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An Operational HF System for Single Site Localization

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Abstract- This paper presents an operational HF (3-30MHz) system designed for single site localization (SSL) of transmitters involved in trans horizon radio links. It associates the estimation of the directions of arrival of incident radio waves refracted by the ionosphere with a ray tracing software based on the PRIME model of the channel.

The direction finding processing is implemented on an array of non identical sensors that presents a polarization sensitivity. A specific version of the MUSIC algorithm jointly estimates the angles of arrival (azimuth and elevation) of incident waves and their polarization.

Statistics of the angles of arrival (mean values and standard deviation) are the input data of a ray tracing software based on the PRIME model of the ionosphere which computes the estimated position of the transmitter.

Numerous radio links have been tested for long distances up to 2000 km. A very good agreement is observed between the exact and the estimated positions of the transmitters with a standard localization error being less than 10% of the distance to the receiving system.

I. INTRODUCTION

Trans horizon radio links are possible in the HF band (3-30 MHz) thanks to the refraction of radio waves by the ionosphere. In this context, the transmitter localization can proceed with a single receiving system and the association of two different functions : direction finding and ray tracing.

Generally, radio direction finding operates on homogeneous antenna arrays, the geometrical inter element phases being directly related to the angles of arrival (AOA). In order to improve the angular estimation of the waves refracted by the ionosphere, we proposed a structure of so-called heterogeneous arrays [1]. This solution presents a polarization sensitivity that reduces the correlation of the acquisitions and improves consequently the angular resolution. In addition, a specific version of the MUSIC algorithm has been derived which estimates the incident polarizations jointly to the AOA.

Statistics of the estimated AOA (mean values and standard deviations) are considered to be the input data of a ray tracing software based on the PRIME model of the ionosphere [2]. For each incident wave detected, a possible region for the end of the corresponding path is identified on the Earth's surface. The intersection of these areas gives the estimated position of the transmitter.

Numerous experiments are carried out with transmitters located more than 1000 km from the receiving site. The results show a standard localization error typically equal to a few per cent of the range of the radio link under test.

II. EXPRESSIONS FOR ARRAY PROCESSING

A. Homogeneous (classical) array

A homogeneous array is made up with NC identical sensors associated with a reference point for the geometrical phase. NS waves are supposed to be incident and the corresponding output signals generated on the reference sensor are denoted by $\{s_k(t)\}$ $k = 1, \dots, NS$.

Each direction of arrival (DOA) is identified by the angle θ_k (or couple of angles in a 3-D search). For such a direction, the geometrical phase between the reference and the n^{th} sensor is denoted by $\phi_n(\theta_k)$

The output on the n^{th} antenna is expressed as:

$$x_n(t) = \sum_{k=1}^{NS} e^{j\phi_n(\theta_k)} s_k(t) + n_n(t) \quad (1)$$

where the noises $\{n_n(t)\}$ $n = 1, \dots, NC$ are supposed to be mutually uncorrelated with identical power.

The NC output signals on the array are written in the output column vector $\mathbf{X}(t)$ as:

$$\mathbf{X}(t) = \sum_{k=1}^{NS} \mathbf{a}(\theta_k) s_k(t) + \mathbf{N}(t) \quad (2)$$

where $\mathbf{a}(\theta_k)$ is the steering-vector for the D.O.A. θ_k and $\mathbf{N}(t)$ is the noise vector. The components of $\mathbf{a}(\theta_k)$ contain the different geometrical phases:

$$\mathbf{a}(\theta_k) = (1, e^{j\phi_2(\theta_k)}, \dots, e^{j\phi_{NC}(\theta_k)})^T \quad (3)$$

Associating the NS steering vectors in the matrix A provides the classical linear model:

$$\mathbf{X}(t) = \mathbf{A}\mathbf{S}(t) + \mathbf{N}(t) \quad (4)$$

where $\mathbf{S}(t)$ is the signal vector.

B. Heterogeneous array

A heterogeneous array is made up of sensors which are different from one another. For each of them, the directional gain relatively to the angle θ , called spatial response and denoted by $F_n(\theta)$, $n=1, \dots, NC$ is supposed to be known. Examples of spatial responses for HF antennas with a simple geometry are calculated in reference [1]. The computation refers to a deterministic model of the polarization at the exit point of the ionosphere.

