DELIVERING A NATIONAL TIMESCALE USING eLORAN

ABSTRACT

A Positioning, Navigation and Timing (PNT) service using Enhanced Loran (eLoran) has been transmitted experimentally in the United Kingdom for more than 3 years. The eLoran transmitter employed, at Anthorn in North-West England, is operated by a commercial company on behalf of the General Lighthouse Authorities of the United Kingdom and Ireland. It is funded in part by the Department for Transport and other UK government agencies. Chronos Technology has used these and other eLoran transmissions to conduct research into the viability of employing eLoran as a means of distributing time traceable to UTC, including for indoor applications. There is growing concern internationally regarding the vulnerability of GPS and other global navigation satellite systems (GNSS) to natural and man-made interference, plus the jamming and spoofing of their transmissions. These vulnerabilities have led to a demand for sources of resilient PNT, including a robust means of distributing precise time nationally and internationally.

This paper explores the ability of eLoran to disseminate UTC-traceable time to applications in GNSS-denied environments. It proposes the creation of a National Timescale with UTC distributed via eLoran signals. Practical results from a test programme are very encouraging: UTC-traceable time signals with an accuracy of better than 100ns and with a quality comparable to that provided by GPS are received even indoors. This new source of precise time meets the latest ITU standards for primary reference timing clocks in Internet Protocol networks.

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1 EXECUTIVE SUMMARY

This paper explores the ability of Enhanced Loran (eLoran) to distribute UTC-traceable time to applications in GNSS-denied environments, including indoors. It sets the foundation for further research into the application and dissemination of UTC using eLoran signals in geographical regions where they are available.

Research into this topic has been conducted by Chronos Technology in collaboration with the General Lighthouse Authorities of the United Kingdom and Ireland (GLA), the UK National Physical Laboratory and UrsaNav, Inc. This has shown that UTC-traceable time of an accuracy better than 100ns and with a quality comparable to that provided by GPS can be received even indoors at ranges of more than 800km (500 miles) from eLoran transmitting stations. This new time service meets the latest ITU performance standards in respect of telecommunications phase stability.

The paper proposes further research to assess spatial and temporal variations in the reception of UTC-traceable time distributed in this way. It proposes this new means of disseminating national sovereign UTC for use at times and in places where GNSS is denied. It will serve critical infrastructure applications, notably telecommunications networks and financial services, in which sub-microsecond UTC-traceable time is essential to the continuity of operations. In particular it will serve these applications without the need for expensive roof mounted GNSS antenna deployments or managing complex fibre connectivity.

2 SCOPE

This study draws on research carried out over the last 5 years in the course of two projects, GAARDIAN and SENTINEL, which were supported by the UK Technology Strategy Board. It demonstrates a method of employing eLoran signals to distribute a “National Timescale”. This would be a simple and reliable way of distributing UTC-traceable time for multiple applications, especially those indoors and in other GNSS-denied environments that require resilient and accurate time of day, phase-synchronized and time-stabilised to UTC. The study shows how this accuracy and stability can be maintained over the long term to within 100ns of UTC, thus meeting currently-accepted ITU standards for primary reference timing clocks in telecoms transport networks.

3 INTRODUCTION

Each nation that contributes to Universal Coordinated Time (UTC) operates a national time standard that is independent of GNSS. Its technology will generally be based on a Hydrogen Maser. This will be adjusted using monthly corrections supplied by the Bureau International des Poids et Mesures (BIPM) in France.

Low-frequency eLoran is now emerging as the preferred source of positioning, navigation and timing (PNT) signals alternative or complementary to global navigation satellite systems (GNSS). ELoran is globally-standardised and does not share the vulnerability of GNSS to accidental or deliberate jamming, intentional spoofing, radio-frequency interference or space weather events.

A number of countries are actively reviewing their dependence on GNSS across multiple critical infrastructure applications and some are planning the implementation of eLoran transmitter networks. Within this context falls the question of how to deliver their national time service to those clients who have come to recognise their own vulnerability to the disruption of GNSS.

This paper examines the concept of delivering such national time services by means of eLoran signals.

4 eLoran AS A TIME STANDARD

4.1 BACKGROUND

eLoran (Appendix A) was conceived as a navigation service; it is the modern, digital-technology, version of the legacy Loran-C system. It re-uses the transmitter stations of its now-obsolete forebear to deliver position fixes of much higher accuracy, integrity, availability and continuity. These transmitters radiate precisely-timed pulses, at a power level of hundreds of kilowatts, on a frequency of 100kHz. To deliver highly-precise navigation, the pulses must be timed with an accuracy of nanoseconds. Because of this, they can fulfil the additional function of distributing precise time over long distances.

The timing of each transmitter station is derived from a local ensemble of three Caesium standard clocks that are themselves synchronised at intervals to UTC by comparison with a master standard. In this way the transmissions are locked to UTC and so provide a source of UTC-traceable timing that is totally independent of GNSS: so-called “sky-free UTC” (See Appendix B). These low frequency transmissions propagate into and through buildings. They can be received indoors by using a magnetic-field antenna – a so-called “H-field antenna”. This capability has been extensively assessed in the course of two UK research projects, GAARDIAN and SENTINEL[1], both led by Chronos Technology.

The time and timing performance of an eLoran signal can be separated into two components: long-term timing stability and phase synchronization to UTC. The long-term stability of an eLoran signal has been shown to be comparable to that received of commercially-available GPS timing receivers; this will be discussed later. Phase synchronization to UTC is achieved via a “UTC Sync” message which is broadcast over an “Loran Data Channel”, as will now be explained.

4.1.1 THE LORAN DATA CHANNEL

One of the most important differences between legacy Loran-C and the new eLoran is the addition of a Loran Data Channel (LDC) to the transmissions. The LDC offers a highly-robust, though low bit-rate, long-range channel that carries digital data messages. The original purpose of these messages was: to carry differential GPS corrections, similar to those in other DGPS systems; to confirm to users the correct and safe operation of the transmission, so ensuring high navigation integrity; and to carry corrections for the small temporal variations of the timing of signals received in certain harbours where the very highest location accuracy is required.

Despite the low data rate, the LDC has sufficient capacity for authorised third parties to use it in order to broadcast high-priority data to their users.

The properties of the LDC are standardised internationally and defined in a document entitled “Eurofix Message Format”; the current version of which, v2.15, is dated March 2014[2]. The Eurofix messages are specified by the Radio Technical Committee for Maritime Services (RTCM) Special Committee-104 (Eurofix working group[3]) and in International Telecommunication Union (ITU) Recommendation M.589-3[4].

One message type, “Message Type 6 in Table 2.3”[2] is the “UTC Sync” message. This provides the information a receiver requires to derive Universal Coordinated Time of Day, Date and Leap Seconds from the eLoran transmission. The message is repeated at intervals of a few minutes. When a timing receiver is being commissioned upon installation, this message allows it to align its 1pps output pulses to within a few microseconds of UTC. The remaining time offset is then removed in a further calibration stage, as explained below.

The Loran Data Channel employed in the UK uses the Eurofix standard described above. Other data standards have been proposed, including some with much higher data rates; future timing receivers will no doubt switch automatically to the data standard of the transmissions they receive. Eurofix is implemented by means of Pulse Position Modulation (PPM) of the pulses that constitute the eLoran transmissions. Groups of eLoran stations transmit their pulses at different rates, each defined by a “Group Repetition Interval (GRI)” and certain stations transmit at two such rates simultaneously. In consequence of these variants, the maximum raw bit rate of the Eurofix data channel can be as low as 50 bits per second (bps) or as high as 150bps.

