A general presentation about the OTH-Radar NOSTRADAMUS

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Abstract— ONERA, funded by the French Ministry of defence has conducted the realization and experimentations of the Doppler Skywave OTH Radar called NOSTRADAMUS. One of the main characteristic of Skywave OTH Radar is the dependence to the ionosphere for successful operation. The use of the HF band allows to Skywave OTH Radar to bounce radio waves from the ionosphere, receiving tiny signals back from reflecting surfaces as the sea, islands, ships and aircraft. The knowledge of the behavior of the ionosphere in a real time configuration is of primary importance because of it influences on the choice of frequencies. Radars systems require developing a real-time frequency management system (FMS) using prediction program or measurements supplied by vertical or oblique sounders. The French OTH Radar concept has been developed and implemented so that the radar could be completely autonomous with respect to others 'ionospheric information providers'.

This paper presents the NOSTRADAMUS system, the frequency management system and shows some results obtained during the past years.

I. INTRODUCTION

Low frequency radars contribute to counter threats evolutions for surveillance and air defence systems. ONERA started to work on low frequency radar from the research on plasma physics in the Seventies. Different studies and developments were conducted to characterise low frequency sensor capabilities and to prepare their introduction in air defence networks.

ONERA, funded by the French Ministry of defence (Aeronautics program department SPAé), has conducted the realization and experimentations of the skywave HF radar, called NOSTRADAMUS. Skywave OTH Radar has been develop to detect targets which may be hundred or even thousand of kilometres away. One of the main characteristic of this kind of Radar is the dependence to the ionosphere for successful operation. The ionosphere can be assimilated to a shell of ionisation surrounding the earth in more or less distinct layers at heights between 50km and 350km. The use of the HF band allows to Skywave OTH Radar to bounce radio waves from the ionosphere, receiving tiny signals back from reflecting surfaces as the sea, islands, ships, aircrafts …

The knowledge of the behaviour of the ionosphere in a real time configuration is of primary importance because of it influences on the choice of frequencies. Radars systems require developing a real-time frequency management system (FMS) using prediction programme or measurements supplied by vertical or oblique sounders. Surface array radar like NOSTRADAMUS system, allows focalizing the beam in elevation and measuring the angle of arrival of each ray propagated through the ionosphere. New sounding techniques exploiting these capabilities have been developed such as the radar is completely autonomous with no need of external sounding means.

In the first part, the NOSTRADAMUS system is presented. The second part is dedicated to the frequency management system and some results are given in the last part.

II. THE NOSTRADAMUS SYSTEM

A. *NOSTRADAMUS Antennas Array*

NOSTRADAMUS radar is an innovative concept of monostatic, surface array HF skywave system. It's a set of 288 bi-cone antenna elements distributed over the arms of a three-branch star, with a buried infrastructure to shelter the transmission and reception electronics. This choice of

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structure allows 360 degrees coverage in azimuth and the control of the beam in elevation. This monostatic configuration limits the problems of propagation : there is only one reflection point to consider. NOSTRADAMUS radar is located 80 km west from Paris.

NOSTRADAMUS array is a surface array structured as a star with 3 arms spaced of 120 degrees (Fig. 1).

Figure 1. Nostradamus Array

Each arm is near 400 meters long. The antennas are randomly distributed on 80 meters width along the arms. The elementary antenna is a biconical one (7 meters high by 6 meters width) with an omnidirectional pattern in azimuth (Fig. 2).

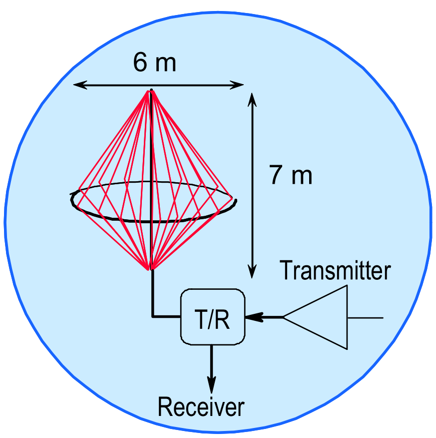

Figure 2. Biconical Antennas

The array association as a star allows all azimuth coverage and the control of the beam in elevation. The employment of large antennas requires the use of a metallic ground plane to reduce the VSWR, voltage standing wave ratio.

One part of antennas is used for transmitting and the whole array for receiving (Fig.3). It is also possible to form simultaneously narrow receiving beams in the two dimensions azimuth and elevation in the footprint of the wide transmitting beam.

