Chapter 8

Ionospheric Probing

8.1 Introduction

Knowledge of the ionospheric status is fundamental for a wide range of civil and military applications that employ this medium as part of the transmission channel (e.g. HF communications, OTHR-SW sensors, satellite positioning, navigation systems, etc.). Typically, such applications make use of seasonal (or climatological) ionospheric models that unfortunately account only for the long-term variations, sometimes periodically updated with real-time data gathered by ionosondes that are able to account for short-term ionospheric phenomena. This approach is mainly limited by the need of considering a wide geographic area, while relying on a small ionosonde network.

Besides its employment for the CR procedure, the SLTI method can be profitably applied in OTHR-SW applications for a periodically update of the Distributed Ionospheric Model with real-time ionospheric data. As for the correction of the radar footprint position, the basic principle of the method is represented by two factors:

- the knowledge of the coastline profiles within the coverage area of the OTHR-SW;
- the ability to identify a sea/land transition in the received OYHR-SW echo.

In fact, by estimating the correct position of the radar footprint related to the received echo, it is possible to evaluate a feedback for the correction of the parameters that characterize the employed Ionospheric model. In the following, without loss of generality, we assume to employ the SLTI algorithm together with the Simplified Ionospheric Regional Mapping (SIRM) model introduced by the Italian National Institute of Geophysics and Volcanology (INGV) [16].

After having introduced the ionospheric modelling problem, we provide an overview of the OTHR-SW simulated scenario, with particular reference to the models developed for the three fundamental scenario's elements: Radar System, Ionospheric Channel and Surface Clutter. A brief description follows of the CR method proposed in the previous chapter and of its evolution for the estimate of ionospheric parameters. Finally some considerations on the method, its application and possible developments are made.

8.2 Adopted Ionospheric model

According to the recommendation ITU-R P.1239-2 [3] and the long-term model provided by the International Reference Ionosphere (IRI-2000) [2, 28] and in respect of the parametrization and updating criteria introduced by the Simplified Ionospheric Regional Model Updating (SIRMUP) [15, 44], we identify in f0F2 (Peak Critical frequency for the F-region) and MUF(3000)F2 (Maximum Usable Frequency for a 3000 km single hop refraction of the F2-layer) the parameters to realize a large area ionospheric model. Such a model is basically structured as the SIRM, i.e. with a geographical grid of [f0F2, M3000F2] couples. M3000F2 is related to MUF300F2 by equation:

$$M3000F2 = MUF3000F2/f0F2$$

The upgrade of the SIRM in the SIRMUP consist mainly in the possibility to update the distributed model with real time ionospheric data locally gathered by Vertical Incidence Ionosonde (VIS) and applied to the whole model through a weight-function. The OTHR-SW interacts with ionosphere in an oblique ("ob") way, hence the conversion given by the following formulas:

$$\begin{cases} h_{ob} = h_v \\ f_{ob} = f_v / \cos\alpha \end{cases}$$

is needed to compare the ionospheric data with that gathered by VIS ("v"). Note that in the previous equation the following parameters are used:

- h represents the equivalent ionospheric reflection height;
- f is the operating HF frequency;
- α is the ionospheric incidence angle.

The maximum electron density of the F2 layer (*NmF2*) and the height corresponding to it (*hmF2*) are then related to the index *M3000F2* and the frequency *f0F2* by the formulas of Shimazaki and Bilitza et al. [2].

$$hmF2 = \frac{1490}{M3000F2+DM} - 176$$

$$DM = \frac{f_1 f_2}{f_0F2/f_0E - f_3} + f_4$$

$$N_mF2 = 1.24 \cdot 10^{10}(f_0F2)^2$$

$$\begin{cases} f_1 = 0.0032 \cdot R12 + 0.222 \\ f_2 = 1 - R12/150 \cdot exp[-(\psi/40)^2] \\ f_3 = 1.2 - 0.0116 \cdot exp(R12/41.84) \\ f_4 = 0.096 \cdot (R12 - 25)/150 \end{cases}$$

where:

- f_0E is the peak plasma frequency for the E ionospheric layer;
- $R12$ is the 12-month-running mean of Smoothed Sunspot Number (SSN);
- ψ is the magnetic dip latitude.

