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Time Domain HF Geolocation : Experimental Measurements and Preliminary Results

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Abstract— In the framework of military or humanitarian operations, it is important to determine the geographic location of High Frequency (HF) transmitters by analyzing the emitted electromagnetic signals. This paper presents a time domain geolocation technique, exploiting the time of arrival of the radio signal received at a set of single antenna stations. A preliminary study showed that the location could be established without explicit knowledge of the ionosphere height. We present a measurement campaign designed to validate this approach, where HF stations are deployed in 5 sites in France. The ionospheric channel is regularly sounded at the frequencies of 6.40 MHz, 8.06 MHz and 9.95 MHz. This experiment allows analyzing the effect of the ionosphere on radio transmission, including the observation of the different propagation modes and the diurnal channel variations. The initial measurement results are then used to evaluate the performance and limitations of time domain HF geolocation.

Index Terms— HF propagation, experimental measurements, geolocation, ionosphere, time difference of arrival, time of arrival

I. INTRODUCTION

Long-range radio transmission in the HF band can cover large geographical areas using light and mobile equipment. It is therefore well suited for communications during military or humanitarian operations. In this context, it is important to determine the geographic location of the transmitters by analyzing the electromagnetic communication signals.

For HF transmissions at distances around 1000 km, the radio signal propagates through a reflection in the ionosphere. The characteristics of this atmospheric layer are highly variable depending on solar activity, geographical location and local time. One of the available localization techniques, called Single Site Location (SSL) [1][2], uses a large network of multiple antennas, which provide the direction of arrival in elevation and azimuth of the incoming signal. Drawbacks of this method lie in the need of deploying a large antenna array and the requirement of an accurate model of the ionospheric profile, which implies estimating the height of ionospheric reflection using a modelling software or a ionosonde.

The aim of this paper is to present an alternative, complementary geolocation technique, entitled Time Difference of Arrival (TDoA). This technique is usually employed for radio localization in the case of Line-of-Sight transmission [3], but has rarely been studied in the case of ionospheric propagation. Based on the knowledge the signal propagation time, it can be applied to a set of non co-located,

single antenna receivers, allowing for a rapid deployment in critical areas.

A preliminary study of time of arrival geolocation [4] has shown that under certain assumptions, the location could be established without explicit knowledge of the ionosphere height. In order to validate this approach, we performed a series of experimental measurements at the scale of a country area. The data collected from multiple transmitting and receiving HF stations will allow better understanding the advantages and limitations of this localization technique.

The remainder of the paper is organized as follows. Section II describes the principles of time domain HF geolocation. The measurement campaign is described Section III. Finally, Section IV provides an analysis of the received signal in terms of ionospheric propagation and discusses examples of ToA and TDoA geolocation.

II. PRINCIPLES OF TIME DOMAIN HF GEOLOCATION

A. Ionospheric Propagation

The ionosphere [5] is the ionized region of the upper atmosphere that extends from 50 to about 2000 km above the surface of the Earth. In this region, the effect of the sun radiation (in the ultraviolet and X bands) on the neutral atmosphere particles produces an excess of electrons that affects radio wave propagation.

The electron concentration is in the form of vertically stratified regions, also called ionospheric layers, which are designated by the letters D, E and F in order of increasing altitude. In each of these layers, the resulting refractive index is variable with the altitude, which makes the ionosphere a dispersive medium, capable of refracting radio waves. For radio frequencies in the HF range (3-30 MHz), radio signals can be reflected to the ground, thus allowing long-haul radio transmission beyond the optical horizon.

Depending on the transmission path followed by the radio signal, different modes of HF propagation can be defined. Single-hop transmission via one reflection in the E or F ionospheric layers are called the 1E mode and 1F mode respectively. Note that signal transmission can also benefit from a further reflection on the ground, leading to multi-hop modes on a single layer (e.g. 2F mode, 3F mode) or even combinations of reflections over several layers.

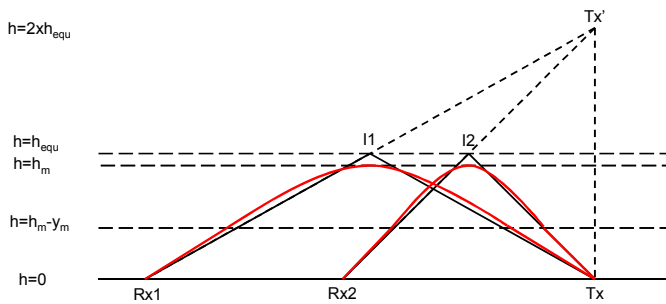


Fig. 1 Schematic of the geolocation principle.

