Full Performance Analysis of IFFT Spectral-Division Technique for Skywave Identification in Loran-C Receivers

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Abstract
Skywave interference commonly affects Loran-C receivers' performance. The skywave rejection methods employed in current designs of receivers are not optimal because they use fixed, worst-case, sample timing. This paper presents a simple but efficient technique (IFFT spectral-division) for adaptive adjustment of the sampling points in Loran-C receivers, and provides a full and comprehensive analysis of the parameters that might affect its performance. Simulation results show that the algorithm can operate successfully with very noisy signals. The paper also demonstrates, for the first time, the results of a prototype receiver employing the IFFT algorithm working in real time on off-air signals.

1 Introduction
Loran-C is a pulsed, low-frequency (100 kHz), hyperbolic, radio-navigation system for position fixing by reference to terrestrial transmitting stations. Loran-C signals are normally very stable in time. However, noise, skywave contamination, propagation effects, and front end filtering all alter the shapes of Loran pulses and so cause inaccuracies in the position measurements.

The ability of Loran-C receivers to resist contamination by unwanted skywave-propagated components of the groundwave signals used for position measurements is its major advantage over continuous-wave navigation aids. As a consequence, a single chain of Loran-C transmitters can provide coverage of a large geographical area.

Measurements show that Loran-C skywaves may arrive with delays from 35 μs to as much as 500 μs, the delay depending on the location, time of day and season of the year. Published *Minimum Performance Standards (MPS)* [1,2] specify the range of skywave parameters which receivers must withstand. If, as is customary, a receiver times its phase samples to cope with the earliest possible arrival of skywaves, a heavy price is paid under more typical conditions in reduced *signal-to-noise ratio (SNR)* at the sampling point. If the samples are taken further up the leading edge, the SNR will be higher, but the effects of skywave interference will be more severe. Thus, a receiver which could always sample just early enough to avoid skywave contamination would be an attractive proposition. It would need to be able to isolate the skywave components and determine their delays quickly, accurately and continuously.

At previous ILA Conventions, and in recent publications [3-7], we have demonstrated and analysed techniques for determining skywave delays that employed the AR, ARMA and MUSIC high-resolution algorithms. In addition, it has long been known that an Inverse Fast Fourier Transform (IFFT) algorithm is much simpler computationally, but this approach has been rejected previously because of its poor resolution and failure at low signal-to-noise ratios. At the ILA29 Convention, however, we revisited this IFFT technique and demonstrated a filtering process that promised greatly to enhance its performance with noisy signals [8].

This new paper will present a detailed analysis of this IFFT technique, evaluating the effects of a number of signal parameters: skywave delay, skywave-to-groundwave ratio, and signal-to-noise ratio. We will explore the relationships between these parameters and the width of the filter window. The performance of our IFFT technique with filtering in operation will then be assessed, first by theoretical analysis, then by computer simulation under a range of realistic conditions, and finally by its response to off-air signals.

2 Rejection of skywave components in Loran-C receivers
This section will describe how conventional Loran-C receivers distinguish between groundwave and skywave components. The technique will be shown to have significant limitations when implemented in receivers of finite bandwidth. Later we investigate the performance of our proposed skywave delay estimation techniques which can be used to overcome these limitations.

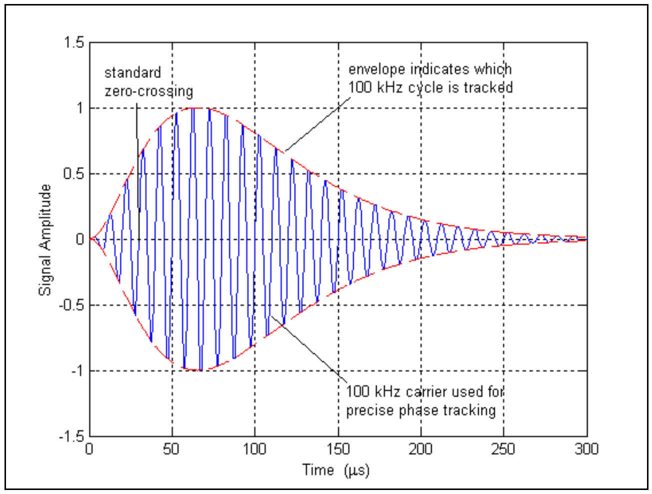


Fig. 1: Pulse shape of Loran-C transmission. The time reference point at 30 μs is marked "standard zero-crossing".