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[1] “*The SENTINEL Report*”, Chronos Technology Ltd , 2014

[2] “*Eurofix Message Format*, Gerard Offermans. ver 2.15 March 2014

[3] *“RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) Service”*, Version 2.2, RTCM Special Committee 104, January 15, 1998.

[4] *“Recommendation ITU-R M.589-3, Technical Characteristics of Methods of Data Transmission and Interference Protection for Radionavigation Services in the Frequency Bands between 70 and 130 kHz”*,

The LDC embodies strong Forward Error Correction (FEC). This makes the performance of the data channel very robust and is an important factor in allowing it to be used over substantial ranges. Radio signals at the eLoran frequency of 100kHz propagate strongly as ground-waves; that is, as surface-waves over the Earth. In consequence, their rate of attenuation with distance depends on the electrical conductivity of the Earth's surface over which they flow, being least over sea-water and greatest over the low-conductivity terrain found in mountains and deserts. The data channel is typically usable at its full data rate out to a range of 1600km (1000 miles) over sea-water and 800km (500 miles) over mixed paths of land and sea. For example, the LDC from the UK Anthorn station, located on the coast of Cumbria, serves the whole of the United Kingdom, with a message data rate of approximately 35 bps and, where required, a message update interval of 2s.

Some 16 LDC message types have been defined. Of these, 8 have been assigned to existing services: they include messages concerning UTC time, differential eLoran corrections, and DGPS corrections and integrity. Additional messages are carried on behalf of third-party clients in government. The LDC is an asynchronous transmission system in which the message type is identified by each message header, allowing messages of one type to be interleaved with messages of other types. This permits flexibility, with messages of high importance (such as those that concern the health of the transmissions or the integrity of navigation fixes) to be prioritised over messages of lower urgency.

This paper proposes that one of the currently unassigned message types be used for "regional ASF timing correction messages". This concept, which will now be explained, will be implemented in the UK on an experimental basis during 2014.

4.1.2 GROUND WAVE

It is not only the rate of attenuation of eLoran ground-wave signals that depends on the electrical conductivity of the surface over which they travel but also, to a slight but important degree, their speed of propagation. This is greatest over sea-water, slightly less over farmland and least over mountainous or desert terrain. The propagation speed of the signal through the atmosphere and over all-seawater paths is known with very high accuracy; so the time delay due to propagation of such a signal with respect to its timing at the transmitter is very precisely known. But, if a signal travels wholly or partly over land, it will experience an additional delay with respect to its propagation over sea-water. This delay is known as the Additional Secondary Factor (ASF). Its magnitude may be several microseconds. Since it directly affects the timing of arrival of signals carrying a UTC service, it must be taken into account, particularly as we are proposing time accuracies better than 100ns.

To the extent that the electrical conductivity of the Earth in the service area of an eLoran station has been mapped, the spatial variations of ASF can be predicted using a computer model. But achieving this with sufficient accuracy for use by timing receivers is not always practicable. Happily, the ASF value at any point in the service area is very stable in time and can easily be measured with great accuracy.

If the very highest timing accuracy is required, the small temporal variations in ASFs can be measured by a reference station and corrections generated, as is already done in differential eLoran navigation systems. This way of dealing with temporal variations of timing due to ASF variations will be discussed in Section 4.2.1 below.

In addition to the ground-wave component of the low-frequency eLoran signal discussed so far, a "sky-wave" component will be radiated. This is reflected by the ionosphere and so returned to earth, especially at night. This unwanted component has the potential to interfere with the ground-wave signal being used for timing or navigation. Fortunately, the sky-wave signal invariably reaches the receiver via a longer path than the ground-wave and so arrives later. The eLoran receiver is designed to make its timing measurements on the ground-wave pulses before any sky-wave interference arrives. This has the major benefit of rendering the eLoran signals employed for timing independent of the ionosphere. So, they are insensitive to the variations of strength and delay of the sky-wave signals which, like GNSS signals, are affected by diurnal variations of the ionosphere and the influence on it of space weather events (see Section 4.2.2.).

Figure 1 maps the signal-to-noise (SNR) ratio values of the signals received from the Anthorn transmitter. There is good coverage of the whole of the UK and Ireland. The signal is also usable for timing purposes in Northern France, Belgium, Holland, Denmark and part of Germany. Similar maps are available for other European transmitter stations.

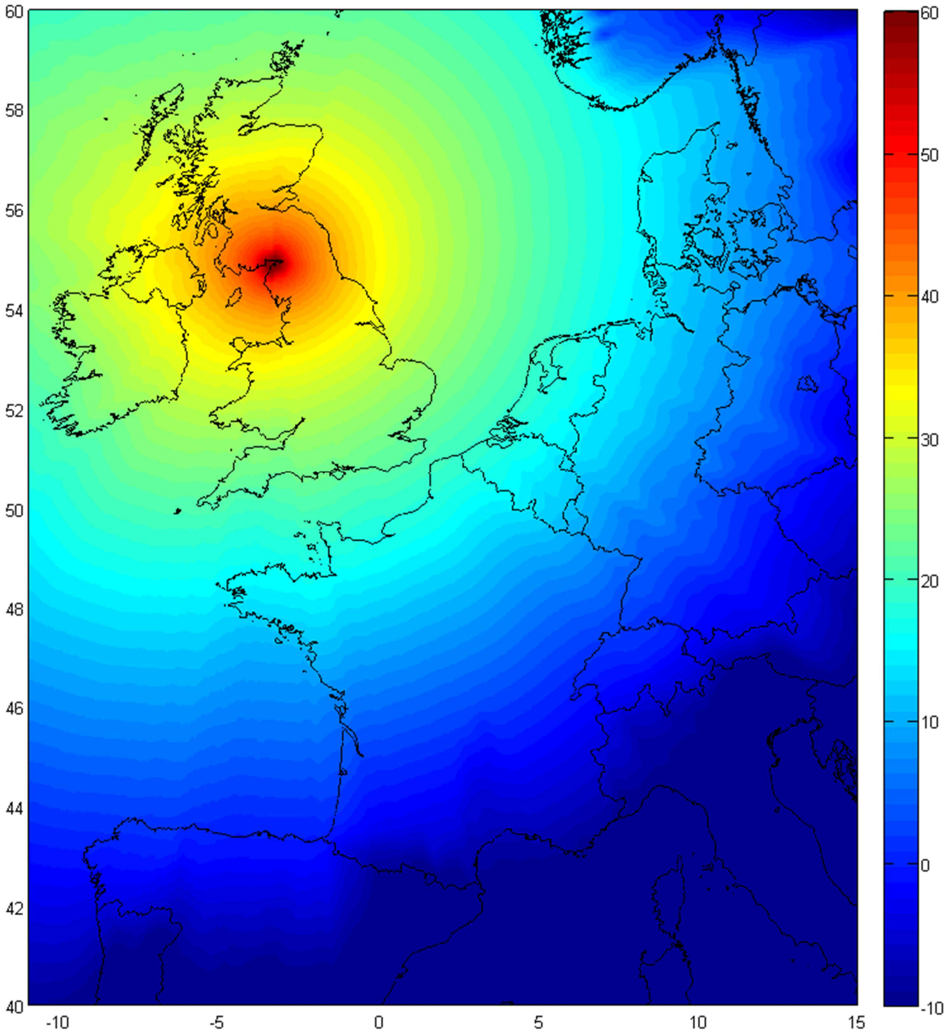

Figure 1: Map of signal-to-noise ratio (SNR) values in dBs of the signals received from Anthorn

[Image: Chris Hargreaves (GLA])

4.2 FACTORS WHICH COULD AFFECT TIMING ACCURACY AND STABILITY

A number of factors that can affect the accuracy and stability of the eLoran timing signal are identified in this section. In each case ways of mitigating or minimising the resulting errors are discussed.

