Integrating GPS and Loran-C

Basic principles and first testing results

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Abstract

Navigation experts predict a huge market for positioning and navigation applications in the very near future. Although satellite navigation, mainly based on the GPS, plays an important role in performing positioning tasks and although there are efforts to establish new satellite-based systems like the European Galileo, the reliability and availability of these systems cannot satisfy all requirements of today’s applications. Therefore, the navigation system of the future will combine various systems that complement each other in an optimal way. As Loran-C is with respect to system characteristics, especially to the propagation behaviour of the carrier wave, very dissimilar to GPS, it seems to be a favourable complement to GPS in an integrated navigation receiver.

Recently, several research projects have been initiated to develop techniques and algorithms for an integration of GPS and Loran-C and first (theoretical) results are very promising. Also the ongoing advancement of static Loran-C receivers towards kinematic use pushes the development of such combined positioning systems.

After an introduction and some basics of GPS and Loran-C with respect to integration, this paper shows some characteristics of Loran-C Time-of-Arrival (TOA) measurements that determined our chosen method of integrating GPS and Loran-C. Furthermore, results of field measurements are shown which demonstrate the opportunities being provided by such integration techniques.

Keywords: Navigation, Loran-C, GPS, Sensor-fusion, Integrated positioning system

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1. Introduction

As a result of the growing popularity of satellite-based navigation systems, which can be summarized by the term GNSS (*G*lobal *N*avigation *S*atellite *S*ystem), land-based systems have been losing importance during the last decades. However, new positioning and navigation applications require higher accuracy, availability and reliability than we are used to obtain from today’s satellite navigation. Well, there is a tendency towards improved satellite capabilities (e.g. the “modernization” of GPS) or even new satellite systems, like the European Galileo. Doubtless, these activities will result in an increased performance of satellite navigation in general, but two or even three satellite systems are basically just offering more of the same – the well-known problems of signal acquisition in urban areas or in other critical environments will persist. To meet all requirements of today's and future navigation applications, the key will be the integration of satellite navigation with other, different and non space-based positioning systems. Recent projects and studies have shown that one very promising candidate for a fusion with satellite navigation is Loran-C[1]. Loran-C, a long-range navigation system based on low frequency transmission, has its strengths there, where GNSS suffers from various shortcomings.

To substantiate, when integrating GNSS and Loran-C, the contribution of GNSS will mainly affect the aspect of accuracy, whereas Loran-C has to contribute to the reliability monitoring of GNSS and to the aspect of accuracy in the absence of GNSS.

2. Fundamentals

2.1. GNSS

The future Global Navigation Satellite System is a compound of various satellite-based navigation systems (GPS, GLONASS and, in the future, the European Galileo) and their, not necessarily space-based, augmentation systems. However, the capability of GNSS of providing a position fix can be reduced to the question, whether sufficient satellite signals (in terms of quality and quantity) can be received or not. Without doubt, GNSS-based positioning is and will remain the most important technique of navigation, because it offers an absolute positioning accuracy that is sufficient for most applications. (Table 1 lists the system characteristics of GPS due to the 1999 U.S. FRP [2].) The problem is, that current GNSS receivers require a direct line-of-sight to the space vehicles, what can often not be guaranteed in certain critical environments. This leads to a reduced availability (and also to a reduced accuracy) of the position fixes, which is, in turn, causing inadequate performance mainly for safety-critical applications.

