EVALUATION OF LORAN TIMING RECEIVERS AT NPL

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Abstract

Telecommunications, finance, power grids and other infrastructure rely heavily on precise time and stable frequency that is acquired from Global Navigation Satellite Systems (GNSS), principally the U.S. Global Positioning System (GPS). It is clear now that the GPS, due to its vulnerability to jamming and interference, needs a backup in the form of a multimodal navigation system. Such a system should not to be subject to the same modes of failure. Amongst the navigation systems considered is a terrestrial radio navigation system called Loran-C which has been operational since the 1950s. However, it has been necessary to launch a modernisation process in order to bring it into the digital era. The process of upgrading in Europe is largely based on expanding the contemporary Loran-C functionality. This system is called Eurofix, thus Loran-C/Eurofix. In the U.S. the process of modernization is supported by extensive Loran-C hardware upgrades. The new, enhanced system is often referred to as eLoran.

The National Physical Laboratory has been evaluating two Locus Inc. CsSync 1000 units. These are examples of the new generation of Loran timing receivers. NPL wishes to determine the capabilities of the upgraded system for both stand-alone and common-view time transfer. In this paper an overview of the Loran-C current status is given, focused mainly on details related to a new Loran time infrastructure and aspects of its precise time distribution. The theory is supported with results obtained from NPL's experiments. A short introduction to the process of time keeping is also included.

1. Loran history

Loran (Long Range Navigation) is a terrestrial, regional radio navigation system that uses ground-based transmitters. Its development was started by the U.S. Department of Defense during World War II. The initial frequency used was in the 1750-1950 kHz region. The post-war redesign of the original Loran-A system was named Loran-B. Many other modifications followed over the course of the following years, such as Loran-E, Motorola's version of Loran, and Loran-D. Loran-D was a low power, short range, high-accuracy tactical system, used as a bombing aid by the U.S. Air Force **[1]**. Wide usage of Loran started in the 1950s with Loran-C, which was developed by the U.S Navy and U.S. Coast Guard. The system used short phase-coherent pulses with a carrier frequency centred on 100 kHz, and a bandwidth range from 90-110 kHz. The Soviet Union built its own Loran-C equivalent known as Chayka. Loran-C was also implemented in India and Saudi Arabia. Today, there are three main Loran-C governing bodies: North American Loran (since 1974 controlled by the USCG), North-West European Loran-C System (NELS, established in 1992) and the Far-East Radio Navigation System (FERNS). The NELS members are France, Netherlands, Norway, Denmark, Germany and Ireland. The FERNS members are Russia, China, Korea and Japan. **Figure 1** shows the world Loran-C coverage map.

Loran-C development virtually ceased with the introduction of GNSS in the 1980s. Given that Loran-C could not match the performance of GPS, the U.S. Department of Transportation (the U.S. Coast Guard was formerly a part of the DOT) announced its intention to cease Loran-C support by the year 2000. In the late 1990's it became clear that GNSS, primarily GPS, needed a backup due to its susceptibility to jamming (Volpe report, issued in September 2001) **[3]**. The U.S. Congress, which recognized Loran's value as a GPS backup, provided the Loran-C Recapitalization Project (LRP) with approximately $120m **[4]**. LRP work is performed under an interagency agreement between the Federal Aviation Administration (FAA) and the USCG. New enhanced Loran-C, known as eLoran, is based on a complete Loran-C infrastructure upgrade that is supported by new all-in-view receivers, and H-field antennas. The superior hardware is coupled with improved signal propagation error corrections (Additional Secondary Factors-ASF). In order to succeed, eLoran has to meet stringent requirements defined by the USCG for Harbour Entrance and Approach (HEA) and by the FAA for Non-Precision Approach. The HEA requirement of less than 20 meters is accuracy intensive while the FAA requirement is integrity of 99.99999%. After an extensive eLoran evaluation program, the DOT has recently announced that eLoran has met these performance criteria.

