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A method to calibrate HF receiving antenna arrays

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Abstract

This paper deals with H.F. direction finding (DF) and calibration processing. Its main purpose is to present a method to verify or even calibrate a DF system. Some experimental results obtained with a circular (homogeneous or heterogeneous) array and collocated antennas arrays are presented.

1 Introduction

Amplitude and phase calibration of receiving antenna array in the HF band remains an important matter. In systems using such arrays where sky waves are considered, errors responses between the antennas within the array must be corrected for all the azimuths and all the elevations.

The DF method [1] leans on physical properties of ionospheric propagation and supposes the knowledge of antenna transfer function between the incident field and the output signal. Thus, a model of received signals has to include antenna characteristics associated to the angles of arrival and the polarisation of the incident wave.

Paragraph 2 presents the response of an HF active receiving antenna, the array overall response is expressed in paragraph 3.

A method to deduce from measurements the differential response of an array is presented in paragraph 4

In paragraph 6, responses obtained using theoretical transfer function are compared to those obtained according to the proposed method for the arrays described in paragraph 5.

In the paragraph 7, the method is used to check an array (for example, two channels are swapped). A mean to improve the DF accuracy is proposed (paragraph 8). It could be defined as “differential calibration”.

2 Response of an HF active receiving antenna

A solution of the Maxwell equations in the ionospheric plasma has been proposed by Appleton and Hartree in the context of the magneto-ionic theory. It underlines the presence of two magneto-ionic propagation modes [2] named ordinary (denoted O) and extraordinary (denoted X) corresponding to two different refractive index.

For the following applications, only the polarisation at the exit point of the ionosphere is required for a given H.F. radio link. It is calculated considering the limit conditions of Budden [3] which express that the electron density tends towards zero (and jointly the longitudinal component of the electric field) at the output point of the ionosphere. In these conditions, the incident wave is transverse electromagnetic (TEM) and elliptically polarized from the exit of the ionosphere to the receiving station. With this description, the output signal $X_r(t)$ can be written as:

$$X_r(t) = F(\theta)S_r(t) + N(t) \quad (1)$$

$N(t)$: Additive noise,

θ : angles of arrival (azimuth and elevation).

S_r : received scalar signal.

Where $X_r(t)$ is the temporal expression of the received signal evaluated at the output of the antenna, $F(\theta)$ is named spatial response of the antenna [4]. $F(\theta)$ is generally complex. It is real valued only for linear polarisations.

3 Expression of the observations for an array

A heterogeneous array is made up of antennas, which are of different type, height above ground, orientation or any of combinations of these parameters. An a priori knowledge is supposed for their respective spatial responses in the case of NC antennas denoted by $\{F_n(\theta)\}_{n=1, \dots, NC}$.

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

$$Xh_n(t) = \sum_{k=1}^{NS} a_n(\theta_k) S_k(t) + N_n(t) \quad (2)$$

$S_k(t)$: received scalar signal for a path k

$N_n(t)$: additive noise,

Xh_n : received scalar signal for the channel n.

NS : number of paths.

The components of $a(\theta_k)$ combine the spatial responses and the phasors expressing the phase's terms $\varphi_n(\theta_k)$ calculated with respect to the array geometry:

$$a(\theta_k) = (F_1(\theta_k)e^{j\varphi_1(\theta_k)}, \dots, F_{NC}(\theta_k)e^{j\varphi_{NC}(\theta_k)})^t \quad (3)$$

In the case of a homogeneous array, the vector is simplified as:

$$a(\theta_k) = F(\theta_k) \cdot (e^{j\varphi_1(\theta_k)}, \dots, e^{j\varphi_{NC}(\theta_k)})^t \quad (4)$$

If the DF array have no spatial diversity, the vector is expressed as :

$$a(\theta_k) = (F_1(\theta_k), \dots, F_{NC}(\theta_k))^t \quad (5)$$

4 A method to estimate the differential response of an array

First, the transmitter must contain a carrier (an AM broadcast HF transmitter for example). In this case, the transmitter location is known [5] and validates the coherency of the angles of arrivals obtained with DF array.

The first part of the treatment consists in an electronic calibration applied to the complex received signals, to take into account the imperfections of the system (antenna's preamplifiers, unequal lengths of the cables, differences of phases and modulus between the receiver channels). This correction is performed after a Hilbert transform.