2.2. Loran-C

Loran-C is a regional land-based navigation system based on a carrier frequency of 100 kHz. The stand-alone accuracy of this system is poor, which is mainly caused by the propagation characteristics of the carrier wave. Within this part of the electromagnetic spectrum, the waves propagate as so-called "ground waves" and therefore follow the curvature of the earth. The propagation speed is significantly affected by the conductivity of the ground, as well as by atmospheric conditions. This leads to an unknown delay of the signal generally referred to as "Additional Secondary Phase Factor" (ASF). Although there are efforts of various research organizations to investigate these ASFs to achieve regional models and tables of the delays, these are not yet mature enough to improve the absolute accuracy of stand-alone Loran-C to a few meters. Anyhow, the relative accuracy of Loran-C, or in other words, the repeatability, is very good; i.e., the ASFs are quite stable with respect to temporal variations. (For the Loran-C system characteristics due to the 1999 U.S. FRP [2], cf. Table 2). Field measurements of the TeleConsult-Austria have shown, that the repeatability within a time interval of about two hours is sometimes in the range of some five meters, presumed that sufficient Loran-C stations can be received. Apart from the very good repeatability, the Loran-C signal hardly suffers from blocking or shading due to obstructions along the signal path. In general, the availability of the signal is very high in comparison to the availability of GNSS. This is also true for urban areas or other GNSS-hostile environments.

[1] In the following, the term "Loran-C" also includes the Russian counterpart Chayka.

Absolute accuracy	10 m horizontal (not yet officially defined after SA was switched off)
Repeatable accuracy	≤ 1 m horizontal (same satellites and approx. same time within a day)
Availability[2]	99.85%
Reliability[2]	99.97%
Integrity	GPS signals are constantly monitored by the control segment. Abnormalities cause a signalled state in the navigation and health message.
Coverage	Global
Fix rate	Continuous (theoretical), typical: 1 – 20Hz
Fix dimension	3D + Time
Uniqueness of solutions	Yes

Table 1: GPS system characteristics

Absolute accuracy	460 m
Repeatable accuracy	18 – 90 m
Availability	99.7%
Reliability	99.7%
Integrity	Loran-C signals are constantly monitored. A "blink" is manually initiated immediately upon detection of an abnormality
Coverage	Regional
Fix rate	10 - 20 Hz, typical : 1 Hz
Fix dimension	2D + Time
Uniqueness of solutions [3]	No, but easily resolvable

Table 2: Loran-C system characteristics.

3. Integration of GNSS and Loran-C

As it becomes clear from the previous sections, the fusion of GNSS and Loran-C should allow a compensation of the main disadvantages of the individual systems. But there arise a few questions on how to integrate the systems:

- *Integration on the basis of pre-computed position fixes vs. raw data:*

  In the first case, the expense of developing a suitable algorithm is quite low, because the position output of the navigation receivers can directly be used. However, to achieve a valid 2D position, at least either three visible satellites (the height of the observation site must be known) or three Loran-C stations must be available. In the

[2] For the definitions of the respective parameters cf. 1999 U.S. FRP [2].
[3] In hyperbolic mode, i.e., the position solution is ambiguous due to the presence of a second point of intersection of the two hyperbolas.

case of integrating the systems on the basis of raw-data, any combination of ample navigation sources can be used to compute a position fix. Therefore, the expense of developing an algorithm is considerably higher than in the former case.

- If the integration is performed on the basis of raw data: *Using Loran-C Time Of Arrival (TOA) vs. using Loran-C Time Differences (TD):*

Originally, Loran-C was designed as a 2D hyperbolic[4] navigation system that uses TDs for computing the position (for a detailed description of the Loran-C mode of operation, cf. [6]). In this case, the receiver clock error is cancelled. A condition for this technique is, that the two stations, which are involved in a certain TD, are time-synchronized. Computing TDs between non-synchronous stations does not make any sense and therefore would result in an invalid position fix. Anyhow, the TDs are still degraded mainly by the ASFs and thus, the absolute positioning accuracy accords with the specifications described in Table 2.
The second option is to work with TOA measurements. TOAs multiplied by the speed of light yield pseudo-distances between the transmitter and the receiver, which are well-known from GPS single point positioning with code ranges. In this case, the receiver clock error must be treated as an additional unknown parameter in the adjustment process. Naturally, the TOAs are also affected by ASFs.
In case of absolute positioning with Loran-C, the usage of TOAs can be seen as to some extent equivalent to the use of TDs – TOAs require an additional unknown parameter in the computation process, whereas this parameter can be saved by using TDs. However, if using TDs the number of observations is reduced by one – the difference between the number of observations and unknowns remains the same!

