GEOLOCATION AND NAVIGATION
IN SPACE AND TIME

Passive HF Geolocation Using TDoA Based Receiver Network

Géolocalisation passive des émetteurs HF par un réseau de récepteurs TDoA

Ankit Jain[1], Pascal Pagani[1], Rolland Fleury[1], Michel Ney[1], Patrice Pajusco[1]

[1] IMT Atlantique, Lab-STICC UMR CNRS 6285, Brest, France, {ankit.jain; pascal.pagani; rolland.fleury; michel.ney; patrice.pajusco}@imt-atlantique.fr

Keywords: HF propagation, passive geolocation, ionosphere, time difference of arrival.
Mots clés : Propagation HF, géolocalisation passive, ionosphère, différence de temps d'arrivée

Abstract

This paper presents the geolocation of a High Frequency (HF) transmitter (Tx) located at distances of about 700 to 1300 km from a network of receivers (Rx's). HF signals propagate through the ionospheric medium using skywaves and are reflected back to the Earth, thereby allowing HF communications over long distances. In our study, the location of the HF Tx is found using time difference of arrival (TDoA) method. Four remotely controllable Rx's which are built to capture HF signals synchronously are installed in four different cities in France. HF radio broadcast signals are captured simultaneously on the four deployed Rx's from the HF Tx situated in Nauen, Germany. The TDoA's between the signals received on all the four synchronized Rx's are obtained using the cross-channel sounding method. Using the obtained TDoA's, the Tx location is found using the geolocation algorithm based on TDoA. Experimental results show that it is possible to locate the HF Tx in Nauen with a geolocation error of about 5 km.

Résumé

Cet article présente la géolocalisation d'un émetteur HF situé à des distances d'environ 700 à 1300 km d'un réseau de récepteurs. Les signaux HF se propagent à travers le milieu ionosphérique en utilisant des ondes de ciel et sont réfléchis vers la Terre, permettant ainsi des communications HF sur de longues distances. Dans notre étude, la position de l'émetteur HF est obtenue en utilisant la méthode "Time Difference of Arrival" (TDoA). Des récepteurs contrôlables à distance, conçus pour capturer des signaux HF de manière synchrone, sont installés dans quatre villes différentes en France. Ce réseau de quatre récepteurs permet l'acquisition simultanée de signaux de radiodiffusion HF transmis par un émetteur situé à Nauen, en Allemagne. La différence de temps d'arrivée entre les signaux reçus par les quatre récepteurs est obtenue par une technique appelée sondage de canaux croisés. En utilisant les différences de temps d'arrivée déduites, la position de l'émetteur est estimée en utilisant un algorithme de géolocalisation basé sur la technique TDoA. Les résultats expérimentaux montrent qu'il est possible de localiser l'émetteur HF à Nauen avec une erreur de géolocalisation d'environ 5 km.

1 Introduction

HF radio signals propagating using skywaves are reflected once or multiple times between the Earth and the ionospheric medium. Thus, long-range communication can be established through radio signals transmitted in the HF band. HF communication is extremely useful in defense and civil applications as a complement or fallback solution to satellite communication. Owing to the importance of HF communication in defense and civil applications, geolocation of HF transmitters are of prime importance. In particular, in the context of signal intelligence, passive geolocation methods consist of detecting the source of an electromagnetic signal using a non-intrusive system i.e. without the transmitter being able to detect the localization process [1].

Numerous methods to measure the Direction of Arrival (DoA) of the incoming HF signals are explained in [2]. Most of these direction finding (DF) systems require deployment of large antenna arrays at multiple locations which can be quite expensive. HF geolocation can also be achieved using the single site location (SSL) method which measures the DoA of the HF signal in terms of azimuth and elevation angles [3]. SSL method requires installation of a large antenna array only on a single site which is an advantage over traditional DF systems. But, the ionospheric reflection profile along the propagation path must be known to estimate the ionospheric reflection height which is required to transform the elevation angle to ground range.

