GNSS and eLoran cooperate to the benefit of both.

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BIOGRAPHY

Philip G Mattos gained Bachelors and Masters degrees in Electronic Engineering from Cambridge, followed by Masters Degrees in Telecoms and Computer Science from Essex in 1977. He joined INMOS in 1979. INMOS was acquired by STMicroelectronics in 1989. He was made a Visiting Research Fellow at Bristol University, and awarded an external PhD on his GPS work in 1996.

Since 1989 he has worked exclusively on GPS implementations, and the associated RF front ends. He is now working on system level integrations of GPS, and on the Galileo system, while consulting on the next generation GNSS chips, including one-chip GPS (RF+digital), and high sensitivity GPS and Galileo for indoor applications, and combined GPS/Galileo/Glonass chipsets.

INTRODUCTION

The two systems can benefit each-other in four ways…Indoor Sensitivity, Accuracy, Integrity, and Availability. The high performance CPU and TCXO of the GNSS receiver complement the simple low-cost RF of the LORAN receiver and calibrate its lesser accuracy, in exchange for signal and timing availability inside buildings and tunnels.

INDOOR SENSITIVITY

GNSS systems suffer from severe signal attenuation indoors as their 1.5GHz frequencies do not pass well through construction materials. Now that self-assisted ephemeris prediction algorithms have removed the data-download threshold, it is the acquisition threshold that limits performance.

The acquisition sensitivity can be improved if the GNSS receiver has a good estimate of time and frequency. While precise time assistance has been specified at 10microseconds accuracy, it has never become widely available from the networks, and we are targeting stand-alone receivers, not network-attached.

An eLORAN system provides precise time, achievable at the 50ns level professionally, but economically achievable even at an estimated position to much better than 100 microseconds.

Time to a few microseconds, with an estimated position, allows the GNSS receiver to limit its time domain search. The search is one(GPS) to four(Galileo) milliseconds, so reduction to 100 microseconds even is a major performance improvement. On fully parallel correlators, this saves no time, just enhances sensitivity as there is only one tenth (one fortieth) the probability of some high noise correlation falling inside the search window. On more configurable correlator systems, the fully parallel search is no longer needed, so the correlator resources can be used elsewhere.

LORAN can also be used for frequency aiding. While indoor sensitive GNSS receivers have TCXO’s with 0.5ppm accuracy, this represents a frequency search space of 1500Hz. Monitoring the LORAN signal for just a few seconds allows the reference clock to be calibrated to a much tighter level, increasing the performance 5x, which can be used either for faster response, or for higher sensitivity if integration times are extended compatible with more precise frequency knowledge.

ACCURACY

LORAN as a standalone system suffers from kilometre sized errors due to the varying speed of transmission over ground/sea surfaces. Some of these are static and known, and available in ASF tables, but others are time-varying, especially due to changing ground conductivity by season, or by rain/snow. The granularity of the tables is also a problem, where a path is along the edge of a bay, a very small movement can change an all sea path to an all land path, changing the correction considerably.

In the combined receiver, the Loran path delays can be calibrated continuously, so that when GNSS is lost, the last LORAN calibrations can be used to maintain the accuracy. This can be done on a single shot basis as described, or alternatively a grid can be stored to allow for more significant user movements. Each grid location would need two values, the correction and a timestamp, with the timestamp being used to modify the confidence.

After any loss of LORAN that does not affect GNSS, for example electrical interference, GNSS can also greatly assist LORAN with precise time and position, allowing LORAN to recover faster, and at lower SNR, than in a stand-alone receiver

INTEGRITY

While most problems affecting GNSS or LORAN result in the particular system failing to deliver a position, there is a further class that results in them delivering a position, but one that is erroneous. These include deliberate spoofing, accidental spoofing (eg re-radiators) and jammers that are misinterpreted as satellites temporarily.

RAIM techniques will frequently isolate these problems, but cannot when the solution is determinate rather than over-determined, as frequently occurs due to obstruction in urban canyons and indoors. Running both GNSS and LORAN in parallel allows continuous comparison of the two results. This applies not only at the position level, but also at the measurement level. 5 satellites allows GPS/GNSS to identify that there is a problem, so it can declare no-fix, but it cannot isolate the grossly erroneous signal that it believes to be a satellite but may not be. Combined with a LORAN position, even if itself of limited (eg 100 metres) accuracy, the receiver can isolate the erroneous satellite measurement.