In this context, the linear model for the output signals of the heterogeneous array is expressed as:

$$\mathbf{X}_h(t) = \sum_{k=1}^{NS} \mathbf{a}_h(\theta_k) s_k(t) + \mathbf{N}_h(t) \quad (5)$$

The components of the steering-vectors $\mathbf{a}_h(\theta_k)$ combine the spatial responses and the exponentials which represent the phases $\varphi_n(\theta_k)$ calculated with respect to the array geometry:

$$\mathbf{a}_h(\theta_k) = (F_1(\theta_k)e^{j\varphi_1(\theta_k)}, \dots, F_{NC}(\theta_k)e^{j\varphi_{NC}(\theta_k)})^T \quad (6)$$

It can be noticed that $\mathbf{a}_h(\theta)$ does not have a constant norm ; this remark will be taken into account when applying the MUSIC algorithm on this particular type of array.

C. Heterogeneous array for H.F. applications

For applications in the H.F. band, two possible types of polarization (ordinary O and extraordinary X) are expected at the end of an ionospheric radio link. Two steering-vectors are then associated to the incident waves and expressed as:

$$\mathbf{a}_{hP}(\theta) = (F_{1P}(\theta)e^{j\varphi_{1P}(\theta)}, \dots, F_{NCP}(\theta)e^{j\varphi_{NCP}(\theta)})^T \quad (7)$$

(P representing the polarization type O or X) where $\{F_{nO}(\theta)\}$ and $\{F_{nX}(\theta)\}$ represent the antenna spatial responses for the two possible polarizations. This particular structure of the steering-vector underlines the polarization sensitivity of the heterogeneous array.

That argument turns out to be an advantage in a context of multi paths with a high level of spatial correlation: several incident signals with a small angular separation can be distinguished by a heterogeneous array assuming that their polarizations are different. This point of view is taken into account in the following paragraph.

III. SPECIFIC VERSION OF THE MUSIC ALGORITHM

MUSIC algorithm [2] uses the eigen decomposition of the data covariance matrix:

$$\mathbf{R}_{xxh} = E[\mathbf{X}_h(t)\mathbf{X}_h(t)^H] \quad (8)$$

Its computation is based on the orthogonality between an incident steering vector and the noise subspace spanned by

the eigen vectors $\{\mathbf{v}_m\}_{m=NC+1}^{m=NSE+1}$ of \mathbf{R}_{xxh} associated with its smaller eigen values.

The implementation includes the following steps:

- estimation of the covariance matrix:

$$\hat{\mathbf{R}}_{xxh} = \frac{1}{N_{ech}} \sum_{n=1}^{N_{ech}} \mathbf{X}_h(n)\mathbf{X}_h(n)^H \quad (9)$$

with N_{ech} snapshots of data

- eigen decomposition of the covariance matrix and estimation of the number of sources NSE based on the dispersion of the eigen values

- computation for all the potential DOA θ , of the angular function (pseudo-spectrum) evaluating the norm of the projection of the steering-vector in the noise subspace. As the projected vector should have a constant norm, the calculus involves the vectors:

$$\mathbf{b}_{hP}(\theta) = \frac{\mathbf{a}_{hP}(\theta)}{\|\mathbf{a}_{hP}(\theta)\|}, \quad P = O \text{ or } X \quad (10)$$

The directions of arrival being estimated for both polarizations, the two sets of steering-vectors are projected in the noise subspace. Consequently, in this original version of the algorithm, two pseudo-spectrums are computed according to the following expression:

$$PSSP_P(\theta) = \frac{1}{\sum_{m=NC+1}^{m=NSE+1} |\mathbf{v}_m^T \mathbf{b}_{hP}(\theta)|^2} \quad (11)$$

This specific derivation of the MUSIC algorithm, resulting from the particular structure of the heterogeneous array, is the principal novelty of the proposed technique. The estimation of the DOA with two different array manifolds induces a reduction of the spatial correlation of incident waves and illustrates the polarization sensitivity of the global processing.

