Study of high frequency surface wave radar (HFSWR)

ESTUDO DE RADAR POR ONDA DE SUPERFÍCIE DE ALTA FREQÜÊNCIA

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ABSTRACT

This work presents the main features of a surveillance system based on High Frequency Surface Wave RADAR (HFSWR). Nowadays, the School of Electrical Engineering, together with the Chilean Navy, is beginning the study of HFSWR technology in order to determine the feasibility of its application in the coast of Chile. The first stage of this study focuses on the arrangement of the receiving system elements.

KEYWORDS

EEZ, HFSWR, Surface Wave.

RESUMO

Este trabalho apresenta as principais características de um sistema de vigilância baseado em radar por ondas de superfície de alta freqüência (ROSAF). Atualmente, a Escola de Engenharia Elétrica, junto com a Marinha Chilena, está iniciando o estudo da tecnologia de ROSAF com o intuito de determinar a viabilidade de sua aplicação na costa do Chile. O primeiro estágio desse estudo focaliza a organização dos elementos do sistema receptor e o desenvolvimento dos algoritmos para a conformação digital da amplitude de recepção (formação da portadora).

PALAVRAS CHAVE

EEZ. ROSAF. Onda de superfície.

INTRODUCTION

Chile has an extensive Exclusive Economic Zone (EEZ). This EEZ corresponds to the 200 nm. (nautical miles) from the sea shore towards the open seas. That distance surpasses widely the Earth curvature (line of sight) [1]. According to United Nations Convention in relation to the Law of the Seas of 1992, the maritime countries have complete freedom to perform exclusive economical activities within their respective EEZ. In addition, those countries have responsibilities in the EEZ; among others: accident preventions, contraband, water pollution, illegal operations and rescue of ships in distress [2]. Therefore, each country must depend on effective monitoring systems, either traditional or special ones.

In Chile, the Maritime Traffic Control is based on the reception of the position information of the ships located in the EEZ. The merchant ships transmit daily their location by means of the ship's communication gear to coastal Maritime Traffic Control radio stations. The Chilean industrial fishing boats, on the other hand, must have, by law, a satellite positioning equipment that provides the ship's position information to be transmitted to the Maritime Traffic Control radio station. In both cases (one is a passive system) the Maritime Traffic Control officials expect that all vessels report daily their location. There may be, however, national as well as and foreign boats whose position is not received. Those ships may very well be involved in dangerous situations, or performing illegal activities or they, even, could mean a threat to the national security.

A more suitable alternative for a real time monitoring of the EEZ is a High Frequency Surface Wave RADAR (HFSWR) surveillance system, taking advantage of the propagation characteristics of Surface Waves on the HF band. These waves propagate over the sea, across the EEZ, over distances well beyond the horizon.

The purpose of this paper is to present the main characteristics of the HFSWR in relation to: the propagation of electromagnetic energy of HF Surface Waves, the configuration of a HFSWR, noise and electromagnetic interference, reflectivity of HF signals, transmitting and receiving antenna arrays and others. The School of Electrical Engineering of the Catholic University of Valparaíso, together with the Chilean Navy, has started the studies to determine alternative configurations for this type of system. The first results deal with antenna arrays and beam forming algorithms applied to HFSWR.

Signals Propagation in HF Band

The earth surface, the sea surface and the ionosphere are the main reasons why the ideal model of the free space electromagnetic energy propagation is not completely valid. The morphology and the conductivity of the sea surface affect the propagation. In addition, the frequency band used will determine the principal mechanisms of wave propagation that have to consider for the analysis a radio link. The classic propagation mechanisms are: Surface Wave, Ionospheric Wave and Direct Wave propagation.

The electromagnetic energy propagation by Surface Wave takes place from the low frequency bands up to the HF band (3 -30 MHz.). This Wave propagates in the "sea surface-to-air" discontinuity. It propagates only in the vertical polarization, since the horizontal component of the electric field is severely attenuated. The distance of propagation depends on the frequency value and the type of ground, the sea surface being the best of all. On the other hand the sea surface is not a perfectly flat one. The sea roughness, therefore, has to, be considered to better predict the attenuation of the wave. This attenuation is proportional to the frequency and the sea state (roughness). The amplitude of the radiated electric field is a function of: the wave frequency, the sea-surface state, the height of transmitting and receiving antennas over the ground, the polarization of the electromagnetic wave, and the distance between transmitter and receiver. Since the intensity of electric field is reduced with increasing frequency values, the propagation by Surface Wave is not an important electromagnetic energy propagation mechanism in large distances for very high frequencies. The attenuation diminishes when increasing ground conductivity. Thus over sea water, the amplitude of the electric field practically varies with $1/R$, whereas over dry earth it varies with $1/R^2$ (R being the transmitting distance). A particular case of interest exists when the location of the transmitting antenna is located inland so that a land-sea discontinuity occurs. In that case the propagation over land increases the propagation losses. Therefore, the antennas must be located as close as it is possible to the sea.