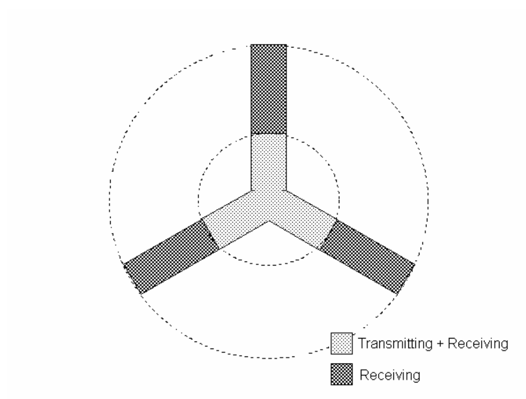

Figure 3. Repartition between transmitting +receiving antennas and receiving antennas

1) Transmitting system

One hundred transmitters associated to each transmitting antenna, constitute the transmitting system of NOSTRADAMUS radar. They are installed in underground technical tunnels under each arm of the array (Fig.4). Each transmitter is interfaced and driven by the management system in order to control the gain and to focalize the beam.

Figure 4. Technical tunnel

2) Receiving system

The whole array, around three hundred antennas, is used for receiving. Antennas are assembled in sub-arrays in order to reduce the quantity of data in the computer. Each signal issued from each sub-array receiver is digitalized and the simultaneous receiving beams are formed by the computing.

B. NOSTRADAMUS Computing system

The management of the radar and the signal processing are realized with a computing system consisting of X bits data acquisition system and a real time computer associated to a network of work-stations. Many work-stations are equipped with their own data acquisition system for the test procedures and the calibration of the radar.

1) Beam Forming

The structure of the surface array allows forming beams in the two dimensions azimuth and elevation. Grouping of antennas in sub-array reduce the quantity of data at the input of the computer. Simultaneous receiving beams are formed in the footprint covered with the transmitting beam. This receiving beam forming is realized in parallel by the computer.

2) Radar Processing

Signal processing consists in a range - Doppler analysis of the backscattered echoes in each receiving channel. All the channels are treated simultaneously in parallel with NOSTRADAMUS computer. The receiving signal could be characterized by a strong ground echo and sometimes with a strong spectral occupation. ONERA develops some adaptative algorithms and process to reduce the effect of contamination. These spoiling phenomena result from the environment, as for the example the ionosphere.

At the end of this procedure, 3D images [amplitude - Doppler – range] are obtained for each beam. Radar detection informations are obtained by the following data :

- the group range, determined by correlation with the replica of the transmitted signal,
- the Doppler frequency obtained by Fourier spectral analysis.

Examples will be given in next paragraph.

3) Data Processing

The principal steps of this process are :

- detection of the presence of targets from the data issued from signal processing,

- extraction of the radar plots associated to detected targets,

- coordinate registration (radar parameters are re-computing from the group range to ground range association),

- visualization of the target tracks of the targets on radar screens.

New developments about coordinate registration are conducted by ONERA in using in real time the behaviour of the ionosphere.

III. NOSTRADAMUS FREQUENCY MANAGEMENT SYSTEM (FMS)

Skywave OTH Radar depends entirely on the ionosphere for successful operation. An important effort has been conducted to optimize the operating frequency system. The operating frequency must be chosen in function of the ionospheric conditions determined in real-time and in function of the kinds of missions of detection for the radar (aircraft, ships or other …). For examples :

- Aircraft targets are discriminated from the ground echoes by the Doppler. For this mission, the radar must be optimized to illuminate the target with the maximum energy.
- Ships echoes have Doppler shifts closed to the sea clutter and sometimes between the Bragg lines for low speed boats. The radar need to obtain a good quality propagation by selecting the adapted frequency in terms of single mode of propagation by optimizing the elevation angle and reducing the ionospheric contamination.

Different kinds of sounding are performed by the radar in order to determinate a good frequency: backscatter soundings by frequency sweeping, backscatter soundings by scanning in elevation. Sounding processes are overlapped in the radar waveform. Informations can provide from Ionospheric Vertical Sounder Data Basis in Europe. Also, various modelling ionospheric propagation, as ray tracing with IRI modelling or MQP ionospheric models can be used in this procedure. These data are involved in the coordinate registration process.

The frequency management of the radar gives optimum operating frequencies to cover the surveillance area. Some details about radar soundings, ionospheric propagation and the FMS's philosophy are now given.

A. Backscatter Soundings

Backscatter soundings consist to analyse the echoes backscattered by the ground. These sounding processes can be differentiated by their operating modes. The different kinds of backscatter soundings implemented in NOSTRADAMUS are : frequency sweep sounding and scanning of the beam in elevation.