Secondly, it is necessary to obtain the angles of arrivals ($\theta = [Az, El]$) from a DF algorithm (MUSIC for example [6]) or with a HF forecast software (LOCAP for example [7]). The incoming paths are identified via the angles of arrival Az and El. If the array is heterogeneous, the results are obtained with discriminating the two magneto-ionic modes (AzO, ElO and AzX et ElX). Indeed, the antenna responses depend on the wave polarisations.

The third part of the treatment is a spectral analysis. Nevertheless, this approach requires acquisition characteristic in accordance with the ionospheric channel (channel stationary, Doppler, duration of the observation ...).

A receiving channel is chosen and an analysis (FFT) is done. The peaks are identified; they are representative of the incoming paths. It is suitable to exploit acquisitions containing only one or two dominant paths as seen on figures 4 and 7.

To improve the frequency identification, it is necessary to use a convergence algorithm based on a DFT. Thus, for each peak, the frequency, the phase and the modulus are obtained with a minimum bias. With this information, the following vector is build:

$$Sr(t) = (b_1 \cdot e^{j(2\pi f_1 t + \varphi_1)} \dots b_{NS} \cdot e^{j(2\pi f_{NS} t + \varphi_{NS})})^t \quad (6)$$

b_1 , f_1 and φ_1 represent the modulus, the frequency and the phase of the path one. NS is the estimated source number.

The following step relates to the estimation of the response of an array. The signals (Xh vector) present on the each channel of reception can be expressed as:

$$\begin{pmatrix} Xh_1(t) \\ \vdots \\ Xh_{NC}(t) \end{pmatrix} = \begin{pmatrix} a_{1,1}(\theta_1) & \dots & a_{1,NS}(\theta_{NS}) \\ \vdots & \ddots & \vdots \\ a_{NC,1}(\theta_1) & \dots & a_{NC,NS}(\theta_{NS}) \end{pmatrix} \begin{pmatrix} Sr_1(t) \\ Sr_2(t) \\ \vdots \\ Sr_{NS}(t) \end{pmatrix} \quad (7)$$

Where $a(\theta)$ represent the antenna responses and the geometrical effect of the array. From these equations the differential response of an array is extracted by the following expression:

$$\tilde{a}_{i,k} = (Sr_k(t) * Sr_k(t))^{-1} \cdot Sr_k(t) * Xh_i(t) \quad (8)$$

*: transposed and conjugated

i represents the channel number and k represents the path number.

Our method identifies the differential response of an array for each angle of the arrival. In practice, the responses are not very different for the several paths by mode (O or X). The estimate array's response is limited to the spectral analysis main peaks. The multi-paths often come with very close angles of arrivals. Consequently, the spatial variation of the antennas responses are locally small regarding close incident paths. Thus, the response of an array takes the following vectorial form:

$$\tilde{a} = (\tilde{a}_1 \quad \tilde{a}_2 \quad \dots \quad \tilde{a}_{NC})^t \quad (9)$$

The theoretical approach contains the geometrical array's response (if the array has space diversity) and the antenna's response (if the array is heterogeneous). The theoretical response is noted: a_{th} in the figures. The responses measurements comparisons are made using a differential approach. It implies however to choose a reference channel. To avoid choosing as reference a default channel, a criterion (LMS) is applied to find the best reference channel. In this case, the differential response of an array takes the following vectorial form (reference channel is channel n°1 for this example):

$$\tilde{a} = (1 \quad \tilde{a}_2 \quad \dots \quad \tilde{a}_{NC})^t \quad (10)$$

Variations observed (modulus and phases) between these two terms a_{th} and \tilde{a} are representative of the quality of the model and of the precision of data-processing. It indicates the need to adjust the array's responses parameters. This calibration can improve the precision of the arrival angles. In the simplest application, this approach confirms that the array is perfectly operational.

5 Experimental arrays

Three types of heterogeneous array have been set up for measurements. The first one (figure 1) contains eight active loop antennas with (or without) different orientations and equally spaced on a horizontal circle with a 25 m radius. When all antennas are oriented in the same direction, the array is homogeneous. It combines diversity of the spatial responses (if different antennas orientations) and space diversity. The second one [8] (figure 2) contains three sensors set up with a moderate spacing (less than 10 meters) along the

vertical direction and one horizontal axis. Each group contains three collocated antennas: two vertical crossed and one horizontal loop antennas. It appears as a relatively compact heterogeneous array.

