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Measurement Qualification Metrics for Passive HF Geolocation

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***Abstract*—Passive HF geolocation methods can be used to extract the location of an unknown transmitter in the range of one-hop HF links through a synchronized time difference of arrival (TDoA) network. This paper aims to highlight that a measurement can be qualified with respect to the different parameters available at the reception sites in the context of passive HF geolocation. In particular, a qualified measurement could be used to estimate the transmitter location whereas unqualified measurement could be discarded which, if processed, would result in a totally incorrect estimate of transmitter location. HF receiver design and the installed receiver network to synchronously capture HF radio signals are presented. Measurements from different transmitters are analyzed in terms of different estimated measurement metrics with the purpose of measurement qualification or elimination. Specifically, data reduction is achieved based on the analysis of the estimated TDoA's by exploiting the assumed coherence of collected measurements over time.**

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

I. Introduction

Radio transmissions from HF band can be propagated over long distances through skywaves where signals are reflected through one or multiple hops in the ionosphere-Earth waveguide. In addition, such long-range HF communication links can be established using compact and cost-effective devices. Considering their importance in defense and civil operations, passive geolocation of HF transmitters are vital and of prime importance.

Passive geolocation can be defined as a process of detecting and locating an object or source of an electromagnetic communication signal using a non-intrusive system, i.e., without the source/object being able to detect the localization activity. The source (i.e. target) location is estimated by processing the signals captured by multiple receivers or a large antenna array. Specifically, HF geolocation can be achieved through angular and time domain methods. In angular domain methods, direction of arrival (DoA) of the incoming HF signal can be found using different methods which are explained in [1]. Another angular domain method known as Single Site Location (SSL) computes the DoA of the received HF signal in terms of azimuth and elevation angles [2][3]. The disadvantages of angular methods lay in deploying antenna arrays and the knowledge of the ionospheric reflection heights along the different HF links, which are unknown in the case of passive geolocation. In time-domain methods, the location of the HF transmitter could be estimated under some assumptions using the time of arrival (ToA) and time difference of arrival (TDoA) principle, without knowledge of the ionospheric reflection height [4]-[6]. In the case of passive HF geolocation, the signal transmission time is not known. As a result, the ToA method cannot be used and the TDoA method should rather be used to estimate the location of a HF transmitter.

The ionosphere [7] is an upper portion of atmosphere extending from a height of about 60 km to about 2000 km above the surface of the Earth. Free electrons in the ionosphere generated by photo-ionization causes refraction (bent) of HF radio signals from different layers of the ionosphere (i.e. D, E, F_1 and F_2), thereby enabling long distance communication. Signals which are reflected once from the E and F layer are referred as 1E and 1F mode, respectively. As the ionosphere is a highly dynamic medium, geolocation using skywaves is difficult. Experiments conducted to measure time delay variations in HF propagation showed that the standard deviation of the mean arrival time is always greater than 10 µs and more often it was found to be around 25 to 50 µs [8]. Experiments presented in [9] showed that TDoA errors between experimental and simulation result for HF broadcast signals were mostly found to be in the range of about 5-25 µs.

This paper describes the different measurement qualification metrics available to the user in the context of passive HF geolocation. From an unknown HF signal captured by a network of receivers, one can estimate noise levels, signal-to-noise ratio (SNR) levels at each reception site and TDoA's between different pairs of receivers. Based on these 3 estimates for a series of captures, a measurement can be qualified for further processing or excluded. The HF receiver prototype and the deployed receiver network setup are explained in Section II. In Section III, the measurement campaign is described. Section IV provides an analysis of the captured HF signals from different broadcasters in terms of different measurement qualification metrics. Finally, based on this analysis, conclusions are drawn in Section V.

