Performance Evaluation of IFFT Technique for Skywave Detection in Loran-C Receivers

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ABSTRACT

Adaptive skywave estimation techniques that allow Loran-C receivers to adjust their sampling points in real-time would let them minimize the effects of skywave interference on the one hand, and noise and interference on the other. This paper investigates the effects of noise and filtering on the skywave delay estimation performance of the Inverse Fast Fourier transform (IFFT) skywave detection technique. Its performance is assessed using computer simulation under a range of realistic conditions, and by the use of off-air signals. The simulation results show that, even with poor signal-to-noise ratios, the time delays of skywave components may be measured successfully. The paper also presents for the **first time** skywave delay and amplitude estimates made by the IFFT algorithm on off-air signals.

INTRODUCTION

Most current Loran-C receivers determine the arrival times of groundwave and skywave pulses by sampling a fixed zero-crossing on their leading edges. If the sampling time is set too late, such receivers suffer unacceptable skywave errors; if too early, they suffer low signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR).

At previous ILA Conventions and in recent publications [1-5] we have demonstrated the feasibility of Fourier-based and other high-resolution techniques in estimating the skywave delays of Loran-C signals. In these papers, we have shown that the high-resolution algorithms, notably AR, ARMA and MUSIC, yield more precise skywave delay estimates in the time domain than do Fourier-based algorithms [3,4]. This improvement, however, is achieved at the expense of higher computational complexity.

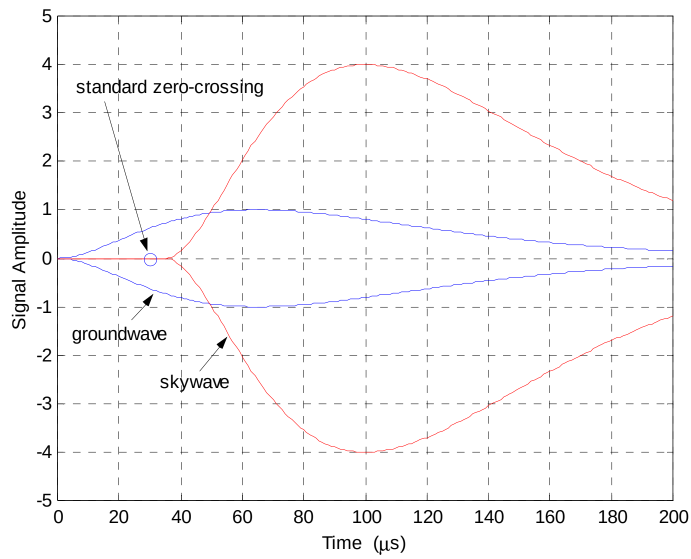
In this paper we revisit the IFFT technique, carrying out simulations to evaluate the parameters that determine its performance. In particular, we investigate the effects of noise and filtering. We show that by careful optimization of a windowing filter, much improved skywave delay estimates can be obtained. The performance of the IFFT technique is assessed by theoretical analysis, by computer simulation under a range of realistic conditions, and using off-air signals.

