# Analysis and Modeling of Skywave Behavior

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## 1.0 Introduction

Skywave signals are an inherent part of low frequency transmissions such as Loran. Unfortunately for navigation users, skywave signals are a source of interference to the Loran groundwave signal used for the range determination. The interference increases the variability of the range measurement. The result is poorer accuracy and a potential threat to navigation safety.

The Loran signal design allows the user receiver to mitigate most skywave. While this is acceptable for many applications, safety of life scenarios require dealing with all likely events. This means handling the most severe form of skywave - short delay skywave or "early skywave". Since early skywave is difficult for a moving user to detect, the *eLoran* system will have to provide warning of these events. Likely, it will utilize a monitor network to detect and warn against situations that would lead to early skywave. These monitors need to be able to detect early skywave and do so in a rapid manner. This paper examines the nature of skywave and how it induces error through the receiver front. First, an understanding how the front end affects the Loran skywave is needed to allow us to develop reasonable models and define the threat space. An understanding of the nature of skywave will assist in developing monitoring algorithms for rapid and accurate detection.

We study how the receiver front end affects the error induced by skywave. We model the front end using simple filter models and examine how differences in ECD and delay affect the error in measured time of arrival (TOA). The paper will show that the filter can result in skywave affecting the commonly used tracking point at 30 μsec even if the skywave is delayed by 30 μsecs or more. The result has important implications for the design of early skywave monitor and monitor network algorithms.

To understand the nature and behavior of skywave, we attempt to characterize its behavior. We model the skywave behavior using measurement data gathered from the US Coast Guard and waveform data from seasonal monitor set up for the FAA Loran evaluation. This allows for an understanding of the changes of delay and skywave amplitude over time. These properties define the effect of early skywave. Examining waveform data provides a more direct opportunity for studying skywave. The paper attempts to demonstrate that the skywave experiences a phase reversal upon reflection from the ionosphere and has ECD that differs from the groundwave.

## 2.0 Background on Skywave and Detection

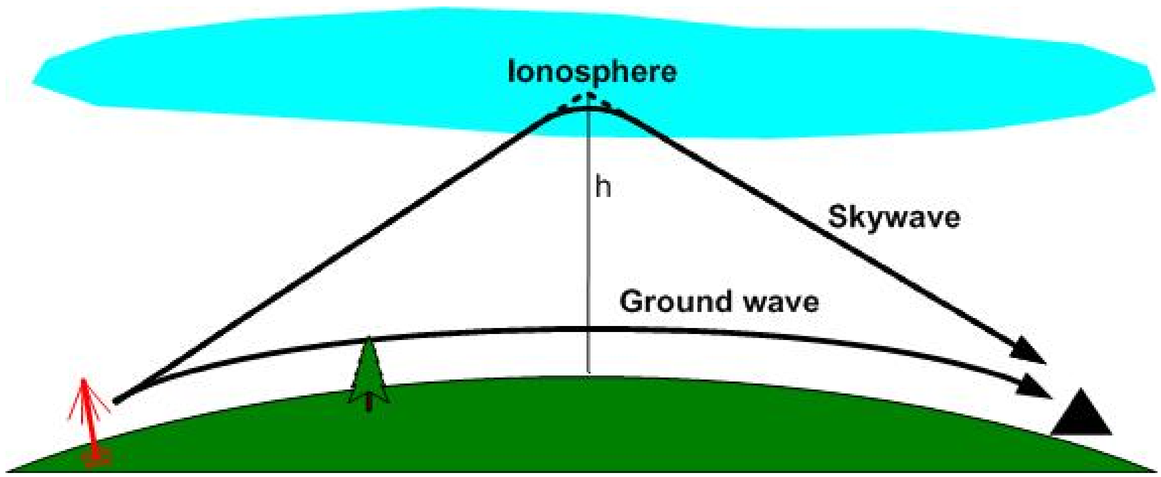


**Figure 1. Skywave and Groundwave**

### 2.1 Skywave & Early Skywave

Skywave is a means of low frequency (LF) signal propagation whereby the transmitted signal traverses through the atmosphere and is "reflected" by ionosphere to a user. While skywave is typically termed a reflection, it is caused by a combination of effects. First, there is a refraction phenomenon. This results in bending of the signal back to the earth as seen in Figure 1. Additionally, there is signal reflection due to LF scattering. For simplicity, we will use the shorthand reflection to stand in for the redirection of the signal. Both single reflection (single hop) and multiple reflections (multi-hop) can occur.

Even with nominal ionosphere conditions, Loran skywaves are commonplace. The nominal nighttime ionospheric environment results in a skywave that is stronger than in the daytime. The nighttime ionosphere also tends to have a higher ionosphere reflection height for Loran resulting in a greater delay relative to the groundwave than in the day time. Figure 2 shows skywave delay and amplitude (for a 1 kW peak power transmitter) for a variety of nominal conditions (summer and winter day, night) and rare conditions such as polar cap disturbance (PCD). The delay and amplitude is typically related to ionosphere reflection heights with day and night time ionosphere reflection heights generally around 60 and 80 kilometers, respectively. Equations 1 and 2 give the difference is path length between the skywave and groundwave ($\Delta p$) as a function of distance ($d$) and reflection height ($h$) for a flat and spherical (radius = $R_e$) earth, respectively. For the spherical earth, $d$ is the propagation distance over the ground and equals $Re*\theta$ where θ is the arc of the earth traversed. The difference in path lengths is converted to delay by dividing by the propagation speed, that is, delay = $\Delta p/v$. Using c, the speed of light in a vacuum, is adequate to get within a microsecond.

$$\Delta p = \left( 2\sqrt{\left(\tfrac{d}{2}\right)^2 + h^2} - d \right) \text{ (flat earth)} \quad (1)$$

$$\Delta p = 2\sqrt{R_e^2 + \left(R_e + h\right)^2 - 2R_e\left(R_e + h\right)\cos\left(\tfrac{d}{2R_e}\right)} - d \quad (2)$$