8.3 Simulated scenario for Ionospheric probing

As for the CR procedure (described in chapter 7) via the application of the SLTI algorithm (chapter 6), the overall simulated scenario consists in three main models: radar system, Ionospheric Channel and Surface Clutter (fig. 7.1).
The radar system consist in a monostatic OTHR-SW that transmits a vertically polarized unmodulated pulse of length τ, with a take-off angle β, an operative azimuth θ and beam span angles $\delta\beta$ (elevation), $\delta\theta$ (azimuth). The Earth magnetic field effects on ray propagation are neglected, although, being time-independent, once the radar site is established, they can be taken into account by only introducing a multiplicative coefficient [36, 35, 38].

As we described in chapter 3 the system noise for an OTHR-SW system is predominantly external and it can be divided into three main components: atmospheric, cosmic and anthropic. In the presented simulation we represent the overall noise as an additive Gaussian process with assigned mean value dependent on the nature of radar site. Its assumed the availability of a stable single-hop ionospheric path (hypotheses that appear to be correct at European's latitudes) [28, 5] with mirror ray reflection, identical for transmitted signal and received echo. The ionospheric electron density profile over the operating area is supposed

to be constant during the whole radar sweep. The surface Sea-Land clutter is modelled by a Gaussian space-time process, with given values of decorrelation distance and decorrelation time. Different values of backscattering coefficients σS and σL are assigned respectively to sea and land areas. The radar footprint is geometrically approximated with an ellipse, while we suppose that the clutter area is limited in range by the radar pulse length projection on the Earth surface (not from the footprint range extent). A more specific characterization of the adopted clutter model is given in [37].
Therefore, ultimately, the assumptions made for the demonstration of the ionospheric probing via OTHR-SW through the employment of the SLTI method are entirely analogous to those taken into account in the previous chapter where the SLTI is used for Geo-referencing the radar footprint.

8.4 Ionospheric probing with the SLTI method

As we deeply described in the previous chapters, the SLTI method takes advantage of the *a priori* knowledge of the displacement of the Sea/Land transitions within the radar coverage area, that is of the Geo-morphological structure of the surveillance area, employing it to build a binary mask to be used as a geographic reference for the received radar echo. The Geo-referencing algorithm is based on the maximization of the cross-correlation between the received radar echo and the binary clutter signatures. The basic idea is to find the best match between the echo received by the OTHR-SW after the transmission of a single sweep and the clutter signatures of the working area and associate it to the actual radar footprint position. A direct range-azimuth correction is hence applied to the process, Geo-referencing the radar data. The method runs in real time (with reduced computational cost) while the OTHR-SW system normally operates, whenever at least one sea/land transitions (or, eventually, a different, but known, Geo-referencing points) is present on the radar scanning azimuthal direction. In this chapter we consider, the employment of the SLTI method to estimate actual ionospheric parameters in real-time, over the OTHR-SW operational area.

The considered OTHR-SW system makes use of a raytracing algorithm [6] based on the IRI model [2]. In case of lack of real-time ionospheric data it employs a climatological model based on monthly median values of $f0F2$, $M3000F2$ and other ionospheric parameters. By running the SLTI procedure every time a reference target (e.g. a coastline profile) is within the radar footprint we are able to correct the estimated position of the radar footprint and consequently to adjust the raytracing calculation that provided the estimated position. Actually the raytracing procedure remains unchanged whereas we introduce a feedback loop to adjust the characteristic parameters of the ionospheric model to which the raytracing procedure refers to. The updated ("corrected") Ionospheric model

is hence employed in the next application of the raytracing algorithm. This way a model based only on statistical data can be continuously updated with real time information while the OTHR-SW continues to perform its main surveillance task.
In other terms, by estimating the range error in the OTHR-SW footprint position, through the identification of a geographically known reference feature, we can identify the actual $[f0F2, M(3000)F2]$ couple that characterizes the electron density profile in the specific operating area. Then, such a correction is applied to the distributed Ionospheric model by employing the SIRMUP updating technique described by Zolesi et al. [15, 44], exactly as the Ionospheric data were gathered via a VIS device rather than via the OTHR-SW.