SKYWAVE REJECTION BY LORAN-C RECEIVERS

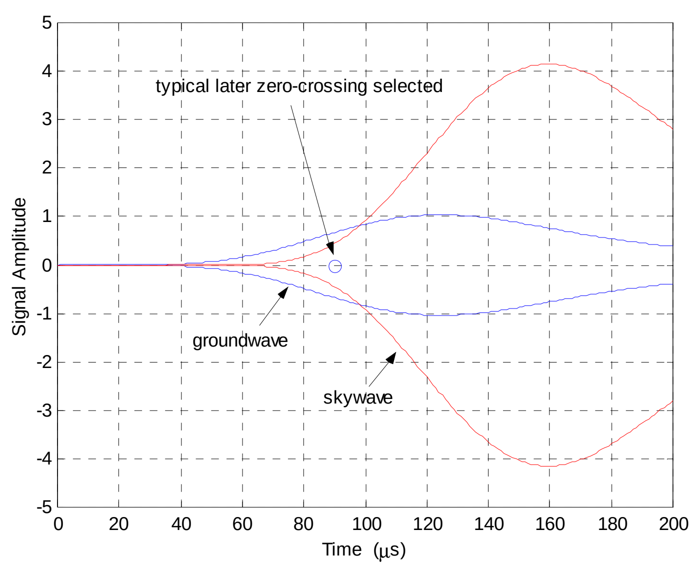
In a perfect world, Loran-C signals would travel from transmitter to receiver as groundwaves. In practice, skywave signal components also reach the receiver, by means of ionospheric propagation. Because these skywave components travel via longer paths, they normally arrive at least 35 μs after the corresponding groundwave components. The receiver is thus presented with the sum of groundwave and skywaves (Fig. 1a). However, the standard zero-crossing (30 μs into the pulse) should always precede the arrival of the earliest skywave component. Thus, the receiver makes its time measurement on the groundwave pulse prior to the arrival of the first skywave component. Ideal receivers, therefore, ought not to suffer from skywave interference.

In practice, Loran-C receivers are limited in their ability to identify the standard zero-crossing in the presence of strong skywave signals, especially those of short delay. The finite bandwidths of their front-end filters increase the rise-times of the received pulses (Fig. 1b). In consequence, the amplitude of the third cycle is so greatly reduced that the timing measurement have to be made on a later zero-crossing. By then it is possible that skywave components will be present. The narrower the filter, the greater this rise-time, and so the greater the susceptibility of the receiver to skywave interference [6]. In practice, therefore, receiver design is a compromise between filter bandwidth and skywave tolerance.

Receiver performance could be optimised if the choice of zero-crossing, rather than being fixed, could be adjusted so that latest zero-crossing prior to the arrival of significant skywave energy were always used. Since the delay of the first skywave varies greatly from moment-to-moment and with time and season, this adjustment would have to be made dynamically. Thus the receiver would need to be able to analyse the incoming signal and measure the delay of the first skywave component with respect to the groundwave. This paper presents and analyses a technique for doing so.



(a)



(b)

Fig. 1 A Loran-C groundwave pulse followed, 37.5 μs later, by a skywave pulse 12 dB stronger, (a) as received, and (b) after passing through a typical receiver bandpass filter.

SIGNAL MODELS

A simple model for representing a received Loran-C signal, employed in [1-5], will be used again here. The model assumes that skywave pulses have the same shape as the groundwave but are delayed, and have different amplitudes. Thus, in the time domain, the composite received signal $x_c(t)$ is:

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

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 $i(t)$ is the total noise and interference.

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

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

where $X_c(f)$, $X_g(f)$ and $I(f)$ represent the Fourier transforms (ie the spectra) of the signals $x_c(t)$, $x_g(t)$ and $i(t)$, respectively.

THE IFFT SPECTRAL-DIVISION METHOD

In the IFFT spectral-division method of analysing the incoming signal [5] we start by dividing the spectrum of the received pulse (groundwave and skywaves) by that of a standard Loran-C pulse. Then, we return to the time domain by taking the inverse Fourier transform (IFFT) of the result; that is:

$$F^{-\mathbf{1}}\left[\frac{X_c(f)}{X_{\mathbf{0}}(f)}\right] = k_g\left[\delta(t) + \sum_{n=1}^{N} k_n \delta(t-\tau_n)\right] + F^{-\mathbf{1}}\left[\frac{I(f)}{X_{\mathbf{0}}(f)}\right] \tag{3}$$

where F^{-1} represents the IFFT operator, $X_0(f)$ is the spectrum of the normalized standard Loran-C pulse $x_0(t)$, and k_g is a constant related to the amplitude of the groundwave signal. The first term on the right hand side of equation (3) clearly shows that any skywave delay time can be found from the corresponding impulses caused by that skywave components. 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.

PERFORMANCE ANALYSIS

This section evaluates the performance of the IFFT algorithm. The evaluation will be conducted by means of computer simulation employing a Monte Carlo method. The simulation set-up is discussed briefly first, followed by the simulation results.