HF geolocation can also be performed using time-domain techniques. The location of a HF transmitter can be found from the time of arrivals (ToA's) obtained from multiple single antenna receivers under some assumptions and without the knowledge of the ionospheric profile along the HF propagation path [4]. Also, the cost of the receiver system is much less compared to SSL or DF systems. In passive geolocation systems, the signal transmission time is not known. Therefore, geolocation cannot be performed using the ToA method. But, the location of the transmitter could be found by multilateration technique using the TDoA's obtained from different receiver pairs. Further, the TDoA technique requires a minimum of four receivers to perform localization [5].

This paper aims to explain that it is possible to perform HF geolocation using the TDoA method. To validate this concept, multiple receivers capable of capturing HF signals synchronously are built using Software Defined Radio (SDR). Section 2 explains the HF propagation using skywaves. In Section 3, the HF receiver network capable of synchronously capturing HF radio signals is presented. In Section 4, a capture from the HF transmitter in Nauen, Germany is analyzed and the geolocation result is presented. Finally, conclusions are drawn in Section 5.

2 HF Propagation Principles

The ionosphere lies from about 50 km to 2000 km above the surface of the Earth [6]. The neutral atoms present in the atmosphere are ionized from the sun's radiation which results in the formation of free electrons which affects HF radio propagation. The ionosphere is split into D, E and the F layer in the order of increasing altitude, respectively. Moreover, the electron density is also variable in each of the layers making the ionosphere a dispersive medium and capable of refraction of the HF radio signals. The D layer mainly accounts for the absorption of the HF radio signals and has the least electron density. The electron density is the maximum in the F layer which is present between 150 to 600 km and it accounts for large propagation paths. The ionosphere is also a highly dynamic medium which varies diurnally, seasonally, geographically and with respect to the solar activity. This variability in the ionosphere is one of the major issues in HF geolocation of signals propagating through skywaves, as it leads to time delay variations [7].

HF radio propagation is possible using ground waves and the skywaves. Long distance HF radio transmissions occur via the skywaves where the radio signals are reflected back to the Earth through the ionosphere. HF radio signals which are reflected once from the ionosphere are referred to as single-hop mode whereas radio signals which are reflected multiple times are known as multi-hop modes. It is possible to communicate up to distances in the range of 500-3000 km using single-hop propagation mode. Due to the presence of Earth's magnetic field, an additional propagation mode due to extraordinary waves exist whereas ordinary waves are present even in the absence of the magnetic field. These propagation modes can be distinguished with respect to the direction of rotation of the waves.

In our geolocation study, we assume that all the received HF radio signals follow single-hop propagation mode considering the distances at which the HF transmitter is located from the receivers. Figure 1 presents the geometry for HF single-hop propagation mode. The transmitter is located at point Tx and receiver is located at point Rx_1. Due to the varying refractive index in the ionosphere, the HF radio signals propagate along a curved path and the real reflection height in the ionosphere is represented by h_m as seen in Figure 1. As per the Breit and Tuve's theorem [6], the time required for the HF radio signal to travel along the red curved path through the ionosphere is equal to the time required to travel along the black triangular path in vacuum. As seen in Figure 1, the reflection height for the triangular path is represented by h_v and it is referred to as virtual reflection height.

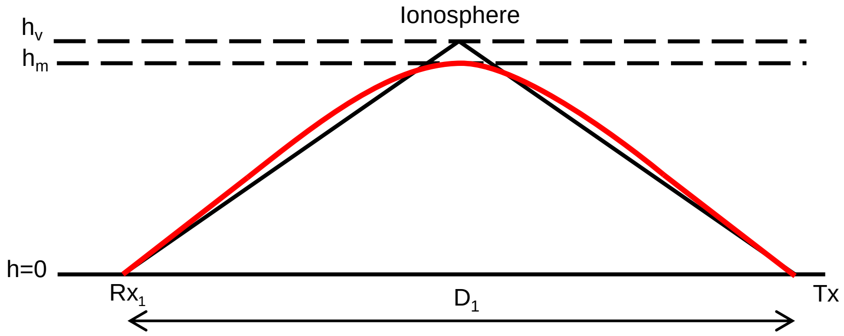

Figure 1 : Single-hop propagation mode geometry

Moreover, the HF geolocation model assumes a uniform ionosphere due to which the reflection height is the same for all the HF paths. The Earth is assumed to be flat by neglecting its curvature. Under these assumptions, it is possible to account for the excess delay due to the ionospheric propagation in the geolocation process, even without information about the ionospheric reflection height [4].

