eLoran measurements in Oslo

Oslo, 14 August 2017

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Summary

Initial findings from short term measurements of eLoran timing signals from the UK Anthorn transmitter in the Oslo area shows that the signals from the transmitter, 1000 km away, after crossing the mountainous mainland of southern Norway and the North Sea give timing accuracy better than 100ns.

This result is a strong indication that the technology could easily be adapted for use in Norway, if the remaining Norwegian Loran towers are not dismantled. The closest Norwegian transmitter on Værlandet is just 360 km away from the capital and will probably cover the populous areas of the country easily.

Use of this technology will reduce the company's dependence on GPS and other GNSS systems and will strengthen the resilience of our critical infrastructure.

Introduction

Background

A request for a review of the timing infrastructure in the grid control communication network was made after a minor event involving timing errors that caused some communication noise in the network in early spring of 2017. The review identified areas to be improved. In particular, the dependence of GPS signals as the only source of timing was identified as a vulnerability.

A literature review was conducted to identify alternate, redundant solutions that would mitigate this vulnerability. Identified candidates were: Long wave radio (DCF77, eLoran), multi GNSS (GLONASS / Galileo / BeiDou), low orbit satellites (STL) and acquiring our own Cesium clocks.

It is Hafslund Nett policy to attempt to utilize solutions where the redundant system has as few common vulnerability factors as possible with the system it works as redundancy for. Any common mode of failure affects the overall reliability. The vulnerabilities of a ground based, high powered long wave radio system appear to be a good redundancy match for the space based GNSS systems with low power microwave transmissions. The immediate and obvious advantage being that it makes it easy and economical to distribute the time in a manner similar to GNSS, as the receiver equipment can be acquired at a relatively low cost, and the technology diversification mitigates the vulnerabilities from factors like jamming and spoofing. Both these last issues appear to be exacerbated by the enormous success of GNSS and the corresponding potential for malicious technology. Contributing factors to our choice of long wave radio was the demonstration of possible problems with GNSS like when the GLONASS system sent gibberish in 11 hours in April 2014 (1) and the GPS system had timing errors in January 2016 (2), the “2016 UTC Anomaly event”. We have also noticed that China, with their own GNSS system and a demonstrated anti-satellite capability (3) still are operating their Loran stations.

The initial assessment was that to meet the desired accuracy of 1 µs, DCF77 was probably not accurate enough. Also, as there is only a single DCF77 transmitter, the Norwegian DoT ('Samferdselsdepartementet') had halted tearing down of the Norwegian Loran-C masts and private investors wanted to start operating the Norwegian Loran stations, eLoran looked promising. We contacted the Norwegian Space Agency (the agency responsible for delivering a national PNT strategy) in order to establish if they were aware of any measurements of eLoran reception from Anthorn in the Oslo area, which they were not.

Next, we contacted Chronos Technology and they reported acceptable signal reception of eLoran from Anthorn in Stockholm and offered equipment on loan to measure signal reception in the Oslo area. This generous offer was accepted and we made preparation for measuring.

During this process, we were informed that the Norwegian DoT had requested that the Norwegian Loran masts be dismantled, with work to start immediately after the summer vacation. DoT was contacted and informed regarding the company's interest in eLoran.

Briefly about eLoran operation

The Anthorn eLoran transmitter is equipped with atomic clocks and transmits radio pulses at known intervals. A stationary receiver can calculate the current time if it knows the amount of time the radio wave takes to travel from the transmitter to the receiver. This time is a function of the distance from the transmitter to the receiver which in this case is known from the fixed positions and the speed of the radio waves.

This radio wave speed is determined by starting with the speed of light in vacuum and adding corrections. The correction for the propagation in air is called the primary factor (PF) and the correction for propagation over saltwater is called the secondary factor (SF). These two corrections can be calculated. Corrections due to the signal propagating over land with varying conductivity is called additional secondary factors (ASF). These factors cannot be calculated, but have to be measured. The ASF also fluctuate slightly over time.

Generally, the energy in the eLoran signal is inversely proportional to the distance from the transmitter, meaning that the closer the receiver is to the transmitter, the better the reception. At night the sky-wave reflection from the ionosphere can significantly degrade the field-strength of the ground-wave signal utilized by eLoran. The sky-wave can go significantly further and at higher field-strengths as it is not attenuated by the Earth's surface.

In addition, information containing the UTC time of the received pulses is transmitted through the Loran Data Channel (LDC), a low bit rate data channel modulated on the eLoran signal. According to information Chronos Technology has obtained from the GLA, Eurofix LDC requires about +6dB SNR for reliable reception, higher is better but there is a significant amount of error-correction in the signal so reception error (noise) does not degrade the data message until the error-correcting code becomes saturated. This means quite a sharp cut-off around +5 to +7 dB SNR. The receiver is often unable to detect whether there is data modulated onto signals with less than 0 dB SNR.

In order to improve the accuracy the ASF can be corrected for by using a reference station near the area of interest. This reference station compares the time received from the eLoran signal with a local clock. These differential corrections can then be transmitted to the receiver either through the LDC or by other means like i.e. the Norwegian 'Nødnett', the marine VHF data exchange system or the internet. The obtainable accuracy increases with the available data rate of the transmitted corrections (4).

