Performance Improvement of the Low Cost LORADD SP Receiver

Cees de Groot & Anton Scheele

Introduction

In the previous article we discussed the basic performance of the LORADD SP receiver. One of the conclusions was that "eLoran in its baseline configuration cannot serve as a back up for GNSS". In this chapter we will explore the possibilities to improve the results. Therefore we will first argue why further research is necessary. Then we will analyse the observation equation of eLoran and concentrate on improvement on the level of observations. Finally we will outline improvements on the level of positions, for which no measurements have currently been made.

Rapid Environmental Assessment and positioning

A lot of research into improvement of eLoran has been done in the past few years. The results show that accuracies in the order of 10 m (95%) are possible. So why should we do research again? The reason for doing our own research is the fact that all research so far has been done with (much) more expensive receivers in dedicated areas with adequate infrastructure (for instance Harwich harbour). As argued in the previous article an expensive back up for GNSS is not justified although for military operations a high availability of PNT data is paramount. Therefore we do the research with a low cost receiver in an arbitrary area with no infrastructure which is the kind of area to be expected for military operations.

In view of Rapid Environmental Assessment (REA) [1] the military command might have a need to assess quickly the influence of the environment

(e.g. ASF) on positioning. The aim of our research is to develop a means to provide the military command with corrections which yield positions that are accurate enough to serve as a back up for GNSS for the duration of the military operation.

eLoran observation equation

The observed travel time τ' of a Loran pulse between a transmitter and the receiver antenna in terms of distance quantities may be written as:

$$d' = d + PF + SF + ASF + B + \Delta UTC + P + r$$

In this observation equation d' is the measured distance ($c \cdot \tau$') and d the true (geodetic) distance between the transmitter and receiver antenna. PF and SF are the Primary and Secondary Factor respectively which are deterministic. PF is an error that occurs due to the fact that the receiver calculates distances using the speed of light in vacuum while the speed of light in the atmosphere should be used. SF is an error that occurs due to the fact that the signal travels over sea water with no perfect conductivity inducing a delay. PF and SF in meters are calculated using the next formulae[1] with d in meters:

$$
\begin{aligned}
PF(d) &= 3.38 \cdot 10^{-4} \cdot d \\
SF(d) &= -122.1654 + 6.4597 \cdot 10^{-4} \cdot d + 1.1594 * 10^{7}/d
\end{aligned}
\tag{1}
$$

ASF is the Additional Secondary Factor. It is an extra error (delay) that occurs when the path between transmitter and receiver antenna is not an all sea water path. ASF depends on the topography and conductivity of the path and can be calculated using a model or can be measured in carefully selected positions. B and ΔUTC are the clock errors of the receiver and the transmitter respectively. P is the processing delay in the receiver and r a random residual error. The term B + ΔUTC + P + r is assumed to consist of a systematic part Δd and a residual stochastic part e yielding the next relation for d':

$$d' = d + PF + SF + ASF + \Delta d + e \tag{2}$$

The systematic part can be estimated from the measurements. The stochastic part can be canceled out by measuring over a sufficiently long period of time.

---

[1]The original version of this formula d is in statute miles.

When we want to improve the performance of the receiver the best thing to do in first instance is to correct for the biggest error namely the ASF. An expression for ASF is found rewriting Formula 2:

$$ASF = d' - d_{true} - PF - SF - \Delta d - e$$

In this formula d_{true} is known to a high degree of accuracy, for instance using DGPS or a fixed position. For absolute ASFs to be estimated the accuracy of τ' (= d'/c) and Δd needs to be in the order of nanoseconds which requires a very accurate clock in the receiver. The LORADD SP receiver does not meet this accuracy. Therefore we will discuss alternative methods to estimate ASFs as accurately as possible in the next sections.

Estimating ASF's using Millington's method

The simplest way to get a (rough) estimate of the ASF is by using Millington's method. In this method the path between the transmitter and the receiver antenna is divided into portions with the same conductivity. For each portion the delay is estimated; the sum of delays gives the total delay.

For the propagation paths between the Klooster and the transmitters at Lessay, Anthorn and Sylt we calculated the land portion and the sea water portion. For Lessay and Anthorn the first 40 and 200 kilometers respectively are over land. We assumed the path between Sylt and the Klooster to be an all sea water path, although there is a small land path of about 5 kilometers on the most westerly part of the Frisian island Ameland. Furthermore we assumed the Waddenzee to have a conductivity of sea water. Using the land and sea water portions and the graphs in figures 13 and 14 of [2] we estimated values for SF+ASF for a ground conductivity (σ) of 0.001 and 0.01 mho/m. The ASFs follow by subtracting the SF calculated with Formula 1. The results are in Table 1.