4.2.1 ADDITIONAL SECONDARY FACTOR (ASF)

The ASF at the receiving site (as explained in Section 4.1.2 above) can be accurately measured once and for all when an eLoran timing receiver is installed and commissioned. One technique is to employ a portable source of UTC time such as a Chronos TimePort™ unit[5]. Alternatively, the approximate UTC value from the eLoran receiver can be measured after the first LDC UTC Sync message has been received. It is then compared with the value from another traceable source of UTC, which can be GNSS if that is healthy. A third possibility is to measure the local ASF value using an eLoran Differential Timing Receiver (EDTR) (see Section 5.2 below). Whichever method is employed, the eLoran

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[5] http://www.chronos.co.uk/index.php/en/product-groups/time-and-timing/timeport

timing unit being installed is then adjusted to take the measured ASF into account, so synchronising it once-and-for all to UTC. Using these techniques, synchronisation can be achieved to within a few tens of nanoseconds.

The Chronos CTL8200 unit (see Section 5.2 below) can carry out the process described automatically. This equipment contains an eLoran timing receiver and a GPS timing receiver. On commissioning the unit, the GPS reading is used to establish the eLoran ASF and so synchronise the eLoran receiver. Thereafter, both sources of UTC will normally be available and when one of them is lost, the other will provide a back-up.

The CTL8200 unit (see Figure 7) employs an H-field receiving antenna; that is, one in which the magnetic component of the eLoran signal is picked up by a small multi-turn loop. The magnetic field of a low-frequency radio transmission penetrates deep into buildings and below the surface of the Earth, with much lower rates of attenuation than the electric field; hence, the superiority of an H-field antenna over the more conventional E-field antenna for indoor use. The CTL8200 unit feeds eLoran signals received by its H-field antenna to an UrsaNav UN-151 eLoran timing receiver. In the SENTINEL research programme, multiple such units with data links to a control and monitoring centre[6], not only made accurate eLoran timing measurements but also provided proof-of-concept evidence of the validity of this approach (see Section 5).

Temporal variations of ASF: The ASF calibration value determined when an eLoran timing receiver is first commissioned is an instantaneous value. The ASF will thereafter be subject to small variations with the season or due to changing atmospheric conditions, especially the passage of weather fronts. The greatest such temporal variations are found in those geographical regions in which the ground freezes and thaws annually; here these very slow ASF changes may well need to be considered. Elsewhere, for many timing applications, they can be ignored. Further research is needed to determine the magnitude of these temporal ASF variations.

ASF Calibration over the LDC: An elegant way to establish initial ASF calibration values and to accommodate subsequent temporal variations of ASF is to apply corrections made by an eLoran Differential Timing Receiver (EDTR) in the vicinity. Corrections for the variations measured by the EDTR are conveyed to the receiver via the Loran Data Channel. The optimal spacing of adjacent EDTRs will depend in part on the timing accuracy required, and also on the distance, proportion of land or elevated terrain, and nature of the path from the transmitter. Paths lying wholly, or substantially, over sea-water require no such adjustments. The optimal deployment of EDTRs will be a subject of the next phase of the research.

Figure 2 shows the approximate magnitude of the temporal ASF variations of the signal transmitted from Anthorn throughout its service area. Similar maps are available for other European transmitter stations.

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[6] http://www.chronos.co.uk/index.php/en/product-groups/time-and-timing/eloran-timing/ctl8200-eloran-gps-utc-timing-receiver

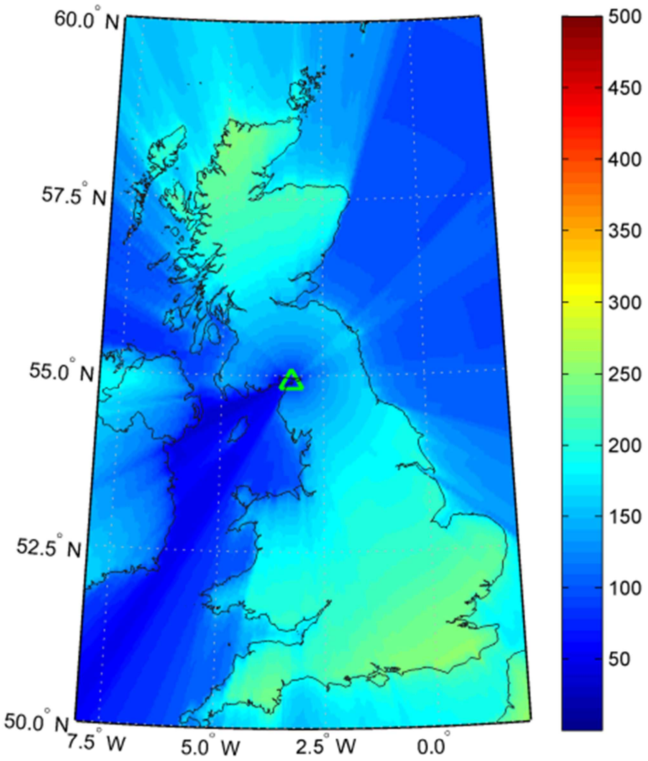

Figure 2: Estimated ASF temporal variations of the Anthorn signal (in nanoseconds).

Chris Hargreaves (GLA)]

It is envisaged that a network of regional EDTRs would supply continuous, fully-automatic adjustments for temporal ASF variations. Using these adjustments, it may well be possible for eLoran timing receivers to maintain their accuracy to within 100ns of UTC at all times, in all weather conditions and at all seasons, and whether they operate indoors or out.

4.2.2 SPACE WEATHER

GNSS signals are affected by extreme space weather in ways identified in the Royal Academy of Engineering publication "*Extreme space weather: impacts on engineered systems and infrastructure*"[7]. In common with all radio transmissions, eLoran signals can be affected by space weather. However, the space weather events which influence eLoran's low-frequency signals are generally not the same ones as affect the microwave signals of GNSS. In addition, it is the amplitude of the eLoran pulses, rather than their timing which are affected. As explained in Section 4.1.2 above, the eLoran receiver ignores the component of the signal received via the ionosphere, and which is vulnerable to space weather effects, and instead employs the less vulnerable ground wave component.

4.2.3 LOCAL ELECTRICAL INTERFERENCE

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[7] "*Extreme space weather: impacts on engineered systems and infrastructure*", Royal Academy of Engineering Feb 2013 http://www.raeng.org.uk/news/publications/list/reports/space_weather_full_report_final.pdf

Broad-band electrical interference at frequencies at and around 100kHz can be generated by devices such as switched-mode power supplies and low-voltage lighting systems. It can reduce the SNR of received eLoran signals, especially indoors. Such sources of interference are usually very localised, but may be intense. They should be identified, quantified, and minimised when a timing receiver is installed.