The third array (figure 3) is an original device made up of collocated antennas: its main advantage is a set up in a reduced size (volume of 2 m^3). Going further in reducing the array size, the original device of eight HF collocated active antennas is considered. An optimization of the diversity of their complex spatial responses and a minimization of the mutual coupling are required for the final structure represented in figure 3: it contains 2 orthogonal vertical loop antennas, 1 horizontal loop, 2 V-shaped dipoles, 1 vertical dipole, 1 dipole and 1 loop with originals shapes.

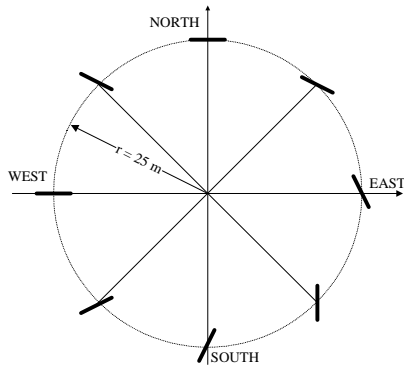


Fig. 1: Array n°1 (heterogeneous circular array)

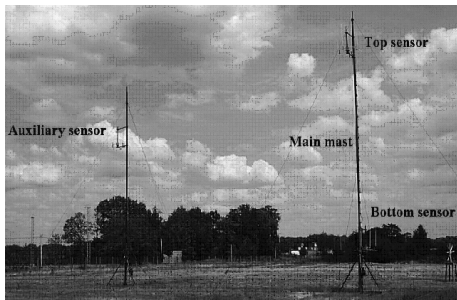


Fig. 2 : Array n°2 (array of collocated antennas sensors)

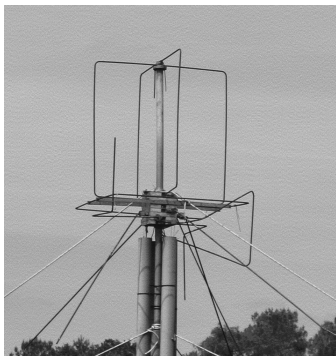


Fig. 3: Array n°3 of eight HF collocated antennas (patent n°99 16112)

6 Some experimental measurements

6.1 A homogeneous circular array (array n°1)

The homogeneous array is made up with antennas that are directed according the East-West axis. Acquisition concerns the Moosbrunn transmitter (March 30, 2006, latitude: 48°N ; longitude: $16^\circ28'\text{E}$, frequency 13.730 MHz) located in Austria with a geometrical azimuth of 83.4° from Rennes (Brittany, France). The analysis duration is 21.85 s and the sample rate is 24 ksamples/s .

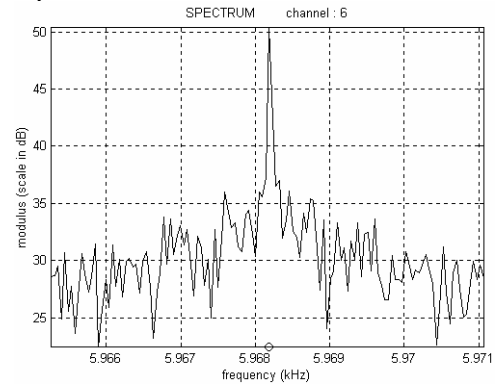


Fig. 4: Spectral analysis; the last IF receiver is 6 kHz.

A experimental DF provides the following angles: azimuth: 82° , elevation: 8° . Phase and modulus of the theoretical (noted a_{th} and drawn with a circle in the figures) responses have been compared with the measurement responses (noted a_m and drawn with a square in the figures). The results displayed on the next figures, illustrate an average phase deviation of 8° and an average modulus deviation of 11% .

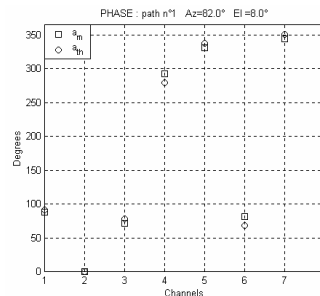


Fig. 5: Phase

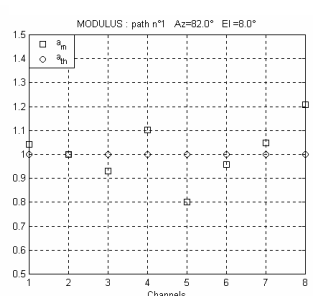


Fig. 6: Modulus

In this experimentation, the array's response corresponds to the geometrical phase array (circular in that case). The reference channel is the channel 2. A good phase's agreement can be observe. The algorithm appears to be coherent.

