Chapter 3

Over The Horizon Radar Systems

With the name *"Over The Horizon Radar"* (OTHR) it is typically indicated a radar system that takes advantage of the peculiar interaction between the HF-band signals and the Terrestrial Atmosphere in order to operate on a very large area, much larger than that of conventional microwaves ground-based radars. This class of systems include two different categories of devices based on different propagation phenomena (see fig. 3.1 and fig. 3.2):

OTHR "Ground-wave" : (aka *"Surface-wave"*) employs signals in the lower part of the HF band, exploiting their attitude tu propagate above the Earth surface, following its curvature. This phenomena is more consistent over water-surfaces and it is restricted to several hundred of kilometres by the intense attenuation and the massive noise level that restrict its coverage in range.

OTHR "Sky-wave" : exploits instead the HF Ionospheric reflection of signals (in the whole HF band $[3-30]$ MHz) to overcome the horizon line. The coverage area can therefore be extremely large (typically up to 3000 km in range with an azimuthal span of about $60 \div 90$), tens of times greater than that of a typical ground-based microwave radar. [70]

For both categories of systems it is necessary to employ a relatively reduced amount of transmitted power if compared with the distances in range that they can achieve. This is perhaps the greatest strength of OTHR systems.
The SLTI method, presented in this thesis, is developed for OTHR sky-wave systems, hence the following sections and chapters are referred only to this category

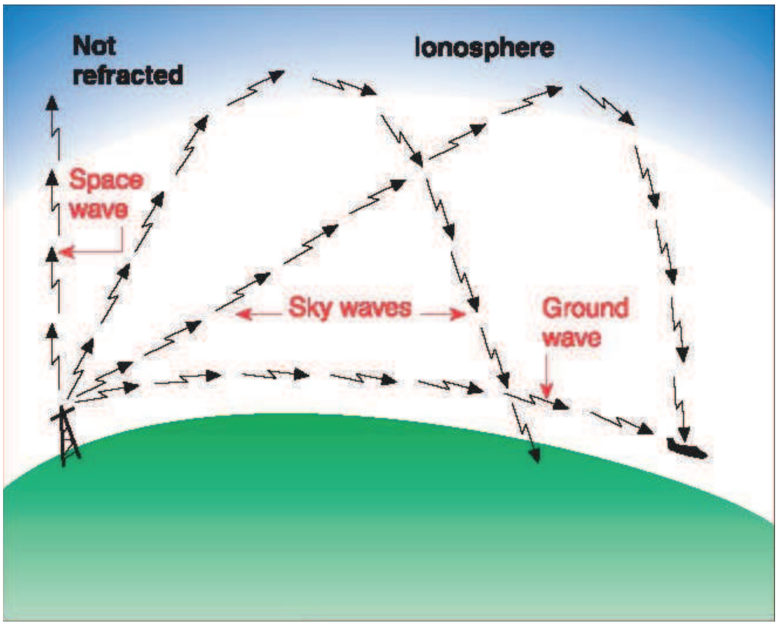

Figure 3.1. *Various HF waves propagation-mode in the Atmosphere.*

of Over The Horizon Radars. In a sky-wave system the signal is transmitted toward the Ionosphere that absorbs part of its power, but also bends the largest part of it according to its actual electron density profile (fig. 4.1) and to frequency and incidence angle of the HF signal (fig. 4.2). The dynamic behaviour of the Ionosphere and the impossibility to evaluate in real-time its structure on large scale are responsible of the uncertainty in the prediction of the signal's path and as a consequence of the origin of the echo received by the OTHR-SW.

In the following section some historical notes on HF radars and in particular on OTHR-SW systems are quickly given, ranging from the born of the radar, to the present time. Hence the OTHR-SW systems are classified according to their main features as typology of the employed signal, conformation of Tx and Rx arrays, etc. Finally the chapter ends with the description of the general architecture of a reference OTHR-SW by its decomposition in functional sub-systems.

3.1 Historical Notes

Some of the first prototypes of radar system, developed in the early 20s, were designed to operate in the HF band and they were employed to probe the Ionosphere and to study its structure and behaviour. Although very different for dimensions, materials, performances and even technology, those devices can be defined indeed as the forefathers of all the modern radar systems. Today the devices employed for the study and characterization of the Ionosphere are not