Weighting up all relevant facts, we decided to integrate GPS and Loran-C on the basis of raw data, particularly to have more possibilities to investigate and develop various algorithms and techniques for position computation. Note that combining positioning results of the two systems would also be problematic due to the ASFs, which are different for every Loran-C station. A constellation change would therefore result in a jump of the position. This is not the case, if a calibration parameter may be determined for every Loran-C station during an initial "learning phase".

The choice between the utilization of TDs vs. TOAs is more complicated and requires a deeper insight into the error sources of Loran-C:
Considering TOA measurements and summarizing Table 3, the main errors can be reduced to

- A drifting part, common for all TOAs (2), and
- A rather stable part, different between all TOAs (1, 3, 4).

Considering TD measurements, we save the receiver clock error and thus, the only remaining error is a composite of (1,2,4).

[4] The Lines Of Position (LOPs) of time differences form hyperbolas.

Error source	Comments
1. Additional Secondary Factor (ASF)	▪ Caused by propagation characteristics of low frequency electromagnetic waves, ▪ Assumed to be stable over not too long time periods, ▪ One ASF per received TOA, ▪ One combined ASF per TD.
2. Receiver clock error	▪ Caused by the instability of the receiver clock, ▪ Usually shows a significant drift over time, ▪ Affects all TOAs in the same manner, ▪ Is cancelled by computing TDs.
3. Transmitter clock error	▪ Caused by the instability of the transmitter clock, ▪ One transmitter clock error per TOA, ▪ One combined transmitter clock error per TD, ▪ Assumed to be negligible due to high-performance clocks in the transmitters.
4. Synchronization error between different chains	▪ In Europe, the chains of the NELS[5] are synchronized among each other; the Russian Chayka System is not synchronized with NELS, ▪ One synchronization error per chain, ▪ Error is assumed to be stable over not too long time periods.

Table 3: Main error sources of Loran-C

Unfortunately, the rather stable part of the errors, that is responsible for the low absolute position accuracy of Loran-C can (at least currently) neither be modeled nor accurately measured. However, the availability of GPS measurements provides help for improving the accuracy. The idea is to calibrate Loran-C measurements during periods of good satellite visibility and to use these calibrated data during periods of limited GPS visibility and/or performance.

Considering all (theoretic) aspects mentioned above and taking into account the more complex observation equations of TDs, we decided to utilize TOA measurements for Loran-C, and, as already indicated, to calibrate them by GPS measurements. Applying a sophisticated algorithm, this allows to obtain an increased positioning accuracy during GPS outages and to support GPS during periods of limited satellite visibility. All these thoughts are based on the assumption that GPS outages do not last for too long intervals and that Loran-C TOAs do not drift too fast during this time period.

4. Characteristics of TOA measurements

To verify above stated theoretical predications, i.e. to explore and verify the characteristics of TOA time series, some field measurements have been carried out at the city of Graz in Austria. Table 4 depicts the involved Loran-C stations and their distances to Graz. Table 5 shows the respective settings of the Locus SatMate 1000 receiver during the measurement.

[5] Northwest European Loran-C System, cf. http://www.nels.org/

Station GRI and ID		Location	Approx. distance to Graz, Austria
Chayka	8000M	Bryansk	1500 km
	80002	Solnim	1000 km
	80003	Simferopol	1400 km
	80004	Syzran	2400 km
NELS	6731M	Lessay	1300 km
	6731Z	Sylt	1000 km

Table 4: Some Loran-C and Chayka stations received at Graz

Since the data have been collected in Graz, which is situated at the outer limit of the nominal NELS coverage and also of the Chayka coverage, the quality (with respect to noise) of the data is rather moderate, but some basic ideas and conclusions can anyhow be derived from the results.

Parameter	**Setting**
Batch min.	1.0 sec.
Batch max.	20.0 sec.
TD averaging	5.0 sec.
Clock averaging time	10.0 sec.
Operating mode	Mobile

Table 5: Locus SatMate 1000 receiver settings

Figure 1 illustrates TOA time series of various Loran-C and Chayka stations received. The subplots are equally scaled, the span of the horizontal axis equals 2000 nanoseconds, which is equivalent to about 600 meters. Some basic messages can already be derived from this figure:

- As it also can be seen from the graphs, the SNR is a good indicator for the quality of the received signal. Thus, the SNR could be used as a weighting factor within the position computation.