2.1 Loran-C Transmission Characteristics

Loran-C employs pulsed transmissions (Fig. 1). The pulses are bursts of 100 kHz signal of a precisely-defined carrier phase and envelope shape. Each of the stations which constitute a Loran chain radiates a group of such pulses (Fig. 2) in a precise time sequence. The interval between the groups of pulses from any station is the Group Repetition Interval (GRI), a time between 40 μs and 100 μs which characterises and identifies the chain.

A Loran-C receiver measures the time differences between the arrivals of corresponding pulses from pairs of stations and uses these measurements to compute its own position. Traditionally the timing point on each pulse is the "standard zero-crossing" (Fig. 1), the third positive-going zero-crossing of the 100 kHz, 30 μs after the start of the pulse. The receiver distinguishes this particular zero-crossing by identifying the corresponding point on the pulse envelope which has the appropriate gradient.

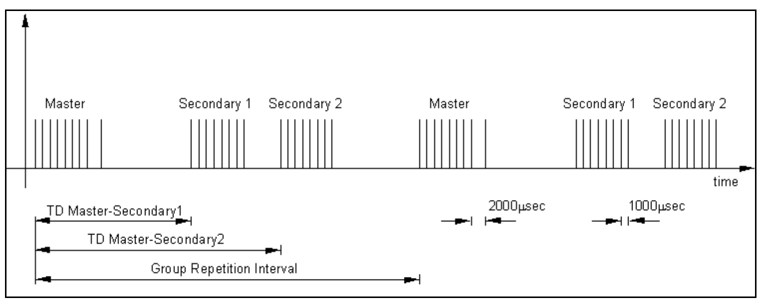


Fig. 2: Sequence of transmissions of pulses by stations of a Loran-C chain.

2.2 Skywave Rejection Principle

In Loran-C signal propagation, there are two routes by which the signals can travel between the transmitters and the receiver: directly along the earth's surface (the groundwave) and by *unwanted* reflections from the ionosphere (skywaves). Thus, the receiver is presented with the sum of groundwave and skywave signals (Fig. 3). The computation of an accurate position by a Loran-C receiver relies on reception of the groundwaves only. The skywave signals can contaminate the wanted groundwave signal and may cause large errors in the computed position.

The skywave signals will always arrive at the receiver later than the groundwaves because they have further to travel. The time difference between the arrival of the groundwave and the first skywave component from a station is known as the *skywave delay*. Within the coverage area of a chain of Loran-C transmitters the skywave delay will be at least 35 μs. Thus, the strategy which has been used traditionally to minimise skywave errors is to choose a zero-crossing that precedes the arrival of the earliest skywave component (Fig. 3). The zero-crossing usually employed is the one that occurs 30 μs after the start of the pulse; that is, the receiver essentially only makes use of the groundwave of the Loran-C transmission and by doing so it reject the skywave components.

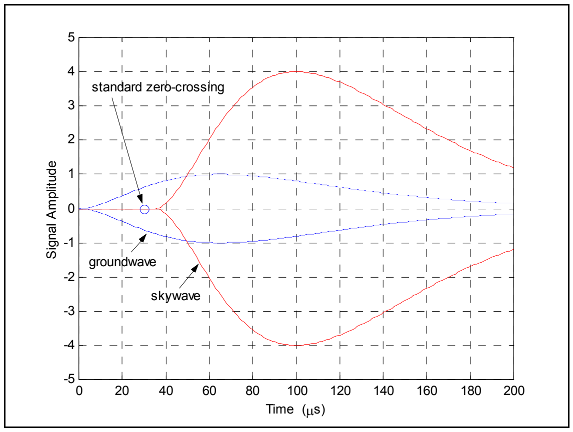


Fig. 3: Loran-C groundwave pulse followed, 37.5 μs later, by skywave pulse 12 dB stronger. Received composite pulse is sum of skywave and groundwave signals.

2.3 Limitations of Skywave Rejection Capability

Loran-C receivers work in noisy environments and in the presence of strong interfering signals. Therefore, in addition to phase-decoding and subsequent integration, a major operation of the receiver signal processing is front-end filtering. Front-end filters provide substantial improvements in signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR) at the timing measurement point in the receiver. However, they also cause distortion of the Loran-C pulses which reduces the ability of the receiver to reject skywave interference [9].

The amplitude-frequency transfer function of a filter is a precise measure of the attenuation of interference it provides. Fig. 4 shows the transfer function of the 5^{th} order Butterworth bandpass filter of 20 kHz width which is used in the analysis in this paper. This filter shape was the one adopted by the North West European Loran-C Technical Working Group as typical of filters in widespread use, and employed by them in predicting the coverage of Loran-C chains.