Synchronizing the receiver to these pulses and reading the UTC time enables the receiver to synchronize itself to the atomic clocks at the transmitter and output accurate UTC time.

A more elaborate explanation of eLoran operation can be found in (5)(6).

Setup

Transmitter

The Anthorn eLoran transmitter is located in Cumbria on the west coast of England, just south of the border to Scotland. This is a prototype eLoran transmitter, originally operated by the General Lighthouse Authority (GLA) of Britain and Ireland, now operated by the British Government. It transmits eLoran timing signals and differential correction through the Loran Data Channel, LDC, this service was implemented by Chronos Technology Ltd as part of the Innovate UK project GAUL in 2015.

Receiver location

An eLoran E-field antenna and an eLoran receiver was set up on Høvik, approximately 8 km west of Oslo city hall. The antenna was mounted on a pole extending 4 meters above the rooftop of a two story, flat-roofed building, the height of the roof being approximately 6 meters above ground level. A patch of trees with height well above the antenna top shielded the direct path towards the transmitter.

Figure 1: Location of the Anthorn eLoran transmitter and the receiver at Høvik. (Map from

http://umap.openstreetmap.fr/)

As the roughness of the ground has impact on both the propagation speed and the signal to noise ratio, the elevation profile along the path is depicted in Figure 2.

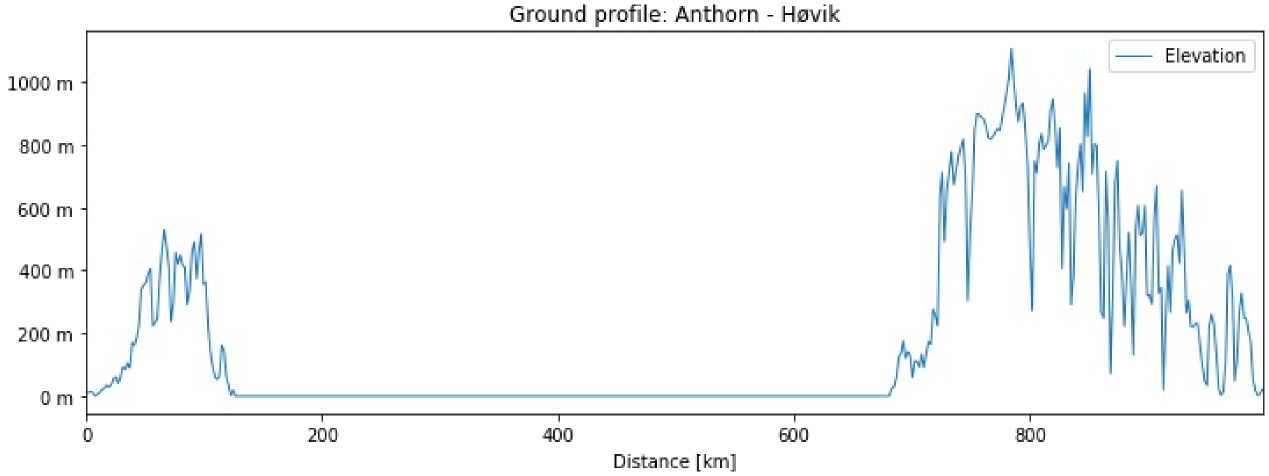

Figure 2: The figure depicts the ground profile along the signal path[1] between Anthorn and Høvik. (Data from: Geocontext-profiler: http://www.geocontext.org/publ/2010/04/profiler/en/)

The distance between the transmitter and the receiver is close to 1000km where around 320km is above Norwegian terrain with elevation up to around 1100m and approximately 130km is above terrain in Great Britain. The rest of the signal path is above seawater.

Instrumentation

Measurements have been carried out with a CTL8200 eLoran GPS UTC Timing Receiver unit from Chronos Technology equipped with an UrsaNav UN-006 E-band antenna and a co-located Sanav SM-66 GPS patch GNSS antenna.

The CTL8200 unit contains an UrsaNav UN151 eLoran receiver (firmware version 3.7.02), a Chronos Technology CTL460 multi constellation GNSS Timing receiver (rev A v1.1.0) and an Altera 4.4 TIE engine (31/07/2012). In addition, the unit contains a communication unit making it possible to transmit selected collected data to the Chronos SENTINEL research platform in near real time.

This equipment was lent to Hafslund Nett AS free of charge from Chronos Technology in order to measure signal reception from the Anthorn transmitter in the Oslo area.

The NMEA string from the eLoran receiver and the NMEA string from the GNSS receiver were recorded locally.

The NMEA string from the eLoran receiver contains among other data parameters relevant for characterizing the reception: UTC date and time, a measure of Signal Strength (SS), Signal to Noise Ratio (SNR), the eLoran Envelope to Cycle Difference (ECD), a state flag indicating if the receiver could successfully identify the correct cycle in the pulse envelope (State), a measure of the Cycle Identification Quality (CIQ) and Time Of Arrival of the pulse (TOA).

The TIE (Time Interval Error) engine measured the time difference between the 1PPS output of the

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[1] The profile displays the rhumb line, the signal travels along the great circle path, the profile difference is small.

eLoran receiver and the 1PPS output of the GNSS receiver. This data was transmitted to the Chronos Sentinel research platform and the data was retrieved from there.

