IMPLEMENTATION OF SPECTRUM MONITORING SYSTEMS OF THE HIGH FREQUENCY RANGE IN DEVELOPING COUNTRIES HAVING RELATIVELY SMALL TERRITORIES[1]

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Abstract

Currently, developing countries are showing increased interest in establishing new and optimizing existing spectrum monitoring networks, including networks for monitoring in the high frequency (HF) range of the radio spectrum. If the planning and optimization issues of spectrum monitoring networks in the VHF/UHF frequency band are reasonably well developed, the same matters concerning the spectrum monitoring in the HF range are still under-researched. To cover this gap, in this paper efficiency of HF monitoring networks containing various numbers of mobile and fixed HF monitoring stations in different compositions is considered in application to countries of different sizes. Some measures to facilitate implementation of Single Station Location (SSL) operational regime are also considered.

Keywords: spectrum monitoring, HF monitoring features, monitoring network planning, monitoring coverage, direction finding, location by triangulation, single station location.

Introduction

As the socio-economic situation in developing countries improves, more attention is being paid to spectrum monitoring, including monitoring in the high - frequency (HF) range of 3 – 30 MHz (100-10 m wavelengths). According to Recommendation SM.1392-2 of the Radiocommunication Sector of the International Telecommunication Union (ITU-R) [1]: "spectrum monitoring systems are often the most expensive part of a national spectrum management system whose optimal implementation, including networking, has a significant economic impact", which is the most relevant for developing countries.

Although HF monitoring stations appeared in many countries, including a number of developing ones, long before the advent of such stations in the VHF/UHF band, in relation to planning and optimizing monitoring networks the ITU-R documentation is exclusively concerned with VHF/UHF monitoring, as it is presented in [2] and in section 6.8 of [3]. Until

[1] The article is in the process of publishing in French. This is its text in English.

recently, the available publications in the general technical press concerned HF monitoring networks of countries and regions with very large territories [4-6], while even the question of the effectiveness of monitoring of transmitters operating in national HF radio links in countries of relatively small size, was questionable. Only recently, the publication [7] has appeared showing that under certain conditions monitoring of transmitters operating in national HF radio links in such countries can be quite efficient. However, the article [7] does not consider changes in such efficiency depending on the number of fixed and mobile HF monitoring stations, which is extremely important in the process of planning and optimizing the HF monitoring networks. This article is intended to fill this gap.

Main features of HF monitoring

HF monitoring has significant features that fundamentally distinguish it from monitoring in VHF/UHF band. According to Figure 1, these features are mainly as follows:

- the presence of reflections of radio waves emitted by transmitters (**TR 1** and **TR 2** in Figure 1) from the ionosphere, which can be represented in a simplified way by two ionized layers ***E*** and ***F*** having different heights; signals are received by the antenna of an HF monitoring station in the form of a sky wave coming from ionosphere at elevation angles **Δ**;
- there are also emissions of transmitters on the earth wave at a distance of 30-50 km from transmitters;
- Figure 1 shows an example of single-hop propagation of HF radio waves, but multi-hop propagation can also occur on long radio links (2 or more hops);
- in a general case, there are silence (dead) zones in the middle parts of the hops, marked by dark lines on the surface of the conditional ground in Figure 1, where reception of signals becomes impossible. However, as it is shown in [7], this effect is not apparent on local short-range HF radio links, typical for countries with relatively small territories, when the elevation angles are high, up to 85° (almost vertical fall and reflection of the wave from the ionosphere). Calculations show that elevation angle in 85° correspond to distance ***D*** equals to about 60 km.

