the transmitter, and an assumed all-seawater path. A time interval counter is used to measure the group repetition interval (GRI) output of the LOCUS receiver against the 1 pps from the local clock (this provides the ability to refine the TOA data output from the LOCUS receiver based on a precise 1 pps). Peterson Integrated Geopositioning (PIG) software† is used to process the standard output of the LOCUS receiver with the time interval counter measurements, and to adjust the LOCUS data so that they actually represent the TOA.

LORAN-C data are averaged for 6 minutes by the PIG software at each site. GPS data are stored every 5 minutes (for ONCORE data) or using the BIPM standard common-view schedule [5] (for the data from the NIST Global Time service). GPS and LORAN-C data are stored locally for 1 day at each site. Each day, the data are transferred to TSC for common-view processing.

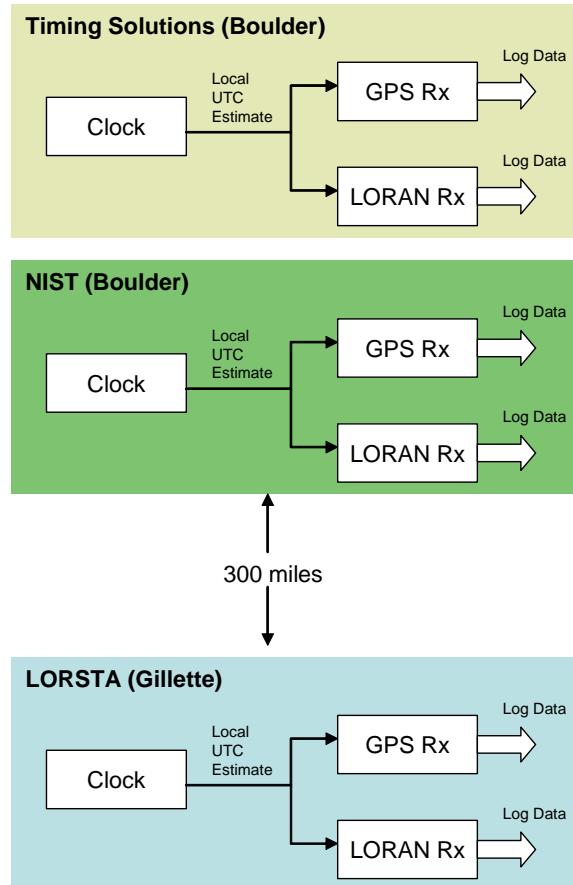


Figure 1. Experimental setup for common-view LORAN-C experiment.

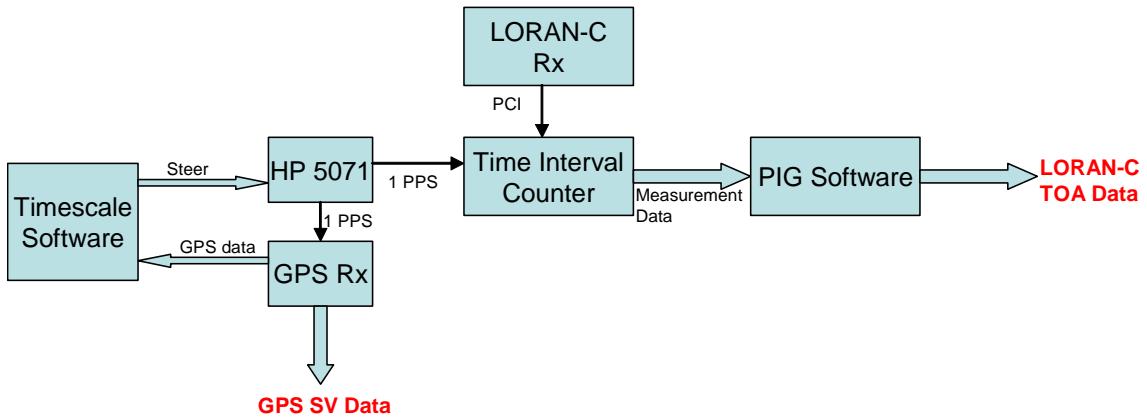


Figure 2. Hardware configuration at each site.

