Figure 3.11. *Antenna configuration for the transmitting (left) and the receiving (right) arrays of a bistatic US Navy OTHR-SW.*

An alternative example of bi-static OTHR-SW is given by the complex Australian system *"JORN"* which, being composed by several devices located in different sites (see fig. 3.6), it is better classified under the category of *Multi-static* OTHR-SW systems [25].

For each bi-static (or multi-static) radar, synchronization is a primary task. For example, the JORN must guarantee synergy between transmitters, receivers, and the wide network of ionosonde and devices for the management of the working frequency deployed all over Australia.
The main advantage of JORN is due to his multi-static configuration that allows to overlay coverage areas in order to reduce the scan time and/or to obtain information about the same target from two different receivers[5]. In the field

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[5] The system allows to obtain more information about the target (tangential component of the velocity; better impression of the RCS feature, etc.). Moreover, using two systems with

of “Over The Horizon Radar”, the bi-static configuration of a system is often marked as *“Quasi-Monostatic”* as the distance between transmitter and receiver site is relatively small compared to the size of the surveillance zone range.

3.3 OTHR-SW Architecture and Subsystems

As we previously mentioned, the subject of this research project is a processing technique for OTHR sky-wave systems, hence the overview of ground-wave systems will be omitted. In this section the general architecture of an OTHR-SW system is briefly described together with the potential technical solutions for the realization of the various subsystems.

3.3.1 General Architecture of an OTHR-SW System

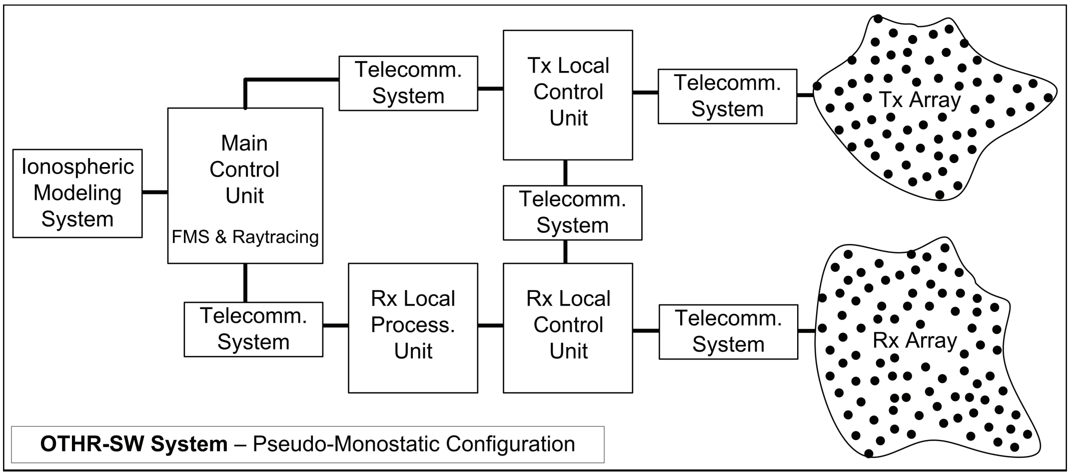

Figure 3.12. *Block diagram of an OTHR-SW system in a pseudo-monostatic configuration.*

The general architecture for an OTHR-SW system in a pseudo-monostatic configuration (Tx and Rx arrays are separated by a distance relatively small respect to the distances covered by the radar in range) is presented in figure 3.12. On the left side of the diagram we find the *Main Control Unit* block, directly connected to the Ionospheric Management block. The first is the principal processing block of the system, responsible, among the other tasks, for the management of the operative frequencies (consequently for the scanning scheme of the surveillance area) and for the raytracing algorithm and the connected CR procedure.

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overlying surveillance zone, performances in tracking radar targets grow significantly thanks to the redundancy of the collected data.

The second block provides the system with a periodically updated model of the Ionosphere in the area of interest. Real-time ionospheric data can be provided by a network of ionosondes, directly by the OTHR-SW or from any other independent external source. In the central part of the scheme we can see the two blocks: *Tx* and *Rx Local Control Units* that are connected respectively with the Tx and the Rx antenna arrays. Telecommunication systems connect the various blocks that can be also really distant from each other. The scheme do not account for several subsystems as the power system, the security and data-link systems and other subsystems that connect the radar to the outside.

The figure 7.1 proposed in chapter 7 shows a side-view scheme of the OTHR-SW simulated scenario, presenting several geometrical parameters and enlightening the 3 main blocks of the simulated scenario, that is:

- the Radar System;
- the Ionospheric Propagation Channel;
- the Surface Clutter.