8.5 Ionospheric Probing: Simulation Setup

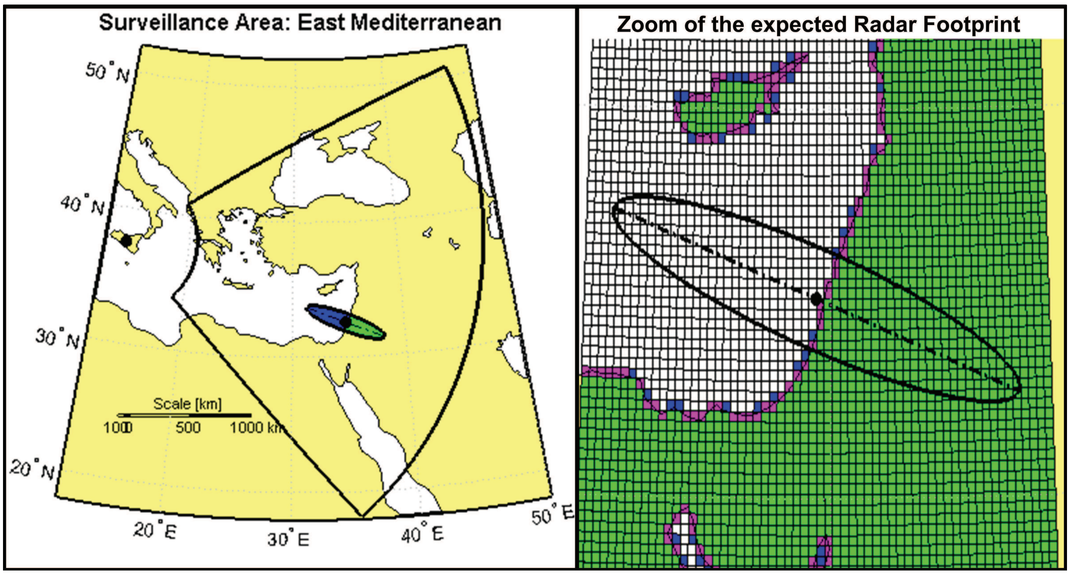

Figure 8.1. Top view of the surveillance area and zoom of the expected radar footprint (after the evaluation of the clutter contribution) for the simulation proposed in section 8.5.

We assume to employ the same parameters values adopted for the CR simulation and listed in section 7.2, introducing only the following changes:

– Pointing Direction in Elevation (aka “take-off angle”): $\beta = 18°$;

– Radar Beam: $\delta\phi = 4°$, $\delta\beta = 6°$;

– Equivalent Ionospheric Reflection Height: variable within the radar beam according to the selected electron density profile (averaging the results of the raytracing algorithm we obtain a mean value $h_{eq} = 310$ km);

– Difference between Sea and Land Backscattering Coefficients: $\Delta\sigma = \sigma_{0S} - \sigma_{0L} = 15dB$.

Using these data we can draw the scheme of the Surveillance Area with the relative "expected" radar footprint. In fact, as explained in the following, the evolved model of the OTHR-SW scenario considers a different interaction with the Ionosphere for each surface element of the radar footprint, according with the relative incidence angle (the frequency is assumed to be constant, neglecting any possible Doppler shift respect the frequency of the carrier in Tx). In other words the radar beam is segmented in a given number of sectors in its elevation-plane. Each of these portions of the radar beam is characterized by its central elevation angle that determines the interaction of the relative contribution with the Ionosphere.
Hence, as we just mentioned, the Ionosphere is not considered any more a specular reflector for the given radar beam, but it is represented by a certain electron density profile that is assumed to be constant during the simulation. Such a

