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Cross-Channel Sounding for HF Geolocation: Concepts and Experimental Results

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Abstract—In the context of passive geolocation of High Frequency (HF) transmitters using the Time Difference of Arrival (TDoA) method, the transmitted signal and the propagation channel is unknown. This paper explains the principle of a method termed as “cross-channel sounding” along with its concepts. This method is used to evaluate the propagation duration differences of an unknown signal received by multiple synchronized distributed receivers. The mathematical description for cross-channel sounding is detailed, emphasizing the importance of the nature of the transmitted signal in the estimation of the propagation duration differences. An operational country wide TDoA receiver network capable of capturing HF signals is presented. HF broadcast signals are captured from different transmitters around Europe. Experimental data are used to analyze the different propagation modes from cross-channel sounding and assess the TDoA estimation complexity in the case of multi-path channels.

Index Terms—HF propagation, channel sounding, time difference of arrival, geolocation, ionosphere

I. INTRODUCTION

HF radio transmissions can be propagated over long ranges using skywaves wherein the radio signals are reflected once or multiple times between the earth and the ionospheric medium. Moreover, it can be achieved using cost-effective and portable equipment making it extremely useful in military operations and for communication in remote regions. As HF communication plays an important role in military and humanitarian operations, passive detection of the transmitter’s location is essential.

The ionosphere is formed due to the ionization of the neutral atoms from sun’s radiation which produce electrons that are responsible for the refraction of the HF radio signals. The ionosphere extends from about 50 to 2000 km over the Earth surface and is split into different layers known as the D, E and the F layers in the order of increasing altitude and varying electron density, respectively [1]. The ionosphere varies highly with respect to the solar activity and geographic location. This leads to an extremely space-time variable nature of the HF propagation paths which in turn results in the variation of the signal arrival times [2].

Single hop propagation mode refers to a radio signal that is reflected once from any layer of the ionosphere and can propagate up to a distance of about 500-3500 km. If the reflection occurs via the E layer it is known as 1E mode and 1F mode if the reflection occurs via the F layer. In multi-hop propagation mode, the radio signal is reflected several times

from the same layer or different layers of the ionosphere. HF signals can travel using two different ray paths, namely the low angle ray path and the high angle ray path for a specific receiver (Rx) and transmitter (Tx) pair. In the presence of magnetic field, a HF radio signal is further split into ordinary and extraordinary wave [1].

HF geolocation can be achieved using different angular domain methods to find the Direction of Arrival (DoA) of the incoming signal [3] or using the Single Site Location (SSL) method which measures the angle of arrival in terms of azimuth and elevation angles of the incoming signal [4]. These methods need the deployment of large antenna arrays which is very expensive and requires an estimate of the ionospheric profile along the propagation path. When considering time-domain methods, we estimated that geolocation of HF Tx’s is possible with an error of about 25 km without the knowledge of the ionospheric profile along the propagation paths [5]. Furthermore, by increasing the number of receivers, the geolocation accuracy is improved significantly using time domain methods [6].

Channel sounding provides information about the propagation channel behavior and different parameters associated between the transmitted and the received signal. In our earlier study, HF channel sounding was performed between a network of Rx’s and one Tx. The propagation time was evaluated by accessing the channel impulse response (CIR) and the Tx was located using the time of arrival (ToA) method [7]. Another example of HF channel sounding for radio link between Antarctica and Spain which evaluates the propagation time is explained in [8].

In the case of geolocation of an unknown emitter, the signal transmission time is unknown. Thus, the ToA method cannot be used. The location of the Tx can be retrieved using the TDoA method. This paper aims to explain a method named as cross-channel sounding in which the received signals on multiple distributed receivers are cross-correlated to obtain the difference in the propagation durations. The principle of cross-channel sounding is explained in Section II. In Section III, an operational country wide TDoA receiver network capable of synchronously capturing HF signal is described. In Section IV, experimental measurement results are presented. They illustrate single and multi-path channels and their effect on the evaluation of time delays using cross-channel sounding. Finally, conclusions are drawn in Section V.