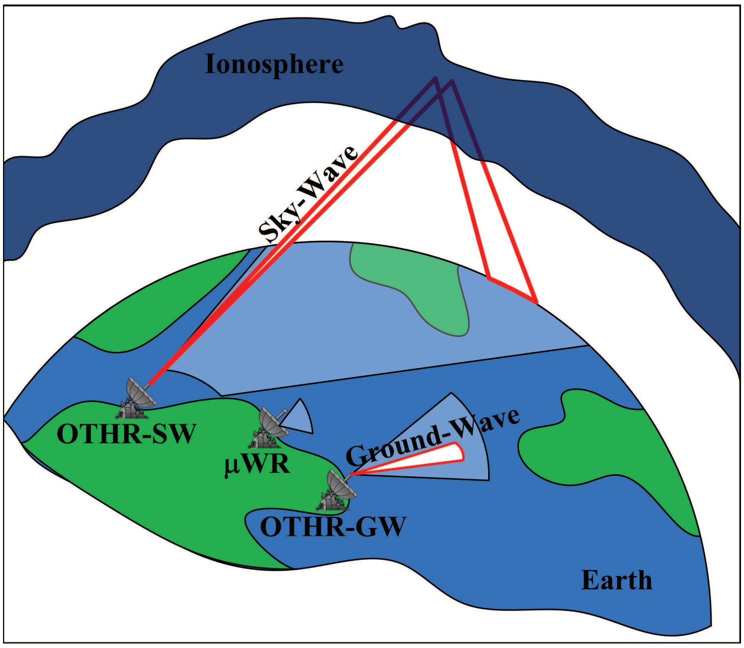

Figure 3.2. *Sketch of the different radar coverage provided by a Sky-Wave and a Ground-Wave OTHR systems and by a* $\mu-$*wave coastal radar.*

so different from those rough prototypes. They are referred to as VIS (Vertical-Incidence Ionosonde) and OIS (Oblique-Incidence Ionosonde) and despite they have a considerably reduced overall dimension, they employ new materials and require less transmitting power, they still works in the same HF band employed by the those prototypes. In fact the peculiar phenomena of the interaction between the Terrestrial Ionosphere and the radio wave with frequency included in the spectrum that goes from 3 to 30 MHz is known and investigated since the first experiments of Marconi, Tesla, Popov and others (end of 19th century) in which they tried to establish a radio-link between two locations without line of sight. Although the most of the modern radar system works in an upper part of the spectrum, the microwaves region, so they can guarantee: improved resolution, reduced overall dimension, lower energy-consumption, and many other features that makes them preferable in many applications, the HF systems are still employed in some specific field as oceanography, coastal-control, early-warning applications, etc.

3.1.1 HF radars in the Second World War

On the eve of the Second World War, Britain created the first radar systems for military purposes. Even those sensors were working in the HF band, and despite the limitations due to the high level of Environmental Noise and the limited

Band available, they succeeded in detecting the German bombers approaching the English coast. The *"Chain Home"* system was an HF radar network designed to cover the south-oriental side of the British coast (fig. 3.3).

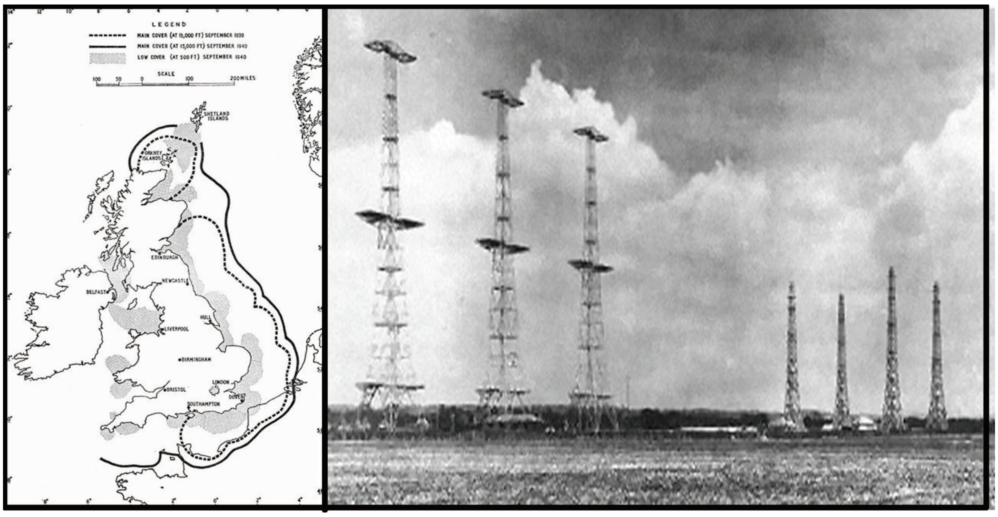

Figure 3.3. "Chain Home" *HF radar network: sketch of the coverage area and picture of some tx and rx antennas.*

After the war, thanks to the war effort and the consequent technological jump forward [1], the research and development of radar equipment for military and civilian applications moves towards the highest part of the frequency spectrum. In fact the above problems are solved when employing the $\mu waves$: the resolution increases while the required transmission power decreases. This allows to realize more-accurate and reduced-size radar equipment.

Yet the vast majority of radar systems for civil and military applications works with $\mu waves$ [46].

3.1.2 OTHR-SW during Cold War

The Cold War represents indeed the starting-event for the research and development of OTHR-SW systems.

The first experiments are conducted in Russia at the end of the '40s and in the United States (*Naval Research Laboratory*) in the early 50's.

