Radionavigation: the Only Way to go?

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Introduction

During the era of the last 6 decades quit a few radio navigation systems have been established, and some of them are still in use today. Loran-A, Omega, DECCA and Transit are gone while GPS, GLONASS and eLoran are operational, and within a couple of years we will see Galileo becoming the third worldwide navigation system while the introduction of DLoran is not yet formally decided. It will depend on the decision of the US, European and Asian authorities whether Loran-C will be continued for indefinite time.

In the mean time people argue about which system is the best, the most reliable and the most beneficial in a cost perspective. The US and Europe officially agreed on a cooperation scheme between GPS and Galileo. The US is somehow concerned about potential military use of Galileo which the Europeans deny. The recent news on the ION website made this European statement questionable:

> ***EC hints at Galileo military use***
>
> *Royal Institute of Navigation, Release date 17-Oct-2006*
>
> *"It is widely reported that Galileo might be opened up for military use – a policy shift that it is suggested would cause a rift between de EC and the UK/US.*
>
> *According to the Independent, the EC Transport Commissioner has suggested that Galileo might have defence applications. The idea could help to recoup some of the financial outlay on the project, the development costs of which have grown by 500 M€. It would also help to boost to develop a larger military capability to backup its foreign policy – and would be welcomed by France (the Transport Commissioner is French)"*

Having satellite and terrestrial systems in operation the question arises whether these systems are used as parts of an integrated user system. What is the most common situation today? The two (three) satellite systems are at the provider site hardly integrated, but we see some progress. However, the user is more interested in integration that the provider, and therefore it will be most unlikely that we will see Galileo-only receivers coming to market. GNSS systems can, with large benefits, be integrated with inertial sensors, a technique widely used in aviation and weapons.

A different result can be observed when integrating GNSS and Loran. From the provider perspective we see integration only with Eurofix, a system that broadcasts DGPS and, for test, also UTC data via the Loran data channel. At the users side integration goes further. Receivers may apply DGPS data, accurate UTC and frequency for the timing group, and finally differential data for eLoran. Deep integration of GPS and Loran pseudo ranges is not yet a generally observed technology.

This lack of integration of GNSS with Loran is amazing. By many, Loran is seen at best as a backup to GNSS, only useful for relatively small user groups in the fields of timing, harbor entrance and approach, and of aviation. We may question whether this is a missed opportunity due to lack of publicity, or lack of public awareness of the risks being dependent on a single system.

What does the public wants Loran to do? It should work in all situations where GNSS signals can not be received and Loran should take over as soon as GNSS becomes jammed. The first condition is not easy to solve by Loran as the new generation of highly sensitive GNSS receivers may still work where Loran itself starts lacking of useful signals. The second case, jammed GNSS, is easier. Jamming

Loran with low power signals is hardly possible over ranges exceeding 10 meters.

Some performance considerations

If one would consider integration of Loran and GNSS signals, should that then be done on basis of integration or selection? Deep integration of both systems is hardly seen today. The form of integration with the highest added value we see today is GPS-calibrated Loran. Loran noise in range trackers is approaching that of GPS code tracking. However, a more challenging issue is the rather unpredictable propagation anomalies encountered in urban areas. That makes integration really a tough job. To demonstrate what GPS and Loran perform on a pseudo range measurement, Dr. Richard van Nee of Delft University developed the following simple formulae for code and carrier tracking:

The noise in the GPS code tracking loop expressed in meters equals:

$$\tau_N = T_c \sqrt{\frac{B_{loop}}{2} \cdot \frac{N_0}{C} \cdot \frac{d}{T_c}} \cdot 3E8 \text{ meters}$$

where

$\tau_N = \text{TOA noise}$

$B_{loop} = \text{tracking loop bandwidth}$

$\frac{C}{N_0} = \text{Carrier-to-Noise ratio}$

$d = \text{correlator spacing}$

$T_c = \text{chip time}$

The noise level in a Loran envelope (code) tracking loop is approximately:

$$\tau_N \approx \frac{10}{\omega} \cdot \sqrt{\frac{B_{loop}}{SNR_i} \cdot \frac{GRI}{8}} \cdot 3E8 \text{ meters}$$

where

$\tau_N = \text{TOA noise}$

$\omega = \text{carrier frequency}$

$B_{loop} = \text{tracking loop bandwidth}$

$SNR_i = \text{Signal-to-Noise ratio}$

$GRI = \text{Group Repetition Interval}$

Let us now go to the performance of carrier tracking. For GPS we find:

$$\tau_N = \frac{1}{\omega} \cdot \sqrt{B_{loop} \cdot \frac{N_0}{C}} \cdot 3E8 \text{ meters}$$

where:

$\tau_N = \text{TOA noise}$

$\omega = \text{carrier frequency}$

$B_{loop} = \text{tracking loop bandwidth}$

$\frac{C}{N_0} = \text{Carrier-to-Noise ratio}$

For Loran we find:

$$\tau_N = \frac{1}{\omega} \cdot \sqrt{\frac{B_{loop}}{SNR_i} \cdot \frac{GRI}{8}} \cdot 3E8 \text{ meters}$$

The values used for GPS are:

$\omega = 2\pi \cdot 1.5 \text{ GHz}$

$d = 1\,\mu\text{sec}$

$T_c = 1\,\mu\text{sec}$

$\frac{C}{N_0} = 30 \text{ dB}$

$B_{loop} = 1/2\pi \text{ Hz}$

and for Loran:

$\omega = 2\pi \cdot 100 \text{ kHz}$

$GRI = 0.08 \text{ msec}$

$SNR_i = 0 \text{ dB}$

$B_{loop} = 1/2\pi \text{ Hz}$

These values are considered as realistic. However, the following conditions were assumed: no GPS multipath, no Loran re-radiation, and finally, perfect Loran transmitters and ASF models. The results are promising for Loran:

	Carrier	Code/Envelope
GPS	0.16 mm	1.07 m
Loran	7.6 m	76 m

With Loran, the ratio of carrier and modulation frequency is approximately 10, so the carrier can be used for range measurements while the risk of possible cycle identification errors remains low. This is not feasible with GPS where this ratio is 15,000 making cycle identification on a single range measurement illusory.

So, we should compare Loran carrier tracking with GPS code tracking. GPS performs better, but we should recognize that Loran is not a continuous system. Just 8 phase samples per GRI can be used for tracking. Taking this into account we see that GPS code and Loran carrier tracking are coming close. Please note that the given calculations are only valid for rather simple tracking loops. Nonetheless, the resulting numbers are still interesting.

In order to really compete with GPS, the tracking noise should significantly be reduced. For stationary receivers this could be established by increasing the integration time in the tracking loop. Increasing the integration time by a factor of 100 will reduce the tracking noise by a factor of 10 dB. In this way we can reliably track signals with a SNR of -20 dB. Unfortunately, this approach will not work when the receiver is moving during the integration time as the received Loran signals will then not be equal in phase which makes the received signals incoherent. The only solution to solve this is to reconstruct the coherence of the received signals during the integration time. This can e.g. be accomplished by estimating the trajectory along the integration time by mechanical sensors. With cars this could be achieved by a yaw-rate sensor and the odometer. It should be noted that next to compensate for movement during the integration time, the propagation conditions should not change either in that period of time. In cities, the largest risk in that respect is variation in re-radiation conditions.

Why worry?

During this decade, studies in the US have shown that eLoran can meet general aviation requirements. Harbor Entrance and Approach performance has been demonstrated in the US and in Europe. Timing control in the US meets the most stringent requirements while studies in the US and Europe show a steady progress in modeling the phenomenon of ASF and its variations. So, why do we still worry about the capabilities of eLoran? The reason is land, the most difficult application of Loran.

Automobile and Loran

This application should be considered as one of the strongest challenges to cope with. The signal environment in a car is flooded with noise made by the ignition, the generator, and a wealth of electronics installed in today's cars. Further, the range measurements may suffer from frequent and large near-field propagation anomalies due to buildings and overhead power lines. So, the utmost performance is needed at places with the poorest signal condition in order to make it feasible to perform map matching correctly. And finally, car dynamics is still a complicating factor.

Luckily, the advances in the field of yaw-rate sensors in respect of performance and cost help to do signal range compensations with high accuracy. Odometers have a proven accuracy once calibrated, which, can be done by map matching or in situations where Loran is beyond any suspicious signal condition. In addition, map matching today is basically a low-cost technology. Detailed street maps of the entire US or Europe can be stored in a 2GB ROM, while the map-matching algorithms do not demand large computer throughputs. Map-matching offers continuous high-performance calibration of the yaw-rate sensor and the odometer. If done properly, the achieved accuracy approaches that of the digital map itself.