II. PRINCIPLE OF CROSS-CHANNEL SOUNDING

A. Channel Representation

The received signal $s(t)$ and the transmitted signal $e(t)$ are related to each other through the channel impulse response (CIR) $h(\tau)$ as per the following filtering operation:

$$s(t) = \int_{-\infty}^{\infty} e(t - \tau)h(\tau)d\tau \equiv (e * h)(t) \quad (1)$$

where $*$ represents the convolution operator. The variable t is used to represent the variations of the function with time, while the variable τ indicates the delay domain. During the localization process, ionospheric variations are negligible. So it is considered here that the channel does not vary with time.

B. Principle of Channel Sounding

In any type of time-domain geolocation, one of the main issues is to get access to the CIR between the Tx and the Rx to evaluate the propagation duration of the signal. In the case of single path ideal channel, the CIR consists of a single Dirac pulse which represents the delay corresponding to the time of flight of the signal. The distance travelled between the Tx and the Rx could be obtained by multiplying the time of flight with the speed of electromagnetic wave. The problem lies in the fact that the CIR cannot be accessed directly. It can be obtained by observing a received signal $s(t)$ which is obtained after transmitting a signal $e(t)$ through the channel $h(\tau)$. In other words, the transmitted signal needs to be wisely selected in order to provide for an easy resolution of (1).

Different methods of channel sounding have been developed to solve this problem [9]. An important type of channel sounding method known as frequency-domain channel sounding relies on the observation of the transmitted and received signal on a wide band of frequencies. This method requires good phase synchronization between the Tx and the Rx; is achieved by connecting cables between the Tx and Rx. Thus, it is not applicable for distinct HF links.

In time-domain channel sounding techniques, the easiest method consists of using a short pulse $\Pi(t)$ as the transmitted signal $e(t)$. The received signal $s(t)$ is an approximation of the CIR $h(\tau)$, provided that the transmitted signal is short enough. However, this method suffers from its low signal-to-noise ratio (SNR), leading to a strong impact of the measurement noise. A practical way to increase the SNR is to use the method of correlation sounding. The cross-correlation between the transmitted and the received signal is denoted by $R_{es}(t)$ and is calculated as follows:

$$R_{es}(t) = \int_{-\infty}^{\infty} \bar{e}(\tau)s(t + \tau)d\tau \equiv (e * s)(t) \quad (2)$$

where $\bar{}$ denotes the complex conjugate, and $*$ denotes the cross-correlation operator. The autocorrelation of the transmitted signal $R_{ee}(t)$ is expressed in a similar manner as in (2). As per the convolution and correlation properties, these correlation functions are linked by a convolution equation where (1) and (2) combine to give the following:

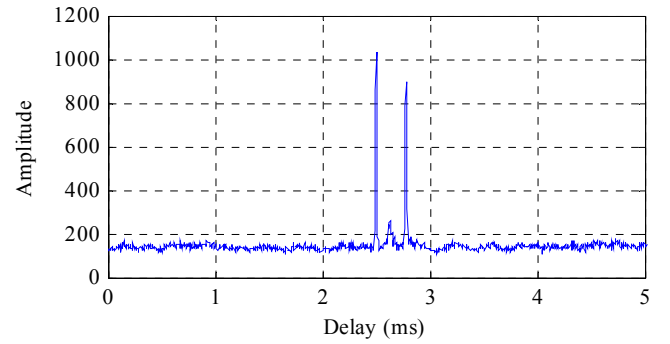


Fig. 1. Example of CIR measured on a HF link using correlation sounding

$$R_{es}(t) = ((e * e) * h)(t) = (R_{ee} * h)(t) \quad (3)$$

If the input signal is close to a white noise, its autocorrelation function is close to a Dirac pulse. In this case, the identification problem is similar to the one occurring in the pulsed technique. In practice, channel sounders use maximum length PN sequences, also called m-sequences. This corresponds to a good approximation of a colored noise with zero mean and limited bandwidth.

As an example of correlation sounding, Fig. 1 represents an experimental CIR measured over a ground distance of 710 km between Brest and Toulouse for a HF link at a frequency of 8.06 MHz [7]. The two observable peaks correspond to the 1E and 1F propagation modes, respectively.