In 1949, the Soviets build the first experimental OTH radar (the *Veyer*), which is followed by: between '60 and '70 *Duga-1* and *Duga-2* (two monostatic OTHR-SW both located in Ukraine, see Fig. 3.4) and in the second half of the

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[1] In particular, thanks to the development of the conversion technique *"Superheterodyne"*, already conceived by L. Levy in 1917

'70s two OTHR bi-static both named *Duga-3* (one in Ukraine and the other in Siberia).

Figure 3.4. *Antenna systems of the abandoned soviet OTHR-SW system* "Duga-2" *that was part of the* "Chernobyl-2" *radio/radar facility.*

As an evidence of the frenetic activity of the Russians in OTHR development, it is worth mentioning the *"Russian Woodpecker"*: an intermittent noise in the HF band (probably generated by the Duga-3 Ukrainian OTHR-SW system) received until the mid-80s by radio hams from all over Europe.
In fig. 3.4 are presented some images of the abandoned soviet OTHR-SW system *"Duga-2"*, once part of the complex radio/radar facility named *"Chernobyl-2"*, located near the city of Chernobyl. The picture were collected on the web [2], where many of them are available thanks to the work of a few amateurs. It is possible to note the proportions of the structure composed by the antenna system compared to that of one of the buildings that were once part of the complex facility.

On the other side of the Iron Curtain, the US-NRL completed in 1955 the project *MUSIC* (the principle of which was later adopted by the oceanographic system *CODAR*), which in '61 was followed by the project *MADRE*.

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[2] http://www.englishrussia.com/2010/09/15/chernobyl-2-a-pearl-of-the-past/#more-18052

Those are primitive OTHR systems whose principal limitations are due mainly to the lack of development in signal processing and data storage. Nevertheless both systems are able to detect via a basic range-Doppler processing special events (such as launching missiles or nuclear explosions) that take place well beyond the horizon. [31]

In 1960 US and GB begin the R&D of *"Cobra Mist"*: a really powerful (about 10 MW) OTHR-SW system to be located in Suffolk, England. Nevertheless, due to a consistent and still unknown source of environmental noise, the radar never became fully operative.

In 1970 the USAF-RADC (Rome Air Development Center) installs in Maine a bi-static OTHR-SW system, first component of a network of OTHR devices designed to guarantee a total coverage of US east and west coastlines. The test-stage of this experimental systems begins in the early 80s.

In the same year the Australian DSTO (Defence Science and Technology Organization) with project *Geebung* begins a series of experiments with HF radars in order to probe the Ionosphere and study its space/time behaviour.
Later, in 1974, the same DSTO runs phase 1 of project *"JINDALEE"* to study the capability of an OTHR-SW system to detect airliners. Following the success of this first experimental phase, in '78, the Australian government approves the *Jindalee Stage B* that leads to the creation of an OTHR-SW system to be employed as a test bed (1982) [25].

In 1982 the GE-Aerospace (today Lockheed Martin - Ocean, Radar and Sensor Systems) wins the tender for the study and development of *"OTH-B (Backscatter) Radar"*. It is part of the previously mentioned project aimed to the construction of an *early-warning* network of OTHR-SW sensors for a whole radar coverage of US boundaries. The project is too ambitious and only six of the 12 foreseen are ultimated and becomes effective: the 3 OTHR-SW in Maine are named *ECRS* (East Coast Radar System) while that at the California-Oregon border are referred to as *WCRS* (West Coast Radar System) [71]. In fig. 3.5 are presented some picture of the Moscow OTH-B facility in Maine. The picture were collected on the web[3] and the site OTHR-SW site with three separated antenna systems (each one to cover a different sector of the surveillance area) is visible also via Google-Maps by searching for "Moscow, Maine". It is easy to note that, as in the case of the Duga system (fig. 3.4), the single array element is still basically a dipole, but with a different shape.

Meanwhile the experimental OTHR-SW system realized in Alice Spring as part of phase B of the Jindalee project is inserted into a series of 7 experiments, referred to as *"JSET"(Jindalee Evaluation Service Trials)*, which take place between 1984 and 1986. In 1987 the same facility, referred to as *"JFAS"* becomes an R&D structure as part of the *JORN* (Jindalee Operational radar Network). The network includes several facilities whose position is represented in fig. 3.6.

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[3] http:coldwarrelics.commoscow_afs

