Chapter 4

The Ionospheric Propagation Channel

4.1 Introduction

The Ionosphere is the region of the upper Atmosphere where the concentration of electrons and ions is high enough to affect the propagation of electromagnetic waves. From a morphological point of view the Earth's Ionosphere can be divided into three different regions (referred to as D, E and F) that are placed at different heights and have different characteristics. The D region extends from 50 to about 90 km and the electron density combined with the concentration of neutral molecules is such that electromagnetic waves suffer a differential absorption and relatively low frequencies (3 to about 9 MHz) are more attenuated. The E region, between 90 and 140 km altitude, has a double morphology: the E layer and a *"sporadic-E"* layer. The existence of this latter in particular is due to the transport of plasma and derives its origin from the effects of photo-ionization and recombination mechanisms. The lower regions of the ionosphere are typically considered in daytime while during night-time the Ionospheric structure changes, these layers disappear and it is experienced a dilatation of the radio-horizon. This phenomena is due to the relevant density of neutral molecules in the lower Ionospheric regions, that causes a considerable excursion of the ionospheric absorption values between day and night. The F region extends over 140 km with an absolute maximum of electron density around 300 km. After this peak, the electron density decreases monotonically. Fig.4.2 shows the typical daytime and night-time profiles of electron density of the Ionosphere in the Tropical region. Besides the plasma-transport phenomena, these profiles depend mainly on the angle of

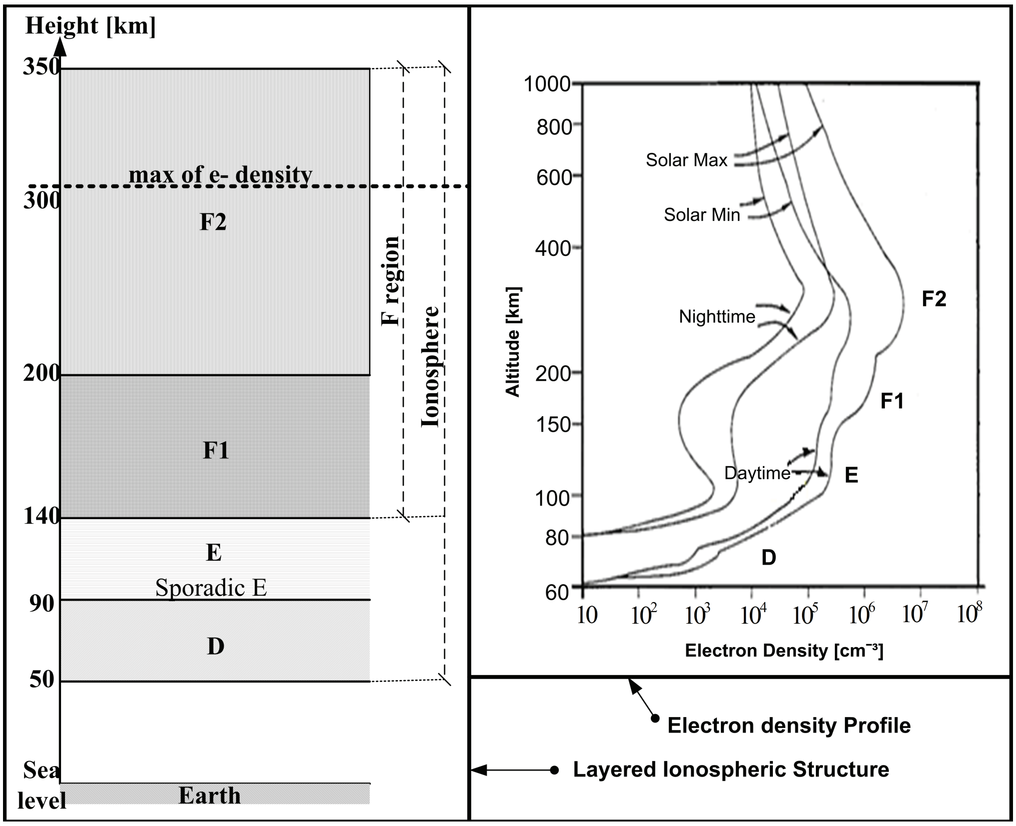

Figure 4.1. *Electron Density Profile (right) and scheme of the layered structure (left) of the Ionosphere.*

incidence of solar-rays, with a variation on diurnal, seasonal and geographical basis. The OTHR system employs frequencies in the HF band that, depending on the considered distance, reflect at various altitudes in the ionospheric layers, travelling across different ionospheric regions. The route along which the waves propagate electromagnetic, referred to as ionospheric channel, is therefore also dependent upon the electron density and upon a series of factors that contribute to its variations in time and space. The dependence of Ionospheric conditions on the activity of the Sun, the propagation modes of the Thermosphere and the geographic location, gives to the ionospheric channel a random nature that is more pronounced in "not-quiet" Ionospheric conditions. Therefore, the ionospheric channel is a medium that has a certain degree of uncertainty because of the spatial and temporal variation to which it is subject. However, by employing a statistical Ionospheric model, it is any way possible to perform some predictions in the short and long term plan for the choice of frequencies and other parameters of interest used by OTH radar in various operating conditions.