Several other propagation mechanisms are likely to occur in the ionospheric medium. For instance, for a given signal frequency and given transmitter (Tx) and receiver (Rx) locations, slant propagation can occur in an ionospheric layer via two possible paths, called the low-angle ray and high-angle (or Pedersen) ray. In addition, the presence of the terrestrial magnetic field generates an additional mode of propagation, called extraordinary mode, which can be discriminated using the wave polarization. In contrast, classical transmission is referred to as the ordinary mode.

B. Time Domain Geolocation

Among the possible ways to identify the location of an unknown HF transmitter [6], time domain geolocation presents the particularity of relying on measurements of the signal transmission durations, providing an estimate of the propagation distances. The Time of Arrival (ToA) technique requires the knowledge of the transmission time. After determining the length of the propagation path from the Tx to several Rx stations, the Tx location can be retrieved by trilateration. If the transmit time is unknown, similar techniques can be developed using the Time Difference of Arrival (TDoA) at different Rx stations. Early examples of time domain HF geolocation can be found in [7] - [9], where the main findings relate to the difficulty of modelling the effect of the ionospheric medium due to its large temporal and spatial variability. In a previous study [4], we demonstrated that, under certain conditions, geolocation can be performed without the explicit knowledge of the ionospheric layers height.

The application of HF time domain geolocation is envisioned for medium-range HF transmission, with Tx-Rx distances in the order of 1000 km. In this scenario, one assumes that the HF signal propagates via a single reflection on the ionosphere. For each ionospheric layer E and F, one defines a virtual reflection height, h'_E and h'_F , that corresponds to the reflection height of a signal with the same group delay propagating via a specular reflection. This parameter is usually measured using an ionosonde.

As illustrated in Fig. 1, the localization problem is equivalent to determining the location of point Tx', situated at an altitude $2 \times h'$ above the Tx location on the Earth surface. Knowing the propagation delays between the Tx and the different Rxs, this problem is easily resolved by trilateration. For the ToA technique, the point Tx' is the intersection of three spheres centered on the Rx stations. If the transmission time is unknown, the point Tx' is determined as the intersection of three hyperboloids where the Rx stations are the focal points.

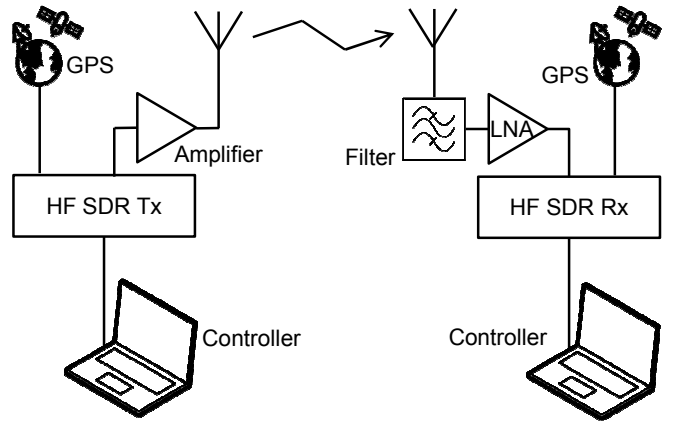


Fig. 2 Experimental setup.

Note that this geometrical problem requires resolving systems of quadratic equations, which cannot be done directly in an analytic way. However the problem can be linearized using differential transformations.

We used the method presented in [10]. Following this approach, the coordinates (x_0, y_0, z_0) of the point Tx' can be successfully retrieved using ToA geolocation as soon as the signal propagation time is measured at 3 Rx stations. The TDoA case involves an additional unknown, namely the transmission time t_0 , and therefore we use the time of arrival measurements at 4 different Rx stations.

III. MEASUREMENT CAMPAIGN

A. Equipment and Signal Processing

In order to validate the concept of time domain HF geolocation, we set up a measurement campaign involving several HF radio transmissions. As described in Fig. 2, both Tx and Rx were developed using a Software Defined Radio (SDR) equipment operating in the HF frequency range. At the Tx, the signal is amplified and fed to a Delta antenna. At the Rx, the signal obtained at the output of a whip antenna is filtered and amplified using a Low Noise Amplifier. In order to accurately estimate the time of arrival of the signal, it is necessary to synchronize all Tx and Rx SDR devices. This is done using dedicated GPS disciplined oscillators, allowing to lock the local oscillators on the GPS signal. Finally, the equipment control is performed at each station using an Ethernet-connected laptop.