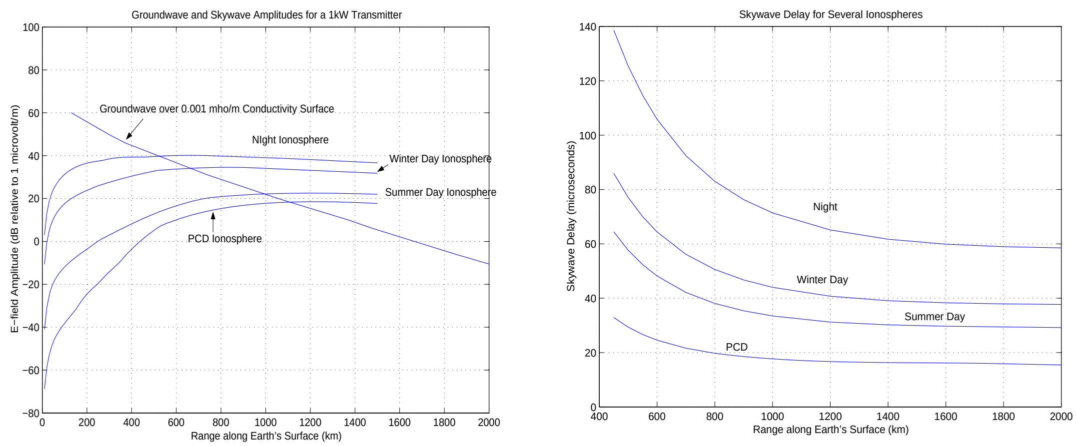


**Figure 2. Typical groundwave and skywave amplitude (Left) & Delay (Right) for different ionospheric conditions [1]**

Most skywave can be mitigated by receiver processing. The Loran signal rise time was designed so that there will be a sufficiently strong signal that is free of most typical skywave. Most skywaves are delayed such that they do not affect the groundwave signal at the standard zero crossing (SZC) point at 30 μsec. The rise time of the Loran pulse results in a signal power at the SZC that is only 4 dB lower than that of the peak. Signal coding design is used to mitigate longer delay, multiple hop skywave.

Early skywave is skywave that is not significantly delayed relative to the ground wave. There is no specific demarcation value of delay between early and typical skywave. Two demarcation points are skywave delays of 35 and 37.5 μsec to the groundwave. These values come from maritime and aviation specifications, respectively [2][3][4] and specifies the minimum skywave delay (and strength) that a receiver must handle. While any demarcation point is somewhat arbitrary, designating a different class of skywave is valuable. As the relative skywave delay decreases, the skywave interferes more and more with the portions of groundwave signal used for tracking. The result is that the receiver's ability accurately track the groundwave and eliminate the adverse effects of the skywave becomes increasingly impaired. The mitigation of early skywave is much more difficult than mitigating typical skywave. This is especially true for receivers on mobile platforms such as aircraft or ships.

Strong early skywave can be reasonably common in the daytime at high geomagnetic latitudes. As seen in the Port Clarence study, early skywave phenomena could be observed about 3.6% of the time for the Port Clarence-Tok, AK baseline [5]. Other studies also indicate an occurrence level of early skywave conditions on this baseline of 2-3 percent [6]. Early skywave is also common when there is severe solar weather activity such as PCD. Under conditions of adverse solar weather, the ionosphere can be disturbed enough to lower the Loran reflection height. This results in a reasonably strong reflected Loran signal with smaller delays than typical. This is also a daytime phenomenon as the reflection region must be illuminated by the sun for the ionosphere to be adequately disturbed. As both phenomena are caused by a lower ionospheric reflection height, the likelihood of early skywave increases with distance from the transmitter. From ionosphere behavior and geometry, early skywave typically only occur at a distances of greater than 800 km from the transmitting source [1].

## 2.2 Early Skywave Monitor Network

As a result, the Loran system has traditionally provided means of alerting users to the presence of early skywave. In Loran-C, a system area monitor (SAM) examines signals to detect out of tolerance (OOT) conditions on the transmitted signal. If such a condition exists, the transmitter initiates "blink" to indicate that its signal is OOT[1]. This captures many early skywave events as they can cause the baseline time difference of arrivals (TDOA) or the envelope to cycle difference (ECD) to be OOT. However, this method cannot definitively detect all early skywave or warn all affected users in the coverage region within a ten second time to alert (TTA). This TTA is necessary to support aviation approach and HEA.

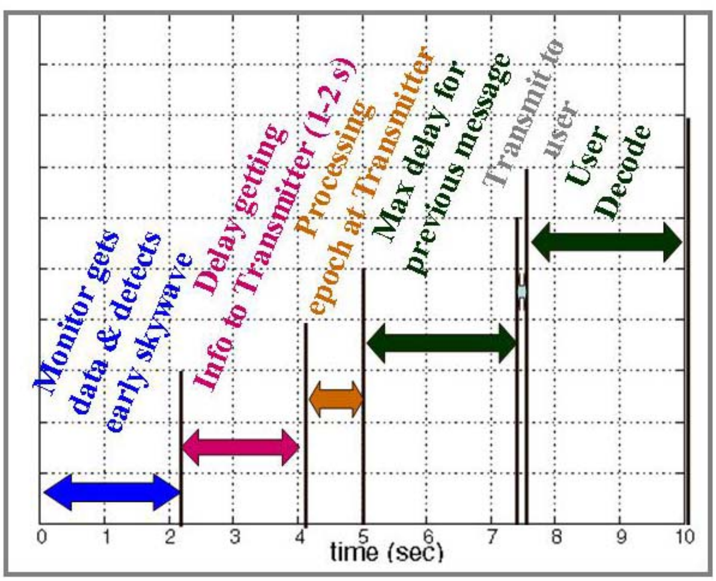


**Figure 3. Timeline for detection of early skywave and broadcast of warning to meet ten second TTA**

The FAA Loran evaluation team determined that an early skywave monitor network is necessary to provide integrity to meet a ten second TTA [8]. It was felt that the approach

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[1] Blink is a repeating on-off sequence on the first two pulses of the eight pulse sequence of a secondary Loran station. It is used to indicate a TDOA or ECD OOT condition as well as other faults (improper phase code or low power) that would case a baseline to be unusable. The sequence is approximately 3.75 seconds where the first two pulses are not transmitter (off) and 0.25 seconds where they are transmitted (on) [7]

allows for better visibility and response to early skywave events. A single monitor may miss detection because local effects vary depending on the relative phase between groundwave and skywave. Additionally, a single monitor may only detect early skywave after it has affected the user. This can occur as the sun illuminated area moves westward. So, a user to the east of the monitor may experience the effect of the event prior to the monitor. A network solution can mitigate these issues. The monitor network provides multiple opportunities to detect early skywave. The network then provides information about the existence of the event and the geographic extent of the event so that a warning can be sent over the *eLoran* data channel.

Even with a monitor network, meeting a ten second TTA is still very challenging as it means that detection must occur in seconds. Given the timeline in Figure 3, the detection may need to occur within two to three seconds of early skywave affecting a user. As a result, a detailed understanding of the behavior and characteristics of skywave is useful for designing monitor algorithms that can achieve fast detection with low false alarm rates. We examine several forms of data to develop a better understanding of skywave.