4.2 Parameters to Characterize the Ionosphere

If we imagine to divide the Ionosphere above the surveillance area of the considered OTHR system into a geographic grid with resolution 1-by-1 degrees and we assume to employ the *Simplified Ionospheric Reference Model* (SIRM) proposed by the Italian *National Institute of Geophysics and Vulcanology* (INGV) , than we can outline the main parameters necessary to characterization the Ionospheric Channel:

- Maximum Usable Frequency (*MUF50* or $MUF_{50\%}$);
- Equivalent Oblique Reflection Height (h_{eq});
- Take-Off Angle (β);
- Azimuthal Angle (α);
- Ground-Range Distance (D);
- Geometric Attenuation (L_g);
- Ionospheric Attenuation (L_i).

In Table 4.2 are listed the values of the maximum excursion of the ionospheric and geometric parameters. The excursion of the ground-distance assumed to $600 - 3000$ km is coherent with the hypothesis to neglect multiple ionospheric hops and analogous complex propagation mechanisms as multipath, fading and defocusing, which manifest themselves at very low angles of elevation of the radar (fig. 4.2).

For what concerns the geometric attenuation, it is variable not only with the distance, but also with the frequency: fig.4.5 shows the geometric attenuation as a function of the ground-range distance for the two limit values of frequency of the HF band (3 and 30 MHz). It is evident that the variation of the attenuation can range between 100 and 130 dB. In fig.4.2 it is schematized the interaction between the HF signal transmitted by the OTHR-SW system and the Ionosphere.

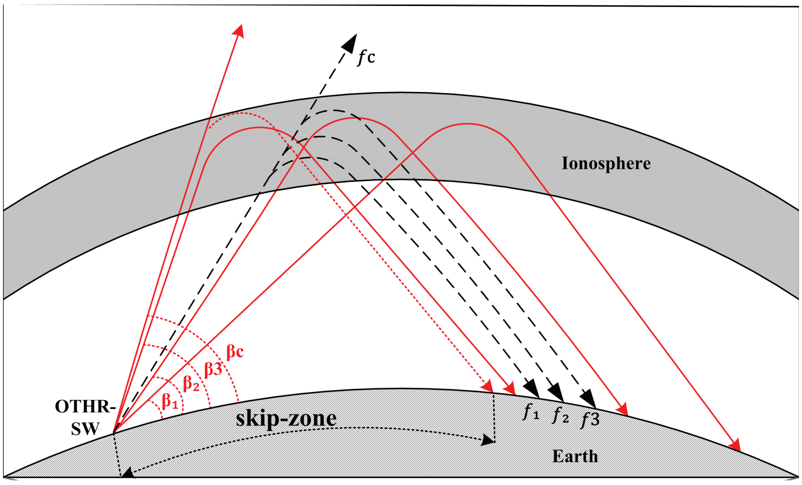

Figure 4.2. *Interaction of the HF signals with the Ionosphere in respect of parameters β (take-off angle) and f (signal's frequency).*

The red continuous line represents the shows how the signal's path changes in function of the take-off angle β while the hatched black line shows how the path and, as a consequence the ground-range distance, change for different values of frequency of the signal ($f_3 > f_2 > f_1 > f_c$). β_c and f_c represent respectively the critical angle and frequency. β_c is the angle that in correspondence of the minimum usable frequency determines the crossing of the entire Ionosphere by the signal. f_c is the frequency that given a certain angle leads to the same result. β_c and f_c are both essential to evaluate the range measure of the *skip-zone*, that is of the area closed to the radar not coverable with that given OTHR-SW system. A valid example of Ionospheric modelling is provided by the *Global Ionospheric Radio Observatory* (GIRO) employing Real-Time and Retrospective HF Ionospheric Sounding Data from Lowell DIDBase (where DID stands for "Digital Ionogram Database") [1]. In fact by scanning the transmitted frequency from 1 MHz to as high as 40 MHz and measuring the time delay of any echoes (i.e., apparent or virtual height of the reflecting medium) a vertically transmitting sounder can provide a profile of electron density vs. height. This is possible because the relative refractive index of the ionospheric plasma is dependent on the density of the free electrons (Ne) in the given Ionospheric layer, as shown in the following equation (where the effects of the Geomagnetic field are neglected):

$$m^2(h) = 1 - k\left(Ne/f^2\right)$$

where

- Ne is the electron density expressed in e^-/m^3;
- $k = 80.5$;
- f is the working frequency [Hz].