On the other hand the ionosphere, the highest region of the atmosphere, (between 60 to 400 Km. in height) due to its ionization produces a reflection of the radio waves bouncing them back to earth. That effect takes place up to a wave frequency of 30 MHz. approximately. The ionization of the upper region of the atmosphere is due to the solar radiations, in particular, is due to the ultraviolet bands, X-ray radiation, cosmic rays and meteorites. This causes that the density of electrons varies according to the hour of the day, season of the year and other factors. The degree of ionization varies also with height. The electromagnetic waves that operate in the HF frequency band, and also in the MF frequency band, are continuously refracted as they travel through the ionosphere. That refraction causes the radio waves to return to Earth. This mechanism is denominated "ionospheric refraction". The distance over the earth between the transmitting station and the point of arrival of the wave from the ionosphere is called a "jump" and it depends on: the frequency, the angle of incidence with the ionospheric-layer, the hour of the day, etc.

For frequencies in the VHF band and beyond, the Direct Wave is the main propagation mechanism, but it s of no interest to us.

Basic System of HFSWR

The HFSWR operates using the propagation of electromagnetic energy waves, over the sea, in the HF Band by means of a Surface Wave which propagates beyond the line of sight, as shown in figure 3.1. A portion of that wave may be reflected from a target, returning to the transmitting point as an echo. It should be remembered that the electric field's vertical component is the only one that contributes to the Surface Wave propagation.

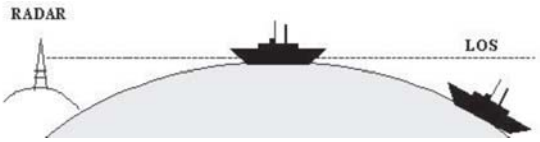


Figure 3.1 - Scheme of reach of a HFSWR [2]

A surveillance system base on this type of RADAR is composed of the following parts:

- Transmitting-Receiving system; or HFSWR sensors.
- Direct Identification system.
- Indirect Identification system.
- A system that combines and controls the information delivered by the previous systems.
- Some of the characteristics of a HFSWR are as

follows: It operates in the pulse-Doppler mode; The zone of surveillance is illuminated by a transmitting array of directional antennas (120º of azimuth beam).

- Echoes, from all the objects within the area of interest, are received by linear array of vertical antennas. Digital Signal Processing techniques are used in the receiving array to produce the beam (“beam-forming” or spatial filtering) and to produce the “sweeping” movement of the beam, through a 120º azimuth angle, with a lobe beam-width between 5° and 8º. The returned echo is analyzed to determine the range, speed and direction of the target. The echo signal detected is compared with a threshold level using a CFAR technique (“Constant False Alarm Rate”). The signal detected that exceeds the threshold is declared a valid detection. Figure 3.2 shows a diagram of the transmitting and receiving antenna arrays.

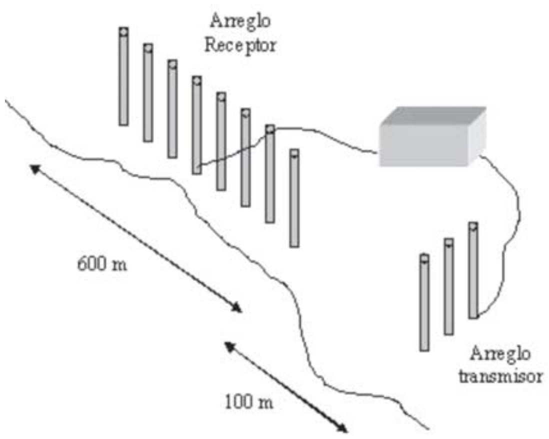


Figure 3.2 - Basic and typical scheme of a HFSWR

Physical Aspects

Several aspects in an HFSWR are different from a regular microwave radar configuration. Some important aspects in HFSWR are: i)the propagation characteristics of the Surface Waves over the spherical earth with above a roughed sea surface and with islands between the HFSWR station and the target, ii)the behavior of the target RCS (RADAR Cross Section) of comparable dimensions with respect to the operating wavelength “l”; iii)adequate prediction of the behavior of larger transmitting and receiving antenna arrays, particularly considering ground losses, iv)detection of masked and immersed target signals in noise, interference and sea clutter.