1) Backscatter sounding by frequency sweep

With this technique, an overview of the conditions of propagation in function of azimuth, range and frequency is directly obtained in real time. This method consists to transmit with the radar, bursts of recurrences for frequencies between 6 MHz to 28 MHz. The signal backscattered by the ground, is sampled just after the receiving, and analysed to determine the energy returning from different ranges. This process is done in each receiving beams (azimuth and elevation). The results are combined to give two 3D images called ionograms, which represent respectively amplitude and elevation versus range and frequency.

The first results are row data Fig 5 and Fig 6 illustrate an amplitude ionogram and an elevation ionogram . The next stage is to clean the ionograms and to filter them by image processing techniques.

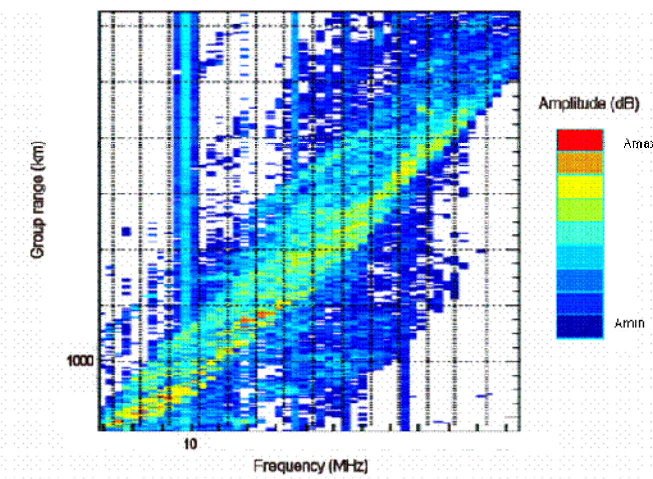

Figure 5. Amplitude backscatter ionogram

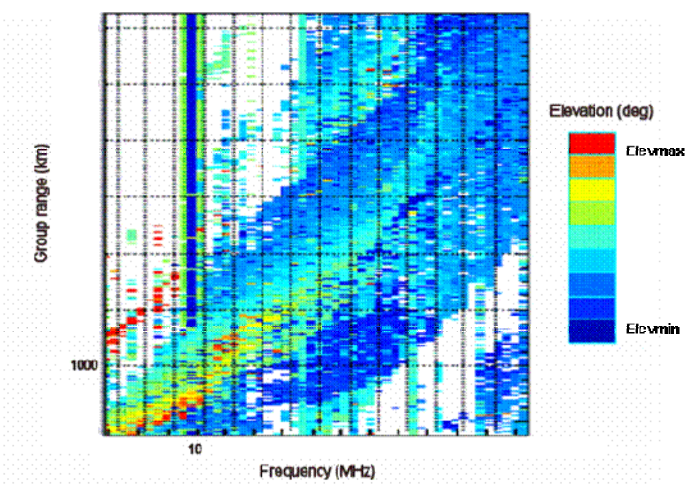

Figure 6. Elevation backscatter ionogram

The next stage is to clean the ionograms and to filter them by image processing techniques. The measurement of the elevation allows for converting the group range in ground range under various hypotheses. Fig 7 and Fig 8 show the transformation under the hypothesis 'absence of horizontal gradient in the ionosphere'.

