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FREQUENCY MANAGEMENT IN HF-OTH SKYWAVE RADAR: IONOSPHERIC PROPAGATION CHANNEL REPRESENTATION

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Abstract—In High-Frequency (HF) Over The Horizon (OTH) radar, the space-time variations of the ionospheric channel, the external noise level (environment and man-made) as well as the transmission channel bandwidth limitations, are among the most critical and challenging aspects for the design and the operational management. Specifically, the knowledge of the ionosphere behaviour in a real time configuration is of primary importance because of the way it influences the frequency selection. This implies that a HF radar must have a high level of adaptability in order to deal with external constraints. For this purpose, a suitable frequency management system is needed. In this paper, a representation of the ionosphere propagation channel from a radar point of view is provided. Specifically, radio-electric parameters of the radar link are revisited by extending the concept of Maximum Usable Frequency (MUF), which is typically used in the communication field. The Ionospheric Propagation Chart (IPC) and Maximum Transmitted Frequency (MTF) are also introduced as new concepts. The present work is supported by simulation results.

1. INTRODUCTION

OTH radar operates at HF band (3 MHz–30 MHz) and can be divided in two categories according to the used propagation channel, namely skywave, (such as NOSTRADAMUS [1, 2], JORN [3, 4], and ROTHR [5]), or surface wave, (such as SECAR [6] and WERA [7, 8]).

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Specifically, OTH skywave radars [9] allow for the surveillance of very wide areas, which range from about 500–600 km up to 3000–3500 km, thanks to the ionosphere reflection. The transmitted signal is reflected by the ionospheric layers and hits targets that are located over the horizon. The same path is then followed by the target echo which travels back to the radar. To understand the benefits and the issues related to the design of HF-OTH skywave radars it is important to recall the main differences with respect to classical microwave radars [9]:

- Transmitted frequencies must belong to the HF band ranging from 3 MHz to 30 MHz in order to exploit the ionospheric propagation channel;
- Long range radar coverage is allowed for up to 4000 km, corresponding to a zero antenna elevation angle;
- A blind coverage distance of about 400–600 km exists. When the e.m. wave hits the ionosphere with an incidence angle greater than a critical value, the transmitted signal is not reflected back towards the earth;
- The propagation channel is space-time variable. The propagation behaviour is dependent on the transmitted frequency, date, solar activity (identified by the Sun Spot Number — SSN), the radar geographical coordinates and the magnetic activity. As a matter of fact, the Earth's ionosphere can change considerably due to the interaction of the interplanetary medium, the Earth's magnetosphere and ionosphere;
- In the HF band, radar performances are heavily affected by the background noise, which is mainly due to atmospheric, cosmic and man-made noise [10]. Internal noise produced by thermal effects is almost negligible;
- Heavy propagation losses due to very long travelling distances as well as strong absorption losses caused by ionospheric dispersions must be dealt with. The whole loss contribution may reach values of up to 100–150 dB;
- The HF spectrum is heavily crowded by communications and broadcasting transmissions, which often restrict the bandwidth available for radar operations. Therefore, free channels are limited and often available only for a limited time;
- The antenna system requirements are particularly demanding because of the wide operational frequency band (i.e., 3–30 MHz);
- High values of transmitted power are required to balance out the strong losses;

- Target radar cross section (RCS) values at HF can be significantly different from those measured at microwave regions;
- The range resolution cell extent depends on the range.

Therefore, it is evident that a HF radar must be an adaptive system where both the transmitted waveform, antenna system as well as the signal processing, must adapt to the space-time changing environment. Dedicated sub-systems are needed in order to collect environmental information.

2. PROPAGATION MODELS

A basic understanding of the ionosphere is paramount in order to understand the HF radio wave propagation; therefore an overview of the most important ionospheric mechanisms is necessary. Because of the fact that the ionosphere's physics is an extremely extensive and complex topic, this chapter makes a simplified dissertation of it.