Simulation Set-up

Fig. 2 shows a functional block diagram of the simulation program, which is a realisation of the concept in equation (3) for skywave estimation. The programs of each functional block are implemented in Matlab. In the simulations, the received composite signals consisting of groundwave and skywave components plus noise are generated in the computer, then processed in a way that duplicates the effects of a typical Loran receiver front end. Finally they are input to the skywave detection channel block which attempts to determine the arrival delays of the skywaves.

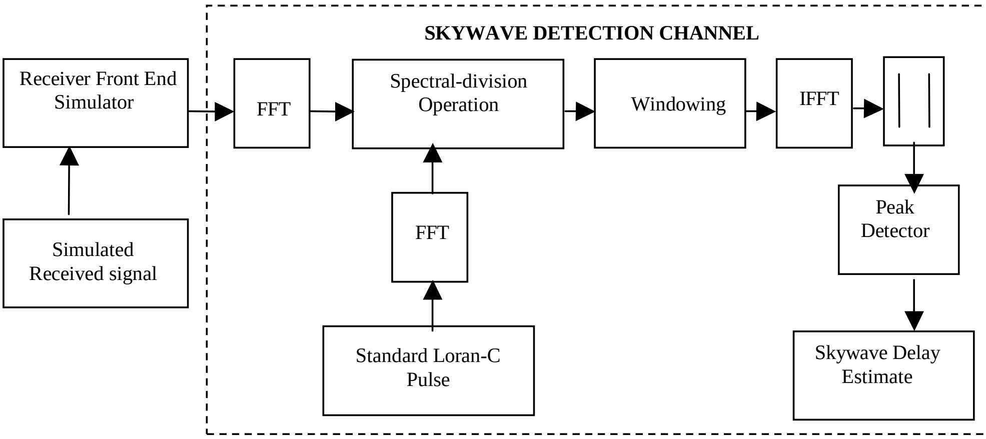


Fig. 2 Functional block diagram of simulation programs to test the operation of the IFFT skywave detection technique.

Results of the Simulation

Fig. 3 shows an example in which the IFFT method is used to analyse a noise-free signal consisting of a groundwave pulse followed, 50 μs later, by a 12 dB stronger skywave component. In the figure, the arrival time of the start of the groundwave has been set to 100 μs, and the strength of its impulse normalised to unity. The delay of the skywave component, 50 μs, and its skywave-to-ground wave ratio (SGR) of 4 (ie 12 dB) are seen clearly. Fig. 4 shows the uniform phase and clean amplitude spectrum of $X_c(f)/X_0(f)$ in this case.

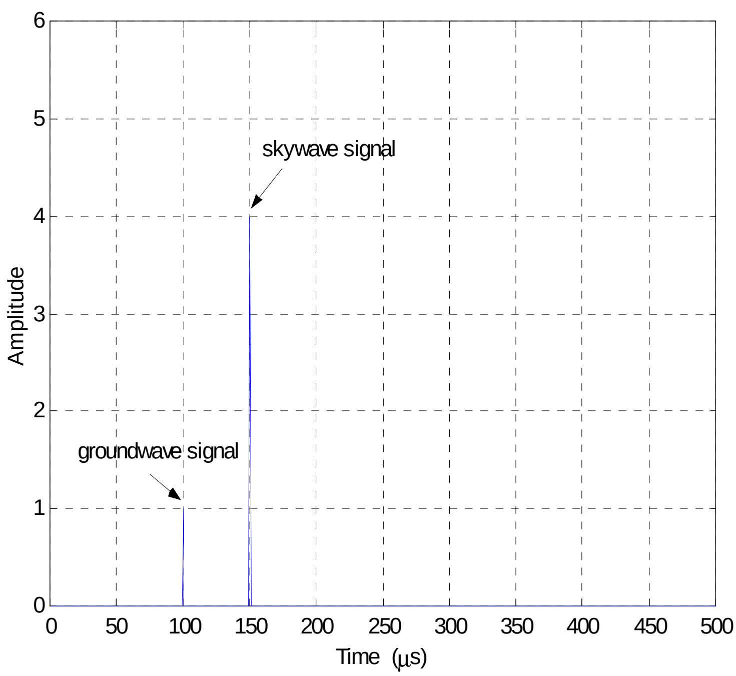


Fig. 3 Groundwave and skywave components separated by the IFFT method under noise-free conditions. SGR=12 dB and skywave delay=50 μs.

