LORAN for vehicle and pedestrian tracking: a viable back-up to GPS?

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BIographies

Martin Brock is an applied physicist who has developed a wide range of electromagnetic, optical and radio sensor technologies. In recent years Martin has taken particular interest in non-GPS location technologies, principally for government or specialist commercial applications. He has worked on systems which range from providing indoor coverage with 30cm accuracy using ultra-wideband signals to others which provide nationwide coverage with networks of beacons.

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Geoff Smithson is the Group Leader of the Sensing Systems Group within Cambridge Consultants. The focus of the work undertaken by the group is the development of complete sensing systems for a wide range of applications and markets. This includes consideration of all aspects of system design, hardware development, mathematical analysis, algorithm development and software.

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abstract

This paper studies the achievable performance of LORAN for land-based applications, and in particular for vehicle and pedestrian tracking in the UK. The sources of error in LORAN measurements are first reviewed. Two sources of error are likely to dominate in urban environments: man-made noise from electrical equipment and variable, position-dependent shifts in the arrival time of the LORAN signal as result of re-radiation by conducting structures.

Potential methods for compensating the LORAN ASF are reviewed, but many have drawbacks for a vehicle or pedestrian tracking application. We present a novel, hybrid method which combines a coarse ASF survey or model with real-time ASF and re-radiation compensation using a Bayesian particle filter to provide map-matching.

LORAN measurements have been made with a pre-production CrossRate eLGPS1110 combined GPS/eLORAN receiver in a variety of UK environments. ASF compensation using both a simple coarse-survey method and the hybrid map-matching scheme are then tested by comparing them with a modern high-sensitivity GPS receiver.

The simple coarse-survey method achieves r.m.s. errors between 50m and 150m depending on the environment. Initial results from a test of the particle filtering method show that improvements of around 20% (in real time) to 30% (off-line post-processing) in r.m.s. errors are possible. Significant further improvements in the accuracy of this technique are likely to be possible in future.

introduction

Over the past 20 years, GPS has seen widespread adoption for military, commercial and personal navigation. Indeed the cost and performance of GPS is now such that it is the system of first choice for nearly all location and navigation problems. However, as GPS has become ubiquitous, concern over its limitations has also increased. In particular, GPS signals are weak and prone to interference - whether accidental or deliberate, and GPS has a single point of control, and hence, potentially, a single point of failure.

Although considerably older and less precise than GPS, the nature of the LORAN navigation system makes its likely failure modes highly independent of GPS: it is ground-based, operates with high transmit powers, and uses a completely different frequency band. The past decade has thus seen increasing interest in whether LORAN could be enhanced to provide a viable back-up to GPS. Much of the interest in this area has focused on marine and airborne applications; in particular harbour approach and aircraft landing.

While GPS alone is likely to offer sufficient reliability for the vast majority of terrestrial applications (for example consumer vehicle navigation), certain applications may benefit from higher integrity. For example, given the ease with which GPS jamming
equipment can be purchased, a tracking system for recovering stolen vehicles would do well to avoid relying solely on GPS. Similarly, a navigation system intended for safety-related applications (for example in an ambulance or fire engine) would benefit from a means to detect and mitigate the failure of GPS to provide accurate information.

This paper studies whether and how LORAN could be utilised for such purposes. Although our work has focused on the UK, it is likely to be relevant to other regions with comparable LORAN coverage, terrain and structures. We have also focused on situations in which the receiver’s motion is normally very likely to follow roads or known linear routes. This assumption holds in the vast majority of vehicle and pedestrian tracking scenarios, and by making use of it we can introduce significant improvements to the resulting positioning accuracy. Under this assumption, tracking will be most difficult in areas with a high density of roads (i.e. cities) and we have thus concentrated on measurements in these areas.

The remainder of this paper first reviews the accuracy achievable using conventional LORAN positioning techniques. An improved technique which makes use of knowledge of road positions is then presented. This is followed by results of measured LORAN performance in urban areas, including the use of this improved positioning technique.

ACHIEVABLE ACCURACY OF LORAN

The details of the LORAN system and its propagation are covered in-depth elsewhere (Pelgrum 2006; Samaddar, 1979). In summary, however, obtaining an accurate position using LORAN requires three things: accurate measurement of the arrival times of signals from at least three transmitters; accurate conversion of time-differences into distance-differences; and that the geometry of the transmitters produces reasonably orthogonal intersection between the resulting hyperbolic lines-of-position. Since the commissioning of the Anthorn transmitter by the UK’s GLA in 2007, the last of these points is now met almost everywhere in the UK. Positioning accuracy will thus depend only on accurate arrival time measurement and accurate time-to-distance conversion.