For each of these elements a dedicated model was implemented while developing the SLTI method.

3.3.2 The Antenna System

Being associated to a large surveillance area, the sky-wave radar systems needs to employ an accurate routine in order to periodically scan a vaste surface. For some OTHR-SW the time needed to scan the entire surveillance area can range up to tens of minutes. Figure 3.13 shows a sketch of the scanning routine for an OTHR-SW with a 70° and $[600 - 3000]$ km surveillance area. The scan can be scheduled in azimuthal direction (i.e. with fixed range and increasing azimuth) or in range mode (i.e. with fixed azimuth and increasing take-off angle).

To generate a radar beam of contained dimensions within the OTHR-SW scenario (HF band and down-range distances up to 3000 km) it is required an antenna composed of a large number of elements spread over an extended area: *“Antenna Array”*. The Antenna Array is composed by many elements and it can assume various configurations depending on the mission of the OTHR-SW system and the consequent project requirements.

Array Configuration

There are several possible configurations for the antenna array and each one can be implemented with a different number of elements.
Two examples of the receiving antenna structure for existing OTHR are:

- *parallel double line with 372 elements*, such as the *ROTHR* (fig.3.11);

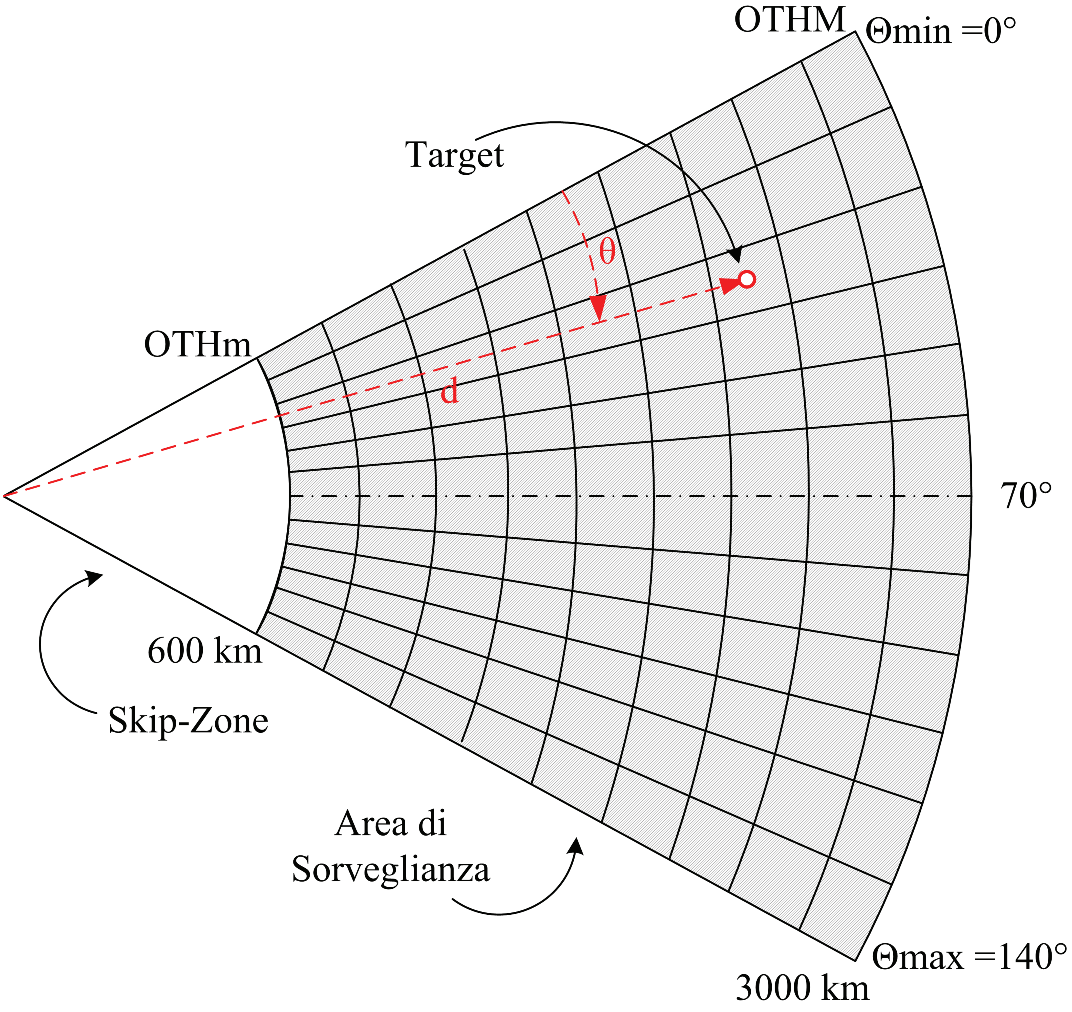

Figure 3.13. *Scan of the surveillance area by the OTHR-SW system.*

– *star with approximately 300 elements*, as the *NOSTRADAMUS* (fig.3.9);