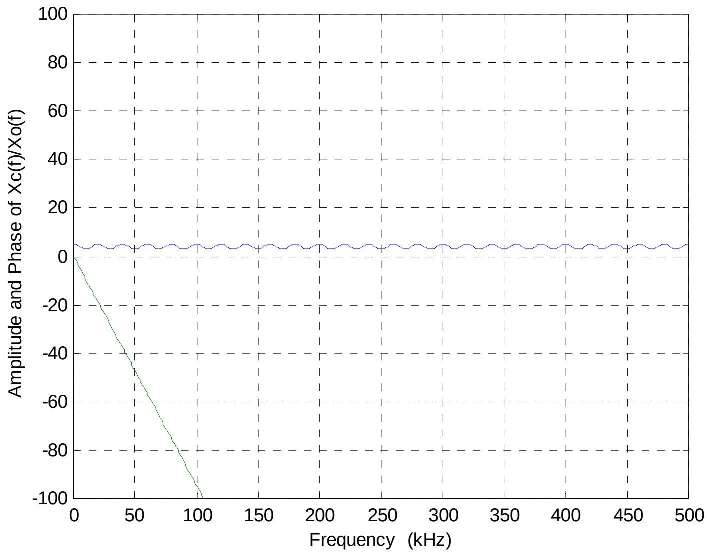


Fig. 4 The phase (green curve) and amplitude (blue curve) components of the spectrum of $X_c(f)/X_0(f)$ for the signals and conditions of Fig. 3.

Let us now examine the ability of the IFFT algorithm to detect skywaves in the presence of noise. Fig. 5 shows the result of the skywave delay estimation process with an SNR of 24 dB. This is the SNR of the signal on which the spectral division operation is performed. It corresponds to an SNR at the antenna of –13 dB in a Loran-C receiver with typical front-end filtering, phase decoding, and averaging operations. The impulse correponding to the skywave component (Fig. 5) is completely buried in the noise. This can easily be explained by looking at the phase and amplitude components of the spectum of $X_c(f)/X_0(f)$ in Fig. 6: the noise outside the Loran frequency band has been magnified substantially by the division operation, and phase fluctuations are also apparent.

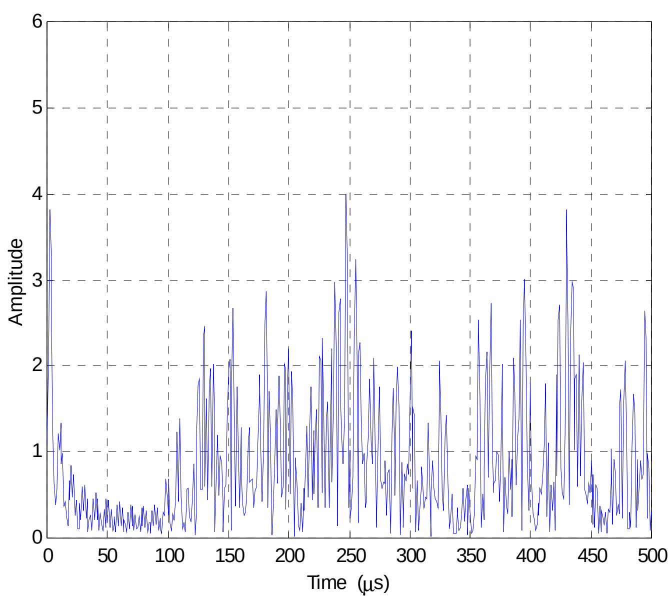


Fig. 5 Skywave estimation result under noisy conditions; the skywave impulse is lost in the noise when no spectral window is employed. SNR=24 dB (equivalent to an antenna SNR of -13 dB).

