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A FREQUENCY SELECTION METHOD FOR HF-OTH SKYWAVE RADAR SYSTEMS

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ABSTRACT

Functionality of a HF-OTH skywave radar is strongly dependent upon several factors. Firstly, the propagation channel is highly time-varying, secondly external radio noise is particularly severe and finally, the spectrum availability is limited by the national plan of frequencies. In this paper we propose a frequency selection method that maximizes the signal-to-noise ratio. The proposed method attempt to solve the aforementioned penalties by inspecting jointly the ionosphere and the external noise behaviour. The former is evaluated by means of simplified regional ionospheric models, while the latter is estimated by considering the recommendation given in ITU's reports.

A numerical simulation is used through the paper to explain the method.

1. INTRODUCTION

HF-OTH skywave radar provides surveillance over wide areas by exploiting the ionospheric refraction [1]. Moreover OTH radar performances are affected by several type of frequency dependent factors, mainly due to propagation and ionospheric absorption, but also related to the background noise. As frequency usable in a time slot can suddenly fade and considering the wide area we are going to survey, skilled radio operators are not sufficient. Therefore, an adaptive transmitted frequency selection method able to provide the frequency map on the surveillance area in real time is required. Existing OTH radars make use of such kind of systems.

Different solution has been proposed in the past. A case in point is NOSTRADAMUS system which implements a backscatter sounding exploiting elevation focalization techniques [2]. A similar approach is used in Jindalee OTH operational radar network (JORN), where backscattering techniques are supported by a network of beacon and sounder. A detailed description of the JORN hardware architecture and signal processing schemes of the frequency management system is provided in [3-4].

In this paper we redefine the radioelectric parameters of the radar link (radar-surveillance area-radar) by extending the concept of Maximum Usable Frequency (MUF) normally used for communication purpose. Subsequently, an adaptive frequency selection algorithm that make use of the above mentioned concept has been developed. Next, we analyze the background noise nature, giving the mean power values reported in ITU's recommendation. The method is illustrated through the paper making use of simulation results obtained by ionosphere and spectral noise prediction models.

2. IONOSPHERE CHARACTERIZATION

The ionosphere is the ionized part of the atmosphere. Ionization processes are mainly due to solar radiation and particle emissions and a measure of the ionization intensity is given by the electron density. Solar radiations split neutral molecules into positive (ions) and negative (electrons) charges. At the same time an opposite process, called recombination, occurs. Such process is mainly dependent on temperature and pressure. The higher the temperature, the less the effectiveness of the ions attraction and the lower the recombination probability. On the contrary the higher the atmospheric pressure, the more the electron density and accordingly the more the recombination probability.
Solar radiation intensity is strictly dependent on the Sun elevation angle (Zenith angle), therefore ionospheric features are variable by hour, season and year. A numerical evaluation of the solar activity is given by the Sun Spot Number (SSN).
To sum up, we can state that ionospheric features are clearly identified by SSN, month and hour. In the present work the ionospheric configuration is identified with the mentioned quantities.

The upper atmosphere electronic concentration affect e.m. wave propagation at HF band. Electromagnetic waves are progressively bended travelling into ionized layers. In some cases the e.m. ray is totally reflected back to the Earth, otherwise it goes beyond the ionized layers.
Several approximations has been proposed in the past [5-7] in order to infer the e.m. path for a given ionospheric configuration. In this paper we adopt the spherical mirror assumption. As showed in Fig. 1, the e.m wave, transmitted with a take off angle β, is reflected by a spherical mirror at a distance h_{eq} above the earth surface. This reflection height (also known as virtual height) is evaluated on the middle point of the great circle path , where R_{gr} is the ground distance between radar site and illuminated area centre. This virtual geometry approximation follows the unmodified version of the secant law and Martyn's theorem.