II. HF Receiver Network

In order to study the performance of a practical HF geolocation system based on TDoA, 4 receivers were built using a Software Defined Radio (SDR) module (Ettus USRP N200/N210) to capture HF radio signals synchronously. The

complete receiver hardware prototype is illustrated in Fig. 1. The principal component of the receiver prototype is the USRP N210/N220 which consists of a direct sampling ADC coupled to an FPGA for downsampling and frequency conversion. The frontend of the USRP is connected to an active HF antenna through a cascaded configuration of junction box and low-pass filter. The LFRX and GPS disciplined oscillator (GPSDO) are inserted within the USRP. The LFRX accepts signals from DC to 30 MHz whereas the GPSDO is locked to global GPS standards using the GPS antenna. The GPSDO allows all the receivers to be synchronized, independent of their locations. Data captures are scheduled by the user and a capture is initialized through several programs. Generated complex samples are saved in different files in the server through Ethernet port.

As seen in Fig. 2, these 4 receivers were installed in different cities in France namely Brest, Bordeaux, Grenoble and Lille resulting in a HF receiver network. This network was controlled from a central machine in Brest. HF radio signals were captured from different HF broadcasters in Europe and their geographical coordinates are presented in Fig. 2.

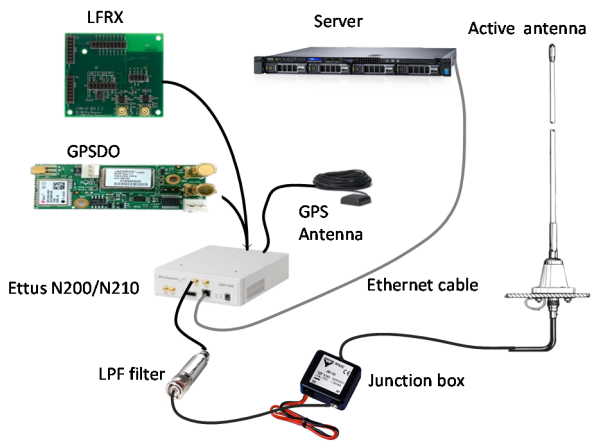

Fig. 1. Receiver hardware prototype configuration

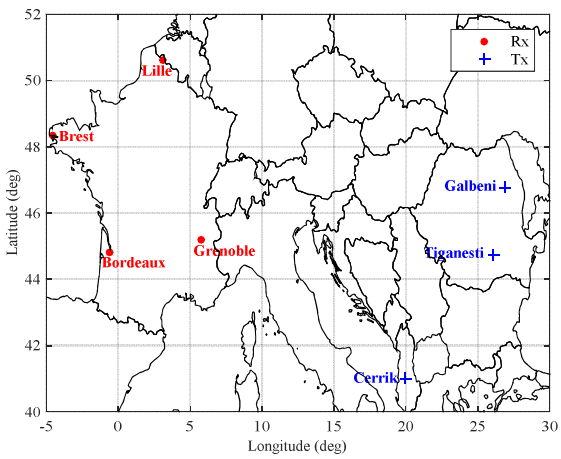

Fig. 2. Geographical coordinates of Rx (red) and Tx (blue) stations

III. Measurement Campaign

A. Measurement Details

Capture details (i.e. capture frequency range, capture months, capture time ranges and capture count) for all measurements made at the 4 receivers from 3 different transmitters are summarized in Table I. In general, data were captured at specific timings and frequencies within the mentioned ranges at different days of the months. The capture duration for each measurement is 5 second and the captured signal is sampled at the rate of 200 kHz.

TABLE I. Capture Details From Different Transmitters

Transmit site	Capture freq. range (MHz)	Capture months	Capture time range (UTC)	Capture count
Cerrik (CER)	5.970 – 13.710	2017: July, Sep. – Nov., 2018: Jan. – March.	07:15:00 – 21:25:00	3082
Galbeni (GAL)	7.360 – 15.400		06:15:00 – 19:05:00	3085
Tiganesti (TIG)	7.230 – 15.430		10:30:00 – 19:24:00	1186

B. Signal Processing

Complex samples (IQ data) are retrieved from the USRP box and the message lies in the envelope of complex samples. This is due to the fact that HF signals are amplitude modulated and then broadcasted using directional antennas. The captured signal (i.e. IQ data) is filtered in the frequency domain to suppress unwanted part of the captured signal. The signal is then transformed back to time domain and demodulated to obtain the message signal. Lastly, using the concept of cross-channel sounding [10], the TDoA estimates are obtained for different receiver pairs.