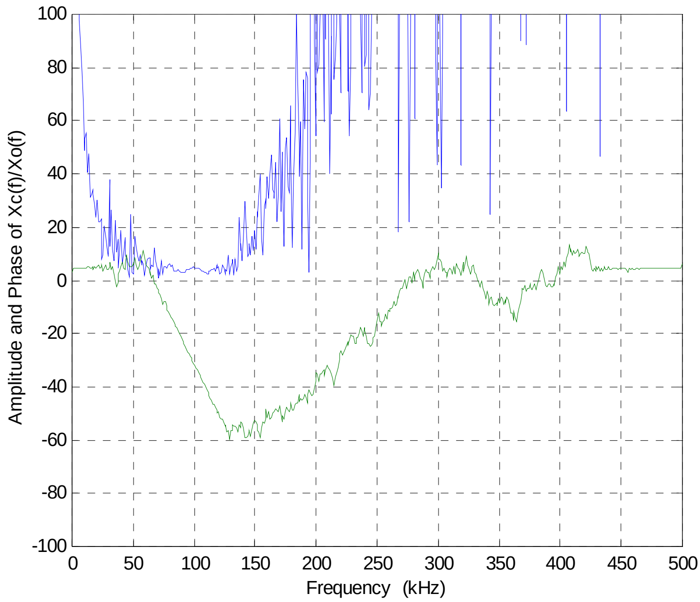
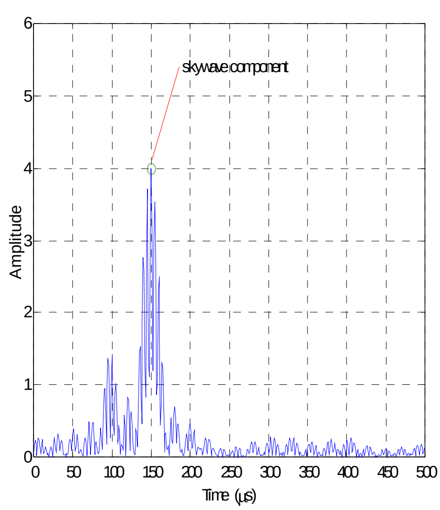


Fig. 6 The phase (green curve) and amplitude (blue curve) components of the spectrum of $X_c(f)/X_0(f)$ under noisy conditions (SNR=24 dB).

To overcome this problem, a windowing function has been employed to attenuate spectral components outside the 90-110 kHz band. The width and type of this function affect the resolution of the skywave estimation process significantly. Multiple computer simulations have shown that 80 kHz is the maximum width for successful skywave detection, and the optimum value is 50 kHz. Fig. 7 shows the performance of the process with this optimum window dramatically reducing the noise: the skywave component stands out clearly and its delay is estimated as 50 μs, which is correct.



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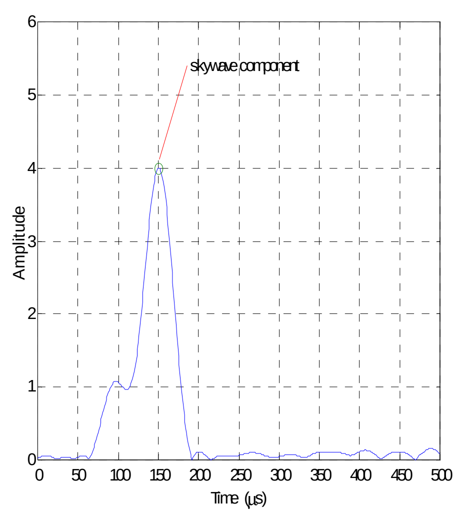


(b)

Fig. 7 Skywave delay estimation under noisy conditions (SNR=24 dB, SGR=12 dB and skywave delay=50 μs). The use of a window filter of 50 kHz bandwidth ensures correct operation. (a) Rectangular window, (b) Hanning window.

Extensive simulations have shown that the IFFT method can detect Loran-C skywaves down to very low SNR's. Successful operation was demonstrated even at an SNR a little below 14 dB, equivalent to an antenna SNR of -23 dB. This figure is more than 13 dB below the minimum SNR specified by the United States Coast Guard (USCG) for correct operation of Loran-C receivers [7].