The ionosphere had been defined as a part of the upper atmosphere which stretches from 50 km to about 600 km. It is a broad layer of ionized gas, called plasma. The plasma consists of charged particles (electrons and ions) which are the result of the ionization of neutral atmospheric constituents. These particles are present in the amount required to influence the trajectory of the radio waves. Due to the nature of the ionosphere, it is especially sensitive to the solar activity, the variations in the geomagnetic field and the density and content of the atmosphere at different heights and latitude. For these reasons, the ionosphere occasionally becomes disturbed. These disturbances (e.g., magnetic storms, SID-Sudden Ionospheric Disturbance, TID-Travelling Ionospheric Disturbance) [11] can affect signal propagation. The most serious effects are the amplitude fluctuation (Fading) and phase shift of the received echo. These effects are strongly dependent on the solar energy that reaches the Earth's atmosphere, which exhibits significant variability both in space and time. Specifically, relevant spatial variations occur across mid-latitude, equatorial and polar regions whereas temporal variations occur diurnally, seasonally and over the 11-year solar cycle. Therefore, in order to predict the characteristics of a radio signal received from the ionosphere, such as its amplitude, polarisation, relative phase, time of flight and dispersive spread, it is necessary to know how the electron density variation influences the radio signal propagation from the transmitter to the receiver. Therefore, an ionosphere monitoring system is needed. The most important technique for ionospheric monitoring, makes use of a network of ionosondes which provides a measure of a number of ionospheric parameters for a discrete number of heights and frequencies. An ionospheric sounder is a very simple device that measures time delay and strength of the echo at various frequencies in the HF region by using basic radar techniques. From these data, the ionization density, and the maximum usable frequency (MUF) are determined and organized in an ionogram (graph displaying the virtual height as a function of the frequency for each layer). The MUF is defined as the highest frequency that guarantees signal propagation over an oblique ionospheric path. An example of an ionogram is shown in Figure 1. The asymptotes in the plot correspond to the critical frequency (maximum frequency value which can be reflected for normal incidence) of the ionospheric layers. Generally, the ionosphere is separated into three main layers, D, E and F, which differ from the electron density content. During the day, the upper-most F layer splits into two sub-layers (F1 and F2).

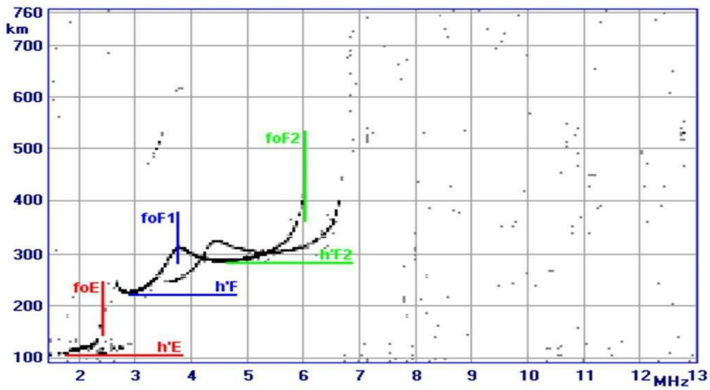

Figure 1. Example of ionogram [12].

Over the years, several models have been developed in order to extract information about the ionosphere from ionograms. Specifically, long term (SWILM [13], SIRM [14], PASHA [15] and IRI model [16]), short term (IFELMOR model [17]) and real time (SIRMUP [18], ISWILM [18]) models have been proposed. Among the long-term models, the most widely used is the IRI model, which provides a monthly averaged electron density profile, ionospheric temperature and ionospheric composition in the altitude range within 50 km and 2000 km. With these parameters, the position of the target can be estimated by using a ray-tracing technique [19, 20], whose main task is to predict (under certain conditions) the electromagnetic path.

In particular, the ray-tracing algorithm used in this work was previously implemented in a code by the authors [19]. The technique used to derive the ionospheric ray paths is based on the numerical integration of the Hamilton's equations solved in a three dimensional spherical polar reference system, as originally proposed by Haselgrove [21]. More specifically, the ray-tracing code used in this paper is based on the Haselgrove's equations and the subsequent equation solution proposed by Jones and Stephenson in [22], which has been chosen by the authors because of its higher computational efficiency.