Because of their finite bandwidth and non-linear phase transfer function, receiver bandpass filters distort Loran-C pulses [9]. The distortion may be examined in either the time or the frequency domain. Fig. 5 shows the amplitude spectrum of a standard Loran-C pulse before and after filtering: the filter greatly reduces the signal energy outside the 90-110 kHz Loran band. This filtering operation, however, causes the precisely-defined, and relatively steep, leading edge of the pulse to be stretched out in time, as shown in Fig. 6. Although the peak magnitude of the pulse remains almost unchanged, its amplitude 30 μs after the start has been reduced so substantially that a much later zero-crossing must be selected for timing measurements. In practice, therefore, receiver design is a compromise between filter bandwidth and skywave tolerance.

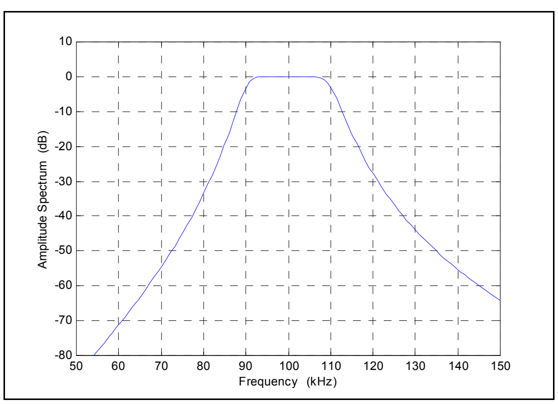


Fig. 4: Amplitude transfer function of 5^{th}-order Butterworth filter typical of front-end filters used in Loran-C receivers.

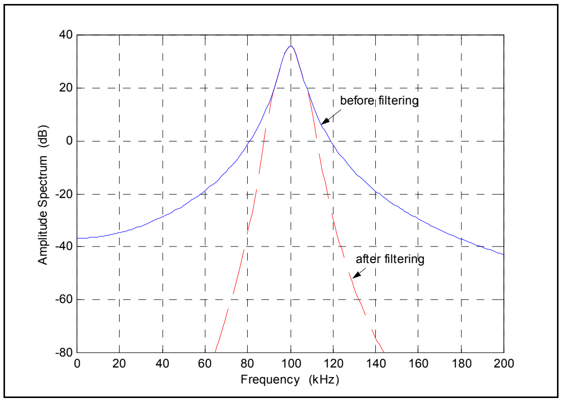


Fig. 5: Energy spectral density of a Loran-C pulse before (solid line) and after (dashed line), band pass filtering.

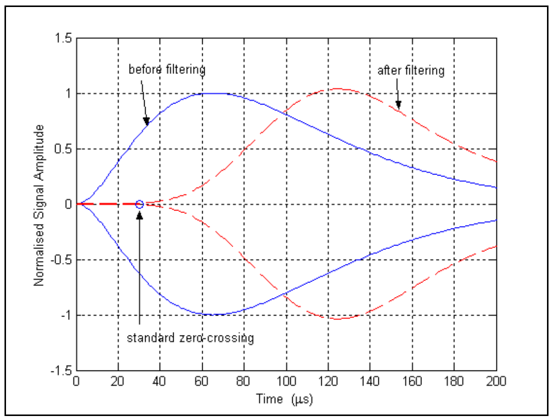


Fig. 6: Distortion of a Loran-C pulse caused by filtering. Circle at 30 μs is strandard zero-crossing point of the unfiltered pulse.

When a later zero-crossing is chosen, the signal there may be contaminated by skywave interference. The solid line in Fig. 7 represents a groundwave pulse and the dashed line is a delayed skywave pulse at the output of the filter. The strength (+12 dB) and time delay (37.5 μs) of the skywave relative to the groundwave are limiting values cited in the Minimum Performance Standards (MPS) for Loran-C receivers [1,2]. Even by 80 μs, the filtered groundwave pulse has only regained an amplitude of half its peak value (equivalent to the envelope amplitude of an unfiltered pulse at 30 μs); however, the skywave signal is four times higher than the groundwave at this epoch! Such a skywave signal would cause a quite unacceptable disturbance of up to 0.40 μs in the time-of-arrival measurements. Thus an important, and undesirable, result of pulse distortion caused by filtering is the reduction of signal amplitude at the sampling point.

2.4 Receivers with Adaptive Sampling Point Adjustment Capability

An attractive solution to the skywave problem is a receiver which adjusts its sampling point adaptively to the optimal value in a constantly-changing skywave interference environment. It would sample well up the leading edges of the pulses during the substantial proportion of time in which skywaves are delayed by more than the 37.5 μs minimum. However, for such a receiver to work, it would need to be able to estimate skywave delays in real time. But if that were possible, we could improve significantly the accuracy and reliability of positioning under adverse skywave conditions. This paper presents a simple, robust, and computationally-efficient technique for making the necessary skywave measurements.