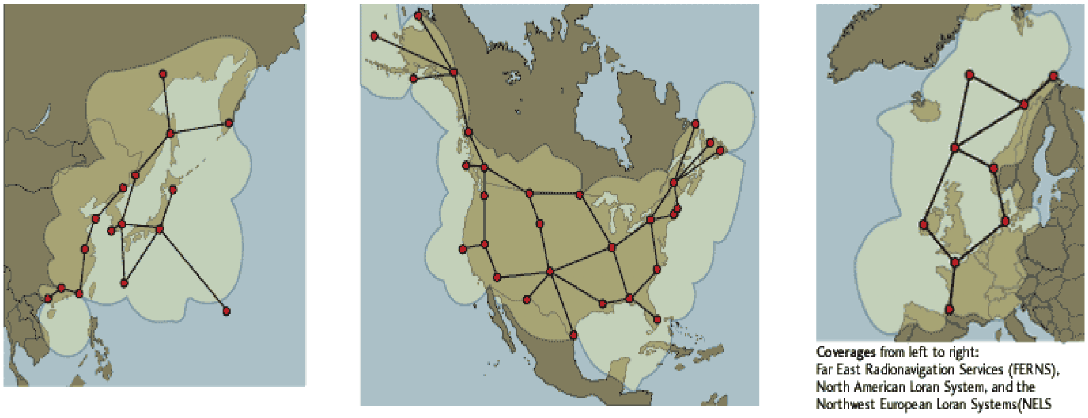


Figure 1. Loran-C map of coverage from left to right: coverage provided by FERNS, North America Loran and NELS (Courtesy of Megapulse, Inc.) [2].

The Loran-C situation in Europe was negatively influenced by the US DOT's initial intention to terminate Loran in the U.S. A number of NELS members are reconsidering the future of their Loran-C stations, with the possibility of withdrawing from the program in 2005. However, France and Germany have expressed a strong will to continue support for Loran-C, and the UK is soon to perform tests by installing a Loran-C transmitter originally intended for use in Ireland **[5].** The process of innovation in Europe is largely based on expanding the contemporary Loran-C functionality, rather than an extensive hardware upgrade, and implementing Eurofix. This system development is funded by NELS. The modernization of Loran-C in Europe is led by Delft University of Technology in partnership with a U.S. company Megapulse Inc. The Dutch company Reelektronika has been involved in the design of new Loran-C/Eurofix receivers. Eurofix utilizes Loran-C to distribute Global Navigation Satellite Systems (GNSS) information. The Eurofix short messages are sent to the user by extra time-modulation of the Loran-C signals. At the present time, only differential GPS and Glonass corrections, and integrity information for the satellite systems are being broadcast with Eurofix **[6].** In 1996, the University of Delft installed an experimental Eurofix station at Sylt in Germany. Since 2000 the Eurofix signal has been transmitted at four Loran-C stations in Europe. Near the end of this year, Saudi Arabia will add Eurofix on three 1 MW Loran transmitters.

2 Frequency and Time via eLoran and Loran-C/Eurofix

2.1 Introduction to Time Creation Process

The atomic timescale used worldwide is computed by the Bureau International des Poids et Mesures (BIPM), the organization responsible for international standards of measurement. The process of gathering and processing information for the purpose of generating atomic time is shown in **Figure 2**. The first step is to gather data from more than 260 atomic clocks, maintained by National Measurement Institutes (NMIs) such as the National Physical Laboratory (NPL). Next, the data is processed by means of weighted averages to create a single "paper clock". The time scale generated by this "clock" is called Free Atomic Time (Echelle Atomique Libre, EAL). In the next step the scale interval of EAL is compared with the duration of the SI second generated by primary frequency standards such as caesium fountains and adjusted accordingly. The time scale created by this process is called International Atomic Time (Temps Atomique International, TAI). In the final stage, Coordinated Universal Time (UTC) is calculated by subtracting a number of elapsed leap seconds from TAI so as to maintain the difference between (UTC-UT1) within less than 0.9 s. The UT1 is a time scale derived from the measurements of the Earth's rotation.