C. Principle of Cross-Channel Sounding

In the framework of passive time-domain HF geolocation, the signal transmission time and transmitted signal is unknown. Thus, the duration of propagation cannot be calculated and the ToA method cannot be used. The TDoA method can be employed, where only the time difference between the reception instants at any pair of receivers is required.

Let the signals received at receiver 1 (R_{x1}) and receiver 2 (R_{x2}) be $s_1(t)$ and $s_2(t)$, respectively. These signals share the same origin which is the transmitted signal $e(t)$ but have different propagation channels $h_1(\tau)$ and $h_2(\tau)$ between the Tx- R_{x1} pair and Tx- R_{x2} pair, respectively. In practice, the received signals also consist of noises captured by the R_{x1} and R_{x2} , which affect the signal detection performance. These noises are mainly from the receiver circuitry and different radiated electromagnetic noise captured by the antenna at the receiver end. For the sake of clarity, we assume that cross-channel sounding is performed in high SNR conditions. Thus, the noise terms are further neglected. The received signals at R_{x1} and R_{x2} can be written as follows:

$$\begin{aligned} s_1(t) &= (e * h_1)(t) & (4) \\ s_2(t) &= (e * h_2)(t) & (5) \end{aligned}$$

The duration of propagation of each signal path is captured by the CIRs $h_1(\tau)$ and $h_2(\tau)$. The TDoA method requires a way to retrieve this information in a similar way as

to what is done in classical channel sounding. In order to find the difference of the propagation durations from the available data which are just the received signals, one can evaluate the cross-correlation between the CIRs $h_1(\tau)$ and $h_2(\tau)$. This method could be named as “cross-channel sounding” and it requires computing the cross-correlation of the received signals $s_1(t)$ and $s_2(t)$, denoted by $R_{s_1s_2}(t)$. It is calculated as follows:

$$R_{s_1s_2}(t) = (s_1 \star s_2)(t) = ((e \star h_1) \star (e \star h_2))(t) \quad (6)$$

Equation (6) can be further simplified using the convolution and cross-correlation theorems and is given as follows:

$$R_{s_1s_2}(t) = (R_{ee} \star R_{h_1h_2})(t) \quad (7)$$

where $R_{ee}(t)$ is the autocorrelation of the transmitted signal, $R_{h_1h_2}(t)$ is the cross-correlation between the two CIRs. The later gives an estimate of the time difference between different propagation paths. A similarity can be observed between (7) related to cross-channel sounding and (3) related to correlation based channel sounding. It also explains that the nature of the transmitted signal plays an important role in cross-channel sounding for the estimation of propagation duration differences. More specifically, the cross-correlation output for the received signals will be close to the cross-correlation of the CIRs, provided that the auto correlation of the transmitted signals resembles a narrow, zero-centered peak with a large SNR.

Different complications may arise while selecting the cross-correlation peak which corresponds to the time delay between the signals received at two distinct synchronized receivers depending on the nature of the two CIRs. Let us assume that both the channels are ideal, single path channels in which the ionospheric propagation occurs via the F layer of the ionosphere. The output of the CIRs cross-correlation of the received signals having different single path channels is represented in Fig. 2. In the case of single path channels, the time delay between the signals received at different receivers can be obtained with ease if the transmitted signal has good auto correlation properties.