In this experiment, the transmitted signal consists of a Pseudo-Noise (PN) sequence with programmable length and chip duration. At the Rx, the received sequence is correlated to the original sequence, providing directly the Channel Impulse Response (CIR) possibly composed of several propagation paths. In order to improve the observed signal to noise ratio, an additional processing is realized, by integrating a number of successively received PN sequences. The deployed equipment can be used not only for the study of geolocation techniques, but can prove useful in the analysis and modelling of the HF propagation channel [11].

B. Stations Locations and Measurement Schedule

The equipment described above was installed in 5 sites in different cities in France. As presented in Fig. 3, the measurement campaign involved 1 Tx station, situated in

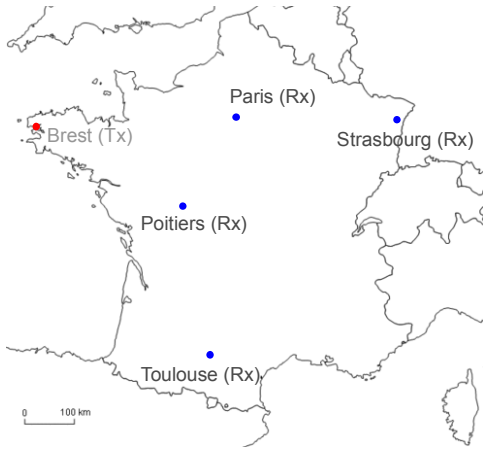


Fig. 3. Localization of Tx (red) and Rx (blue) stations.

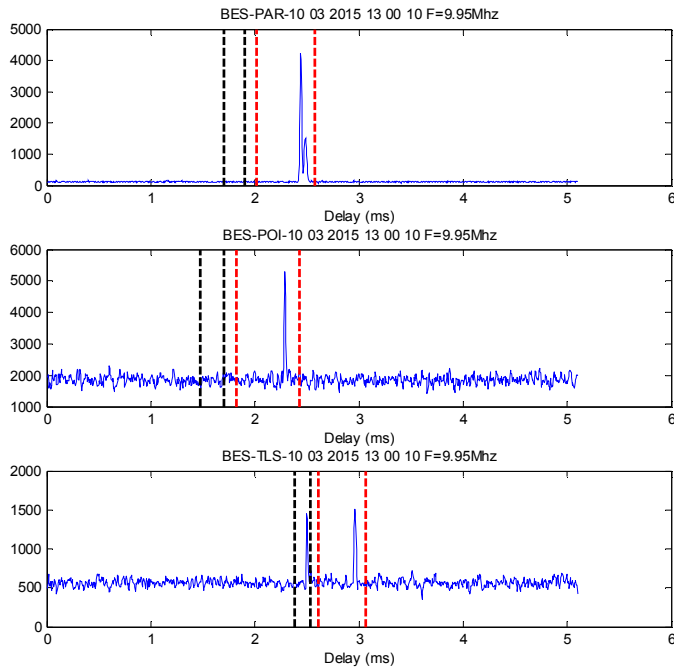


Fig. 4. Example measurement performed in March 2015 at 13h00, frequency of 9.95 MHz, Rx stations of Paris (PAR), Poitiers (POI) and Toulouse (TLS).

Brest, and 4 Rx stations, situated near Paris, Poitiers, Strasbourg and Toulouse. Table 1 provides the distances of the 4 available HF links. Measurements are performed at 3 different frequencies in the HF range: 6.40 MHz, 8.06 MHz and 9.95 MHz. For each HF link, the CIR is evaluated regularly at a rate of one measurement every 30 minutes. This allows observing the effect of the daily variations of the ionosphere on the measurements.

TABLE I. MONITORED HF LINKS

Link	1	2	3	4
Tx	Brest	Brest	Brest	Brest
Rx	Paris	Poitiers	Toulouse	Strasbourg
Distance	483 km	417 km	710 km	890 km

At the Tx station of Brest, as well as at the Rx station of Poitiers, vertical ionosondes were also deployed. Furthermore,