Fig. 8 plots the skywave delay estimates made by the IFFT process at this SNR over 100 individual runs of the simulation (skywave delay and strength as previously). The mean value of the delay estimates was 50.17 μs and their standard deviation a very acceptable 1.263 μs. Fig. 9 shows a typical estimation result from one of these runs.

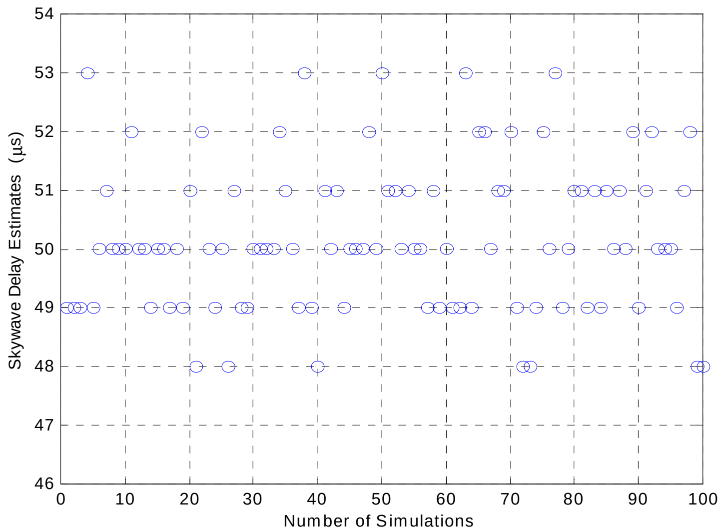


Fig. 8 Skywave delay estimates made by the IFFT method over 100 individual simulation runs. SNR=14 dB (-23 dB at antenna), SGR=12 dB and skywave delay=50 μs.

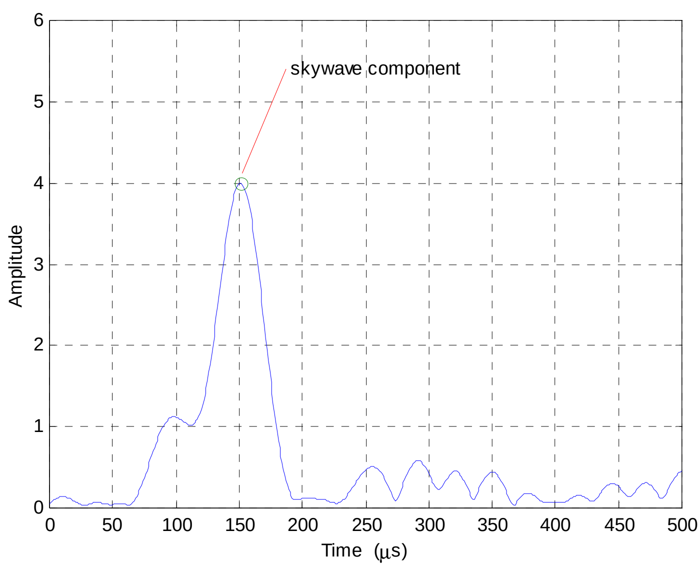
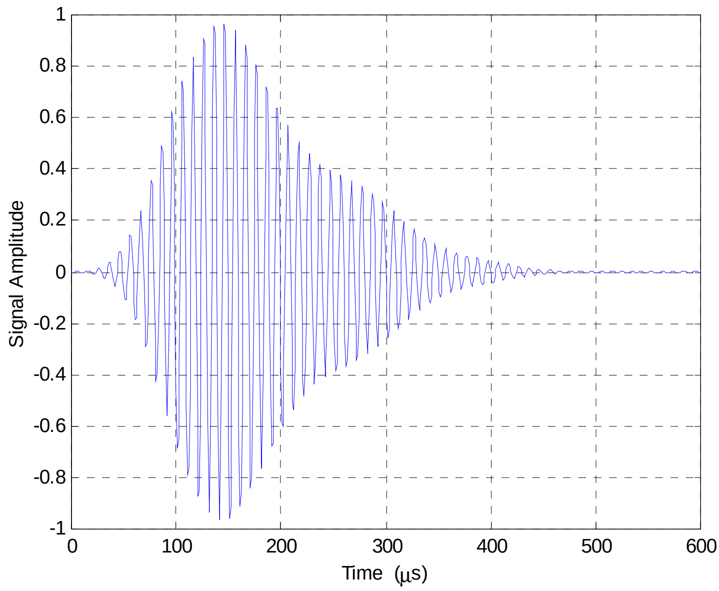


Fig. 9 A typical skywave delay estimate result made by the IFFT method, which corresponds to one of the circles in Fig. 8.