IV. ANGULAR ESTIMATIONS

In order to provide reliable angular estimations, a large acquisition file (typically 120000 samples at a rate of 40 ksamples/s) is arranged in consecutive frames for which an independent computation of the MUSIC algorithm is processed. Actually, if the acquisition file is globally processed, a single pseudo-spectrum will be computed (for each polarization) with the total number of samples. A single set of angles of arrival will be estimated with a low level of reliability: some secondary peaks, due to artifacts, will be potentially considered as actual DOA.

To cope with this problem, the acquisition is divided into 20 consecutive parts containing 6000 samples ; each part is divided in 5 series with a 50% overlapping and a length of 2000 samples . For each part, separated from the previous one with an interval $6000/40000=0.15s$, a pseudo-spectrum for each polarization is computed by averaging the angular functions provided by the 5 time series.

A set of criterions [3] checks the coherence of the successive pseudo-spectrums and rejects the artefacts,

assuming that a single transmitter is operating within the bandwidth (3 kHz) of the receivers. For example, after identification of the maximum peak (considered as a reference) for a given polarization, local maxima are sorted and eventually rejected arguing that the estimated azimuths should be separated from the reference by less than a fixed threshold.

Another criterion expresses the constraint that the estimated azimuths for the two polarizations O and X have to be contained in a limited interval, considering that the possible tilts of the ionospheric layers are moderate.

After passing these tests, the final output file contains the number of detected signals (resulting from a multipath propagation) and, for each of them, the mean value and the standard deviation of the estimated azimuth and elevation.

V. SINGLE SITE LOCALIZATION

The PRIME model of the ionosphere (Prediction and Regional Ionospheric Modelling over Europe) has been selected for this project [3]. It is the result of the COST 238 program (European Cooperation in the field of Scientific and Technical Research) in the 1991-1994 period and describes the structure of the plasma in the mid latitudes and particularly above Europe. Based on the ionospheric parameters predicted by the model, the profile of vertical ionization (electron density) is calculated, using Epstein functions (Fig. 1).

Real-time measurements, provided by a vertical ionosound, can improve the estimation of these parameters. The benefit however is limited to moderate range localization (less than 500 km): due to the existence of horizontal gradients in the electron density, measurements at the zenith of the receiving site can not be extrapolated along a typical radio link.

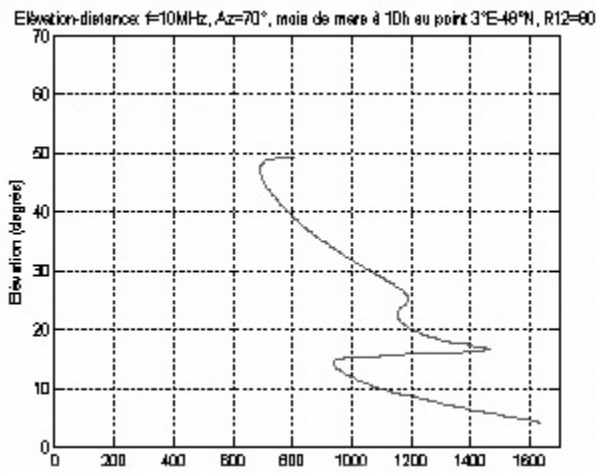


Fig. 1. Vertical profile of the ionization

For a given AOA, the ray tracing (Fig. 2) is computed considering that the ionosphere is finely stratified: each slice is characterized by a refraction index bound to the electron density. An application of Descartes' laws gives continuously

the ray trajectory. For each detected path, the directions of arrival are considered in a volume defined by the mean values of the AOA and their standard deviations; the corresponding ray ends define a region of the Earth's surface. When the calculation for the different incident waves is repeated, the intersection of the corresponding areas gives the possible location of the transmitter.

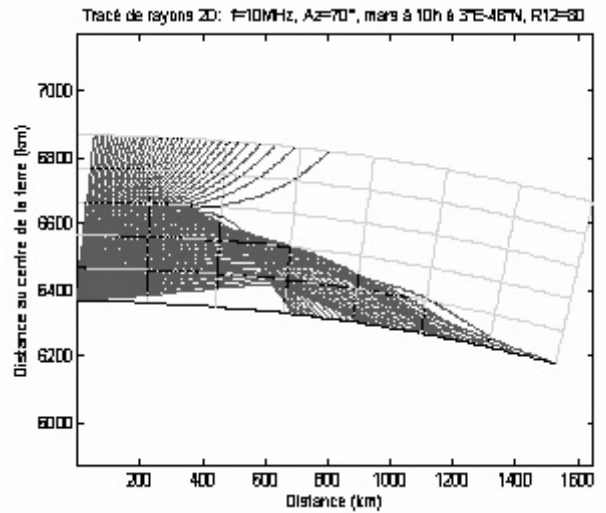


Fig. 2 : Ray tracing

To summarize, the different steps of the localization procedure are :