AVAILABILITY

This is the obvious advantage… GNSS signals are frequently lost in obstructed environments. GPS can be maliciously jammed over a wide area due to its very low signal strength. LORAN suffers from neither of these problems. In addition to gross go/no-go availability, the combined system has greater availability also because every interruption is reduced in duration, because with time aiding the GNSS system can start so much faster or with a significantly weaker signal.

IMPLEMENTATION

Adding LORAN/eLORAN to a GNSS design is very simple. It needs only the 100kHz RF subsystem, feeding its output into the existing CPU or DSP.

A demonstration version has been created using a single quad op-amp chip with four LC pairs to define the band-pass filtering. The interface to the baseband can be a single wire connecting to an extended function timer in the baseband to work in the time domain, or alternatively an analogue signal connecting to an ADC in the baseband, allowing sophisticated notch filters to be implemented in software.

The time domain approach is recommended when only time assistance is needed from the LORAN, as the CPU load is then very small.

If the full integrity and availability advantages are required, then the analogue–ADC approach is recommended, needing a 400kHz sample rate and considerable dsp processing.

A laboratory prototype of the time-domain implementation is shown in Figure 1. It is a single quad CMOS op-amp chip, each stage configured with an LC tuned circuit at its input. The stages are non inverting to maintain a high input impedance, and each LC is driven from the previous stage through a series resistor that defines the Q, to achieve the necessary bandwidth.

The prototype board is 5cm x 4cm including power supplies. It is laid out to accept both large and small inductors and capacitors, hence the open space. In a production environment it would be less than 3x2cm of single sided board space.

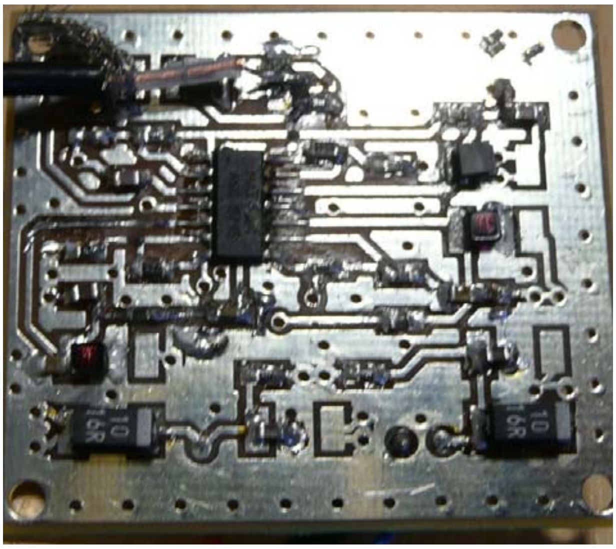

Figure (1) Simple LORAN 100kHz RF section

Some traces of the output waveforms from the simple 100kHz radio are shown below. The first (figure 2) shows the pulse transmission from a master station, being eight pulses at one millisecond spacing, then a ninth pulse two milliseconds later.

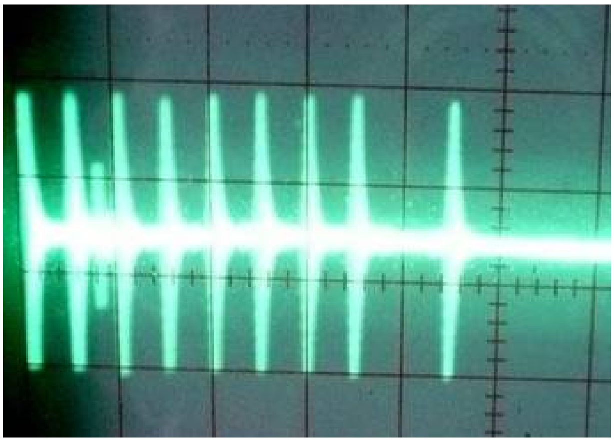

Figure (2) Master pulse group

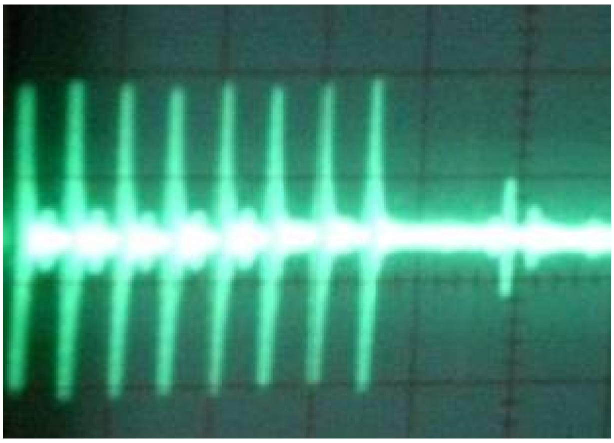

Figure (3) Slave pulse group

The second (figure 3) shows the transmission from a slave station, being simply eight pulses at one millisecond separation.