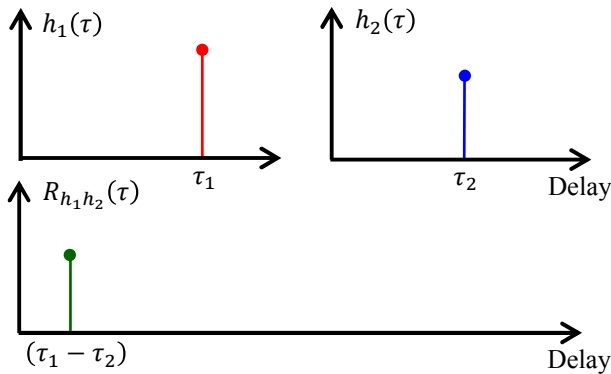


Fig. 2. Output of the CIRs cross-correlation for single path ideal channels

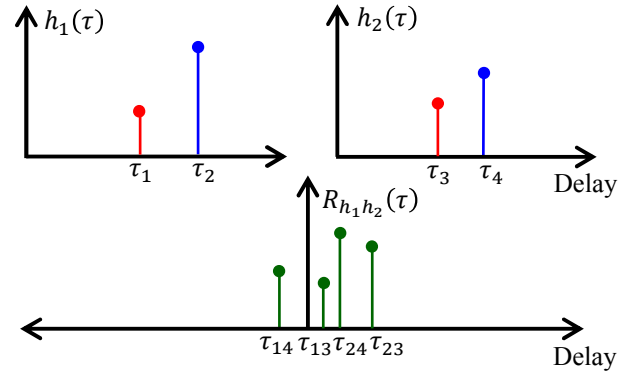


Fig. 3. Output of the CIRs cross-correlation for multi-path ideal channels

Further, let’s assume that both the channels are multipath channels where ionospheric propagation occurs via different layers of the ionosphere (e.g. one through the E and the other through F layer). The output of the CIRs cross-correlation of the received signals having different multi-path channel is represented in Fig. 3. Due to multipath channels, the CIR’s when cross-correlated results in multiple peaks. It then becomes difficult to select the peak which provides the most accurate time delay between the received signals by different receivers. For practical purpose, we suggest to select the peak with the strongest signal level in the cross-correlation output. In the example of Fig. 3, it corresponds to the time delay between the signals reflected via the F layer for both propagation paths. This issue is still under study, but in order to achieve better geolocation accuracy, it appears necessary that the selected time delay corresponds to the same propagation mode on different receivers [7].

III. OPERATIONAL TDOA RECEIVER NETWORK

A. Receiver Design and Placement

In order to study the feasibility of using cross-channel sounding in a practical HF TDoA geolocation system, multiple receivers were built using Software Defined Radio (SDR) to capture HF radio signals synchronously. The RF frontend of the SDR box is connected to an active HF antenna. The SDR box also consists of a GPS disciplined oscillator (GPSDO) which is locked to global GPS standards from the GPS signals captured by the GPS antenna. All the receivers are synchronized with the same clock through the GPSDO kit irrespective of their locations.

The receivers communicate to their respective computer via the ethernet connection. Multiple programs written in Java and python are used to initiate the data capture through the SDR box and store it in the host computer. The whole receiver setup is designed to be compact and cost efficient. We deployed this receiver setup in 4 different cities in France. This operational HF receiver network enables a synchronous capture of HF broadcast radio signals on all the receivers from different transmitters located around Europe. Fig. 4 represents the geographic location of the network of receivers and some HF transmitters which are monitored for

the purpose of the present study. The ground range for the different HF radio links used for data capture is summarized in Table I. The whole receiver network is managed from a central machine remotely.

TABLE I. GREAT CIRCLE DISTANCE FOR DIFFERENT HF LINKS

Rx \ Tx	Brest	Bordeaux	Grenoble	Lille
Nauen	1320 km	1313 km	976 km	710 km
Cerrik	2049 km	1680 km	1197 km	1631 km
Galbeni	2376 km	2168 km	1676 km	1805 km

B. Measurement Details and Signal Processing

The data is received in the form of IQ samples from the SDR box and the message lies in the magnitude envelope as most of the HF broadcast signals are amplitude modulated. All the radio broadcast signals are captured for duration of 5 sec by mentioning the carrier frequency of the HF transmitter and capture start time. The captured signal is sampled at the rate of 200 kHz. Furthermore, the captured signal is filtered in the frequency domain to remove the unwanted part of the spectrum which acts as interfering signals. The signal is transformed back to the time domain and demodulated to obtain the message signal. Finally the message signals from different receiver pairs are cross-correlated to obtain the TDoA between the received signals as explained earlier.

IV. RESULT ANALYSIS

Numerous amounts of data were captured from different HF broadcast transmitters around Europe using the receiver network. As explained earlier, the difference of the propagation durations was evaluated using the cross-channel sounding method. The receiver in Brest is assumed to be the reference receiver. In this Section, we present a few measurement examples characterizing the different propagation modes and explaining the selection of the cross-correlation peak corresponding to the approximate time delays. Note that the propagation mode for all the received signals is assumed to be single hop.