HFSWR Equation

The HFWSR has an excellent capacity to detect vessels and icebergs over a great distance. The power received from a target for a “monostatic” HFSWR is defined as [3]:

$$P_r = \frac{P_t G_t G_r \sigma A^4 \lambda^2}{(4\pi)^3 R^4 L_s} \qquad (4.1)$$

Where P_r is the peak received power; P_t is the peak transmitted power; G_t is the transmitting antenna gain, G_r is the receiving antenna gain, s is the target “Radar Cross Section” (RCS), λ I s operating wavelength of the surface radar, R is the range to the target, L_S represents the system losses and A is the Norton Surface Wave attenuation factor (SW) for the range R (A<1).

Noise

The Noise signals come mainly from three contributions: External Noise, Ionospheric Self-Interference and Sea-Clutter.

EXTERNAL NOISE

External noise is due to signal originating in distant transmitters using ionospheric wave propagation. Due to changing characteristics of the ionosphere layers those signal may arrive at the HFSWR receiver facilities. This type of noise is predicted by the ITU. It changes from day to night due to the disappearance of the “E layer”. This noise has greater amplitude in the lower part of the HF frequency band.

IONOSPHERIC SELF-INTERFERENCE

One of the most important sources of interference in HFSWR comes from the “Sky reflected rays” produced by the ionosphere itself. The electromagnetic wave may travel through different path when propagating from the target back to the HFSWR station. These various waves arrive at this station having different delays and their sum produces a self-interfered received signal. In order to mitigate this harmful effect, it is desirable that the transmitting and receiving antenna systems have a null in their patterns near the vertical direction. It would also help if the radar uses the critical frequency (CF) during daytime; thus the “Sky” waves are absorbed by the D-layer. Also, when using the “Maximum Usable Frequency” (MUF) the electromagnetic energy propagated by “Sky Wave” through the ionosphere is not bounced back to Earth.

SEA-CLUTTER

The echo (“clutter”) returned from irregular oceanic surface has characteristics of a Doppler Spectrum. The dominant contribution is produced by reflection from ocean waves that have a wavelength (λ) corresponding to half of radar's electromagnetic wave wavelength, moving inwards or outwards in the radar's wave direction. This phenomenon originates two types of return Doppler frequencies [3-4]:

$$f_D = \pm\sqrt{\frac{g}{\pi\lambda}} \quad [Hz] \tag{4.2}$$

Which are related to the ocean wave's propagation velocity. Where "g" is the acceleration of gravity and "λ" it is the wavelength of the radar's wave. This phenomenon makes it difficult to detect low speed ships.

RADAR CROSS SECTION "RCS"

The reflectivity of the targets in HF band is different from the reflectivity in microwave bands. Whereas the latter behaves as in an optical regime, in the HFSWR, the behavior is that of a resonance regime (l is of a size comparable to the dimensions of the targets) [5]. It should be noted that the RCS values vary according to the: frequency, angle of incidence and size of the target. In addition, there is some mutual interaction between targets that are near to each another.

SATURATED SPECTRUM

The election of the HFSWR's operating frequency should consider the electromagnetic interference sources. The frequency should be located in a small empty band within of a frequency spectrum that is usually saturated.

REQUIREMENTS OF THE ANTENNAS ARRAYS

GROUND

The antennas are usually located over a ground that contributes with energy losses. The electrical parameters of the ground play a critical role in the performance of the antennas.

In the HF band, the surface of the ocean acts like an almost perfect electrical conductor (PEC). Such surface has an impedance value close to 0 [Ohm]. A vertical element of $\lambda/4$ on a PEC surface acts like $\alpha/2$ dipole in free space. Therefore, the radiation pattern has its maximum in the horizontal plane. This is one is the design goals for an HFSWR antenna system.

A ground with a conductivity s_g and a dielectric constant $å_g$ has a surface-impedance given by [3]:

$$Z_s = 120\pi\left[\frac{i\omega\varepsilon_o}{\sigma_g + i\omega\varepsilon_g}\right]^{1/2}\left[1+\frac{i\omega\varepsilon_o}{\sigma_g + i\omega\varepsilon_g}\right]^{1/2} \tag{5.1}$$

An acceptable value of surface impedance can be obtained in two ways:

- locating the antenna array as close to the sea as it is possible;
- installing a system of wires (radial or others) buried at the base of the antenna array to improve the conductivity of the ground.