4.3 Space/Time Behaviour of the Ionosphere

The Ionosphere shows some variations that can be considered predictable because depending on the zenith angle of the Sun and on the irradiance in the UV and X-band spectrum. To these "regular" changes overlaps a non-predictable variability which may have various origins. Perturbations on a small geographic scale, which we denote as irregularities, are generally attributable to transport phenomena that cause both local non-homogeneity and distortions in the layers of electronic iso-density, with a consequent alteration of the radio propagation conditions. Effects like focusing, defocusing and small multipath can be attributed to these phenomena.

On the other hand, phenomena that occur on a global scale have all an origin or external to the Atmosphere and generally imputable to the Sun. The most important perturbations that effect HF propagation are caused by electromagnetic and corpuscular emissions from the Sun, where occurring phenomena known as *"Solar Flares"* that typically cause *"Sudden Ionospheric Disturbances"* (SID) or even *"Short Wave Fadeout"* and *"Sudden Frequency Deviation"*. While the first implies a significant absorption of electromagnetic waves in the illuminated hemisphere, the second and the third are lower intensity effects that cause abrupt attenuation and fading of the radio signal and phenomena of magneto-ionospheric storms on different temporal and spatial scales.

Other problems take origin from the circulation of neutral thermo-spherical winds, as for the sporadic E layers and pseudo-wavy propagation phenomena, as the *"Travelling Ionospheric Disturbances"* (TID) [55], associated to wavy medium wavelength disturbances with a frequency that ranges from minutes up to about an hour, and wavy perturbations on a larger scale, with time interval up to 2 hours, referred to as *"Acoustic Gravity Waves"* (AGW). On a time-scale, both the Ionospheric and the phenomena that caused it may involve a time period that ranges from tens of microseconds to eleven years (a complete Solar cycle). The category of disturbances characterized by a relatively low space-time scale is referred to as *"Small Scale Disturbances"*(SSD). All of these disturbing phenomena act in various ways on the propagation of electromagnetic waves in the Ionosphere. So the Ionospheric reflector, generally considered as a coherent reflector, must be considered *"not-coherent"* in not quite Ionospheric conditions. From experience it is known that above Europe on a time scales beyond the 23s, in particular conditions, phenomena of inconsistency that degrade the HF signal may be experienced. In this case, if the integration time of the received signal is too long the effect caused by the Ionosphere can seriously compromise the operation of the OTH sensor. Moreover the variability in the short time scale can also degrade the Doppler resolution of the radar system.

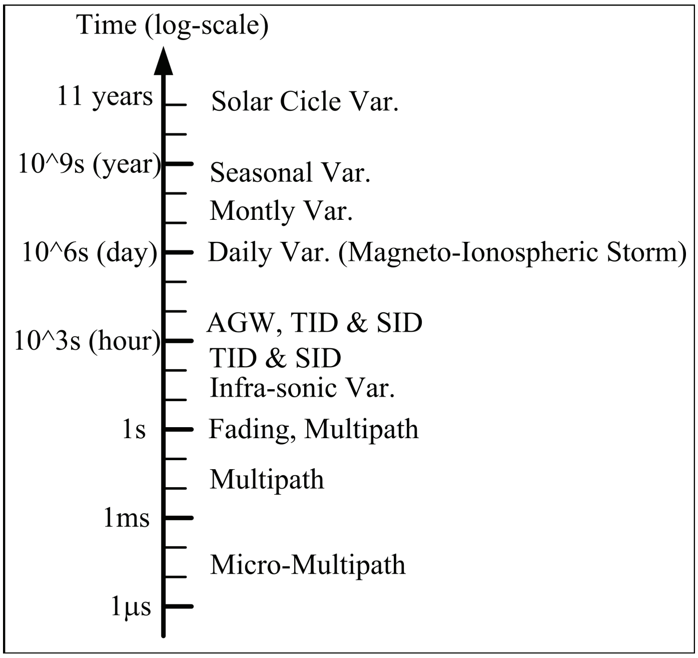

Figure 4.3. *Time scale of the most common Ionospheric Disturbances.*

All these phenomena disturbances are difficult to predict in advance. However, they can be detected during the early stages of formation and their intensity can be evaluated in order to predict their evolution. On larger time scales we can experience disturbances associated with geomagnetic storms that alter both the Ionospheric critical frequencies the virtual height of the ionospheric layers. In general, in case of magnetic storms due to transport processes, the critical frequencies undergo strong declines, heavily modifying the frequency planning and geometries established to exploits the propagation by Ionospheric reflection in quite conditions. The magnitude and occurrence of these phenomena is highly dependent upon the geographic latitude and the Ionospheric regions interested. Their effects on OTHR-SW activity could be somehow mitigate when the sensor operates at full capacity mode, if real-time data on the Ionospheric conditions are available to correct the employed Ionospheric model.