## 2.3 Data for Assessment

The primary set of data used for the assessment comes from the operational SAMs of United States Loran system. The SAMs provide various forms of data from the Locus LRS IIID monitor receivers. We use the "Out" data from 2005 which provides the measured TDOA and ECD at a 0.1 Hz rate. The data was examined to find potential instances of early skywave. Some instances indicating the presence of early skywave were found between September 6$^{th}$ to 8$^{th}$ of 2005. The Point Cabrillo monitor is located at 39° 20' 54.1" N and 123° 40' 29.4" W. The Point Pinos monitor is located at 36° 38' 12.36" N and 121° 56' 7.95" W. The Searchlight, NV and George, WA transmitters are located approximately 1130 km and 1020 km away from the Point Cabrillo monitor site, respectively. These stations are 1150 and 1040 km away from the Point Pinos monitor site.

Another source of data used for the analysis was collected at Stanford, CA using the Enhanced Loran receiver (ELR) [9]. Averaged waveform data was collected from the receiver from a few days in June 2008. An averaged waveform is outputted at roughly 25 seconds. Each waveform is presented with inphase (I) and quadrature (Q) samples taken every 2.5 µsec (400 kHz). The waveform data from signals in the U.S. West Coast chain (GRI 9940) as well as the Gillette, WY station is collected. This data has two benefits. First, it allows us to see the entire waveform and how it evolves through time rather than to extrapolate this behavior from the observations parameters available from the SAM data. Second, the filtering and algorithms employed by the ELR are well known and their effects can be well modeled. In this first generation ELR, there is almost no filtering prior to sampling except by the antenna. As early skywave is rare in this region, no data sets with early skywave were found in the short amount of time these samples were collected.

### 2.4 Basic Skywave Model

The basic model developed for the composite signal uses from the definition of the nominal Loran signal. The nominal signal (with positive phase code) is given in Equation 3. The groundwave ECD and envelope are given $\tau_g$ and $B_g(t)$, respectively. Skywave (single hop) is modeled as a replica of the groundwave with its ECD ($\tau_s$), delay relative to groundwave ($d$), and amplitude ($A_s$). The skywave model and the resulting composite signal are given in Equation 4 and 5, respectively. The difference in amplitude is quantified by the skywave to groundwave ratio (SGR) given by Equation 6.

There is a growing belief that a one hop skywave is roughly phase inverted[2]. Peterson, Morris and others have suggested the existence of a phase reversal[6]. Peterson shows many estimated skywave delays in Figures 5, 7, and 8 of [5]. One noticeable feature is the lack of skywave delays between 28 and 31 μsec. This is despite having many estimated skywave delays that are greater and less than these values. The reason is that the delays were estimated with a template for skywave based on the groundwave. This means that skywave has the same phase code as the groundwave. If the template was reversed, many samples would result in delays between 28 and 31 μsec as that was the envelope delay. This is more consistent with the physics which would not show any bias for or against such delays.

In our analysis, we use the variable $sign_s$ to model the two possible phase configuration of the skywave. If the ionosphere reflection inverts the phase (shifts phase by 180 deg) then $sign_s$ is -1 = cos(180°). The inversion is a reversal of the phase code on the signal. If the phase is not changed by the ionosphere, $sign_s$ is +1. Having the variable allows us to test whether the skywave signal is inverted relative to the incident signal.

$$g(t) = A_g (t-\tau_g)^2 e^{\left(\frac{-2(t-\tau_g)}{65\mu\sec}\right)} \sin\left(\frac{2\pi t}{10\mu\sec}\right) = B_g(t)\sin\left(\frac{2\pi t}{10\mu\sec}\right) \quad \textbf{(3)}$$

$$s(t) = sign_s A_s (t-\tau_s-d)^2 e^{\left(\frac{-2(t-\tau_s-d)}{65\mu\sec}\right)} \sin\left(\frac{2\pi(t-d)}{10\mu\sec}\right) = sign_s B_s(t)\sin\left(\frac{2\pi(t-d)}{10\mu\sec}\right) \quad \textbf{(4)}$$

$$c(t) = B_g(t)\sin\left(\frac{2\pi t}{10\mu\sec}\right) + sign_s B_s(t)\sin\left(\frac{2\pi(t-d)}{10\mu\sec}\right) \quad \textbf{(5)}$$

$$SGR = 20\log\left(\frac{A_s}{A_g}\right) \quad \textbf{(6)}$$

# 3.0 Filter Effects

[2] The inversion is a simplification assuming a uniform flat ionosphere. If the reflection height is not uniform, the inversion measured will not be exactly 180 degrees. In this case, the skywave may come in from a different direction than the groundwave.

The receiver front end filter alters the Loran signal and so it affects the TOA, TDOA and ECD measurements. As any data collected is filtered by the receiving equipment, it is important to quantify the impact of filtering. This analysis allows us to better understand and perhaps incorporate the effect of our data collection equipment. To see the impact, we use the basic composite model to study the effect of skywave through some simple filtering. Butterworth filters are used for the analysis as these filters are commonly used. For example, the Austron 5000, a Loran monitor receiver, had a fairly wide two pole Butterworth filter in the coupler and a five pole Bessel filter in the receiver. It tracks at about the 53 μsec point. This is because of the delay caused by filtering and is equivalent to tracking at roughly the 30 μsec point of an unfiltered signal.