ANTENNA ARRAYS

Some aspects were already reviewed in relation to the physical location of the antennas arrays. In summary, their installation should be as symmetrical as possible, so that, all losses are the same for all the antennas in the array. Large rocky edges should be avoided.

TRANSMITTING ARRAY

The transmitting array of the HFSWR must have a large gain value for a vertically polarized Surface Wave. Besides, the antenna array must produce a 120° beam width to cover the zone of surveillance In addition an adequate ground plane should be included to improve the impedances. A vertically polarized periodic semi-logarithmic antenna is highly recommended.

RECEIVING ARRAY

This has to be an antenna array with a particular configuration so that it may fulfill the following requirements:

- vertical polarization
- very narrow beam pattern (the larger the antenna array the narrow the beam; this, however, requires more space for the installation of the antenna array).
- large front-to-back antenna ratio.
- horizontal beam sweeping by means of digital "beam-forming" techniques; the corresponding beam-forming algorithms are dependant on the array characteristics and configuration.
- installation of the antenna array closer to the sea and parallel to the coastal line, to reduce losses due to the land-sea discontinuity.
- a good ground plane (with radial conductors or

other means) should be provided to reduce the radiation in directions other than the horizontal plane.

- it should include suppression techniques in the direction of arrival of eventual interfering waves (additional spatial filtering).

In summary an adequate "beam-former" is a device that will make it possible to receive very weak signals coming from great distances in a particular direction of arrival.

RECEIVING ANTENNAS ARRAYS

The results of several simulations of the behavior of different types of receiving antennas arrays will be shown. These simulations are related to various characteristics and specifications related to the performance of the antenna arrays

HPBW V/S RESOLUTION

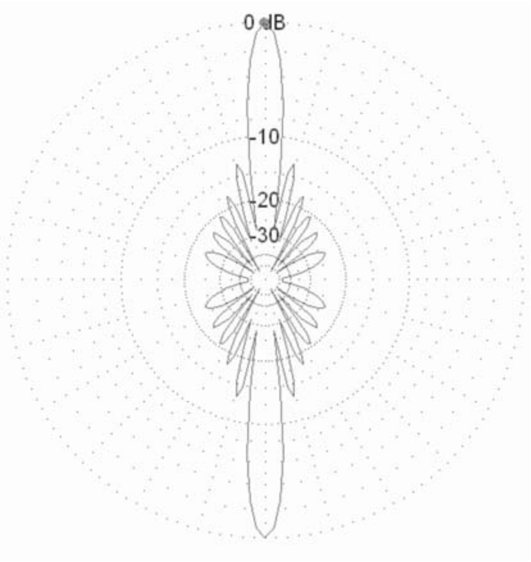
In a radar system, one of the most influential aspects on the azimuth resolution is the main beam lobe width used for the targets detection. A narrow beam width allows a better target resolution, which is important when there are two or more close targets. A larger beam width, on the other hand, will detect those targets as a single one. The main beam lobe width, also known as "Half-Power Beam-width" (HPBW), is measured in degrees and it is defined as the angle between two points in the main lobe or that are at -3dB (half-power points) with respect to the maximum point of radiation or reception. In antennas arrays, such as the ones of our interest, there are two variables relevant to determine the main lobe width. These are: the number of elements in the array and the separation between these elements.

The HPBW for a linear array of "N" elements and with separation "d" is given by [6]:

$$HPBW = \cos^{-1}\left[\cos\theta_o - 0.443\frac{\lambda}{(L+d)}\right] - \cos^{-1}\left[\cos\theta_o + 0.443\frac{\lambda}{(L+d)}\right] \qquad (6.1)$$

Notice that: N=(L+d)/d, $\grave{e}_o$ is the angle of the main beam direction and L is the overall length of the array.

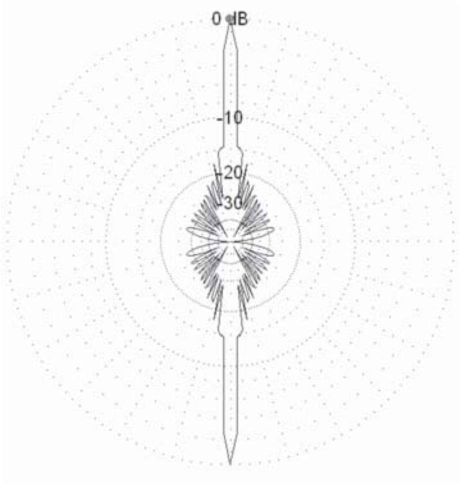
Next, through a simulation, the influence of those variables in the HPBW (eq. 4) will be separately analyzed.