- All time series show an equal trend, which is assumed to be caused by the receiver clock – this can be compensated by introducing a receiver clock parameter into the computation,

- The magnitude of TOA variability during the whole period differs between NELS and Chayka measurements. This is likely to be caused by a changing time difference between the Time Of Emission (TOE-) controlled[6] NELS system and the System Area Monitor (SAM-) controlled Chayka system. (There is no timing control between NELS and Chayka!)

[6] System Area Monitor (SAM) control and Time Of Emission (TOE) control are the two basic methods in use for monitoring and adjusting the clocks in Loran-C systems. For details see [6].

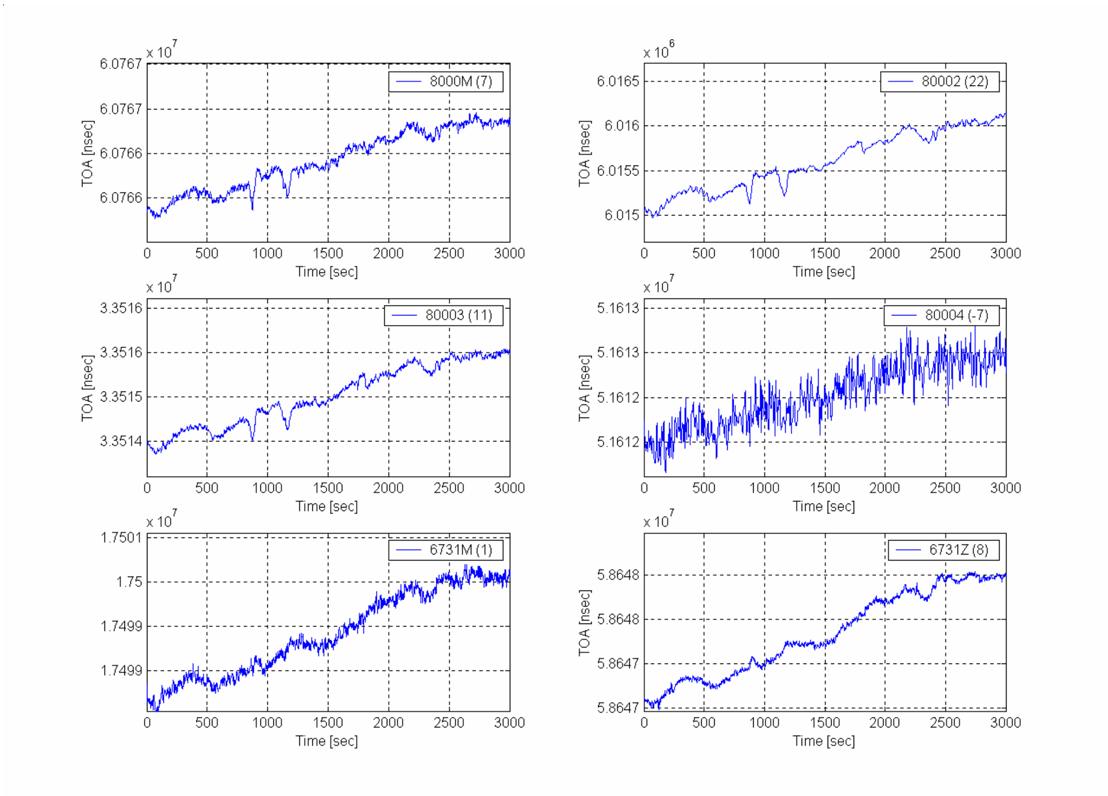

Figure 1: TOA time series. (The values in brackets denote the mean SNR of the concerning signal.)

Figure 2 shows a time series of TOA differences between two NELS and two Chayka stations, respectively. This time series can be seen as a composite of the above-mentioned errors, excluding the receiver clock error.