Each pulse has a rapid rate of growth of the envelope, with a slower decay as shown below. While all the energy is used to lock on to the signal, only the phase information in the first three cycles of the 100KHz carrier is used to calculate delays, and hence positions, as this is the direct path (ground wave), while later cycles may have been corrupted by signal reflected or refracted from the ionosphere.

The rapid rate of envelope growth means the signal has a wide bandwidth, and in order to detect the first few cycles the receiver filters must be similarly wide. The response is shown on a spectrum analyser below the burst.

The burst itself is made up of individual 10uS carrier cycles, but as the bursts are coded with a pseudorandom phase (positive or inverted), the cycles are not distinct on the analogue scope screen.

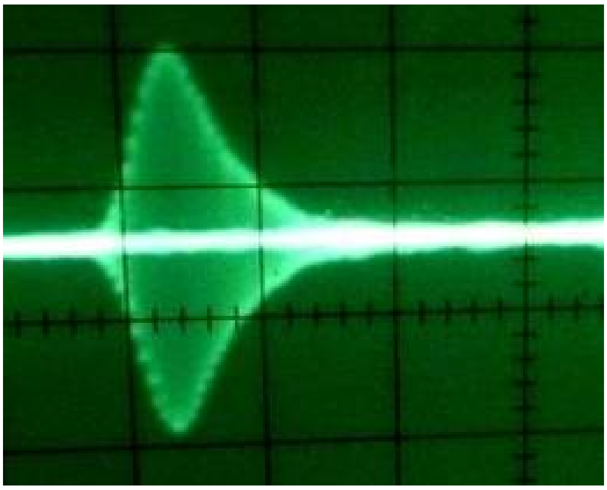

Figure (4) Single burst of carrier cycles

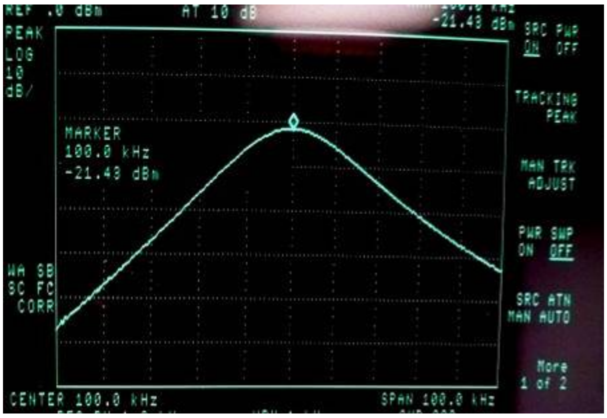

Figure (5) Response of LORAN Receiver RF

The green scope traces were taken in a country environment with an analogue scope during daylight, ie no electronic lighting.

Below are shown plots of the interference in the city office environment. The general background noise is the multiplicity of high-efficiency lights, then the spike every 20 milliseconds is the 50Hz mains electricity through electronic switchers.

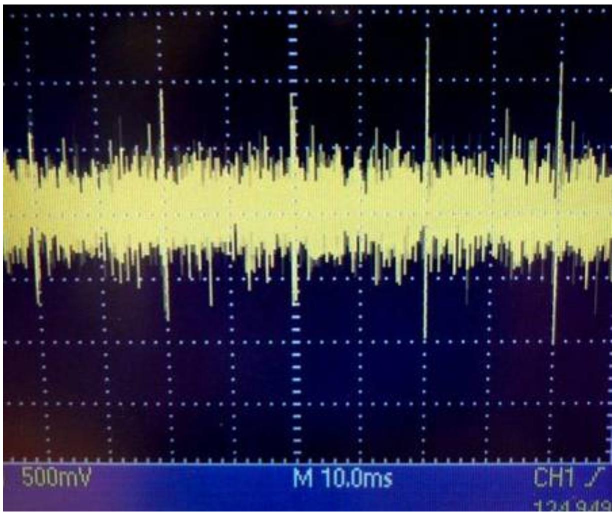

Figure (6) 20ms Interference spikes from 50Hz mains switching

Synchronising the scope at a much faster rate shows another source of interference at a 750uS rate…..this is the LCD screen of the ‘scope itself… a real illustration of Heisenberg’s principle….if you look at something you change it !