We can not assume that one is better than the other: each one is optimized for a different type of radar, that is for a different mission of the sensor (note the the star configuration presents a symmetry that allows a 360 radar coverage while the double line array privileges a perpendicular pointing direction in the horizontal plane).

There are many other possible configurations of the antenna vector: "T", "X", "+" , rectangular, circular, etc. Therefore, whichever the choice is, it is generally based mainly on the requirements imposed by the geographical conformation of the surveillance area.

In the appendix B it is also briefly describe one of the solutions proposed for the

Italian OTHR-SW system LOTHAR.

Single Array Element

Similarly, the single element of array can have several possible structures: fig. 3.9 also shows the structure of the "diablo", that is the single antenna element of the French OTHR-SW *NOSTRADAMUS*); fig. 3.4 shows some details of the bi-conical structure of the antenna element of the Russian OTHR-SW *Duga 2*; fig. 3.11 shows the linear structure of the single elements of the US OTHR-SW *ROTHR*; and other different examples can be found.

The main requirements in the design of each antenna element are:

- gain and directivity maximization;
- Side Lobe Level (SLL) reduction;
- pattern variation minimization for different take-off angles;
- agility in frequency within the HF band;
- minimal overall dimensions and EM isolation from adjacent elements;

It is clear that it's not possible to reach a simultaneous optimization on all fronts, but it is good attitude to orient the project towards the best compromise possible.

In addition, since the design phase, it is essential to consider the inclusion of the single element in the final array configuration and the eventual variation of parameters due to this cause.

In case of mono-static device for some element (in general, the ones positioned at the center of the array) it must be also foreseen the possibility to work with high power in transmission and with reduced amplitude of the signals in reception, minimizing the switching times and the interference between the two operative modes.

Fig. 3.14 shows, from the left to the right, a sketch of the single bi-conical monopole antenna's element and its radiating diagram in the elevation plane for three values of HF frequency, respectively 2, 7 and 30 MHz. The height of the pylon ranges between 30 and 35 meters, while its diameter ranges between 20 and 25 meters. Note how, for the higher frequency the diagram presents an evident deformation of the main lobe. This is a possible solution to realize the single radiating element of the antenna array for the Italian OTHR-SW system "LOTHAR". The radiation of this antenna element is isotropic in the horizontal plane, but we need to remember that the directivity and the steering of the radar beam are controlled by electronically operate each single element of the entire transmitting and receiving arrays, in order to scan the surveillance area as suggested by figure 3.13.

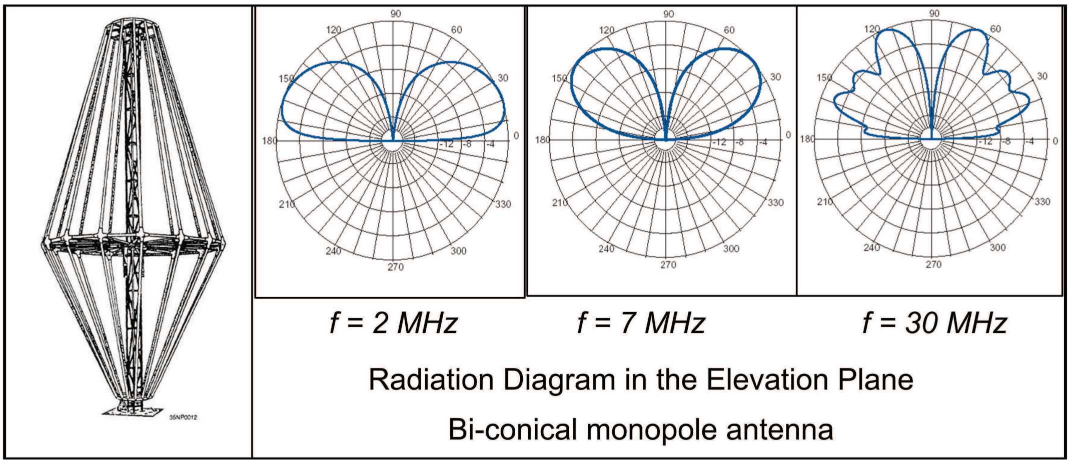

Figure 3.14. *Bi-conical monopole antenna and radiation diagram in the elevation plane for* $f = [2, 7, 30]$ *MHz.*