4.0 INITIAL COMMON-VIEW LORAN-C DATA

Phase II of the common-view LORAN-C experiment began in the fall of 2003, and only a small amount of data has been collected to date. While it is not possible to make any definitive conclusions about the predicted performance of common-view LORAN-C, the initial data are still of interest, since they show the potential of the method.

Data are processed using two baselines: a short baseline between NIST and TSC (5 km), and a longer baseline between TSC and Gillette (approximately 500 km). The short baseline represents the best possible performance of the technique, since it maximizes the common-view noise cancellation (the propagation path from a transmitter to the two locations is almost exactly the same). The long baseline between TSC and Gillette represents a more typical baseline that a LORAN-C user would have relative to a LORAN-C monitor station.

4.1 SHORT-BASELINE DATA

The short-baseline LORAN-C common-view data show excellent cancellation of propagation delay effects and, therefore, excellent common-view performance. Figure 3 shows LORAN-C data collected at TSC and NIST. The data in Figure 3 represent the time-of-arrival of a LORAN signal from a single transmitter (9610M in Boise City, Oklahoma) as received at TSC and NIST. The only processing applied to the data in this plot is an external calibration at the beginning of the data collection (via GPS). The data show a diurnal variation of approximately 40 ns as well as a general upward trend of over 100 ns due to a combination of the clock offset at LORSTA Boise City and the seasonal propagation effect, which is well documented for LORAN-C timing data [5].

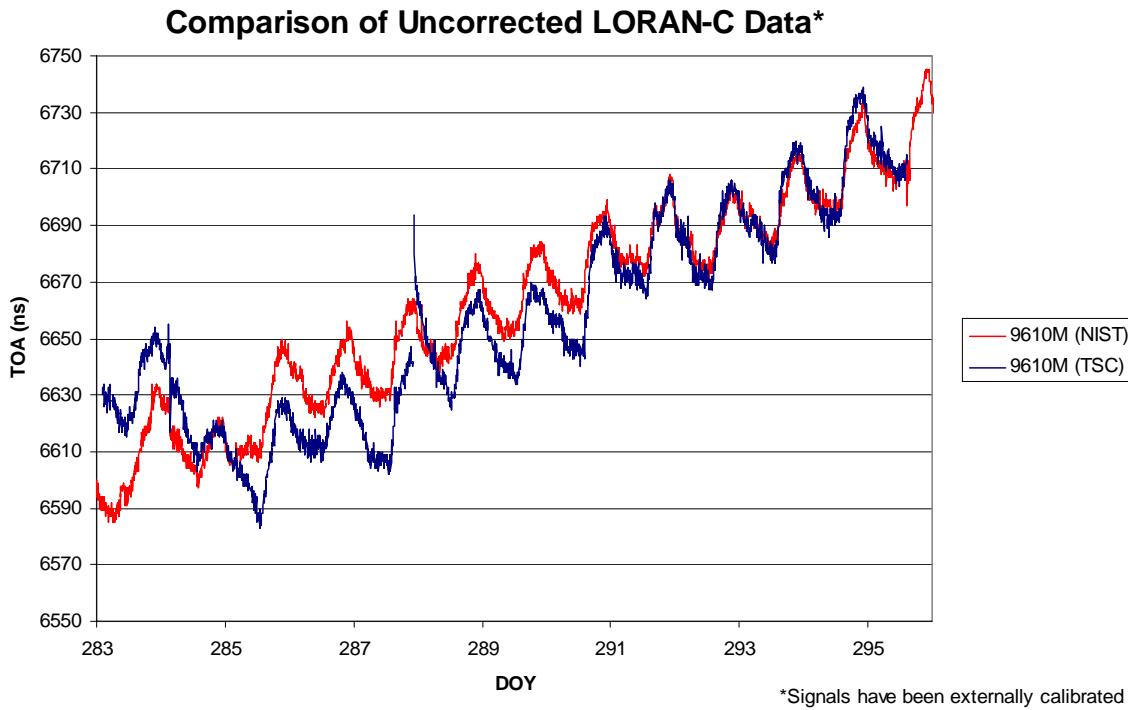


Figure 3. One-way LORAN-C data.