An oscilloscope, a Phillips PM97 50Hz scopemeter, was used to locally estimate and verify the TIE between the GNSS receiver and the eLoran receiver by measuring the difference between the 1PPS pulses locally.

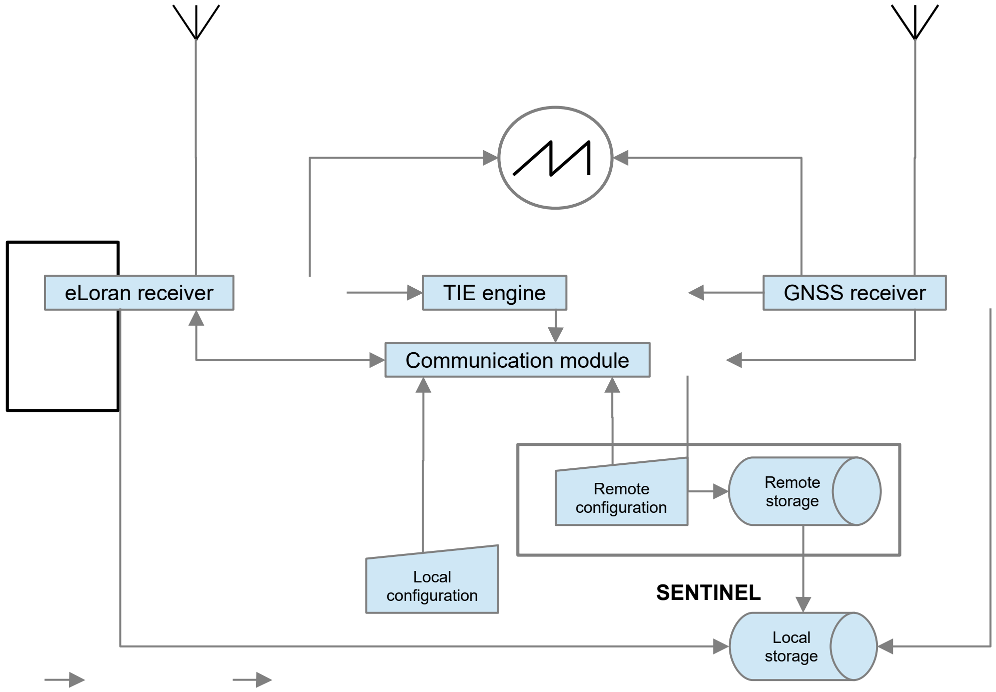


Figure 3: Instrumentation setup

Receiver configuration

The receiver was manually calibrated after one day of TIE recording. The recorded TIE mean offset was applied to the target TOA value and then left without adjustment for the period of the measurements.

After the signal was acquired the receiver was manually set to so called 'fine steer' by adjusting the parameters of the PI clock controller, setting P=1E-8 and I=1E-12. The TOA sliding window length used was 10 seconds and ECD delay was set to 5µs.

Analysis

The data analysis was carried out with python 3.5.1 with pandas 0.20.3 for data manipulation and matplotlib 2.0.2 for plotting.

As this is an initial, short term study exploring the possible use of timing signals from the Anthorn transmitter, the analysis is kept at a basic level. Further measurements and analysis will be needed in order to determine long term stability and more detailed coverage as well as exploration of periodicity and events in the data.

The most important parameter to be discussed is the Time Interval Error, TIE. This parameter describes the relative accuracy and stability of the time from the eLoran receiver. In addition, a measure of the rate of correct cycle identification is derived from the state variable and a description of the signal strength (SS) and the signal to noise ratio (SNR) will be given.

Results

Weather

During the measurement period from August 3 and the following 10 days, the weather was characterized by intermittent rain showers and a few evenings with thunderstorms between some sunny days and some overcast days. In other words, a typical Norwegian summer.

Antenna positioning

Initially the antenna was mounted flush with the gutter, just below the rooftop. This positioning, however, only gave intermittent reception with low SNR. Raising the antenna on the pole appeared at the moment of pole erection to increase the signal strength by around 10 dB and simultaneously increased the SNR by around 15 dB.

No further investigation of the effect of antenna positioning was made.

Acquiring signal lock

The receiver used a relative long time acquiring lock on the transmitted signal (several hours). However, after a lock was acquired the signal was lost only due to restart of the receiver.

LDC reception

The reception of LDC data was patchy and intermittent. It does however, appear to be sufficient reception of messages in order to align the eLoran receiver with UTC.

An estimate of the LDC reception rate was done by counting the relevant lines in the recorded NMEA file. The LDC message is sent and normally recorded in the NMEA message approximately every 2 seconds. Counting these lines in the NEMA file recorded here and comparing this number to the number of recorded time strings which is recorded every second indicates that 11% of the LDC messages are received (number of LDC records / number of time string records / 2).

These LDC messages carry a checksum which can be used to estimate the error rate in the received messages. This estimation has not been carried out.