Considerations on the Antenna Subsystem

The need to control electronically the radar beam in regions extremely distant from each other also requires a considerable agility in the use of the individual elements. Depending on the area of interest and the radar purpose, the number of Tx/Rx components and the value of the transmitted power must be capable of rapid variations. This requirement and the need to avoid undesired magnetic couplings between the elements suggest the realization of individual generators located underground in correspondence of each element of the Tx vector.
It must be also established if the radar echo amplification should take place directly in correspondence of the receiving element or in a "centralized" mode, through the employment of matched lines.

Some primary needs for the radar site to be taken into account are:

- construction of underground tunnels along the perimeter of the antenna in order to operate the necessary maintenance system;
- ground shielding (via under-ground wire net) in the antenna transmitting sector in order to limit the penetration of the decametric waves due to the conductivity of the soil and the possible undesired coupling between the antenna elements;
- absence of natural barriers (mountains, forests, etc.) or anthropomorphic ones (buildings, towers or high-voltage lines, etc. ...) deployed on the possible path of the signal or echo (*"Clear Radio Horizon"*);

- fencing the area next to radar site, along a *"Security Perimeter"* in order to guarantee protection of persons or things from electromagnetic radiation;
- accurate local analysis of passive (due to external radar factors) and active (generated from OTHR to other users) interferences in HF band.

The directivity of a vector antenna like this is maximized for a particular combination of parameter values f, β and θ; it must, however, be guaranteed a performance cut-off level for the different combinations that these quantities can assume during the operational phase.

As mentioned, the radar beam will be controlled electronically during the coverage area scanning or in the eventual operation of target tracking and it will have different characteristics depending on the radar parameters. It brings to an amplitude variability of the radar beam footprint (which is function of its positioning in range and azimuth and of the working frequency) that must be taken into account.

3.3.3 The Transmitter

Transmitted Power

To reach down-range distances up to 3000 km it is necessary to transmit high power.

For example, the *Jindalee* radar, that is actually an important part of the Australian *JORN* network, requires a peak value of the transmission power that is around 240 kW [12], whereas the *NOSTRADAMUS* uses a peak power of 100 kW [43].

The use of such a high value of transmitting power clashes with the need to receive low intensity echoes. This problematic is particularly important in case of mono-static configuration of the radar, where a series of electromagnetic precautions must be taken so the Tx/Rx equipment can coexist without interferences generation or circuit-damages.

Occupation of the HF Band

It is known that the HF band extends from 3 to 30 MHz and it is used in many applications: analogue AM; marine and coastal communications; decametric-wave radio broadcasting; aeronautical beacons, ham stations, etc.

The *Table "A"* of the Italian *"Nation Frequency Allocation Plan"* shows that the HF spectrum has been divided into small portions of band and illustrates how the allocation of these portions is set on the Italian territory.

The frequency agility requirement of the OTHR-SW apparatus (essential to control the radar beam in range, to maximize the Clutter-to-Noise Ratio (CNR)

and to optimize the established radar mission) does not combine well with the high density of users in the HF spectrum.
In fact, the need to be able to shift the bandwidth of the transmitted signal within the dense HF spectrum involves the need to know, on a real time basis, the portions of the HF band which are not occupied by any other users.
At this point the *"Frequency Management System"* (FMS) plays its part. The FMS is a device that, in a passive mode, analyses the frequencies between 3 and 30 MHz, generating a real-time spectrum of the received noise and indicating the portions of available bandwidth.
By employing a FMS it is possible to obtain the characteristics of frequency flexibility and agility useful for the radar OTH operation.

However, in order to periodically shift the band of the transmitted signals in different positions of the HF spectrum it is necessary that it is characterized by a small width (also to reduce the noise contribution to the echo), and this implies a transmitted pulse of long time duration, capable to contain the energy necessary to operate over large distances.

It is also noteworthy the need to limit the interference generated by the radar to other HF band users. For this reason the use of the FMS is essential.