As we said, the Ionospheric variability is determined by a series of phenomena which can influence in different measures the propagation of the radio waves employed by the OTHR. The scheme presented in fig.4.3 summarizes the temporal scale of these phenomena which obviously affect the coherence times of the Ionospheric reflector. In case of quiet Ionosphere the coherence time can arrive at 60-100 s. It can be stated that, apart from rare particularly intense perturbing phenomena, during the operational phase of the OTHR, most of the presented effect on signal propagation can be evaluated and then corrected or compensated in the received echo.
Table 4.1 resumes the main Ionospheric phenomena previously introduced, together with the effect that they cause on the OTHR-SW signals.

Phenomena affecting the OTHR-SW Propagation Channel	**Relative Effects on the HF Signal**
Reflection	Delay time
Refraction	Dispersion (propagation time-delay), group delay
Not-deviating and deviating Absorption, Propagation in hiding E layers, Diffusion, fading a Defocusing	Power-lost (Magnitude of the EM field and power density)
Faraday Rotation and Double-refraction	Decomposition of the wave in two rays (ordinary and extraordinary) and lost for depolarization
Multipath	Different delays depending on the multiple geometries of the propagation channel
Ionospheric Doppler Effect	Frequency-shift and phase-distortion

Table 4.1. Ionospheric Phenomena and relative effects on the HF signals.

Whenever vertical drifts of the reflective layers are present, they introduce a Doppler shift in the radar signal. The analysis of the Ionospheric Doppler modulation plays an important role both in the disorder that can be introduced in the radar echo, either in the eventual measurement of target speed. In fact the Ionospheric plasma is subject to drift motions and the electron density results variable in time. The Doppler shift which results in the echo may have values ranging from a few tens of mHz to a few Hz in the very rare eventuality of particular plasma-drift phenomena. The presence of a Doppler shift induced by the Ionospheric motion, on one hand generates disturbances due to clutter in frequency bands where the clutter should not have components, on the other hand creates ambiguities in the estimation of speed. The vertical drifts of the Ionospheric plasma are those that contribute to the Doppler shift of the signal, but the effect is mitigated by the fact that the vertical component of motion must be projected on the direction of propagation of the electromagnetic wave. Moreover, in real operating conditions, such phenomena can be largely predicted and then the appropriate corrections can be made. This is the reason why in our implemented Ionospheric model we did not take into account of these effects on the received OTHR-SW echo.

From an experimental study conducted by the INGV within the "LOTHAR" project it results that, for radiated power lower than the tens of MW and for frequencies above the *Cyclotron Frequency* (1.2 MHz), the Ionosphere can be considered as a linear medium where it is valid the principle of the overlapping effects. Such behaviour may be considered largely valid also for wideband signals, with bandwidth of the order of a few hundred kHz. The ionospheric phenomena that can introduce non-linearity in the ionospheric response are rare and usually they occur in different operating conditions from those assumed for a pulsed OTHR-SW system. One can therefore conclude that the ionospheric behaviour in operating conditions can be assumed to be linear.

4.4 The Multi Quasi-Parabolic Ionospheric Model

The MQPIM is one of the most employed models (NOSTRADAMUS, JORN, etc..) for the vertical characterization of the Ionosphere through its electron density profile. The Ionosphere is vertically divided into four regions (see sec. 4.1), but the "D" region, accountable only for the attenuation of the signal (also referred to as *"Non-Deviative Absorption"*) is considered only implicitly by the model. For each of the other three regions it is processed a parabolic profile representing the vertical distribution of Ionospheric *Plasma-Frequency* characterized by the following three parameters:

- f_c: critical frequency;
- h_b: minimum height;
- h_m: maximum height.

There are also introduced two additional transition layers (referred to as *"Joining Layers"*): $E/F1_{jl}$ ed $F1/F2_{jl}$, that are necessary to link[1] the three parables representatives of the Plasma-Frequency of regions E, $F1$ ed $F2$. The graph in

---

[1] The function of Joining Layers is essentially to give continuity to the curve formed by the three parables referring to the regions E, $F1$ and $F2$.