Measurement results

Signal Strength

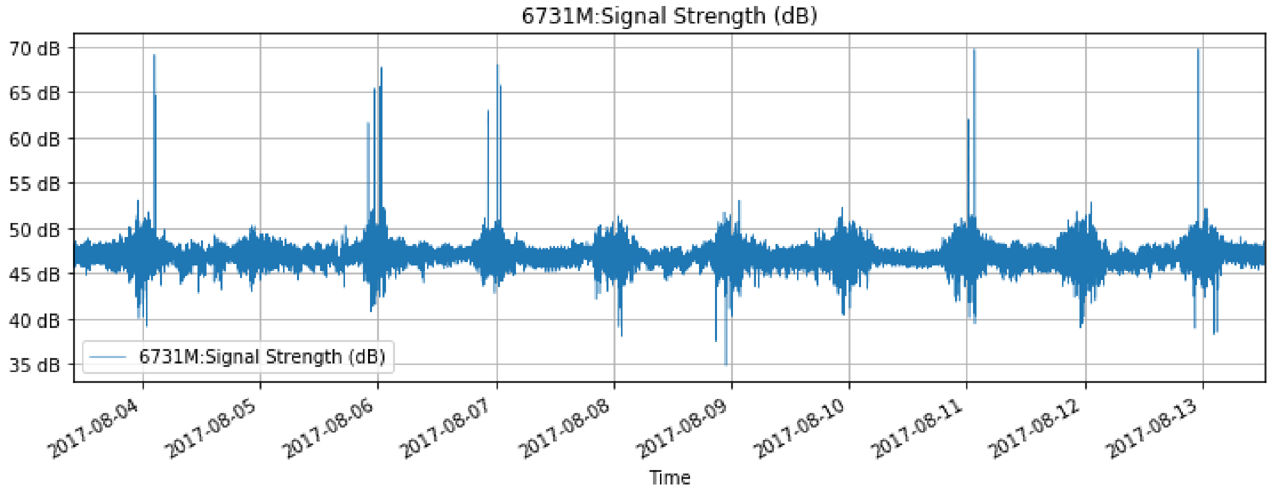


Figure 4: Signal strength time series

Notice the diurnal increased variation that occurs late in the day.

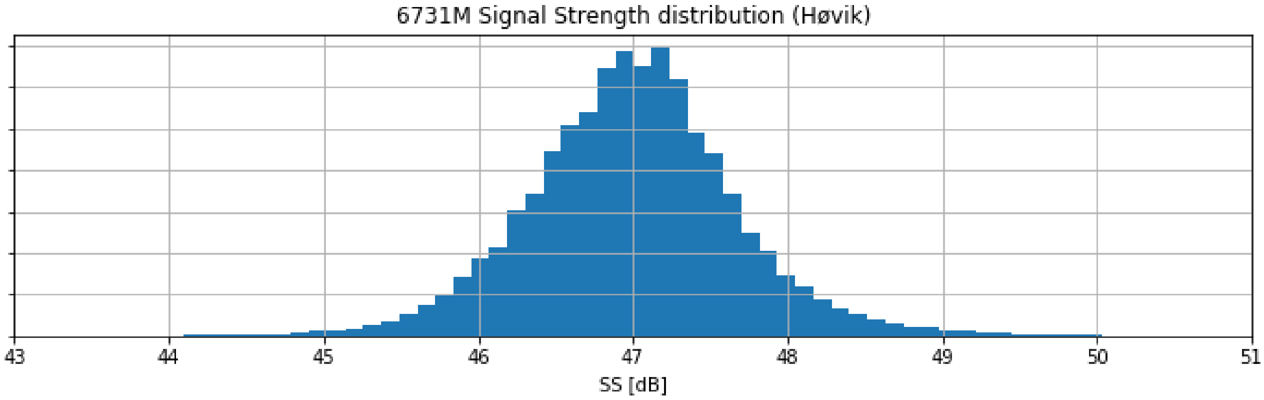


Figure 5: Signal strength histogram

The signal strength appears to be rather stable in mean value with increased variation when the SNR is dropping.

Signal to Noise Ratio

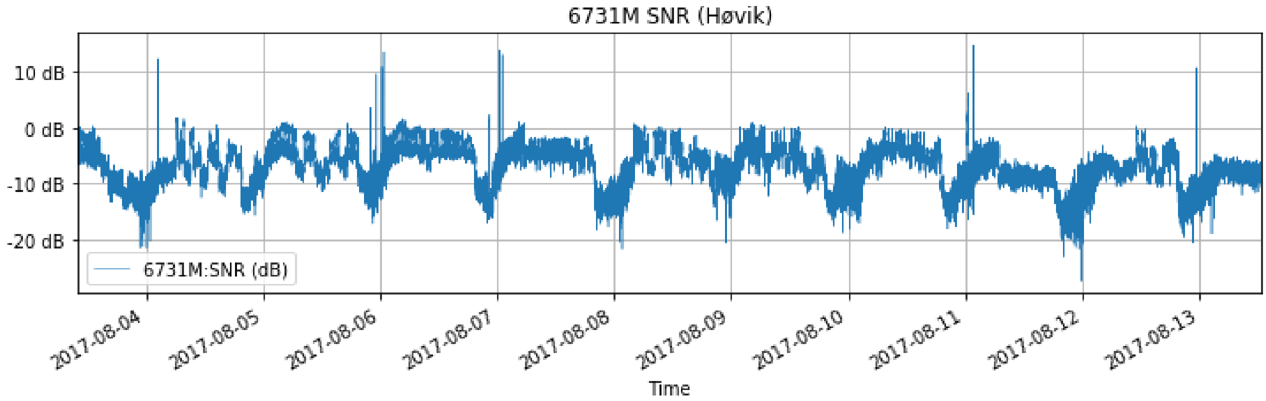


Figure 6: Signal Noise Ratio time series

Notice that there appears to be periodic variation in the SNR data. A coarse estimation indicates one period of around 36 minutes. Diurnal variations can also be observed with lower SNR during night time.