6.2 An example with two paths (Avlis)

Another acquisition relates to the Avlis transmitter (latitude: $38^\circ23'\text{N}$; longitude: $23^\circ36'\text{E}$, April 4, 2006, freq.: 9.420 MHz) located in Greece with a geometrical azimuth of 108° from Rennes. The spectral analysis shows two paths (fig. 7). The DF provides the following angles for the path one azimuth:

106°, elevation: 22° for the path two azimuth: 108°, elevation: 31°.

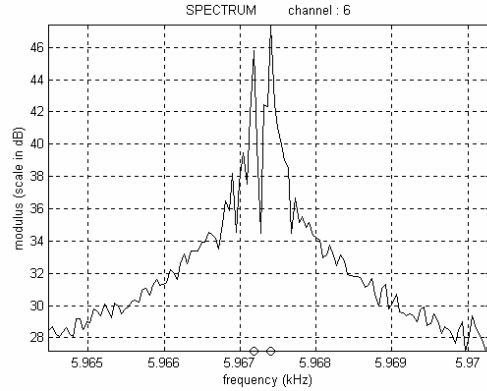


Fig. 7: Spectral analysis

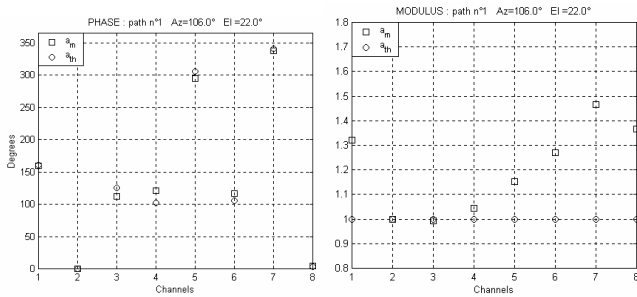


Fig. 8: Phase path n°1

Fig. 9: Modulus path n°1

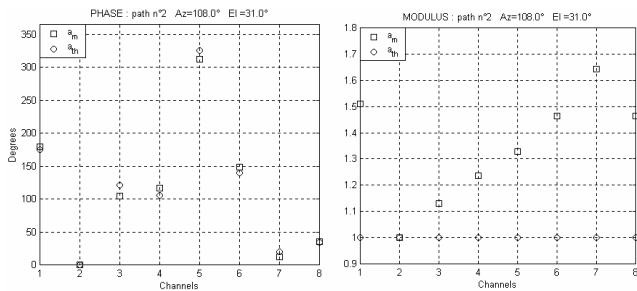


Fig. 10: Phase path n°2

Fig. 11: Modulus path n°2

The reference channel is the channel 2 for the both paths. The phase variations between the two paths are coherent and in conformity with the theoretical expressions. The modules are also coherent between paths but divergence appears compared to the theoretical expression. Further studies should attempt to improve the identification of these modulus variations.

6.3 A heterogeneous circular array (array n°1)

The acquisition is relative to the Moosbrunn's transmitter (March 2, 2004). The DF provides the following angles: Azimuth: 83°, Elevation: 21°. The spectral analysis shows the presence of only one path.

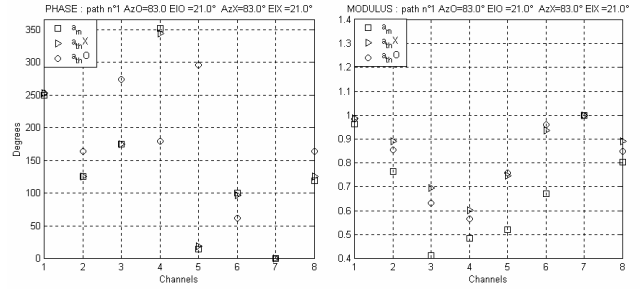


Fig. 12: Phase

Fig. 13: Modulus

In this experimentation, the array's response contains both the geometrical phase and the antenna's response.

The theoretical responses are calculated respectively with an O mode and with an X mode. The reference channel is the channel 7. Phase's measurements are in agreement with the presence of an X mode. The modulus measurements fit the evolution of the theoretical modulus. The average modulus deviation is 17% and the average phase deviation is 4°.

6.4 Array of collocated antennas sensors (array n° 2)

Acquisition is relative to the Moosbrunn transmitter (March 2, 2004), it has been made with the second array at the same time than with the circular heterogeneous array (array n°1). Only one path appears in the spectral analysis.