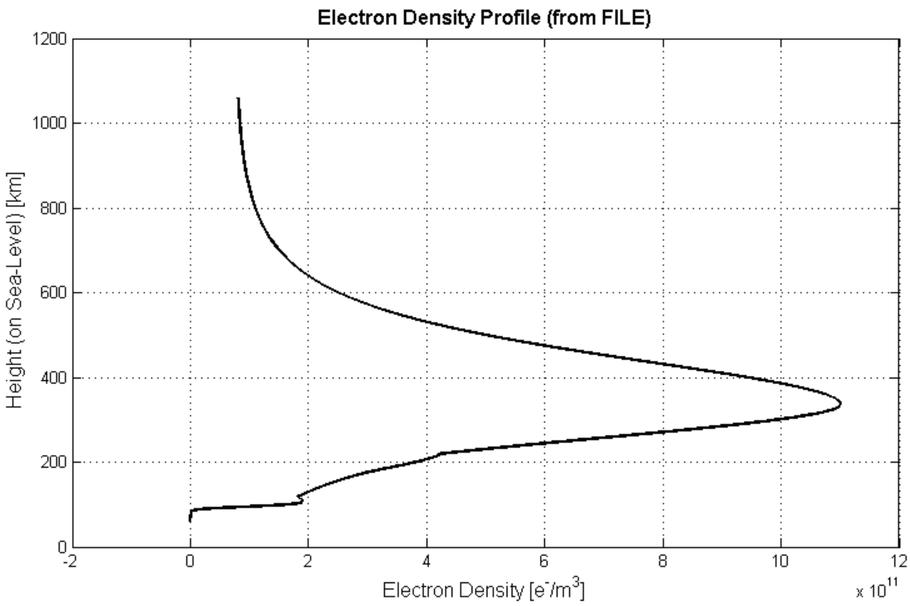

Figure 8.2. Electron Density Profile extracted from the IRI database for the simulation proposed in section 8.5.

profile is extracted from the IRI database assuming the following configuration of the input parameters:

- Month: *June*;
- Local Time: $12am$;
- SSN: 144.

The relative electron density profile is represented in fig. 8.2. The value $h_{eq} = 310$ km indicated in the previous list is not a simulation parameter imposed by the user, but it has been evaluated (by applying the raytracing procedure) according to this given e^- density profile and it has been employed to evaluate the range position of the expected radar footprint. Fig. 8.3 shows an instantaneous realization of the clutter process simulated for the selected area. On the top of the picture it is proposed the top-view of the "clutter area" (that is the area where the expected footprint is located) with position and dimensions of the expected radar footprint. On the side the main parameters of the simulation are resumed. Note that, since some parameter has been modified respect to the simulation proposed in the previous chapter, the dimension and position of the expected radar footprint results relatively different from that of fig. 7.7. At the bottom of the picture the 3d view of the instantaneous realization of clutter is shown.

8.6 Ionospheric Probing: Simulation Results

The set of assumptions described in the previous section is employed to evaluate the simulated radar return. The intent of the simulation is to demonstrate how the SLTI procedure can be used to evaluate the actual ionospheric condition in the area interested by the radar beam. In order to accomplish that, without introducing any further complication in the already complex model, we extract from the IRI database a set of N electron density profiles and we evaluate (with a coarse resolution) the relative N radar returns. Than we run N correlation between the simulated echo and the N rough references, trying to evaluate the best match. In this case the best match would correspond to the estimated electron density profile. Note that the evaluation of these rough reference can be carried out *a priori*, once the radar parameters have been set and the clutter contribution of each cell within the surveillance area has been estimated. Hence we can imagine to populate a database for every pointing direction and every Ionospheric condition to be used as reference to compare the received echo.
In the presented simulation, without a generality loss, we assume to extract a set of electron density profiles from IRI by changing the value of SSN and keeping the same value for the month and the local time. In figure 8.4 are shown:

- Top-side: the e^- density profile extracted from IRI assuming $SSN = 144$ (left-side) with the relative received echo reconstructed according to the Time Of Arrival (TOA) of each surface-element contribution (right-side).