Fig. 5 shows the TDoA estimate for a HF broadcast signal captured simultaneously in Brest and Bordeaux on 21st of July at 19:13 UTC. The broadcast transmitter is located in Germany and is emitting at a frequency of 11.79 MHz. As seen in Fig. 5, there is only a single peak in the cross-correlation output which implies that the radio signals arrived at the different receivers through single path channels (i.e. 1E or 1F mode). This example resembles to the case of two ideal single path channels as explained earlier and depicted in Fig. 2. The TDoA corresponding to the peak is 20 μ s. Assuming that the received signals were reflected from a virtual height of 100 km (i.e. from E layer), the corresponding TDoA evaluated from the Breit and Tuve’s theorem is about 18.65 μ s [1].

Another example showing the TDoA estimate for a HF broadcast signal captured synchronously in Brest and Grenoble on 18th of July at 11:21 UTC is presented in Fig. 6. The broadcast transmitter is located in Albania and emitting at a frequency of 13.665 MHz. As seen in Fig. 6, there are 2

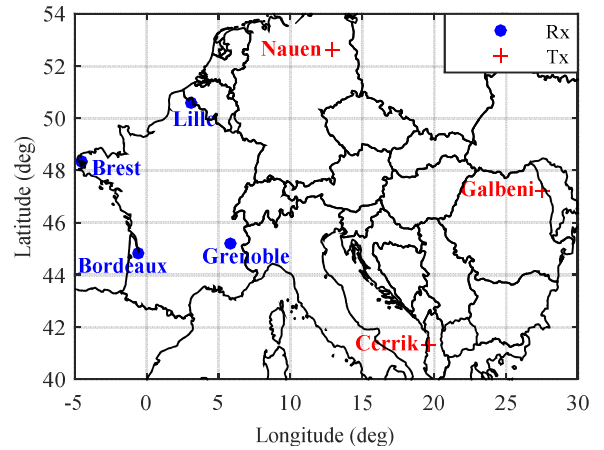


Fig. 4. Location of Rx network and Tx in terms of GPS coordinates

peaks with different amplitudes in the cross-correlation output. This implies that the radio signals arrived at one of the receiver through single path channel whereas on the other receivers through multi-path channel. The propagation modes can be interpreted as 1F mode for the signal received in Brest whereas a mix of both 1E and 1F modes for the signal received in Grenoble. The TDoA corresponding to the maximum peak is 2.765 ms which is consistent with the 1F propagation mode for signals received on both the receivers. The other peak obtained at 3.065 ms corresponds to the signal received in Brest and Grenoble through 1F and 1E mode, respectively. The time delays corresponding to these peaks are approximately equivalent to the TDoA’s obtained from Breit and Tuve’s theorem assuming reflections from virtual heights of 250 km (i.e. from F layer) and 80 km (i.e. from E layer) [1], respectively.

Fig. 7 shows the TDoA estimate for a HF broadcast signal captured simultaneously in Brest and Lille on 13th of July at 11:46 UTC. The broadcast transmitter is located in Romania and emitting at a frequency of 15.13 MHz. As seen in Fig. 7, there are multiple peaks in the cross-correlation

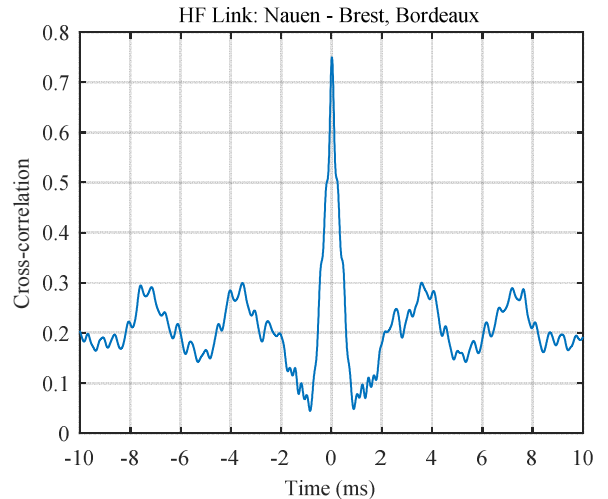


Fig. 5. Example of cross-channel sounding for HF broadcast signals received in Brest and Bordeaux from the Tx site in Nauen, Germany