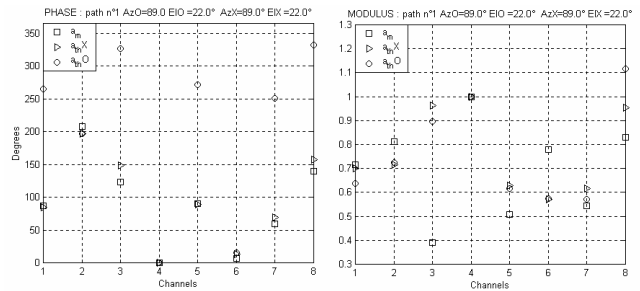


Fig. 14: Phase

Fig. 15: Modulus

The phase comparison confirms the presence of an X mode with an average deviation of 11°. The module always follows the X modulus behaviour with an average deviation of 55%.

6.5 A heterogeneous array without geometrical phase (collocated sensor)

Acquisition (array n°3) relates to the Avlis transmitter (freq.: 9.420 MHz, April 4, 2006) with an analysis duration of 21.85 s with the same sample rate than in the previous cases. The spectral analysis has been made on channel 1, it indicates one path. The DF result (via the circular heterogeneous array) indicates the presence of one X mode (Az = 113°, El = 53°). The differential response is computed with the channel 5 as the reference.

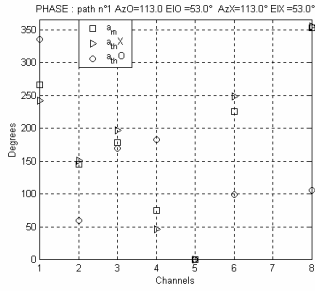


Fig. 16: Phase

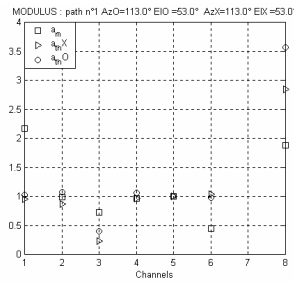


Fig. 17: Modulus

The phase's comparison confirms the presence of a X mode path with an average deviation of 18° . The channel 7 has been removed from the treatment because it appeared damaged. The modulus still follows the X modulus behaviour as with the array n°1 with an average deviation of 66%.

7 An error identification (circular array)

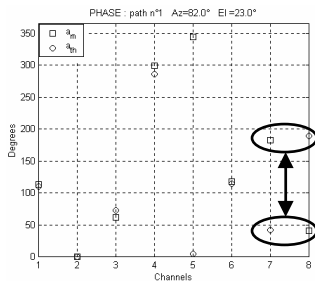


Fig. 18 : Phase identification

In this experimentation, we deliberately permuted two reception channels of the homogeneous circular array. Thanks to the algorithm process, the error can be detected. In this example (fig.18), channels 7 and channel 8 are not in agreement with the expected values. It appears clearly that channel 7 and channel 8 were switched round.

Thus, it is possible to check the array conformity and to identify quickly simple errors. This approach can be done at the array installation time or regularly to check the operational character of the array (to search a defective antenna for example).

8 The DF improvement after a calibration

The objective of this part is to improve the DF results with a calibration method with the homogeneous circular array and a HF broadcast usually used.

The MUSIC algorithm is applied on ten acquisition files (Pori, Finland, latitude: $61^\circ 28'N$, longitude: $21^\circ 35'E$, freq.: 11.755 MHz, 20 mars 2006). The geometrical azimuth of Pori is 36.15° from Rennes. The software LOCAPI gives (with the parameter of Pori) elevations between 14° and 16° as one hope via the F2 layer.

The results provide the angles of arrivals (tab.1: average and standard deviation). On one file, we apply our calibration method (variations phases measurement and variations phases theoretical). From this information, we obtain corrections coefficients which are applied to the signals. Music algorithm

is again compute. The comparison between the angles of arrival (with and without calibration) shows results improvement.

Pori	Mean Azimuth	Az Standard Deviation	Mean Elevation	El Standard Deviation
Without	31.9°	1.85°	1°	0°
With	35.3°	1.41°	14.9°	1.28°

Table 1: DF (MUSIC) results with and without calibration

9 Conclusion

This article shows the possibilities of verifying or calibrating in a passive way a HF DF array.

Tests on various arrays have been done and show the agreement between theoretical antenna responses and the experimental real responses.

A regular array calibration can show possible anomalies (via the modules and the phases).

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