By subtracting the two data sets in Figure 3, a common-view LORAN-C data record is created between TSC and NIST. The common-view LORAN-C data for a 2-week period is plotted with common-view GPS data in Figure 4. The common-view LORAN-C data compare favorably with the common-view GPS data collected over the same baseline. The LORAN-C data show a standard deviation of 8 ns and track the GPS data. At day 288, the timing system at TSC was moved to a new location and cold-started (meaning the Kalman filter was re-initialized and the system experienced a start-up transient). Figure 5 shows a section of data from Figure 4 with the x-axis reduced to show the timing system cold-start. The common-view LORAN data clearly show the 40 ns effect of an initial offset and filter pull-in with precision that rivals common-view GPS.

While the common-view LORAN-C results are encouraging over the short baseline, they are not representative of the performance that users could expect with a realistic monitor network providing the corrections. Most users will not be co-located with a monitor and would likely have to use correction values from monitor stations that are hundreds of kilometers away. The short baseline data provide a best-case scenario of the potential of common-view LORAN-C and are useful only in bounding the performance.

Comparison of GPS Common View and LORAN Common View*

Short Common View Baseline - TSC-NIST - Std Dev = 8ns

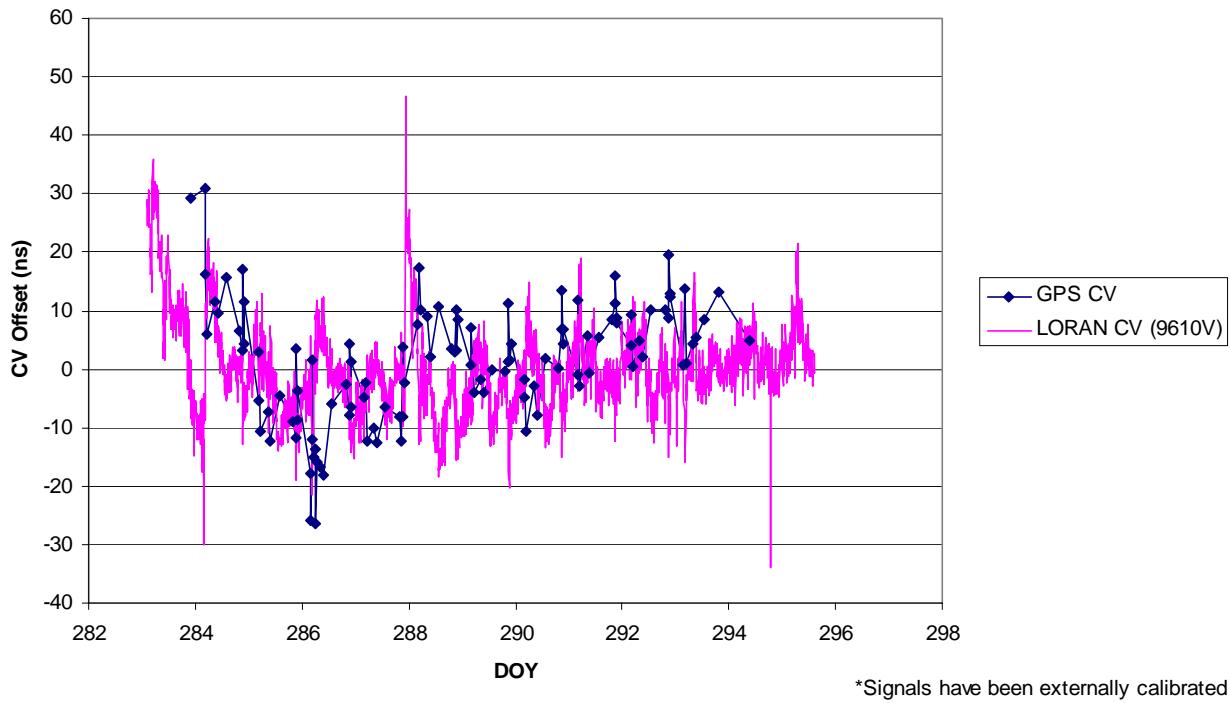


Figure 4. Common-View LORAN-C and Common-View GPS Data.