Frequency Management System

Despite its rule in the analysis of the external noise and in the consequent determination of the available bands, the Frequency Management System is also continuously employed by the OTHR-SW system to determine the scanning routine of the surveillance area. In fact, as explained in section 4.2 (see also fig. 4.2), the propagation of the HF signal through the Ionosphere is dependent from:

- the distribution of the e^- in the Ionosphere (referred to as "Electron Density Profile");
- the radar operative frequency;
- the take-off angle of the transmitted signal.

Hence for every azimuthal pointing direction the FMS needs to:

1. estimate the Ionospheric Conditions (in this task it is supported by Ionospheric sensors and by the radar itself) in the area where the "reflection" take place;
2. generate a 3D matrix that gives the achieved distance in range in function of the frequency and the take-off angle;
3. quantize the matrix in range-cells with maximum usable frequency (MUF) within the range $[f_{M_i} \pm 5\%]$;

4. select the operative frequency according to the principle of the maximum energy return, that is maximum Signal-to-Noise Ratio (SNR).

Fig. 3.15 shows the graphic version of the matrix described at point **3**, elaborated during the LOTHAR-fatt project. The lower curve (in red) represents the "Lowest Usable Frequency" (LUF), while the upper curve (in blue) represents the "Maximum Usable Frequency" (MUF). Note that the value in degrees at the center of each cell indicates the relative take-off angle. In [42] it is proposed the FMS developed for the Australian OTHR-SW sensor "JINDALEE" [25], ancestor of the actual "JORN", that employs a network of Ionosondes to sound the Ionosphere within the operative region.

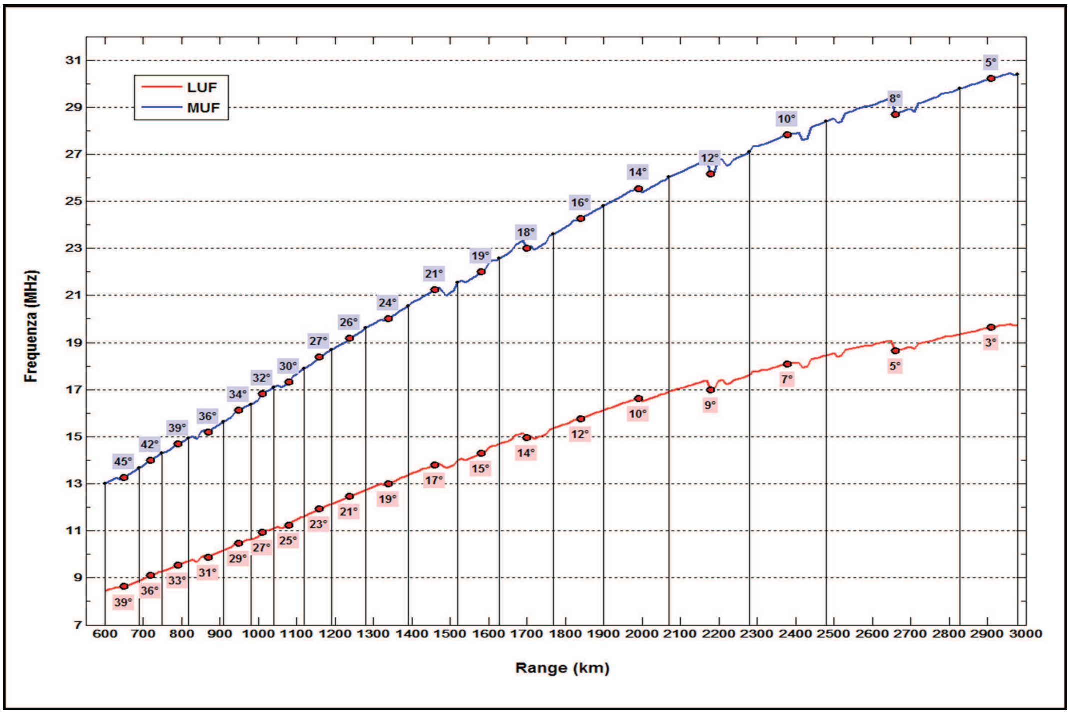

Figure 3.15. Example of the evaluation of minimum (red) and maximum (blue) frequencies in function of the ground-range distance and the take-off angle.

3.3.4 The Receiver

In OTHR applications the receiver needs to be adaptive as the transmitter, since the operative frequency of the radar needs to be periodically corrected to account for any eventual variation of the Ionospheric conditions. Before the processing for the target detection, the receiver needs to:

- operate an A/D conversion of the echo received by each single element of the Rx array;
- run the beam-forming in Rx, by electronically driving the single antenna elements and the Rx sub-arrays;
- carry out a matched filtering.