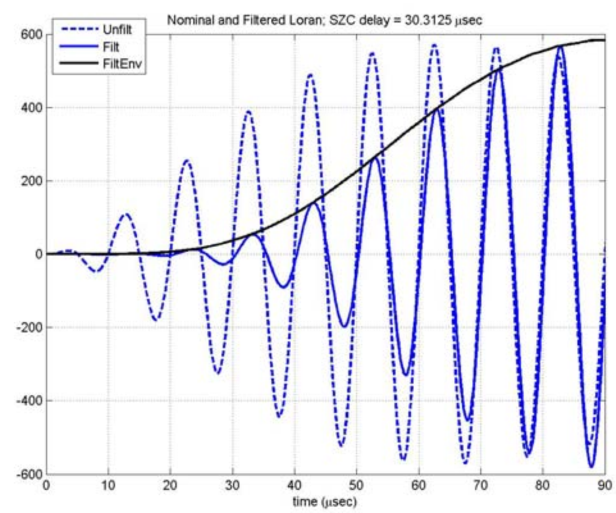


**Figure 4. Nominal Loran signal and Filtered Loran signal and envelope (8th order butterworth)**

The filtering causes differential group delay which effectively shifts and alters the envelope relative to the carrier. The shift is not the same for the entire envelope with the resulting pulse being effectively elongated as finite filters increase rise time[10]. These filtering effects can be seen in the signal. Figure 4 shows a nominal unfiltered Loran signal along with a signal that has been filtered through an 8th order Butterworth bandpass filter (30 kHz). The peak of the envelope and the peak determined "SZC" of the filtered signal are delayed 27.6 μsec and 30.3 μsec relative to the peak of the unfiltered signal, respectively. The "SZC" is the nearest positive zero crossing that is 35 μsec from the peak. However, the start of filtered signal is delayed only 15 μsec relative to the start of the unfiltered signal significant amplitude. In this example, if the peak of the envelope is defined as the 65 μsec then there will be signal energy -15 μsec before the nominal start (0 μsec) of the signal. So a receiver that uses the peak to determine the SZC will actually be tracking 45 μsec after the start of the pulse. A similar result, where the receiver tracks at a point noticeably later than 30 μsec after the pulse energy starts, also occurs if envelope slope is used to find the SZC. This is because the envelope is "elongated". In this example, a skywave with 35 or 40 μsec delay can effect 30 μsec tracking point. A receiver could be designed to track earlier such that it is tracking 30 μsec after the start of the filtered pulse. However, this results in a degradation of the signal amplitude relative to the 30 μsec point on an unfiltered pulse.

As a result, the filtering will either result in the receiver tracking later than 30 μsec from the start or suffer a loss of received energy. It is important to note that the shift and elongation due to filtering is common to all signals and so does not affect the position solution.

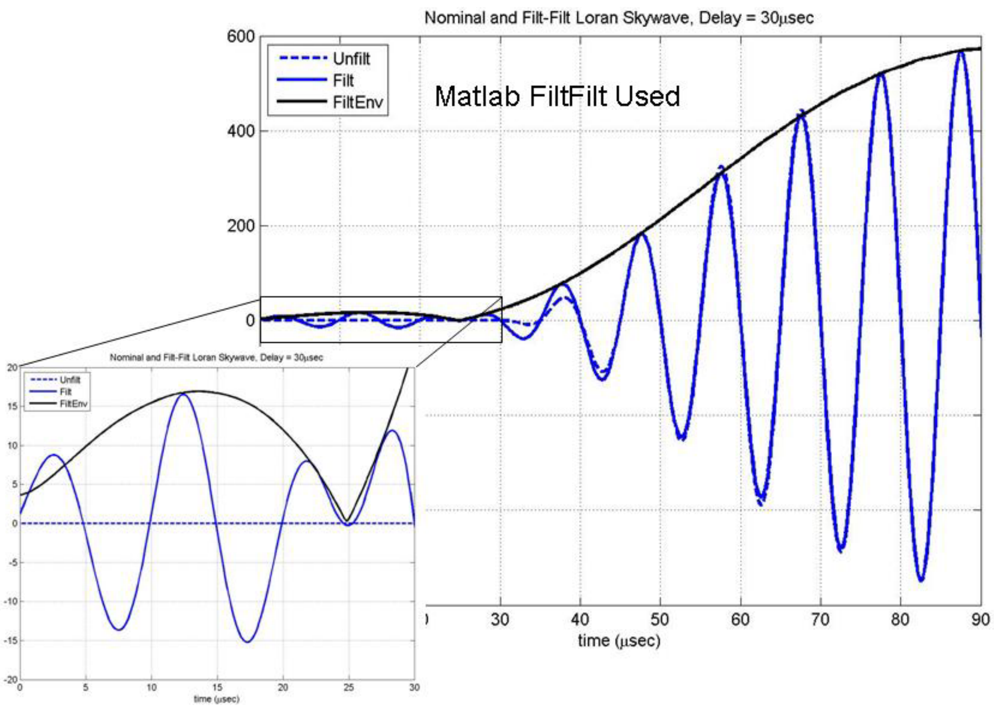


**Figure 5. Effects of a Noncausal Butterworth filter (filt-filt)**

The effect is even more clear when examining a noncausal filter. Figure 5 compares the unfiltered signal to one that has been through a non-causal Butterworth filter using the Matlab filtfilt function. The envelope of the unfiltered and the filtered signal match quite well after 30 μsec (the signal starts at 25 μsec). However, with the filtered signal, there is very visible energy prior to the "start" of the unfiltered pulse.

Filter induced effects have implications on which delays the skywave monitor needs to be concerned with. The filter induced effects on measurements from the signal is seen in Figure 6 where the resulting TOA and ECD errors from tracking at the 30 μsec point is shown for different skywave delays. The analysis assumes that the skywave phase is 180 degrees (phase inverted) from the groundwave. With no filtering (right), skywave delays of 25 μsec or more have relatively little or no effects. However, with filtering, skywave delays of 30 μsec cause noticeable errors in TOA and ECD. A 2$^{nd}$ order Butterworth filter was used in this case.

The effect of skywave on the TOA and ECD from an LRS IIID receiver is seen in [6]. Using those results, an approximation of the effect of a phase inverted skywave is presented in Figure 7. The results differ from the 2nd order Butterworth, particularly for ECD. This is not surprising because ECD is a measure of group delay and not well suited as a metric for interference. The effect of skywave on the calculated ECD depends on how and at what locations on the pulse the calculation is performed. For Figure 6, the ratio of the pulse at 17.5 and 22.5 µsec is used to estimate ECD. If 12.5 and 17.5 µsec are used, the effect of the same skywave on ECD would be much smaller. Also note that we do not follow the exact definition of ECD from [7] as ECD is allowed to exceed 5 µsec. The TOA error between the basic 2nd order Butterworth filter model and the LRS IIID also differ with the LRS IIID generally having lower error magnitudes. The lower magnitude may be the result of using tracking points prior to the SZC or using an average over several zero crossings.