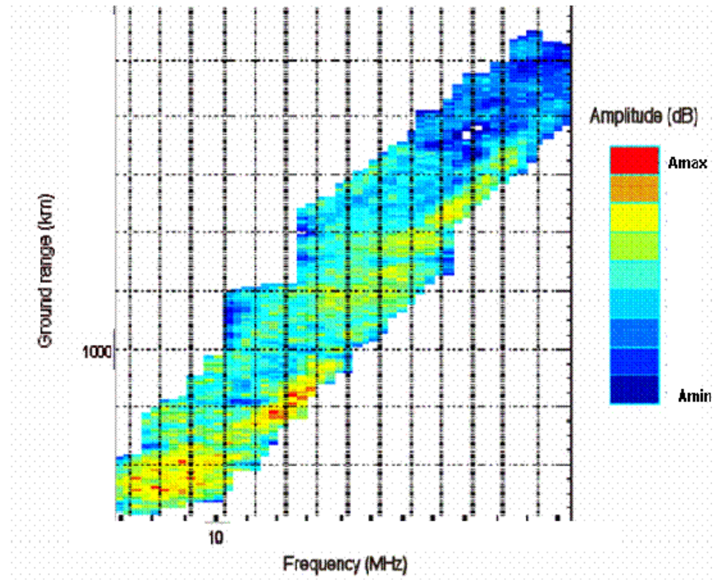

Figure 7. Amplitude backscatter ionogram in ground range

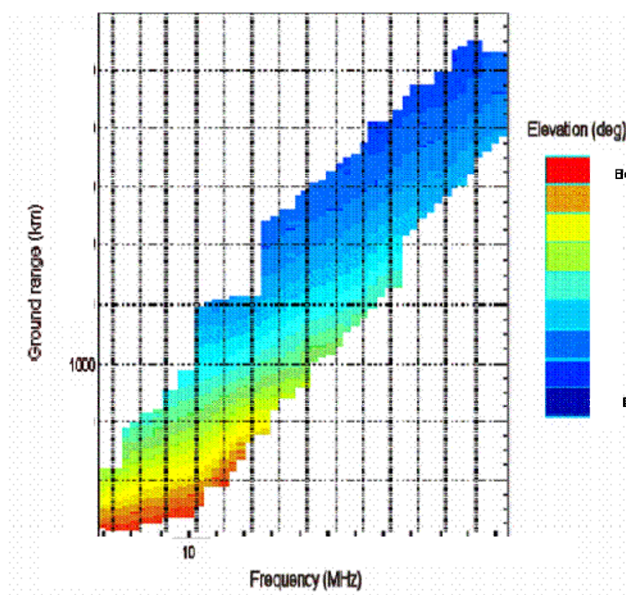

Figure 8. Elevation backscatter ionogram in ground range

An another stage is to define criteria in order to determine the most energetic frequencies and the optimum elevations in terms of signal to noise ratio for radar detection. Fig 9 and Fig 10 indicate the couple (frequency, elevation) under the hypothesis of the choice of criteria. The example shows that the best choice is for optimal detection obtained with a frequency around f0 with an elevation angle around Elev0 degrees.

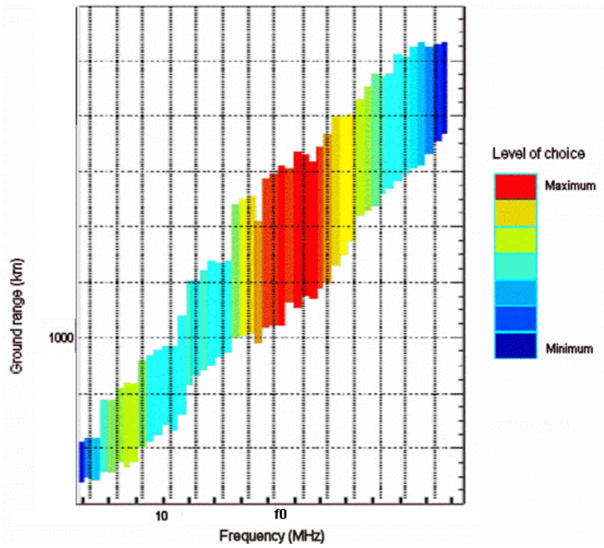

Figure 9. Backscatter ionogram : choice of frequency

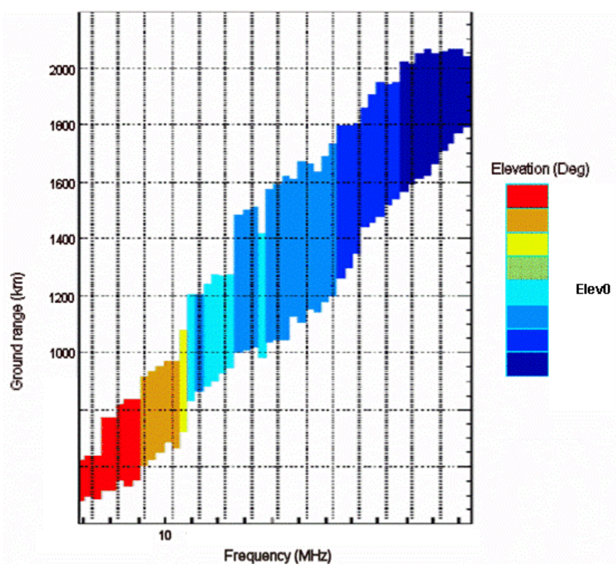

Figure 10. Backscatter ionogram : choice of elevation angle

2) Backscatter sounding by scanning elevation

The principle of this method consists to scan the beam of the radar in elevation (from Elevmin to Elevmax) in a fixed azimuth at one operating frequency. The delay of the clutter echo is measured for each angle of elevation. A 3D image [amplitude – elevation – group range] is generated. Fig 11 illustrates a result. Notice the presence of a skip distance (near d1). It corresponds to the focalisation zone associated to a specific ionospheric layer (F region in this picture).