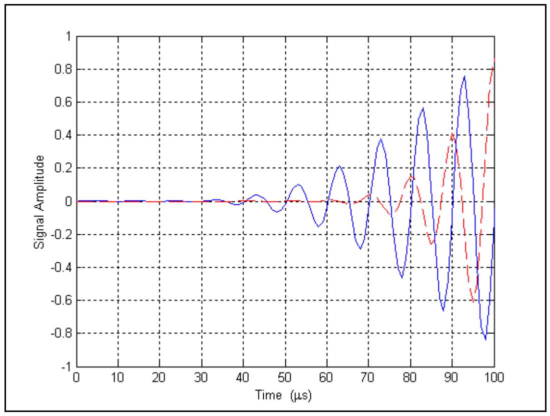


Fig. 7: Groundwave (solid line), and skywave (dashed line), signals after passing through typical bandpass filter.

3 Mathematical formulation of the skywave analysis problem

This section sets up a signal model that will be used later when we attempt to identify skywave parameters, and explains the main principle of the IFFT technique.

3.1 Signal Model

The total received Loran-C signal $x_t(t)$ may be represented in the time domain by [3-8]:

$$x_t(t) = x_g(t) + \sum_{n=1}^{N} k_n x_g(t - \tau_n) + e(t) \tag{1}$$

where $x_g(t)$ is the groundwave signal. The amplitude and delay of the n^{th} skywave component relative to the groundwave are represented by k_n and τ_n, respectively, and $e(t)$ is the total noise and interference.

The equivalent representation of this composite signal in the frequency domain is given by:

$$X_t(f) = X_g(f)\left[\mathbf{1} + \sum_{n=1}^{N} k_n \,\mathbf{exp}(j\mathbf{2}\pi f\tau_n)\right] + E(f) \tag{2}$$

where $X_t(f)$, $X_g(f)$ and $E(f)$ represent the spectra of $x_t(t)$, $x_g(t)$ and $e(t)$, respectively.

3.2 IFFT Spectral-Division Method

The principle of the IFFT spectral-division method of analysing the incoming Loran signal is extremely simple: we start by dividing the spectrum of the received total pulse by that of a standard Loran-C pulse and later take the Inverse Fast Fourier Transform (*IFFT* or F^{-1}) of the result. That is:

$$F^{-1}\left[\frac{X_t(f)}{X_0(f)}\right] = k_g\left[\delta(t) + \sum_{n=1}^{N} k_n \delta(t - \tau_n)\right] + F^{-1}\left[\frac{E(f)}{X_0(f)}\right] \tag{3}$$

where $X_0(f)$ is the spectrum of the normalised standard Loran-C pulse $x_0(t)$, and k_g is a constant related to the amplitude of the groundwave signal. The time domain expression of equation (3) contains impulses at the arrival times of the groundwave and skywave components which allow them to be separated and their relative magnitudes estimated. Since it is an IFFT operation that we use to analyse the ratio in equation (3), this technique is called the "IFFT spectral-division" method, or more briefly here, the **"IFFT"** method.

4 Evaluation of IFFT performance under noisy conditions

In the previous section we explained the principle of applying this IFFT technique to the problem set out above of estimating skywave delay. This section describes the results of computer simulations designed to evaluate its performance of the IFFT technique when used on noisy signals. The simulation set-up is discussed briefly first, followed by the simulation results.

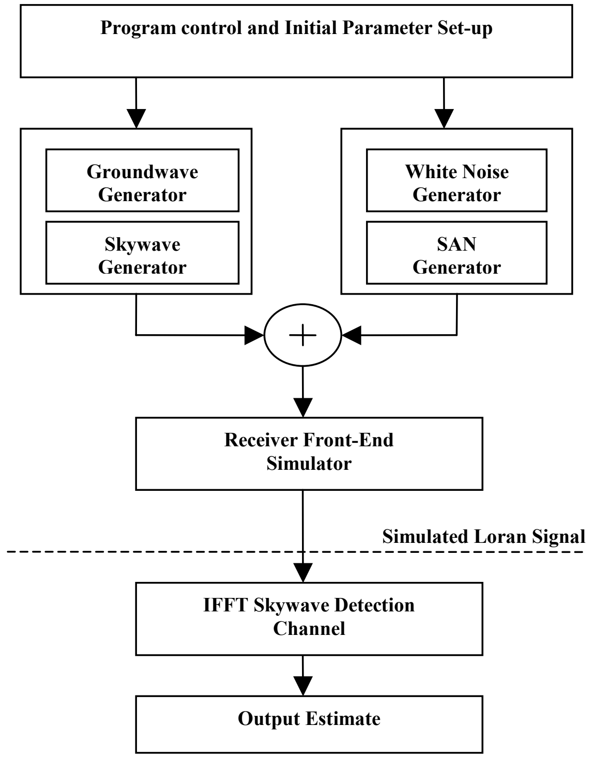


Fig. 8: Functional block diagram of programs to simulate operation of IFFT skywave detection technique under noisy conditions.