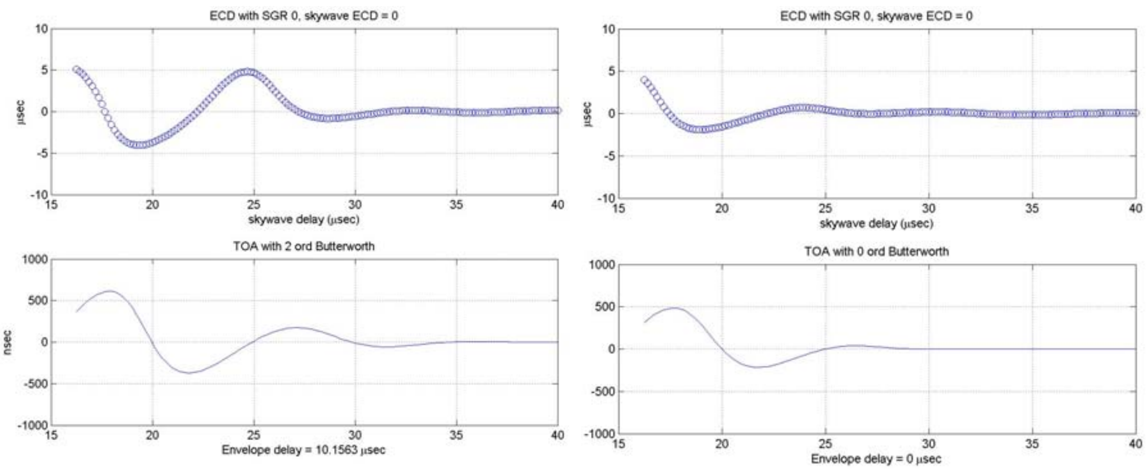


**Figure 6. Effect on ECD (top) and TOA (bottom) with a 0 dB SGR skywave when signal passes through no bandpass filter (Right) and 2nd order Butterworth filtered (Left)**

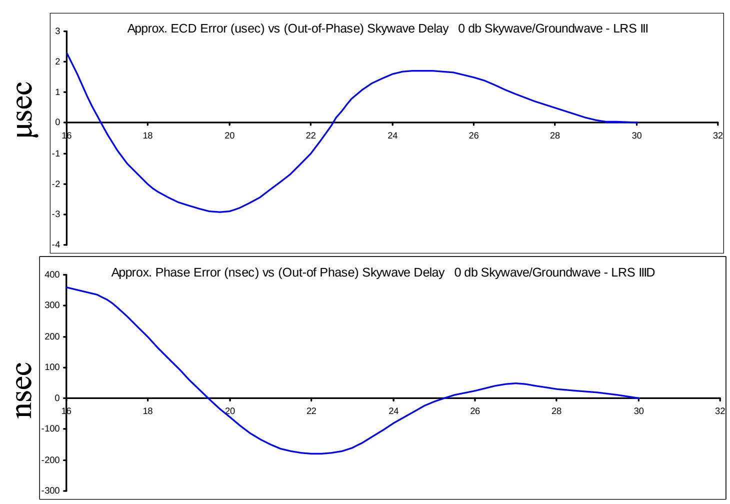


**Figure 7. Effect on ECD (top) and TOA (bottom) with a 0 dB SGR skywave when signal passes through Locus LRS IIID based on results in [6]**

We developed several 2nd order Butterworth filter models with different methods of estimating ECD and TOA. From these models, curves of the TOA and ECD errors as a function of SGR and ECD of the incident skywave are generated. Figure 8 and Figure 9 show results from a basic model ("basic model") and a model that attempts to match the LRS IIID ("LRS model"), respectively. A family of curves for different SGR is shown. Different relative ECD (between skywave and groundwave) are also tested. These curves are generated and used for the estimation in Section 4.1. The basic model uses the SZC and the ratio from 17.5 and 22.5 μsec for TOA and ECD, respectively. The LRS model uses multiple tracking points and envelope ratios to calculate TOA and ECD, respectively. The model attempts to match the results of Figure 7. Unfortunately, there are no results from the LRS IIID for skywave with delays greater than 30 μsec to match. From Figure 7, it is likely that such skywaves produce very small (less than a few nanoseconds) or no effect on TOA. The overall match is reasonable but not exact.

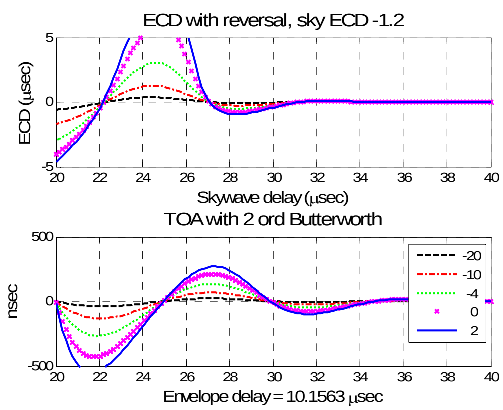


**Figure 8. Effect of 2nd Order Butterworth (basic model) on ECD and TOA for different SGR**

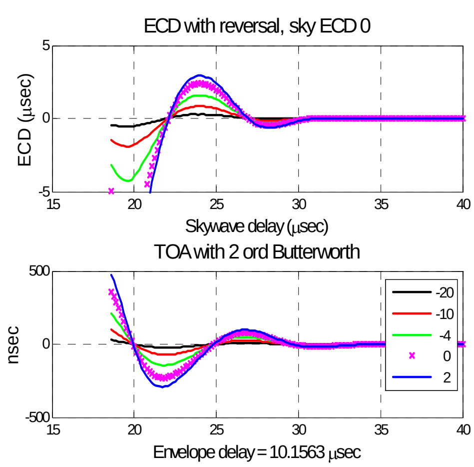


**Figure 9. Effect of 2nd Order Butterworth (LRS model) on ECD for different SGR**

# 4.0 Skywave Behavior & Modeling

Modeling the effects of a skywave signal on the ground wave is an important first step to developing monitoring for early skywave. Creating a reasonably accurate model of the composite groundwave and skywave signal allows us to estimate the phase and ECD of the skywave relative to the groundwave. This allows us to extract these behavior characteristics from the limited data available which in turn allows us to develop detection mechanisms based on this better understanding.

## 4.1 Modeling Skywave with SAM data

The composite signal model is the basis for estimating skywave parameters on the United States Coast Guard (USCG) SAM data. Estimates of the unknown skywave parameters (delay, SGR, and $sign_s$) are made using the observations of TDOA and total ECD. Note that there are three unknowns but only two observations at any time interval. However, the sign is a fixed quantity and does not change over any time period. Both possible phase codes are tested.

To solve for the skywave parameters at each interval, we used a search process and previous estimates of the unknowns. As mentioned previously, we first generate TDOA and ECD errors as a function of skywave delay for different values of SGR and incident skywave ECD. The SGR values used range from 11 to -20 dB (power). Several values of skywave ECD are used as well. As skywave and groundwave likely experience different ECD and the groundwave, ECD difference of -1.2 μsec is often used. This value is roughly the amount of ECD change experienced by groundwave over 900 kilometers (500 nautical miles). This assumption does not significantly effect the match of the model. Then, we examine the residual TDOA and ECD for different possible skywave delays and SGR. This is to determine the value that provides the model with the best fit to the measured TDOA and ECD. The fit is based on a cost function that accounts for differences between the model TDOA and ECD relative to the measured values of those parameters. No optimization is done on the relative weight on the TDOA and ECD difference. Previous estimates are used to enforce near continuous skywave behavior. This was done by limiting the change in the estimated unknown skywave parameters from the previous interval. As long as the initial guess for these parameters are reasonable, the results converge well. There is some sensitivity to initial guess and a few different values are tested for each scenario.