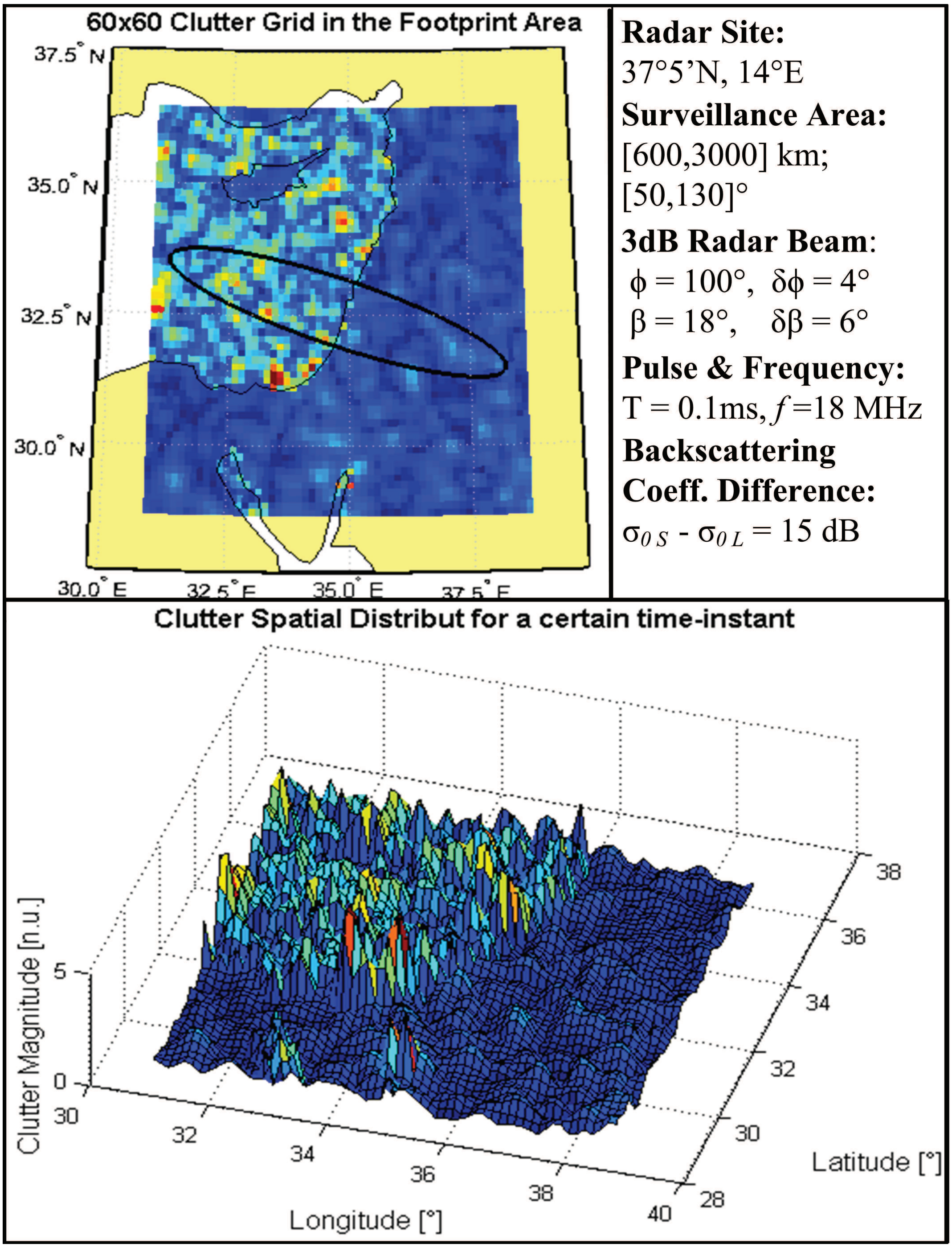

Figure 8.3. Simulated Clutter Model for the application of the SLTI method to a Ionospheric Probing test.

