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# Accurate time difference of arrival estimation for HF radio broadcast signals

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## Abstract

Geolocation of high frequency (HF) transmitters at distances in the order of 2000 km is possible by exploiting the time difference of arrival (TDoA) among multiple distributed single antenna receivers. HF radio signals propagate via skywaves between the Earth-Ionosphere medium and the signals are received through non-line-of-sight mode. This experimental study demonstrates that it is possible to evaluate the TDoA between two receivers for a HF radio broadcast signal propagating through the ionospheric channel. The HF propagation path geometry for one hop propagation mode is explained. Simulations are performed using this model to evaluate the theoretical TDoA between the signals received at two synchronized receivers. In the second step, two remotely controllable receivers built to capture distinct HF signals are deployed in two cities in France. Radio broadcast signals from different HF transmitters across Europe are captured simultaneously on the two synchronized receivers. The TDoA is obtained by cross-correlating the captured signals from the receivers. The TDoA obtained by experimental and simulation methods are compared for different radio propagation paths and results show some very good agreement.

## KEYWORDS

HF propagation, ionosphere, passive geolocation, time difference of arrival

## 1 | INTRODUCTION

High frequency (HF) radio signals can travel long distances in the range of 500–3500 km via a single reflection from one of the layers of the ionosphere. Thus, geolocation of HF transmitters is of prime importance for both military and civil operations. Initially, geolocation of HF transmitters was performed using angular domain methods which measures the direction of arrival (DoA) of the incoming signal at multiple locations and the transmitter location was found by triangulation. Numerous methods to evaluate the DoA of the HF signals are proposed by Gething.<sup>1</sup> Most of these direction finding (DF) systems require the deployment of several large antenna arrays. Another HF geolocation method known as single site location (SSL) measures DoA of the incoming signal in terms of the azimuth and the elevation angles.<sup>2</sup> The drawback of this method lies in the need to deploy a large antenna array. In addition, the ionospheric reflection profile along the propagation path must also be known to transform the obtained elevation angle to ground range.

Source localization is also achieved using time domain techniques such as time of arrival (ToA) and time difference of arrival (TDoA). A positioning system based on GSM signal using the TDoA method is described by Azaro et al.<sup>3</sup> However, to achieve higher accuracy, signals received at multiple receivers must have direct path, ie, line-of-sight (LOS) propagation. One such example of passive source localization using TDoA method is explained using real time measurements by Wei and Yu,<sup>4</sup> but very little work on the localization of HF transmitters using time domain techniques has been reported. In the case of HF propagation via skywaves, radio signals are reflected from the ionosphere and do not follow LOS path. In our earlier work, we explained that HF geolocation can be performed using ToA obtained from distributed single antenna receivers and also without the knowledge of the ionospheric reflection height.<sup>5</sup> Moreover, the cost of the receiving setup is much lower compared to a SSL or DF system.

In the framework of passive geolocation, the signal transmission time is unknown; therefore, localization cannot be performed using the ToA method. But the TDoA method can be used to locate the position of the unknown transmitter. It is experimentally shown that it is possible to estimate the time delay for an ultra-wideband signal backscattered from a wall.<sup>6</sup> But in the context of unknown HF radio broadcast signals, the signal bandwidth is quite narrow. This has an impact

on time resolution and, in addition, the propagation path is less stationary and unknown. Thus, it is necessary to experimentally validate the feasibility of measuring accurate TDoA using radio broadcast signals as a first step, before setting up a complete HF time domain localization network. In this letter, we show for the first time that it is possible to evaluate the difference between propagation durations for a HF radio broadcast signal propagating through the ionospheric medium and received by two distinct synchronized receivers. The TDoA obtained from experiments and simulations for different HF propagation paths across Europe are very similar.

## 2 | HF PROPAGATION PATH GEOMETRY

The HF radio signals are captured from transmitters located as far as about 3000 km from the receivers. At such communication ranges, it can be assumed that the radio signal propagates via a single reflection from the ionosphere and it is referred to as single hop propagation mode. Figure 1 represents the way along which a HF radio signal propagates assuming that the radio signal is reflected once from the ionosphere. The transmitter is located at point Tx and the receivers are located at points Rx<sub>1</sub> and Rx<sub>2</sub>. The varying refractive index in the ionosphere leads to the propagation of the signal along a curved path and  $h_m$  denotes the real height at which the signal is reflected as seen in Figure 1. According to the Breit and Tuve's theorem,<sup>7</sup> the time required by the radiowave to travel the curved path "Rx<sub>1</sub>-Tx" through the ionosphere is equal to the travel time along the triangular path "Rx<sub>1</sub>-I<sub>1</sub>-Tx" in vacuum, the same applies for the "Rx<sub>2</sub>-Tx" pair. The reflection height for the triangular path is denoted by  $h_v$  and is known as virtual reflection height. The ionosphere is assumed to be flat and uniform. Thus, the reflection heights  $h_m$  and  $h_v$  are the same for the "Rx<sub>1</sub>-Tx" and "Rx<sub>2</sub>-Tx" pairs. The altitude at which the transmitter and receiver are placed is assumed to be equal to zero, thereby assuming the Earth to be flat. The group path ( $P_1$ ) between Rx<sub>1</sub>-Tx is calculated as