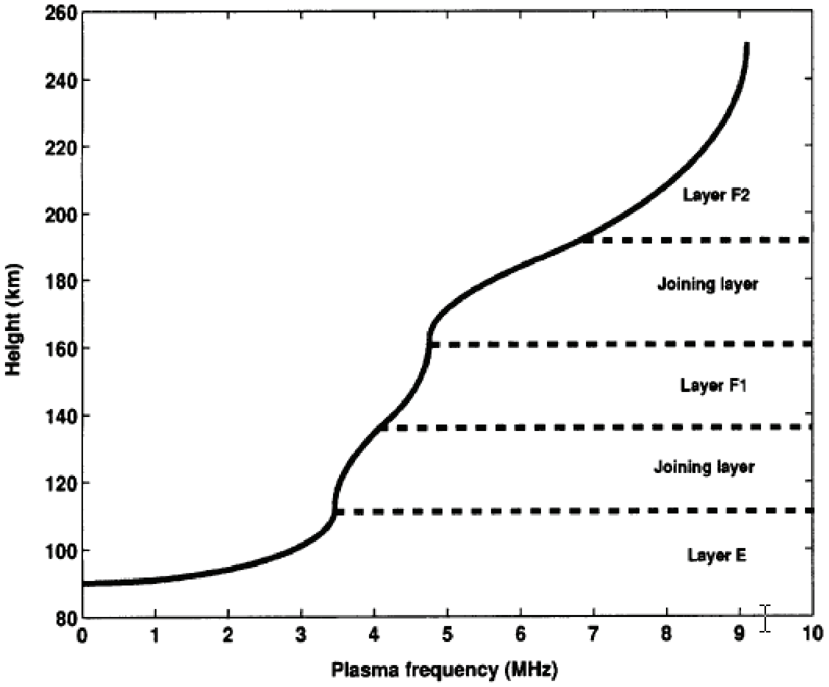

Figure 4.4. Scheme of the "Multi Quasi-Parabolic Ionospheric Model" (MQPIM) [26].

Fig. 4.4 shows the trend of the *Plasma Frequency* (parameter directly related to the *Refractive Index*) as a function of the altitude and provides the consequent division of the curve in parabolic segments.
The squared value of the Plasma-Frequency is therefore expressed by the formula:

$$f_p^2(r) = \sum_{i=1}^{L}({f_{c_i}}^2[1 \pm (\frac{r - r_{r_i}}{t_i})^2 (\frac{r_{b_i}}{r})^2]$$

where:

- L: number of Ionospheric layers;
- $r = r_0 + h$: elevation or height [km];
- r_0 is the average radius of Earth $\simeq 6374$ km;
- $t_i = h_{r_i} - h_{b_i} = r_{m_i} - r_{b_i}$ is the thickness of the i-layer [km].

Note that the operative HF frequency f, the Plasma-Frequency f_p and the refraction index n are connected by the formula:

$$n^2(r) = 1 - \frac{{f_p}^2(r)}{f^2} = 1 - \frac{81N(r)}{f^2}$$

where $N(r)$ represents the electron density at the height r.
Hence it is sufficient to fix the operative working frequency and the pointing elevation-angle of the HF Ionospheric radar (or, more generally, of the Ionospheric sensor) and then build, in respect of the adopted MQPIM, the equation of propagation in range of the signal [62, 26, 27].

An alternative formulation of the MQPIM's equation is that provided in 1979 by by R. Hill (page 885 of "Radio Science 14") who describes each of the three Parabolic "Normal" Layer with the formula:

$$N = N_m \cdot [1 - \frac{(r - r_m)^2}{{y_m}^2} \cdot \frac{{r_b}^2}{r^2}] = A + \frac{B}{r} + \frac{C}{r^2}$$

where:

- N is the electron density;
- r is the Geo-centric distance;
- r_m represents the value of r at the upper boundary of the layer (Maximum ionization height);
- N_m similarly represents the value of N at the upper boundary of the layer (Maximum ionization value);
- r_b is the minimum value of r ("bottom-side" of the layer);
- y_m is the half-thickness of the Ionospheric layer.

To these three parables are then added two parabolas with reversed concavity that guarantee the continuity of the curve.

A direct evolution of the MQPIM is the "Quasicubic-Segmented Ionospheric Model" proposed in [66], where the parabolic approximation is replaced by a cubic one and the square of the plasma frequency is given by the equation:

$$f_N^2 = \frac{A}{r^3} + \frac{B}{r^2} + \frac{C}{r} + D$$

In [61] the author proposes an interesting numerical method to obtain Quasi-Parabolic layer parameters from several Ionograms, while in [67] a different author illustrates the evaluation of oblique Ray-Path Parameters for a Quasi-Parabolic Ionospheric Layer.

4.5 Prediction and Estimate of Ionospheric Parameters

Due to continuous variations of the Ionosphere related to the season, the time, the Sun activity and its disturbances (that trigger a series of phenomena which influence the ionospheric propagation), it is essential that the algorithms for calculating the actual path of the electromagnetic waves for the employed frequencies are based on real-time data. Furthermore, if we wish to model the Ionosphere above a wide area as the Mediterranean sea, it is necessary to employ a large network of ionosondes capable of providing automatic interpretation of the measured data and, ultimately, produce a vertical electron density profile, after automatically reverse the generated ionogram. There are also different techniques based on the tomographic reconstruction of the Ionospheric with satellite data, but they seem to be not well established yet.