Arrival time measurement

The accuracy with which the arrival time of a LORAN signal can be measured will depend on the received signal-to-noise ratio (SNR), observation time and the receiver implementation. In the LORAN frequency band, the dominant noise sources are atmospheric noise from electrical storms and man-made noise from, for example switch-mode power supplies, spark ignition systems and fluorescent lighting. Although atmospheric noise varies with time-of-day and time-of-year, in a typical urban UK environment, man-made noise is likely to dominate (ITU, 2003). At distances of 500-1000km from a 250kW transmitter, SNRs of around 0 to +10dB are likely.

For vehicle navigation applications, an update rate of around 1Hz is likely to be required. A lower rate is likely to be suitable for pedestrian applications, and these are thus likely to be less demanding, at least from an SNR standpoint. Allowing for the pulsed nature of a LORAN signal, a total effective observation time of around 1ms is possible for each measurement at a 1Hz rate. A Cramer-Rao lower bound on the standard deviation of arrival-time differences can then be established (Hult, 2004) as being between 60ns (for 10dB SNR) and 200ns (for 0dB SNR). With ideal transmitter geometry this would result in a position error of between 18m and 60m (r.m.s.). This is a mathematical construct and does not take account of receiver design limitations; real receivers will probably perform at least a little worse than this.

Time to distance conversion

Conversion of arrival-time-differences into distance-differences requires the effective propagation velocity to be known. The nature of ground-wave propagation means that the LORAN signal travels at a velocity which is slightly less than the speed of light by a variable amount which depends on the environment between the transmitter and receiver. Typically, the true propagation velocity is arrived at by considering three factors:

1. The primary factor (PF), which simply accounts for propagation at a uniform velocity in the earth’s atmosphere (rather than in vacuum).
2. The secondary factor (SF) which is a non-linear (i.e. distance-dependent) velocity correction taking into account propagation over an all-seawater path.
3. The additional secondary factor (ASF) which accounts for the additional delay due to any overland-component of the propagation path.

The PF and SF can easily be computed for any location. However, accurate positioning requires the ASFs to be computed. If only the PF and SF are used for a position estimate then the failure to account for the ASF will result in delay errors of order 2-5µs (Williams, 2000), corresponding to position errors of order 1km. Computing ASFs is not straightforward since they are affected by several factors including:

- Variations in ground conductivity: the LORAN signal will propagate more quickly over fertile farmland than rocky or sandy ground.

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1 We will here ignore the rho-rho mode of operation which uses only two transmitters but requires a precise local clock.

2 This assumes that each pulse is observed for a single cycle (10µs) and around 100 pulses are then integrated (GRI of order 80ns and 8 pulses per GRI). A longer per-pulse observation time is possible, but at the potential expense of greater sensitivity to skywave effects.
• Variations in elevation: the LORAN signal will tend to ‘stick’ to the ground and thus travel a longer path than the expected point-to-point distance.

• Seasonal variations in ground temperature and conductivity. These can be particularly dramatic in continental regions where lakes freeze in winter.

Several approaches have previously been taken to compensate for ASFs, each with their limitations. Possible methods include:

• Surveying - the US National Oceanic and Atmospheric Administration has surveyed the maritime areas covered by the US LORAN chains and published charts which include ASF corrections sufficient to meet the US Coast Guard’s requirement for 0.25 nautical mile (463m) 2DRMS accuracy. This, however, is an expensive and time consuming approach.

• Modelling - several models for ASF compensation have been developed; the best studied of these is probably the BALOR model developed at the University of Wales, UK (Williams, 2000), which uses high-resolution terrain and conductivity data to model ASFs. This model shows promising performance, especially when the residual biases were corrected using experimental data.

• Real-time compensation - for example using a GPS receiver. In this method a second source of positioning information is used to dynamically compute the ASF. Should this second source fail, the stored ASF can then be used to provide accurate positioning, providing the receiver does not move sufficiently far for the ASF to be invalid.