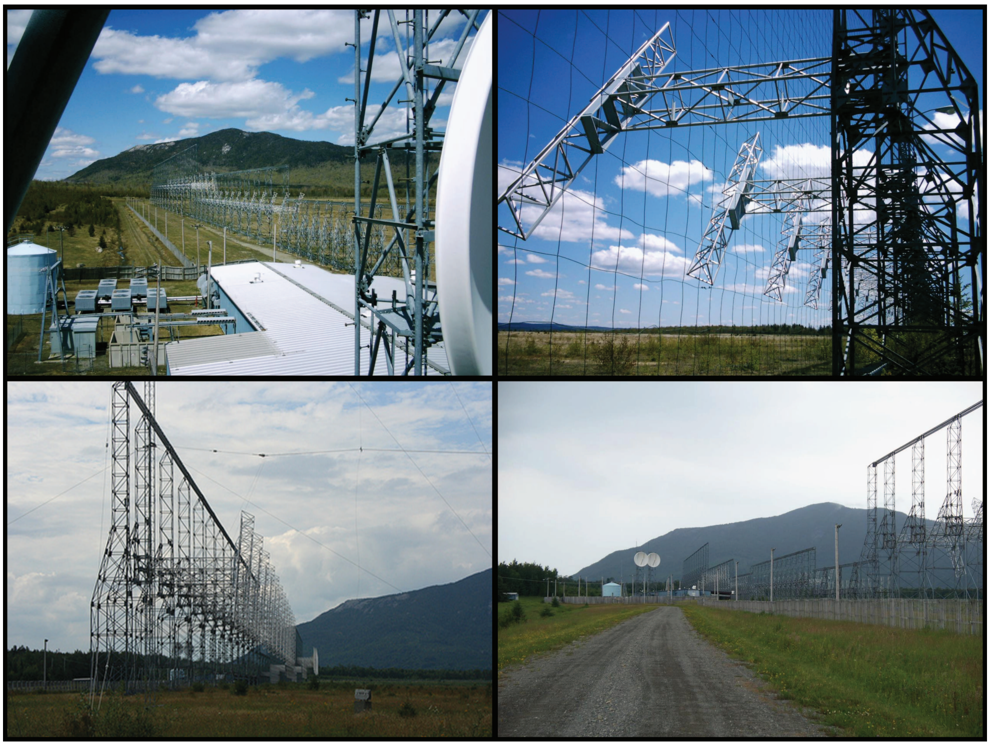

Figure 3.5. *Antenna's Array of one of the USAF OTH-B radar system located in Moscow, Maine.*

[25]

3.1.3 OTHR-SW Applications at the End of the Twentieth Century

With the attenuation of the hostilities between Russians and Americans, the interest for an early-warning system able to detect the lounch of intercontinental ballistic missiles is drastically reduced. We are probably at the age of the satellite era and the idea of a *"space-shield"* supplants that of a long-range ground-based radar system.

At the end of the 80s the sovietic OTHR-sw systems are not-operative since long time and some facilities are up to be dismessed. In 1986, after the incident to the Chernobyl nuclear powerplant, the entire Chernobyl-2 radio/radar facility is abandoned. After about thirty five years the Russians leave their leadership in the development of OTHR-SW.

On the other side, the last OTHR-SW system is the *ROTHR (Relocatable OTHR)* that the Raytheon Company builds in Alaska (Amchitka Island) for the US Navy in order to monitor the eastern coast of Russia. The construction of

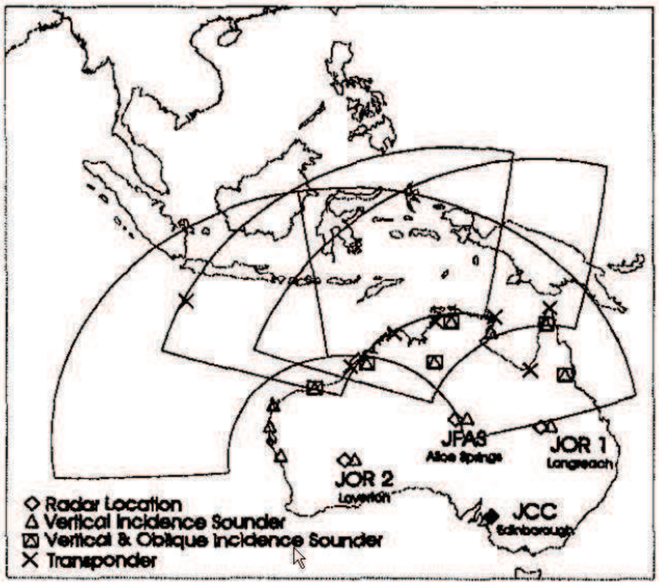

Figure 3.6. *JORN: displacement of OTHR-SW and ionospheric sensors and radar-coverage map.*

the apparatus began in 1988 and the radar became fully operational in '91. When the military base was dismissed, in '93, the antenna system of ROTHR was moved in Virginia (Chesapeake) and converted for civilian applications.

In '95 it becomes operational a second ROTHR realized by Raytheon in Texas (Corpus Christi). The basic idea is to employ the two system jointly [72], perhaps overlapping their surveillance areas or integrating theme in an existing network of coastal microwave radars [77].
In the same period it is planned the realization of third ROTHR in Puerto Rico (Juana Diaz). The antenna unit was partially built, but the project was abandoned when the U.S. military presence in the country was drastically reduced. [4].