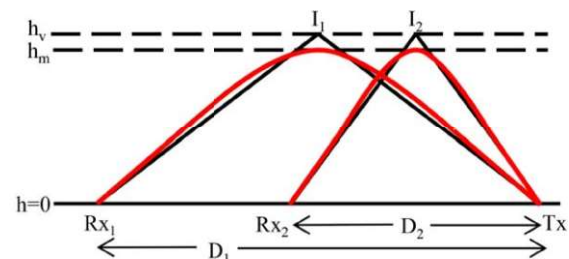


FIGURE 1 One hop IIF propagation path geometry [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

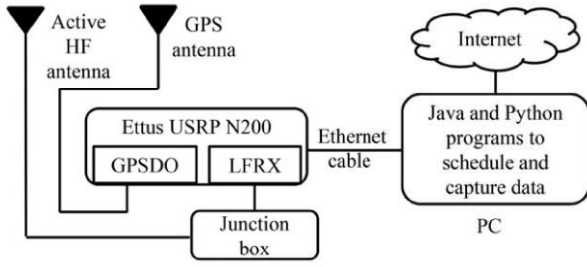


FIGURE 2 Receiver setup

$$P_1 = \sqrt{D_1^2 + (2h_v)^2} \quad (1)$$

where  $D_1$  is the ground distance between “RX<sub>1</sub>-Tx.” The group path ( $P_2$ ) between “RX<sub>2</sub>-Tx” can be calculated in a similar manner. Knowing the speed of a radiowave, the signal travel time is calculated for the two propagation paths and the corresponding TDoA between the two receivers is obtained.

### 3 | RECEIVER DESIGN AND EXPERIMENTAL RESULTS

#### 3.1 | Receiver prototype

Figure 2 represents a remotely controllable receiver setup designed to synchronously capture distinct HF radio signals on multiple receivers. The main component of the receiver prototype is the software defined radio (SDR) Ettus USRP N200 module which consists of a direct sampling analog to digital converter (ADC) capable of sampling at the rate of 100 MHz and is coupled with a FPGA for down sampling and frequency conversion. The Ettus LFRX RF frontend daughterboard accepts signals from DC to 30 MHz and it is connected to an active HF antenna. The Ettus module contains a GPS disciplined oscillator (GPSDO) which timestamps the captured samples with GPS GMT time and synchronizes the clock of both FPGA and ADC. The GPSDO is locked to global GPS standards from the GPS signals captured by the GPS antenna. The GPSDO kit allows multiple SDR’s to synchronize their captures with the same clock independently of the receiver locations. Multiple programs are written in Java and Python to capture the signals. The Java programs are used for the scheduling of the capture while the python script captures the signals as per the GNURadio standards. The whole receiver setup can be managed from a remote location.

#### 3.2 | Experimental data capture and analysis

Radio broadcast signals were captured from HF transmitters located at a minimum distance of about 700 km to a maximum distance of about 3100 km from one of the reception sites. The GPS coordinates of all the HF broadcast transmitters and the two reception sites where the radio broadcasts were captured

synchronously is shown in Figure 3. All the radio signals were captured for 5 seconds by specifying the carrier frequency of the transmitter and capture start time. The bandwidth of the captured signal (ie, baseband samples) was 200 kHz. The captured signal was filtered to remove other strong unwanted interfering signals which were captured along with the radio signal. The bandwidth of a shortwave broadcast is about 10 kHz. The received samples were transformed to the frequency domain; only 5 kHz of the signal on either side of the carrier frequency was kept and the remaining part of the spectrum was initialized to zero. The signal was transformed back to the time domain, demodulated, and the radio signal samples were obtained. Finally, the radio signal samples from both the receivers were cross-correlated to obtain the TDoA between the two received signals. The TDoA  $\Delta t$  is experimentally obtained by finding the maximum value of the cross-correlation function and is expressed as follows

$$\Delta t = \max_t R_{s_1 s_2}(t) = \max_t \int_{-\infty}^{\infty} s_1(\tau) s_2(\tau+t) d\tau \quad (2)$$

where  $R_{s_1 s_2}(t)$  is the cross-correlation of the radio signal samples  $s_1(t)$  and  $s_2(t)$  obtained by post processing the signals received in Brest and Lille, respectively. An example of the cross-correlation output for a radio broadcast signal captured from the transmitter at Santa Maria di Galeria (SMDG) is shown in Figure 4. A summary of some TDoA obtained between the HF broadcast signals received in Brest and Lille from different transmitters at different times of different days is presented in Table 1. The TDoA is calculated assuming the receiver in Brest as the reference receiver.