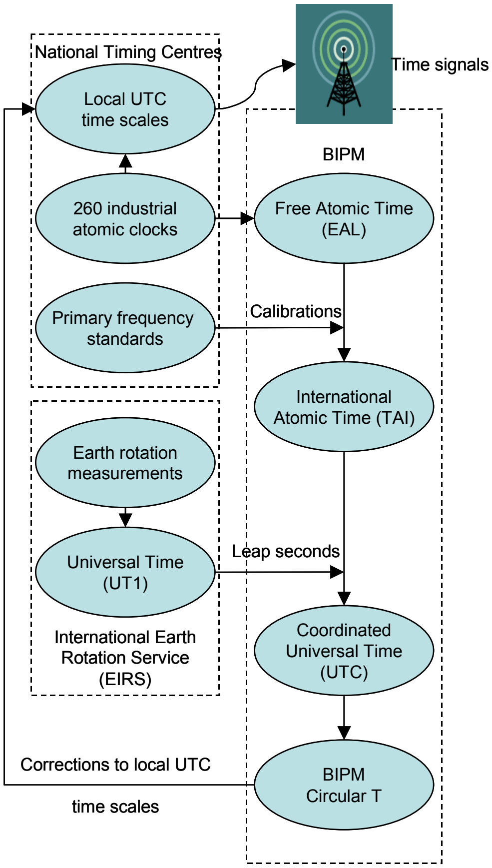


Figure 2. Diagram showing the formation of Atomic Time scale [7].

Twenty-two leap seconds have elapsed since the current procedure was introduced on 1st January 1972, resulting in the (October 2004) difference between TAI and UTC of equal to 32 s. Note that in 1972, UTC was already 10 s behind TAI. GPS Time is 19 seconds slower and Loran-C time is 10 s behind TAI.

2.2 Timing via eLoran and Loran-C/Eurofix

Timing within the eLoran network is provided via a new system called Timing and Frequency Equipment (TFE), installed as part of the Loran-C modernization process in the U.S. The main system features are divided into: UTC recovery and time scale computation, Loran-C signal generation, timing measurements of transmitted signals, closed loop control, and Loran-C integrity monitoring Automatic Blink System (ABS). The ABS controls the timing accuracy, strength and the correct phase of transmitted signals. Each TFE contains three HP5071A caesium clocks: these form the TFE time scale which is steered via a GPS receiver to UTC(USNO). By doing so, the clocks can to be kept within 15 ns (rms) of UTC(USNO), providing that GPS is available. Kalman filter processing is used to flywheel the system time across possible GPS outages **[4].**

NELS Loran-C station timing is controlled by the Control Centre Brest (CCB) in France. CCB clocks are compared to UTC via the French Naval base in Brest and the Paris Observatory. The Brest time reference is transported across the NELS network from one station to another through round-trip Loran measurements starting at the Lessay transmitter (France). Since this is rather a lengthy process, the Loran-C time-of-emission accuracy at all stations is only between 100 and 130 ns from the Brest time reference **[8].**

3. Experiments with Locus CsSync 1000 Timing Receivers at NPL

Two CsSync 1000 receivers, the latest generation of Loran-C timing receivers each with an E-field antenna, manufactured by Locus Inc., were installed at NPL in April 2004. The receiver and antenna are shown in **Figure 3** and **Figure 4** respectively. NPL's Time and Frequency group has this Loran-C equipment on loan from Locus Inc. The units were installed in the time transfer laboratory, where equipment such as TWSTFT (Two Way Satellite Time and Frequency Transfer), geodetic GPS and GPS common view (GPS-CV) is located. The E-field antennas were mounted on the roof of the time transfer laboratory, ensuring that the antennas were free of obstructions in all directions at elevation angles above 30˚ **[9].** The CsSync 1000 is a Digital Signal Processing (DSP)-based timing and navigation receiver. It is classified as an all-in-view receiver since it can track over 40 stations simultaneously to improve the signal quality and signal-to-noise ratio of the primary stations of interest.

Figure 3. Cs-Sync 1000 receivers

Figure 4. E-field antenna

In its timing mode, the receivers can provide Stratum 1 performance, including generation of a time scale traceable to UTC. When a receiver's internal 10 MHz oscillator is phase-locked to the signal of a chosen Loran-C transmitter, a caesium clock reference can be established **[9, 10].** Note that receivers track stations and calculate time differences (TD's) with reference to the 10 MHz oscillator. CsSync 1000 receivers provide standard 10 MHz and 1 pulse-per-second (1pps) outputs. The RS232 interface utilises a full-duplex communication, and for example timing information is sent via the RS232 interface. A schematic diagram of the measurement system used to evaluate the CsSync receivers is given in **Figure 5**.