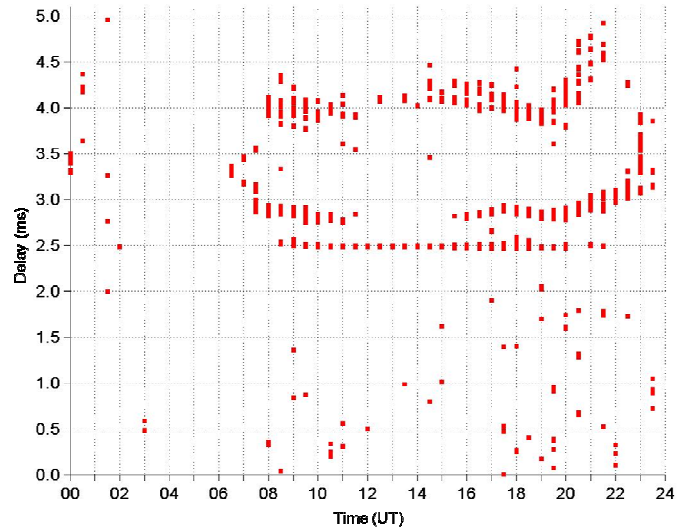


Fig. 5. Time of Arrival (delay) as a function of the Time (UT) for all detected signals on the measurements performed at the Rx station of Toulouse during one week in March, frequency of 6.40 MHz.

two oblique sounding links were operated, namely Brest - Poitiers and Brest - Paris. A description of the sounder used for this purpose is given in [12]. This allows retrieving a precise description of the local ionospheric profile, which can be used for the interpretation of the distant HF sounding results.

C. Example Measurement

Figure 4 provides an example measurement of the CIR retrieved in Paris, Poitiers and Toulouse in March 2015 at 13h00 at a frequency of 9.95 MHz. Based on the physics of ionospheric propagation, one can assume that the E layer, when present, produces signal reflections at a virtual height h'_E in the range between 80 and 150 km. Similarly, the F layer corresponds to reflections at a virtual height h'_F in the range from 180 to 300 km. As the Tx-Rx distance is known in our experiment, it is possible to determine for each receiver a range of delays corresponding to single hop paths via the E layer. This range is materialized with the black dashed lines on Fig. 4. Similarly, the delays corresponding to single hop paths via the F layer are delimited with the red dashed lines.

This measurement example can be analyzed as follows. For the Brest-Poitiers HF link (central graph), a single path via the F layer is observable. For the Brest-Toulouse HF link (lower graph), the signal propagates along two different paths via the E layer and the F layer. Finally, on the Brest-Paris HF link (upper graph), one distinguishes two paths via the F layer, which can be interpreted as one path following the ordinary mode and one path following the extraordinary mode.

IV. RESULTS ANALYSIS

A. Observation of Time of Arrival Measurements

From a series of measurements like the ones presented in Fig. 4, it is possible to study the Time of Arrival distribution for a given link. For this purpose, we identified the peaks in the measured CIR by defining a threshold above the observed noise. Each peak crossing the threshold is then interpreted as propagation path with a given Time of Arrival.

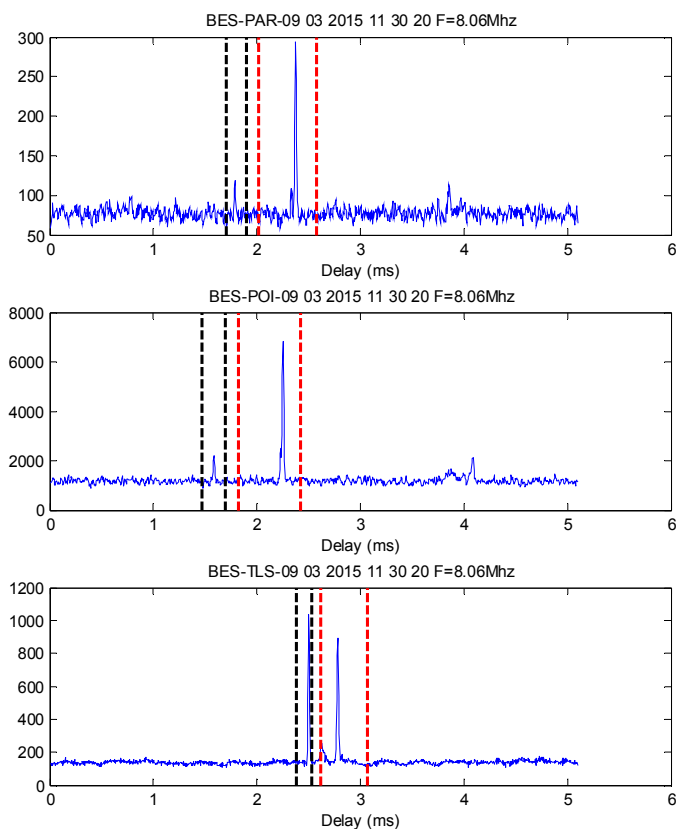


Fig. 6. Example measurement performed at 11h30 in March, frequency of 8.06 MHz, Rx stations of Paris (PAR), Poitiers (POI) and Toulouse (TLS).