The electron density profile is calculated from measurements of vertical ionospheric soundings by means of small HF radars called “VIS” (Vertical Incidence Ionosondes). This measurement is performed with the usual radar techniques performing a frequency scan in the range $2 - 20$ MHz. The output generated from the VIS after this procedure is the Ionogram, that is a graph showing the group delay timing as a function of the frequency. Hence a dedicated code is necessary for both the automatic interpretation of the parameters that characterize the Ionosphere, and for the inversion techniques employed to estimate the true reflection height from the group delays. In order to provide the data to a 3D Ionospheric model on a real-time basis the procedure must be fully automated.

In order to obtain a complete characterization of the path followed by the HF OTHR-SW signal and its relative echo, we must know, with the maximum available resolution, the electron density profile above the geographic area interested by the considered ray-path. This can be done employing a real-time 3D Ionospheric model based on statistical data and periodically updated with real time data from a fixed network of ionosondes. Therefore what it is required is the development of a technique of reconstruction of the Ionospheric electron density via the employment of an adaptive 3D model and of real measurements gathered by the ionosonde network. Within the context of the “LOTHAR” project (that considers an OTHR-SW sensor operating above the Mediterranean area), in order to reconstract a 3D model of the Ionosphere above the latitudes of the ray-path, it was sufficient to update the statistical ionospheric model with data from three existing Ionosondes located in:

- *Rome*: c/o National Institute of Geophysics and Volcanology (INGV);
- *Gibilmanna (Sicily)*: c/o the INGV’s observatory;

– *Athens*: c/o the National Observatory of Athens.

By itself the 3D Ionospheric Model is not sufficient to estimate the trajectory of the HF signal from the radar site to the radar footprint. In fact, in order to accomplish this task it is necessary to employ also a raytracing procedure.
The raytracing technique is used to determine with a good approximation the actual path taken by the radio waves in a complex medium as the "Ionospheric Collisional Magneto-Plasma". The raytracing algorithm must necessarily take into account the horizontal and vertical gradients of the electron density for the various layers considered by the employed stratified ionospheric model and it must also account for the correcting factors due to the Earth's magnetic field. Note that, while the first parameters are time-variant, the latter is static and depends only upon the geographical location of the radar and of its surveillance area.

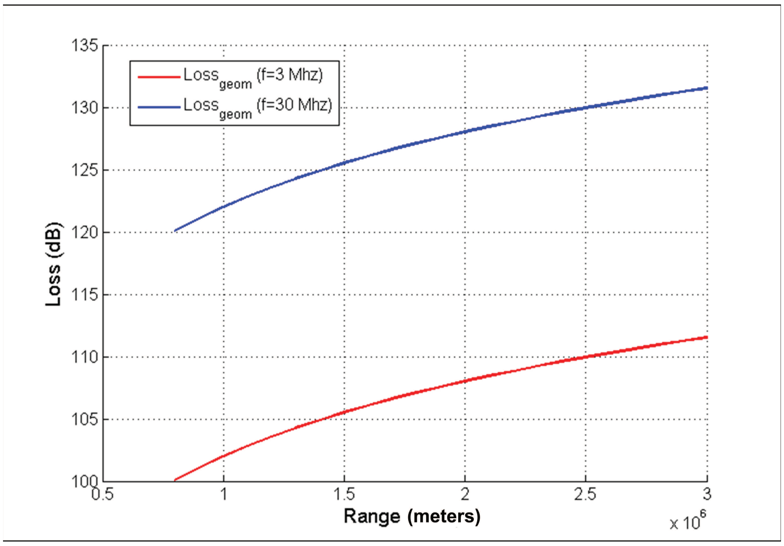

Figure 4.5. *Geometric losses of HF signals in function of range distance for the two frequencies that limit HF band.*

4.6 Raytracing

The *"Raytracing"* is the focal point of many CR techniques and it is the identification of the most likely paths taken by the signal in its travel there and back from radar to target. The raytracing can be performed in a two-dimensional (limited to single cross-track plane) or in a three-dimensional (range-azimuth-elevation) way, depending on the amount of calculations that the system is able to manage within the limited time imposed by the real-time mode.

In order to define a raytracing procedure we need to start by assuming a given model for the vertical structure of the Ionosphere. Several of these models are available in literature, for instance:

- *Multi Quasi-Parabolic Ionospheric Model* (sec. 4.4);
- *Triple Chapman Layer Ionospheric Model* [45];
- *Quasi-Cubic-Segmented Ionospheric Model* [66];
- etc.

For the chosen model we need then to extrapolate a correct form of the signal-propagation equation. The first hypothesis to be made is related to the *multi-path* and in particular the number of reflections that the radar echo undergoes before returning to the radar. In the simplest case it is assumed that the echo produced by *path*2, *path*3, etc. is too attenuated to be considered and we consider only the geometry of *path*1 [2] (see Fig. 4.6). The picture also shows how the *multipath* phenomena in a multiple target scenario introduces uncertainty in the association of the received echo to the correct target. Nevertheless, clearly the return from the most remote targets reaches very attenuated the radar and moreover, since the revelation occurs in the range-Doppler domain, different targets can be discriminated by a different radial speed). Secondly we must consider the possible paths of the signal in the radar-target-radar journey with respect to the different interaction modes between the HF EM wave and the Ionosphere.