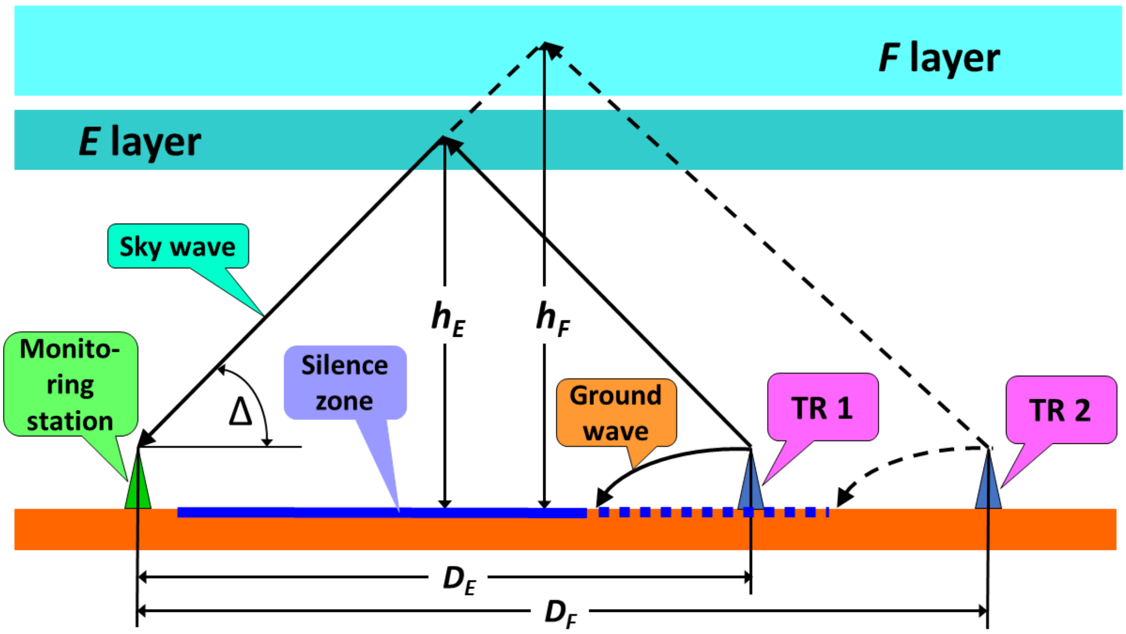

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Figure 1. Main features of HF spectrum monitoring

Since modern techniques of direction finding (DF), namely correlative interferometry (section 4.7.2.2.5 of [3]), allows to accurately measure the elevation angles **Δ**, in conditions of knowledge of the height of the wave reflection from the ionosphere ($\boldsymbol{h_E}$ or $\boldsymbol{h_F}$ in Figure 1), it is possible to calculate the distance from the fixed HF monitoring station to the sought transmitter ($\boldsymbol{D_E}$ or $\boldsymbol{D_F}$ in Figure 1) using the simple formula: $D = 2h / \tan \Delta$. This feature provides a unique Single Station Location (SSL) operation regime (section 4.7.3.4 of [3]) that is not available for monitoring in any other frequency range.

Figure 1 shows a special case of HF propagation of radio waves (necessary for the analysis that will be presented below), when the **TR 1** and **TR 2** transmitters are positioned so that the waves reflected from the ionospheric layers ***E*** and ***F*** come to the antenna of the HF monitoring station at the same elevation angle **Δ**. In the general case, the sky waves from layers ***E*** and ***F*** come under different elevation angles. As a rule, the elevation angles of the sky waves coming from the ***F*** layer have larger values.

It is well known that radio waves propagation in the HF range is very variable because of the large dependence of ionization, especially of layer ***F***, on the time of a day, the location of the transmitter and receiver, season of a year, and solar activity, characterized by the averaged sunspot number ***R*** [8]. Therefore, to ensure stable radio communication, different frequencies are usually chosen for day and nighttime; night frequencies are always lower. As it follows from [7], manipulating by HF monitoring during the day and night hours of a day, it is possible to monitor HF transmitters operating on local radio links of countries with a relatively small territories with a fairly high degree of probability, although achieving a stable 100% probability is very difficult.

To ensure efficient DF and SSL by means of correlative interferometry, receiving antennas should have dimensions comparable to HF wavelengths, i.e. tens of meters in size. This is usually achieved by constructing antenna fields containing a sufficiently large number of antenna elements distributed over the territory (up to 18 elements according to [9]). Cross loop antennas are used as antenna elements (section 3.2.3.3 of [3], [9]). Since such antennas cannot be installed on mobile HF monitoring stations, such stations can only provide sky-wave measurement of HF transmitter emission parameters (frequency, bandwidth, modulation/class of emission), but not DF function. Such DF function by mobile HF monitoring stations is possible only in the homing mode on the earth wave.

Due to the presence of silence (dead) zones, fixed HF monitoring stations in countries with relatively small territories cannot provide sky wave monitoring of national transmitters operating on long international radio links using the upper frequencies of the HF band. Monitoring of such transmitters is possible only on the ground wave using mobile stations. To do this, the mobile station must approach the sought transmitter at a distance of less than 50 - 30 km. To do this, the coordinates of such transmitter must be known. It can be achieved if a National frequency register would contain data concerning HF transmitter coordinates.

Functions provided by a various number of HF monitoring stations of different composition

Based on the specific features of HF monitoring described above, let us consider capabilities provided by a various number of HF monitoring stations of different composition, referring to fixed monitoring stations equipped with and not equipped with an SSL system. These capabilities together with relevant restrictions are summarized in Table 1 below.