4.1 Simulation Arrangements

All simulations were written using the advanced software package Pro-Matlab [10]. Fig. 8 shows a functional block diagram of the simulation program. The Program Control block sets up the initial parameters for the other functional blocks and controls their operations. Simulated Atmospheric Noise (SAN) is generated in accordance with the standard defined in the Loran-C Minimum Performance Standards (MPS) [1,2], added to the separately-generated Loran-C groundwave and skywaves, and fed into the Front End Simulator block. Finally, the filtered composite signal is applied to the IFFT Skywave Detection Channel (SDC) which analyses it to determine the arrival times of the skywaves. The IFFT-SDC block is simply a realisation of the concept of equation (3); that is, the core operation is the inverse Fourier transform of the spectral-division result (see reference [8]). It is worth mentioning that we need to employ a windowing function in SDC in order to overcome the noise amplification problem caused by the spectral-division operation in equation (3); interested readers are referred to [8] for detailed analysis of this problem.

4.2 Performance Evaluation

In this section we evaluate the performance of the IFFT algorithm under noisy conditions, by means of computer simulations that employ a Monte Carlo approach. A number of factors, such as the signal-to-noise ratio, skywave-to-groundwave ratio, skywave delay, and window width, affect the accuracy of skywave delay estimation. These factors will now be considered in turn.

4.2.1 Window Width

To illustrate the importance of the windowing operation, simulations have been performed by varying the window width and fixing all other factors. Fig. 9 shows the mean and standard deviation values calculated from a set of these simulations. Each circle was calculated from 100 simulation runs. The principal factor which determines the optimal window width was found to be the SNR [8]. In this figure the SNR was set to 27 dB (equivalent to –10 dB at the antenna input); this is the value employed by the US Coast Guard as their minimum acceptable antenna SNR value. The signal consists of a groundwave pulse followed, 50 μs later, by a skywave component 12 dB stronger; these skywave interference parameters are chosen from the MPS specifications. It is clear from Fig. 9 that the optimal window width is of the order of 50 kHz and that the technique produces inconsistent estimates if the window is wider than 70 kHz.

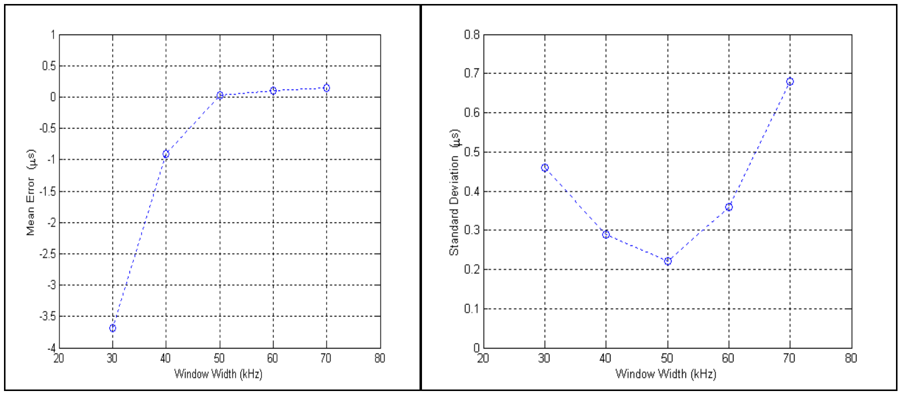


Fig. 9: Mean and standard deviation values of skywave delay estimation errors as values of window width are varied. Each circle is calculated from 100 simulation runs of the algorithm.

4.2.2 Signal-to-Noise Ratio

To quantify the influence of noise on the accuracy of the skywave delay estimations, simulations have been performed by varying the SNR and fixing other factors that might potentially affect the estimation accuracy. Fig. 10 shows the mean and standard deviation values calculated from 100 simulations at each SNR value. A window width of 50 kHz was used in these simulations and in producing all later results. It is clear from this figure that the algorithm produce excellent results at an SNR of 17 dB (–20 dB at the antenna); at this SNR value, the mean error is 0.12 µs and the standard deviation is 0.93 µs. Fig. 11 shows a typical estimation result from one of these runs. In fact, the algorithm produces correct estimates, albeit with a higher standard deviation, from signals with SNRs as low as 10 dB (–27 dB at the antenna). The results become inconsistent when the SNR falls below this value.