3 HF Receiver Network

In order to perform HF geolocation using the TDoA method, four remotely controllable receivers are built to synchronously capture HF radio signals.

3.1 Receiver Design

The receiver system design is illustrated in Figure 2. It is composed of both hardware and software. The main component of the receiver setup is the SDR Ettus USRP N200/N210 box whose RF frontend is connected to an active HF antenna. The SDR box consists of a direct sampling analog-to-digital converter (ADC) capable of sampling up to 100 MHz, coupled with an FPGA that performs downsampling and frequency conversion. The LFRX daughter card is capable of accepting signals from DC to 30 MHz. Using the GPS antenna, the GPS disciplined oscillator (GPSDO) can be locked to global GPS standards and the signal fluctuation is within ±50 ns [8]. The GPSDO allows multiple USRP's which are located far away from each other to synchronize their captures with the same clock.

The receiving setup communicates to their respective computers via the Ethernet connection. The computer consists of several programs that are used to schedule and capture data according to user requirement. The scheduling of the captures is done by a Java interpreter. It also manages the launch of the Python scripts which act as an interface between hardware and software. Python scripts are written to synchronize the capture time with the GPS time, initialize the capture and capture the data as per GNU Radio standards [9]. A capture generates two files: a DAT file and a HDR file. The DAT files contain complex samples of each capture whereas the HDR files consist of metadata corresponding to the respective DAT files.

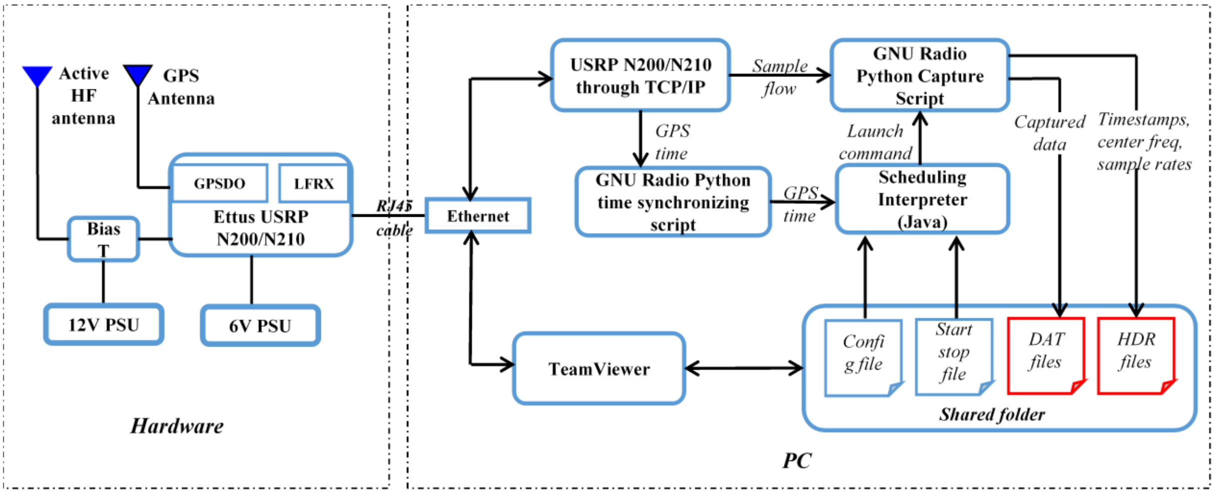

Figure 2 : Receiver system design

3.2 TDoA Receiver Network

The receiver system explained above is deployed in four different cities in France. As illustrated in Figure 3, the receivers are deployed in Brest, Bordeaux, Grenoble and Lille. HF radio signals were captured simultaneously from the HF transmitter located in Nauen, Germany. The geographic location of the HF transmitter in Nauen is presented in Figure 3. All the receivers in the network are managed from a central machine located in Brest. The ground ranges for the different HF links is summarized in Table 1.