According to table F-1 of [3] we estimate the true conductivity of the land portions to be in the order of 0.005 mho/m (pastoral land, medium hills and forestation).

Table 1: ASFs estimated using Millington's method.

Transmitter		Lessay	Anthorn	Sylt
Distance total	[km]	611	572	309
Distance land	[km]	40	200	0
$\sigma = 10^{-3}$	[mho/m]			
SF+ASF	[μs]	1.67	2.67	0.74
SF	[μs]	0.97	0.89	0.74
ASF	[μs]	0.70	1.78	0.00
	[m]	210	534	0.00
$\sigma = 10^{-2}$	[mho/m]			
SF+ASF	[μs]	1.17	1.58	0.74
SF	[μs]	0.97	0.89	0.74
ASF	[μs]	0.20	0.69	0.00
	[m]	60	207	0.00

Estimating ASFs from observed differential ASFs

The clock of the (low cost) LORADD receiver is not accurate enough to estimate Δd to a sufficient degree of accuracy. Therefore the receiver cannot calculate absolute ASF's. Instead the receiver calculates the so called dASF which is the difference between the ASF of a measurement and a reference ASF_{ref}. ASF_{ref} is the ASF of the measurement from the transmitter with the largest Signal-to-Noise ratio, mostly being the nearest transmitter. By differencing Δd cancels:

$$dASF = (ASF + \Delta d) - (ASF_{ref} + \Delta d)$$

To estimate ASFs using dASF's we measured dASFs of the three transmitters in chain 6731 and the dASFs of the transmitter at Ejde (chain 9007). The propagation path between Ejde and the Klooster is completely over sea water, so the ASF of Ejde should be zero. Given that Sylt is the reference this leads us to the next relation:

$$dASF_{Ejde} = ASF_{Ejde} - ASF_{Sylt} = -ASF_{Sylt}$$

Substituting this relation into the relation of the dASF of Lessay and Anthorn gives:

$$\begin{aligned} dASF_{Lessay} &= ASF_{Lessay} - ASF_{Sylt} \\ &\Rightarrow ASF_{Lessay} = dASF_{Lessay} - dASF_{Ejde} \end{aligned}$$

$$\begin{aligned} dASF_{Anthorn} &= ASF_{Anthorn} - ASF_{Sylt} \\ &\Rightarrow ASF_{Anthorn} = dASF_{Anthorn} - dASF_{Ejde} \end{aligned}$$

Figure 1 gives the results calculated from static measurements at the Klooster between 13 and 20 February 2009.
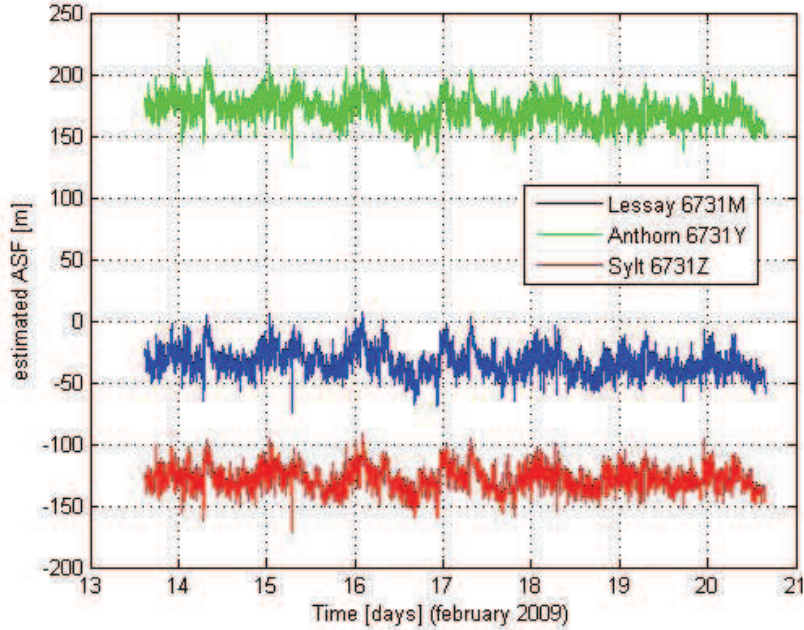

Figure 1: ASF's estimated using observed dASF's.