(a)

HPBW AGAINST ARRAY ELEMENTS SEPARATION

A 24 elements linear antenna array (24 x 1) was simulated using three different spacing ("d") between elements; the values used were: 0.25λ, 0.5λ and 0.75λ, respectively. The horizontal radiation patterns obtained are shown in figures 6-1: a, b and c. All 24 elements in the simulations were assumed to be 0.25λ vertical monopoles.



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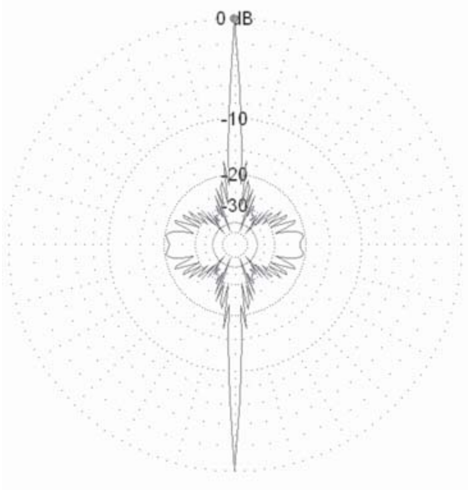


(c)

Figure 6-1 - Horizontal radiation pattern of a linear array 24 x 1 Broadside (0.25λ vertical monopoles) with: a) 0.25λ separation, b) 0.5λ separation and c) 0.75λ separation

Table 6-1 contains a summary of the results.

Table 6-1 - HPBW against element separation

	D = 0,25λ	d = 0,5λ	d = 0,75λ
HPBW	8.4°	4,2°	1,8°
Large area sec. lobes	NO	NO	YES
Qty. of sec. lobes above -15 dB.	4	0	0
Gain [dBi]	17,29	20,27	21,72

For the 0,25λ separation case (HPBW=8,4°) and for the 0,5λ separation case (HPBW=4,2°) the HPBW equivalent arc values for several ranges are shown in Table 6-2 and Table 6-3 respectively.

Table 6-2 - Arc vs Range (N= 24)

HPBW=8,4° d=0,25λ

Range [km]	Equivalent Arc [km]
370	54
277	40
185	27
92	13

Table 6-3 - Arc vs Range (N = 24)

HPBW=4,2° D=0,5λ

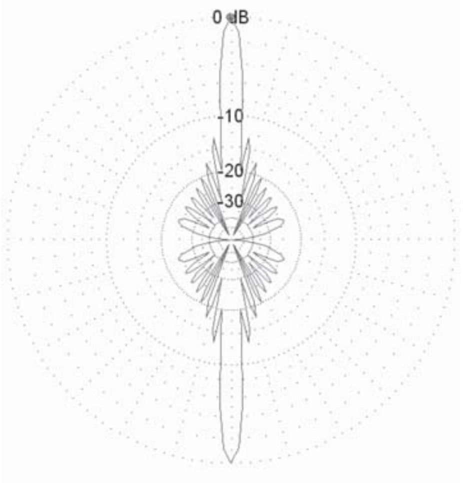
Range [km]	Equivalent Arc [km]
370	27
277	20
185	13
92	6.7

As it can be observed the arc length is proportionally related to the target range. This means that at great distances it will be impossible to distinguish two targets that are closely located. It can be seen that for larger values of "d": a smaller HPBW is produced, a smaller equivalent arc results and, therefore, a better resolution is obtained.

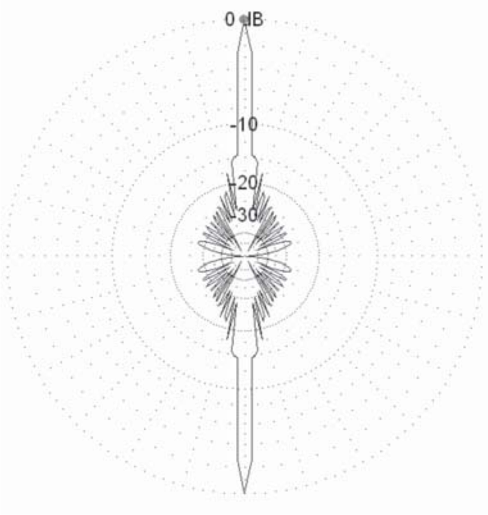
The best decision should be the election of an array with 0.5λ separation because, on the one hand, it produces better resolution and has less secondary lobes compared with the 0.25λ separation array and, on the other hand does not have secondary lobes with large area. A large area secondary lobe should be avoided, since it may produce false target echoes when the main lobe is swept across the surveillance area.