Despite of the great distances between the Loran-C transmitters and the measurement site, these time series show a surprising stability during a time period of nearly one hour. Although the distances of the involved NELS stations from Graz are similar to those of the Chayka stations, the noise behaviour of the NELS TDs is considerably worse. This can be explained by the transmitter power of the stations: NELS stations feature a power of 250-400 kW, whereas Chayka transmits with a power of up to 1150 kW. The varying power is also reflected by the individual SNR values.

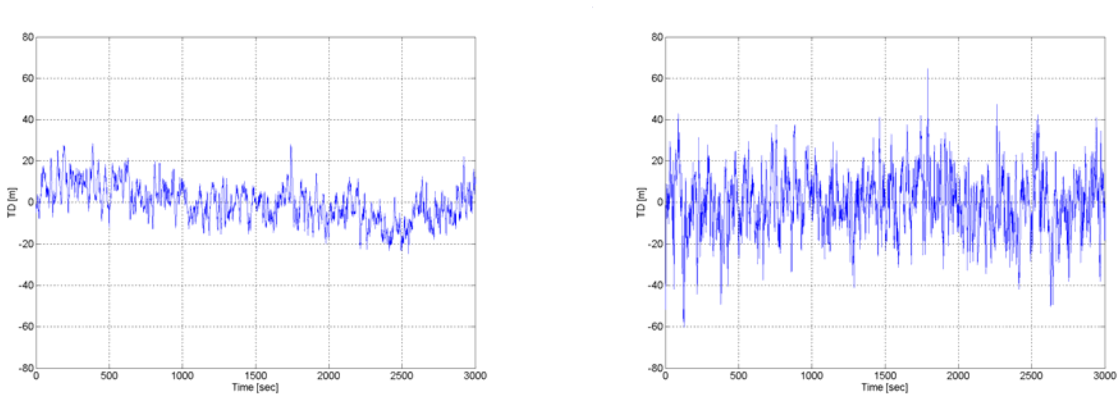

Figure 2: Differences of TOA time series (left: Chayka: 8000M – 80002, right: NELS: 6731M – 6731Z). Note: The unit of the vertical axis is meters.

Finally, a plot of position fixes of a Loran-C stand-alone measurement should once more demonstrate the high repeatability (i.e. stability) of Loran-C measurements (cf. Figure 3). These measurements have been carried out in The Netherlands, where the Loran-C coverage is fairly good[7].

Figure 3 shows a dominant diagonal spreading of the position fixes. This is caused by the geometrical situation: The measurement site was situated at about half the distance between the two nearest Loran-C transmitters (Sylt and Lessay). Naturally, these stations have the best SNR and thus, the stations get the highest weight in the position computation compared to the other measurements.

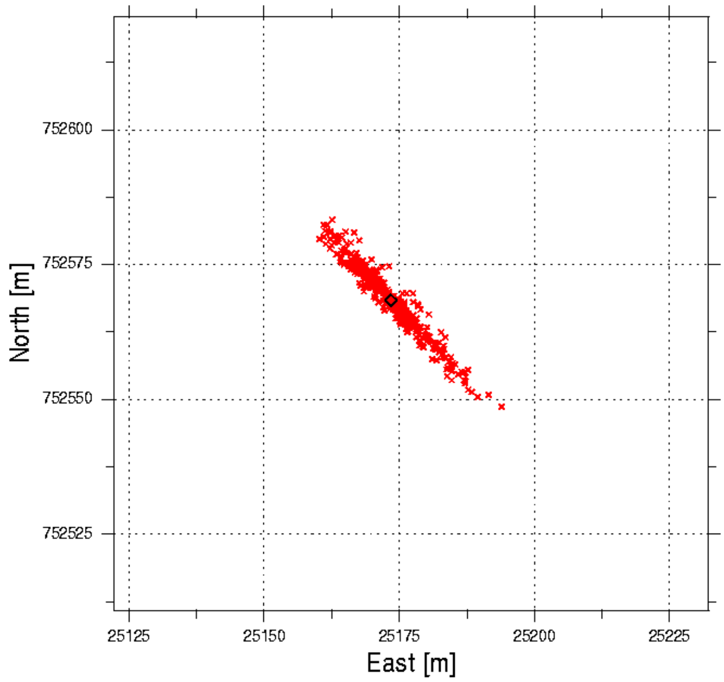

Figure 3: Scatter plot of Loran-C position fixes (Gauss-Krueger projection). The repeatable accuracy is about 13 m (95%) in north and east direction. The across error is only about 5 m (!).