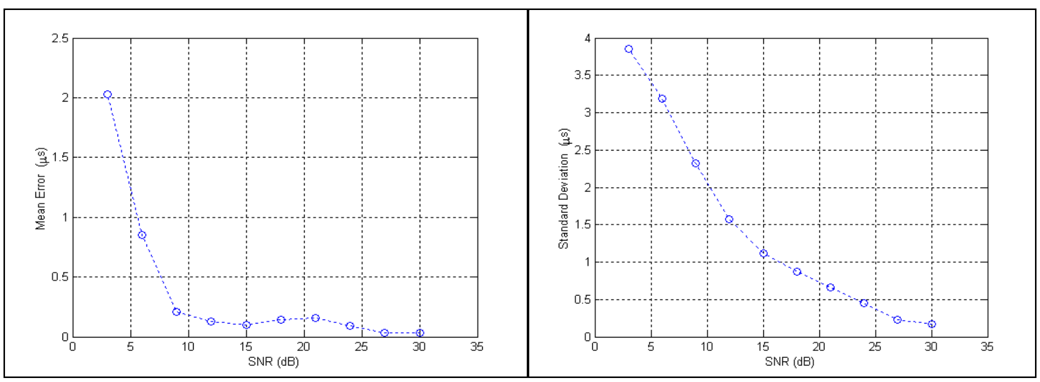


Fig. 10: Mean and standard deviation values of skywave delay estimation error as signal-to-noise ratio (SNR) is varied.

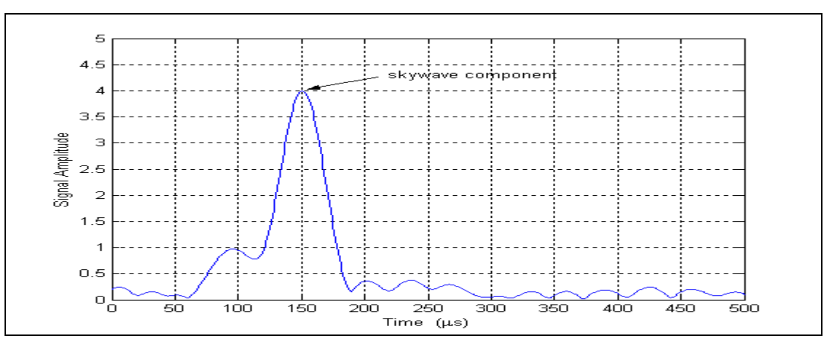


Fig. 11: Typical skywave delay estimate made using the IFFT technique at SNR of 17 dB (–20 dB at antenna).

4.2.3 Skywave-to-Ground Ratio

The effect of the strength of the skywave relative to the groundwave has also been investigated, by varying SGR value and fixing all other factors in the simulations. The mean and standard deviation values calculated from 100 simulations at each SGR value are shown in Fig. 12. This figure clearly shows that the algorithm yields good estimation accuracy across the SGR range of 3–18 dB. In addition, the best estimation accuracies (i.e. the lowest mean error and standard deviation values) are obtained at higher SGR value, which is desirable outcome in this skywave estimation problem.

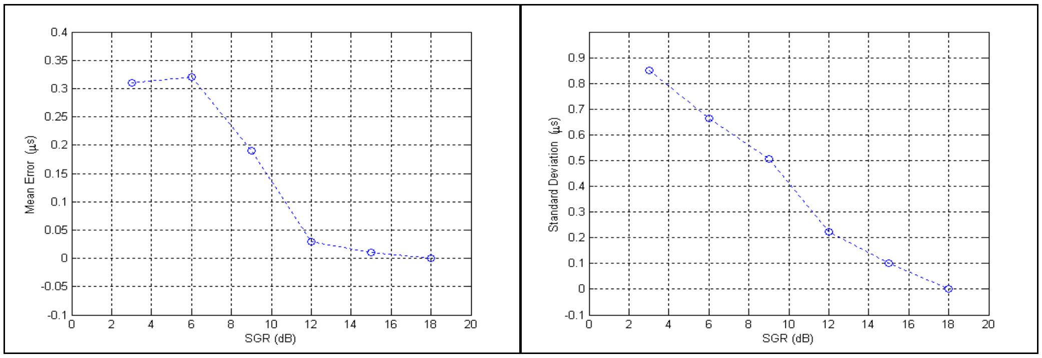


Fig. 12: Mean and standard deviation values of skywave delay estimation errors as skywave-to-groundwave ratio (SGR) is varied. SNR= –20 dB (antenna).