HPBW AGAINST NUMBER OF ELEMENTS

A linear array with 0.5λ element separation was simulated using three different numbers of elements to determine the relation between the quantity (N) of elements and the HPBW. The horizontal radiation patterns for N=16, 24 and 32 are shown in figures 6-2: a, b and c, respectively. All the elements in the simulations were assumed to be 0.25λ vertical monopoles.



(a)



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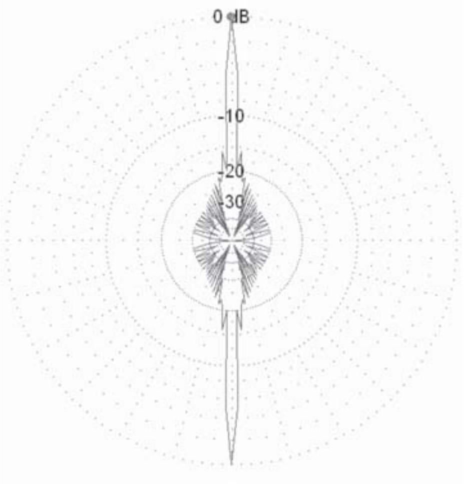
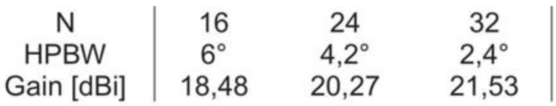


(c)

Figure 6-2 - Horizontal radiation patterns of 0.25λ vertical monopoles linear array, with 0.5l element separation with: a) N=16 monopoles, b) N=24 monopoles and c) N=32 monopoles

Table 6-5 contains a summary of the simulation results.

Table 6-5 - HPBW and gain v/s N



N	16	24	32
HPBW	6°	4,2°	2,4°
Gain [dBi]	18,48	20,27	21,53

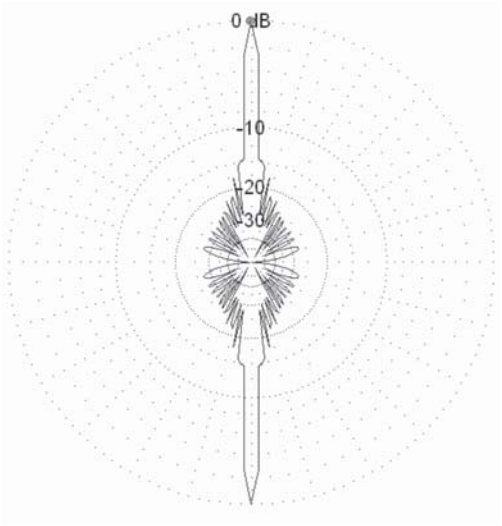
A reasonable decision is to design the array with 24 or more elements since the level of the secondary lobes is strongly diminished; practically below -20 dB. Another important point of consideration is the gain value produced by the different number of elements. It can be seen that the gain difference between the 32 and the 24 array elements is 1.24 dB whereas the gain difference between the 24 and the 16 elements array is 1.79 dB. These are not significant differences.

SUPPRESSION OF A SECOND MAIN LOBE IN A LINEAR ARRAY

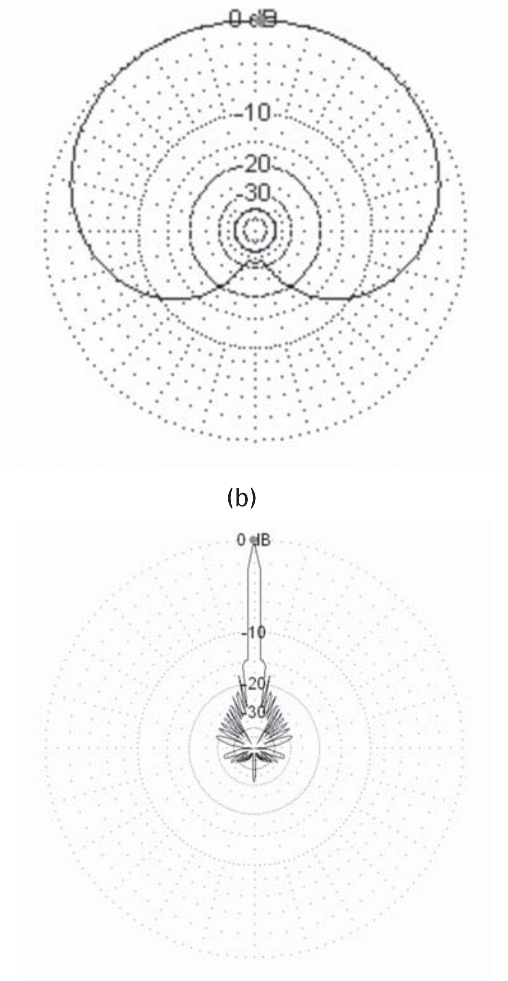
Unfortunately in some linear arrays there is not a single main lobe but there two similar main lobes of the same size and form. This can be seen in figures 6-1 to 6-2.