3. IONOSPHERIC PROPAGATION CHARTS (IPC)

As explained in the previous section, ground range distance, elevation angle and frequency are variables involved in the ionospheric propagation issue and they are strongly interconnected. Therefore, to take full advantage of an OTH radar, the prediction of the usable frequency and respective antenna elevation angle values relative to the ionospheric conditions, becomes essential. In this work, a new method to predict the ionospheric propagation conditions from a radar point of view is proposed. The method is carried out through the following steps [23]:

- ***Ionospheric data collection by means of a network of ionosondes (step 1)***: during this phase a 3D electron density estimate of the ionospheric volume of interest must be carried out by means of ionospheric models or by means of a network of ionosondes (Figure 2). A further approach, proposed in [24], which jointly combines theoretical models and ionospheric measurements, could be used under the assumption of space-sparse ionospheric sounders;
- ***Ionospheric data management and radar parameters evaluation by means of a ray-tracing algorithm (step 2)***: once the radar site, date and sun activity (SSN) are defined, the ray-tracing algorithm is applied to the estimated ionosphere electron density (step 1), in order to estimate the radar parameters (i.e., group delay, ray-path, ground range distances R_{gr}, one way propagation and absorption losses, equivalent reflection height and ionosphere entering angle) prediction (Figure 2). Specifically, the reflected ground range distances (R_{gr}) are estimated for a fixed elevation angle by varying the frequency within 6-30 MHz (Figure 3);
- ***Radar parameters collection and display (IPC System) (step 3)***: step 2 is repeated for elevation angles that range between 6° and 55°, in order to form an Ionospheric Propagation

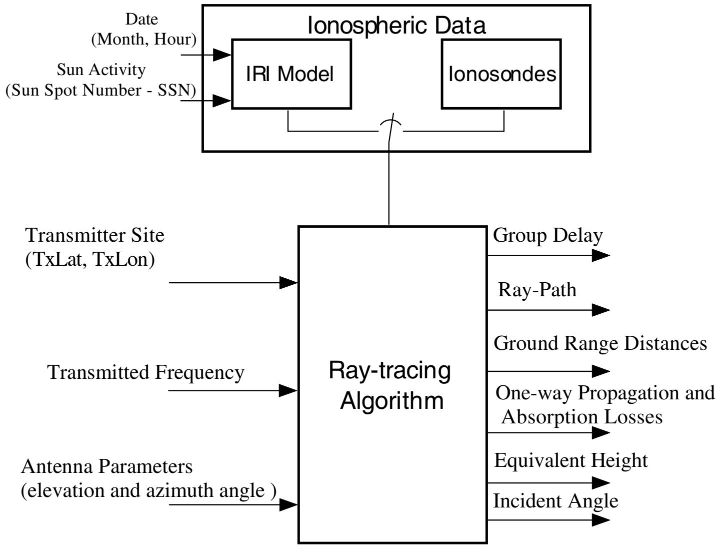

Figure 2. Functional block of ray-tracing algorithm.

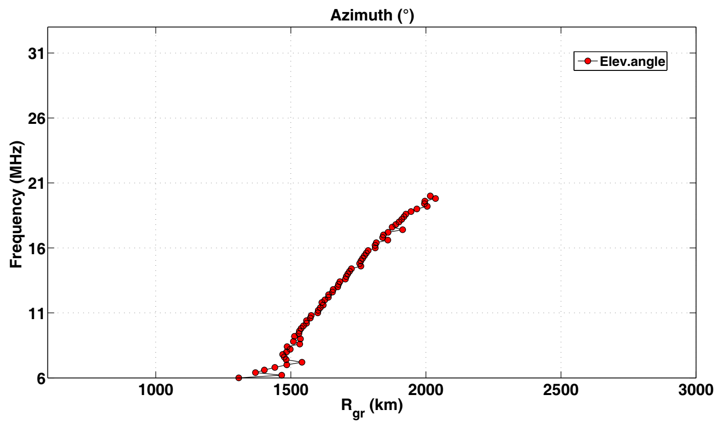

Figure 3. Theoretical example of a single elevation angle IPC in ground range.