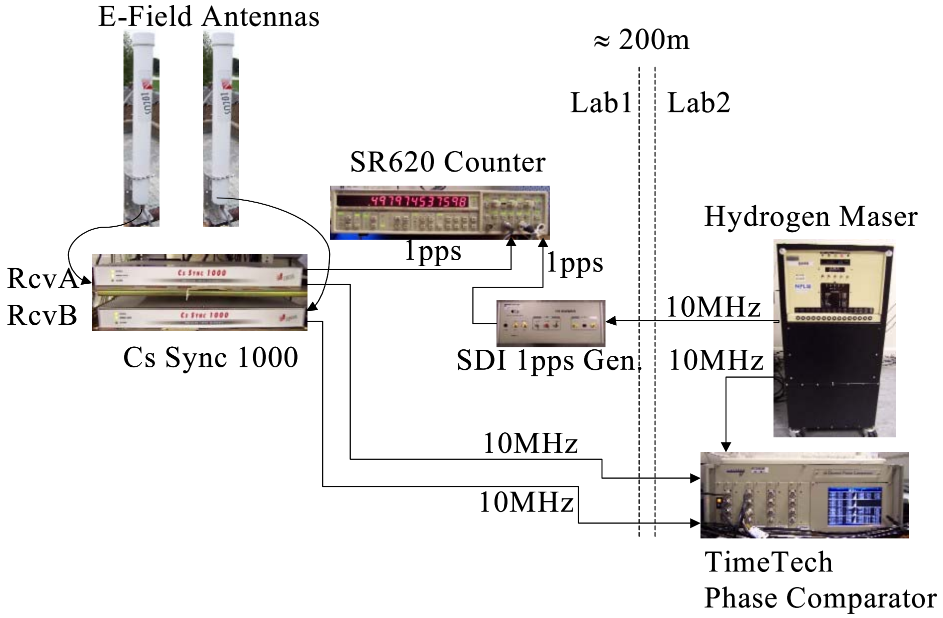


Figure 5. Schematic diagram of measurement system

As can be seen from **Figure 5**, the equipment is split between two locations: the clock room (Lab2), where two of NPL's hydrogen masers (HM) and the other time scale equipment are located, and the time transfer laboratory (Lab1). The time transfer laboratory is connected to the clock room by a number of high quality phase-stable cables, approximately 200 m long (one way). Some of the cables are used to feed the time transfer laboratory with the 10 MHz reference taken directly from one of the hydrogen masers. The others are used to feed the locally generated 10 MHz signals back to the clock room, where they can be compared against the masers.

The experiment took place from 9 June until 6 September 2004. During the period of receiver evaluation, the receivers were locked to the Loran-C station in Lessay, France. Consequently the receivers' 10 MHz internal oscillators were driven by the signal from Lessay. The two receivers under test were named RxA and RxB. The RxA 1pps output was compared using a Stanford Research Systems SR620 counter timer against a 1pps reference generated from a maser. The RxA and RxB 1pps were not aligned to TAI, as the TAI calculation process doesn't function properly with the European Loran-C signal. The 10 MHz outputs from both RxB and RxA were compared against the 10 MHz output from another maser using a TimeTech 16-channel phase comparator. The RxA 1pps measurements are shown in **Figure 6.** The phase comparison results between RxA and RxB and a maser are shown in **Figure 7 and Figure 8** respectively.

The 1pps data was sampled at a 30 s rate, whereas the sampling rate for the phase-comparator measurements was 10 s. Note that the initial data contained a large arbitrary offset as the receivers had not been calibrated. For clarity the data mean values were subtracted from each one of the corresponding data sets. As can be seen from all of these plots, there are clear daily cycling variations with a maximum amplitude of 80 ns, and short-term variations are in the 50-60 ns range. The biggest variations coincide with midnight, when ASF play the dominant role. In general the contamination of Loran-C signals from sky-waves is higher during the night. The pattern of variations in the 1pps logging strongly correlates with the pattern obtained from the phase measurements. This confirms that the receivers' 1pps pulses are directly derived from the receivers' 10 MHz reference as expected. In addition the RxA phase data correlates strongly with the RxB data, however the RxB phase data is slightly noisier. This could be caused by a difference in the phase noise contribution from the cables bridging the distance between the Loran receivers and the hydrogen masers. There is also a long term instability which is likely to be caused by clock drifts in the Loran-C reference signal.