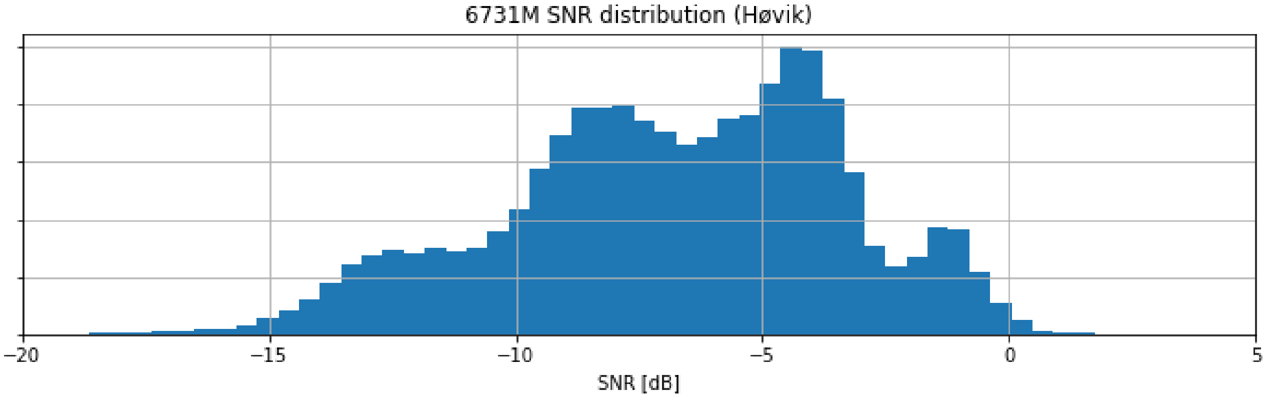


Figure 7: Signal Noise Ratio histogram

The SNR histogram depicts three peaks at around -8 dB, -4 dB and -1 dB and most of the distribution between -15 dB and 0 dB.

Time Interval Error

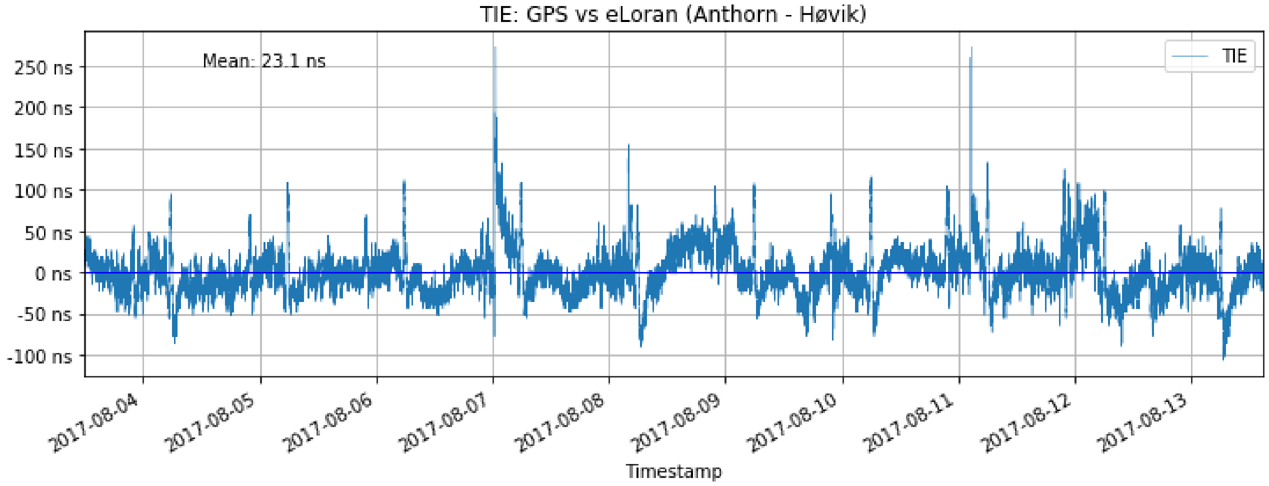


Figure 8: Time Interval Error, TIE showing the variation between eLoran and GNSS time

Notice the somewhat peculiar jump in the TIE data at around 0300 UTC in the morning. The data has been plotted adjusted for mean offset to enable better depiction of the variation. At night between the 6th and 7th and between the 11th and 12th there was an event causing more than 200ns deviation. The cause of these events is not known, but there are indications in the data set that this is a receiver artifact.