Figure 10 compares the TDOA and ECD derived from the LRS model with their actual values for the George, WA signal as measured by the Point Cabrillo, CA monitor on September 7, 2005. For the phase reversed case (left), the model results are in good agreement with the measurements. For the phase same case (right), the fit is not as good. This is partially due to the limit on SGRs considered. The SGR would have be significant (~ 15-20 dB) to match the ECD. This can be seen in Figure 11 which shows the estimated delays and SGR derived from the model. While SGR of ~15 dB is unlikely for early skywave at 1000 km, the result depends on the accuracy of the model for delays

> 30 μsec.  Similar fits are seen for all data sets examined and result from the following day is seen in Figure 12.

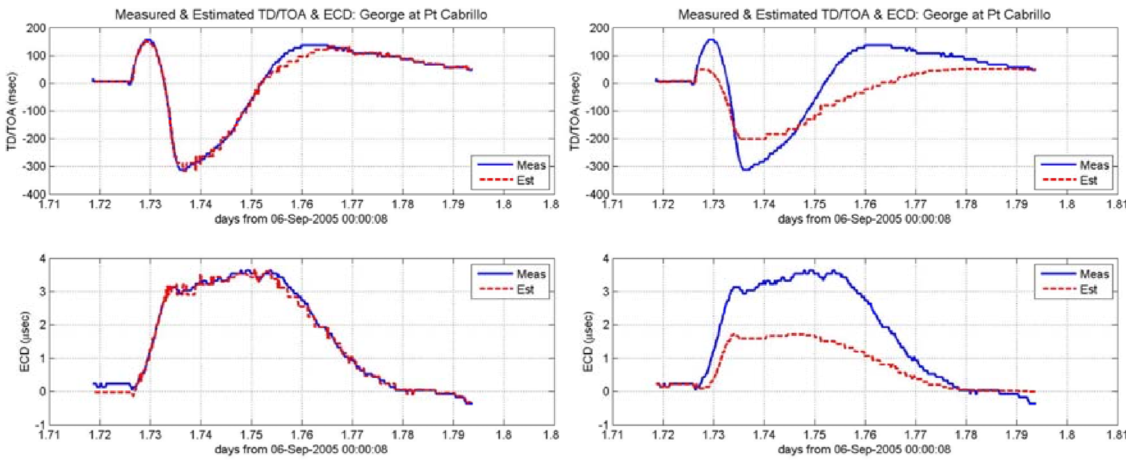


**Figure 10. Measured & Estimate Derived TD & ECD from George, WA at Pt. Cabrillo Sept 7, 2005 (LRS Model), Reverse (Left) and Same Phase (Right) (baseline: 1020 km)**

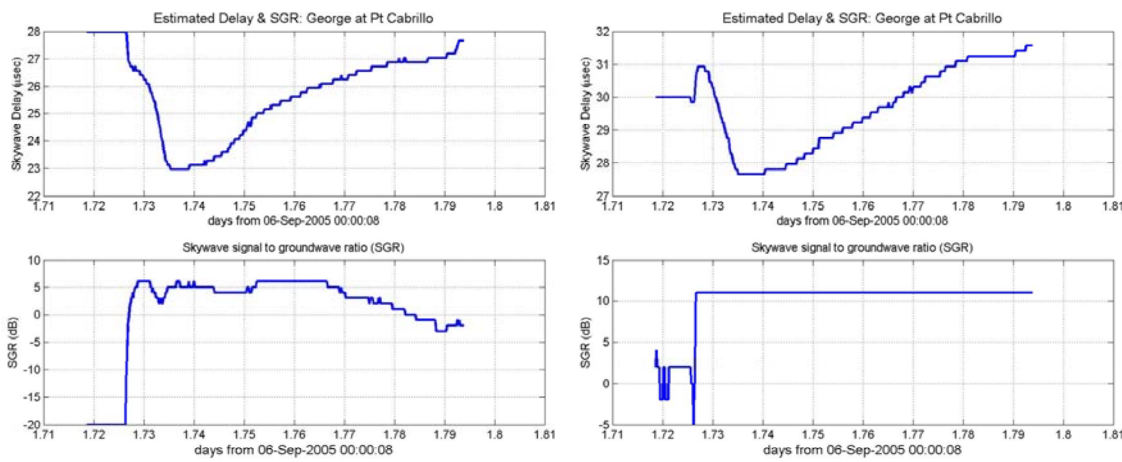


**Figure 11. Estimated Parameters of George, WA signal at Pt. Cabrillo, CA Sept 7, 2005 (LRS Model), Reverse (Left) and Same Phase (Right)**

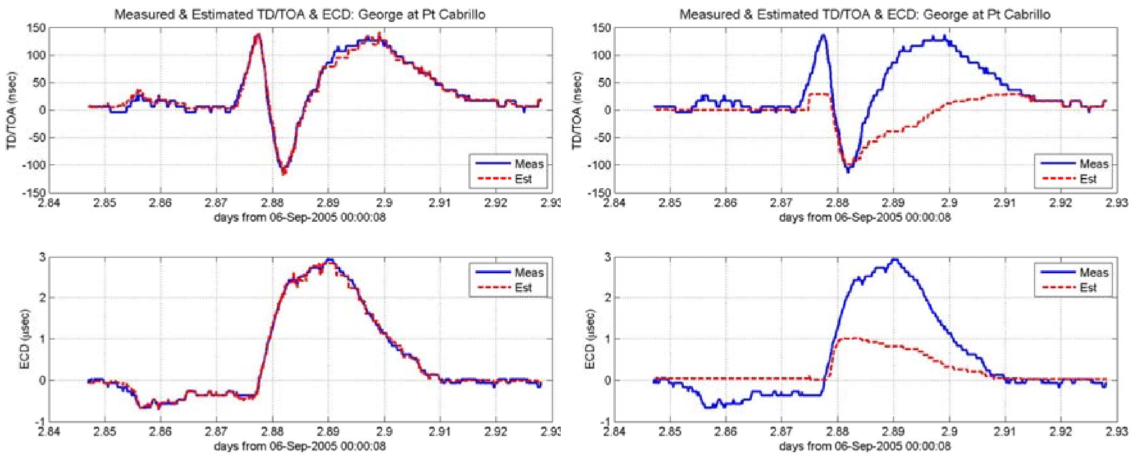


**Figure 12. Measured & Estimate Derived TD & ECD from George, WA at Pt. Cabrillo Sept 8, 2005 (LRS Model), Reverse (Left) and Same Phase (Right) (baseline: 1020 km)**