The mean values of the ASFs for Lessay, Anthorn and Sylt are mentioned in Table 2. The ASFs of Sylt and Lessay turn out to have a negative value. This is highly improbable. This might indicate that the ASF of Ejde does not equal zero although the path between Ejde and the Klooster is completely over sea water. Let us therefore assume again (as in the previous section) that the ASF of Sylt should be zero (or a small positive value). By adding 128 m to all ASF's we get the results of the second line of Table 2.

Table 2: Mean values of ASF's estimated using observed dASF's.

Transmitter		Lessay	Anthorn	Sylt
ASF ($\mathrm{ASF}_{Ejde} = 0$)	[m]	-34	171	-128
ASF ($\mathrm{ASF}_{Sylt} = 0$)	[m]	94	299	0

Estimating ASFs from eLoran positions and residuals

The LORADD receiver does not output values for Δd. In order to estimate ASFs we therefore first estimate values for ASF + Δd according to the next

relation:

$$ASF + \Delta d = d' - d_{true} - PF - SF - e$$

Because the LORADD receiver does not output d' (or τ') we estimated d'
from:

$$d' = d_{loran} + e$$

In this relation d_{loran} is the distance between the calculated eLoran
position and the transmitter. Figure 2 depicts the relation between d',
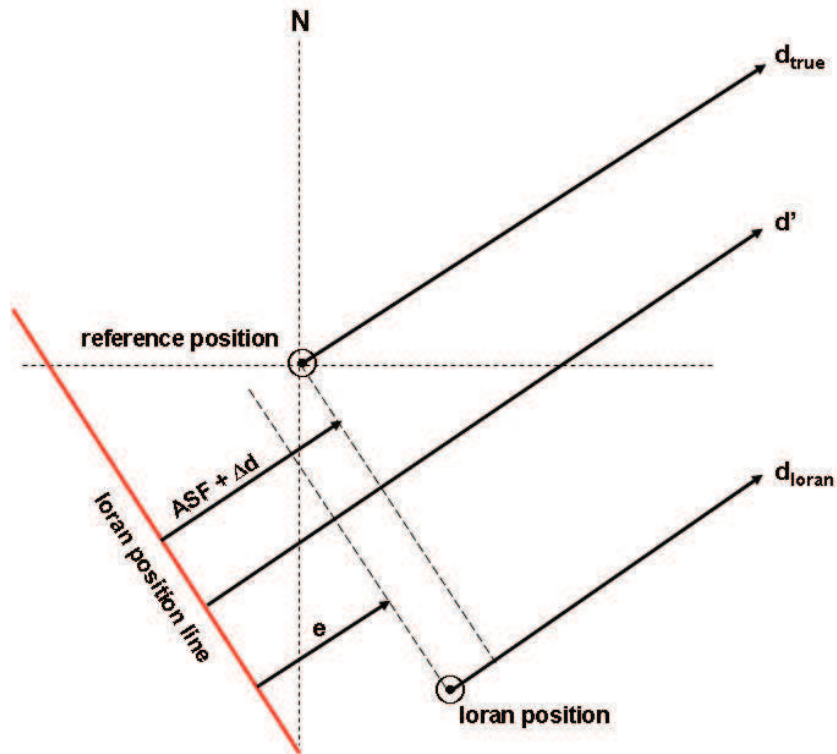d_{loran}, d_{true}, ASF + Δd and e.

Figure 2: Relation between observed distance (d'), distance between transmitter and
eLoran position (d_{loran}), distance between transmitter and true position (d_{true}), distance
between observed eLoran line of position and true position (ASF + Δd) and residual e.

To calculate ASF + Δd eLoran measurements were done from 13 Febru-
ary 2009 14:53:08 UTC until 20 February 2009 15:42:09 UTC with 1 minute
intervals. Figure 3 shows the results graphically while Table 3 gives the
mean values.