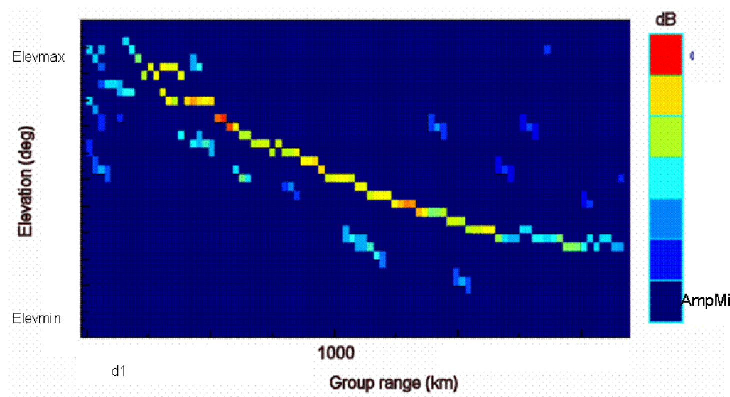

Figure 11. Backscatter ionogram : scanning elevation

The coordinates of the focalization (minimum of group range, focalization angle) are extracted from the ionogram, then and fitted to a ionospheric model, the Multi Quasi Parabolic (MQP) model in this case. The ionospheric parameters at midpoint are determined by an inversion procedure so that the MQP profile gives an equivalent to the behaviour of the ionosphere at this point. (Fig 12).

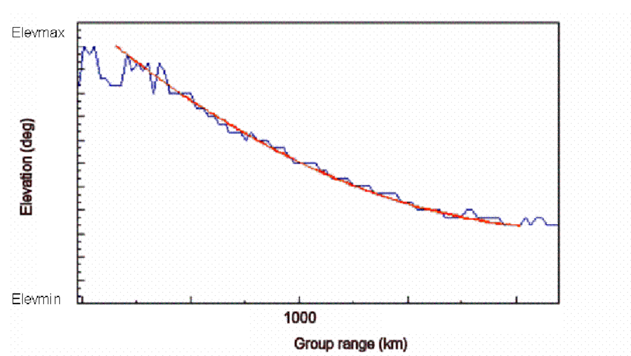

Figure 12. Backscatter ionogram by elevation scanning fitted by MQP Modelling

The ground range is computed by a ray tracing method (Fig 13).

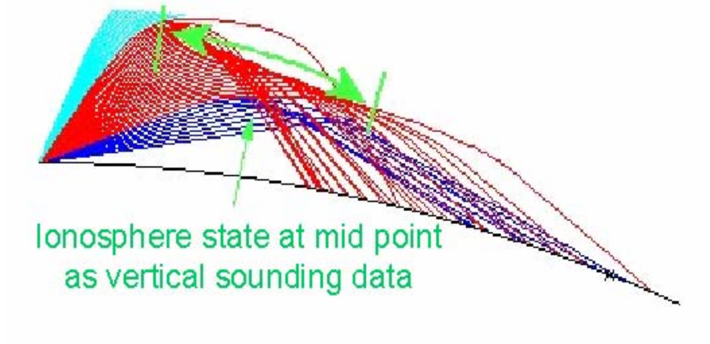

Figure 13. Ray tracing : inversion of backscatter ionogram by elevation scanning

By these two methods of backscatter soundings, NOSTRADAMUS is fully autonomous in order to deal with the ionosphere in real time.

B. Spectral Surveillance

In order to determine the optimum frequencies by evaluating the occupancy of the channels and the level of noise, a clear channel research runs permanently in bands of operating frequencies. This measurement is accomplished by a biconical antenna separated from the NOSTRADAMUS array. This antenna is connected to an autonomous receiver coupled to a computer with an analogic digital converter. A statistic based on the level of noise, is established for each channels which are classified as free or occupied (Fig 14).