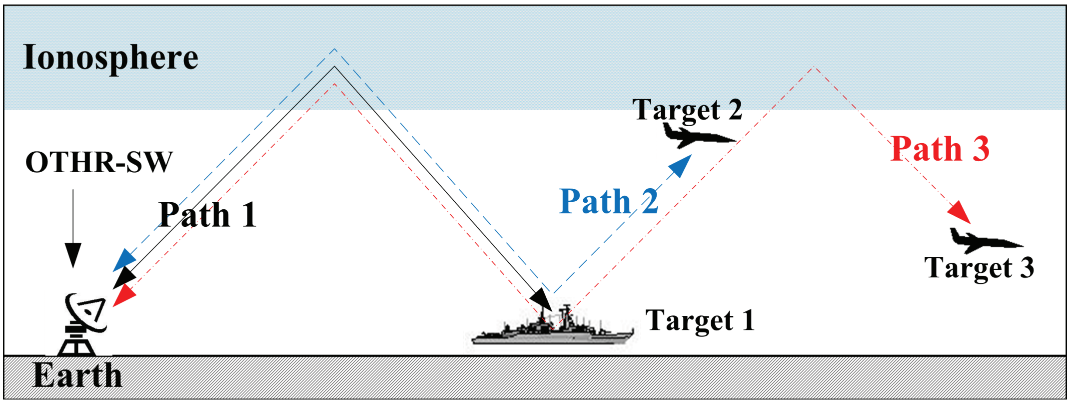

Figure 4.6. *Scheme of multiple paths of the HF signals in OTHR-SW applications.*

The typical representation of the Ionosphere (adopted in most models) includes several concentric shells (*layers* or *regions*) which are distinguished by different sign and median value of the gradient of the electron density (see sec. 4.1 and 4.4). Referring, for example, to MQPIM described in 4.4 the possible *propagation*

---

[2] The employed model adopts this hypothesis, however justified by the high geometric attenuation of the signal for the multi-hop paths.

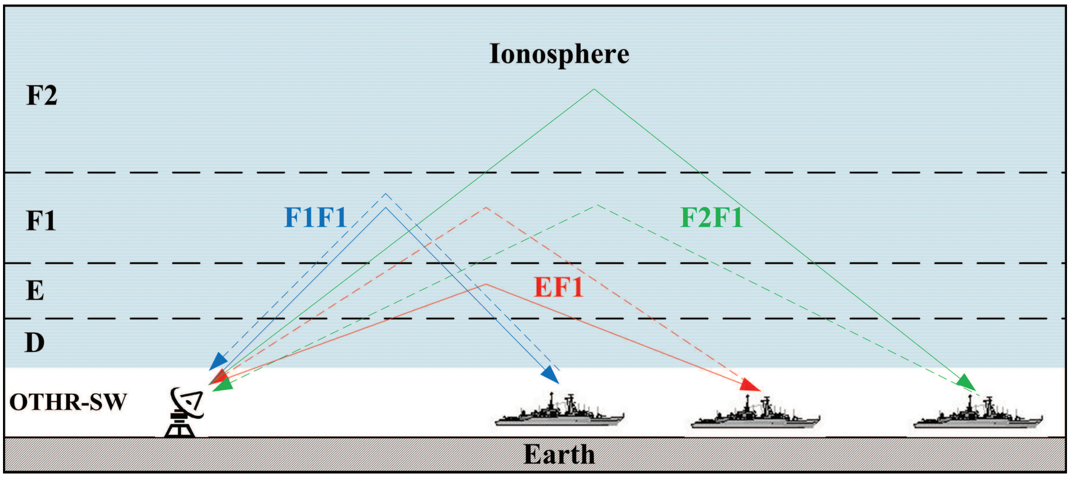

Figure 4.7. *Possible propagation modes in a simulated OTHR-SW scenario.*

modes of the electromagnetic wave are nine: EE, EF1, EF2, F1F1, F1F2, etc. Generally we consider only the most reasonable modes, namely those characterized by the highest energy return, and for each of them we perform the actual ray-tracing procedure.

In Figure 4.6 some of the possible propagation modes for the transmitted signal are represented. Heterogeneity and temporal variability of the Ionosphere are responsible to those multiple propagation modes. An optimal raytracing procedure decompose the received echo in the contributions from different paths. However the adopted raytracing algorithm assumes that the transmitted signal and the relative received echo follow the same path, thus assuming only modes EE, $F1F1$ or $F2F2$ to be possible. Fig. 4.8 shows the graphic result of a raytracing program, where the presence of multiple modes and different paths is evident and obviously dependent on the layered Ionospheric structure and on the frequency and take-off angle of the HF transmitted signal.