Table 1. Different options of HF monitoring network creation

Type of HF monitoring stations	Capabilities / advantages	Restrictions / disadvantages
One mobile station	- Providing measurements of HF transmitters emission parameters (ITU measurements) on the ground and sky waves (with a certain probability), i.e. both at distances up to 30 – 50 km on the ground wave, and at distances up to several thousand km on the sky wave. - Providing DF (with subsequent finding at the place) of the desired national HF transmitters on the ground wave, i.e. after the mobile station approaches the transmitter at a distance of 30-50 km. - Providing full on-site monitoring and finding at the place of national transmitters working in the entire HF frequency range upon requests through the ITU International monitoring system (IMS), since such requests usually indicate frequencies and coordinates of the national transmitter that are considered as to be interfering ones. - Providing full monitoring and on-site detection of local and foreign HF radio transmitters whose frequencies and coordinates are listed in the National frequency register. Consequently, the station allows periodic monitoring of registered national HF transmitters for compliance with licensed parameters and operating conditions.	Due to antenna limitations, a mobile HF station is fundamentally unable to provide DF on the sky wave, which makes it extremely difficult to find illegal and interfering transmitters that are separated from the station at distances exceeding 30-50 km, i.e. located on most of the country's territory. The increase in the number of mobile stations does not lead to the elimination of this problem, which is a great negative feature of monitoring in the HF frequency range.
One fixed station	Providing measurements of emission parameters and DF (with a certain probability) of HF transmitters working in local radio communications links using the ground and sky waves, i.e. at distances up to 30 – 50 km on the ground wave and at distances from about 60 km up to several thousand km from the station on the sky wave.	- There is no possibility to provide DF of transmitters in the narrow ring-shaped zone around the fixed station with a minimum radius of 30 km (ground wave reception boundary) and a maximum radius of about 60 km (sky wave reception boundary). - Due to the specific propagation of radio waves in the HF frequency range, sky wave monitoring, including DF, of local transmitters operating in foreign radio links at the high

		frequencies of the HF range cannot be provided. The increase in the number of fixed (and mobile) monitoring stations does not lead to the elimination of this problem which is a great negative feature of monitoring in the HF frequency range.
One fixed station with SSL capabilities	In addition to capabilities of one fixed station described above, the addition of the SSL means provides location (with a certain probability) of HF transmitters working in local radio communications links at distances from about 60 km up to several thousand km from the station using the sky wave.	In addition to limitations of one fixed station described above, the SSL option does not provide location of sought HF transmitters within ground wave zone i.e. at distances 30 – 50 km from the station.
Two fixed stations	- Providing (with a certain probability) full-scale monitoring (measurements of emission parameters, DF and location) of transmitters of HF local radio links throughout the whole country using sky waves (in addition to measurements and DF provided within ground wave zones i.e. at distances up to 30 – 50 km from each station). - Since the sought transmitter is usually stay at different distances from the monitoring stations, there can be slightly different conditions for the propagation of HF radio waves along the corresponding paths, that can somewhat increase the probability of monitoring in comparison with the option of one fixed station containing SSL means.	- Similarly as for monitoring in VHF/UHF frequency band, there is a DF and location "dead zone" along the line connecting two fixed monitoring stations. - Due to the specific propagation of radio waves in the HF frequency range, sky wave monitoring, including DF and location, of local transmitters operating in foreign radio links at the high frequencies of the HF range cannot be provided.
Two fixed stations one of which is provided by SSL	Providing (with an increased probability and reliability) full-scale monitoring (measurements of emission parameters, DF and location) of transmitters of HF local radio links throughout the whole country (including abovementioned "dead zone) using sky waves (in addition to measurements DF and location provided within ground wave zones i.e. at distances up to 30 – 50 km from each station).	Due to the specific propagation of radio waves in the HF frequency range, sky wave monitoring, including DF and location, of local transmitters operating in foreign radio links at the high frequencies of the HF range cannot be provided.
Two fixed stations both of	- Providing (with even greater increasing the probability and reliability) full-scale monitoring (measurements of emission	Due to the specific propagation of radio waves in the HF frequency range, sky wave monitoring,

which are provided by SSL	parameters, DF and location) of transmitters of HF local radio links throughout the whole country using sky waves (in addition to measurements DF and location provided within ground wave zones i.e. at distances up to 30 – 50 km from each station). - Providing 3 location points through sky-wave (one by triangulation and 2 by SSL) that increases in about 3 times probability and reliability of location.	including DF and location, of local transmitters operating in foreign radio links at the high frequencies of the HF range cannot be provided. The increase in the number of fixed (and mobile) HF monitoring stations even provided by the SSL capabilities does not lead to the elimination of this problem which is a great negative feature of monitoring in the HF frequency range.