The next step is to try to eliminate Δd. Therefore we can follow two
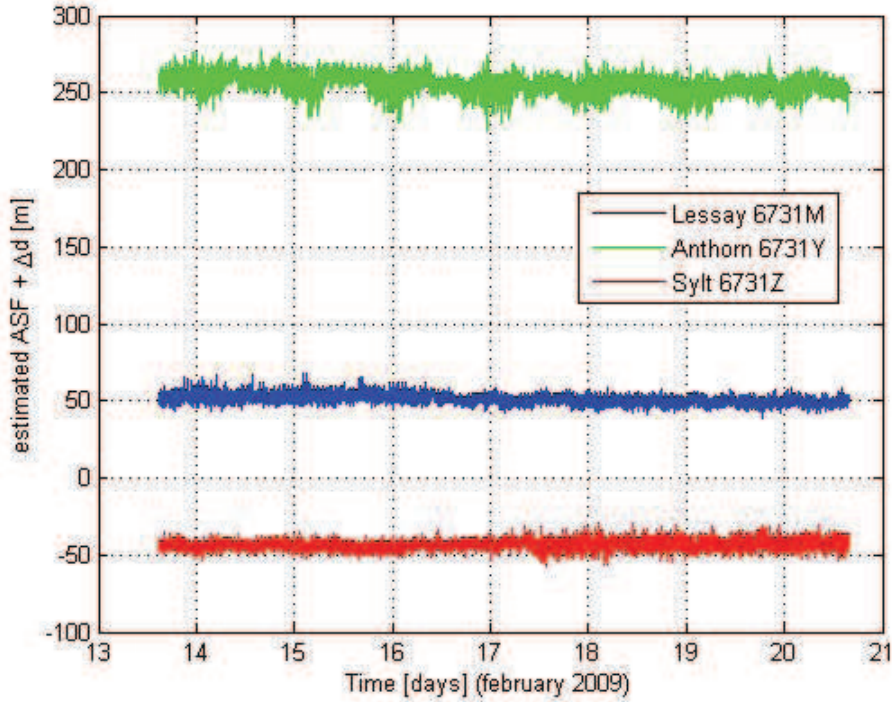different independent ways:

Figure 3: ASFs estimated from eLoran positions and residuals.

1. Based on the assumption that the ASF of Sylt should be zero we find a mean value of -43 m for Δd. The ASFs for Lessay and Anthorn can now be estimated to be 94 m and 298 m respectively (see Table 3).

2. The geometry of eLoran position lines in Den Helder Roads is such that position lines of Sylt and Lessay run parallel while the one position line of Anthorn is nearly perpendicular to them. This means that the distance between the reference position at the Klooster and the mean eLoran position may assumed to be equal to the ASF + Δd of Anthorn (see Figure 4). Using -43 as the value for Δd we conclude that the ASF for Anthorn equals 305 m (= 261 + 43) yielding an ASF of 6 m for Sylt and 100 m for Lessay.

Table 3: Mean values of ASF's estimated using eLoran positions and residuals.

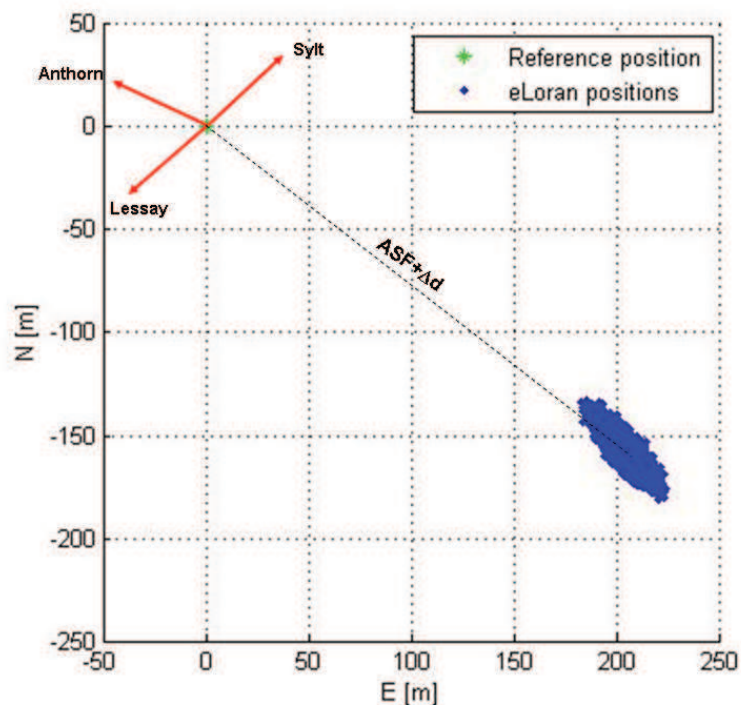| Transmitter		Lessay	Anthorn	Sylt
ASF + Δd	[m]	51	255	-43
ASF (ASF_{Sylt} = 0 m)	[m]	94	298	0
ASF ($ASF_{Anthorn}$ = 304 m)	[m]	100	304	6

Figure 4: Geometry of eLoran position lines at the Klooster. The distance between the reference position and the mean eLoran position nearly equals ASF + Δd of Anthorn (261 m).