4.2.4 Skywave Delay

Finally the influence of skywave delay on the estimation accuracy of the algorithm is evaluated. Fig. 13 shows the mean error and standard deviation values of the skywave delay estimates as the skywave delay is varied. The results confirm that the performance of the algorithm is consistent across a wide range of skywave delay values.

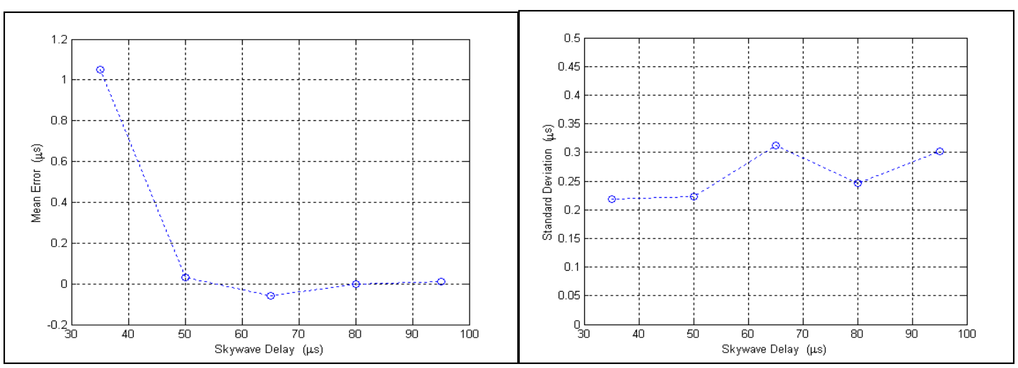


Fig. 13: Mean and standard deviation values of skywave delay estimation erro as skywave delay value is varied. SNR = –20 dB (antenna) and SGR = 12 dB.

4.2.5 Optimisation Results

The major conclusion to be drawn from varying these several parameters individually is the pronounced effect of two main parameters on the accuracy of skywave delay estimates of the IFFT technique: the bandwidth of the windowing filter and the signal-to-noise ratio of the incoming signal. Fig. 14 summarises the effects of these two parameters. The skywave delay was 50 μs, the SGR 12 dB, and a Hanning window was used. Again, each point is the average of 100 simulation runs.

The results show that the estimation error is affected more by the bandwidth than by of the SNR. The flat triangular plateau in Fig. 14a can be regarded as the region where the algorithm operates reliably. A window bandwidth of 45 kHz gives a reliable delay estimates, even with low SNR values, although the lowest SNRs cause the highest standard deviations (Fig. 14b). With the USCG minimum SNR value of –10 dB, which corresponds to a simulation SNR of 27 dB in the figure, filter bandwidths of up to 68 kHz can be accepted, with the mean error and standard deviation values both remaining below 1 μs.

Special attention must be paid to those parts of the figure where small changes in the two parameters lead to significant increases in the estimation errors; these are represented by the steeply sloping boundaries of the range of reliable operation. We conclude that the safest operation is the green area in Fig. 14 with a fixed filter bandwidth of 45 kHz.

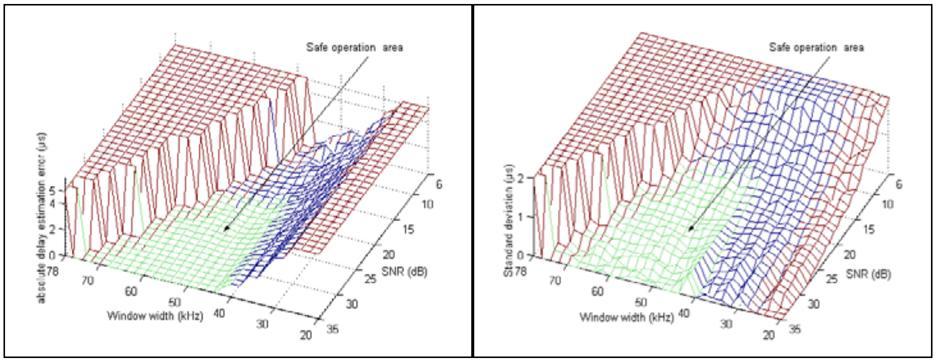
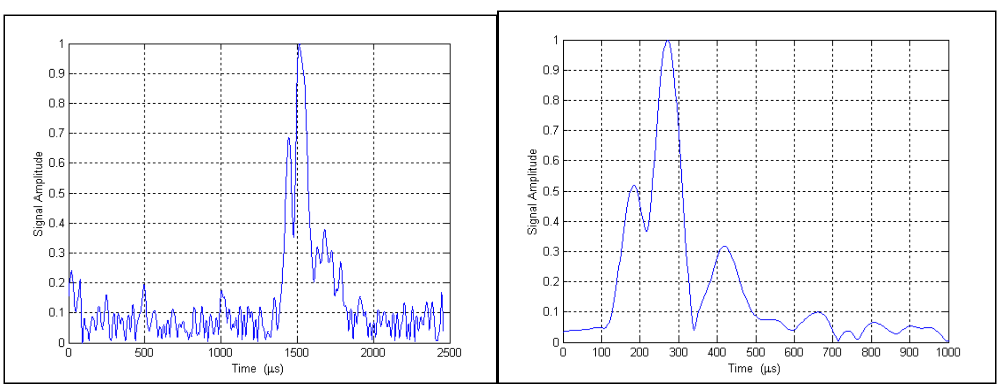