In many cases their effects can be greatly reduced by a combination of filtering and choice of antenna position and orientation. It may be appropriate to fit a filter to an electrically-noisy piece of machinery. Alternatively, the eLoran receiving antenna should be installed some distance from the noise source. Fortunately, an H-field antenna has a horizontal polar diagram in the form of a "figure-of-eight", with two nulls, allowing it to be oriented so as to minimise interference pickup. A timing receiver displays to the installer the SNR it is experiencing, so allowing the location and orientation of its antenna to be optimised.

If the interference is of narrow bandwidth, for example a carrier-wave interferer (CWI) or a communications signal, the receiver itself will minimise its effect by deploying a notch filter at the frequency of the interferer. Notch filters are tuned and adjusted in this way automatically by the receiver, which can deploy multiple notches within the 90-110kHz eLoran band and the spectrum adjacent to it.

4.2.4 TRANSMITTER AND ANTENNA MAINTENANCE

Experience of using the Anthorn transmissions for timing has disclosed two ways in which maintenance activities at the transmitter station impact the operation of eLoran receivers. First, during routine maintenance shut-downs the signal is lost. However, eLoran receivers pick up signals from multiple stations (often as many as 10) since at least three signals of good quality are required for eLoran navigation. While many of these stations are too distant to serve as timing sources, it is typically the case that at least one other station (and often many more) is providing a back-up timing signal; the maintenance of eLoran stations is scheduled to maximise the availability of such back-ups. Timing receivers, such as the eLoran unit in the Chronos CTL8200, switch automatically and seamlessly (that is, in a phase-coherent way) from the transmitter whose signal has been lost to one of the back-ups, reverting to the preferred station when its signal returns. This capability has been demonstrated during the SENTINEL programme.

The other vulnerability to transmitter station maintenance is an unwanted change in the phase of the transmission, sometimes of hundreds of nanoseconds, when certain antenna maintenance operations are performed. It is suggested that during such operations a "Do Not Use" message be sent via the LDC. This would cause the eLoran receiver to switch to a backup station for the duration of the maintenance operation.

5 MEASUREMENTS OF TIME ACCURACY FROM eLoran

A key metric for assessing the quality of a timing receiver, defined in ITU standards for telecoms synchronisation, is "Maximum Time Interval Error (MTIE)". MTIE is derived by sliding windows of different of observation intervals through a dataset of time interval error (TIE) values (Figure 3). As in Figure 4 shows, the resulting MTIE data points are plotted on a log-log graph.

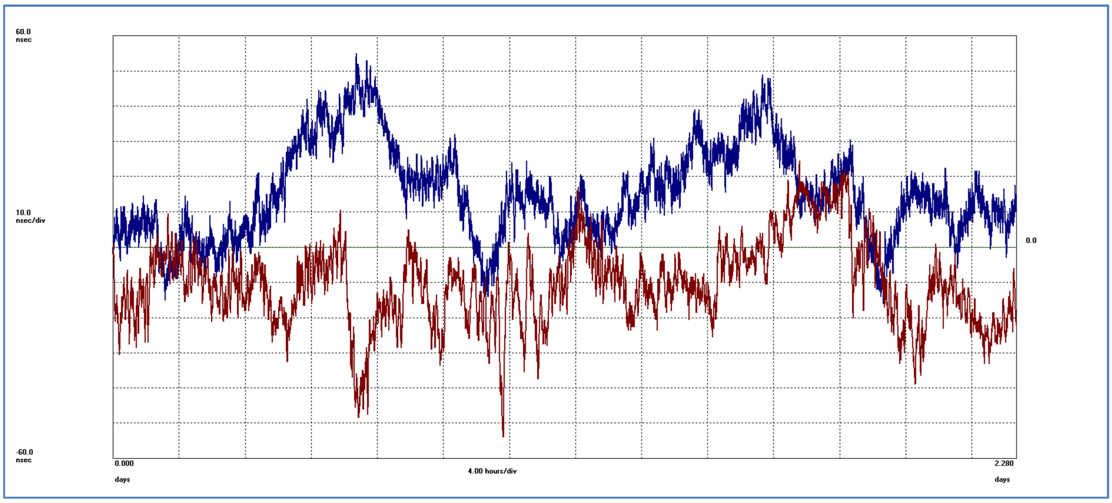

Figure 3: Time Interval Error (TIE) diagram. Red: eLoran TIE. Blue: GPS TIE.

Y-Axis 10ns/div. X-axis: 3 days.

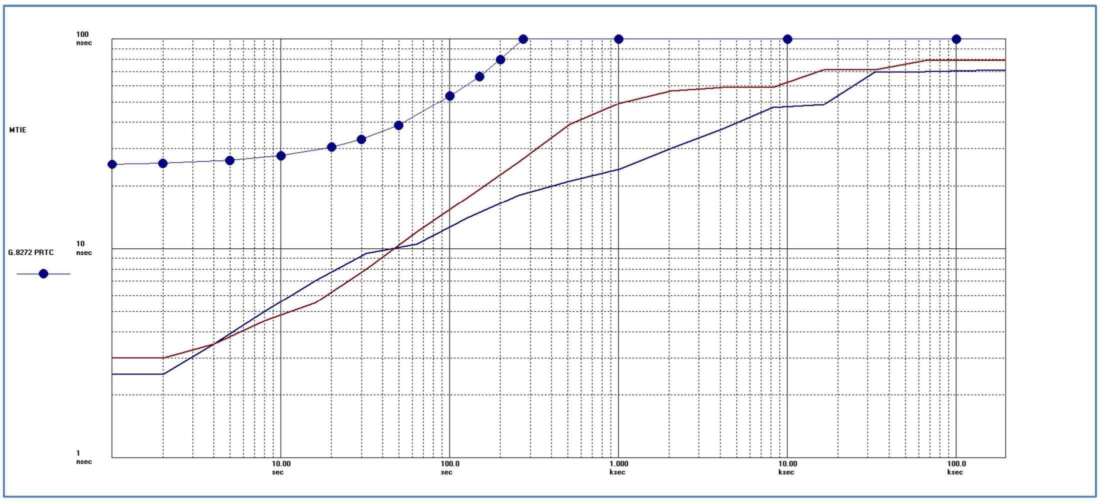

Figure 4: Maximum Time Interval Error (MTIE) diagram of Figure 3

Data collected with a CTL8200 timing receiver over 3 days.

Upper curve with blue points is the G.8272 MTIE mask below which plotted lines must fall. Red: eLoran MTIE. Blue: GPS MTIE.

In **FIGURE 4** the upper curve with blue points is the MTIE mask, below which the plotted lines must fall if the receiver is to meet the ITU G.8272 standard for a primary reference timing clock (PRTC). The results show clearly that not only the GPS receiver but also the eLoran receiver both meet this specification. Indoor timing tests were undertaken using an H-field antenna with a Cs reference with daily drift of <10ns.

Extensive testing has been undertaken in a lab environment which shows that eLoran signals can deliver UTC-traceable timing from transmitter stations that are relatively distant. Whilst it is always preferable to use the strongest signal, there may be times when the nearest transmitter will not be available.