HF radio link (Rx-Tx)	Ground Range (km)
Brest-Nauen	1320
Bordeaux-Nauen	1313
Grenoble-Nauen	976
Lille-Nauen	710

Table 1 : Ground distance between the HF transmitter and all the receivers

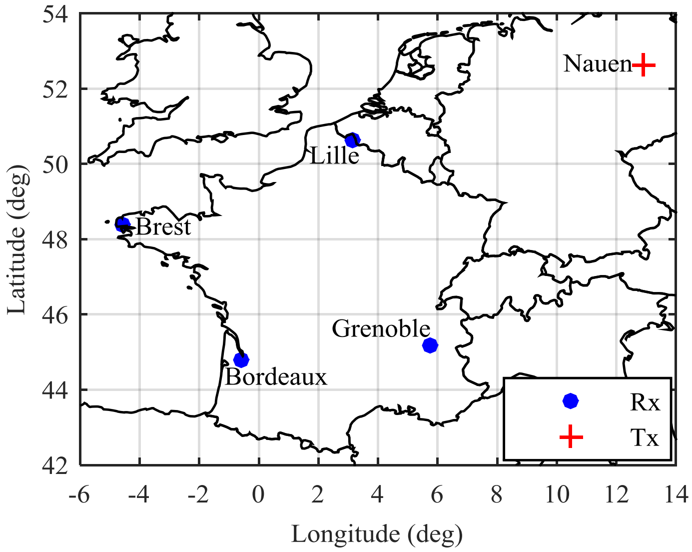

Figure 3 : GPS coordinates of the transmitter site and all the receiving sites in the network

3.3 Measurement Details and Signal Processing

All the HF radio broadcast signals are captured for a span of 5 seconds and sampled at the rate of 200 kHz. The captured signal is filtered in the frequency domain to remove undesired parts of the spectrum. As most of the HF broadcasts are transmitted over a 10 kHz band, only signals within this bandwidth around the carrier frequency of the transmitter are used, the rest is filtered out. The signal is transformed back to the time domain and received signal average power is calculated. Finally the message signal samples are obtained by demodulating the transformed signal.

3.4 Reference Receiver Selection

The geolocation algorithm used to estimate the geographic location of the HF transmitter is dependent on the reference receiver [10]. The received signal average powers for all the receivers were compared and the receiver with the highest average power was considered as the reference receiver. Using the cross-channel sounding technique [11], the message signal samples from the reference receiver are cross-correlated with the message signal samples from the other three receivers to obtain the three TDoA estimates. The TDoA estimate (Δt) corresponds to the maximum value of the cross-correlation and is expressed as follows:

$$\Delta t = \max_{t} R_{s_1 s_\mathrm{i}}(t) = max_t \int_{-\infty}^{\infty} s_1(\tau) s_\mathrm{i}(\tau + t)\, d\tau \qquad (1)$$

where $R_{s_1 s_i}(t)$ is the cross-correlation between the message signal samples $s_1(t)$ obtained from the reference receiver and the message signal samples $\mathrm{s_i}(t)$ obtained from the other three receivers $(i = 1{,}2{,}3)$, respectively.

4 Experimental Results

Multiple HF broadcast radio signals were captured simultaneously by all the receivers in the network between 19:11–19:20 UTC on 18th July 2017 from the HF transmitter located in Nauen. The interval between the start times of each capture was equal to one minute. The transmitter was emitting at a frequency of 11.790 MHz. The GPS locations of the broadcast transmitter in Nauen and all the four receivers were transformed to x and y coordinates using the azimuthal equidistant projection [12] and considering the selected reference receiver as the origin of the coordinate system. An analysis of a data capture is presented in the following section.