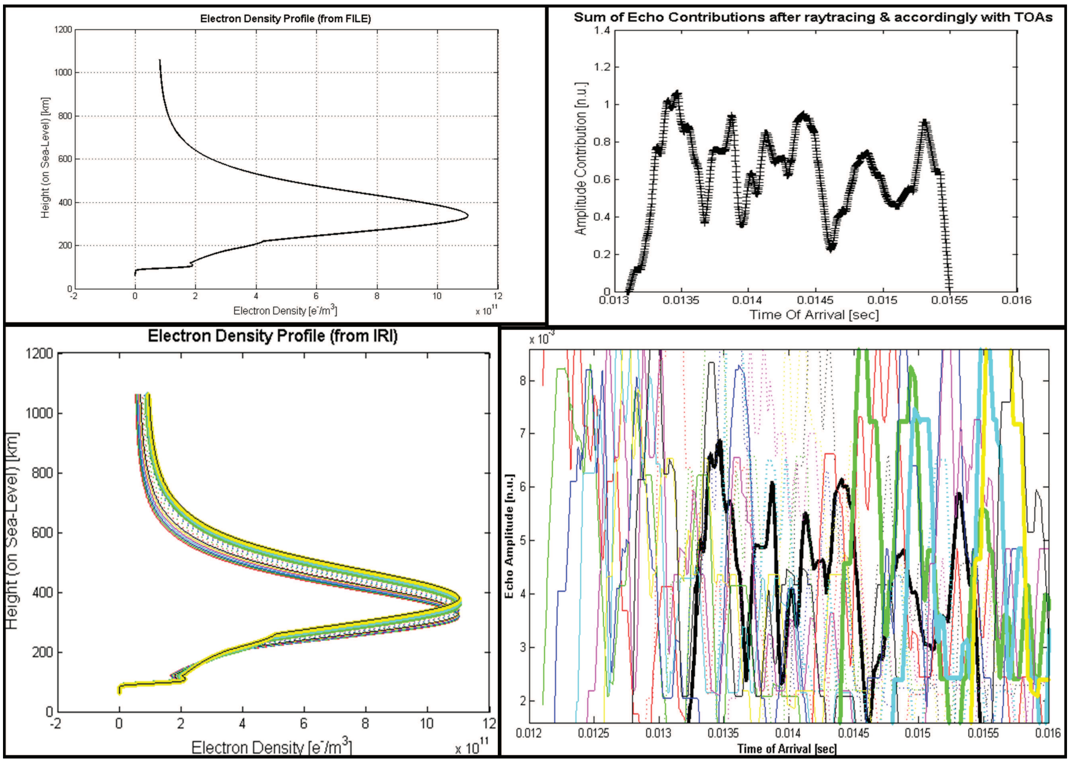

Figure 8.4. Chosen electron density profile and relative simulated echo (top); Set of electron density profiles extracted from IRI and relative rough returns.

– Bottom-side: the set of e^- density profile extracted from IRI assuming SSN equal to 21 values equally spaced between 100 and 200 (left-side) and the relative reference rough returns evaluated with the same principle, after the application of the raytracing (right-side).

Figure 8.5 shows the curves of the equivalent ionospheric reflection height H_{eq} vs the take-off angle β relatively to each considered electron density profile. Note that, according with the parameters set in the previous section, the elevation angle on the x-axis ranges from $\beta + \delta\beta/2$ to $\beta - \delta\beta/2$. In fact the x-axis has been reversed to match with the TOA, since we always need to remember that in OTHR-SW applications lower values of β correspond to higher distances in range.

