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THE IDENTIFICATION OF POSSIBLE APPLICATIONS OF THE E-LORAN SYSTEM

ABSTRACT

Global Navigation Satellite Systems (GNSS) more and more affect many areas of human activity in the world. Every day human activity around the world depends upon satellite systems for positioning, navigation and timing. As these systems are commonly used further efforts must be made to make GNSS more immune to on occurring more and more frequently incidents of jamming and spoofing. It seems that eLoran system is currently the best the technical and scientific solution to allowing for effective protection of the Global Navigation Satellite Systems. Last year the authors presented eLoran system as a potential tool for transmission of the national time signal [Curry et al., 2017]. This time the authors present abilities of additional use of the eLoran as a back-up system for GNSS.

Keywords: Marine Navigation, GNSS, PNT, eLoran, Positioning.

1. INTRODUCTION

Enhanced Loran (eLoran) is the latest in the longstanding and proven series of low frequency, **LO**ng-**RA**nge **N**avigation systems. eLoran evolved from Loran-C in response to the Volpe Report on GPS vulnerability [Volpe, 2009]. The next generation of the Loran systems, eLoran, improves upon Loran-C through enhancements in equipment, transmitted signal, and operating procedures. The improvements allow eLoran to provide better performance and additional services when compared to Loran-C, and enable eLoran to serve as a backup to satellite navigation in many important applications [Safar et al., 2011].

GNSS is something more for professionals than just another new navigation system, or simply speaking a magic box receiver for a layman. It's a technology used for much of critical infrastructure and by almost every major industry, as well as the military, law enforcement, and first responders. We are increasingly reliant on the precision, navigation, and timing services that GNSS provides. From land navigation on cell phones to a timing source for our regional, national and local infrastructure, we need a reliable backup system to GNSS.

2. CURRENT STATUS OF GLOBAL NAVIGATION SATELLITE SYSTEMS.

Nowadays, users of satellite systems may receive signals emitted by global and regional satellite systems. Another group consists of support systems for these global ones in the areas of transport requiring greater accuracy, such as in air transport [Czaplewski, 2018].

2.1. Global Systems

Satellite systems of global range include the American system NAVSTAR GPS, the Russian-built GLONASS, the Chinese BeiDou and the European Galileo.

NAVSTAR GPS System

The NAVSTAR GPS system was created for the U.S. Army. Work started on the system as long ago as in 1960. The first research works were completed between 1964 and 1966. The team, formed under the leadership of prof. Bradford Parkinson in 1973, devised and implemented the final concept of the system that has been in operation since 1978. It reached full operational capability on 17th July 1995.

Presently, GPS is used by more than billion receivers, emitting 4 civilian signals:

- L1 C/A – original signal,
- L2C – second civilian signal,
- L5 – aviation safety of life,
- L1C – international signal.

Furthermore, GPS emits signals for military purposes. At the moment, the system constellation consists of 31 satellites [Martin, 2017]. It is noteworthy that in recent years the constellation of the system has been rejuvenated very intensively. The constellation is planned to be radically renovated with new generation satellites between 2019 and 2023. During this time, 22 satellites of GPS III block are to be inserted into orbits to transmit 4 civilian signals: L1 C/A, L1C, L2C, L5 and 4 signals for military use: L1/L2 P(Y), L1/L2M [Martin, 2017].

GLONASS System

The first Russian GLONASS satellite was launched on 12th October 1982. The system reached full configuration for the first time in 1995. However, due to the short lifetime of the satellites and insufficient funding of the programme between 1995 and 2001, the constellation shrank to 7 satellites [Czaplewski & Goward, 2016]. Since 2001, the system has been gradually revitalised and modernised, and in effect the constellation has quickly expanded. The current constellation of the system comprises 25 satellites. In 2016 and 2017, three GLONASS-M satellites were launched into orbit (07.02.2016; 29.05.2016, and 22.09.2017) [Revnivykh, 2017] and presently, the system constellation consists of 28 satellites.