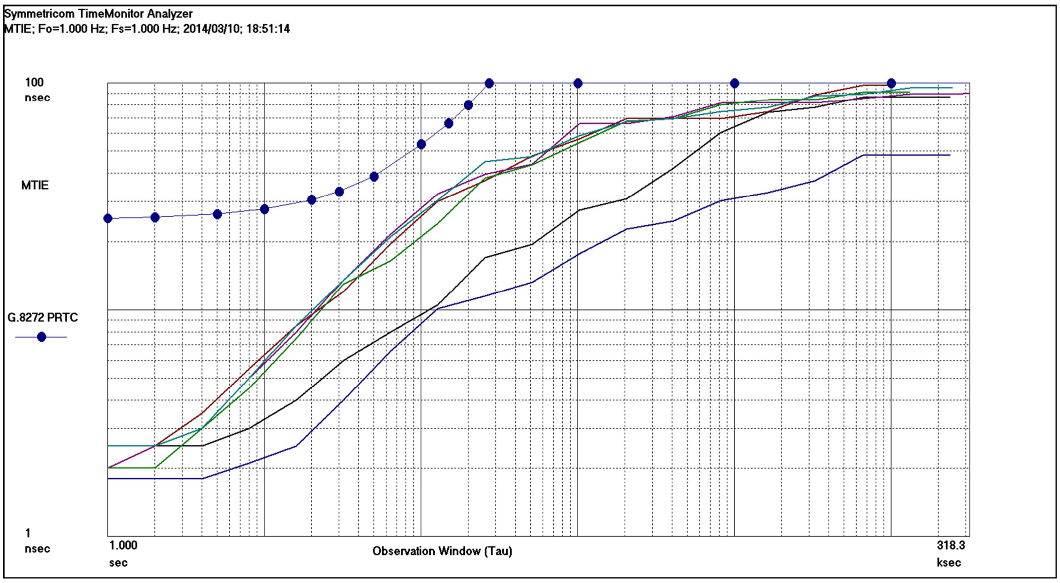

Figure 5: MTIE plots from indoor eLoran timing receiver.

Figure 5 shows MTIE plots for an eLoran timing receiver when using signals from stations at various ranges. The receiver was a Chronos CTL8200 operated at Chronos Technology in Gloucestershire, England. It used an H-Field antenna at an indoor location unsuitable for GPS timing reception. The 5 stations monitored, in order of proximity, are:

Colour	Station	Range	Location	Path
Red	Lessay	300km	Northern France	Land and Sea
Blue	Anthorn	350km	North-West England	Land
Cyan	Sylt	800km	North Germany	Land and Sea
Green	Soustons	900km	North Germany	Land and Sea
Magentas	Vaerlandet	1150km	South-West Norway	Land and Sea

The locations of these stations relative to the UK are shown in Figure 6 below as the red markers. The orange markers are differential GPS stations.

Figure 6: eLoran Stations

The SNR values of the signals from Anthorn and Lessay were excellent; those from the other stations less than ideal. Lower SNR values like these make it harder for the receiver to acquire the signal and complete the initial synchronisation process. But that done, the MTIE plots show that all these stations, at ranges from 300km to 1150km, were able to supply timing readings. The errors, measured over periods ranging from 1s to 3.5 days, were less than 100ns. Telecom timing applications at the edges of networks and indoors currently require synchronisation with respect to UTC and stability of the order of 1 µs; these measurements show that eLoran can provide viable, reliable and resilient timing from multiple stations for such services.

5.1 CTL8200 TEST RECEIVER USED IN TRIALS

Figure 7: CTL8200 eLoran Timing Receiver

The Chronos CTL8200 shown in Figure 7, contains an UrsaNav UN-151 eLoran timing receiver module and a GPS timing receiver. It was developed as part of the SENTINEL programme, supported by the UK Technology Strategy Board. It is available for organisations that wish to evaluate eLoran timing signals aligned to UTC and can be remotely managed and configured using the SENTINEL research platform.

The receiver retains the valuable features of the SENTINEL GPS Jamming and interference detection Sensor including long term event analysis. Specifically, it can be networked via an Ethernet connection allowing it to be managed and monitored remotely using the SENTINEL management platform. The key feature additional to requirements of SENTINEL is its built-in ability to implement automatically the process described in Section 4.2.1 above: that is, it will measure the UTC offset of $eLoran_{UTC}$ due to ASF delay and synchronise the eLoran time to GPS_{UTC}, so removing the effects of the ASF delay.

The CTL8200 is also an effective EDTR, as described in Section 4.2.1 above. Operating as an eLoran Differential Timing Receiver it will continuously measure the regional eLoran UTC offset, and supply corrections to be broadcast over the LDC. These can be received by remote eLoran timing receivers that lack built-in GNSS receivers.

The CTL8200 has two 1pps outputs, one derived from eLoran and the other from GPS. These can be connected to an oscilloscope or to TIE measuring equipment for long-term analysis, either locally or remotely. This makes the unit a valuable tool for research into long-term seasonal ASF variations. Deploying multiple units will allow the spatial distribution of regional ASFs to be mapped. Results of research into seasonal and regional ASF and UTC offset variations measured in these ways will be published in due course.

The SENTINEL platform continuously monitors the relative MTIE between eLoran and GPS, thus providing valuable long term analysis of the accuracy and stability of both. If a user settable MTIE threshold is broken, alarm events are registered and email sent to designated network observers and researchers.

5.3 CONCLUSIONS OF MEASUREMENTS OF TIME ACCURACY USING eLoran

The principal conclusion from these tests, and from monitoring eLoran timing signals during the GAARDIAN and SENTINEL programmes is that eLoran can provide a timing source, which we will call $eLoran_{UTC}$, that is aligned to GPS_{UTC} (and hence $USNO_{UTC}$), but which is available independently of GPS.

eLoran appears to be a perfectly acceptable source of precise timing for telecommunications use, in particular in the next generation of LTE TDD services where eICIC and CoMP will become increasingly relevant to preserve and utilise efficiently scarce spectrum resources. It thus forms a viable means of mitigating the loss of GPS, and other GNSS, since it works in GNSS-denied environments. These include in particular indoor operation and also denial of GNSS due to interference, intentional jamming or solar events.

6 NATIONAL DEPLOYMENT

Some nations are now actively considering deploying eLoran systems either by installing new transmitting stations or by upgrading legacy Loran-C systems. There is a widespread view that eLoran is the most effective complement to GNSS as a source of PNT. Among the most visionary countries is South Korea whose plans and rationale were described in a paper delivered at the 2013 European Navigation Conference by Prof. Jiwon Seo et al: "*eLoran in Korea – Current Status and Future Plans*"[8].

The paper opens with this statement "*After the annual GPS jamming attacks from North Korea started from August 2010, the South Korean government realized the importance of a complementary navigation and timing system. Among various options, a high power terrestrial radio navigation system, eLoran, was considered as the most effective candidate*"

This section describes how a wide-area national UTC timescale system using eLoran signals can be deployed.