Regardless of the adopted algorithm, any raytracing procedure is affected by the static nature of the employed Ionospheric model. Hence, in order to maximize its efficiency, it is appropriate to periodically update the model of the Ionosphere with real-time measurements, so as to continuously adapt the value of its parameters to the changes of the medium.

Therefore it is clear that the raytracing itself does not represent a comprehensive solution to the Geo-referencing problem, but outlines a procedure to be applied in parallel to any other method that allows to characterize the Ionosphere in real-time [62, 78, 45, 65].

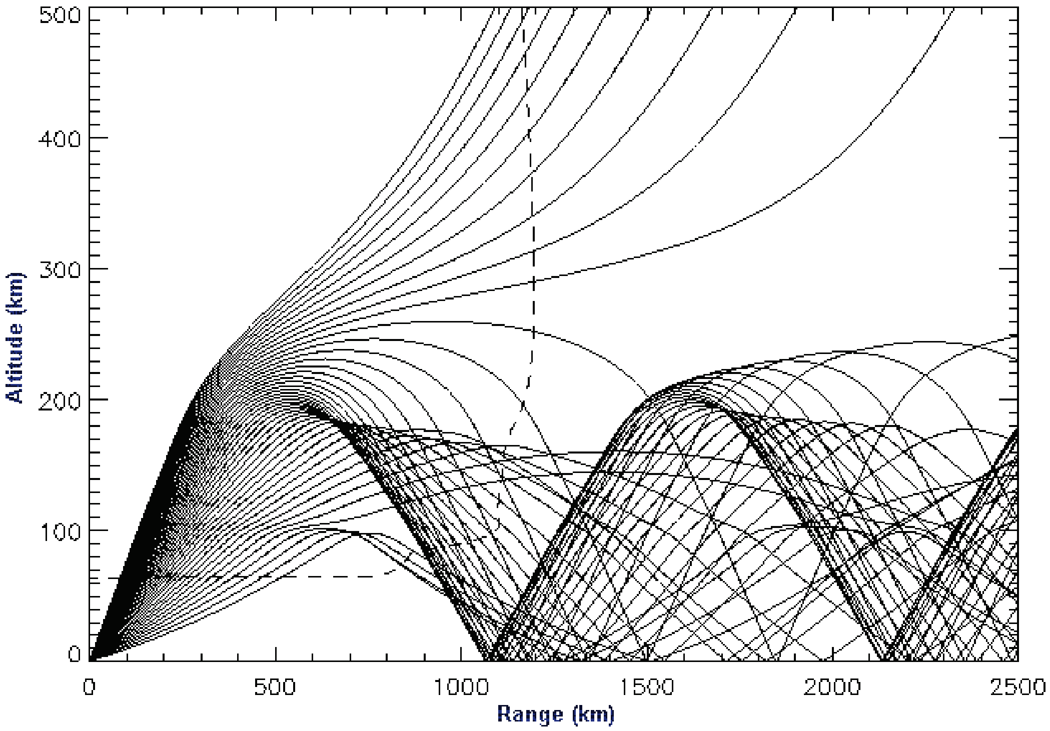

Figure 4.8. *Multi-mode propagation paths generated with a raytracing software.*

4.7 Considerations

In respect of what has been said so far, we can assert that it is possible to determine the values of the main ionospheric and geometric parameters necessary to estimate the path of HF signals transmitted by a monostaic and pulsed OTHR-SW system over the Mediterranean area in a *"Quite Ionosphere"* condition (that is whenever the short-time and rare Ionospheric Disturbances, presented here in respect of their spatial and temporal scales, are not experienced). We pointed out the need for a raytracing procedure based on a chosen stratified model of the Ionosphere above the area interested by the OTHR-SW sensor. This 3D Ionospheric model is built employing both statistical data and real-time information gathered by ionosondes or different HF radars. Table 4.2 resumes the meaning and the range of the most significant parameters to model the Ionospheric Propagation Channel above the Mediterranean area.

Parameter	**Symbol**	**Min.Value**	**Max.Value**
Maximum Usable Frequency	$MUF_{50\%}$	3 MHz	30 MHz
Equivalent Oblique Reflection Height	h_{eq}	100 km	500 km
Take-off Angle	β	5°	53°
Azimuthal Angle	α	0°	360°
Ground-range Distance	D	600 km	3000 km
Geometric Attenuation (one-way)	L_g	100 dB	130 dB
Ionospheric Attenuation (one-way)	L_i	1 dB	20 dB
Ionospheric Coherence Time	T_c	23 s	100 s
Frequency Shift from Ionospheric Doppler	Δf	0 Hz	4 Hz

Table 4.2. Range Values for the main Ionospheric and Geometric Parameters