Extending the range of Loran-C ASF modelling

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Abstract

There is ever-increasing interest in employing accurate values of Additional Secondary Factors (ASFs) in Loran-C receivers. Precise ASF values are essential if Loran is to deliver the high absolute accuracies now demanded of it for aircraft approaches, maritime harbour entrance guidance, and land vehicle tracking. In some situations, accurate ASFs can be measured. But in many other applications, we find it more economical to employ a computer model to predict ASFs, and then store the results within the Loran receiver itself. This paper will introduce readers unfamiliar with the concepts of ASFs to the principles involved. It will briefly review the use of measured and modelled ASF values in a range of applications.

The *BALOR* computer model developed by the authors calculates the values of ASFs along complex propagation paths, taking into account the variations of both ground conductivity and land height between the transmitter and the receiver. It has been used to produce ASF data sets for the region served by every NELS Loran station, and many North American stations, too. These results are available in the form of maps and tables of numerical values. Typically, data points are spaced at intervals of 0.01^o degree of latitude by 0.01^o degree of longitude (approximately 1 x 1 km).

Recently, the authors have extended the BALOR model to take into account more accurately the curvature of the earth at ranges beyond 1000km. This extended model employs a more complex, and more accurate, integral equation. The equation was developed, using the Compensation Theorem, by Wait at the US National Bureau of Standards. It describes the changes in the amplitude and phase of the Loran signal as it propagates from the transmitter to the receiver. As in the existing BALOR model, Monteath's numerical approach is then used to solve this integral equation. The paper will demonstrate the validity of this extended model by reference to NBS results, and present examples of ASF data it has produced for specific Loran stations.

Introduction

We have already heard in this conference about some of the important work going on in the Loran community concerning Additional Secondary Factors (ASFs). Mr. Kurosu talked about Japanese ASF mapping efforts and Sherman Lo gave an excellent summary of the related work of the LORIPP/LORAPP panel.

It has been interesting to see over the past couple of years how Additional Secondary Factors have moved from being an obscure perversion, practised by strange people in the mountainous regions of a primitive Celtic country, to the mainstream of Loran thinking. Loran-C simply cannot achieve the accuracy and integrity needed for aircraft approaches, or maritime harbour entrance, without a firm understanding and correct use of ASFs. There are a substantial number of people in this meeting who now have that understanding. But, if this is all new to you, here is a quick tutorial.

ASF tutorial

Loran receivers determine where they are by measuring the time delays of the signals they pick up from the transmitting stations (see Slide 2). The receiver knows the velocity of propagation (the speed at which radio waves travel) so it can convert these time delays into its ranges from transmitting stations, or range-differences from pairs of stations if it is working in the traditional hyperbolic mode. ASFs are the small shifts in Loran measurements caused by the signals' travelling more slowly over land than over sea. Ignore them, and the ship's Loran measured position (Slide 2) will not be where it should be.

Loran nowadays is very like GPS in that we measure a set of pseudoranges and use them to compute a position. And just as in GPS, Loran is sensitive to tiny changes in the speed of propagation. With GPS, we do our best to understand and adjust the pseudoranges for the tiny delays as the signals travel through the ionosphere and troposphere (Slide 3). The Loran equivalent is the variations due to the earth's surface. The signals go fastest over sea-water, more slowly over farming land, and most slowly of all over ice-fields or deserts or bare mountains.

Loran receivers compute their pseudoranges from the stations in two stages. First, they assume that the signals travel over sea-water alone. Then, they adjust for the delays due to the land along the path: the ASFs. Unlike GPS corrections, Loran ASFs are virtually constant. Measure them once, record them, and then use them in the receiver. Ignoring ASFs can give big errors, up to 2km in Europe. Using them, as God intended, gives Loran's full accuracy. This is very close to the repeatable accuracy, well below 50m under favourable conditions - and getting better, it would seem, by the week!

Sources of ASF data

You can measure ASFs and map them using a survey ship or land vehicle or helicopter. But for an area as immense as the European or the Asian Loran coverage (even more so the United States) that would be very slow and expensive. A better technique for getting precise ASF values over large areas is to calculate them as accurately as possible using a computer model, then measure the real thing and use those measurements to adjust the computer model (Slide 4). The model gives the detail; the measurements remove the biases. And because the positions at which measurements are made can be far apart, we save time and money.