It is assumed that the modernisation of the system will increase the accuracy fourfold due to [Karutin 2015]:

- the implementation of a new CDMA signal,
- the modernisation of the ground control segment,
- the introduction of new atomic frequency references (2 CAFs + 2 RAFs),
- the introduction of advanced control of satellites, their orbits and clocks,
- the change of the geodetic system of reference from PZ-90 to PZ-90.11 equalized with the International Terrestrial Reference Frame (ITRF) to a degree of millimetres,
- the synchronisation of GLONASS time with UTC (SU) time to an accuracy of below 2ns and simultaneous maintenance of long-term stability.

GALILEO System

The need to start the European satellite system Galileo emerged in the 1980s. Between 1999 and 2000, the project’s technical and economic requirements were set forth. In December 2004, the testing of the ground segment of the Galileo system was finished and on 28th December 2005 the first satellite, GIOVE-A was launched into orbit. The size of the constellation in December 2017 was 22 satellites [Kautz, 2017]. The initial problems with activation of the system were resolved. Presently, the system constellation consists of 22 satellites.

According to the European Union’s assumptions, the system will have reached its full operational capability by 2020.

BEIDOU System

Although BeiDou is declared to be a regional system by the Chinese People’s Republic, covering the area vital for the Chinese People’s Republic and a part of the Southeast Asia, its satellites may be used worldwide

The first satellite of the Chinese system was launched into geostationary orbit on 30th October 2000. Currently, the BeiDou system (BD-2) consists of:

- 5 geostationary satellites (located at 58.75°E, 80°E, 110.5°E, 140°E and 160°E),
- 20 satellites in IGSO and MEO orbits.

After reaching its full operational capability, the system constellation will include 3 geostationary satellites (GEO), 3 satellites in geosynchronous orbits (IGSO) and 30 satellites on medium Earth orbits (MEO). The system is planned to reach its full configuration and operational capability by the end of 2020.

2.2. Regional Satellite Systems

Regional systems are the rather new tendency in satellite navigation systems and for the moment this group of systems include only two: the Japanese QZSS and Indian IRNSS.

Quasi-Zenith Satellite System (QZSS)

The Japanese government approved the construction of its own satellite system in 2002. QZSS is a Japanese satellite positioning system composed mainly of satellites placed in quasi-zenith orbits (QZO). However, besides QZO satellites, the system relies also on satellites in geostationary orbits (GEO). In the regions of Japan which are dense with skyscrapers, the global satellite system service lacks continuity and stability due, among others, to a MultiPath phenomenon which prevents satellite signals from arriving in a straight line. Instead, the signals are transmitted in multiple routes as they are reflected off mountains, buildings, etc. The reflected signals take more time to arrive at their destination.

Currently, the constellation comprises of 4 satellites. 3 are deployed in QZO and 1 is placed into GEO (127°E) [Takizawa, 2017]. Further development of the system is planned for 2023 when 7 satellites will be available.

Indian Regional Navigational Satellite System (IRNSS)

By decision of the government of the Republic of India in May 2006, construction of a regional system called IRNSS was started. The decision was dictated by the concern for the country’s safety and willingness to become independent of GPS. The system will cover the Indian Ocean, South and East Asia, East Africa, and most of Australia [Czaplewski & Goward, 2016].

The system is composed of 7 satellites:

- 4 satellites in geosynchronous orbits at 55°E and 111,75°E, inclination 29°,
- 3 satellites in geostationary orbits at 32.5° E, 83° E and 129.5°E.

The first satellite of the system was put into orbit in July 2013 and the following ones in April and October of 2014, and March 2015. A fifth satellite (IRNSS-1E) was launched into orbit on 20th January 2016. A further two satellites were launched on 10th March and 28th April 2016. The IRNSS system transmits signals in the L5 band (1176.45 MHz) and S-band (2492.048 MHz).

2.3. Augmentation Systems

In order to provide greater accuracy than offered with the use of GPS system, as well as better integrity, availability or other improvements in positioning, navigation and timing, supporting systems were devised. The satellites of augmentation systems are put into geostationary orbits, which means that they rotate together with the Earth and are always over the same spot on Earth, as opposed to GPS satellites which orbit around the Earth. The main task of this systems is to transmit correction and integrity information to users. The major non-commercial systems of this kind are WAAS in the USA, EGNOS in Europe and MSAS in Japan.