Chart (Figure 4) for a given antenna azimuth angle and for a fixed solar activity. Therefore the IPC is created as a collection of curves that provide the ground range where the reflected e.m. ray path reaches the Earth's surface for any given frequency (f) and elevation angle (β).

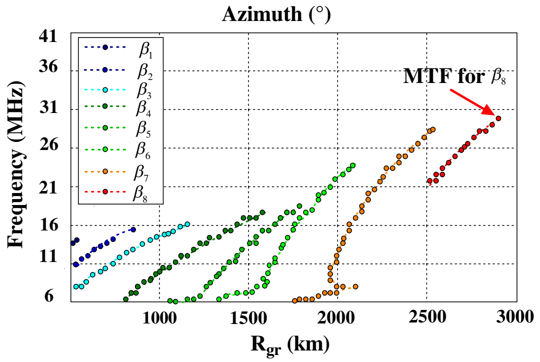

Figure 4. A theoretical example of IPC in ground range and MTF value for a given elevation angle.

Figure 4 shows an example of IPC. Each colour refers to a different elevation angle (β) and each coloured curve, named iso-elevation curve, is upper bounded by the MTF (Maximum Transmitted Frequency), which is defined as the frequency value 15% lower than the MUF. The idea of introducing the MTF concept arises from the observation that the MUF is strongly dependent on the solar activity and on the Earth's magnetic field. For instance, a geomagnetic field disturbance could lead to a temporary decrease in the ionospheric electron density, which consequently causes a sharp decrease in the maximum usable frequency. In addition, temporal variations in the MUF can produce skip fading [25]. This occurs when the transmitted signal is nearby the skip zone. Because of the existence of skip fading, target detection becomes ambiguous when the transmitted frequency is close to the MUF and the target is near the skip zone [26]. To sum up, the MTF concept arises from a conservative choice aiming at maximizing the probability of keeping the radar operational, taking also into account the possibility of experiencing ionospheric disturbances capable of temporary reducing the maximum usable frequency. The use of IPC from an operative point of view is not optimal because of the fact that it provides one frequency for every single ground range distance within the surveillance area (see Figure 4). Since the number of ground range distances could be theoretically infinite, the number of transmitted frequencies should be infinite too. In order to reduce the dimensionality of the problem, a method for selecting a single frequency able to cover a defined ground range interval is introduced in the next section which discusses the iso-MTF cell.

4. ISO-MTF CELLS

For a given azimuth angle (θ) and for a fixed ground range distance (R_{gr}), the iso-MTF cell is defined as the ground range interval (ΔR_{iso}) where the maximum MTF variation is less than 10% (1):

$$\Delta R_{iso}(R_{gr}) = \max_d\left(\frac{|MTF(R_{gr}) - MTF(R_{gr}+d)|}{MTF(R_{gr})} \leq 0.1\right) \quad (1)$$

The physical mining of Equation (1) is that all ranges belonging to an iso-MTF cell can be illuminated by transmitting the same frequency. Therefore, by adopting the iso-MTF cell concept, it is possible to identify a combination of transmitted frequency and antenna elevation angle (f,β) which is optimized for a specific ground range interval. By iteratively applying this idea to the entire ground range interval of interest, the surveillance area can be subdivided into a number of MTF cells defined as N_{iso} (Figure 5). This operation reduces the computational complexity when estimating the N_{iso} frequencies required to cover the surveillance area.

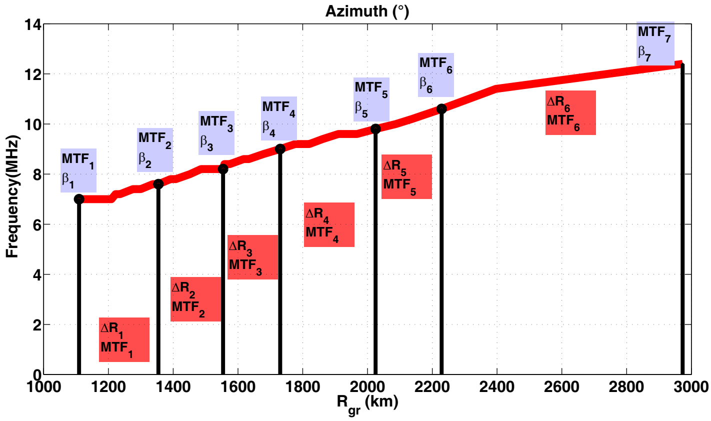

Figure 5. A theoretical example of iso-MTF cells.