Fig. 14: Joint optimization results: SNR and window width versus (a-left) absolute delay estimation error, and (b-right) standard deviation.

4.2.6 Real Time Prototype Receiver Results

The IFFT technique has also been evaluated using signals recorded off-air. Fig. 15 shows an on-line analysis performed by the IFFT spectral-division algorithm on a real time, skywave-corrupted, signal received at Bangor, North Wales, from station in Vaerlandet, Norway at 02:30 local time. The receiver was the prototype set-up described in [3]. The ground-wave component is seen to start at 185 µs (this is an arbitrary time delay), a first skywave arrives at 270 µs and a later, smaller, one at 420 µs. The delay between the arrival of the groundwave and the onset of the first skywave, therefore, is 85 µs. This is certainly sufficient to allow the sampling point to be safely moved later in time to the peak of the pulse. A 6 dB SNR benefit would result. This is the *first time* that skywave delay estimates have been made using a prototype receiver employing the IFFT algorithm.



(a) **(b)**

Fig. 15 Off-air signals received in Bangor (North Wales) from Vaerlandet (Norway): (a) Pulse waveform, and (b) arrival times of groundwave and skywave components estimated using the IFFT algorithm operating in real time on recorded signals.

5 Conclusions

The IFFT technique for skywave delay estimation is a robust, simple, and computationally efficient algorithm. It offers the possibility of receivers' detecting and monitoring the delays of skywave components continuously and using these results to adapt their sample timing so as to minimise the errors caused by those skywaves. The paper has investigated the performance of the algorithm and the effect of signal parameters on the estimation accuracy. Simulation results have shown the ability of the algorithm to resolve closely-spaced groundwave and skywave signals under noisy conditions. The paper has also demonstrated, for the *first time*, skywave estimates made by the IFFT algorithm working in real time on results recorded using a prototype receiver. This clearly demonstrates the promise of the algorithm to operate reliably under adverse signal propagation conditions.

6 References

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BIOGRAPHIES

Dr. Abbas Mohammed is an Associate Professor and Head of the Wireless Radio Systems Group at Blekinge Institute of Technology, Sweden. He was awarded the Swedish "*Docent degree"* (equivalent to 2 PhD degrees in different fields of research) in *Radio Communications and Navigation* from Blekinge Institute of Technology in 2001, and the PhD degree by the University of Liverpool, United Kingdom, in 1992. From 1993 to 1996 he was a Post-Doctoral Research Fellow in the Radio Navigation Group at the University of Wales, Bangor. He has published many papers on telecommunication systems and the detection and minimization of skywave interference in Loran-C receivers. He is the Guest Editor for a special issue "Advances in Signal Processing for Mobile Communication Systems" of Wiley's International Journal of Adaptive Control and Signal Processing, Fall 2002. He is a member of IEEE, IEICE and a life member of ILA. He is also a Board Member of IEEE Signal Processing Swedish Chapter.

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Professor David Last holds a Personal Chair in the University of Wales and is Head of the Radio-Navigation Group at Bangor. He was awarded the university degrees of BSc(Eng) at Bristol, England, in 1961, a PhD at Sheffield, England, in 1966, and a DSc by the University of Wales in 1995. Prof. Last is Vice-President and holder of the Medal of Merit of the International Loran Association. He is a former Vice-President of the Royal Institute of Navigation, a Fellow of the Institution of Electrical Engineers and a Chartered Engineer. He has published many papers on navigation systems, including Loran-C, Decca Navigator, Argos, Omega, Marine Radiobeacons, GPS and DGPS. In Loran, he has specialised in understanding signal propagation and employing that knowledge to predict system coverage and ASFs. He has also developed receiver techniques for measuring skywave delays. He acts as a Consultant on radio-navigation and communications to companies and to governmental and international organisations. He is an instrument-rated pilot and user of terrestrial and satellite navigation systems.