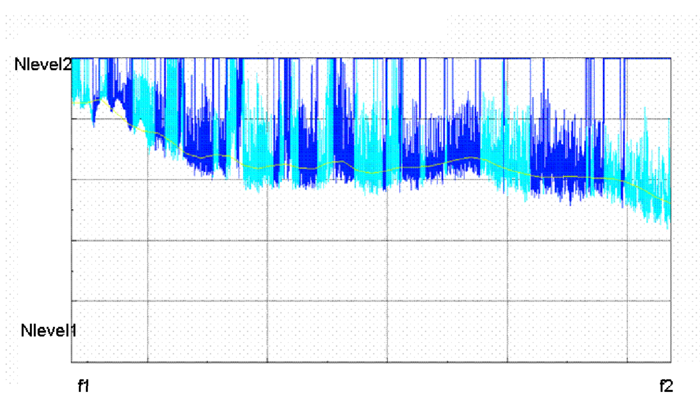

Figure 14. Spectral Surveillance from f1 to f2, colour specified if the channel is free or occupied

IV. FREQUENCY MANAGEMENT PHILOSOPHY

OTH performances in terms of detection and localization depend strongly on the knowledge of the spatio-temporal variabilities of the ionosphere and the availability of the channels propagation. To illustrate the variation of the ionosphere, NOSTRADAMUS is able to construct a panoramic sounding : for a given frequency and elevation angle the azimuth angle vary from 0 to 360 degrees. Fig 15 and Fig16 shows the amplitude of the signal for 2 different moments in the same day at the same frequency and elevation angle for 0-360 degrees azimuth angle.

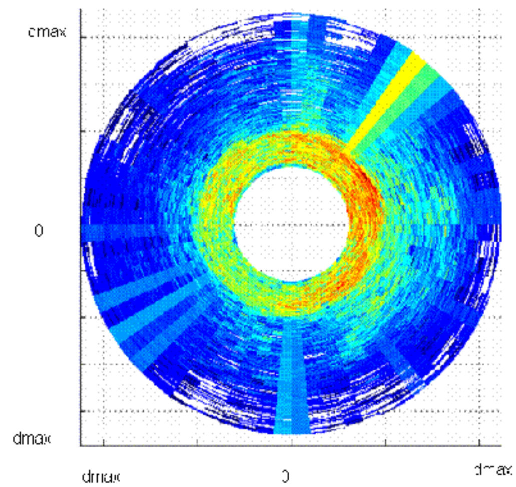

Figure 15. Variability of the ionosphere: panoramic sounding for one frequency and one elevation angle (moment 1)

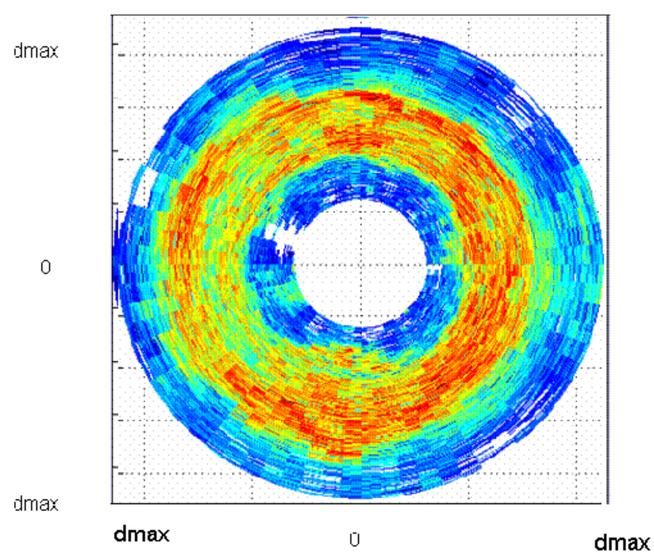

Figure 16. Variability of the ionosphere: panoramic sounding for one frequency and one elevation angle (moment 2)

To find NOSTRADAMUS operating frequency, NOSTRADAMUS FMS is principally based on the two backscatter sounding techniques: one by frequency sweeping with elevation information (**BSS**) and the other by elevation scanning at one frequency (**ELS**). The inversion of the backscatter ionograms could be done by combining these two sounding modes. The time passed at this task could be automatically computed by specific procedures or parameterized directly by an operator. Notice that the localization of this kind of radar or the schedule during the day could influence the duration of FMS step.

A. Global Mapping of the ionosphere

BSS soundings are carried out each X minutes, X is automatically fixed or chosen by the operator. These soundings can take less than one minute to sweep the whole band 6 to 28 MHz by step of 1 MHz. The ionogram represents the group range versus the frequency with the elevation in third dimension. This type of ionogram is the succession of many ELS ionograms respectively obtained for each frequency and which represent the group range versus the elevation. BSS soundings are performed in many directions in azimuth so that a map of the ionosphere can be established every X minutes by inverting respectively all the ELS ionograms. The similar procedure can be modelled by numerical process. Fig 17(BSS) and Fig 18 (ELS) are issued from data for 2D and 3D ray tracing algorithm for the propagation prediction program and coordinates registration.