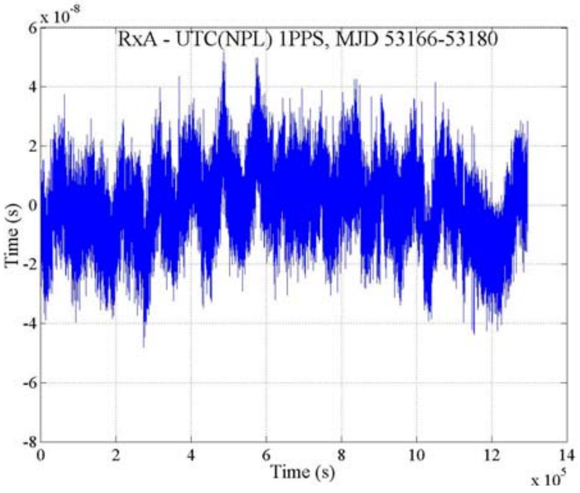
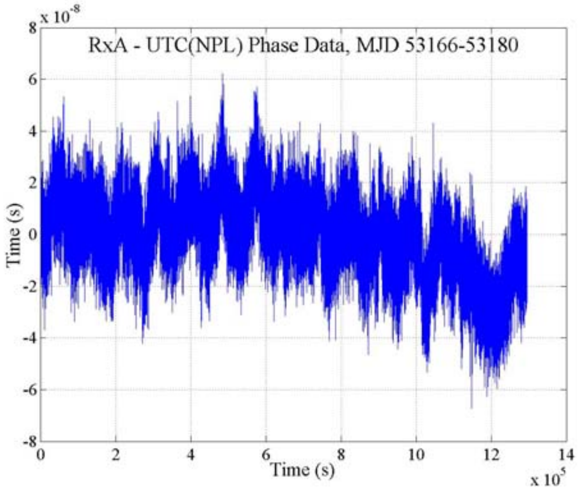


Figure 6. RxA-UTC(NPL) 1pps data



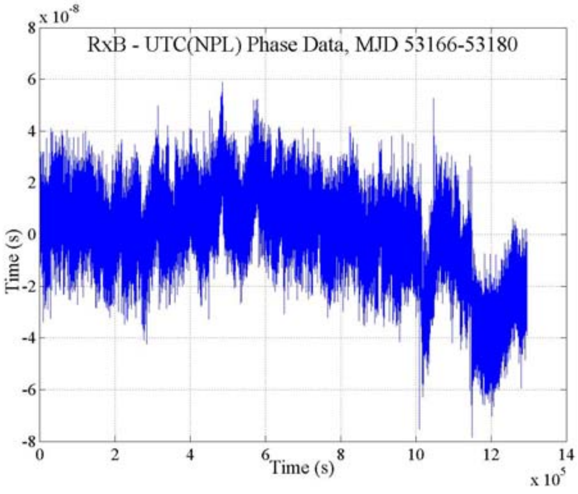


Figure 7. RxA-UTC(NPL) 10 MHz signals phase data

Figure 8. RxB-UTC(NPL) 10 MHz signals phase data

The frequency stability of RxA is shown in **Figure 9**. The Allan deviation (σ_y-τ) plot shows the normalized frequency stability to be $2x10^{-13}$ at an averaging time (τ) of one day. The dominant noise process may be either White Phase Modulation (WPM) or Flicker Phase Modulation (FPM). The Allan deviation does not distinguish between WPM and FPM. **Figure 12** shows the Time Deviation (TDEV) of RxA. The TDEV statistic is a scaled Modified Allan deviation (MDEV), which can be used to distinguish between WPM and FPM.

Since NPL has two Loran-C receivers, we were able to perform a comparison between GPS and Loran-C in common-view mode (CV). Common-view is a differential time and frequency transfer method used between two timing laboratories. The baseline may vary between a few miles and many hundreds of miles. The majority of errors associated with the signal transfer and system reference (GPS or Loran-C) errors cancel out. Common-clock, common-view occurs where both receivers are driven from the same reference clock. Although this configuration is not used for time transfer, it is very useful for a receiver's performance evaluation. GPS-CV is widely used by the timing community for efficient and highly accurate time and frequency transfer. GPS-CV at NPL uses Time and Frequency Solutions (TFS), TimeTrace single frequency, C/A code, multi-channel receivers.