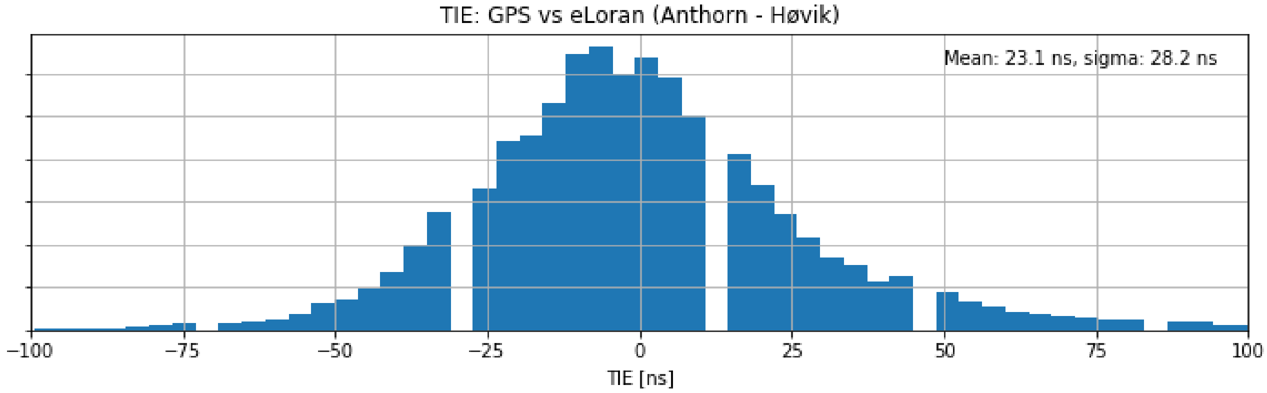


Figure 9: TIE distribution

The resolution of the measured TIE data is somewhat coarse for the task. The peculiar gaps in the histogram is due to the resolution of the measured values: 0, 4, 8, 12, 16, 21, 25 … The uneven, discrete data spacing where the initial spacing of 4 ns is changed to 5 ns between 16 and 21 renders some bins empty (the first one at 20).

The 3-sigma value (99.7% in case of normal distribution) is around 85 ns. As we can see from the histogram the distribution is approximating a normal distribution, but it appears to have a somewhat 'fat tail'. This is probably caused by the diurnal spikes in the TIE, an indication of systematic deviations and the events noted above.

No attempt has been made to isolate possible stationary components nor to fit the data to a suitable distribution.

State

The ratio between correctly identified cycles (state equal to 0x200) to all cycles were 0.974 in the measurement period. Alternatively this can be expressed as a cycle identification error rate of 0.026.

Discussion

This initial short term study of eLoran reception from the Anthorn transmitter at Høvik in the Oslo area give results in accordance with published values. The 3 sigma variation is around +/- 85 ns, even though the Signal to Noise ratio is rather low, in the range -15 dB to 0 dB. The observation of reduced SNR during night time may be due to an increase in sky-wave interference.

A considerable part of the signal path is above mountainous terrain, indicating that the Norwegian terrain is not a major obstacle to the accuracy of this technology when used for timing purposes. It also indicates the possible use of the Anthorn transmitter in order to explore to what extent the Norwegian terrain affects the ASF, signal strength and noise level.

The transmitter at Værlandet is much closer to Oslo (approximately 360 km) than the measured Anthorn transmitter. Værlandet has the potential of giving much better Signal to Noise ratio in the central, populous south eastern parts of the country. The distance from Værlandet to Oslo is around a third of the distance to Anthorn and there is a shorter propagation path above land. Keeping in mind that the energy of the transmitted signal is inversely proportional to the distance the signal travels, this indicates that Værlandet can supply time in the sub-microsecond range to all of Norway south of Nordland without any differential correction. And the two remaining Norwegian mainland transmitters could probably cover the whole country with accurate time signals.

The findings indicate that antenna positioning is important in relatively low signal to noise conditions such as these, and this issue should probably be given more attention.

The 4 ns resolution of the measured TIE data is somewhat coarse. It might be advantageous to use a local Time Interval Analyzer with better resolution and compare the 1PPS signal from the eLoran receiver to either a GNSS clock as used in this study or to a clock source with even better accuracy.

No correction for time variations in ASF was performed after the initial measurement. A study detailing the expected accuracy when using the system without differential ASF correction and an estimation of potential accuracy gain by deploying differential correction would be interesting.

The intermittent and patchy LDC reception is apparently sufficient to align the receiver with UTC, but it does not appear to be usable for other tasks like DLoran corrections because of the low reception rate. This is expected from the GLA provided information requiring +6dB SNR for reception. The received LDC data in this test may have been due to sky-wave.

Conclusions

As it looks from this short, initial study, using the Anthorn transmitter as a redundant source of time is a viable solution here in Oslo. This technology appears to complement GNSS, filling in with different vulnerabilities which is exactly what we are looking for in order to mitigate the vulnerabilities of the GNSS systems. It could even be argued that not using such a system in critical application would be negligence given that the system was operational.

The results appear to indicate that it will be possible to cover the Norwegian mainland with accurate time by upgrading the transmitters to eLoran and without additional infrastructure investments.

We understand from our communication with the DoT advising agency, Norwegian Space Center, that this information is new to the department. In our opinion, this information should be given consideration in the assessment of the need to demolish the Norwegian Loran towers. It may look like the potential challenges with this technology have been exaggerated and that the benefits may have been underestimated.

Our assessment is that this technology can be of great use in the safe and resilient operation of the distribution grid and be beneficial both to the company and its customers as well as to other grid utility companies, and all other users of timing within critical infrastructure such as telecommunication and broadcast in Norway.