Wide Area Augmentation System (WAAS)

The regional system WAAS is the effect of cooperation between the US Department of Transportation and Federal Aviation Administration as an element of the Federal Radionavigation Plan supporting the GPS system [Czaplewski & Goward, 2016]. It was launched in 1994 in North America to enable aircrafts to use high-accuracy satellite navigation during take-off and landing (comparable to category I of instrument landing system - ILS). Not until WAAS was introduced could GPS be used in aviation. Ionosphere delays, clock drifts and satellite orbit deviations rendered GPS not accurate enough to meet the requirements of precise plane take-off and landing. Currently, the WAAS constellation is composed of four geostationary satellites and sends correction messages to GPS receivers, augmenting the horizontal position accuracy provided by GPS to 2-3 m.

European Geostationary Navigation Overlay Service (EGNOS)

EGNOS was built in 2006. It is a European system augmenting the GPS and GLONASS systems built on the basis of the same standard as WASS. Once Galileo is activated, it will also be supported by EGNOS. The space segment comprises of three geostationary satellites providing coverage to the entirety of Europe. The ground segment consists of 40 reference and retransmission stations and 6 control, as well as control and verification, stations [Czaplewski & Goward 2016]:

- 40 Ranging and Integrity Monitoring Stations (RIMS) – receiving navigation signals from GPS satellites,

- 6 Navigation Land Earth Stations (NLES) – sending correction messages to satellites to be further transmitted to users,
- 4 Mission Control Centers (MCC) – processing the data and calculating differential corrections,
- 2 control and verification stations: DVP (Development Verification Platform) and ASQF (Application Specific Qualification Facility).

The European Commission has approved a project relating to the further development of the system in the coming years which has already been partially realized. EGNOS is to provide full coverage to all 28 EU Member States. A new version of the system will provide augmentation to the Galileo system and other systems to be activated as part of GNSS in the future. In the years to follow, EGNOS may expand its service to other non-EU countries in Europe.

Multi-functional Satellite Augmentation System (MSAS)

The Japanese augmentation system MSAS was activated in 2007. It provides service to the territory of Japan. Unlike in other systems, when compared with WAAS and EGNOS, its space segment is composed of two geostationary meteorological satellites (140°E and 145°E), whilst other systems of this kind use commercial telecommunication satellites. The first satellite was put into orbit on 1st August 1999, and the system was commissioned on 27th September 2007. The Japanese government does not intend to further develop the system. It is expected that once QZSS achieves its full operational capability (FOC), it will take over the tasks of MSAS.

GPS Aided Geo Augmented Navigation (GAGAN)

The Indian Space Research Organization (ISRO) and Airports Authority of India (AAI) reached an agreement in August 2001 on the construction of their own satellite augmentation system and so GAGAN became the fourth augmentation system in the world, after WASS, EGNOS and MSAS. Similarly, to other systems of this type, it is intended to support air navigation making use of GPS. The space segment of the system is made up of 3 geostationary satellites located at 55°E, 82°E and 83°E [Czaplewski & Goward, 2016]. The first satellite, GSAT-8, was launched in March 2011, the second, GSAT-10, in April 2012. The last, GSAT-15, was launched on 11th November 2015 from Kourou in French Guiana.

In 2013, the Directorate-General for Civil Aviation (DGCA) confirmed GAGAN for enroute operations (RNP 0.1) and on 19th May 2015 certified it for precision approach services (APV 1). GAGAN is the first augmentation system in the world to provide services to the equatorial region.

Korean Augmentation Satellite System (KASS)

KASS is the youngest satellite-based augmentation system project started by South Korea. In October 2014, the Korea Aerospace Research Institute (KARI) took up the role of the leading research organization for the development of KASS [KASS, 2017].