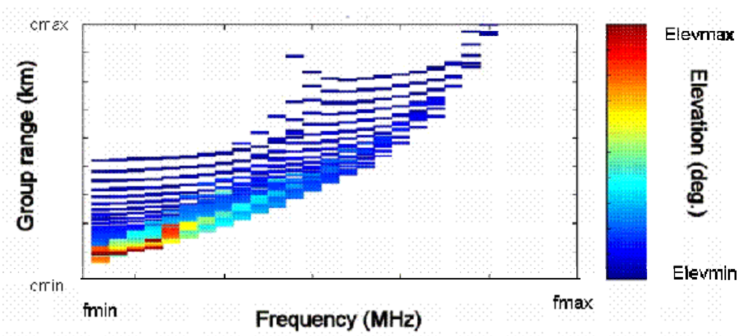

Figure 17. Backscatter soundings (BSS-frequency sweeping)

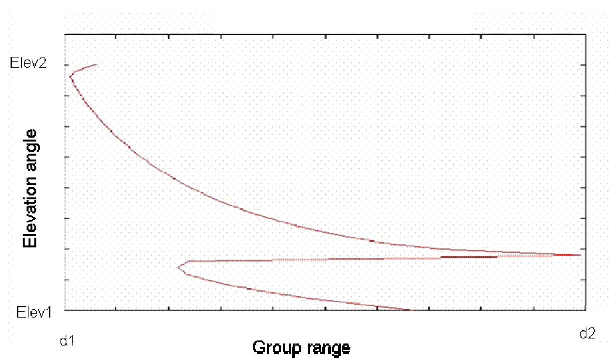

Figure 18. ELS ionogram (group range versus elevation)

B. Real-time re-actualization of the map of the ionosphere

While the system is operating in radar mode, the clutter signal is used for ELS sounding during each integration time. The inversion of the ELS ionogram gives the ionospheric parameters at mid-point of the link for this radar operating frequency in the corresponding azimuth as if a vertical sounder would be at this point. So that at each integration time, new parameters are available for a particular point of the ionosphere. As the radar sweeps in frequency and azimuth, the map of the ionosphere could be re-actualized continuously.

C. Frequency management system

With NOSTRADAMUS, a mapping of the ionosphere is established and re-actualized as if data from distant vertical sounders have been used. This map represents input data for short term predictions program and ray tracing algorithms. With these items, the FMS provides in real-time:

- the best operating frequencies for the missions of the radar in terms of coverage and type of targets to be detected,

- the coordinate registration to position targets in real coordinates for the operating frequency.

V. Some Results obtained by Nostradamus

Over-the-horizon radars were developed to detect military targets far beyond the optical horizon. But civilian application can also be considered by this kind of radar. For example, NOAA adapted the Air Force OTH-B radars in Maine to map surface wind streamlines in the hurricane breeding grounds of the tropical Atlantic. DSTO developed similar processes with the Australian OTH-R Jindalee to remotely monitor ocean-surface winds. In this paragraph, various applications are showed.

(i) tracking planes over the Mediterranean sea

Fig 19 illustrates various checked plane tracking (yellow, blue, pink, green) which are flying at various heights and various speeds.

(ii) tracking boat in the Mediterranean sea

A boat (speed : 68km/h, length 102m, width 15m) has been tracked from Corsica Island to Nice (Fig 20).

(iii) Studies about sea clutter

Fig 21 illustrates the difficulty related to the perturbation of ionospheric propagation through a sea clutter spectrum. The horizontal lines represent the ground reflexion (ground clutter, line at 0 Doppler) or the sea clutter (two braggs lines). In this picture, the Bragg lines sustain a diffusion phenomena related to the irregularities and the fluctuations of the ionosphere.

(iv) Studies of oceanic parameters

Some oceanic parameters are computed from NOSTRADAMUS, data. Fig 22 indicates the height of sea wave at the east of Irish coast.

Others studies are carrying of earthquakes trackings with the team of Pr. Lognonné (IPGP, France).