Results using off-air data

The performance of the IFFT algorithm has been further evaluated using off-air data collected by Van Nee of Delft University of Technology, Netherlands (Fig. 10a). Even though Van Nee's sampling rate was only 250 kHz (which allows some aliasing) and the resolution of his data only 8 bits (resulting in quantization error), the IFFT successfully isolated the skywave components and measured their delays (Fig. 10b). The start of the skywave at 55 μs is clearly separated from that of the ground wave at 155 μs; the skywave delay is thus estimated as 100 μs. A Hanning window of 50 kHz was used in this test. This is the **first time** off-air Loran-C skywave delays have been successfully estimated using the IFFT technique.



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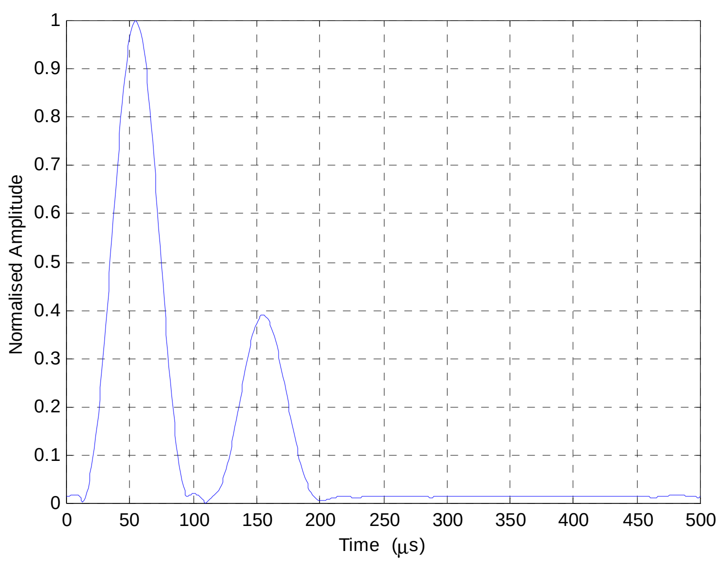

(b)

Fig. 10 Off-air data plotted in (a) and estimated times of its groundwave and skywave isolated by the IFFT method. Off-air data supplied by Van Nee of Delft University.

CONCLUSIONS

The IFFT technique is a computationally efficient and robust algorithm for use in Loran-C receivers to estimate skywave delays. This paper has analyzed the effects of filtering and noise on the accuracy and quality of skywave delay estimates made using this algorithm. It has been shown that the IFFT technique can be used to separate the groundwave and skywave components of the composite received pulse, and that it can operate successfully with very noisy signals, down to more than 13 dB below the USCG minimum standard. The paper has also demonstrated for the **first time** skywave estimates made by the IFFT algorithm using off-air signals.

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BIOGRAPHIES

Dr. Abbas Mohammed is a Senior Lecturer and Head of the Telecommunications Group (Ronneby Site) at Blekinge Institute of Technology (formerly the University of Karlskrona/Ronneby), Sweden. He was awarded the degrees of MSc by Cranfield Institute of Technology, England, in 1987 and PhD by the University of Liverpool, England, in 1992. From 1993 to 1996 he was a Post-Doctoral Research Fellow in the Radio Navigation Group at the University of Wales, Bangor. Between 1996 and 1998 he worked on a European Project in Satellite Mobile Communications at the University of Newcastle, England. 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.

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 a Board Member and holder of the Medal of Merit of the International Loran Association. He is also 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.

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