Furthermore, even if the ASF can be accurately determined, there will still be local perturbations in the measured arrival time of a LORAN signal due to nearby conducting objects. Any non-earthed conducting object will absorb some of the LORAN signal and re-radiate it. This multi-path propagation will perturb the LORAN wave-front in the vicinity of the conductive object, advancing or retarding the measured phase of the signal. To a receiver, this effect thus appears identical to an incompletely compensated ASF. The effect is most pronounced for objects with sizes which are an appreciable fraction of the LORAN wavelength - i.e. those longer than about 100m - for example tall buildings and power lines. Previous studies have indicated that errors of order 100m may result from these factors (Pelgrum, 2006, pp. 233-240).

AN IMPROVED METHOD FOR ASF AND RE-RADIATION COMPENSATION

In this paper we present what we believe is a novel method of compensating for ASFs and the local effects of re-radiation. This is essentially a hybrid of surveying and real time compensation. A coarse survey (for example, around 1000 points covering the entire UK) is used for initial ASF compensation. In principle, a model such as BALOR could also be used to provide these compensation points. Finer grained compensation is then performed in real time by using a map-matching algorithm which makes use of the prior knowledge that vehicles are constrained to follow roads.

This method thus has relatively simple surveying requirements yet has the potential to compensate for even fine-grained arrival-time perturbations. It also places no reliance on GPS, although GPS may prove useful in the initial coarse survey stage. It does, however, only work when the object being tracked is wholly or mainly constrained to follow known paths.

The map-matching algorithm at the core of this ASF compensation is based on particle filtering. For a full description of this powerful Bayesian technique see (Doucet, 2008). In summary, however, the filtering process works as follows.

Rather than attempting to directly track the true position of a vehicle, a large number, \(N\) (=2000 in the current work) of virtual particles are tracked. These particles are constrained to follow the road network.

Initially, the particles are placed on roads near to the first measurement point, with the range of positions chosen according to the size and distribution of the measurement error. Alternatively, if the starting position is known, all particles can be started from this position.

Each particle is assigned a starting velocity. In our current implementation, all particles are assumed to be initially at rest. Each particle is also assigned a weight, which can be considered as the current degree of confidence in that particle’s position. Initially all weights are set to be equal.

The following steps are then performed for each subsequent position measurement:

1. The positions of the particles are first propagated by updating their positions based on their velocity and a small random acceleration consistent with the dynamics of a road vehicle.

2. A LORAN position is obtained using coarse ASF compensation based on a weighted average of the measured ASFs at the nearest survey locations.

3. Each particle’s weight is multiplied by a factor proportional to the probability of the particle being in its current location given the current measured LORAN position and expected position error. Thus particles which are further from the measured position have their weights lowered while those which are closer receive raised weights.

4. After a number of iterations, a large number of particles will have weights close to zero, reflecting the fact that their positions are highly inconsistent
with the previous sequence of measurements. When this happens, the particles are re-sampled using Importance Resampling: \( N \) new particles are created in positions distributed according to the weights of the old particles. Most old particles with a low weight are thus culled, while those with high weights are duplicated.

At each iteration, an estimate for current position can be obtained by averaging the positions of the particles according to their weights. Alternatively, positioning can be delayed until a number of future measurements have been received (a process often referred to as ‘smoothing’ rather than ‘filtering’). This provides enhanced accuracy, since particles can be eliminated not only based on their history but also based on their future behaviour. It has the disadvantage of introducing delay into the reporting of a position. In certain applications (for example determining the route taken by a stolen vehicle) this may, however, be a worthwhile compromise.

RESULTS AND DISCUSSION

Data collection was performed using the pre-production CrossRate eLPGS 1110 illustrated in Figure 1 below. This unit incorporates a DSP-based LORAN receiver using dual H-field antennas and a modern GPS receiver based on the SiRFstarIII chipset. Three principal areas were investigated using this receiver: the stability of LORAN measurements at a fixed site; the influence of local conductive structures on ASFs; and the performance of a vehicle-mounted LORAN receiver in a range of environments. Finally, the performance of the particle-filtering algorithm discussed above was studied.

Figure 1. CrossRate eLPGS 1110 LORAN receiver.

Measurement stability

Measurement stability was investigated with the LORAN receiver mounted in a fixed, roof-top location in suburban Cambridge, UK. Measurements of reported LORAN position without any ASF compensation were made at regular intervals over a six week period. Stability over both short-term (minutes-hours) and long-term (days-weeks) periods was investigated. Received SNRs for the three stations used to produce the LORAN position fix (NELS Lessay, Sylt and Anthorn stations), are typically between 0 and +10dB.