IV. Measurement Qualification Parameters

Different means of qualifying a measurement include computing the noise and SNR level of the captured signal. It may happen that the noise and the SNR level are dependent either on the transmitter or on the receiver or on the broadcast frequency or even on a combination of these parameters. Based on the previous outputs, one can qualify a measurement for further processing or exclude it. In the latter case, this would result in data reduction.

A. Noise level analysis

In order to compute the noise level of the captured signal, the retrieved complex samples (IQ data) were transformed to frequency domain. Out of the available 200-kHz bandwidth, data representing only 30 kHz of the spectrum was used to calculate the noise floor level (i.e. 15 kHz on either side of the capture frequency was used); this was mainly done to reduce the processing time required for the calculation of the noise floor. Finally, the noise floor level was calculated using the sliding window method. The sliding window length was equivalent to the number of samples corresponding to 1 kHz of the spectrum.

The obtained noise floor levels for all signals captured at different receiver sites from Cerrik and Galbeni as a function of their corresponding capture frequencies can be seen in

Fig. 3 and Fig. 4, respectively. The dots in the legend boxes of both figures corresponds to the receiver site (i.e. BRE: Brest, BOR: Bordeaux, GRE: Grenoble and LIL: Lille). From Fig. 3 and Fig. 4, it can be observed that the level of the noise floor generally decreases with the increasing frequency of the HF link. In addition, the noise level at frequency bands corresponding to different transmitted signals varies with the location of the reception sites. For example, most of the signals captured from Cerrik and Galbeni are received with a lower noise level in Brest as compared to the noise level in Lille.

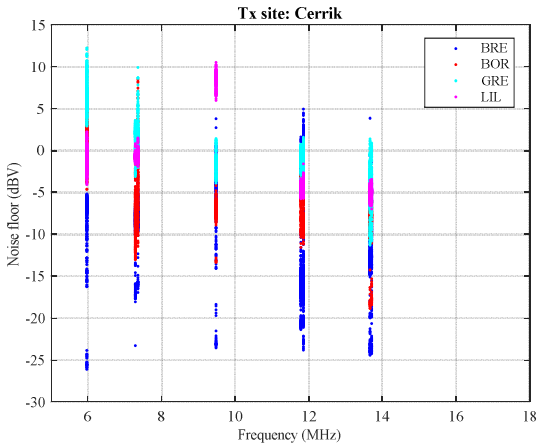

Fig. 3. Estimated noise floor as a function of capture frequency for the broadcasting frequency plan of Cerrik at different receiver sites

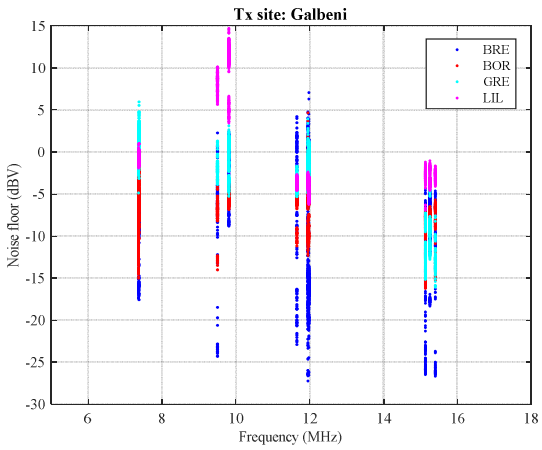

Fig. 4. Estimated noise floor as a function of capture frequency for the broadcasting frequency plan of Galbeni at different receiver sites

Table II provides details of the frequency range of 6 discrete bands out of the available 10 bands for HF broadcasting over frequency range (5.9 – 26.1 MHz) [11]. The total number of captures corresponding to the different frequency bands is also specified in Table II.