Two key-factors for the design of the receiving system are:

- the signal attenuation;
- the noise level at the receiver.

Signal Attenuation

The large size of the surveillance area that generally characterizes an OTHR-SW system is responsible for a strong geometric attenuations of the signals. This is the reason why a sky-wave system needs to employ high power levels in transmission.

Just to get an idea of the numerical proportions, we can make a numerical example.

Let's suppose that we want to reach a down-range distance $d = 2700$ km and let's assume that the equivalent ionospheric reflection height is $h_q = 280$ km, corresponding to a reflection within the F2 region (see chapter 4). Under such conditions, the distance covered by the signal in the one way radar-to-target path (*slant-range radar-to-target distance*) is $R = 2\sqrt{{h_{eq}}^2 + (\frac{d}{2})^2} \approx 2758$ km. Assuming a working frequency of $f = 20$ MHz (and, consequently, a wavelength $\lambda = \frac{c}{f} \approx 15$ m), the losses due to geometric attenuation result as $L_{sl} = 10log((\frac{4\pi R}{\lambda})^2) \approx 127$ dB.

The entity of this parameter largely justifies the need of high values of transmission power.

Noise in the HF Band

In the HF band ([3-30] MHz) the most significant noise contribution is not amenable to the "thermal noise" inside the receiving apparatus (as it happens for the $\mu - wave$ radar equipment), but it comes from the outside of the system and then it's classified as *"Environmental Noise"*.

The *environmental noise* is due to an heterogeneous combination of phenomena and it can be sub-classified into various categories based on the causing reasons:

- **"Atmospheric"** Noise;
- **"Cosmic"** Noise;

– **"Anthropic"** Noise.

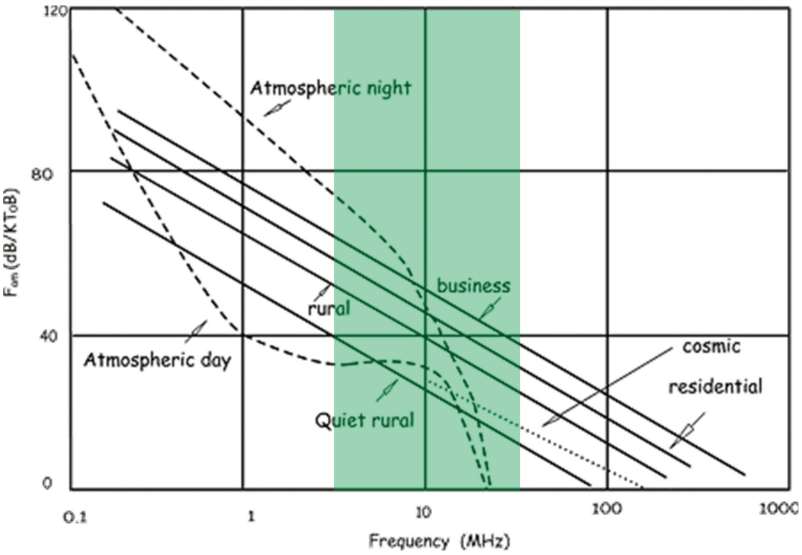

Figure 3.16. *Noise in the HF band.* The x axis shows the frequency [MHz] (in a logarithmic scale), while the y axis reports the mean value of the noise figure F_{am} expressed in dB/(Thermal noise at $T_0 = 288$ K). The continuous lines represent the *Anthropic Noise*, the dashed lines correspond to the *Atmospheric Noise* and the dotted line shows the *Cosmic Noise* [21].

The *atmospheric noise* is represented by natural phenomena that take place in the earthly Atmosphere. In this context, the main sources of electromagnetic interference are represented by lightning and electrostatic charge.

Eso-Atmospheric interferences are classified as *cosmic noise* and, as they are strongly attenuated by the Ionosphere in the band of interest, their weight is relevant only for frequencies above $10MHz$. Also the radiation from the Galaxy and the electromagnetic interactions of the Planet with the other celestial bodies are considered under this contribution.

The *anthropic noise* (also referred to as *"man-made"* noise) represents a noise phenomena directly related to the presence of man, but it is characterized also by an involuntary nature (it is not to be confused with jamming or other interference techniques). Its origin is caused by particular industrial processes, AM radio transmissions, undesired coupling among high-power devices, EM emissions from high-voltage lines, etc.
This type of noise is dominant in the lower part of the HF band and it assumes a large importance in industrial or urban centers, that is wherever the human activity is particularly intense.