6.1 TRANSMISSIONS

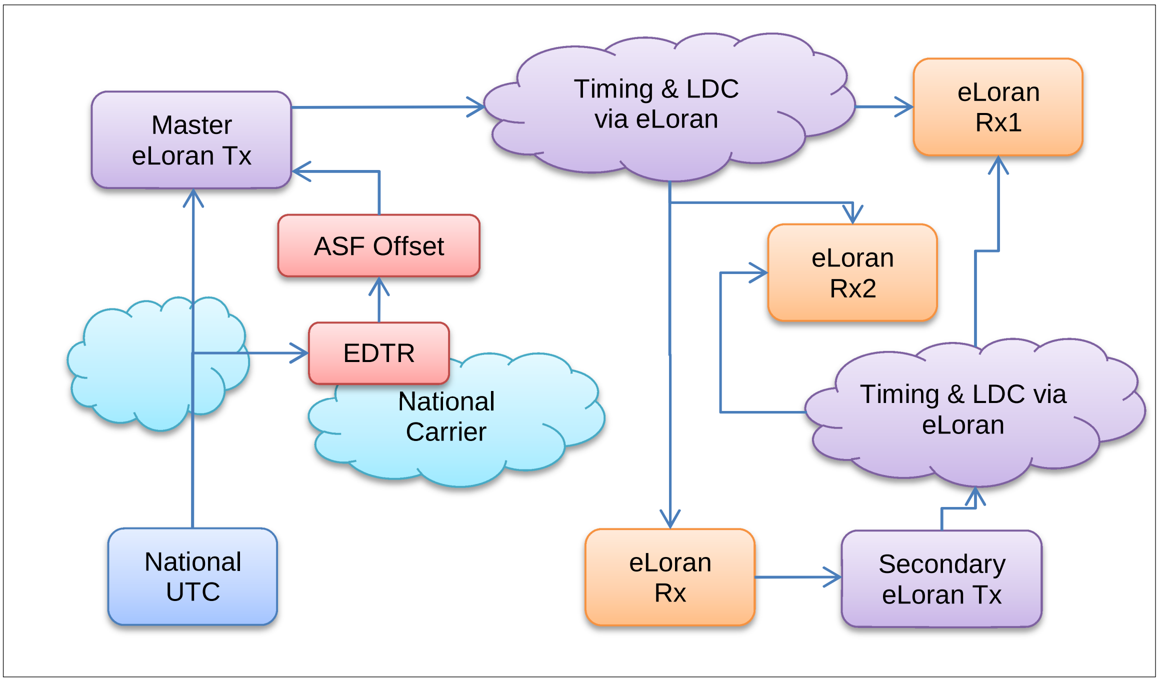

Figure 8: National UTC Timescale Network

Assuming a nation is a member of the TAI/UTC community linked to the BIPM, its local UTC will be derived from, and so traceable to, a national time laboratory. In Figure 8 this source of National UTC is in the lower left-hand corner. Local UTC will be transported to a master eLoran station (top left) via a resilient link and the eLoran transmissions synchronised to this source. The link could well be provided by a national telecoms carrier: such carriers are likely to have a vested interest in the provision of resilient and accurate time and timing both for their wholesale customers and for their own applications. This would be a mutually-beneficial relationship.

Local eLoran timing receivers "eLoran Rx1 & Rx2", when first switched on will be syntonous with the broadcasted eLoran timing signal, but not yet synchronous. Once it has received the first UTC Sync message its time output will be close to the national UTC timescale, but will still be in error by the amount of the local ASF. To fully synchronise its 1pps to local UTC requires knowledge of that ASF.

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[8] "*eLoran in Korea – Current Status and Future Plans*", ENC 2013, Prof. Jiwon Seo et al, Yonsei University, Korea

The “Secondary eLoran Tx” would be set as a backup for “eLoran Rx1 & Rx2” and would have its own eLoran receivers monitoring other nearby transmitters and of course multiple backups can be set in this way.

As explained in Section 4.2.1 above, there are several ways of obtaining the ASF. The most attractive, in that it requires few skills and keeps the solution entirely “sky-free”, is to derive the ASF from a relatively local EDTR, received via the LDC.

Local EDTR units could be collocated with major synchronisation sites of the national telecoms carrier. A carrier which is already transporting national UTC will employ it as the reference time for its EDTRs, giving a continuous source of local ASF values to send over the LDC. In this way, not only will the local timescale be directly traceable to the national UTC timescale, but eLoran users who require the highest timing accuracy will remain very accurately locked to it through changing seasons and weather. Those who require lower accuracy will simply ignore the EDTR corrections.

6.2 STATION MASTER CLOCK

The highly reliable master clocks of eLoran stations are usually an ensemble of triplicated Caesium atomic frequency standards with multiple redundancy throughout their architecture. Their 1pps output will be synchronised to the national UTC timescale. This arrangement will ensure that the eLoran stations have an inherently resilient architecture. Operational characteristics of station master clocks will be the subject of future publications.

7 POTENTIAL MARKETS OPENED UP BY ACCURATE INDOOR PNT SIGNALS

7.1 LTE TDD, CoMP and eICIC

New services and applications for the next generation of mobile telecom networks are being planned. These include time Division Duplex (TDD) modulation schemes, which require more precise time alignment at the edge of the network than is currently available. Other enhancements employ Coordinated Multipoint (CoMP) transmission and reception and Enhanced InterCell Interference Coordination (eICIC); these techniques which enable scare spectrum to be more efficiently used are driving the requirement for phase alignment between cell sites, or within clusters of cell sites, down to below 1 µs.

Implementing these tighter timing requirements will be particularly challenging where multiple cell sites share an indoor GNSS-denied environment or where the delays of Ethernet connectivity between cell sites cannot be easily managed.

A potential solution here is the IEEE standardised Precision Time Protocol (PTP), created with 3G and 4G mobile networks conforming to the 3GPP Standards in mind. ITU are standardising PTP for transporting time to the edges of networks. But there are problems in PTP with packet delay variations and network symmetry. It is possible, of course, to calibrate out these fixed delays by using a local UTC source, but that is cumbersome and requires expert technical intervention and specialist test equipment.

Particularly challenging will be the synchronization of evolved Node B’s (eNB) deployed indoors.

In this and these other applications a low-cost, small footprint, eLoran timing receiver could prove very attractive.

7.2 FINANCIAL TIMING MARKETS

High Frequency Trading using Computer Based Trading equipment now requires UTC-traceable synchronised time stamps with an accuracy of better than 1µs. How will precise time be delivered to these systems across a wide-area trading environment? Also, how will fraudulent attacks using GNSS time-spoofing be avoided?

GPS based Network Time Protocol (NTP) systems give only millisecond, not sub-microsecond, accuracy and are vulnerable to GPS jamming. With PTP, the delivery process is cumbersome and may require fixed delays to be calibrated out on installation. GPS antenna path delays also require calibrating out at commissioning.

In this context, eLoran timing is an ideal solution which would work well indoors.

8 BENEFITS OF eLoran OVER OTHER PNT SYSTEMS

Let us examine the benefits of eLoran in comparison with alternative PNT systems when used for timing.

8.1 TRANSMISSIONS INTERNATIONALLY STANDARDISED

The eLoran system is well documented and standardised internationally. Essential characteristics are defined in the following documents:

- International Loran Association, "Enhanced Loran (eLoran) Definition Document", Version 1.0, October 16, 2007.
- "Recommendation ITU-R M.589-3, Technical Characteristics of Methods of Data Transmission and Interference Protection for Radionavigation Services in the Frequency Bands between 70 and 130 kHz", International Telecommunication Union Recommendations.
- Minimum Performance Standards for Marine eLoran Receiving Equipment, RTCM Special Committee SC127, Revision 2.0, March 2010.

8.2 BROADCASTS NATIONAL UTC OVER A WIDE AREA

eLoran ground wave signals can be received indoors or outdoors over ranges of hundreds of kilometres from the transmitters. Timing receivers can maintain synchronisation to within 100ns of UTC to the edge of coverage by receiving timing corrections broadcast over the LDC.

Transmissions from multiple eLoran stations can generally be received since these are required for the navigation use of eLoran. For timing, these multiple sources ensure that alternative signals are available even during transmitter maintenance periods, so maximising the availability of the service.