Figure 5 shows a theoretical example of iso-MTF cells obtained from iso-MTF curves, which are extracted from the IPC in Figure 4. Specifically for each identified iso-MTF cell, the (MTF, β) pair that allows for the coverage of the ground range interval ΔR is reported in the plot.

5. NUMERICAL EXAMPLES

Numerical results that have been carried out in order to test the above proposed technique for ionosphere characterization are reported in this section. Two radar scenarios have been considered as a case study. The radar scenarios concern a radar located at Lat/Lon = 45.5°N/15.5°E pointing at $\theta = 135°$ (azimuth angle) with respect to North, respectively, for a Sun Spot Number (SSN) SSN = 50, Month = April, Hour = 18 (case 1) and for a SSN=50, Month=January and Hour = 2 (case 2) (Table 1).

Table 1. Radar Scenarios.

Radar Site		Solar Activity			Azimuth	Ground Range
TxLat	TxLon	SSN	Month	Hour	Angle	Extension
45.5°N	15.5°E	150	April	18	135°	600 km–3000 km
45.5°N	15.5°E	50	January	2	135°	600 km–3000 km

The International Reference Ionosphere (IRI) model has been used to estimate the electron density distribution as a function of the altitude (Figure 6). Specifically, diurnal and nocturnal electron density profiles (under the same external conditions — SSN and month), are depicted. By comparing the different profiles, it is possible to note a strong daily variation of the electron density. These profiles have been used as input for the ray-tracing in order to obtain the IPCs reported in Figure 7 and Figure 8.

According to the mechanism of refraction provided by the ionospheric layers and by looking at Figure 7 and Figure 8, we can notice that:

- Further distances can be reached with higher frequencies for a fixed elevation angle or with a smaller elevation angle for a fixed frequency;
- For a given ground range distance (R_{gr}) there are several frequency and elevation angle pairs that allow the ground range distance to be reached. For example, referring to Figure 7, a ground range equal to 1500 km is reached with a frequency that ranges from 7 MHz to 15 MHz and with elevation angles variable between 15° and 21°. By looking at the second scenario (Figure 8), it is worth underlining that the same distance (1500 km) can be reached with different (f, β) pairs, specifically, with a frequency belonging to the interval (15 MHz,16 MHz) and with an elevation

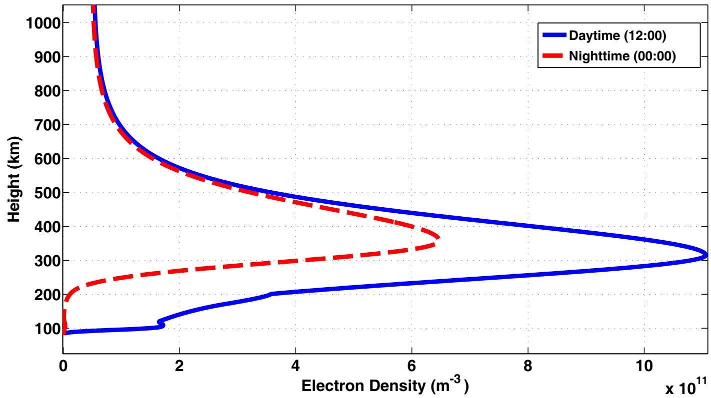

Figure 6. Example of simulated electron density distribution (Figure 7).