References

(1) Gerhard Beutler, Rolf Dach, Urs Hugentobler, Oliver Montenbruck, Georg Weber, and Elmar Brockmann, June 24, 2014: “The System: GLONASS in April, What Went Wrong”: http://gpsworld.com/the-system-glonass-in-april-what-went-wrong/

(2) GPS World staff, February 2, 2016: “Air Force determines cause of GPS timing issue”: http://gpsworld.com/air-force-determines-cause-of-gps-timing-issue/

(3) Norwegian Space Center: Mars 2013, “Vurdering av sårbarhet ved bruk av globale satellittnavigasjonssystem i kritisk infrastruktur”: https://www.romsenter.no/Aktuelt/Publikasjoner/Rapport-om-saarbarhet-ved-bruk-av-satellittnavigasjon

(4) Durk van Willigen, René Kellenbach, Cees Dekker, and Wim van Buuren, June 28, 2014: “eDLoran: The Next-Gen Loran”: http://gpsworld.com/edloran-the-next-gen-loran/

(5) Stephen Bartlett, Gerard Offermans and Charles Schue, November 23, 2015: “A Wide-Area Multi-Application PNT Resiliency Solution”: http://gpsworld.com/innovation-enhanced-loran/

(6) International Loran Association: 16 October 2007, “Enhanced Loran (eLoran) Definition Document”: http://ila.rin.org.uk/otherarchives/2007%20eLoran%20Definition%20Document-1.0.pdf

Appendix 1: Abbreviations

1PPS	1 Pulse Per Second
ASF	Additional Secondary Factors
CIQ	Cycle Identification Quality
DCF77	D =Deutschland (Germany), C = long wave signal, F = the longwave transmitters on the premises of the transmitting station Mainflingen (due to its vicinity to Frankfurt am Main), 77 = frequency: 77.5 kHz.
DLoran	Differential Loran
DoT	Department of Transportation ('Samferdselsdepartementet')
ECD	Envelope to Cycle Difference
eLoran	enhanced Loran
GLA	General Lighthouse Authority
GLONASS	Global Orbiting Navigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LDC	Loran Data Channel

LORAN	Long Range Navigation
NMEA	National Marine Electronics Association
PF	Primary Factor
PI	Proportional Integral
PNT	Positioning, Navigation and Timing
SF	Secondary Factor
SNR	Signal-to-Noise Ratio
SS	Signal Strength
STL	Satellite Time and Location
TIE	Time Interval Error
TOA	Time Of Arrival
UTC	Coordinated Universal Time
VHF	Very High Frequency

Addendum

Commentary and Suggestions for Future Tests

by
Gerhard Offerman / David Last

The results reported were excellent given the available signal conditions at a location that is almost 1000 km from the signal source and provides additional verification that eLoran can provide very good time synchronization over a very wide area. This is with an estimated effective radiated power from Anthorn of 190 KW. This addendum is intended to help clarify some of the results and provide recommendations for future test scenarios.

Page 2, “Briefly about eLoran operation”. "At night the sky-wave reflection from the ionosphere can significantly degrade the field-strength of the ground-wave signal utilized by eLoran.” This is a bit of a misunderstanding of how Loran works and is one of the main reasons that it is a pulse based system and not a carrier wave system. The groundwave signal strength is exactly the same day and night and is not interfered with by the skywave.

Page 4, Figure 2 “ground elevation profile”. The principal effect of the mountains on the timing service is to attenuate the signals. Indeed, the ground conductivity there is the equal lowest in the world, and so the rate of attenuation with distance is the greatest. This is because the depth of the soil covering the rocks there is minimal.

The mountains over which the signals have travelled are complex, with multiple peaks and narrow fjords. This makes it difficult to model the spatial changes of ASF along the path. But, it's not important for the temporal stability of the timing signal reaching Oslo; the path will cause a certain, nearly constant, delay which can be measured and eliminated.

In short, it is the spatial variations of delay that are determined by the complexity of the mountains, not their temporal variations.

Page 7, “Acquiring Signal Lock”. “The receiver used a relative long time acquiring lock on the transmitted signal (several hours).” We know this model of receiver is not the best at acquiring stations in very low SNR conditions, especially if there is no “stronger” station in view. It’s kind of like using an all-in-view receiver to receive a single GNSS satellite because the rest of the constellation is not available. If there are at least two stations, and one is stronger than the other, then the receiver will be able to discipline the clock more easily, which will make acquisition of the weaker station, or stations, more successful. This is one of the reasons why it is best to have at least two eLoran stations in a “network”. Note that increasing the transmitted power from Anthorn, or other transmitting sites would help eliminate this problem. Although a lot of power might be seen as overkill for some applications, it helps significantly in challenging environments such as over long distances, underground, in noisy environments such as server rooms, and electrical utility sub stations.

Page 7, “LDC Reception”. “The reception of LDC data was patchy and intermittent.” As before, increasing the transmitted power from Anthorn, or other transmitting sites, helps eliminate this problem.