Comparison of GPS Common View and LORAN Common View*

Short Common View Baseline - TSC-NIST - Std Dev = 8ns

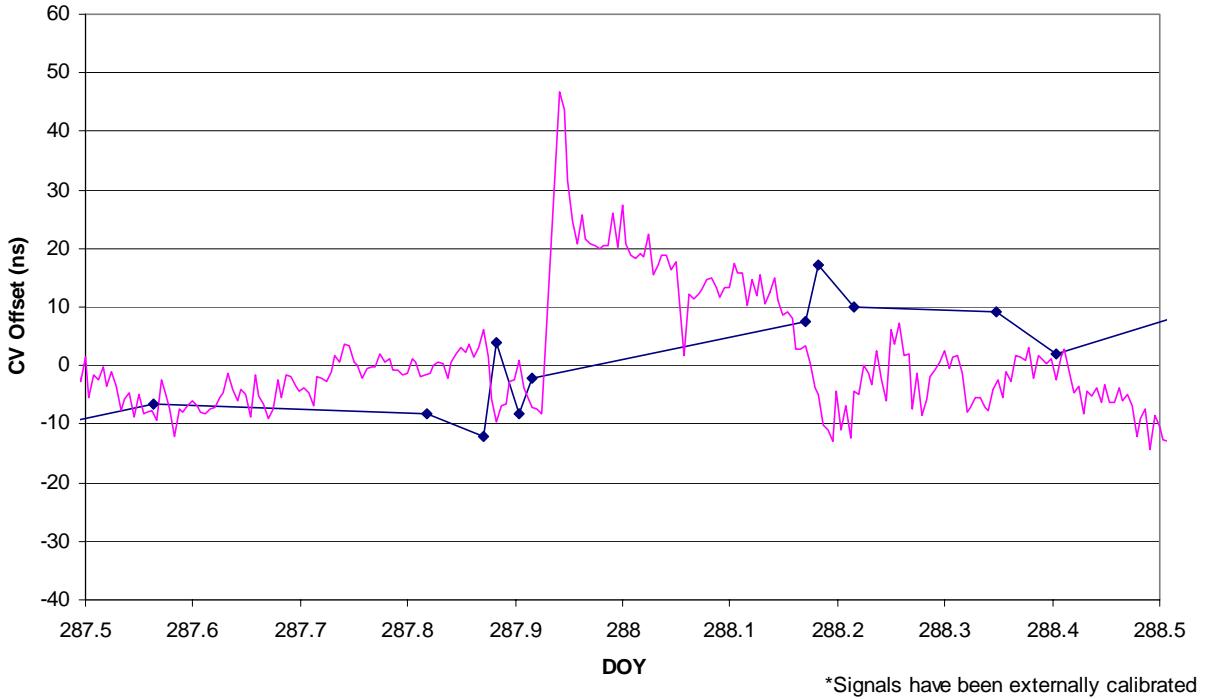


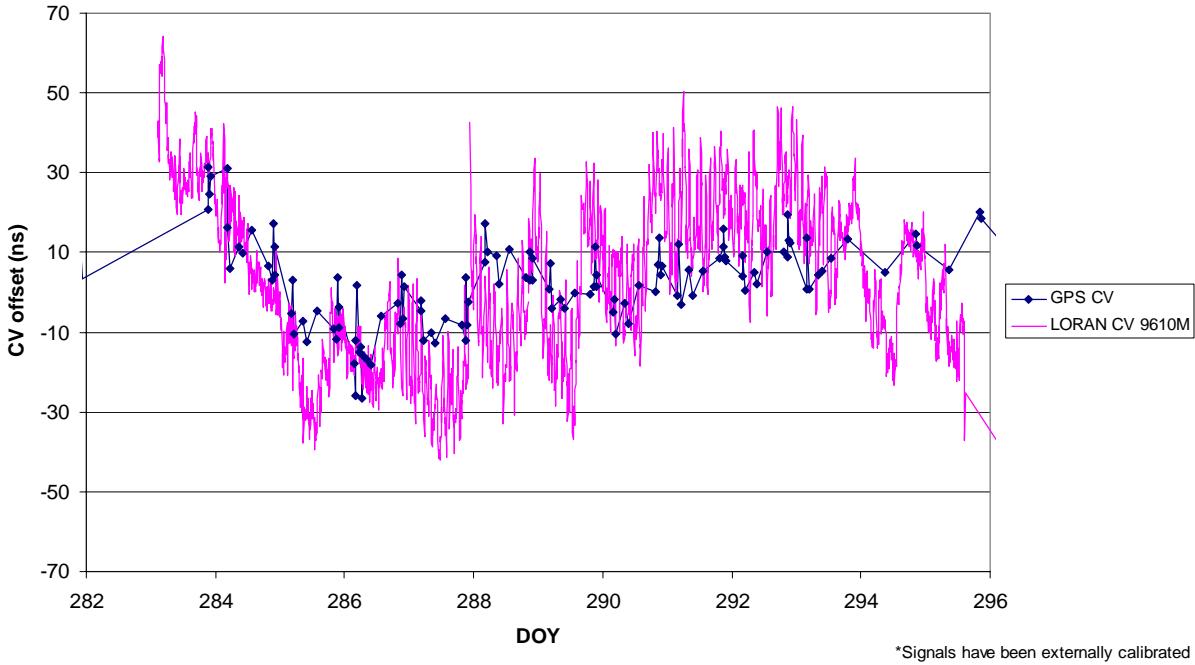
Figure 5. Common-View LORAN-C and Common-View GPS Data (zoom of Figure 4).

4.2 LONG-BASELINE DATA

The longer baseline between Boulder and Gillette, Wyoming provides a more realistic view of the potential of common-view LORAN-C. The 500 km baseline between the two antennas provides a significant difference in the propagation paths with a lower expected correlation between the data (than the short-baseline case). Figure 6 shows a comparison of GPS and LORAN-C common view over the long baseline using data collected from the 9610M (Boise City, Oklahoma) transmitter. As expected, the data are not as good as the data in Figure 4, but still show significantly better performance than one-way LORAN-C timing data. The common-view LORAN-C timing data ranged from 20 ns RMS (seen in Figure 6) to 50 ns RMS, depending on which transmitter was the source of the common-view data. Figure 7 shows the common-view record from the 8290M transmitter in Havre, Montana over the same time period as Figure 6. The data show significantly worse variations than the 9610M data with RMS of 50 ns.

Comparison of GPS Common View vs LORAN Common View*

Long Common-View Baseline - TSC (Boulder) to Gillette (WY)