Fig. 5 represents the CDF's (cumulative distribution function) of the noise floor for all signals captured in Grenoble while listening to transmissions from Cerrik, Galbeni and Tiganesti with regards to different broadcasting frequency bands. From the per-frequency band CDF curves, it can be again observed that the noise floor level decreases with the increase in the broadcast frequency. Unexpectedly, this effect was not observed with the data captured at the other 3 receivers. It may be due to the influence of unbalanced surrounding noise environment considering the different receiver locations. Thus, one can say that the noise level of received signals also depends on the receiver.

TABLE II. NUMBER OF CAPTURE IN DIFFERENT SHORTWAVE BANDS

Frequency range (MHz)	5.9 - 6.2	7.2 - 7.45	9.4 - 9.9	11.6 - 12.1	13.57 -13.87	15.1 - 15.8
Band (m)	49	41	31	25	22	19
Number of captures	324	1731	858	2471	865	1104

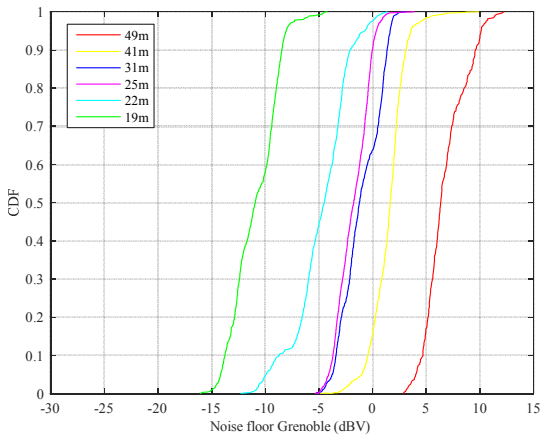

Fig. 5. Noise floor for all signals from 3 different transmitters (CER, GAL, TIG) captured in Grenoble with regards to different frequency bands

B. *SNR analysis*

The signal level was calculated using retrieved samples corresponding to the signal of interest in the frequency domain. The captured signals being broadcast signals from different transmitters, the actual signal bandwidth was unknown and different for each transmitter as well. While computing the signal level, it was assumed that it was received within the bandwidth of 10 kHz. Data samples corresponding to only 5-kHz band on either side of the center frequency were considered when evaluating the signal level. Finally, the 95 percentile value of the samples in the considered 10-kHz band was assumed to be the signal level and the corresponding SNR was evaluated.

Fig. 6 and Fig. 7 represent the CDF curves of the estimated SNR values for signals from 3 different transmitters captured in Bordeaux and Lille, respectively. It must be noted that the number of captures from each transmitter location is different. From Fig. 6 and Fig. 7, it can be observed that the estimated SNR's at both receiver sites are different w.r.t the transmitter site. The signals from 3 transmitters are captured with a higher SNR at Bordeaux as compared to the estimated SNR at Lille.

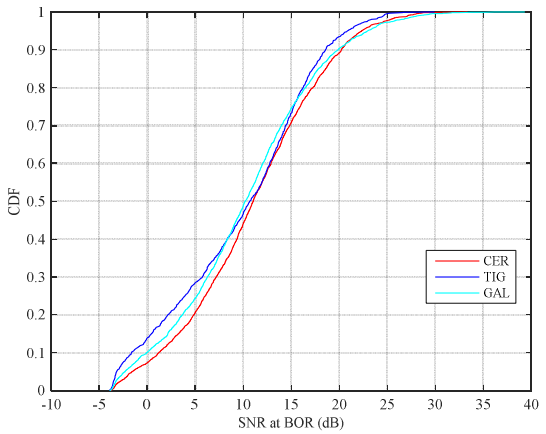

Fig. 6. Estimated SNR for all signals from different transmitters captured in Bordeaux, assuming a signal bandwidth of 10 kHz