The system will support GPS and GLONASS. After reaching Full Operational Capability status, safer take-off and landing by aircraft will be possible only with the aid of KASS. The system will also provide benefits to various spheres of life, from road, railway and sea transportation, to IT, logistics and rescue activities. The system is planned to be completed in 2019 and in 2020 KASS will start providing an open service. The system is expected to be duly certified in 2022, which will render it suitable for use in aviation.

3. PRESENT THREATS TO SATELLITE SYSTEM OPERATION

Recent headlines about possible threats to the GNSS network is bringing new life to the discussion about the vulnerability and potential backups to the ubiquitous system. The threat of GPS interruption, intentional or otherwise, remains a reality for the land, marine and aviation industry.

GNSS signals received on Earth are weaker than cosmic noise and therefore are easily disrupted whether deliberately or incidentally. The most frequent threats observed globally include [Czaplewski & Goward, 2016]:

- solar activity; A coronal mass ejection has disrupted GNSS signal twice since 2007. Greater and more durable events such as a magnetic storm in 1859, for example, can potentially destroy satellites or electronics on Earth. Then, ionospheric disturbance may be observed for a long enough time to prevent the receipt of signals [NASA, 2017];
- hostile military action: Presently, there are still not many countries with independent access to space, however GNSS interference is increasingly used as a tool of war. One event that was in the closest proximity to the border of Poland was in 2015 during war in the Ukraine [InformNapalm, 2016]. A lot of similar events are nowadays observed at Mediterranean and Black Seas, in Arab Bay and in many other areas;
- space debris collisions; Cosmic space is becoming more and more congested with satellites which produce even more space junk. This poses an increasing

threat to the functioning of GNSS. It seems that the probability of collision is low for a single satellite, but the risk of "cascade" collisions is getting higher.

Regional-scale threats are also very real. Currently, the most common events may be classified into two:

- hostile military action; Most national military forces are capable of blocking GNSS signals in a substantial area, and some of it has already done that. The Korean Peninsula has seen satellite signals being disrupted by the North Korea on many occasions [BBC, 2016]. In the Middle East, such actions are performed by most of the conflicting armies (e.g. Iraq 2007 – [CNN, 2007]);
- terrorist action; Terrorist organisations have GNSS jamming devices that can be used for small distances. As the possibility of transmitting disturbing signals over a larger area is mainly a matter of a more potent transmitter, it is reasonable to assume that GNSS jamming and spoofing by terrorists on a large area is a serious threat.

Local threats to the functioning of satellite systems are possible due to Internet availability of receivers which may affect everyday operation of:

- municipal public transport; The latest example comes from Moscow (11.01.2018), where spoofing of the signal to protect top officials caused public transport to malfunction [RNTF, 2018];
- criminal activity: American Federal Bureau of Investigation reported that spoofing devices were used for stealing valuable cargo. Similar problems were documented in the UK and within the European Union;
- individuals seeking to protect their privacy and avoid supervision of their employers and others have reportedly caused interferences to airport landing systems;
- tactical spoofing devices; Special law enforcement units protecting political leaders and police officers. Specialists in weapons and tactics are able to block the receipt of GNSS in limited distances while performing their duties.

A bigger problem still may be presented by impersonation. Difficult to build and costly in the past, the devices are becoming more available now. In 2015, during a hacking conference in Las Vegas, USA, a spoofing device was demonstrated. What is more, construction plans were presented enabling the device to be constructed from easily accessible materials [Czaplewski & Goward, 2016; Czaplewski, 2018].

According to researchers between several dozen and several hundred jamming incidents were detected every day over last years. Unquestionably, such continuing investigations can only be an endless cat-and-mouse game between adversaries, during which time experts anticipate civil GNSS jamming will continue to escalate in intensity, coupled with decreasing availability and integrity for users, while underscoring the increasingly urgent need for an unjammable GNSS backup for land, marine, aviation and all other critical local, national and international needs for positioning and timing.

4. MODERN LORAN SYSTEM

4.1. Enhanced Loran

Enhanced Loran (eLoran) 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 [Curry, 2014].

eLoran meets the accuracy, availability, integrity, stability and continuity performance requirements for aviation non-precision instrument approaches, maritime port and 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. It 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.