Unlike the previously mentioned OTHR systems, the two ROTHR placed in Texas and Virginia are not conceived as an exclusively military "early-warning" sensors, but with the idea to employ theme fo two different tasks:

- *Monitoring and study on a large scale of Oceanic phenomena* in co-operation with NOAA (National Oceanic and Atmospheric Administration) [72];
- *Detecting drug-traffic: Mexican Gulf - Caribbean Sea* as part of the ARPA Counterdrug Program [34]: in co-operation with the JIATF-S (Joint Inter-Agency Task Force), organization that includes the DoD (Department of Defence), the Department of Homeland Security (U.S. Coast Guard) and the Department of the Treasury (U.S. Customs Service).

The 90s also mark the entrance of France in the circle of OTHR-SW R&D: the results of project *STUDIO ("Systme de Traitement Universel de Diagnostic IOnosphriques")*, launched in 1968, are placed in the context of the realization of an experimental OTHR-SW system that will be called *"NOSTRADAMUS"*. The NOSTRADAMUS system (a monostatic radar capable of achieving a 360 coverage), will become operational in early 2000, showing to be able to monitor airliners above Corsica and Sardinia islands.

In the late 80s, the WCRS is placed in stand-by active mode (*"Warm Storage"*) and occasionally employed by NOAA for oceanographic purposes. For the ECRS instead it is studied a conversion plan that involves him for a few years in the fight against drug trafficking. Its final retirement takes place in the early 90s [71].

The enormous building and maintenance costs of the OTH-B and the short period of actual employment of WCRS, ECRS and Jindalee represent at that time a strong topic of debate for the public opinion in the U.S. and in Australia.

In the late '90s, the DSTO ends the realization of the JORN: a complex network of ionosonde-stations and OTHR bi-static systems (fig. 3.6) set to become fully operational around 2002.

The last decade of the millennium sees the entry of many other countries in the scenario of OTHR R&D: China, France, Iran are just some of the involved countries.

However, as the Cold War was the event engine for the development of this technology, so its end it defenetly slowed down or even immobilized the development mechanisms.

3.1.4 Current Employment of OTHR Systems

Today, about sixty years after its inception, due to a series of factors as the widespread diffusion of GPS, the enormous progress in μ-waves radar technology, and the advent of satellite surveillance systems, it may seem anachronistic to write about the possible development and implementation of OTHR systems.
Nevertheless the interest around these category of radar is all about dead. Nations that cannot afford the entire cost for developing and putting into orbit a satellite surveillance system; countries, like China, that lately experienced an economic explosion and that want to catch up with the technology leaders; nations like Australia that for geographic features are interested in a tool that provides a wide radar coverage area around the borderlines; and so on, they are all interested to carry on the development of OTHR-SW systems. Italy takes part of this enlarged group of countries with the projects *"LOTHAR"* (2005) and *"LOTHAR-FATT"* (2008), that is with the study of pre-feasibility and feasibility of an HF Ionospheric radar for the surveillance of the Mediterranean area.

In fact, today more than ever, the Mediterranean sea is home to a continually

expanding shipping traffic. *LegaAmbiente* (the largest non-profit environmental organization in Italy) estimates an amount of almost 200,000 units, as the total traffic of large boats in 2007 [33].
The economic explosion occurred in China in recent years makes it necessary to trade routes to and from the east. Due to the long-terms instability of the Balkans and the Caucasus region, it seems appropriate to pursue these routes into the Mediterranean itself. Together with the industrial growth, also the service and logistic sectors lately experienced an explosion, with the result that commercial and touristic traffic in the Mediterranean area follows a continuous growing in the last years, independently from the actual crisis.

It is also important to underline the recent improvements and the following diffusion of HF OTHR-GW coastal systems (aka *"HFSWR")*, installed by many countries all around the world for maritime surveillance and oceanographic studies. Among all the developed and marketed OTHR-GW system it is worth to mention:

- *CODAR* for USA;
- *SECAR* for Australia;
- *WERA* for Germany;
- *NIIDAR* for Russia.

As previously said these systems are generally employed to extend the radar coverage up to the 200 nautical miles off the coast that limit the *"Exclusive Economic Zone"* (EEZ) of a given country, well outside the limits of the typical microwave coastal systems (see Fig. 3.8). Nevertheless, since they can easily be trained to observe the ocean and its phenomena, the HFSWR were recently found to be really effective tools to monitor Tsunamis evolution on a large scale [19, 7].
Also the sky-wave HF systems were considered, in virtue of their really large surveillance area, for the study of Tsunami [13], but because of the uncertainties introduced by the Ionosphere, they have so far proved not so effective.
In the appendix it is provided a not-exhaustive, but updated, list of the OTHR-SW systems located all around the world.

3.2 Classification of OTHR Systems

OTHR systems can be classified on the basis of a long series of characteristics and attributes. Each configuration of the OTHR system favours a particular mission or feature of the radar or advantages the detection of a particular type of targets.