In [54] it is illustrated the operational mode employed for the measurements of the HF *man-made* noise in different typologies of site, providing a description of the established criteria to classify both the site and the corresponding anthropic noise.

The graphic in fig.3.16 shows on a logarithmic scale how the contribution from different types of noise can vary depending on the operating frequency of the OTHR-SW [21].
The curve of anthropic noise is provided for four radar sites of different nature: “industrial”, “residential”, “rural” and “quite rural”.

The *Radio Society of Great Britain* (RSGB) provides a different classification of the noise in the HF band which, unlike the previous one, it is not based on its origin, but on the nature of its occurrence (persistence and bandwidth) [64]. Following this criterion, there are defined three categories of noise:

- *background ambient noise floor* (it is the constant noise across the band);
- *man-made noise from specific local sources* (temporary broadband noise);
- *narrow band interference* (interference which occupies very limited portions of the band).

In the present work we consider the first classification of noise, assuming that the anthropic noise is dominant respect to the other components.

3.3.5 Transmitted Signal and Received Echo

Transmitted Signal

The OTH radar can operate with a high variety of signal. Here we just briefly consider a few of this, highlighting pros and cons, and taking into account that, for the purposes of this work, it was assumed to operate with a pulse signal having a duration τ, without considerations on its Duty-Cycle or on its possible compression method.
The most employed signals in OTHR-SW applications are:

- *Frequency Modulated Continuous Wave* (FMCW). These are frequency modulated continuous wave signals that, unlike the pulse signals, have a tiny bandwidth and allow to reduce the peak transmitted power.
  A fundamental requirement for their use is the bi-statical nature of the radar system, that allows the decoupling between transmitted and received signals. This type of signal is adopted by OTHR-SW systems like the Australian *Jindalee* or the U.S. *ROTHR*.
- *Coded-Phase Pulses*. These signals can be used also in mono-static mode and they consist in pulses having a duration τ and a pulse repetition frequency PRF.

As we will see later, the pulse duration determines the maximum resolution that can be reached in down-range δI and, as this parameter is normally assigned by the design specifications, the result is an upper limit to the value of τ. However τ, together with the maximum achievable distance and at the minimum clutter-to-Noise Ratio required, determines the minimum power to be employed in transmission.

In order to reduce the entity of the latter parameter it is necessary to introduce techniques of phase encoding and pulse compression. The limitation of this approach is the difficult generation of a phase encoding for high power signals. In fact this waveform comports abrupt transitions of the signal's intensity in a very short time and transient of this kind are generally particularly deleterious for power amplifiers.

- *Chirp Signals*. To overcome the phase encoding problem, "Chirp" pulses can be used. In fact their phase variation follows a quadratic trend, that is less abrupt and easier to generate.

  The French OTHR-SW *NOSTRADAMUS*, for example, employs this type of waveform which, seems to be the more convenient choice also for the LOTHAR apparatus.

The polarization adopted for the transmitted signal is generally vertical. The V-polarization in fact guarantees higher values for the RCS of the targets of interest [6], even if possible rotations or polarization due to the Ionospheric crossing should be considered (see *"Faraday effect"*).

Received Echo

The down-range resolution of an OTHR is closely related to the bandwidth of the transmitted signal:

$$\delta I = \frac{c\tau}{2\cos\beta}$$

where c is the speed of light, $\tau = 1/B$ is the transmitted pulse duration (i.e. the reciprocal of the bandwidth) and β is the elevation pointing angle (or *"take-off angle"*).

Increasing the band, δI decreases and the down-range resolution improves. However, as previously explained, the need of frequency agility within an interval of overcrowded frequencies, places an upper limit to the size of the band.

Considering, for example, a band $B = 30$ kHz and a take-off angle $\beta = 15°$, we get a down-range resolution $\delta I \approx 5$ km: it's greater than the overall dimensions of any target of interest.

If we add that the clutter component in the received echo has (by its distributed

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[6] Note that adopting a vertical polarization of the signal also the clutter contribution results higher. This fact is positive in oceanography, but negative in maritime target detection.

nature) energy content significantly higher than any other echo, it is clear that any target of interest can be detected only through a Doppler processing of the radar echo.
A Range-Doppler analysis is based on the coherent observation of a single area for a period T_{oss} and it distinguishes the elements within that region with different radial component of velocity. In this way also targets with not high RCS are able to result from the strong contribution of clutter.