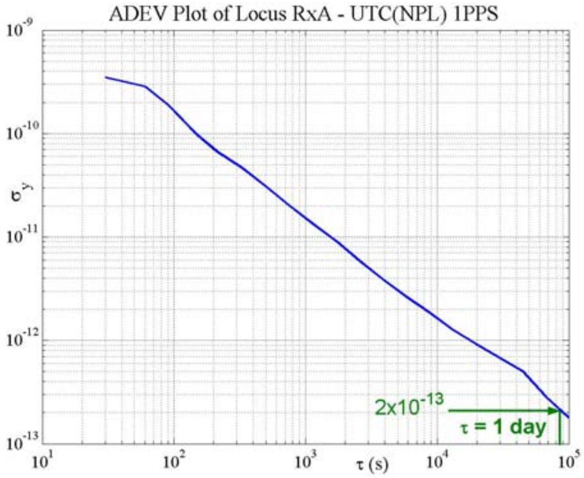


Figure 9. Frequency stability plot of RxA 1pps compared to 1pps from HM1

One can use a single frequency, C/A code GPS or a Loran-C receiver to acquire precise time from GPS or Loran-C respectively. However, the result obtained is subject to errors mainly due to atmospheric effects associated with signal propagation. The time transfer between two GPS or Loran-C receivers will remove, to a large extent, variations arising from signal propagation. It will also eliminate variations coming from GPS and Loran-C system references, leaving only contributions from the receiver reference clocks and the receivers themselves. **Figure 10** shows Loran-C, common-view, common-clock phase data. Data was sampled at 10 s intervals. Although the atmospheric and signal propagation effects are still clearly visible, daily peak to peak variations decreased to approximately 40 ns, with short-term noise not exceeding 30 ns. The standard deviation obtained is 18 ns (2σ) respectively. All results are in good agreement with the Loran-C common-view results presented at the 35th PTTI meeting **[11]**.

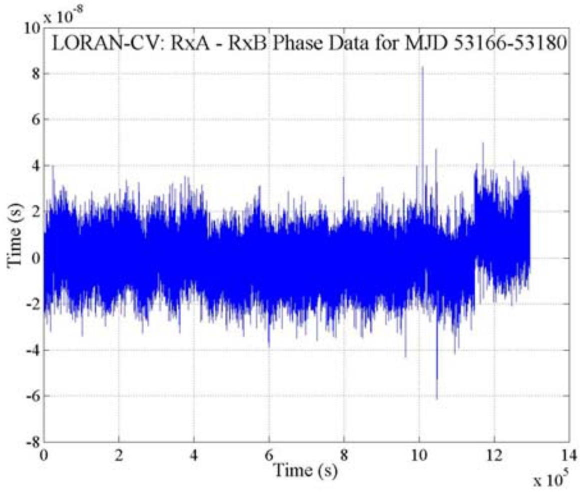


Figure 10. Loran-C common-view phase data

The frequency stability results of comparing GPS-CV and Loran-C common-view are given in **Figure 11**. The GPS-CV data is sampled at 960 second intervals, whereas Loran-C common-view is sampled at 10 second intervals. The frequency stability of GPS-CV is 4.5 times better than that of Loran-C common-view (1.8×10^{-13}) at an averaging time (τ) of a day. The Loran-C receiver frequency stability is dominated by the frequency stability of the Loran-C signal transmitted from Lessay. The stability difference is also likely to be caused by a dissimilarity of propagation phenomena affecting signals in the LF and L bands. The time deviation plot of comparison between Loran-C common-view and GPS-CV is given in **Figure 12**. As can be seen, the timing performance of Loran-C receiver in common-view mode is better than that of a stand-alone Loran-C receiver, the difference being most evident for averaging times exceeding 1000 s. The WPM plays the main role for averaging times ranging from 80-1000 s, but FPM is the dominant noise process for averaging times exceeding 1000 s. The poor time stability for the averaging time between 10 and 60s is the most likely due to the receiver's process of locking its internal oscillator to the Loran-C signal. Again, the effects of the atmosphere on the Loran-C signal propagation and diurnal effect are clearly visible.