As an example, Fig. 5 presents the Time of Arrival as a function of the time (UT) for all detected signals on the measurements performed at the Rx station of Toulouse during one week in March, for the frequency of 6.40 MHz. From 8h00 UT to 21h30 UT, one observes the single reflection of the signal on the E layer, with a delay of 2.45 ms, corresponding to a virtual reflection height h'_E of 97 km. Between 6h30 UT and 23h30 UT, the reflection on the F layer is observable, with delays spreading from 2.7 to 3.0 ms. In particular, between 6h30 UT and 7h30 UT, one can interpret the two observed traces as two different 1F propagation modes: the low-angle ray and the high-angle ray. From 7h30 UT on, the high-angle ray is occulted. Similarly the E layer shadows the propagation via the F layer between 11h30 UT and 15h30 UT. The variable virtual reflection height h'_F is due to the variation of the electronic density during the day. In particular, the F layer is rising with a rapid delay increase after 20h00 UT.

Finally, propagation paths generating a delay in the order of 3.7 to 4.3 ms are interpreted as a 2F mode, where the signal undergoes two reflections on the F layer and one reflection on the ground. These propagation paths cannot be exploited by the ToA or TDoA geolocation algorithms, that assume single-hop propagation paths.

B. ToA Geolocation Examples

Using measurements performed simultaneously on 3 Rx sites, it is possible to localize the Tx site using the ToA technique. This method uses the principle of trilateration and assumes that the 3 signals are received via one reflection on a uniform ionospheric layer.

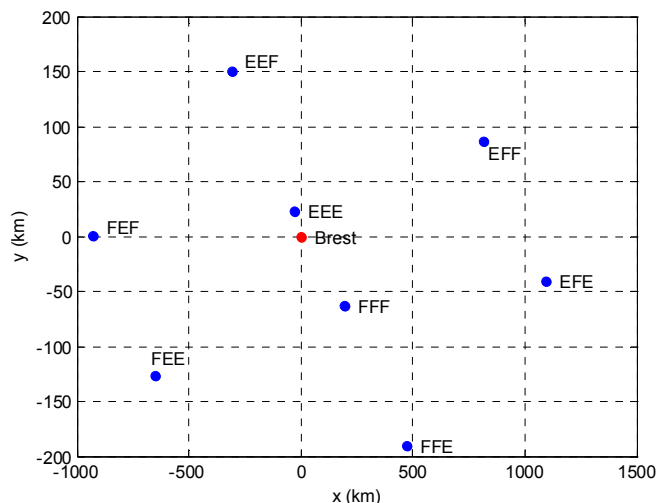


Fig. 7. Geolocation results using the ToA technique, as a function of the selected propagation modes.

As a first step, the ToA algorithm is applied to the example measurement presented in Fig. 4. This example is a favorable propagation case where, for each Rx, the received propagation path with the highest power corresponds to the same propagation mode 1F. Applying the ToA algorithm on this example allows geolocating the Tx station with an error as small as 5 km. However, the propagation conditions are not always so favorable. As observed on Fig. 5, the transmission of HF signals at the selected frequencies is not possible at night. Also, even during the period when transmission is possible, the detected propagation paths do not always correspond to the same propagation mode, leading to large errors.

This problem will be illustrated through the following example. The measurement presented in Fig. 6 is a representative case where the signal propagates via the modes 1E and 1F for all 3 Rx stations. It is noteworthy that depending on the Rx site, the relative power of the 1E and 1F modes is highly variable. In such case, the geolocation error will strongly depend on the capacity to discriminate a single propagation mode for the 3 measurements.

Figure 7 represents the geolocation results obtained as a function of the selected propagation modes for each measurement. The output location is represented on a grid in km where the actual Tx station location is situated at the coordinates (0,0). Selecting the 3 E modes allows locating Brest with a low error of 38 km. Choosing the 3 F modes provides a moderate error of 206 km. As soon as the propagation modes are not identical for the 3 Rx stations, the error increases drastically, with geolocation errors between 340 km and 1100 km. Obviously, the possibility to physically interpret the observed measurements is key for an increase in the localization performance.