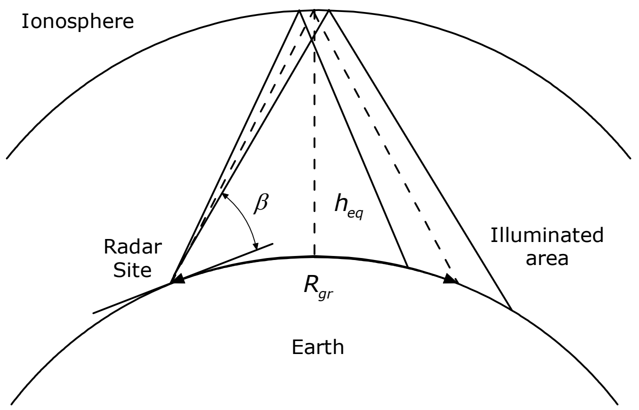

Figure 1 – Reference geometry

In OTH radar the main requirement is to reach a defined surveillance area. In order to accomplish this, it is necessary to select the proper set of transmission parameters, that are operative frequency and take off angle, $\{f, \beta\}$.
Moreover, different couples of $\{f, \beta\}$ allow a fixed ground path distance R_{gr} to be reached.

The maximum usable frequency, given the ionospheric configuration and path, that ensures the reflection is defined in literature [5] as *Maximum Usable Frequency* (*MUF*). Furthermore, a lower limit for the usable frequency is recommended to avoid high ionosphere losses. We define such a limit *minimum Usable Frequency* (*mUF*), in order to ensure radar performances we adopt the following assumption: $mUF = 0.65 \cdot MUF$.

For evaluating the above defined quantities we make use of a long-term ionospheric prediction model, namely Simplified Ionospheric Regional Model (SIRM) [9]. SIRM is based upon the Fourier analysis of the monthly median values of ionospheric characteristics of vertical incidence. The reference database is drawn on data collected with seven ionospheric stations in Europe.

Since we adopt a prediction model approach, the *MUF* has been treated as a random variable; to avoid misleading notation this r.v. is identified with MUF_{rv} .

With this assumption, the upper and lower usable frequencies (*mUF, MUF*) can be statistically evaluated as follow:

$$\Pr\left\{MUF_{rv} \geq mUF\right\} = 1 - F_{MUF_{rv}}\left(mUF\right) = 0.99$$

$$\Pr\left\{MUF_{rv} \geq MUF\right\} = 1 - F_{MUF_{rv}}\left(MUF\right) = 0.5$$

where $F_{MUF_{rv}}(\cdot)$ is the cumulative distribution of MUF_{rv} .

A ionospheric prediction example is given in Fig. 2. The figure is referred to the month of January, at 10:00 a.m. with a SSN=100. Radar site is supposed to be located Lat/Lon: 45 00N/010 00E. It should be noted that this coordinates do not correspond to an actual radar location, but just identify an area for simulation purpose. Simulation results are reported for a surveillance area ranges from 600 km to 3000 km. For each ground range value (stepped by 10 km), the middle-point ionospheric parameters are estimated. The simulation provides take off angle values as well. To give an example, a distance of 1200 km can be reached with all frequencies in the range between 12 MHz and 19 MHz with a take off angle variable from 22° to 26°.

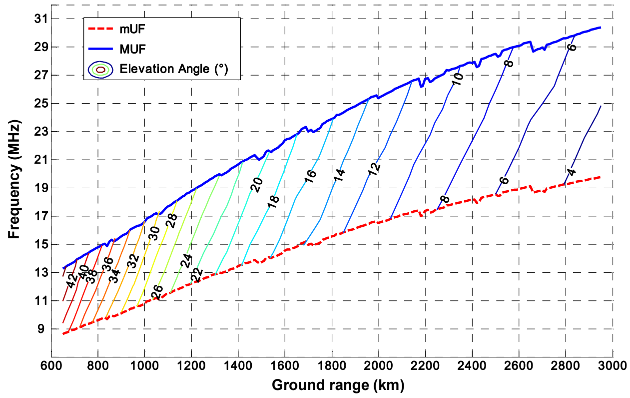

Figure 2 – Ionospheric chart {SSN=100, Month=Jan, Hour=10}

3. EXTERNAL NOISE

In the HF band radar performances are heavily affected by background noise, which is mainly due to external noise.
In addition, internal noise caused by thermal effect is almost neglectable. Specifically the external noise is composed by atmospheric noise, cosmic noise and manmade noise. The first two are produced by natural sources typically identified as environmental noise, mainly due to:

- Lighting discharges.
- Sun and planets radiations.
- Galactic electromagnetic radiations.