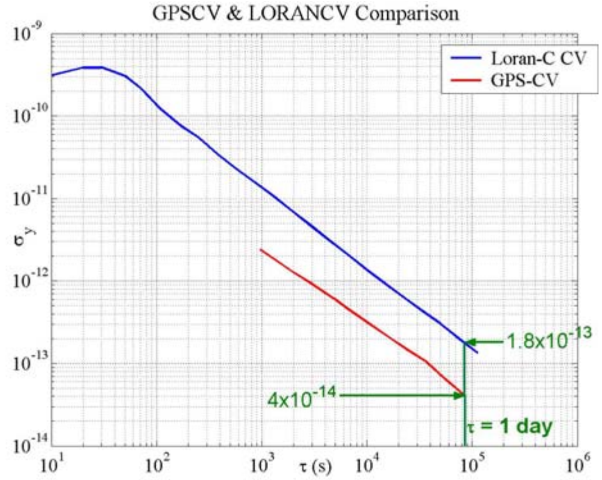


Figure 11. Frequency stability comparison of GPS-CV and Loran-C common view

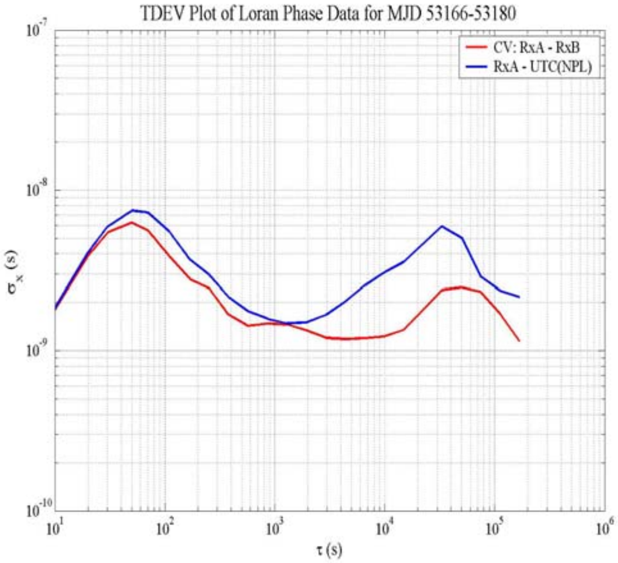


Figure 12. Time stability comparison of GPS-CV and Loran-C common view

Conclusions

Loran-C/Eurofix and eLoran can be readily used as a very stable source of frequency, since the 100 kHz carrier is in both cases controlled by caesium atomic clocks which have a typical stability of $4\text{-}8 \times 10^{-13}$, averaged over one day. However, at present it is more difficult to derive precise time from either eLoran or from Loran-C/Eurofix. The UTC service provided by eLoran using Pulse Position Modulation (PPM) of an extra pulse has yet to be implemented. The timing and frequency performance is expected to meet the current requirements of the system as specified by the FAA and USCG: a minimum frequency stability of 1×10^{-11} averaged over a day, a target frequency stability of 1×10^{-12} averaged over a day, and a timing accuracy of 100ns (rms). The UTC service is currently not available via Loran-C/Eurofix. However, once fully implemented, it is expected that timing coded into Eurofix messages will provide an accuracy of 100 ns at the user.

Given our results, it is evident that the new Loran-C performs well above its current timing and frequency requirements. The frequency stability of CsSync Loran-C timing receivers of 2×10^{-13} averaged over a day is comparable to that of single frequency C/A code GPS receivers. Stand-alone Loran-C timing performance can be improved by a factor of 2 by using Loran-C receivers in common-view mode to 18 ns (2σ). Nevertheless the frequency stability of Loran-C common-view was not found to be significantly better than the frequency stability of a stand-alone receiver. Although the results obtained from Loran-C common-view common-clock experiments are promising, it should be emphasised that this is an artificial configuration, with a far smaller baseline than most users would employ in practise.

Acknowledgements

This work has been supported by the Time and Frequency program of the National Measurement System Policy Unit of the Department of Trade and Industry, UK. The authors would like to express their thanks to Locus Inc. for providing us with the CsSync 1000 receivers and E-field antennas and to Linn Roth at Locus Inc. and colleagues John Davis and Peter Whibberley at NPL for their valuable advice.

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