Figure 4 illustrates the resulting line of position that nearly degrades to a straight line. The 2D orientation of this line corresponds to the orientation of the diagonal spreading of the position fixes.

Summarizing, it can be stated that field measurements have proven the assumed stability of TOAs (and TDs) over certain time periods, which favours the technique of supporting satellite navigation during outages by Loran-C measurements. However, not only total GNSS outages can be bridged, also the computation of a 3D position employing, e.g., two satellites and three Loran-C stations becomes possible.

[7] These measurements have been carried out within the project GLORIA financed by the European Commission (EC). Thanks to the team of GLORIA for providing this figure!

Figure 4: Geometric situation at the measurement site in The Netherlands. The red curves represent the Loran-C hyperbolas for the TDs between the transmitter stations at Lessay and Sylt (low curvature hyperbola at the center of the figure), Lessay and Soustons (bottom left), and Sylt and Værlandet (top right).

5. Combined GPS/Loran-C position solutions

As already pointed out in section "Integration of GNSS and Loran-C", the indicated algorithm calibrates Loran-C TOA measurements during phases of good satellite visibility and uses these calibrated measurements to bridge GNSS outages and to support GNSS during periods of bad satellite visibility.

Again it should be mentioned, that all measurements for the combined position solution have been taken in Graz, Austria. It has to be noted that we do not intend to show the performance of Loran-C within this paper, but we want to point out the opportunities, this technique of integrating GNSS and Loran-C could offer. It would not make sense to comment on the power of a system while measuring outside or at the absolute limit of its nominal coverage area!

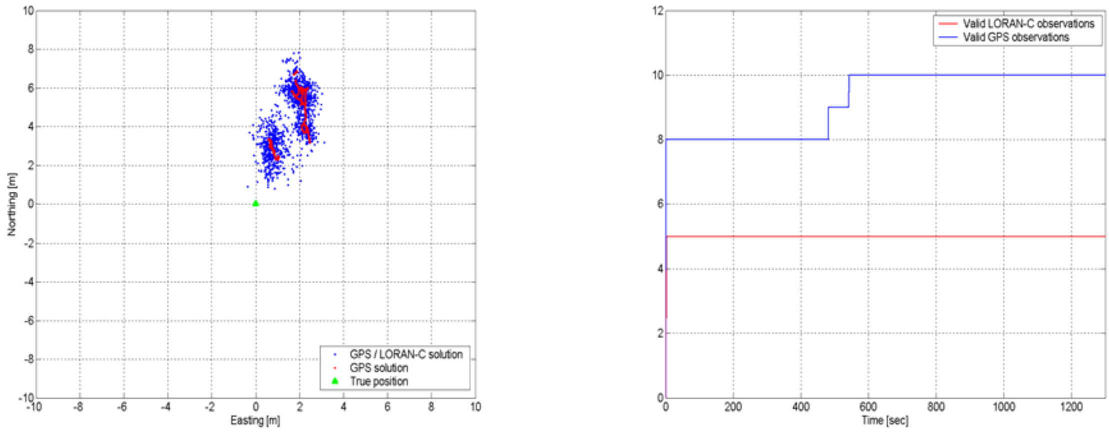

Figure 5: Left: Position fixes computed from all GPS stand-alone and integrated GPS/Loran-C, right: Number of visible navigation sources.

Figure 5 illustrates the difference between GPS in stand-alone mode and the combined GPS/Loran-C solution, using all available navigation sources[8]. It is evident, that the combined

[8] Here, "Navigation source" is a synonym for either GPS satellite or Loran-C station.

solution shows a higher spreading than the GPS stand-alone solution. The reason is, that previously (that is within the prior epoch) calibrated TOAs also contribute to the position solution of the current epoch, even though their weight is significantly lower than the weight of GPS observations.