Summary and discussion

The values for the ASFs of Lessay, Anthorn and Sylt for the position of the Klooster in Den Helder are summarized in Table 4. Outcomes with negative values for one or more ASFs have been omitted beforehand.

Table 4: Mean values of ASF's in m.

Method	Lessay	Anthorn	Sylt
Millington			
$\sigma = 10^{-3}$	210	534	0
$\sigma = 10^{-2}$	60	207	0
dASF's			
	94	299	0
eLoran positions and residuals			
$\text{ASF}_{Sylt} = 0$	94	298	0
$\text{ASF}_{Anthorn} = 304$	100	304	6

The resemblance between the ASFs calculated using dASFs and using eLoran positions and residuals is striking and deserves a closer look. When we calculate the correlation coefficient between both sets of ASFs we find

values of 0.44 and 0.60 for Lessay and Anthorn respectively. This indicates, neither method is completely independent, but the independency is such that both methods deserve supplementary research for validation.

The ASFs calculated using measurements are in the range of ASFs calculated using Millington's method.

Based on the results so far we assume that the ASF at the Klooster equals 94 m and 298 m for Lessay and Anthorn respectively.

In order to ascertain these values they should be entered into the LORADD receiver. Basically this is possible, but users themselves cannot enter an ASF map. From a point of view of the 'normal' user this is understandable to avoid errors which could affect the safety of navigation. From the point of view of research this is a drawback of the LORADD receiver. Also from a military point of view this is a drawback, because it reduces the flexibility and the independency of the military command.

Improving the performance on position level

Since the receiver does not offer the possibility for the user to enter ASF maps eLoran measurements cannot be corrected for ASF. Therefore for the time being we shifted the focus of the research from corrections on observation level to corrections on position level. The assumption is that the receiver always uses the same transmitters in a certain area. The mean bearing and distance between observed eLoran and DGPS positions can be used as a correction. No systematic field work has been done for this research so far.

Based on research mentioned in the previous article and based on small tests the next topics need our attention:

1. To avoid relative bearing dependent errors inherent to an H-field antenna measurements will be taken using an E-field antenna.

2. On a moving platform the LORADD receiver shows a difference (latency) between the eLoran position of a certain epoch and an (independent) DGPS position of that same epoch. Part of the research will concentrate on modelling this error.

The future of eLoran

On 28 October 2009 the President of the United States, Barack Obama, announced the termination of Loran-C and hence the termination of eLoran in the United States. According to [4] Obama stated:

"This system once made a lot of sense, before there were satellites to help us navigate. Now there's GPS. And yet, year after year, this obsolete technology has continued to be funded even though it serves no government function and very few people are left who still actually use it."

The US Coast Guard supports the president by stating [4]:

"In a submission to the Federal Register, the Coast Guard said Loran-C was not established as, nor was it intended to be, a backup for GPS. Other radio navigation systems, or operational procedures, can be used as backups for GPS navigation and other critical applications, the Coast Guard said."

We will continue to do research into eLoran, because presently there is no adequate backup; since the European eLoran transmitters will be operational until 2022 we can continue the research. Over a period of 12 years there will likely be a GNSS incident serving as a wake up call to the PNT community.

References

[1] J. Appelman, *One Theatre, One Forecast; Working Paper Maritiem Optreden nr. 2*. Den Helder: Maritiem Doctrine en Tactieken Centrum, 2009.

[2] S.N. Samaddar, "The Theory of Loran-C Ground Wave Propagation - A Review," *Navigation, Journal of the Institute of Navigation*, vol. 26, no. 3, Fall 1979.

[3] United States, United Sates Coast Guard, "Appendix F; Millington's Method," *LORAN-C User's Handbook*, COMDTPUB P16562.6

[4] M.M. Ahlers, "World War II-era navigation system shutting down," CNN.com, 8 february 2010.