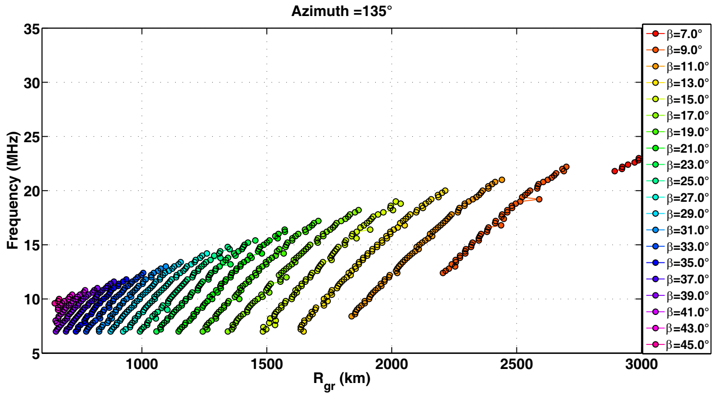

Figure 7. IPC in ground range {SSN = 150, Month = April, Hour = 18}.

angle that ranges between 15° and 16.5°. This means that the (f, β) pairs that allow a given ground range to be reached depending on the ionospheric conditions. Moreover, it must be pointed out that the same ground range distance is not always achievable for all ionospheric conditions;

- All iso-elevation angle curves are upper limited by the MTF which depends on the elevation angle, the time of the day, the season and the solar activity. Indeed, by comparing the above figures for a given elevation angle of 9°, the relative MTF value

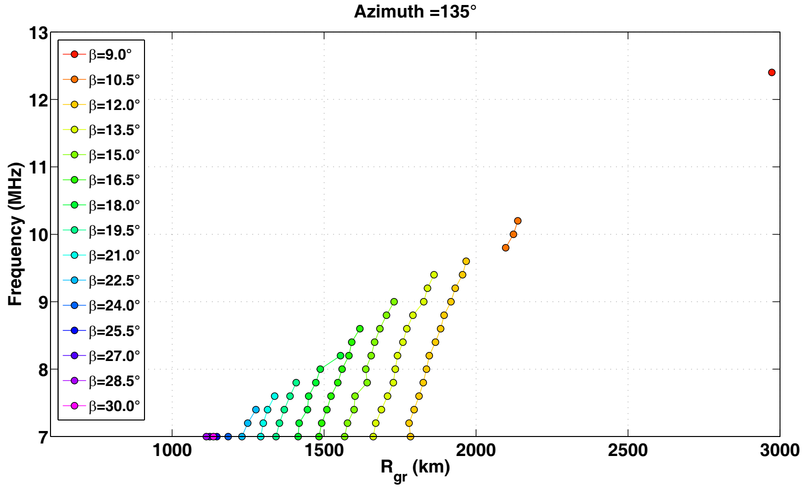

Figure 8. IPC in ground range {SSN = 50, Month = January, Hour = 2}.

is approximately equal to 24 MHz in the first scenario and to 12.5 MHz in the second scenario.

As explained in the previous section, the IPC outcome is a map of frequency and elevation angle pairs capable of illuminating a defined surveillance area. Because of the fact that a wide set of frequencies and more than one elevation angle exists, we have introduced the concept of iso-MTF cell which ensures the coverage of the whole region of interest with the minimum number of $(f,\, \beta)$ pairs. The technique presented to the section 4 is applied to the IPCs relative to both of the studied scenarios and the results are shown in Figure 9 and Figure 10.

Once the iso-MTF cells have been determined, it is worth nothing that:

- It is possible to scan the whole surveillance area with a number of frequencies equal to the number of identified iso-MTF cells;
- Under the hypothesis of defining the radar site location and the radar azimuth angle, the number of iso-MTF cells varies as a function of the ionospheric conditions. Specifically, it is equal to ten in the first case and to six for the second case.

Once the set of frequencies\elevation angle that allows the surveillance area to be covered has been determined, the above algorithm is repeated for a new radar azimuth angle of interest.