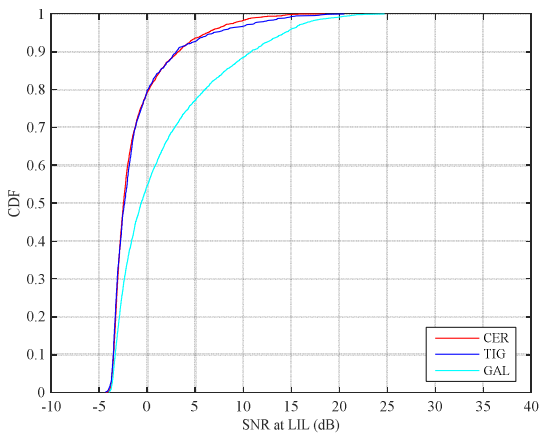

Fig. 7. Estimated SNR for all signals from different transmitters captured in Lille, assuming a signal bandwidth of 10 kHz

The signal level was computed assuming that the signal of interest is present in a 10-kHz band, which may not be true in all the cases as different broadcasters use different bandwidths while transmitting the signal. If that signal of interest lies within a smaller bandwidth, the obtained signal level using the method explained above will give incorrect results. Thus, the signal level is also computed assuming that the signal is received in a 5 and 3-kHz band.

CDF curves of the calculated SNR for 3 different bandwidth values (10, 5 and 3 kHz), for all signals captured in Bordeaux from Cerrik, Galbeni and Tiganesti can be seen in Fig. 8. As expected, one can observe that the median SNR increases about 4.5 dB when the assumed signal bandwidth decreases from 10 kHz to 5 kHz and then to 3 kHz.

In general from noise and SNR analysis, one cannot decide whether a signal can be considered to estimate the location of the transmitter as many of the captured signals in Lille have a low SNR. Moreover, the transmitted signal bandwidth is unknown, which further complicates the calculation of the received SNR at different locations. Another metric that can be used to qualify a measurement could be by analyzing the estimated TDoA's of the collected measurements over the capture time.

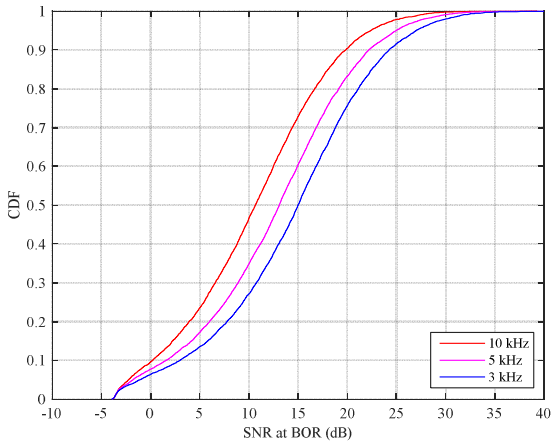

Fig. 8. CDF curves for estimated SNR for different signal bandwidths (10, 5 and 3 kHz) of all captured signals in Bordeaux from 3 different HF transmitters (CER, GAL, TIG)

C. TDoA analysis using statistical likelihood algorithm

Let us suppose that there is an unknown transmitter which is static and it is broadcasting HF radio signals. These radio signals propagate through skywaves and are received by multiple distributed synchronized receivers. TDoA estimates between signals captured by 2 synchronized receivers would be approximately the same for different signals captured over different times of a day/month/year, provided that the propagation mode is the same (i.e. 1E, 1F …) and the signals are received with low noise levels. For instance, one could look at the distribution of observed TDoA's over time (over all measurements months), and consider a TDoA output as valid if it is within a given range around the most probable value. It is a kind of validation by repetition of the TDoA estimate over time.

This approach is only valid for fixed unknown targets, but could be refined for moving targets as long as the accurate TDoA variation can be evaluated over time and with sufficient efficiency to separate the actual TDoA from noisy ones.