8.3 eLoran CAN BE RECEIVED INDOORS

H-Field antenna technology allows indoor reception of eLoran timing signals in areas that GPS and other GNSS signals cannot reach. This has significant benefits, chiefly resulting from the lack of a requirement for a roof antenna. It avoids the requirement for: long cable runs; specialised installation staff, materials, and processes; permission from local facilities management staff; and the risk of mutual interference between adjacent GNSS antenna installations.

The requirements and ease of deployment of H-Field antennas will be investigated further in both typical and exceptional indoor locations through collaboration with potential user community.

8.4 PROVIDES TIMING SYNCHRONOUS TO UTC WITHIN 100ns

Telecom requirements: The definitive ITU document for precise time synchronisation in telecom transport networks is now "*Recommendation ITU-T G.8272/Y.1367*"[9]. This specifies the requirements for primary reference time clocks (PRTCs) suitable for time and phase synchronization in packet networks under environmental conditions normal for the equipment. A typical PRTC provides the reference signal for time synchronization and/or phase synchronization for other clocks within a network or a section of a network. In particular, a PRTC can provide the reference signal for a "Telecom Grand Master" within the network nodes where the PRTC is located. The PRTC provides a reference time signal traceable to a recognized time standard, usually UTC. The Recommendation defines the output requirements and accuracy that a PRTC must maintain.

Indoor trials with eLoran differential timing receivers have shown that they can provide precise UTC corrections in conformance to G.8272 Figure 1 (see Section 5 above). Further research needs to be undertaken to quantify seasonal ASF variations and the resulting requirement for differential timing corrections.

Financial Services requirements: After the so-called "Flash Crash" of 2010, when $1T temporarily evaporated from US markets, a UK Government report "*The Future of Computer Trading in Financial Markets*"[10] recommended that all computer-based trading be synchronised to within 1 µs of UTC.

Indoor eLoran timing systems can easily meet this requirement, even without differential timing corrections.in most locations.

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[9] http://www.itu.int/ITU-T/recommendations/rec.aspx?rec=11817

[10] "*The Future of Computer Trading in Financial Markets*" Government Office for Science, Foresight Committee 2012

8.5 RESILIENT AGAINST GNSS JAMMING AND SPOOFING

The high susceptibility of GNSS signals to low-power jamming is described in the SENTINEL Report[11] and the Royal Academy of Engineering report "*Global Navigation Space Systems: reliance and vulnerabilities*"[12]. In contrast, eLoran timing signals are transmitted in a very different part of the spectrum. They are thus immune to the effects of GNSS jammers.

Like all radio signals, eLoran transmissions can be jammed. However, the power level of the signals reaching receivers (which the jammer must overcome) is many orders of magnitude greater than that of GNSS signals. Further, to transmit jamming signals at 100kHz over all but very short ranges requires large transmitting antennas, substantial transmitter power and dangerously high voltages.

For the same reasons, eLoran is much more resilient than GNSS to spoofing attacks, of the kinds that have been studied and demonstrated recently.

8.6 RESILIENT AGAINST SPACE WEATHER EVENTS

The susceptibility of GNSS signals to space weather events is well described in the Royal Academy of Engineering report "*Global Navigation Space Systems: reliance and vulnerabilities*"[13]. eLoran timing signals are transmitted in a very different part of the spectrum and employ the wholly-different, ground-wave, mode of propagation. As explained in Section 4.1.2 above, this renders them much less susceptible to space weather effects and they are not susceptible to many of the events that threaten GNSS.

8.7 COMPLEMENTARY TO PTP

Precision Time Protocol (PTP) has been developed from the original IEEE 1588 specifications. ITU is developing the G.827x series of Standards. PTP is vulnerable to variable delays in Internet Protocol transmission systems. These are of greatest concern in third-party systems employing transport networks over which the carrier has no control. To transfer phase with the required accuracy, PTP employs "on-path-support" using embedded "client" clocks throughout the network.

In contrast, eLoran with its LDC is a simple and elegant stand-alone wireless technology that delivers precise UTC-traceable time indoors. If required, eLoran can work alongside PTP to mutual benefit. Trials currently underway at Chronos Technology are exploring this combination of technologies.

9 CONCLUSIONS

This paper has proposed the use of eLoran to disseminate precise time, timing and phase traceable to UTC for both indoor and outdoor applications. Continuous accuracies of better than 100ns with respect to UTC are being achieved in current proof-of-concept and technology-readiness trials.

The paper proposes and illustrates a method of establishing national time standard services using eLoran. These would be traceable to sovereign national UTC. They would be of great benefit to a wide range of users, notably telecommunications providers and financial sector organisations for whom precise time synchronisation will be required by future services. These organisations are also becoming concerned about their dependence on GNSS timing, given its vulnerability to jamming and interference and the complexity and expense of deploying it, especially when required indoors.

Further research, already under way, is evaluating the accuracy and optimising the delivery via the Loran Data Channel of UTC time corrections from remote differential timing receivers.

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[11] "*The SENTINEL Report*", Chronos Technology 2014

[12] "*Global Navigation Space Systems: reliance and vulnerabilities*", Royal Academy of Engineering, March 2011 http://www.raeng.org.uk/news/publications/list/reports/RAoE_Global_Navigation_Systems_Report.pdf

[13] "*Global Navigation Space Systems: reliance and vulnerabilities*", Royal Academy of Engineering, March 2011 http://www.raeng.org.uk/news/publications/list/reports/RAoE_Global_Navigation_Systems_Report.pdf

Chronos Technology is working with partners, and actively seeking additional collaborators, in both the supply and user timing community as well as Academia and Government as it widens the scope of this research.

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b. "*BIPM Annual Report on Time Activities*", Volume 7, 2012
c. "*Eurofix Message Format*", Ver 2.15, Gerard Offermans, March 2014
d. "*RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) Service*", Version 2.2, RTCM Special Committee 104, January 15, 1998
e. "*Recommendation ITU-R M.589-3, Technical Characteristics of Methods of Data Transmission and Interference Protection for Radionavigation Services in the Frequency Bands between 70 and 130 kHz*"
f. "*Enhanced Loran (eLoran) Definition Document*", ver 1.0 16th Oct 2007, International Loran Association
g. "*Extreme space weather: impacts on engineered systems and infrastructure*", Royal Academy of Engineering February 2013
h. "*Global Navigation Space Systems: reliance and vulnerabilities*", Royal Academy of Engineering, March 2011
i. "*Recommendation ITU-T G.8272/Y.1367- Timing characteristics of primary reference time clocks*" October 2013 Study Group 15, Question 13.
j. "*The Future of Computer Trading in Financial Markets*" Government Office for Science, Foresight Committee 2012
k. "*eLoran in Korea – Current Status and Future Plans*", ENC 2013, Prof. Jiwon Seo et al, Yonsei University, Korea

APPENDIX A – eLORAN

The following information is extracted from the “Enhanced Loran (*eLoran*) Definition Document” Report Version: 1.0, 16 October 2007. Please refer to the original document for a full definition.