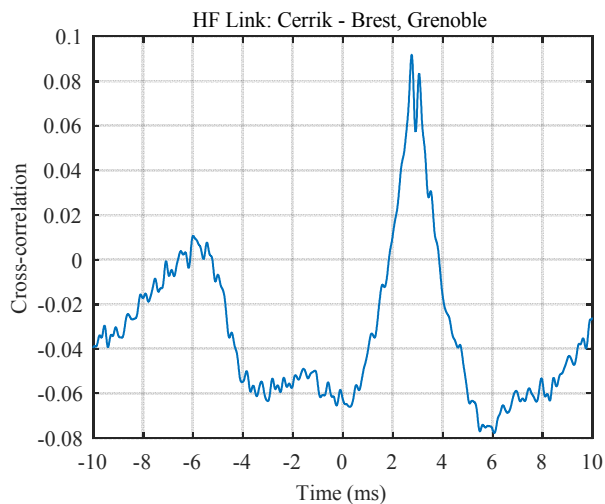


Fig. 6. Example of cross-channel sounding for HF broadcast signals received in Brest and Grenoble from the Tx site in Cerrik, Albania

output which implies that the radio signals arrived at both the receivers through multi-path channels. It can be further interpreted that the received signal at both receivers, consists of signals reflected from both the E and F layers of the ionosphere. This example resembles the multi-path channel case explained earlier and depicted in Fig. 3. The different amplitudes, with which signals are received for different propagation modes, translate in different amplitudes for the cross-correlation peaks. The maximum peak corresponds to a time delay of 1.86 ms which is approximately equal to the TDoA obtained from Breit and Tuve's theorem assuming a reflection from a virtual height of 225 km (i.e. from the F layer) for both the propagation paths [1]. It can also be interpreted that signals reflected from the F layer are received with higher amplitudes at both receivers.

V. CONCLUSION

In this paper, we have presented a new concept termed as cross-channel sounding which is used to estimate the TDoA between signals received at multiple receivers. The TDoA estimate can be obtained with a higher accuracy depending on the correlation properties of the transmitted signal. In order to study the use of cross-channel sounding in a practical HF geolocation system, a countrywide TDoA receiver network was deployed in France, capable of capturing HF signals synchronously.

Using different measurement examples, we demonstrated the feasibility of using cross-channel sounding to obtain the TDoA between HF broadcast signals received at multiple receivers and we proposed an identification of the different propagation modes. In the case of single path channels, the estimation of the TDoA is easier, as there is only a single peak in the cross-channel sounding output. But, for multi-path channels, the multiple peaks in the cross-channel sounding make the estimation of the most accurate TDoA more difficult. In such cases, the TDoA corresponding to the peak with maximum amplitude can be selected.

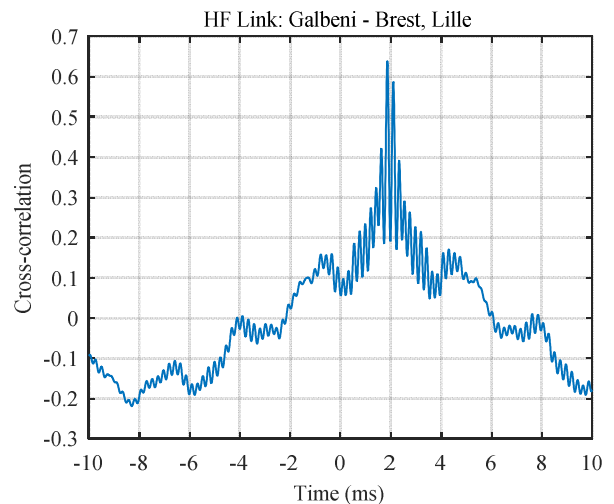


Fig. 7. Example of cross-channel sounding for HF broadcast signals received in Brest and Lille from the Tx site in Galbeni, Romania

In our future work, we plan to use data from different ionosondes in Europe to analyze the multiple paths and verify the propagation modes. We also plan to study the impact of selecting different TDoA's corresponding to different peaks on the geolocation accuracy. Finally, the impact of the received signal's SNR on the cross-channel sounding output will also be assessed.

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