For radar application a single very narrow main lobe is required making it possible to avoid receiving signals from opposite directions at the same time. Therefore the suppression, or cancellation, of the second main lobe is of utmost importance. This can be done by means of a two dimensional array which produces, in addition, an increase in the gain value of the array.

The radiation pattern is simply obtained by multiplying the radiation pattern produced by a linear antenna array in one dimension (X-axis) and the radiation pattern produced by a linear antenna array along the other dimension (Y-axis), the latter being, in our case, an array of two antennas in the “end-fire” mode. Figure 6-3 shows: to the left, a 24 element radiation pattern along the X-axis, in the center the end-fire pattern of a 2 element array along the Y-axis and, to the right, the 24x2 elements antenna array pattern. This results from the multiplication between the two previous array patterns.



(a)



(b)

(c)

Figure 6-3 - Multiplication of two one-dimensional array patterns resulting in a one two-dimensional, linear array, antenna pattern

It can be seen that the one dimensional end-fire pattern in the center of figure 6-3 perfectly cancels the second main lobe of the previous one-dimensional 24 elements linear array pattern. In other words, the end-fire pattern multiplies by 1 the lobes in two of the four quadrants of the one dimensional 24 elements linear array pattern and multiplies by 0 the lobes in the two remaining quadrants. This is not absolutely true, however, since the one dimensional 24 elements array pattern occupies a small portion of the latter two quadrants.

The proposed array is made of 42 elements: 24 elements along the X-axis and two elements along the Y-axis. The separation between elements are 0,5l and 0,25l in X-axis and in the Y-axis respectively. The phase angle between each pair of adjacent elements is of 0º along the X-axis and 90º along the Y-axis.

It should be noticed this array pattern hast to be steered through a 120º azimuth angle to cover the surveillance area. Figure 6-3 perfectly fulfills the requirements for a "broadside" array only.

In the graphs, previously shown, it is clearly appreciated the difference between a one dimensional linear array and a two dimensional antenna array. The one dimensional linear array has at least two main lobes, whereas the two dimensional ones (if a suitable separation is chosen) have only one main lobe. It is therefore required to use two dimensional antennas arrays. The examples shown in this report fulfill the requirements for a HFSWR. Trough the simulations a 4,2º HPBW was obtained and the main to secondary lobe ratios were better than 15 dB. Therefore, the two dimensional 24 x 2 elements antenna array is chosen.

Although the secondary lobes levels are still high, it is necessary to point out that these values will be reduced by an appropriate digital beam-forming subsequent process.