- collection of the synchronous acquisitions (IF frequency) on NC channels
- computation of the MUSIC algorithm for the different time series of the acquisition file, providing statistics of angular estimations (azimuth and elevation) for the two expected polarizations
- computation of the ray tracing for each detected path, considering a reverse propagation from the receiving site to the transmitter
- definition of the possible location of the transmitter as the intersection of the different ray end areas on the Earth's surface.

VI. EXPERIMENTAL RESULTS

A. Heterogeneous circular array

A circular uniform array of 8 active whip antennas is set up with a 20m radius as shown in Fig. 3. Each sensor is associated with a low noise preamplifier and has a typical length of 1.5m which is small if compared with the wavelength : these condition guarantees an efficient spatial sampling of the incident waves. A heterogeneous structure is obtained with the alternation of vertical and horizontal antennas, the pointing azimuth of which is different from one position to another, in order to optimize the diversity of the antennas' responses. The 8 sensor array is connected to 8 identical coherent receivers with a set of calibrated cables. The intermediary frequency (IF) outputs are then sampled with a synchronous 8 input analog to digital converting card,

the sampling frequency being adjustable up to 1 Msamples/s and equal to 40ksamples/s for most of the acquisitions.

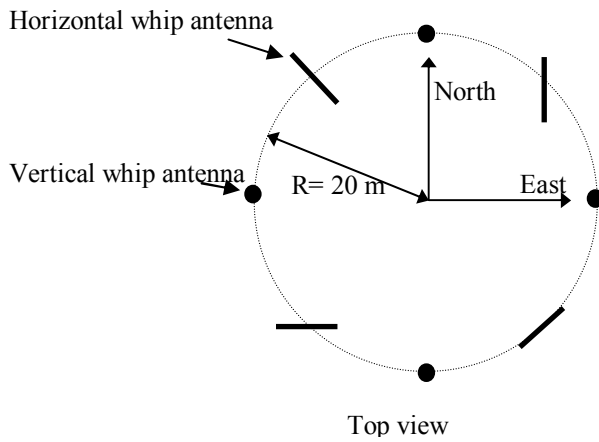


Fig. 3. Heterogeneous circular array

B. Examples of localization

The direction finding system is set up near Orléans (France). The tests consisted in localizations of H.F. transmitters located in Europe and North Africa at a maximum distance of 2000 km. More than 100 experiments, involving 35 military beacons or broadcast transmitters, were carried out during a period of 3 weeks, at various times in the day (and during the night) and for different expected azimuths. Fig. 4 and 5 show an example of result relatively to a transmitter with a carrier frequency of 17.745 MHz and located in Tiganesti (Romania).

Fig. 4 plots a couple of pseudo-spectrums (one for each polarization O or X) picked up in the collection calculated with a long term acquisition of 3 seconds : 2 incident signals are detected with both estimated azimuths being equal to 92°.

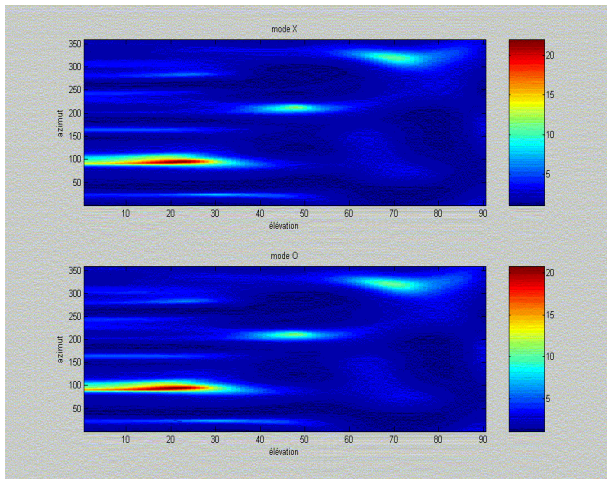


Fig. 4. Pseudo spectrums O and X (Tiganesti acquisition file)

Fig. 5 represents the localization chart resulting from the ray tracing in this case. The estimated location of the transmitter is inside the red surface whereas the exact site is plotted with a black point and appears close to the estimation: this point is separated from the centre of the surface by 85km when the transmitter–receiver distance equals 1860km.