What is important, eLoran meets a set of worldwide standards and operates wholly independently of GPS, GLONASS, Galileo, BeiDou or any other 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.

eLoran transmissions are synchronized to an identifiable, publicly-certified, source of Co-ordinated 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 [Curry, 2011, 2014, Curry et al., 2017]. 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. New Loran is also capable of providing the exceedingly precise time and frequency references needed by the telecommunications systems that carry voice and internet communications.

4.2. Loran C vs. eLoran

eLoran 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 100 kHz. 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 synchronized 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*”. 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 [Sentinel, 2015], both led by Chronos Technology [Chronos, 2017].

eLoran retains the powerful long range and unjammable at 90-110 KHz low frequency signals of its predecessor, plus their solid coverage from the surface to well above 18 km and out to over 1,000 miles, it is otherwise totally different.

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 a “*Loran Data Channel*”, as will now be explained.

5. E-LORAN AS A TIME STANDARD

5.1. Time Service

There are a lot of time definitions. Let's present some of them. Time is the indefinite continued progress of existence and events that occur in apparently irreversible succession from the past through the present to the future. Time is a component quantity of various measurements used to sequence events, to compare the duration of events or the intervals between them, and to quantify rates of change of quantities in material reality or in the conscious experience. Time is often referred to as the fourth dimension, along with the three spatial dimensions [Davies, 2005; Ridderbos, 2002; Weintrit, 2011, 2017].

High Frequency Trading using Computer Based Trading equipment now requires UTC traceable synchronised time stamps with an accuracy of better than 1μs. GPS based Network Time Protocol (NTP) systems give only millisecond, not sub-microsecond, accuracy and are vulnerable to GPS jamming. With NTP, the delivery process is cumbersome and may require fixed delays to be calibrated out on installation. In this context, eLoran timing is an ideal solution which would work well indoors.

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 [Curry, 2011, 2014]. This study draws on research carried out over the last ten years in the course of two projects, GAARDIAN and SENTINEL, which were supported by Innovate UK, the UK's Innovation Agency. 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 100 ns of UTC, thus meeting currently-accepted ITU standards for primary reference timing clocks in telecoms transport networks.

5.2. 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 authorized third parties to use it in order to broadcast high-priority data to their users. The properties of the LDC are standardized internationally and defined in a document entitled "*Eurofix Message Format*"; the current version of which, ver.2.15, is dated March 2014 [Offermans, 2014]. The Eurofix messages are specified by the Radio Technical Committee for Maritime Services (RTCM) Special Committee-104 (Eurofix working group [RTCM, 1998]) and in International Telecommunication Union (ITU) Recommendation M.589-3 [ITU, 2001].

One message type 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 1 pps output pulses to within a few microseconds of UTC. The remaining time offset is then removed in a further calibration stage.

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. 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 100 kHz 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.

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. In [Curry, 2014; Curry et al., 2017] there is presented propose that one of the currently unassigned message types be used for "*regional ASF timing correction messages*".

It is now generally recognized that advanced low frequency signals, of which eLoran is one example, can provide alternative timing — either as a standalone service or as a component of an existing positioning, navigation and timing service. High power, virtually jam and spoof proof low-frequency signals operate independently of GNSS and provide Universal Coordinated Time (UTC) reference. The recognition of the criticality of time to many aspects of our overall critical infrastructure beyond simply GPS has hopefully finally led to an evaluation of the benefits of a nationwide low-frequency timing system.

5.3. Factors which could affect timing accuracy and stability

There are many factors that can affect the accuracy and stability of the eLoran timing signal. The most important of them are listed below:

- Additional Secondary Factor (ASF),
- Space weather,
- Local electrical interference,
- Transmitter and antenna maintenance.

The ways to mitigate or minimize the errors that have been made were discussed in [Curry, 2014, Curry et al. 2017].