In Figure 6, the Loran-C TOAs are calibrated during the first 60 epochs of the treated time frame. It can clearly be seen, that the spreading of the position fixes is becoming significantly higher, but the position remains quite stable with respect to time. In the right figure, the respective time series of the coordinates are shown.

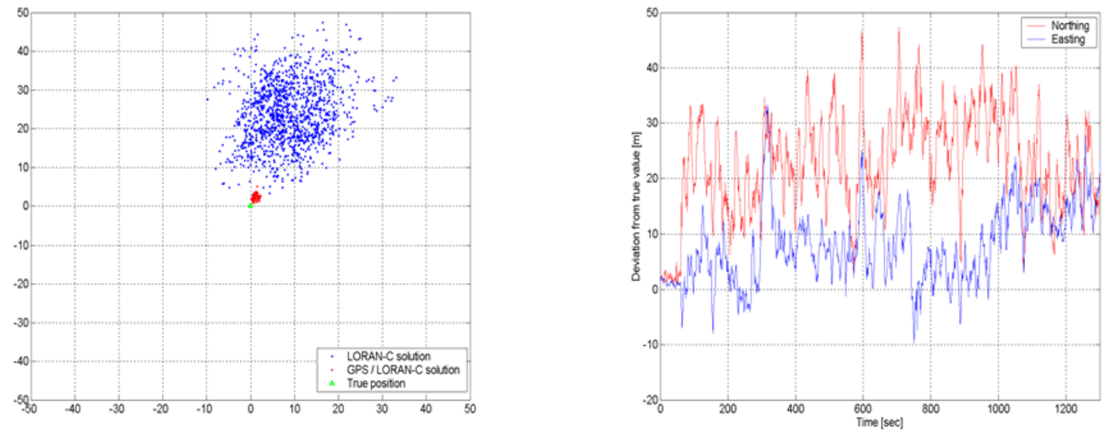

Figure 6: Left: Position fixes from Loran-C after a calibration phase, right: Time series of respective north and east coordinates.

Figure 7 and Figure 8 simulate a kind of realistic situation: The number of visible GPS satellites is changing and suddenly falls below four, whereas the number of Loran-C stations remains constant. The algorithm computes a position fix out of all available measurements, which yields a higher accuracy compared to a Loran-C only solution.

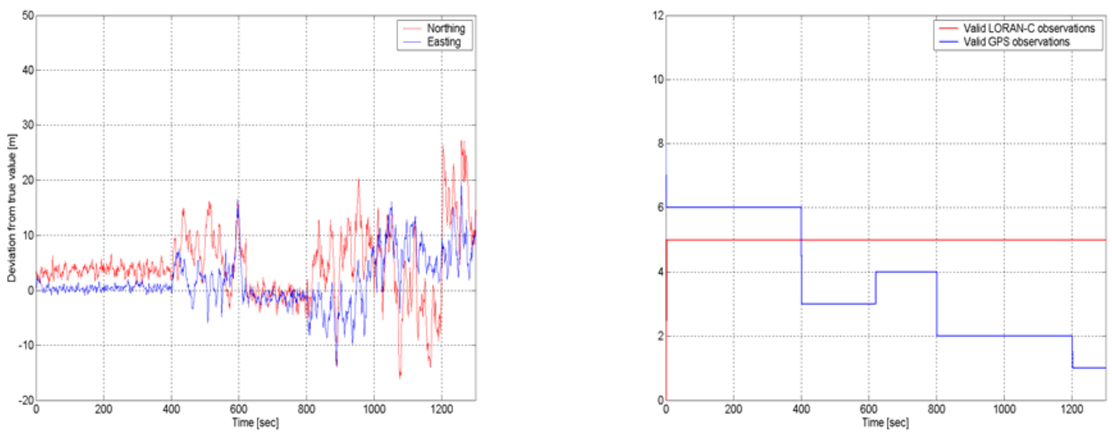

Figure 7: Left: Position fixes from an integrated GPS/Loran-C solution under changing satellite visibility, right: Number of visible navigation sources.