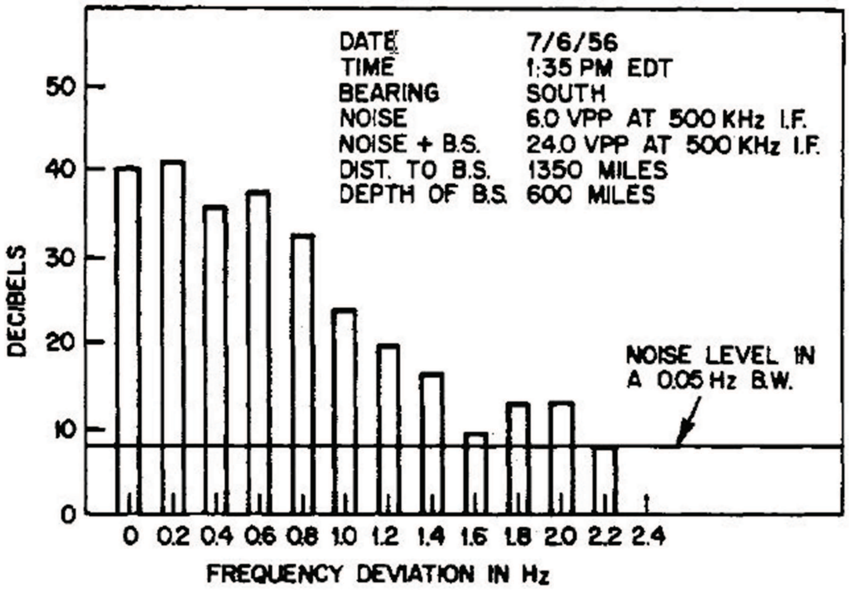

Figure 3.17. Typical example of *Earth backscattered Doppler Spectrum* [46].

The equation relating the Doppler shift f_d to target radial velocity V_r and carrier frequency f_0 is as follows:

$$f_d = \frac{2V_r f_0}{c}$$

If the target of interest moves slowly (for example a boat moving with a speed comparable with that of the sea waves) or moves in a transverse direction relative to the radar (low radial component of the velocity), the coherent period of observation necessary to distinguish its spectrum from the clutter one increases. The upper limit of this interval is given by the ionospheric coherence period (see chapter 4).
The ability to "extract" the Doppler signature of a target out of the most powerful clutter return in which it is immersed is based on the limited spectrum occupation of the clutter.
In fig. 3.17 a typical example of *Earth backscattered Doppler Spectrum* is provided. The information are given in form of histogram where each bar represents

the averaged value obtained considering a 2 minutes CIT and 0.05 Hz bandwidth. Thirteen bands spaced by 0.2 Hz are considered. the horizontal line represents the power level in a 0.05 Hz bandwidth. Note that after a certain value of the Doppler frequency $f_{d_{MAX}}$ (in this case 2.2 Hz), the clutter power level disappears below the noise threshold. Any target with a level power greater than the noise threshold and Doppler signature f_{d_T} greater than $f_{d_{MAX}}$ appears separately in the Range-Doppler domain.

3.3.6 Superficial Clutter in the HF band

With the term *"Clutter"* we indicate the contribution to the radar echo due to the backscattering of the signal by a given portion of the Earth's surface.
In OTHR-SW applications the clutter is without any doubt the return with higher energy content and typically the echo relative to the targets of interest presents a power of 50-80 dBs lower than that of the clutter.
The high magnitude of this parameter is due to the high extension of the radar beam's footprint and varies according to the "roughness" of the relative surface region.
To the purposes of this research we briefly discuss the "Clutter" topic by dividing it into two categories:

- *Sea Clutter*;
- *Ground Clutter*.

Sea Clutter

It is possible to find in literature many scientific papers based on the study and characterization of the sea with HF radars [52, 18, 17, 30, 8, 48]. In fact in oceanographic applications the Sea Clutter, that generally in radar surveillance applications is considered deleterious to target detection and tracking, becomes the "target" of interest for the radar. HF sensors are known to be powerful tools for the study of the sea behaviour on a large geographic scale, especially in the case of OTHR-SW sensors.
To an HF OTHR system the Sea surface appears, for a given time instant, as a rough medium characterized by hills and valleys that alternate with a certain regularity. Not every type of sea-wave can be detected by an HF radar: the waves of interest, referred to as "swells" or "dead waves", are those due to a wind that blew previously (up to four days earlier) in sea regions even far away from the area under observation. Hence the region where the swells propagate is called "Dead Sea". The main Sea-parameters observable with an HF radar system are:

- *sea wavelength*: maximum horizontal distance between two consecutive crests;