The result from the model is not surprising. The early skywave events observed start with a significant (~150 nanosec) increase in phase shift. Skywaves should not suddenly appear or increase in strength (this is enforced by the continuity assumption). Given the LRS model which has small effects for skywave delays > 30 µsec, the only reasonable way for this to happen under the conditions described is for the skywave to be phase reversed. For a phase unchanged skywave, the TOA should begin by being negative if skywaves with delays > 30 µsec have no effect. With the LRS model, skywave delays > 30 µsec have minimal effect and so a skywave must be very strong to achieve the increase in TOA and ECD observed.

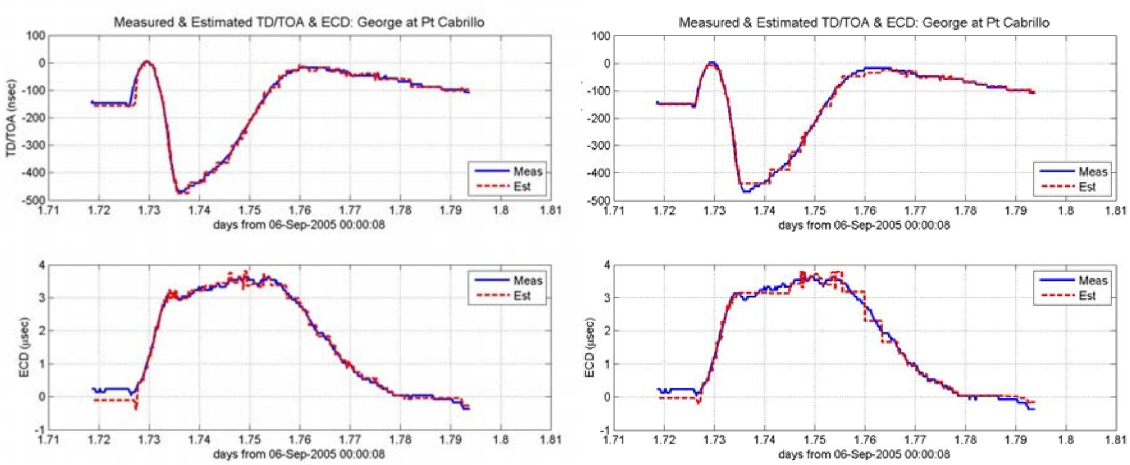


**Figure 13. Measured & Estimate Derived TD & ECD from George, WA at Pt. Cabrillo Sept 7 with basic TOA, ECD determination (Basic Model), Reverse (Left) and Same Phase (Right)**

Given that we are solving for two unknowns with two observations, having a good fit can result despite having an inaccurate model. The estimation process yield reasonable matching, regardless of the phase code assumption, when using the 2$^{nd}$ order Butterworth filter model. Figure 13 shows the TDOA and ECD results for the phase reversed and phase same (right) conditions using the basic model.  Notice that both fits are quite reasonable.  So we can only gain true any insight into the phase effect of the ionosphere from this analysis if we have a very accurate model for the calculation of TOA and ECD along with filter effects is needed.

## 4.2 Using Waveform Data

Waveform data provides another opportunity to examine skywave.  The data allows for direct observation of the skywave.  Data was collected from five stations though only Searchlight, NV and Fallon, NV are used.  The Middletown signal is quite strong resulting in clipping since 1st generation ELR does not have automatic gain control (AGC).  The two other signals have significant noise making a precise estimate of the groundwave and skywave difficult.

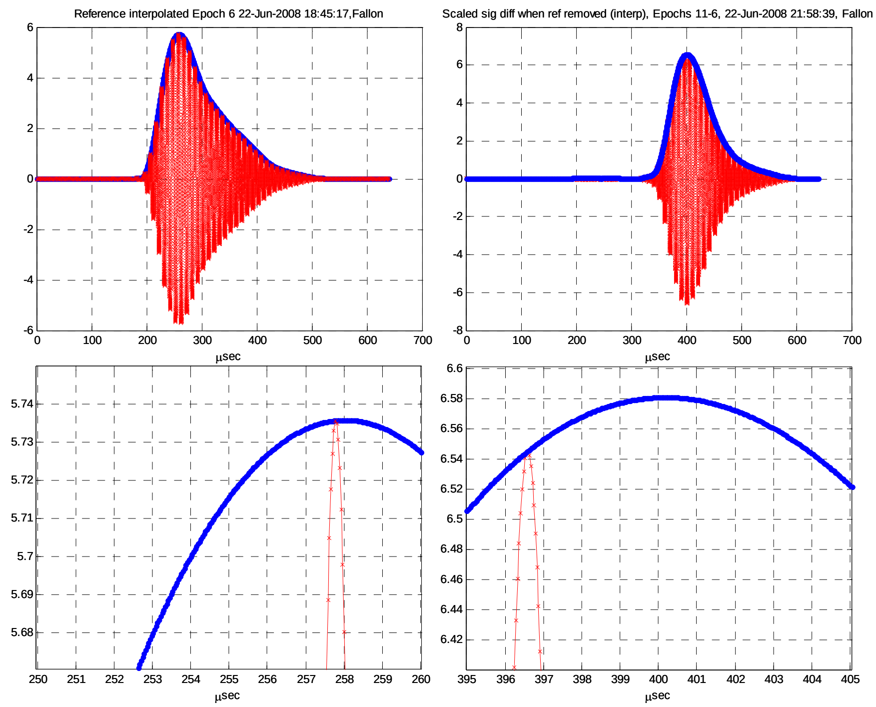


**Figure 14. Groundwave template (Left) and Skywave after groundwave removal (right) with zoom in near envelope peak (bottom), Fallon, NV measured at Stanford, CA 25 June 2008**

The data can be processed to isolate the skywave signal.  One method is to subtract out the groundwave from a signal containing skywave.  This is accomplished by first choosing a reference measurement that contains only the groundwave.  This is the reference or template signal.  Next, a desired measurement containing both skywave and groundwave is found.  To subtract the reference signal from the desired measurement, the reference signal must be up-sampled and shifted to align with the groundwave in the desired measurement.  This is because the data is sampled every 2.5 μsec.  Interpolation based on fast Fourier transform (FFT) is utilized to do the up-sampling to a resolution of 0.15625 μsec or less.  The reference signal is shifted until the residual groundwave post subtraction is minimized leaving the isolated skywave. The result is seen in Figure 14 where the plots on the left and right side show the reference signal and the isolated skywave signal from the Searchlight, NV transmitter, respectively.