C. TDoA Geolocation Example

In the practical cases of geolocation for unknown HF transmitters, the signal transmission time is not determined. We solve this problem by using the time of arrival measured at 4 different Rx stations. This section provides an example of TDoA geolocation using measurements collected in Paris, Poitiers, Strasbourg and Toulouse (Fig. 8). The sounding was performed at 15h00 in April, at the frequency of 8.06 MHz.

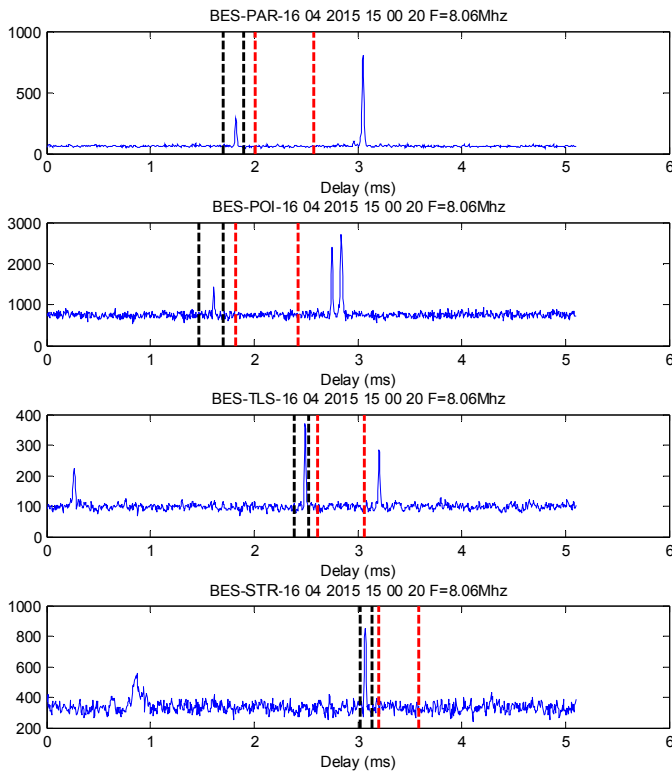


Fig. 8. Example measurement performed at 15h00 in April, frequency of 8.06 MHz, Rx stations of Paris (PAR), Poitiers (POI), Toulouse (TLS) and Strasbourg (STR).

On this example, the propagation path via the mode 1E is received at each of the 4 Rx stations. However, this path is not always the strongest one. The Rx in Paris receives an echo with a delay of 3.1 ms, corresponding to a mode 2F. A similar situation is observable for the Rx in Toulouse and Poitiers (with two modes 2F in this last case). Finally, the Rx in Strasbourg does not receive any signal through the F layer.

Clearly, realizing a blind geolocation by selecting the strongest echo for each Rx station will lead to a large error, due to the combination of path of different modes. Indeed, applying the TDoA algorithm this way results in a large error of 718 km. In order to increase the geolocation performance, one needs to find a way to identify the physical nature of each propagation path. Applying the TDoA algorithm to the delays associated with the mode 1E for all Rx stations leads to a much lower geolocation error of 65 km. As a conclusion, the physical interpretation of the received signal is paramount in order to achieve localization with acceptable accuracy.

V. CONCLUSION

In this paper, we presented the time domain HF geolocation techniques ToA and TDoA. These passive techniques can be employed complementarily to the classical direction finding and SLL techniques, without requiring the deployment of large antenna arrays or ionosondes. They are thus well suited for a rapid deployment in critical areas. In order to validate this approach, we performed a series of experimental measurements with HF stations in different cities in France: Brest, Paris, Poitiers, Strasbourg and Toulouse. The sounding equipment consists of HF SDR Rx and Tx modules, which are synchronized using GPS signals.

As a first result, this measurement campaign allowed us analyzing the propagation phenomena of HF ionospheric transmission, including the identification of different propagation modes and the observation of the diurnal variations of the ionosphere. In a second step, we exploited preliminary measurements from the sounding campaign to assess the possibility of geolocation using the ToA and TDoA algorithms. In favorable propagation conditions, these techniques provide a localization accuracy of a few tens of km. However, different propagation conditions on the different HF links lead to an increase in the localization error. We conclude that the ability to discriminate the different propagation mechanisms is important for an efficient application of time domain geolocation.

The methods for such identification of the propagation modes will be investigated in our future research. In particular, a calibration method will be studied exploiting RF signals with identified emitters [13], such as broadcast signals or beacon networks.

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