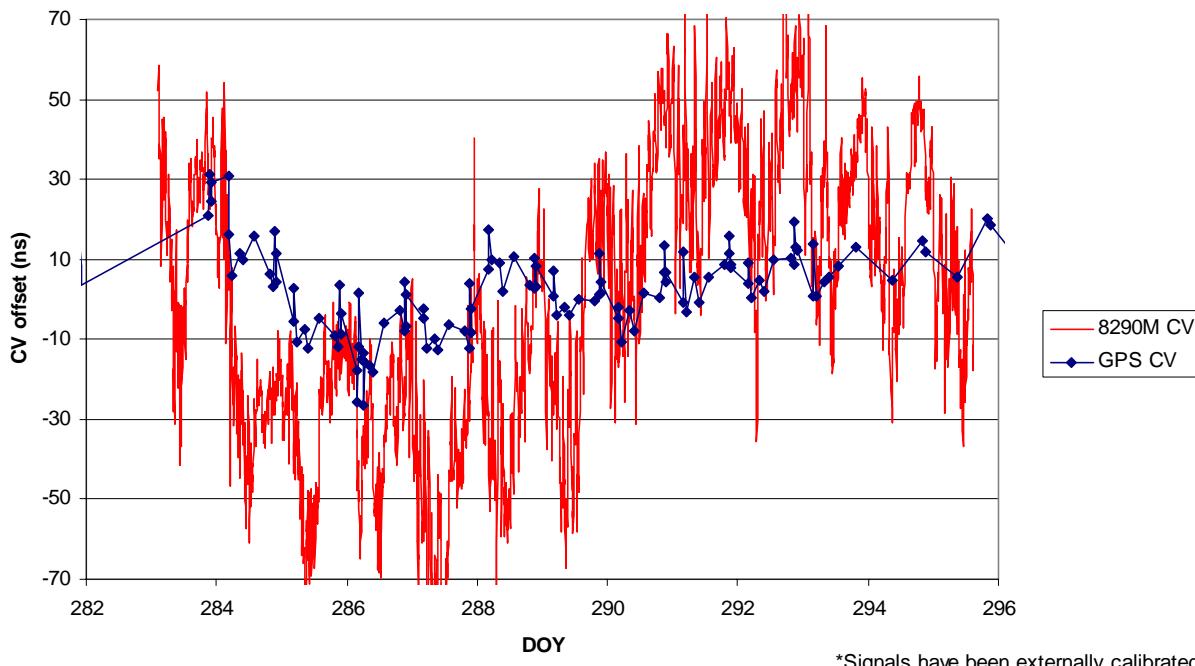


*Signals have been externally calibrated

Figure 6. Common-view LORAN-C and common-view GPS over a long baseline.

GPS Common View vs LORAN Common View*

Long Common-View Baseline - TSC (Boulder) to Gillette (WY)



*Signals have been externally calibrated

Figure 7. Common-view LORAN-C and common-view GPS over a long baseline.

4.3 ABSOLUTE PERFORMANCE

The data presented in Sections 4.1 and 4.2 address the stability of common-view LORAN-C data from time recovery. In all of the plots presented, the data were externally calibrated at the beginning of the data collection using GPS. One significant disadvantage of common-view LORAN-C is the inability to easily calibrate the receiver. In common-view GPS, a receiver can be calibrated at a source of UTC (NIST or USNO) and then shipped to a user location and used with the same calibration factor. In the common-view LORAN-C case, the calibration factor is location-dependent and cannot be calculated at a central site for use in the field. This means that common-view LORAN-C timing receivers will have to be calibrated in the field or be combined with GPS (at least at startup) to enable precise time transfer. We are currently researching the best way to calibrate the receivers for time transfer purposes.

4.4 FREQUENCY RECOVERY

The benefits of common-view LORAN-C for frequency transfer will be evident primarily for long averaging times (many weeks and/or months). The primary benefit of common-view LORAN-C is the reduction of the seasonal component, which causes long-term phase deviation on the order of a microsecond. By reducing this seasonal component, frequency users will see improved performance for long-term averages. This is not evident in the initial data presented in this paper, as the time periods used here are too short.

5.0 CONCLUSIONS

An investigation of common-view techniques for LORAN-C time and frequency transfer has been initiated by the LORAPP. The common-view technique can reduce the impact of the performance limiting seasonal variations that are evident in one-way LORAN-C timing measurements. An experimental network has been established to collect data and estimate the expected performance of common-view LORAN-C timing. The data collected so far show a best-case performance of < 10 ns (RMS) over an extremely short baseline and < 50 ns (RMS) over a more typical common-view baseline. These preliminary results point to the ability of a differential LORAN-C service (Enhanced LORAN-C) to be a viable backup to GPS for precision time recovery in the United States.

We continue to collect data to improve our estimate of expected LORAN-C common-view performance. In addition, the common-view LORAN-C technique presents calibration challenges that have not yet been addressed. These issues will be documented in future papers based on the LORAPP work.