Some tests

Tests carried out in The Netherlands gave surprisingly good results with dead-reckoning based on a low-cost yaw-rate sensor and the onboard odometer. In Fig. 1 the true and the estimated tracks are shown. After a test drive of 3.2 km, the accumulated position error was still less than70 meters. Fig. 2 shows the yaw-rate sensor and a linear accelerometer on top of a 1 sq inch GPS patch antenna. These micro electro mechanical systems (MEMS) are master pieces of modern solid state electronics. Fig. 3 shows part of the inside of a MEMS device. The development of devices needed to perform very accurate range measurements continuous. Fig. 4 shows a Cesium atomic clock developed by NIST in the US. This miniature clock measuring not more than 4 mm in height with a floor plan of 1.5 mm square.

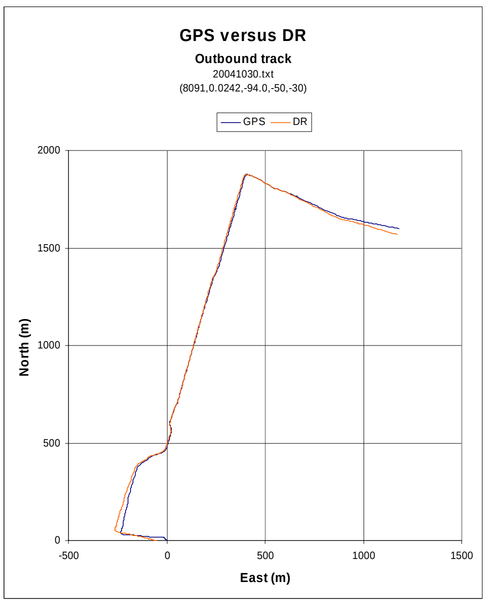

Figure 1 – Estimated and true track of test runs.

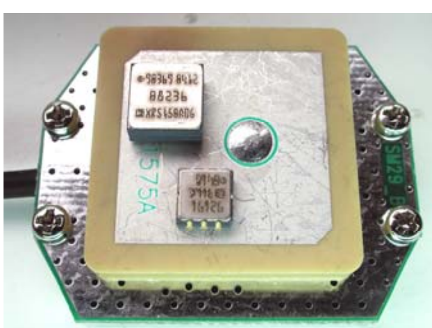

Figure 2 – GPS patch antenna with MEMS yaw-rate linear acceleration sensors.

Just for curiosity we did some tests with standard production car navigation systems, in this case a Carminat in a Renault automobile. It uses a yaw-rate sensor, the odometer, GPS and map matching. First the car has been driving for about 30 minutes to get the yaw-rate sensor and odometer accurately calibrated. Then the GPS was disabled simply by generating a 100 µW jammer signal. It took a 100 km to return to the garage at home. No errors were made during this GPS-less trip which proofs the power of integrating yaw-rate sensor, odometer and map matching. When the car was parked underground the initialization when leaving was correct as the position and the heading were stored in memory. The next test was driving the car along a road not present in the digital database and with GPS disabled once more. The dead reckoning was still satisfactory. After driving about 10 km, the position error remained less than 200 m, or less than 2 %.

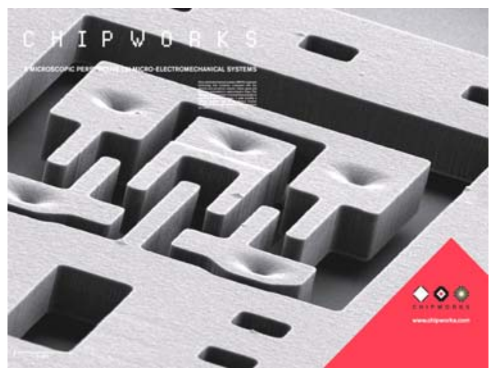

Figure 3 – Inside of a MEMS yaw-rate sensor.

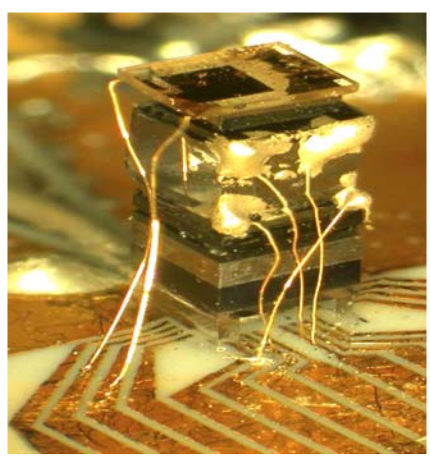

Figure 4 – Chip-scale atomic Cs clock as developed by NIST.