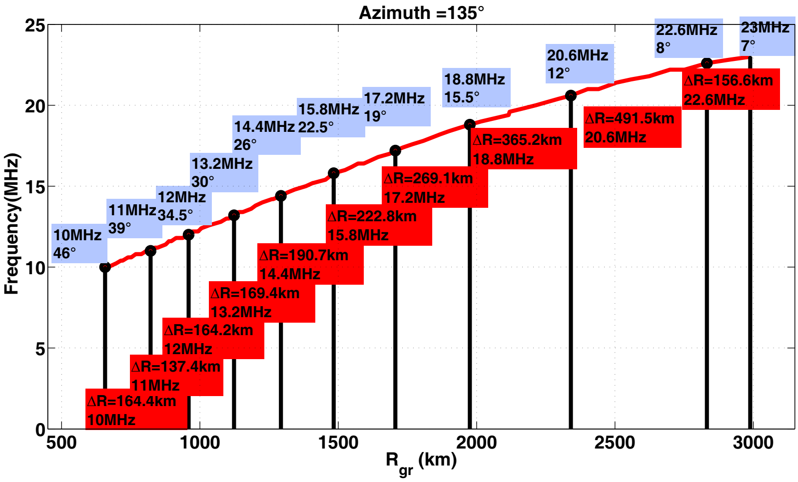

Figure 9. iso-MTF cells (Figure 7).

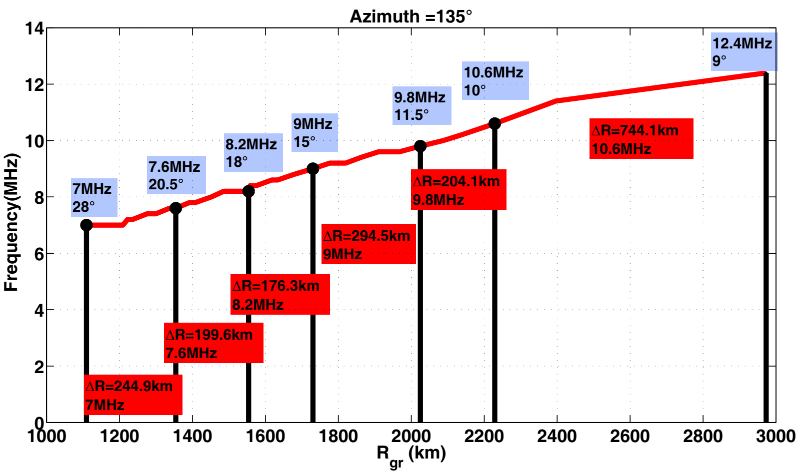

Figure 10. iso-MTF cells (Figure 8).

6. CONCLUSIONS

High-Frequency radio-wave propagation in the ionosphere still excites much interest in both radar and broadcasting applications. To find an ionospheric channel representation, due to its space-time variability, it is imperative to meet the requirements of systems. In this work, a new method to predict and represent the ionospheric behavior from a radar point of view has been presented.

To sum up, this method is based on following steps:

- **Construction of the IPC**: this step provides, for a given azimuth angle, all frequency\elevation angle pairs which propagate through the ionosphere. These pairs are all those that allow every distance, within the surveillance area, to be reached. The characterization of the IPC is based on the ray-tracing algorithm which provides the ray path of the signal and the ground range distance (point of the intersection between the path and the Earth's surface). The ray-tracing makes use of the 3-D electron density profile, which is estimated by mean the IRI model or by a network of ionosondes. The charts are carried out off-line by a dedicated work station. Despite the IPC are exhaustive from an ionospheric point of view, it is clear that transmitting a many different frequencies is wasteful from a radar point of view. For this purpose, the iso-MTF concept has been introduced;
- **Estimation of the iso-MTF cells**: the iso-MTF cell are derived from the IPC. Therefore every distance within the same cell can be illuminated by transmitting the same frequency. This means that by splitting the surveillance area into iso-MTF cells, the number of transmitted frequencies is at most equal to the number of the iso-MTF cells. This implies a considerable reduction in the number of frequencies required for illuminating the whole surveillance area.

It is worth nothing that the proposed ionospheric channel can be seen as a functionality of the radar sub system called the Frequency Management System, whose main task is to select the optimal transmitted frequencies as a function of the ionospheric conditions, external noise and available clear channels. All these aspects will be discussed in future work.

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