The phase of the carrier from the groundwave and isolated skywave signal can now be examined. The phase relative to the envelope peak is examined. An assumption is that the mixing signal used to generate the I and Q signals has the same phase at the beginning of the sampling epoch. The relative phase between the mixing signal and the measured signal is indistinguishable from the ECD and hence a relative measurement is used. We compare the difference between the signal peak and the envelope peak for from both the groundwave and isolated skywave. The bottom plots of Figure 14 show the carrier phase relative to the envelope peak. Table 1 shows the result for Fallon and Searchlight at two different epochs. For the Fallon signal, differences of +4.5 and +6.7 μsec are seen with the skywave delay of approximately 140 μsec. For Searchlight, the differences are smaller at -0.5 and +0.25 μsec with a skywave delay of approximately 90 μsec. Fallon results suggest the possibility of phase reversal while Searchlight does not. The interpretation of the results also depends on the ECD due to propagation and estimation errors. The transmitted Loran signal has an ECD of 2.5 μsec with the groundwave propagation nominally decreasing in the ECD such that it is 0 at 1000 nautical miles. However, a skywave does not experience the same dispersive effect (frequency dependent delay) and will have a different ECD. Even with a relative measurement, there are some possible sources of error that can be significant. Changes in the groundwave between the template (reference) and current measurement can cause shifts in isolated skywave peak. Changes of concern include variations in amplitude, ECD and envelope. An error would also occur if the assumption that initial phase offsets for the mixing signal for each epoch is incorrect.

| Station | Reference Time | Measurement Time | Ref Phase offset (sig peak-env peak) | Meas Phase offset (sig peak-env peak) |
|---|---|---|---|---|
| Fallon | 18:45<br>22-June | 21:58<br>22-June | -0.225 μsec | -3.6 μsec, +6.5 μsec |
| | | 03:08<br>23-June | -0.225 μsec | +4.3 μsec |
| Searchlight | 17:21<br>25-June | 20:34<br>25-June | +1.45 μsec | +1.0 μsec |
| | | 21:13<br>25-June | +1.45 μsec | +1.7 μsec, -8.25 μsec |

**Table 1. Time difference between positive signal peak and envelope peak for Reference Groundwave (column 4) and Isolated Skywave (column 5)**

From the analysis so far, we can conclude that groundwave and skywaves can have significantly different ECDs. As a phase reversal is equivalent to an ECD of 5 μsec, it suggests that phase reversal may exist but it cannot definitively confirm the result. It should be noted that phase reversal may be just one of several contributing factors to phase differences between groundwave and skywave. Furthermore, the methodology and equipment provides a process for determining phase relationship. Additionally, the data lends itself to more power analysis methods which we will explore in the future.

## 5.0 Conclusions & Future Work

This paper studies the fine scale behavior and modeling of skywave. This is important for developing monitoring that can detect early skywave to support aviation and maritime harbor approach needs. First, the bandpass filtering is examined for its effects on receiver measurements. This quantification is used for developing the model. The paper shows with bandpass filtering, skywave can affect the SZC even if its delay is greater than 30 μsec. This one reason why previous requirements for the use of Loran in maritime and aviation applications only required performance in the presence of skywaves with delay greater than roughly 35 μsec. Results from observation and modeling shows that single hop skywave likely reverses phase upon reflection and that skywave ECD differs from that of the groundwave. While these two facts were suspected previously, the knowledge was not important for traditional Loran uses and hence generally not discussed or examined in depth. However, high integrity applications require being able to detect early skywave with ten second time to alert (TTA). And so these results may prove useful to fulfilling that need.

Still much work is needed to develop good early skywave monitors. However, the model is a good start. The model described in the paper allows us to determine the skywave delay and its progression. With a time history and rate of evolution, thresholds may be developed to flag potentially developing early skywave conditions. The detection and threshold then must be assessed for its false alarm rate, integrity and availability.

## 6.0 Disclaimer

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Federal Aviation Administration, Department of Transportation or Department of Homeland Security or any other person or organization.

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# 8.0 Bibliography

[1] Morris, Peter B., "Conditions Leading to Anomalously Early Skywave," Proceedings of the 32nd Technical Symposium of the International Loran Association, Boulder, Colorado, 3-7 November 2003.

[2] "Navigational Aids and Related Equipment," NAV 39/4/12, International Maritime Organization, July 1, 1993

[3] Department of Transportation, Federal Aviation Administration, Aircraft Certification Service, "TSO-C60b, Airborne Area Navigation Equipment using Loran C Inputs," Technical Standard Order-C60b (TSO-60b), May 11, 1988, Washington DC

[4] Radio Technical Committee Aviation (RTCA), Minimum Operational Performance Standard for Airbourne Area Navigation Equipment Using Loran-C Inputs, RTCA DO-194 17, November 1986.

[5] Peterson, Benjamin, Gross, K., Chamberlin, E., and Sheppard, E., "Port Clarence. Skywave Interference Study." The Proceedings of the 22nd Technical Symposium of the Wild Goose Association (now International Loran Association), Santa Barbara, CA, October 1993

[6] Wenzel, Robert, and Montgomery, Kirk, "Early Skywave Examples from U.S. Coast Guard Primary Control Monitor Set Data," Proceedings of the 32nd Technical Symposium of the International Loran Association, Boulder, Colorado, 3-7 November 2003.

[7] Specification of the Transmitted LORAN-C Signal, COMDTINST M15662.4A, Commandant, USCG, May 1994.

[8] Lo, Sherman, Morris, Peter and Enge, Per, "Early Skywave Detection Network: Preliminary Design and Analysis", Proceedings of the 34th Technical Symposium of the International Loran Association, Santa Barbara, CA, October 2005

[9] Montgomery, Kirk, "Overview of the Enhanced Loran Research Receiver, Symmetricom," Proceedings of the 36th Technical Symposium of the International Loran Association, Orlando, FL, October 2007

[10] Mohammed, Abbas, Le Roux, Fernand, Last, David, "Eigendecomposition Techniques for Skywave Interference Detection in LORAN-C Receivers," Proceedings of the 32nd Technical Symposium of the International Loran Association, Boulder, Colorado, 3-7 November 2003.