The verdict on radionavigation?

From the foregoing we can come to some challenging conclusions:

1. The combination of odometer, yaw-rate sensor and map matching makes radio position determination nearly superfluous. Mutual calibration of the sensors makes this team nearly unbeatable.
2. Radio position determination is only needed to initialize the map-matching process. The system must know where the trip starts. However, the last position and car heading are stored while parked. So, when correctly initialized, the position determination is degraded to a process monitoring device.

So, we may now come to another important question. Is in a car, equipped with an integrated navigation system, the radio position determination part a primary or a secondary system?

During the navigation process initialization the GPS or eLoran part is primary. After that the map matcher makes it secondary. Calibration is also done by map matching. In case no map matching is incorporated, radio position determination is required to calibrate the mechanical sensors.

However, calibrating these sensors by radio systems is rather error prone if the integrity of the latter one is questionable. This is not a trivial issue while driving in areas where large fluctuations in 100 kHz propagation might be experienced. Fig. 5 gives the basic block diagram of a system as discussed above. If GPS becomes unavailable, Loran can take over. It is a challenging task to accurately define the required Loran performance parameter values. It depends on propagation, the correctness of the digital maps, the fineness of the road network, and stability of the mechanical sensor calibration and so on.

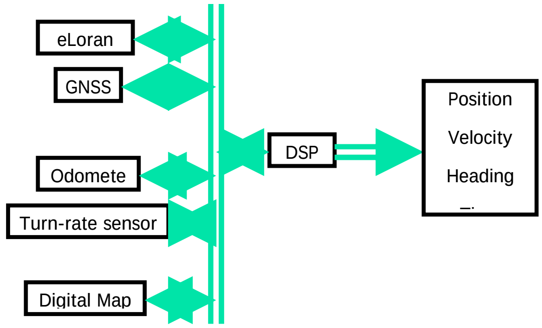

Figure 5 – B asic car navigation concept.

In conclusion we can identify some potential pitfalls:

1. Relatively small radio position errors needed with a high integrity level,
2. Calibration of mechanical sensors only allowed when radio position is unquestionably correct,
3. Radio position determination in urban areas filled with power lines and large buildings.

Although these requirements are generally speaking more difficult to meet with eLoran than with GPS, current eLoran is expected to meet this.

The ultimate challenge: Pedestrians

Pedestrian position determination is the maybe the most challenging application of eLoran one can imagine. Considering that pedestrians do walk in inner city areas, the propagation conditions can be said to be extreme while at the same time the required accuracy is very high. To make situations even worse, the antenna of a walking person can be at any attitude, especially with children. The poor signal conditions can hardly be tracked with long-integrating tracking loops as the dynamics are unpredictable. This makes inertial aiding a necessity. Further, volume restrictions to the antenna and low-level signal conditions brings the designer in an conflicting situation as high sensitivity requires more power for the antenna amplifiers which challenges small volume designs. The elegant escape of map-matching is now useless as pedestrians are not tied to roads at all.

In conclusion, the only solution with good prospects is to use a miniaturized

3-dimensional antenna in conjunction with a 3-dimensional inertial support to enable long integration times to counteract low SNRs. This is a challenging task. However, if the pedestrian has only eLoran available, then this is the way to go. This may sound somewhat pessimistic today, but the progress made in MEMS inertial systems and complex signal processing is impressive. So, the author expects that in the next decade, this approach may be very realistically applicable.

Challenges and Conclusions

Integration of Loran and inertial systems is a promising solution to achieve excellent availability with good accuracy. However, in order to achieve that improvement, one must be sure about the integrity of both systems. In other words, it means that aiding Loran with inertials makes only sense when an improvement can be obtained. This holds for aiding Loran to calibrate the inertial system as well. In the open field far away from re-radiating obstacles good Loran integrity is achievable. So far, there is still little experience with integrity analysis in harsh radiation environments like near power lines and large conductive objects as buildings and bridges.

The next question is whether what the role of Loran will be with ever increasing performance of MEMS inertials. Loran will then be pushed more and more to the background where its main task will be to give the starting position and heading of a vehicle, and to calibrate the odometer and inertials. Today, we have reached that situation with GPS aided car-navigation. The star role is given to the odometer, the yaw-rate sensor, and to some extent to GPS.

The author does see this as a logical step forward in navigation. If applied correctly, integrated navigation is an efficient and a very powerful solution which the human beings use since the creation of our planet.