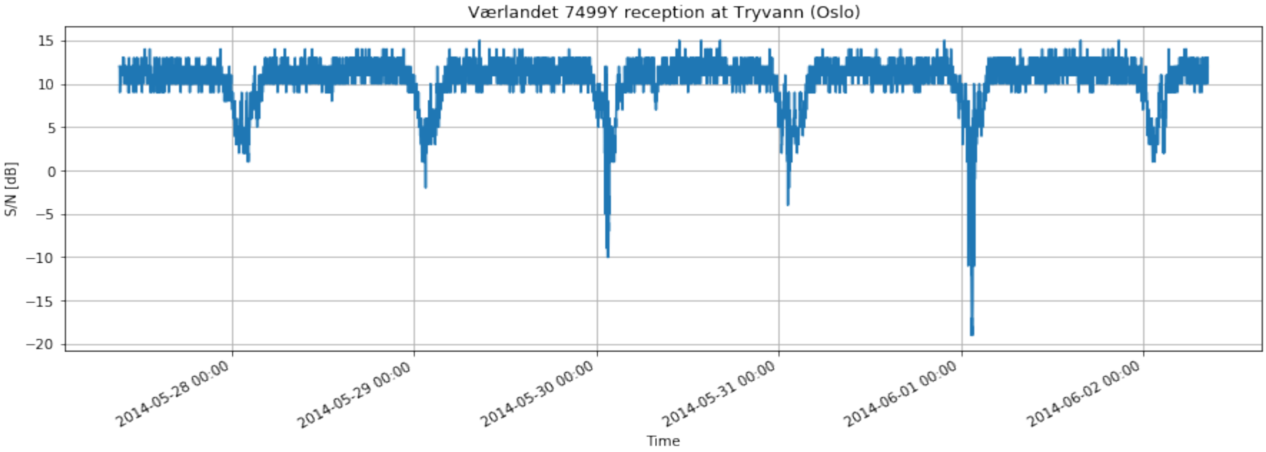
Page 9, “SNR”. The SNR is lower at night than during the day because of increased distant noise that propagates to the receiver via skywaves.

Page 10, “TIE data at 0300 UTC”. This may actually be a GPS induced artefact. The GPS constellation repeats every 24 hours (minus 4 minutes). There is no equivalent periodicity in (e)Loran signals.

Page 10, “receiver artefact”. The receiver artifact referred to on Page 9 is unrelated to eLoran performance and has to do with a known issue in the CTL 8200 that will be addressed in the near future.

Page 11, “LDC reception” If the LDC were from the Norwegian site at Vaerlandet, providing +5 dB SNR signals in the area, there would be excellent Loran timing performance (even less outliers) and virtually error-free LDC for all sorts of services. For timing, the receiver only needs one good UTC message, after which the receiver just continues to count GRIs.

Terje Nilsen from Norkring provided some data from measurements taken in Oslo[2] when Værlandet, was still operational. The measured SNR was generally +12dB due to much higher signal strength. This additional signal strength would help to improve the timing stability even further while providing a robust data channel for many other kinds of services such as emergency broadcast and notifications.



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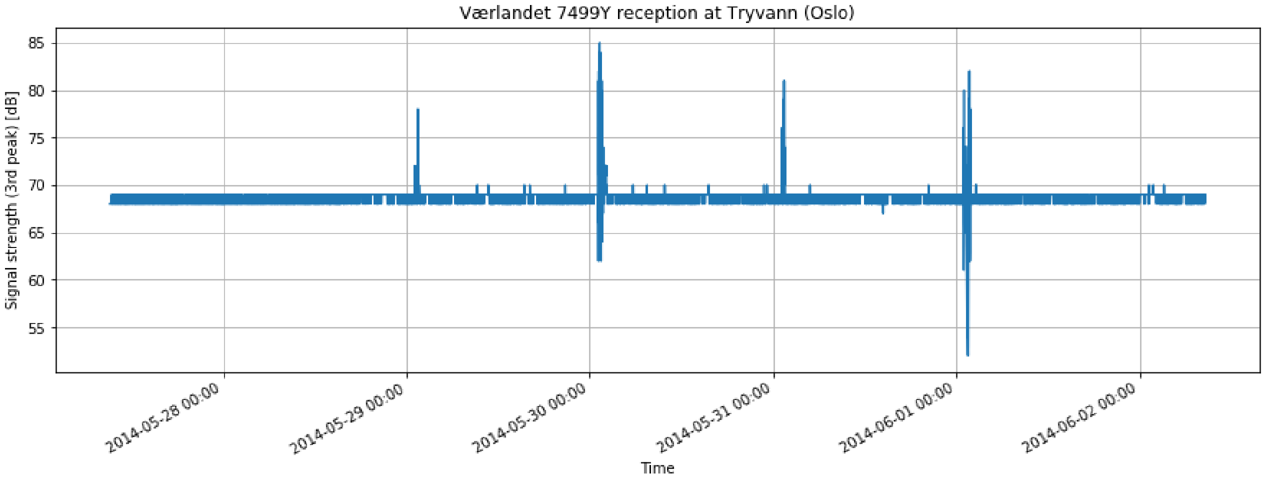
[2] The Norkring receiver is located at Tryvann (530 moh), 10.9 km NNE of the receiver at Høvik (35 moh). Receiving conditions are not necessarily comparable.


Værlandet 7499Y reception at Tryvann (Oslo)
Signal strength (3rd peak) [dB]
85
80
75
70
65
60
55
2014-05-28 00:00
2014-05-29 00:00
2014-05-30 00:00
2014-05-31 00:00
2014-06-01 00:00
2014-06-02 00:00
Time