4.1 Data capture analysis

A HF radio broadcast signal captured from Nauen simultaneously by all the four Rx's on 18th July 2017 at 19:17 UTC is analyzed. The signal received in Grenoble was considered as the reference signal on the basis of the received signals power. The signal captured in Grenoble is presented in Figure 4.

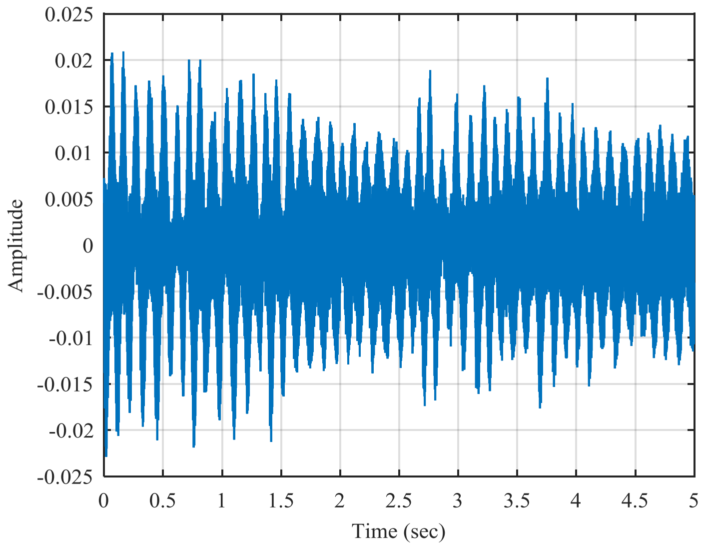

Figure 4 : HF signal received in Grenoble from the HF transmitter in Nauen on 18th July at 19:17 UTC

The message signal samples were obtained from the four receivers as explained earlier. The propagation duration differences for the signals received at different receiver pairs (i.e. Grenoble-Brest, Grenoble-Bordeaux and Grenoble-Lille) were obtained using the cross-correlation method. An example of the cross-correlation output for the signals captured in Grenoble and Lille is shown in Figure 5. Using the obtained TDoA estimates, the Tx coordinates were found by solving a system based on quadratic equations [10]. The estimated coordinates were transformed to geographical coordinates and the geolocation error was found to be 5.7 km.

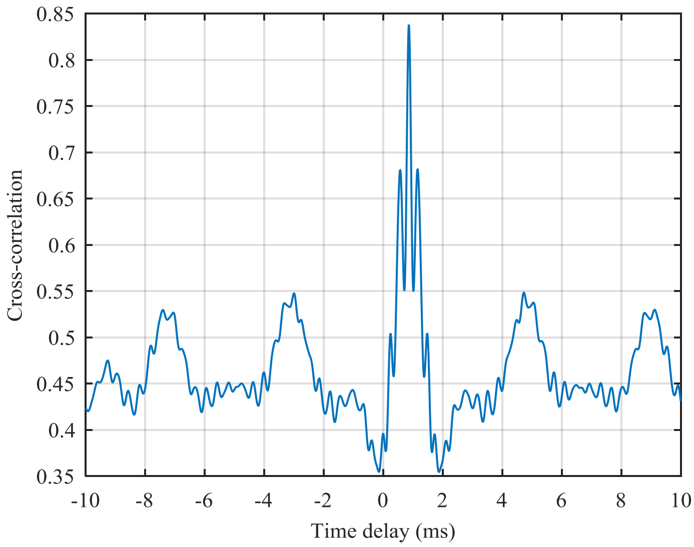

Figure 5 : Cross-correlation of radio signal captured in Grenoble and Lille from the HF transmitter in Nauen

Table 2 provides the summary of the geolocation error for the 10 different captured signals from the HF transmitter in Nauen on 18th July between 19:11-19:20 UTC. For all ten captures, the received signal in Grenoble was selected as the reference receiver on the basis of received signal intensity. The signal-to-noise ratio (SNR) for all ten signals captured in Grenoble was at least 12 dB. The minimum geolocation error of 5.7 km corresponds to a relative error of about 0.6% computed with respect to the maximum ground range among the four possible HF paths whereas the maximum geolocation error of 112.6 km corresponds to a relative error of about 5.9%.