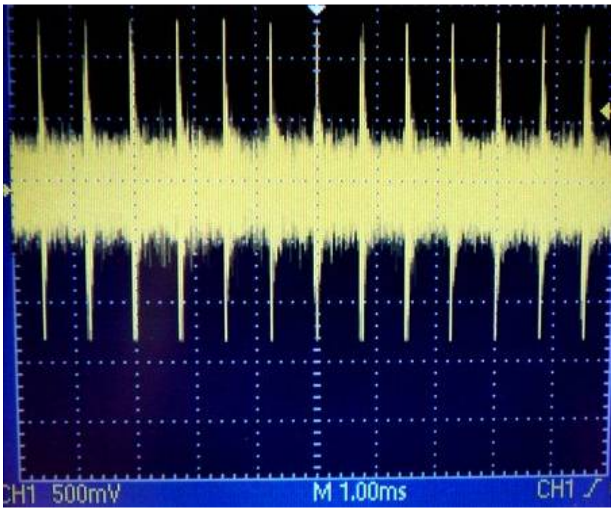

Figure (7) 750microsecond interference spikes from ‘scope LCD screen drivers

However the software processing of the signal is able to extract it from well below the noise. The scope was unable to show the LORAN signal in the office environment, because the display trigger was always fired by the interference, not the signal.

In the software controlled receiver, a minimum of 16 bursts of carrier are integrated together, compensating for the +/- phase coding, before the energy is assessed as being signal or interference, then about 6 cycles of carrier are used to assess the timing, making 96 cycles in all. The oscilloscope must make an instant decision to trigger or not on a single cycle.

COVERAGE AREA

While LORAN originates from the marine environment, illustrated by the coastal location of all the transmitters shown in the tables and maps below, the 6731 chain covers the land areas of the UK, France, Benelux, Germany very well, and if eLoran is adopted as the aviation backup to GNSS, it is expected that the Mediterranean chain, currently not operational, will be re-activated.

North America is fully covered, both coast and inland, as is Japan, Korea etc, and the Russian Chayka system is sufficiently similar that the same receiver can be used.

Figure (8) Operating European Loran stations

All the currently operating transmitters in Europe are shown in figure(8), while figure(9) shows the 6731 chain useful for most of Europe, also listed in table (1)

Lessay	6731M	49,14867 N	1,50473 W
Soustons	6731X	43,73975 N	1,38044 W
Anthorn	6731Y	54,91083 N	3,28717 W
Sylt	6731Z	54,80833 N	8,29357 E

Table (1) 6731 chain transmitters

Figure(9) 6731 chain covers much of Europe’s land area

Geometrical problems make the use of a transmitter when on a baseline extension very inaccurate… no problem for timing use, but not for positioning.

For this reason Scotland, Ireland, Northern Germany and Poland would use the 7499 chain shown in Table (2)

Sylt	7499M	54,80833 N	8,29357 E
Lessay	7499X	49,14867 N	1,50473 W
Vaerlandet	7499Y	61,29707 N	4,69628 E

Table (2) 7499 chain transmitters

Northern areas of Norway, Sweden and Finland would use the 7001 chain shown in Table (3)

Bo	7001M	68,63506 N	14,46315 E
Jan Mayen	7001X	70,9143 N	8,73237 W
Berlevag	7001Y	70,84528 N	29,20444 E

Table (3) 7001 chain transmitters

The signal waveforms captured by the receiver under test and shown in this paper were measured near Bristol, UK (Red pin in Figure 10). They came from Lessay in Northern France, Anthorn in the UK Lake District, and Sylt in Northern Germany, with ranges of 270km, 375km, 516km respectively

Figure(10) Ranges to transmitters as tested.

They can be identified in the plots as the strong master signal, the strong slave signal, and the weak slave signal respectively. The weak slave can be seen under the strong slave in figure (3). Obviously it would not normally be under another slave, the emission delays being arranged to avoid this. However as some stations are dual rated, the normal collisions of independent chains can occur.

SIGNAL REQUIREMENTS.

The initial purpose of this project was to augment the GNSS sensitivity by giving the indoor GNSS receiver a precise idea of time.

This occurs on several levels.

An accuracy of 2 milliseconds allows the Galileo receiver to identify a particular secondary code chip, and this wipe-off the secondary code and operate with arbitrarily long coherent integration times for extreme sensitivity.

An accuracy of 0.5 milliseconds allows a GPS receiver to correctly locate the 20 millisecond data-bit edges, and thus integrate coherently for 20 millisecond periods synchronous with the data-bits.

An accuracy of 100 microseconds makes it worthwhile to reduce the codephase search window, so rather than 2046 possibilities(GPS), we need only search 200, with the benefit of both statistical gain(there is less likely to be a noise spike in 200 than in 2000), and TTFF benefit of a smaller search, which can be traded for further sensitivity.