Figure 2 below shows typical results for measurements over a 1 hour period at a 1Hz measurement rate. The r.m.s., 95% and 99% errors are 26m, 47m and 67m, respectively. This corresponds well with the 18-60m r.m.s. error range expected from the Cramer Rao bound discussed above. Note that with additional integration (and a corresponding slower measurement update rate) lower errors would be expected. For example, given the near-Gaussian nature of the errors, a 5s update rate would give a 95% error of order 25m.

Figure 2. Short-term LORAN position errors - 1 hour of data at 1Hz update rate.

Figure 3 below shows the trends in measured arrival time difference between two pairs of stations in the 6731 NELS LORAN chain (Lessay-Sylt and Lessay-Anthorn) over a period of six weeks. The total variation - presumably due to ground conductivity changes - is around 0.2\( \mu \)s. This corresponds to a typical long term measurement repeatability of order 50m.

Figure 3. Variation in ASF differences over six week period.

Influence of local conductive structures

To investigate the influence of re-radiation from conductive structures in a controlled fashion, measurements of local arrival-time variations were made in a rural environment crossed by two parallel
high-voltage transmission lines (one carrying 2x400 kV circuits carried on ~60m high pylons; the other carrying 2x132kV on ~30m high pylons).

Figure 4 below plots the apparent differential ASF (i.e. that reported by the LORAN receiver, rather than the true ASF in the absence of re-radiation) for two pairs of LORAN stations while driving under these power lines three times.

These results show that the measured ASF shifts by several microseconds due to the effect of re-radiation from conductive structures. However, the effect rapidly diminishes with distance and is negligible more than 50-100m away. In addition, the effect is dependent on the geometry of the transmitters, re-radiating structure and receiver. This is not surprising since in certain directions, the re-radiated signal will be in phase with the original signal and will thus not result in a net ASF shift. Furthermore, LORAN positions are determined by differential ASFs, and the symmetry of a particular situation may result in there being no net differential ASF shift. In total, however, in an urban environment with many conductive structures, local position errors of several hundred metres should be expected.

LORAN performance on moving vehicle

The performance of the LORAN receiver has been studied in three representative environments: a mixed suburban and rural environment around Cambridge, UK; a dense urban environment in London, UK; and a very dense, high-rise district in Canary Wharf, London. In the Cambridge area, buildings are typical two storeys high and widely spaced; in central London buildings are continuous along roads and 4-8 storeys high; in Canary Wharf building heights range from around 100 to 235m forming deep urban canyons.

Figure 5, Figure 6, and Figure 7 below show typical LORAN performance in these three environments. Each figure, however, only presents a small fraction of the total data set which comprises around 10 hours of data. Measurements from the LORAN receiver are at a 1Hz update rate without any dynamic (e.g. Kalman) filtering. Good LORAN signals from at least three transmitters (NELS Lessay, Sylt and Anthorn) could be received in all locations with SNRs for the various transmitters typically +5 to +15dB around Cambridge and -5 to +10dB in London. ASF compensation has been performed using calibration measurements at points on a very coarse grid (three points cover the 40x90km survey region).

GPS performance is generally excellent except in the Docklands region, where significant errors occur (see Figure 7). A manual interpolation method has thus been used to provide truth data for this region. Elsewhere, GPS has been assumed to provide a reliable measure of true position: empirical measurements suggest that outside of Docklands, GPS errors are less than 10m and typically around 3m.

Figure 5. LORAN performance in suburban Cambridge. GPS position is indistinguishable from true position.

Figure 6. LORAN performance in central London. GPS position is indistinguishable from true position.
The results above show that LORAN achieves reasonable performance in all but the most challenging of urban environments. To give a more detailed understanding of LORAN’s accuracy, position errors have been computed for the ASF corrected data in the three environments shown above - these are given in Table 1 below. GPS positions have been taken as truth data, except in the Docklands region.