6. E-LORAN AS A BACKUP FOR GNSS

6.1. Factors which could affect timing accuracy and stability

Since the onset of threats to satellite systems, scientists all around the world have worked on solutions aimed at making GNSS signals more robust. Until now the best solution from the scientific perspective and one that has been technically tested, has been the upgraded Loran-C system. The Loran system has more than a half-century history of successful operation as a navigation system [UrsaNav, 2018]. Its latest modification, called Loran-C, is still in use, providing positioning, navigation and timing services to mariners. Now that satellite system receivers are commonly used, its significance has dropped.

As satellite systems are increasingly under threat of interference, a modernised version of Loran-C, called eLoran, was proposed to address the problem. As a GPS backup, the upgraded eLoran may provide many services comparable to those offered by systems forming GNSS. The technical potential of eLoran was described in reports delivered by research centres, such as [Johnson et al., 2007, ILA, 2007, Volpe, 2009, GLA, 2012].

eLoran (the upgraded Loran) is a system of low frequency ground-based navigation, making use of transmission stations emitting precisely timed and shaped radio pulses centred at 100 kHz [GLA 2012]. Furthermore, coastal stations are equipped with cutting-edge appliances, software and caesium atomic clocks. Even if eLoran is different to the well-known earlier versions of a hyperbolic Loran, still, its mode of functioning is similar. Similarly, to GNSS, it is an independent and supplementary to the GNSS system operating without failures in cooperation with GNSS. eLoran may offer greater accuracy and integrity in order to ensure a backup copy and integrity for GNSS. The prototype of the system, which has been in a continuous operation in Harwich (UK) since 2008, provides an accuracy of about 10 m (95%) [GLA 2012]. With broader cooperation among the European countries, this accuracy is expected to improve. The system allows its users to use GNSS navigation safely even if the satellite service is disrupted.

Presently, eLoran is operating or being activated in the UK, USA, and South Korea [Seo. & Kim, 2013]. Also, EU institutions are debating over whether to use chains of eLoran systems in the European Union.

6.2. New concept and working conditions

eLoran is an existing and underused long-range navigation system. Used as the backup system would step in when GNSS signals are corrupted, damaged, degraded, unreliable, or otherwise unavailable. A ground-based system, eLoran would not be exposed to atmospheric disturbances such as solar storms, or jamming or spoofing aimed at GNSS.

The eLoran PNT system would use enhanced long-range signals (eLoran) providing overlapping fields from which a device can derive its location. The back-up system would use the remaining Loran infrastructure and provide a secure and reliable cybersecurity insurance policy.

The atomic clock serves as the base timing source for this backup GNSS capability. It exceeds the timing needs of modern cell phones, creating an infrastructure backbone that is prepared to handle the evolution of consumer and industry electronic communications in the years ahead.

There is set out numerous requirements for the system. e-Loran should:

- be wireless, terrestrial, and wide area,

- provide a precise, high-power 100 kilohertz signal,
- be resilient and extremely difficult to disrupt or degrade,
- be able to penetrate underground and inside buildings,
- take full advantage of existing, unused Loran infrastructure,
- work in concert with and complement any other similar positioning, navigation and timing systems, including eLoran.

The United Kingdom began using eLoran already in October 2014 to protect its shipping lanes, which carry 95 percent of UK trade, in case of GPS signal loss. In January 2015, the United States Army began soliciting information for eLoran receivers for the warfighter, either independent stand-alone or integrated with GPS, for use in Army and other Department of Defense maritime, aviation, or vehicular platforms, and for position and timing.

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 100 kHz 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.

eLoran, an enhanced version of the Loran-C long-range, ground-based navigation system, could provide a backup to GNSS from the ground up and the essential timing signals for the nation’s critical infrastructure. Today, eLoran is the only system that can fully back up GPS, and all other GNSS systems planned or in use [Schue, 2014]. UrsaNav, a diversified technology company based in Chesapeake, has assembled what could probably be described as one of the world’s leading centers of excellence in the field of Loran-C and eLoran.