† Products or companies named in this document are cited only in the interest of complete scientific description, and their mention neither constitutes nor implies endorsement by NIST or by the U.S. Government. Other products may be found to serve just as well.

6.0 REFERENCES

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QUESTIONS AND ANSWERS

JIM JAEGER (Clockvault.com): The new Loran stations use GPS to set the time of the cesium clocks, so in a way Loran is dependent on GPS.

TOM CELANO: Well, there is a link to GPS right now, that's true. The way they get around that right now is that there are three cesiums in each Loran location and we are time-scaling those clocks together. So we get the stability of three cesiums. The mitigation against GPS dependence right now is the fact that we flywheel for very long periods of time with that three-clock ensemble and are okay.

It also can revert to a Loran-only operation where we use Loran timing receivers at stations that are there now. They are called casualty receivers. But you will take a hit in the timing performance of the sites. Thirdly, we are looking at future studies where we are going to have GPS-independent techniques to measure and group the clocks nationally across the United States. But you are right.

DENNIS McCARTHY (U.S. Naval Observatory): There are a couple questions that come to mind. One of them is: are you planning to look at how this would work in an area where the ground conductivity is a little more susceptible to changing than on the West Coast of the United States, e.g. the East Coast, where I think your numbers would show a lot less correlation, perhaps.

CELANO: There are also a lot more stations. But I would agree with you. Each time we get more encouraging news, we are willing to expand our coverage. But the short answer is yes.

McCARTHY: And do you intend to be able to supply ionospheric information somehow in this so that the user might be able to make ionospheric corrections?

CELANO: What they are looking at right now in terms of what kind of information they will provide via the data of the ninth pulse is more ionospheric warnings. When the ionosphere gets lowered during solar events, they call it a Polar Cap Event, or something like that; it impacts obviously the sky bounce in the Loran system. The sky bounce can make the ground wave unusable. So what they are doing right now is putting in go/no go or a PCA event knowledge in the data. So it won't be a correction; it will be more a "don't use me, I'm being affected by a solar event in the ionosphere." But it is a ground wave, so the only way the ionosphere affects Loran is the impact of the sky bounce.

KEN JOHNSTON (U.S. Naval Observatory): Is there any way you can actually put calibration to the ground wave by looking at rainfall and things of that nature to improve your accuracy?

CELANO: There is a lot of work being done by multiple people in taking AIS maps and from that coming up with corrections based on mathematic models, ray tracing if you will, of the path as it goes from a transmitter to the receiver. Professor David Lass from England is really the leader in that. There is a lot of work being done in that area. I cannot speak to how well it works, but they are getting pretty favorable results in the navigation community. It hasn't been applied to timing yet. But the short answer is that it is being looked into.

BILL KLEPCZYNSKI (U.S. State Department): I would like to amplify one of Dennis McCarthy's comments about the changes in ground conductivity, especially over the wintertime, due to the snow on the ground. Experience has shown that if you are going to do common-view Loran, then if one path is covered by snow and one is not, you will see literally hundreds of nanoseconds. We have seen in the past, historically, jumps of about 500 nanoseconds in timing data from using Loran.

CELANO: I agree, and I expected to see that in my data. I expected also to see it in the comparison I showed you between Flagstaff and Boulder. Obviously, you could not find two more different climates than Flagstaff and Boulder. But I was amazed at how well it did agree. I think we will see short disturbances that we will have to deal with in either a filter or somehow. I agree with you, but I haven't seen them yet. There is already snow on the ground in Gillette, but there is no snow on the ground in Boulder. I haven't seen this horrible stuff yet, but that is why I say we need to collect more data before I can say anything definitive about how this is going to work.

KLEPCZYNSKI: Yes, if I recall correctly, the instance in the East Coast versus Central U.S. is one of the paths you should be looking at. I think that is where you will probably find the gaps.

CELANO: Yes, we will probably get in there next. It is easy to have it where it is now because I can drive to where it is. But I agree with you.