In this paper, we will focus on the model that computes the estimates of the ASFs. That is our speciality and we have some exciting developments to report.

In calculating ASFs, the model follows the path the radio signals take from the Loran station to the receiver (Slide 5). It looks up the electrical conductivity of the ground along the path (he principal factor affecting ASFs) in a database of conductivity values. And because the greatest ground conductivity changes happen at the interfaces between land and sea, we employ a coastline database to tell the model exactly where these are. We also take the ASF effects of mountains along the path into account, using a terrain elevation database.

Once we have established the conductivity and terrain profiles of the path, we employ an equation that describes the propagation of the Loran signal along it. This is difficult and mathematically demanding. The equation must take into account variations in the conductivity, coastline, curvature of the earth, and the effects of mountains. There is a really powerful technique for doing all that, which we were the first to use in a Loran ASF model: Monteath's method (Slide 6) [1]. The diagram at the top left of the slide shows the earth's surface with its conductivity variations and mountainous terrain. Starting at the Loran station (A), we solve the integral equation shown below the diagram, Hufford's equation [2]. We do so point-by-point along the path to the receiver (B). The phase delays, of course, build up along the route. We compare them point-by-point along the path with the delays we would get along a smooth sea-water path of the same length. Since, by definition, the sea-water path has zero ASF, the differences between the delays of the real and sea-water-only paths are the ASFs. In the equation at the bottom line of the slide, the delay of the real path is $G(R)_{\text{Mixed-Path}}$ and that of the sea-water, $G(R)_{\text{Salt-Water}}$.

BALOR

We made Monteath's method the basis of a powerful and flexible computer model software package which we called **BALOR**, for the **BA**ngor **LOR**an model (Slide 7) [3] [4] [5]. It was only later we learned that BALOR was the Irish God of death and destruction, the inventor of the Evil Eye (Slide 8)!

Our BALOR, however, turned out to be a great hero, a mighty warrior. He generated ASFs across most of Northern Europe – including his former kingdom in Ireland (Slide 9) [5]. Then the FAA hired him and he slew dragons and plotted ASFs across the US as an important member of Mitch Narin's team [6]. Slide 10 shows a BALOR-generated map of the ASFs of signals from the Seneca Loran station. It covers the region around Cape Elizabeth on the coast of Maine. BALOR also provides field strength plots: Slide 11 shows the strengths around Cape Elizabeth. And, as we showed at last year's ILA Conference [7], you can even compute envelope-to-cycle differences (ECD), like those shown in Slide 12. BALOR has generated these ECDs by calculating the attenuation and phase delay values of signal components at various frequencies across the spectrum of the Loran pulse. From these components, it has then reassembled the Loran pulse as it would be received, and computed its ECD.

BALOR was the first model that could predict all these Loran parameters over mountainous terrain. But, Loran is an exceptionally demanding system requiring ASFs with a precision of nanoseconds out to ranges of some 2000km from each station. And when we came to push the operation of BALOR to those long ranges, we discovered an oddity in the results.

The 1000km wobble

At distances from the station of over 1000km, we saw the small variations in ASFs visible in Slide 13, which we could not explain. Notice that these variations are different at the three frequencies shown, 90kHz, 100kHz and 110kHz. So, when ECDs (which depend on subtle variations in propagation between frequencies) are computed, the small ASF variations result in quite large variations of ECD (Slide 14).

Because we did not understand these phase variations, we restricted the range to 1000km when predicting ASFs for NELS. Later, as part of the FAA team, we decided to look for evidence of these variations in measured data. Ohio University sent us records of time-of-arrival readings along flight routes in the US, which we analysed carefully. We focussed on the blue-coloured route section shown in Slide 15. Here the aircraft is travelling almost directly away from the Baudette Loran station and towards the Carolina Beach station. Unfortunately, we discovered that the airborne equipment that had been used to measure the times-of-arrival did not have a sufficiently stable clock to measure variations as small as those in our ASFs. The equipment was entirely suitable for the purpose for which it had been designed, but not for this more-demanding task. The ASF variations we were attempting to explore were simply too small. And, even if we had been able to measure them with confidence, it became clear that the ASFs effects due to the terrain variations along the route (Slide 16) would have masked them.