What’s more, it’s becoming clearer and clearer that GPS interference, whether inadvertent or deliberate, will continue to grow, thereby causing GNSS to become less and less valuable. In that arena, eLoran provides two benefits. First, it can prevent the interruption or loss of vital satellite services. But second, and less widely appreciated, it can vastly reduce the incentive to jam GNSS systems when it becomes known that they have constant and essentially unjammable backups [Schue, 2014].

7. ACCURACY OF E-LORAN

7.1. Accuracy, availability, integrity, 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 [ILA, 2007].

Table 1. eLoran's accuracy, availability, integrity and continuity [ILA, 2007]

Accuracy	**Availability**	**Integrity**	**Continuity**
0.01 nautical mile (20 meters)	0.9999	0.999999	0.9999 over 150 sec

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

Loran-C suffered from two serious drawbacks — precipitation static and the transmitter station's inconvenient configurations in "chains" or groups of three or four stations to provide regional navigation coverage. eLoran dispenses with the old "chain" concept. Every eLoran transmitter would be totally independent of all others, with the system operating on an "all in view" basis, exactly like GPS, where incoming signals are selected for their best fix geometry.

But while the old Loran-C concept provided fix accuracies of less than a quarter mile, differential eLoran has met and exceeded IMO standards of to 10 meters for harbour entrance applications, with that performance attributed to its much higher signal stability of its predecessor. Similarly, its 100 nanosecond accuracy at the receiver antenna underscores its unique timing capability.

7.2. Measurements of time accuracy from e-Loran

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 (Fig. 1). As in Figure 2 shows, the resulting MTIE data points are plotted on a log-log graph.

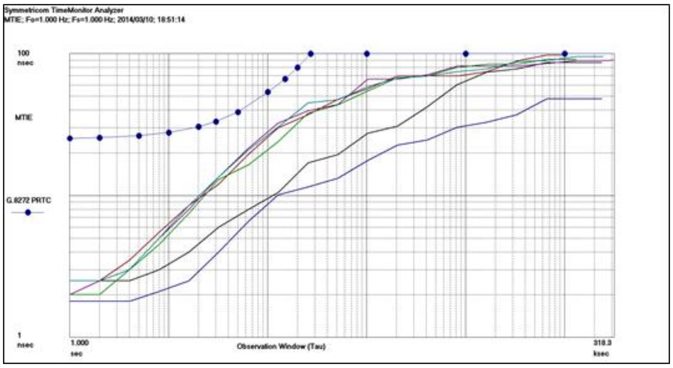

Figure 1. Time Interval Error (TIE) diagram. Red: eLoran TIE. Blue: GPS TIE. Y-Axis 10ns/div. X axis: 3 days. Source: Curry, 2014.

Extensive reference timing clock (PRTC) [ITU, 2013]. 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 < 10 ns. 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.

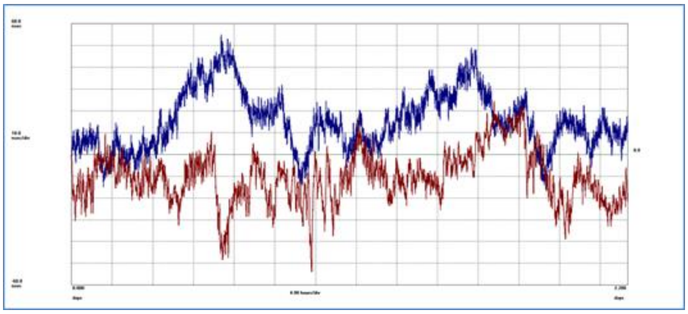

Figure 2. MTIE plots from indoor eLoran timing receiver. Source: Curry, 2014.

Figure 2 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 Sentinel platform [Sentinel, 2014] 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.

eLoran appears to be a perfectly acceptable source of precise timing for telecommunications use. 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.