### 4 | SIMULATION RESULTS

The GPS locations of the broadcast transmitters and the two receivers were transformed to  $x$  and  $y$  coordinates using the

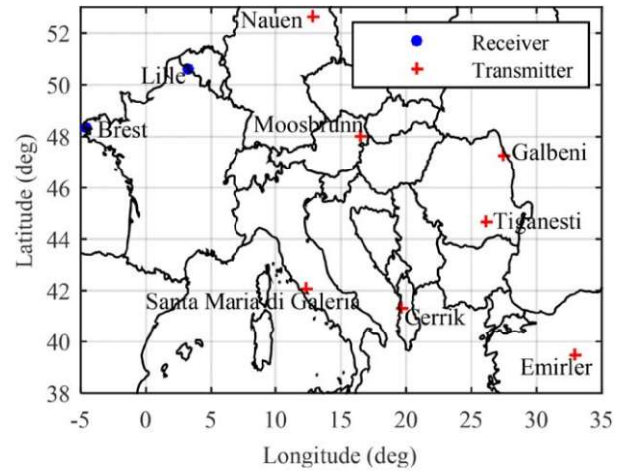
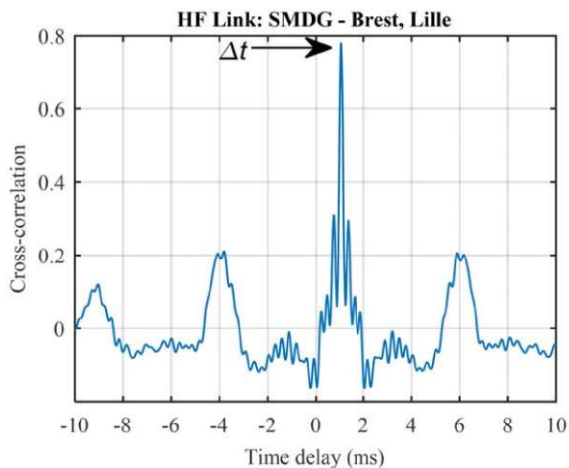


FIGURE 3 GPS coordinates of receivers and HF radio transmitters [Color figure can be viewed at wileyonlinelibrary.com]



**FIGURE 4** Cross-correlation of HF broadcast signals captured in Brest and Lille from the transmitter in Santa Maria di Galeria, Italy [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

azimuthal equidistant projection considering the receiver in Brest as the origin of the coordinate system. The virtual reflection height at the midpoint of the propagation path can be found if an accurate model of the ionospheric profile is known at that location which is practically unrealizable. Digital ionograms which gives an estimate of the different ionospheric parameters are recorded every day in different locations around Europe and are available online.<sup>8</sup> Also the ionospheric variations around the mid-latitude regions is not very high, thereby allowing us to use the ionograms available from the closest location of the midpoint of the propagation path to obtain the virtual reflection height. The ionograms recorded in Dourbes or Rome with respect to the capture times of the radio signal was used. Using the secant's law and the known distance between Tx–Rx, the vertical incidence digital ionogram was converted to oblique incidence ionogram as explained by Davies.<sup>7</sup> An approximate virtual reflection height corresponding to operating frequency of the transmitter was obtained and is listed in Table 2. The TDoA was calculated as explained in the earlier section of HF

**TABLE 1** Summary of TDOA results obtained from data captures

Tx site—Frequency (MHz)	Capture date	Start time (UTC)	TDoA (ms)
1. Galbeni—15.130	18/7/17	13:40	1.890
2. SMDG—15.570	18/7/17	16:14	1.045
3. Nauen—11.790	18/7/17	19:13	2.005
4. Moosbrunn—11.880	18/7/17	20:17	1.850
5. Cerrik—13.710	25/7/17	08:19	1.330
6. Tiganesti—13.660	25/7/17	17:15	1.890
7. Emirler—9.460	26/7/17	17:20	1.675

**TABLE 2** Simulation results

Distance “Tx–Rx <sub>1</sub> (Brest), Tx–Rx <sub>2</sub> (Lille)” (km)	Reflection height (km)	TDoA (msec)	TDoA error (%)
1. 2376, 1805	100	1.893	0.16
2. 1493, 1184	110	1.016	2.85
3. 1320, 709	110	1.984	1.06
4. 1552, 1004	110	1.798	2.89
5. 2048, 1633	320	1.307	1.76
6. 2365, 1832	270	1.717	10.07
7. 3120, 2618	235	1.648	1.64

propagation path geometry and simulation results are presented in Table 2. As it can be seen, the TDoA obtained by simulations and experiments are almost similar and the average TDoA error between simulation and experimental result is just 2.9%. The average TDoA difference error between the simulation and experiment result is 46  $\mu$ sec. Further, geolocalization of HF transmitters can be performed if signals are captured by, at least, four distributed receivers.

## 5 | CONCLUSION

This letter proposes a concept of geolocalization of HF transmitters using the TDoA method and showed that it is possible to obtain the time delay for a HF radio broadcast signal propagating via skywaves. In order to validate this concept, two receivers capable of capturing HF radio signals were built and deployed in Lille and Brest. HF radio broadcast signals were synchronously captured at both receivers from different broadcasters around Europe and TDoA was obtained by post processing the captured signal. The TDoA evaluated using real time experimental data and by simulations for different HF radio links were found to be almost similar. In our future work, we plan to deploy two additional receivers and perform geolocalization of HF transmitters.

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