Concerning the manmade noise, common sources are:

- Electrical machineries.
- Radio stations.
- Electrical discharges produced by internal combustion engine ignition.

For radar design purpose, a statistical description of each component is required. In our simulated scenario, the reference power knowledge is sufficient, while in an actual system a real time spectral analysis should be performed.
In this paper we adopt the ITU's model [8]. This recommendation provides the mean power values for each noise component, as well as the overall noise. An example is given in Fig. 3.

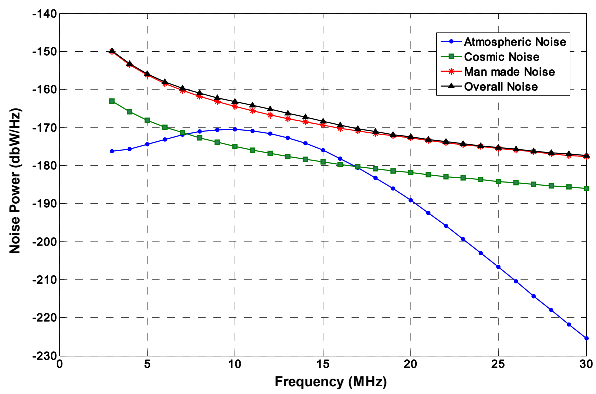

Figure 3 – Noise power {SSN=100, Month=Jan, Hour=10}

The above figure shows the overall noise trend with frequency, it is obtained by a statistical analysis of a large amount of data collected in several measurements campaigns. Although the presented overall noise is a monotonous decreasing function, this is not generally true (e.g. when atmospheric noise is the uppermost). This dependency plays a key role in signal to noise ratio optimization, therefore in a frequency selection method it must be managed.

We would like to point out that the frequency choice is also controlled by short term interferences, such as radio stations emission, which are not considered in the ITU's recommendation. This type of interferences can be tackled by using a real time spectrum analyzer.

4. METHOD DESCRIPTION

As showed in Fig. 2, a specific ground range is reachable with an uncountable number of couples $\{f, \beta\}$. Therefore, a selection criteria is required to define the transmission parameters properly. The aim of this section is to describe a novel method suitable for OTH radar application.

As a first step, it is necessary to observe that Fig. 2 is a representation of a mathematical function (Ω), that is:

$$\Omega : (f, \beta) \rightarrow R_{gr} \tag{1}$$

Where the transmission parameters $\{f, \beta\}$ are mapped into ground range (R_{gr}) values.

Secondly, we define the concept of ISOMUF cell. As reported in Fig. 4, for a given ground range $R_{gr}^{(i)}$ the i-th ISOMUF cell is the ground range interval $\left[R_{gr}^{(i)}, R_{gr}^{(i)} + \Delta R^{(i)}\right]$ in which the MUF varies at most five percent. In formula:

$$\Delta R^{(i)} = \max_{r} \left(\frac{\left| MUF\left(R_{gr}^{(i)}\right) - MUF\left(R_{gr}^{(i)} + r\right) \right|}{MUF\left(R_{gr}^{(i)}\right)} \leq 0.05 \right) \tag{2}$$

This assumption is supported by the MUF stability within a 1° square cell [6]. At this scale the ionosphere is almost homogeneous.