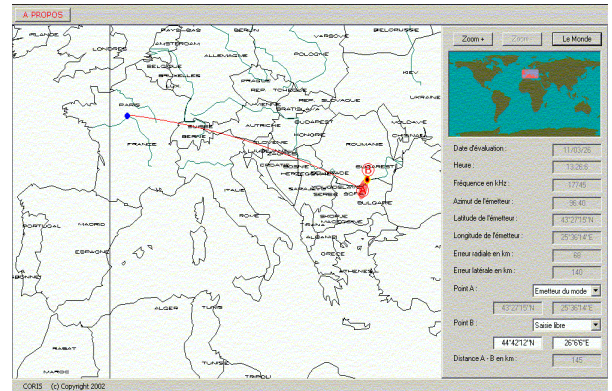


Fig. 5. Estimated location of the transmitter

Fig. 6 and 7 represent the couple of pseudo-spectrum and the localization chart for a beacon located in Prato Smeraldo (Italy ; distance of 1100km , geographical azimuth 128°). The accuracy appears globally adequate.

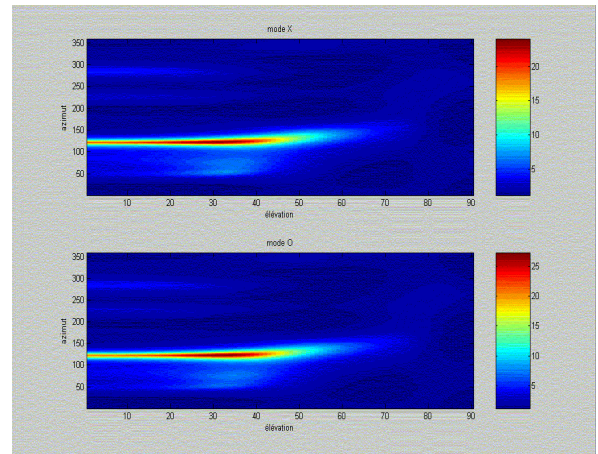


Fig. 6. Pseudo spectrums O and X (Prato Smeraldo acquisition file)

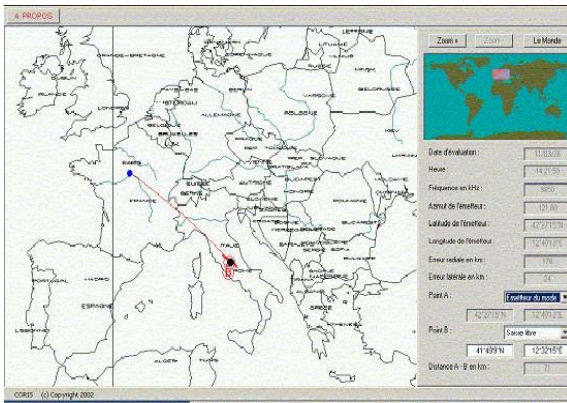


Fig. 7. Estimated location of the transmitter

VII. CONCLUSION

This article presents a global project of single site localization of HF transmitters revealing performances quite compatible with military objectives since the relative localization error appears moderate; however, the proportions of it attributed either to the angular estimation or to the defaults of ionospheric model are not easy to separate.

The main originality of the direction finding system is the heterogeneous structure of the antenna array: its polarization-sensitivity reinforces the high resolution capacity of the algorithm and provides reliable estimations of the AOA in a context of multiple incident waves with a reduced angular separation. However, the robustness of the method requires an accurate model of the spatial response for each sensor, implying a thorough knowledge of the propagation in the ionospheric medium.

The ray tracing software is based on the PRIME model of the ionosphere which gives statistical values for the channel parameters. Its reliability and, consequently, the localization accuracy, could be improved by using real time measurements to correct these estimations: therefore, it appears interesting to complete the global system with a ionospheric sounder.

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