Could the wobble be in the model?

By the time this became clear, we were pursuing another approach to the problem. We had noted the similarity of the ASF "wobble" to the ASF variations observed in signals that have passed over pronounced hills. For example, Slide 18 shows what happens after a signal at 1 MHz has crossed a 1500m high hill: downstream there is a series of signal variations in both magnitude and phase. The values in the slide are as predicted by Johler and Berry [8] [9], and using Hufford's equation [2]. Our BALOR results agree with those predictions. We asked: could the much smaller phase variations we are trying to explain be due to the presence in the propagation path of a low, wide, hill? And could that hill, perhaps, be the Earth?!

We noted that most published propagation models are demonstrated over relatively short ranges. The models generally contain approximations that have little effect on accuracy, but do speed up the very complex calculations. So, for example, Johler and Berry demonstrate their work out to ranges of just 400 km [8]. In contrast, we were trying to predict phases out to 2000km, a distance at which the earth's curvature is equivalent to a 78km-high hill.

The equation used in BALOR, which Monteath had taken by from Hufford, turned out to contain an approximation that gave significant errors due to the earth's curvature at ranges in excess of 1000 km. Specifically, this approximation is in the ξ term in the two equations shown in Slide 19.

The solution

The solution we proposed was to replace Hufford's equation (Slide 20 top) with the much more complex one of Wait (Slide 20 bottom) [10], [11]. Wait starts with a spherical earth, and so avoids the simplifying assumption employed by Hufford and

Monteath. Unfortunately, however, solving Wait's more-complex equation takes a lot more computer power than the simpler alternatives.

We installed Wait's equation into the BALOR software and used it to generate ASFs along the 2000 km path from the Bø Loran station in northern Norway to Bangor in Wales (Slide 21). The signals set out over high mountains, and then travel down a long path over the North Sea before finally reaching Britain. Slide 22 shows the ASF variations (in dark blue) over the initial, mountainous, part of the path; the terrain heights are in green. Slide 23 shows the ASFs and terrain variations along the whole path; strikingly, this time no ASF variations are visible at ranges beyond 1000 km, or anywhere over the North Sea part of the path down to a range of 1600 km. Only when the signals finally reach the British coast do the ASFs begin to increase with variations due to the terrain. Even more convincing is Slide 24 in which we plot the values of ECD, the parameter that earlier proved the most sensitive to unwanted variations in the earlier model. The wobble has disappeared!

Thus, we now appear to have the basis of an extended, long-range, model for Loran ASFs, ECDs, and field strengths. We plan to validate it and also to speed up the computations. Solving Wait's equation takes some 13 times longer than solving Monteath's. Where previously it took a day to produce an ASF map for a substantial area, with Wait's equation it would take nearly 2 weeks!

Next steps

We have switched to the more complete propagation equation created by James Wait. First, we proposed to validate our implementation of the new technique thoroughly (Slide 25). Then, we will compare its results with those from the old model and also check them against results against third party software [12].

We also plan to review the techniques we use to compute ECDs. The objective is a definitive method for computing either the ECD of a propagating signal, or an ECD-like parameter or parameters, using the new propagation equation. We will discuss this work with Dr. Ben Peterson and feed back our results into the Loran integrity panel as a step towards the standardisation of eLoran.

Because the new, more powerful, propagation equation takes one to two orders of magnitude longer to compute than Monteath's, and because ASF modelling is required over large areas, we will optimise the method to minimise computation time. This will include maximising computational efficiency. We plan to explore the effect of varying the integration interval of the equation, and also investigate the use of a *vectorising compiler* (ie a compiler that takes advantage of the MultiMedia Xtension instructions in the Pentium processor) [13].

Finally, driven by frequent questions from the aviation community about ASFs aloft, we propose to explore the capability of the new model to deliver ASFs at altitude.

Summary

We have discovered the source of the 1000km wobble that we were seeing in our model results (Slide 26). We have identified a much more powerful propagation equation that takes into account the curvature of the earth at the kinds of distances needed for eLoran, and experimentally incorporated it into the BALOR software package. The result is a “wobble-free model”; you might wish to call it *eBalor*!

References

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