An iterative application of the condition stated in eq. (2) leads to the range (600 km – 3000 km) subdivision in ISOMUF cells. Moreover, it is interesting to note that each ISOMUF cell can be reached with frequencies between $[mUF, MUF]$ with associated take off angles. In mathematical terms the set of $\{f, \beta\}$ that allows the *i*-th ISOMUF to be reached is defined as:

$$D^{(i)} = \left\{ (f, \beta) : \Omega(f, \beta) \in \left[R_{gr}^{(i)}, R_{gr}^{(i)} + \Delta R^{(i)} \right] \right\} \tag{3}$$

Inside the $D^{(i)}$ set a suitable couple of parameters has to be chosen. First of all, symmetric justification lead to a reasonable domain restriction as follows:

$$d^{(i)} = \left\{ (f, \beta) \in D^{(i)} : \Omega(f, \beta) = R_{gr}^{(i)} + \frac{\Delta R^{(i)}}{2} \right\} \tag{4}$$

By this way, radar and geometric footprint are centred. Working on $d^{(i)}$ we notice a biunivocal correspondence between frequencies and take off angles, thus a frequency selection implies a unique take off angle value.

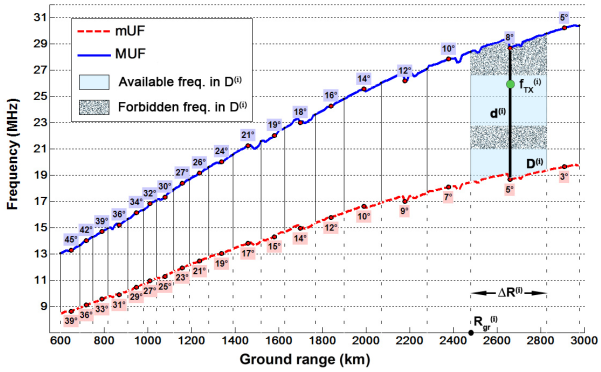

Figure 4 – Operative TX chart {SSN=100, Month=Jan, Hour=10}

However, the HF band is densely populated, therefore the frequency selection method must comply with national frequency allocation, since mutual interferences has to be minimized. In addition, real time spectrum analysis has to be performed in order to transmit in less crowded spectrum region. Accordingly in each ISOMUF cell the frequency-take off angle search domain must be further reduced. A hypothetical restriction is showed in Fig. 4 with a grainy pattern. The available band over the restriction $d^{(i)}$ is termed $\bar{d}^{(i)}$. The selection of the optimum $\left\{f^{(i)}, \beta^{(i)}\right\}$ values is performed in the $\bar{d}^{(i)}$ domain.

As underlined before, in OTH radar several contributions are frequency dependent. Therefore a reformulation of the signal to noise ratio is required in order to emphasize the frequency dependent parameters of the radar. In this work, we adopt the following:

$$\begin{aligned} SNR_N(f) &= \frac{SNR \cdot L_{sys}}{P_T \cdot T_i \cdot PRF \cdot T_{oss} \cdot G_{tM} \cdot G_{rM}} \\ &= \frac{4\pi}{c^2} \cdot \frac{g_t(f) \cdot g_r(f) \cdot \sigma(f) \cdot f^2}{L_p^2(f) \cdot \left(N_0(f)/2\right)} \end{aligned} \tag{5}$$

where P_T is the peak power, T_i is the pulse length, PRF is the pulse repetition frequency, T_{oss} is the coherent integration time, L_{sys} are the system losses, $N_0(f)/2$ is the noise power, $L_p(f)$ is the propagation loss (one-way) , $\sigma(f)$ is the ground radar cross-section . The functions $g_t(f)$ and $g_r(f)$ are the receiving and transmitting antenna gains normalized to their maximum values G_{tM}, G_{rM} :

$$\begin{cases} g_r(f) = \dfrac{G_r(f)}{G_{rM}} \\ g_t(f) = \dfrac{G_t(f)}{G_{tM}} \end{cases} \tag{6}$$

The optimum frequency for the *i*-th ISOMUF cell is obtained maximizing $SNR_N(f)$:

$$f^{(i)} = \arg\max_{f\in\bar{d}^{(i)}} \left\{ SNR_N(f) \right\} \quad (7)$$

the corresponding value $\beta^{(i)}$ is directly obtained.

The proposed method can be summarized as follows:

1. Synthesis of the map $\Omega:(f,\beta)\rightarrow R_{gr}$ by means of ionospheric sounding.
2. Total range subdivision in ISOMUF cell.
3. For each ISOMUF cell:
    a. Frequencies and take off angles selection ($d^{(i)}$ identification).
    b. Masking with National Frequency Plan, obtaining $\bar{d}^{(i)}$.
    c. Real time spectrum analysis searching for free frequency slot.
    d. Selection of the couple $\left\{ f_{TX}^{(i)}, \beta_{TX}^{(i)} \right\}$ that maximizes SNR_N.