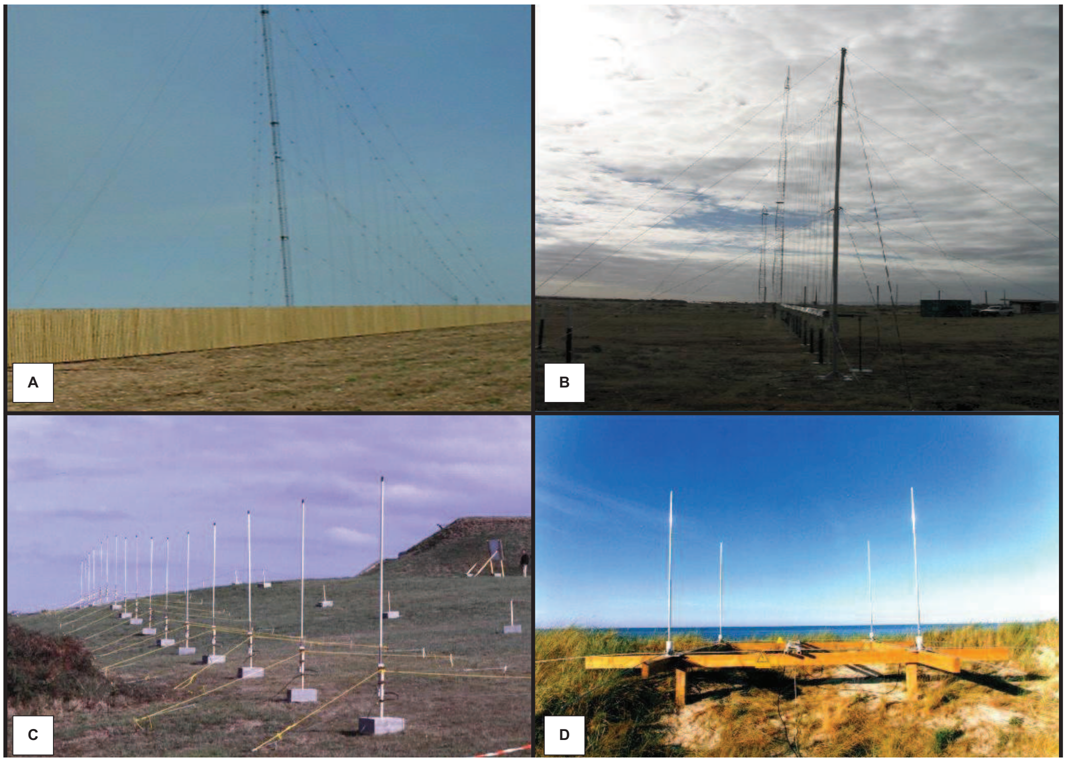

Figure 3.7. Antenna Systems for the HFSWR: SECAR (A and B) and WERA (C and D).

Here below we present an overview of the main types of OTHR systems, listing the possible project solutions, together with their limitations and strengths.

3.2.1 Surface Wave and Sky Wave Radar Systems

A first basic classification of OTHR system was already given at the beginning of this chapter and it involves *ground-wave* and *sky-wave systems*. We are talking about two completely different radars that exploit different propagation mechanisms of HF signals in the Atmosphere.

Surface Wave OTHR

While the sky-wave radar exploits the interaction between HF signals and the Ionosphere, the ground-wave systems take advantage of the propagation of the vertically polarized HF wave over the Earth's surface, especially on water-regions, by following the sea-to-air discontinuity [9].
The propagation distance depends upon the frequency of the transmitted signal and the roughness of the surface over which the signal propagates. For a sea

region the roughness is represented by the Sea State, that is an index of the Sea surface activity. Fig. 3.8 shows a sketch of the range achievable by a typical microwave coastal radar and of that achievable by an HF OTHR-SW system. It is easy to see how, even respect to a microwave radar installed on a 800 meters cliff, the maximum coverage distance is more than tripled. Moreover the HF sensor doesn't need to be mounted on a hill or on any other elevated site, since its signals follow the Earth's curvature reaching areas well behind the horizon. On the opposite, for an HF surface-wave radar the antennas of both Tx and Rx (generally those systems are bi-static) must be close to the water and are usually placed on the high dunes adjacent to the beach.