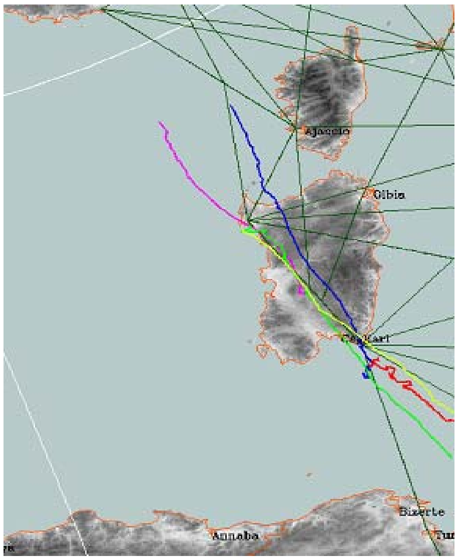

Figure 19. Various aiplane tracks over Sicilia(Italy, Europe)

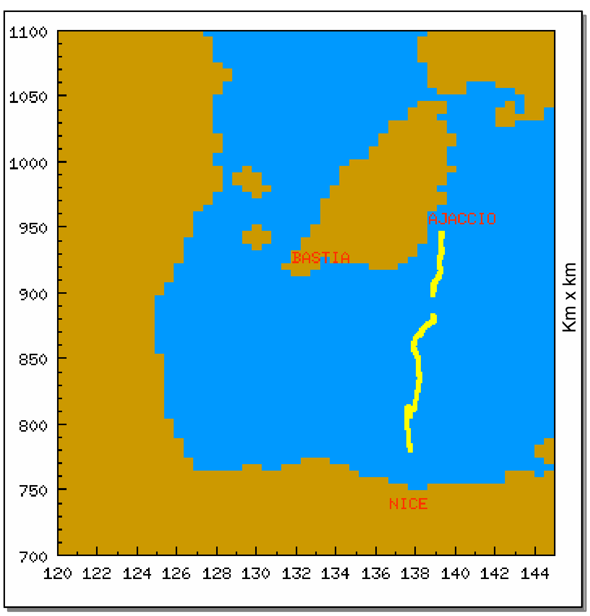

Figure 20. Boat tracks between Nice and Corsica Island (France)

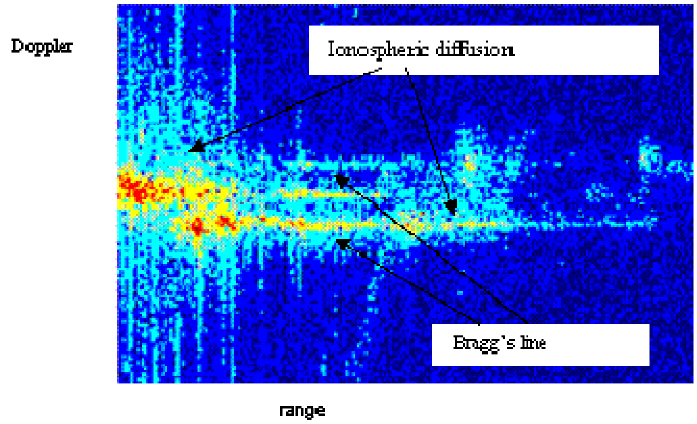

Figure 21. *Sea clutter*

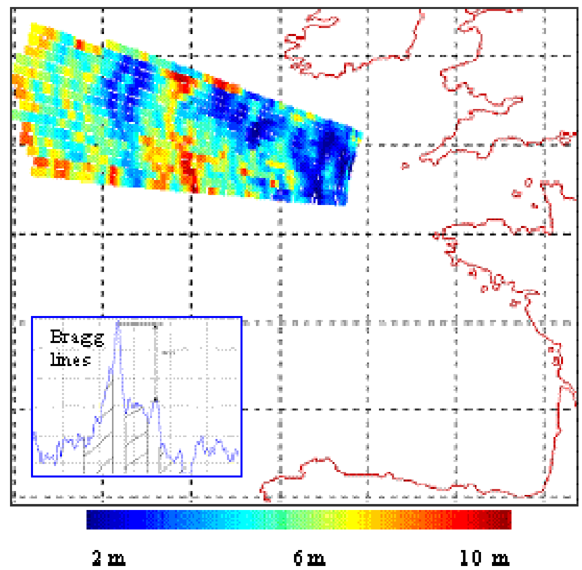

Figure 22. Wave height map over Atlantic ocean (south of Ireland)

VI. CONCLUSION

In this paper it has been shown that the NOSTRADAMUS radar, with its original antenna array, allows for determining the operating parameters (frequency, elevation, angle …) which optimize the budget power for the coverage of interest without using external data describing the ionosphere provided by sounders. NOSTRADAMUS is able to qualify the state of the ionosphere in real time using special processes based on soundings techniques. The philosophy of FMS has been presented. Various output data issued from NOSTRADAMUS has been showed.

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