A.1 eLORAN OVERVIEW

Enhanced Loran is an internationally-standardized positioning, navigation, and timing (PNT) service for use by many modes of transport and in other applications. It is the latest in the long-standing and proven series of low-frequency, LOng-RAnge Navigation (LORAN) systems, one that takes full advantage of 21st century technology.

eLoran meets the accuracy, availability, integrity, and continuity performance requirements for aviation non-precision instrument approaches, maritime harbour entrance and approach manoeuvres, land-mobile vehicle navigation, and location-based services, and is a precise source of time and frequency for applications such as telecommunications.

eLoran is an independent, dissimilar, complement to Global Navigation Satellite Systems (GNSS). It allows GNSS users to retain the safety, security, and economic benefits of GNSS, even when their satellite services are disrupted.

A.2 THE eLORAN SYSTEM

eLoran meets a set of worldwide standards and operates wholly independently of GPS, GLONASS, Galileo, Beidou or any future GNSS. Each user’s eLoran receiver will be operable in all regions where an eLoran service is provided. eLoran receivers work automatically, with minimal user input.

The core eLoran system comprises modernized control centres, transmitting stations and monitoring sites. eLoran transmissions are synchronized to an identifiable, publicly-certified, source of Coordinated Universal Time (UTC) by a method wholly independent of GNSS. This allows the eLoran Service Provider to operate on a time scale that is synchronized with, but operates independently of, GNSS time scales. Synchronizing to a common time source will also allow receivers to employ a mixture of eLoran and satellite signals.

The principal difference between eLoran and traditional Loran-C is the addition of a data channel on the transmitted signal. This conveys application-specific corrections, warnings, and signal integrity information to the user’s receiver. It is this data channel that allows eLoran to meet the very demanding requirements of landing aircraft using non-precision instrument approaches and bringing ships safely into harbour in low-visibility conditions. eLoran is also capable of providing the exceedingly precise time and frequency references needed by the telecommunications systems that carry voice and internet communications.

A.3 ACCURACY, AVAILABILITY, INTEGRITY AND CONTINUITY

eLoran’s enhanced accuracy, availability, integrity and continuity meet the requirements for aviation non-precision instrument approaches, maritime harbour entrance and approach manoeuvres, land-mobile vehicle navigation, and location-based services. It also allows absolute UTC time to be recovered with an accuracy of 50 nanoseconds as well as meeting the Stratum 1 frequency standard needed by telecommunications users.

Accuracy	Availability	Integrity	Continuity
0.004 – 0.01 nautical mile (8 – 20 meters)	0.999 –0.9999	0.999999 (1 x 10-7)	0.999 – 0.9999 over 150 seconds

Notes:
1. Accuracy to meet maritime harbour entrance and approach
2. Availability, integrity and continuity to meet aviation non-precision approach in the U.S.

APPENDIX B – TAI, UTC AND LEAP SECONDS

The global reference for time is International Atomic Time (TAI), a time scale calculated at the Bureau International des Poids et Mesures (BIPM) in France, using data from some 400 atomic clocks in over 70 national laboratories[14].

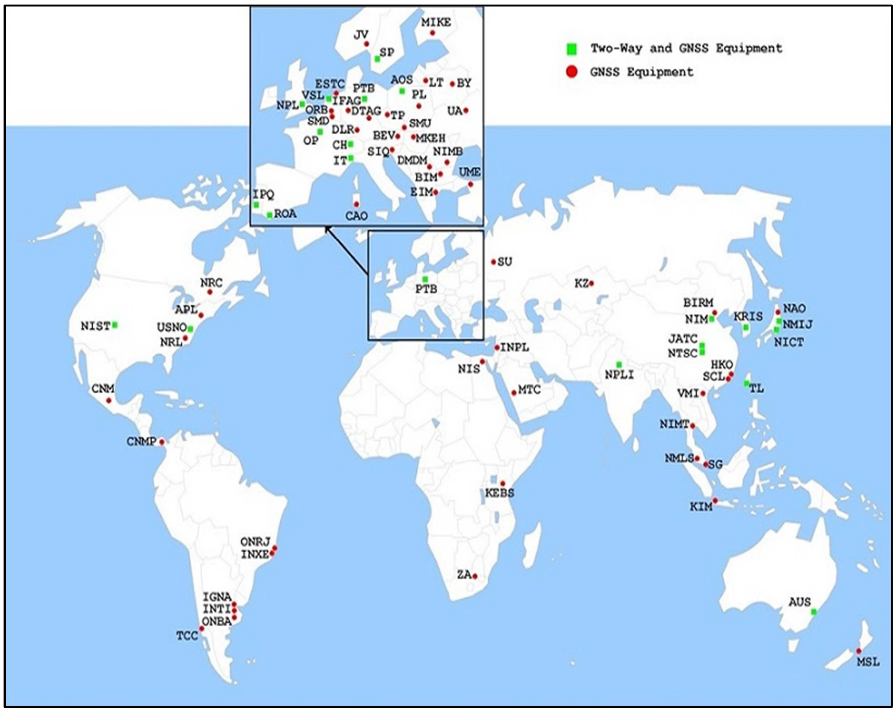

Figure 9: National Time Laboratories which contribute to TAI (UTC)

The BIPM organizes clock comparisons for the determination of TAI through an international network of time links, as shown in Figure 9. Corrections to local national timing laboratory clocks are generally applied monthly or weekly and typically will be a few nanoseconds (ns).

A list of participating laboratories and their respective clocks and an almanac of monthly corrections can be found in the BIPM annual report.

TAI long-term stability is set by weighting participating clocks. The scale unit of TAI is kept as close as possible to the SI second by using data from those national laboratories which maintain the best primary standards. These will generally be Hydrogen Masers or high performance Caesium standards.

Coordinated Universal Time (UTC) is identical to TAI except that from time to time a leap second is added to ensure that, when averaged over a year, the Sun crosses the Greenwich meridian at noon UTC to within 0.9s. The dates of application of the leap second are decided by the International Earth Rotation Service (IERS).

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[14] "BIPM Annual Report on Time Activities", Volume 7, 2012, http://www.bipm.org/en/scientific/tai/time_ar2012.html

APPENDIX C – ABBREVIATIONS & ACRONYMS

3GPP	The Third Generation Partnership project
ASF	Additional Secondary Factor
BIPM	Bureau International des Poids et Mesures
CoMP	Coordinated Multipoint
CWI	Carrier Wave Interference
Cs	Cesium, Cæsium
DGPS	Differential GPS Corrections
DNU	Do Not Use
EDTR	eLoran Differential Timing Receiver
eICIC	Enhanced InterCell Interference Coordination
eNB	Evolved Node B
FEC	Forward Error Correction
GAARDIAN	**G**NSS **A**vailability **A**ccuracy **R**eliability an**D** **I**ntegrity **A**ssessment for timing and **N**avigation
GNSS	Global Navigation Satellite Systems
GRI	Group Repletion Interval
IEEE	Institute of Electrical and Electronics Engineers
ITU	International Telecommunication Union
LDC	Loran Data Channel
MTIE	Maximum Time Interval Error
ns	Nanoseconds
OOT	Out of Tolerance
PNT	Positioning, Navigation and Timing
PPM	Pulse Position Modulation
PRTC	Primary Reference Timing Clock
PTP	Precision Time Protocol
RNT	Resilient Navigation and Timing
RPNT	Resilient Positioning, Navigation and Timing
RTCM	The Radio Technical Commission for Maritime Services
SENTINEL	GNSS **SE**rvices **N**eeding **T**rust **I**n **N**avigation, **E**lectronics, **L**ocation & timing
SNR	Signal-to-Noise Ratio
TAI	International Atomic Time
TIE	Time Interval Error
UTC	Universal Coordinated Time