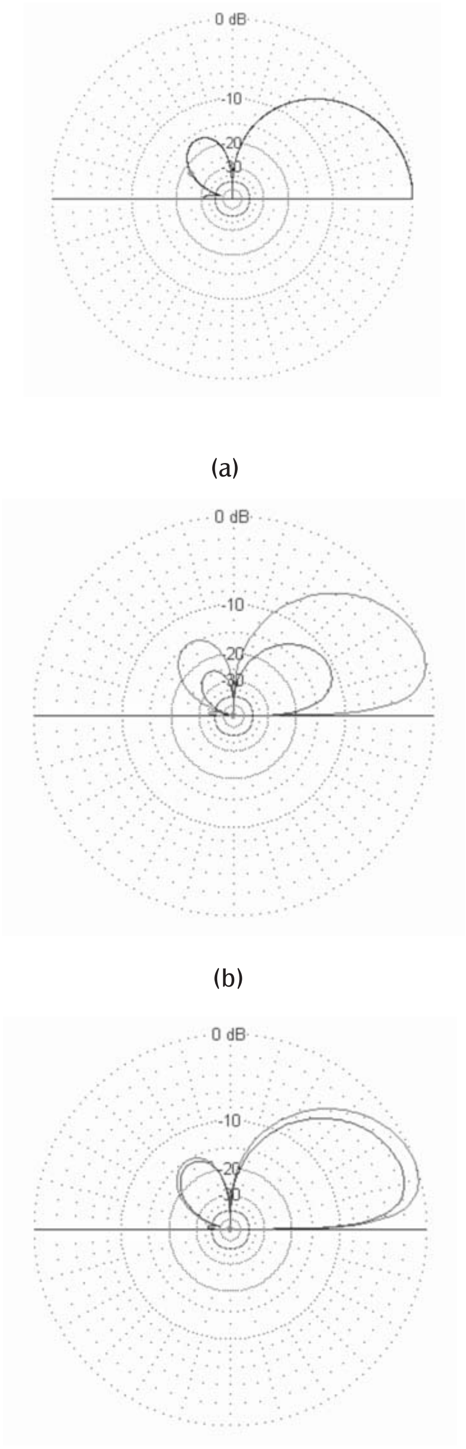
GROUND ELECTRICAL CHARACTERISTICS EFFECTS OVER THE RADIATION PATTERN

In the previous graphs the antenna array's radiation pattern was shown assuming perfect conducting ground. But this is not a real case. The effects of not having a PEC will be: a reduction of the antenna array gain and a maximum electromagnetic radiation, or reception, in an angle above the horizontal direction. This angle, between the horizontal plane and the direction of maximum radiation/reception is known as "take-off angle" (TOA). A vertical monopole, for example, over a PEC has a TOA of 0º but as ground loss increases, so will the TOA value.

A surface with good electrical characteristics will be one with large conductivity and permittivity values. It is known that the ocean surface behaves almost like a PEC on the HF band. Equation 5,1 shows the dependence of the surface Impedance of the ground against ground's conductivity and permittivity as well as the wave's frequency value.

In order to improve the conductive characteristics of the ground where the antenna array will be installed, there are two possible solutions: to increase the soil humidity or to bury a grid of radial wires beneath the antenna array.

Te effect upon the antenna array's radiation patterns was simulated for various types of ground characteristics. Figure 6-4 shows the antenna array patterns, in the vertical plane, for various conditions for a 24x2 two dimensional array.



(a)

(b)

(c)

Figure 6-4 vertical plan patterns for: a) PEC ground, b) dry ground (blue) and humid ground (red) c) humid ground (red) and 16 radial wire grid

For the perfect electrical conductor (PEC) case (fig. 6-4 a) the antenna array gain is 23.32 dBi with the pattern's maximum in the horizontal plane; TOA = 0º.

The following case (fig. 6-4 b) shows the vertical plane pattern for dry-ground condition in blue color ($\varepsilon r=4$ and $\sigma=0.001[\Omega^{-1}/m]$) and for humid-ground condition in red color ($\varepsilon r=30$, $\sigma=0.02\ [\Omega^{-1}/m]$). It is clear that for a humid-ground condition there is a better performance as compared with the dry-ground case. There is a 18.15 dBi gain for the humid-ground condition. In both cases, however, the TOA increases to 20º.

The latter case (fig. 6-4 c) corresponds to an antenna array over a 16 radial wire grid in blue color and the same humid-ground condition as before in red color. For the radial grid case there is a 19.47 dBi gain and a TOA of 20°.

It can be seen that the TOA begins to increase, so ten main radiation intensity of transmission/reception begins to separate form the horizontal plane, as the ground becomes an electrically imperfect conductor. The more imperfect the ground, more radiation towards the sky or reception from the sky will take place. This produces an increase in the ionospheric self-interference.

It should be emphasized that for the High Frequency Surface Wave Radar (HFSWR) the maximum of energy radiation/reception in the array pattern should be in the horizontal direction. If not, there will be severe impairments upon the HFSWR performance.

It is therefore highly recommended: i) to install radial wire grid buried in the ground in order to improve the equivalent ground conductivity (ground plane) for the antenna arrays (see figure 6-4 c) and ii) to install the antenna arrays as close to the sea as it may be possible because of the sea's good electrical conductivity properties.

CONCLUSIONS

The fundamental concepts of a HFSWR and the variables that affect its performance have been reviewed. Some important differences with respect microwave band radar have been reviewed. Various aspects such as: noise, interferences, reflectivity, propagation of HF waves in rough sea surfaces, ground plane, transmitting and receiving antenna arrays and many others, should be carefully considered in the design of the HFSWR components. It is clear, from the revision of the HFSWR properties, that the surveillance of the 200 nm national EEZ in real time is perfectly possible.

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