8. MULTI-SYSTEM SHIPBORNE RADIONAVIGATION RECEIVERS DEALING WITH THE HARMONIZED PROVISION OF PNT DATA

The International Maritime Organization (IMO) is working on Guidelines for Shipborne Position, Navigation and Timing Data Processing [Weintrit & Zalewski, 2017]. The purpose of these Guidelines is to enhance the safety and efficiency of navigation by improved provision of position, navigation and timing (PNT) data to bridge teams (including pilots) and shipboard applications (e.g. AIS, ECDIS, etc.). The shipborne provision of resilient PNT data is realized through the combined use of on-board hardware and software components. The shipborne PNT Data Processing (PNP-DP) is the core repository for principles and functions used for the provision of reliable and resilient PNT data. These Guidelines define principles and functions for on-board PNT data processing taking into account the scalability of PNT-DP. Within the e-Navigation strategy the IMO has identified the user need on improved reliability, resilience and integrity of bridge equipment and navigation information as one of the five prioritized e-Navigation solutions, whereby the resilient provision of PNT data acts as Risk Control Option.

There are a lot of benefits of eLoran in comparison with alternative PNT systems. The most important of them are listed below [Curry, 2014, Curry et al., 2017]:

- transmissions internationally standardised [ILA, 2007], [ITU, 2013],
- broadcasts national UTC over a wide area,
- eLoran can be received indoors,
- provides timing synchronous to UTC within 100 ns,
- resilient against GNSS jamming and spoofing [RAE, 2011],
- resilient against space weather events,
- complementary to Precision Time Protocol (PTP).

Very important are the algorithms used in the eLoran system receiver for navigational calculations. From the early days of the development of basic navigational software built into navigational receivers it has been noted that for the sake of simplicity and a number of other reasons, this navigational software is often based on simple methods of limited accuracy. Even nowadays navigational software is sometimes used in a loose manner, adopting oversimplified assumptions and errors such as the wrong combination of spherical and ellipsoidal calculations in different steps of the solution of a particular sailing problem. The lack of official standardization on both the “accuracy required” and the equivalent “methods employed”, in conjunction to the “black box solutions” provided by GNSS and eLoran receivers and navigational systems (ECDIS and ECS) suggest the necessity of a thorough examination of the issue of sailing calculations for navigational systems receivers. Despite the fact that contemporary computers are fast enough to handle more complete geodetic formulas of sub meter accuracy, a basic principle for the design of navigational systems is the avoidance of unnecessary consumption of computing power. Saving and reserving computer resources is always beneficial for the improvement of the systems effectiveness on the evolving new navigational functions and applications such as the handling of greater amounts of cartographic and navigational information, the capability for data presentation [Weintrit & Kopacz, 2012].

CONCLUSIONS

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

Each country that contributes to Universal Coordinated Time (UTC) operates a national time standard that is independent of GNSS. Its technology is generally based on a Hydrogen Maser. This is adjusted using monthly corrections supplied by the Bureau International des Poids et Mesures (BIPM) in France [BIPM, 2017].

A number of countries are actively reconsidering 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 recognize their own vulnerability to the disruption of GNSS. This paper discusses the concept of delivering such national time services by means of eLoran signals and at the same time points to the great predisposition of the eLoran system as a back-up system for GNSS in every respect.

A backup system could also reach places that GNSS currently cannot, such as inside many buildings. This would help first responders and law enforcement more effectively protect the public. The potential of the eLoran system now seems much larger than originally was expected.

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STRESZCZENIE

Globalne systemy nawigacji satelitarnej (GNSS) coraz bardziej wpływają na wiele obszarów ludzkiej działalności na świecie. Każdego dnia działalność człowieka na całym świecie zależy od satelitarnych systemów pozycyjnych. Ponieważ systemy te są powszechnie używane, należy podjąć dalsze wysiłki, aby uczynić GNSS bardziej odpornym na coraz częstsze przypadki zagłuszania i podszywania się. Wydaje się, że system eLoran jest obecnie najlepszym technicznym i naukowym rozwiązaniem umożliwiającym skuteczną ochronę globalnych systemów nawigacji satelitarnej. W ubiegłym roku autorzy przedstawili system eLoran jako potencjalne narzędzie do transmisji krajowego sygnału czasu [Curry i in., 2017]. Tym razem autorzy prezentują możliwości dodatkowego wykorzystania systemu eLoran jako systemu rezerwowego dla GNSS