Using all the estimated TDoA's for a specific receiver pair, the probability distribution function (PDF) can be computed. The peak of the PDF will represent the most likely TDoA value w.r.t. all measurements. Later, by selecting a time range on either side of the peak, one can decide on the measurement qualification. If the TDoA estimate lies within the specific time range, the measurement can be considered for further processing and if the TDoA estimate lies beyond the specified time range, the measurement can be rejected. If the PDF represents a random curve without any peak, it means that estimated TDoA's are highly scattered, which cannot be true. In such cases, all the measurements have to be rejected. TDoA estimates for a specific receiver pair for all measurements from Cerrik are analyzed using the proposed algorithm and discussed in the following section.

1) Algorithm output example: The estimated TDoA's for all signals (number of measurements: 3082) captured during the measurement campaign in Bordeaux-Grenoble from Cerrik can be seen in Fig. 9, along with corresponding PDF plot represented by the blue curve. For many measurements, TDoA estimates between the receiver pair (Bordeaux-Grenoble) looks repetitive with time over a certain range around thePDF peak. The PDF curve over TDoA estimates of Bordeaux-Grenoble data collection represent a sharp peak which can be clearly identified. It implies that captured data have a quite high SNR at both recievers. Measurements can be further rejected if estimated TDoA's are found to be beyond the selected range of ± 0.25 ms around the peak of the PDF.

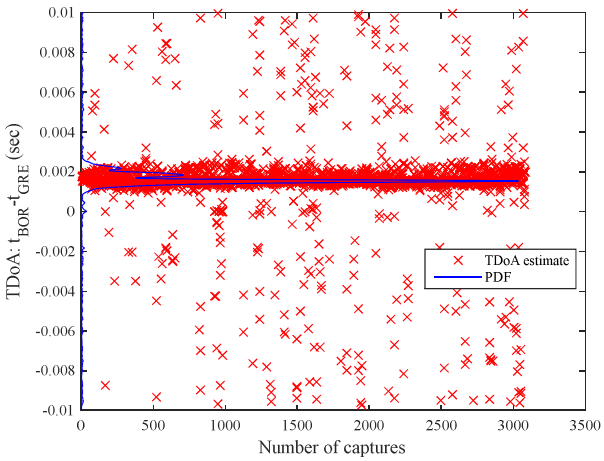

Fig. 9. Plot representing TDoA estimates between all signals received in BOR-GRE from Cerrik along with its likelihood function

One can also classify a measurement over estimated TDoA's from data captured over a course of day or within an hour or within a span of a few minutes from an unknown transmitter. Then, using the statistical likelihood algorithm, measurements can be accepted or rejected.

V. Conclusion

In this paper, we presented different measurement qualification metrics for passive HF geolocation. In order to study HF geolocation using TDoA method, 4 synchronized receivers are assembled and deployed in 4 different cities in France. Data are collected from different HF radio broadcasters located around Europe at all receivers.

As a first result, data captured on all receivers from 3 different transmitters allowed us to analyze the received noise and SNR level. It is observed that the noise level decreases with the increase in the frequency of the HF link. The calculated noise level is found to be varying at all receiver sites and is different for different transmitters. Thus, it can be concluded that the noise level is highly dependent on the receiver location. Signals captured are received with a higher SNR on all receiver sites except Lille where most of them are received with a low SNR. The SNR could not be used as a measurement qualification metric as the transmitted signal bandwidth is unknown. In a second step, data reduction is achieved by exploiting the assumed coherence of collected measurements over time. Using the PDF, the most likely TDoA value is computed over several measurements and then by selecting a range around the most probable value, the measurements are either selected or discarded. Thus, it can be concluded that analysis of estimated TDoA's over time is an efficient metric of measurement qualification as compared to the noise and SNR analysis.

In future work, we will apply the data qualification method presented in this paper to select the appropriate data from a large measurement database in order to statistically analyze the performance of TDoA geolocation algorithm. In addition, we plan to capture data from moving HF transmitter and study the ability of measurement qualification based on the TDoA analysis.

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