<table>
<thead>
<tr>
<th>Location</th>
<th>R.m.s. error</th>
<th>95% error</th>
<th>99% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cambridge</td>
<td>51m</td>
<td>86m</td>
<td>114m</td>
</tr>
<tr>
<td>Central London</td>
<td>88m</td>
<td>172m</td>
<td>225m</td>
</tr>
<tr>
<td>London Docklands</td>
<td>150m</td>
<td>338m</td>
<td>398m</td>
</tr>
</tbody>
</table>

Table 1. LORAN position errors in different moving scenarios

When comparing the results in Table 1 with other studies it is important to note that a high update rate (1Hz) was used and that the results include no attempt at fine-grained corrections for re-radiation or ASF variations on scales smaller than 25km. Much of the r.m.s. error difference between Cambridge and Central London can be explained by the fact that SNRs in London were generally around 5dB poorer than Cambridge. In the Docklands region, errors are dominated by fine-scaled arrival-time perturbations due to re-radiation from the many large conducting structures.

Map-matching particle filter for ASF compensation

A 2000-particle version of the particle filter described above was implemented in MATLAB and tested using a subset of the measured LORAN data for the Cambridge area route (see Figure 5 above). Performance in London has not been considered due to a lack of availability of vector map data for this area. LORAN position errors were modelled using a simple bivariate Gaussian distribution.

Two scenarios were considered:

1. Real-time navigation, where a position update is required with a latency of no more than 2s.
2. Object tracking, for example determining the route taken by a high-value asset, where all position data for a route is already available and the aim is to reconstruct the route taken as accurately as possible.

Figure 8 shows results for both these scenarios. In both cases, the resulting route is a close approximation of the true route. The output of the real-time filter contains occasional glitches where the filter momentarily believes the vehicle to have followed a different route from the true one. The delayed filter removes almost all these glitches since they are inconsistent with the subsequent measurements.

The resulting errors after applying the particle filter have been quantified and are given in Table 2 below.

<table>
<thead>
<tr>
<th>Method</th>
<th>R.m.s. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASF-corrected LORAN measurements</td>
<td>54m</td>
</tr>
<tr>
<td>Real-time particle filter</td>
<td>44m</td>
</tr>
<tr>
<td>Delayed particle filter</td>
<td>37m</td>
</tr>
</tbody>
</table>

Table 2. Effect of particle filtering on LORAN position errors.

These results are perhaps a little worse than would be expected from an initial examination of Figure 8. The principal reason for this is that the particle filter currently fails to accurately model vehicle dynamics: the acceleration is modelled as a Gaussian error applied to the velocity. This results in the velocity of the particles fluctuating much more than would be expected for a genuine vehicle. In turn this means that while the particles overwhelmingly follow the correct route they often lag behind or get ahead of the true vehicle position. The significance of these errors depends on the scenario: in a real time application they
would be critical; in an off-line reconstruction of the route taken by an object, they are unlikely to be important.

The particle filter described and used for this work is a straightforward implementation. Significant improvements could be made by using a more realistic vehicle dynamics model and by better modelling of the LORAN errors. In particular, LORAN errors are currently treated as being independent between successive samples. In practice errors are caused both by noise (which is largely independent) and by local arrival-time perturbations (which are highly correlated). Attempting to track these local arrival-time variations within the particle filter could result in significant improvements in accuracy.

Finally, the particle filtering approach is highly flexible in its source of input data. Data from other sensors, for example vehicle speed sensors or a gyroscope, could readily be included into the filter by modifying step 3 above to include the conditional probabilities from these sensors. This approach should result in improved positioning, particularly in urban environments.

CONCLUSIONS AND FURTHER WORK

This work has demonstrated that a modern LORAN receiver can successfully receive and process LORAN signals in a variety of challenging urban environments. The achievable accuracy in these environments is limited both by man-made noise and by small-scale arrival-time perturbations introduced by re-radiation from conductive structures. In typical central urban environments in the UK, these two factors are similar and a 95% error accuracy of around 90-170m is likely for a 1Hz position update rate and with coarse (25km grid) ASF corrections. In very high density environments with many buildings over 100m tall, local re-radiation effects dominate and 95% errors of around 300m should be expected.

Initial results from testing a particle filtering approach for ASF compensation show promise with significant reductions in r.m.s. errors for both real-time positioning and delayed tracking.

In summary, LORAN is able to provide sufficiently good performance for vehicle or pedestrian tracking in low- to medium-density environments. Further enhancement is, however, likely to be required in high-density environments.

Further work should focus on improving the particle filter by better modelling both vehicle dynamics and the nature of LORAN errors. The addition of information from other sensors should also be considered. The performance of the particle filter requires assessment in a wider range of environments, including mountainous areas and dense city centres.

REFERENCES