The right-bottom image of figure 8.4 shows the simulated echo overlapped to the 21 rough reference returns. The echo is the same as the one showed in the upper part of the same figure, but it has been resided to match with the time-scale employed for the x-axis. The multiple correlations between echo and references give the best result for the reference corresponding to a value of SSN equal to 145 (the echo was simulated according to the electron density profile relative to

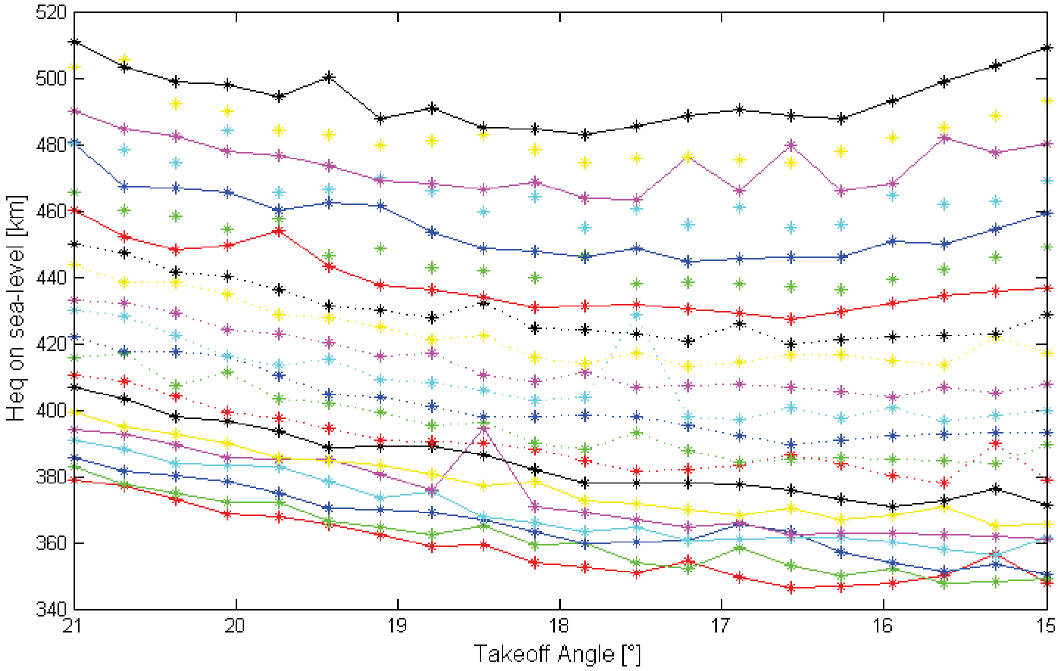

Figure 8.5. The 21 extracted electron density profiles and the relative curves of the equivalent ionospheric reflection height (H_{eq}) in function of the elevation angle evaluated by the raytracing algorithm.

$SSN = 144$), that is the value closest to the one of the selected electron density profile. This result, as the many similar results that we obtain, does not give any information about precision, resolution and reliability of the proposed method for Ionospheric probing purposes, but it certainly confirms its feasibility.

8.7 Considerations

In this chapter we introduced the application of the SLTI method for the real-time estimate of Ionospheric parameters via a pulsed and monostatic OTHR-SW system. By employing the SLTI procedure, together with an appropriate ionospheric model (here we referred to the SIRM model) and a raytracing algorithm it is possible to transform the radar in a real-time, wide-area, Ionospheric sensor. The SLTI algorithm links the received echo to the relative position of the radar footprint, providing the information necessary to correctly model the signals path. Since the geometry of this path depends on the electron density of the Ionosphere in the region interested by the radar beam, an indirect estimate of the actual e^- density profile can be accomplished after the application of the SLTI procedure.

The idea to employ an OTHR-SW as a ionospheric sensor is not new (see section 5.6 and [75]). In fact this system, as a matter of fact, works in the same band of Ionosonde and interact with the Ionosphere in an analogous way, but on a very large scale. What it is different in the proposed approach is the possibility to perform Ionospheric soundings without removing the radar from its surveillance primary mission. The method to apply local Ionospheric information to a geographically distributed Ionospheric model are described in [28, 15, 44] that shows how to update a distributed Ionospheric model (the SIRM) with real-time data from Ionosondes (hence transforming it into the SIRM-UP). Note that in the simulation proposed in this chapter, for sake of simplicity, only the SSN was changed for the generation of the various reference returns, but this simple assumption does not mean that the SLTI method cannot be employed for the estimation of different Ionospheric parameters.