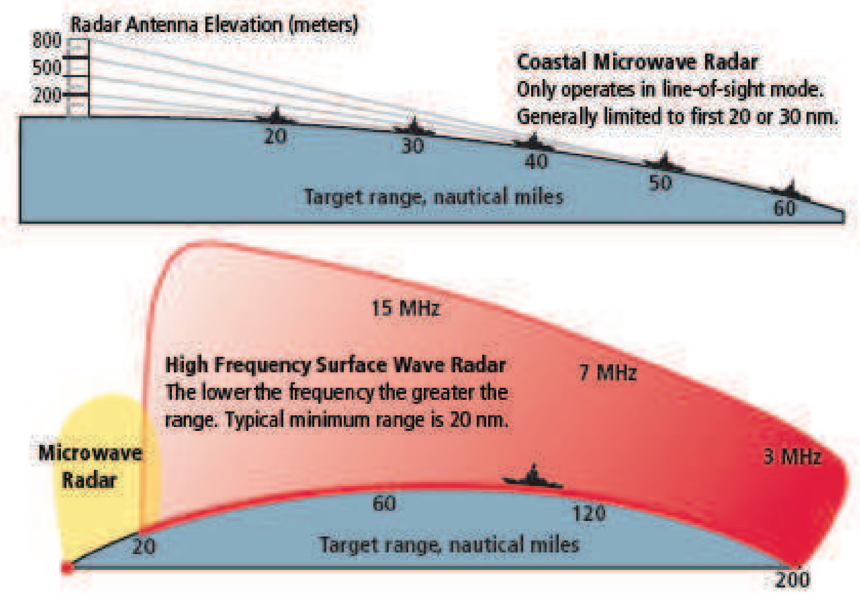

Figure 3.8. *Achievable range distance comparison between OTHR-GW and microwave coastal radars.*

It can also be noticed that in order to reach long distances, the HFSWR needs to employ lower frequencies (remind that for sky-wave systems it is true the opposite) (fig. 4.2). Note that the maximum detection range for this class of radar systems depends on many factors, including: transmit power, radar frequency, radar cross section of the target, target range, background noise, and interference level as well as sea-state. Of these parameters, only the transmit power and transmit frequency can be controlled by the radar operator. Both the noise and interference levels are dependent on the geographic location of the radar site, time-of-day and season, and also on the level of sunspot activity. The picture presented was collected on the Raytheon's web site.

According to United Nations Convention in relation to the 1992 Law of the Seas, the maritime countries have complete freedom to perform exclusive economical

activities within their respective *Exclusive Economic Zone* (EEZ) [56]. Moreover in this area those countries have responsibilities in the for threats as accidents, contraband, water pollution, illegal immigration and they are in charge for any SAR (Search And Rescue) operation. By employing a HFSWR-based surveillance system it is possible to monitor vessel activity up to a range distance much larger than that guaranteed by any other ground-based system [4].
As previously mentioned, besides their employment as surveillance systems, the OTHR-GW sensors are also employed to monitor the ocean activity on a very large scale. The principle of operation is very simple (see fig. 3.18): as the ocean has a rough surface, when an HF signal reaches its surface, a portion of the incident energy is scattered back towards the source and the receiver measures the reflected signal. This backscattering produces an energy spectrum at the receiver, even if the transmitted signal was single-frequency, because the shape and motion of the sea surface introduces a Doppler shift, spreading the band of the echo. Interpreting the spectral returns for various transmitted frequencies is the key to extracting information about the ocean and, in particular, to measure surface currents.
Working in the HF band, the OTHR surface wave is a particularly resilient sensor and it can operate also in adverse meteorological conditions [10],

Sky Wave OTHR

The OTHR sky-wave system is the radar considered by the present research. In fact the Sea-Land transition Identification (SLTI) algorithm here proposed has been developed with the purpose of Geo-reference the OTHR-SW received echo, overcoming the uncertainty in the signal's path introduced by the Ionosphere. Since it is deeply described in the following (with many schemes, sketches of its geometry and details on the adopted models), we believe that it is unnecessary to provide, in this section dedicated to the classification of the OTH radars, any additional information about this particular system.

3.2.2 Monostatic and Bistatic System

A second classification of OTHR systems considers the distinction between *monostatic* and *bistatic* sensors. Since the HFSWR systems generally all belong to the latter category, in the following we focus only on sky wave systems.

Monostatic OTHR-SW

In the monostatic configuration the receiving (Rx) site is the same of the transmitting (Tx) site. Generally the antenna's employment follows a time division

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[4] http:www.raytheon.comtechnology_today2012_i2persistent_surv.html