The above method applied to the ionospheric chart of Fig. 2, provides a set of useful information. A practical way of representing this data is showed in Tab. 1.

The use of the synoptic table is straightforward.

For instance, the ISOMUF cell number 10, which covers a ground range between 1281 km and 1388 km, can be optimally reached using a frequency of 18.6 MHz with a take off angle of 22.3°.

SSN=100, Month=January, Hour=10				
Cell n°	R_{gr} (km)	ΔR (km)	f_{TX} (MHz)	β_{TX} (°)
1	600	92	11.5	40
2	692	59	13	38.4
3	751	75	12.3	34.8
4	826	91	13.3	32.7
5	917	72	14.6	30.8
6	989	49	15.1	29.0
7	1038	76	11.7	24.3
8	1114	73	17.2	25.8
9	1187	94	18.6	24.6
10	1281	107	18.6	22.3
11	1388	135	20.5	20.6
12	1523	107	21	18.5
13	1630	143	22.7	17.2
14	1773	127	23.8	15.4
15	1900	170	24	13.3
16	2070	210	25.6	11.4
17	2280	201	27.1	9.8
18	2481	348	27.9	7.2
19	2829	171	29.3	5.6

Table 1 – TX synoptic table, Lat/Lon: 45 00N/010 00E

5. CONCLUSION

Operative frequency selection plays a key role in OTH radar transmission strategy. A number of factors are frequency dependent, such as external noise, ionospheric absorption and propagation losses. In addition, further constraints are the National Frequency Plan, and the reduction of the mutual interference between the radar and other system operating in the HF band. For this reason, frequency management cannot relies only on operators capability, but it needs to be supported by an automatic selection method.

In this paper, we propose a frequency selection method for OTH radar, that aims to maximize the signal to noise ratio. In order to accomplish this task, we have introduced the ISOMUF idea and a new reformulation of the classic radar equation. For an actual application of the proposed method, the OTH radar has to be supported by a network of ionosondes and by a local spectrum analyzer. Data gathered by these auxiliary systems must be processed and supported by regional long term prediction models, thus obtaining a full description of the ionospheric propagation channel and of the surrounding electromagnetic environment.

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REFERENCES

[1] J. M. Headrick and J. F. Thomason, "Application of high-frequency radar," Radio Science, vol. 33, pp. 1045–1054, Jul-Aug. 1998

[2] Saillant, S., Auffray, G., Dorey, P., "Exploitation of elevation angle control for a 2-D HF skywave radar", in *Proc. International Radar Conference 2003*, Adelaide, Australia, 3-5 Sept. 2003, pp. 662 – 666.

[3] Soame, T.A., Jarrott, R.K., "Architecture of an HF Skywave Radar Network", in *Proc. HF Radio Systems and Techniques*, 4-7 July 1994, pp. 253 – 257.

[4] Earl, G.F., Ward, B.D., "The Frequency Management System of the Jindalee ovet-the-horizon backscatter HF radar," Radio Science, vol. 22, pp. 275–291, Mar-Apr. 1987

[5] C.C.I.R./I.T.U., "C.C.I.R. Interim method for estimating sky-wave field strength and trasmission loss at frequencies between the approximate limits of 2 and 30 MHz", Report 252-2, 1970

[6] Davies K., *Ionospheric radio propagation*, U.S. Department of Commerce National Bureau of Standards, April 1965

[7] Budden K. G., *The propagation of radio waves. The theory of radio waves of low power in the ionosphere and magnetospher*e, Cambridge University Press, 1988.

[8] ITU (International Telecommunication Union), Radio Noise, ITU-R P.372-8.

[9] B. Zolesi, Lj. R. Cander, G. De Franceschi, "Simplified ionospheric regional model for telecommunication applications", Radio Science, vol. 28, pp. 603-612, 1993.