Number of captures considered	10
Minimum geolocation error (km)	5.7
Maximum geolocation error (km)	112.6
Median geolocation error (km)	30.7

Table 2 : Summary of geolocation error for all HF signals captured from Nauen

5 Conclusion

In this paper, we presented the results of geolocation of the HF transmitter in Nauen, performed using the TDoA method. The TDoA method is well suited for passive geolocation and can be performed using light and portable equipment. Four receivers capable of synchronously capturing distant HF signals have been built and deployed in four different cities in France. We have also presented the receiver design in detail. Multiple signals are captured simultaneously using the receiver network from the HF transmitter in Nauen. The measurement data are analyzed and the geolocation errors are presented. The analysis of the geolocation output allows us to believe that HF geolocation can be performed using the TDoA method.

In future, we plan to capture large amount of data using different HF broadcast transmitters around Europe and perform a statistical study with respect to the different parameters of the received signal. In order to improve the geolocation accuracy, several aspects related to the use of ionospheric information along with the estimated TDoA's need to be studied further in detail.

Acknowledgements

This work is supported in part by the Carnot Institute and the Brittany region in France. The authors thank the Atmospheric Optics Laboratory in University of Lille 1 and the Electrical Engineering Department in IUT1-University Grenoble Alps for hosting our receiver setup.

References

[1] D. Heurguier, “La localisation d'émetteurs de radiocommunication en zone urbaine,” Journées Scientifiques URSI France, Mar. 2014.

[2] P. J. D. Gething, “HF direction finding,” Proceedings of the Institution of Electrical Engineers, vol. 113, no. 1, pp. 49–61, Jan. 1966.

[3] G. Fabrizio and A. Heitmann, “A multipath-driven approach to HF geolocation,” Signal Processing, vol. 93, no. 12, pp. 3487–3503, Dec. 2013.

[4] P. Pagani, R. Fleury, Y. L. Roux, and D. L. Jeune, “A study of HF transmitter geolocation through single-hop ionospheric propagation,” 8th EuCAP, 2014, pp. 2689–2693.

[5] D. J. Torrieri, “Statistical theory of passive location systems,” IEEE Trans. on Aerospace and Electronic Systems, vol. AES-20, no. 2, pp. 183–198, Mar. 1984.

[6] K. Davies, “Ionospheric radio,” IEE Electromagnetic Waves Series 31, pp. 124-158, n° ISBN: 0 86341 186 X, May 1989.

[7] R. W. LaBahn and R. B. Rose, “Time delay variations in HF propagation,” Radio Science, vol. 17, no. 5, pp. 1285–1299, Sep. 1982.

[8] “GPSDO Selection Guide - Ettus Knowledge Base.” Available: https://kb.ettus.com/GPSDO.

[9] “USRP-GNURadio-gnuradio.org.” Available:http://gnuradio.org/redmine/projects/gnuradio/wiki/USRP.

[10] A. Jain, P. Pagani, R. Fleury, M. M. Ney, and P. Pajusco, “Efficient time domain HF geolocation using multiple distributed receivers,” 11th EuCAP, 2017, pp. 1852–1856.

[11] A. Jain, P. Pagani, R. Fleury, M. M. Ney, and P. Pajusco, “Cross-Channel Sounding for HF Geolocation: Concepts and Experimental Results,” The 12th European Conference on Antennas and Propagation (EuCAP), 2018, accepted for publication.

[12] J. P. Snyder, “Map projections: A working manual,” U.S. Government Printing Office, Washington, D.C., Series 1395, pp. 191–202, 1987.