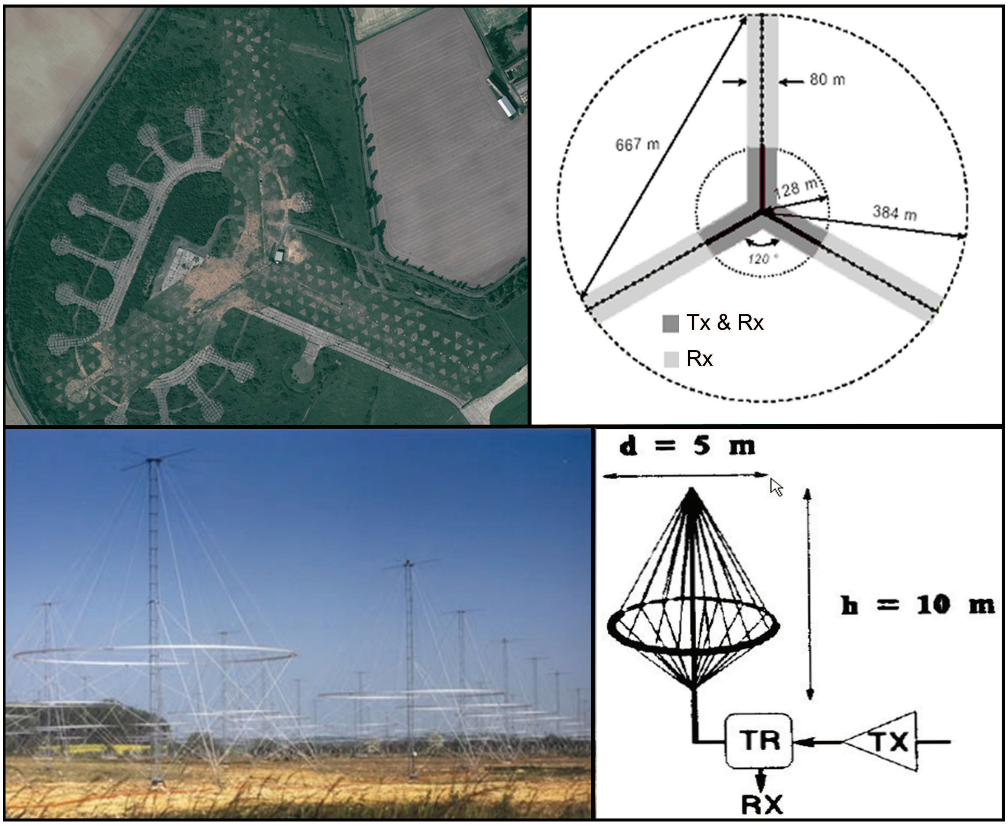

Figure 3.9. *The French OTHR-SW "NOSTRADAMUS"*. Clockwise from up-left: a picture of the previous airport with the Y-shaped antenna array on top; the antenna array configuration with central elements employed alternately in Tx and Rx; a sketch of the single radiating element of the antenna with the switch between Tx/Rx; a picture of the antenna elements called "Diablos".

schedule (TDM), making use of the echo's time delay (referred to as "Group Delay") to switch between the two modalities.

The most obvious advantages are the reduction of synchronization problems between Tx and Rx and the lower cost of implementation and maintenance of the system.

On the other hand, the major problems relate to the switch-dynamics of the antenna (or just part of it) between the two phases that are characterized by an enormous gap in the managed power level. Furthermore, the use of the only antenna in a TDM mode involves (considering an equal extension of the surveillance zone) an increase of the scan-time respect to bistatic configuration.

A classic example of monostatic OTHR is given by the French *"NOSTRADAMUS"* where the central section (about hundred elements) of the Y-shaped array consisting of 288 bi-conical elements (the so called *"Diabolos"* [75]) is switched among the Tx and Rx phases (see fig. 3.9).

Since in OTHR-SW applications the distance between the radar and the target is very large (in the order of thousands of kilometres), the radar system is often classified as *"quasi-monostatic"*. In this case Tx and Rx are physically separated, but their distance is much smaller than the possible target's range, so that the paths of the transmitted signal and the received echo can be considered identical.
The geo-referencing technique presented in this work was developed for the employment on a monostatic or on a quasi-monostatic sky-wave system, even though most of the considerations made and of the obtained results could be easily applied to bistatic systems.

Bistatic OTHR-SW

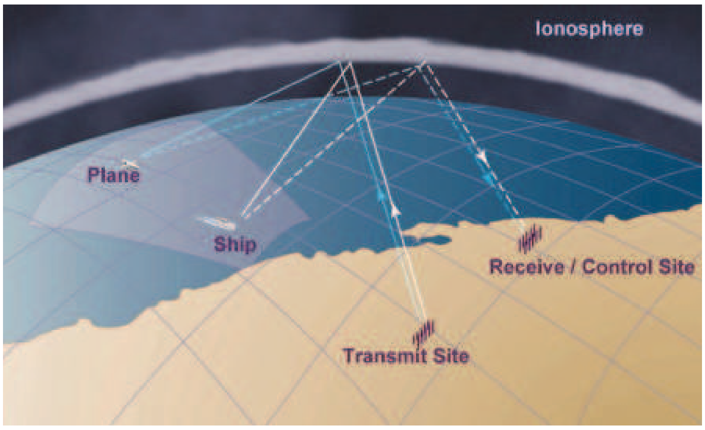

Figure 3.10. *Scheme of the geometri of a bistatic OTHR Sky-Wave.*

In the bistatic configuration transmitter and receiver are placed at a minimum distance of one hundred miles (in this case in fact we have the quasi-monostatic configuration). This precaution prevents the receiving antenna to pick up, through its side lobes, the interference due to the powerful signal controlled by the transmitter included within the frequency band of the receiver.
Although it is necessary an initial phase of optimization for a bi-static system [11] and the synchronization of the two sub-systems requires the use of sophisticated "clock devices", this configuration is to be preferred for particular radar schedules that impose limited scanning time.

In figure 3.11 are presented two pictures of respectively Tx and Rx array for one of the US Navy OTHR-SW system realized by Raytheon. The system is a classical example of bi-static OTHR-SW apparatus. Note that for this particular radar both the transmitting and the receiving array are organized in a linear configuration.