As it can be seen in Figure 8, the algorithm is still able to compute integrated position fixes through a minimum availability of navigation sources, i.e. two satellites and three Loran-C stations. However, due to a lack of additional navigation sources, the quality of the solution gets worse.

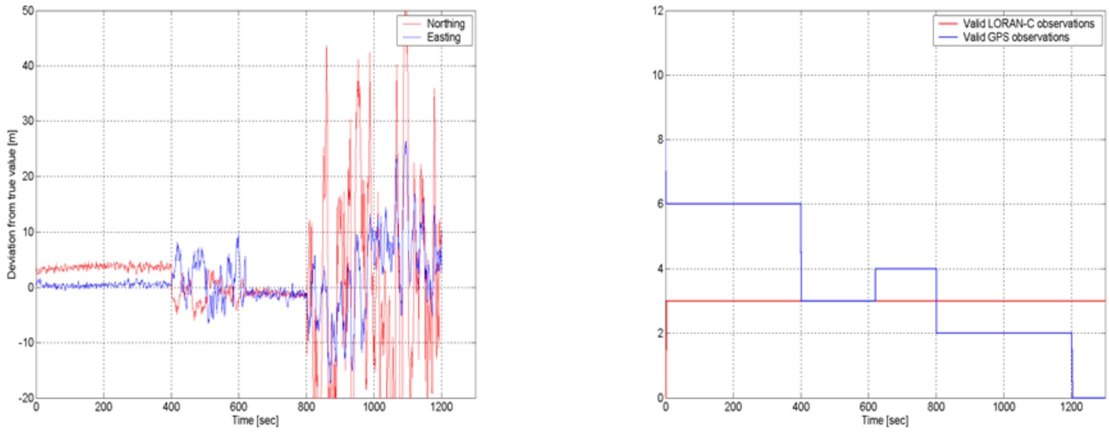

Figure 8: Left: Position fixes from an integrated GPS/Loran-C solution under changing satellite visibility, right: Number of visible navigation sources.

All the charts shown above are based on epoch-per-epoch adjustment computations. For the sake of clearness while showing system characteristics, in this case we decided to avoid filtering algorithms, which would effect smoothed curves. In navigation applications, however, the application of Kalman filters could yield an improved positioning quality because of the filter's ability to introduce the kinematic behaviour of the real system into the mathematical model that underlies the computations.

6. Summary and Outlook

Within the previous sections, the basics of integrating GNSS (GPS) and Loran-C/Chayka have been shown and also proven by some measurements. As an overall result, it becomes clear, that the presented method of integrating those very dissimilar systems seems to be very encouraging! Doubtless, the leading role of GNSS will also retain its justification in the future. However, GNSS fails at locations without a direct line-of-sight to the satellites (e.g., in urban areas, within buildings or also within forests). In such situations, which are characteristic for land applications, Loran-C has a great potential to bridge GNSS outages, although there are many subjects concerning Loran-C to be investigated in more detail than they are known today, e.g., the antenna-problem (H-field antenna vs. E-field antenna) and others. Also, for a usage of Loran-C in Central Europe, the existing network of the Northwest European Loran-C System (NELS) should be extended to the existing, but at present not operational transmitters in Southern Europe as well as to new transmitters in Central Europe. This would lead to a by far better performance of Loran-C all over Europe. The overall costs of installing a new Loran-C transmitter including Eurofix capability only amount to about six million Euros.
Concluding, it can be stated that the strategy of integrated navigation algorithms has its strengths in relying on highly dissimilar systems. Such combinations by far have more potential than two or even three satellite systems, which are basically just offering more of the same! Beyond this point of view and not only for technical but also for political reasons, the maintaining and extension of Loran-C as well as the pushing of Galileo as the European contribution to GNSS-2 should be intended by the European Community. This would

improve the accuracy and availability of positioning and navigation in Europe while simultaneously achieving independency of U.S. navigation facilities.

7. References

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