If the position is adequately estimated, only one LORAN signal is required to give the time aiding. However the inaccuracy grows at the speed of light, so to get 100 microseconds accuracy we need a position estimate much better than 3km. However the millisecond requirements can be met for an entire city area.

There are two reasons why we may use more LORAN signals when available. One is to get a position estimate, which makes our time estimate perfect, and can also be used to keep the GNSS receiver searching for local satellites…..and not timing-out and searching over the whole world… and the estimate can also –in extremis- be delivered to the customer, as long as its accuracy is suitable noted.

Another is in the leadup to eLORAN, when most transmitters are still old fashioned LORAN with no data on it express the time. Then the time has ambiguity of +/- one repetition interval. This can be resolved by listening to two signals (even if from the same mast) which operate on different rates.

The combined information from the two rates gives a beat interval, and hence ambiguity, of about 15 minutes, which the watch crystal based real time clock in the GNSS receiver can easily resolve

FURTHER WORK

The availability and size of the LORAN antenna for handheld devices and phones, and the problem of manmade electrical interference are problematical. H-field antennas can give a good signal, and eliminate much of the electrical interference. Local electrical interference is a major problem. Previously it was generally from fluorescent tubes and neon signs driven from the mains. Now CRTs and LCD screens and lighting systems use electronic drivers in the 50kHz range and upwards.

All the signal plots in this paper were derived from an E-field whip antenna between 2ft and 5ft in length as used in the standard marine LORAN environment. Clearly any handheld device will need a much smaller H-field version.

Further measurements are needed in the road environment to investigate interference from traffic detector loops.

The accuracy of the LORAN-only position must be investigated in cities and in buildings, although only planned in this equipment to be used to assist the GNSS. Marine e-LORAN accuracies can be achieved at any open site using conventional LORAN after calibration in this dual GNSS/LORAN equipment. The Marine e-LORAN accuracy test results can be found in [1].

OTHER STUDIES.

Other authors have presented useful material that supports this application. Figure 11 shows a chart from Offermans(Elsis trial) [2] giving positioning coverage over mainland Europe

The green area shows viable positioning, while the circles show signal availability at different signal strengths for specific transmitters. Thus for Western Europe only Spain, Portugal and Italy are not covered for positioning, but time aiding is possible in the Northern part of Italy. Turin and Milan receive sufficient transmitters for positioning, but suffer poor accuracy due to geometry (DOP)

Note that the move of the UK transmitter from Rugby to Anthorn probably removes the green positioning coverage from Northern Spain and the Pyrenees.

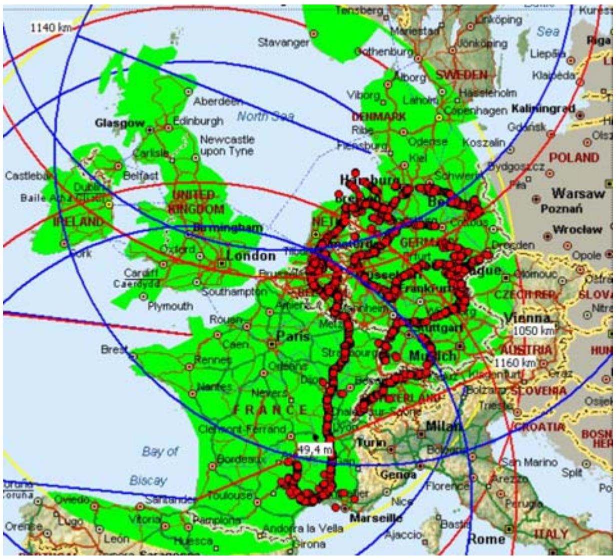

Figure (11) LORAN coverage 2006 from [2]

CONCLUSIONS

It has been shown that a single chip analogue Rf front end (a general purpose quad op-amp) can be added to a GNSS receiver to give it LORAN capabilities. It has been shown that those LORAN capabilities include precise time even inside buildings, and that the precise time availability can greatly increase the sensitivity of the GNSS receiver, allowing it too to operate inside most buildings.

While applicable also to GPS, it is particularly useful for Galileo, as it allows the secondary code to be removed from the E1-C pilot signal, making it a true pilot with very high sensitivity.

REFERENCES

[1]*Harwich e-LORAN test results*, Paul Williams, Sally Basker, Trinity House/GLA

[2]*E-loran, partner of GNSS*, Gerard Offermans, Navconf 2007, Nordic Institute of Navigation.