Table 1 shows that local transmitters operating on long foreign radio links at frequencies located in the upper part of the HF range cannot be monitored over the sky wave by a local HF monitoring network even consisting several fixed stations. However, there is no great tragedy in that. The fact is that such transmitters, due to the peculiarities of the radio wave propagation in the HF range, cannot provide an interference effect on local receivers operating on the same long foreign radio links and at the same frequencies. They can only provide interferences on foreign receivers but that may be the subject of complaints through the IMS of ITU. Such complaints usually contain data relating not only to the frequency of the interfering signal, but also to the coordinates of the corresponding source, which makes it much easier to find such a transmitter in place using a mobile RF monitoring station over the ground wave.

As it follows from Table 1, the technical features of HF monitoring networks containing two fixed monitoring stations and one monitoring station equipped by SSL capabilities are close to each other. However, the cost effectivity of one monitoring station equipped by SSL capabilities almost twice greater than of two stations. Due to this, fact the option of one fixed HF monitoring station provided by SSL capabilities combined with one mobile DF station looks very attractive.

From Table 1 it can be also concluded that the combination of two HF-SSL fixed and one mobile HF monitoring station provides (with a rather high probability and reliability) full-scale monitoring (measurement of emission parameters, DF and location) of HF transmitters of local radio communications throughout the whole country in the entire HF frequency range. Nevertheless, the DF and location of illegal and interfering transmitters operating on foreign radio links in the upper part of the HF frequency range generally remains very difficult. This is due to the fact that fixed HF monitoring stations cannot receive signals of such transmitters by sky waves. As it concerns a mobile HF station, in order to monitor such transmitters, the station must be close to each transmitter at 30 – 50 km i.e. to enter into its ground wave coverage area, but it is not possible to determine, at least the approximately, the place of such transmitter over the territory of the country. Due to this fact, location of such transmitter using mobile monitoring station appears to be very problematic.

As a general conclusion from Table 1, it can be suggested that the option of one mobile HF monitoring station is the minimal workable configuration quite suitable for countries with relatively small territories. One mobile and one fixed SSL HF monitoring station is the most optimal solution for such countries in terms of the ratio: performed functions/cost.

Supporting SSL operations

In accordance with section 4.7.3.4 of [3], the key issue in the practical implementation of the SSL method is to determine the virtual height ***h*** of the radio wave reflection from the ionosphere. Some sources for obtaining such information are also mentioned but it seems that not all of them can be practically accessible.

It seems that these difficulties can be overcome by calculating the dependence ***D*** **=** f **(Δ)** for a specific country at different values of the averaged sunspot number ***R***, i.e. bypassing the need to take into account the height ***h*** of the ionosphere reflection. In the case of Tunisia, such calculations were performed using the software called MINIFTZ, which previously was in the list of ITU software. It is still popular among specialists for fast and visual calculations of HF radio links that do not require highest accuracy of calculations. This software requires a minimum number of input data and provides an illustrative output. Operation with the software and its outputs are described in [7].

Calculations were performed for nine gradations of radio link lengths in the range from 60 to 450 km and for four values of the averaged sunspots numbers: 10 (a value close to the minimum), 50, 100 and 190 (a value close to the maximum). The calculation results are shown in Table 2, as well as in Figures 2 and 3.

As it follows from these Table and Figures, the ***D*** = f **(Δ)** dependences for reflections from layer ***E*** are very stable and do not depend on the time of a day or on the averaged sunspot numbers. ***E***- reflections occur during mid-day hours at the lower HF frequencies (see [7]). The same dependence for reflections from the ***F*** layer shows a significant dependence of the elevation angle on the time of a day and averaged sunspot numbers, which forced to present in Figure 2 two lines of the ***D*** = f **(Δ)** function for the ***R*** values equal to 10 and 190. Dependencies for other ***R*** values are located between these two lines.

Table 2. Dependence of elevation angles **Δ** from radio link lengths ***D***

Distance *D*, km	**Elevation angle Δ, degrees**				
	E – reflection (*R* = 10 – 190)	*F*- reflection			
		R = 10	*R* = 50	*R* = 100	*R* = 190
60	75	84	84 85	85	85 86
82	69	81 82	82 83	83 84	84
100	65	80	80 81	81 82	82 83
144	56	75 76	76 77	78 79	79 80
201	47	70 71	71 72	73 74	75 76
254	40	65 66	66 67 68	69 70	71 72
297	36	61 62 63	62 63 64	66 67	68 69
366	30	55 56 57	57 58 59	61 62 63	63 64 65
450	25	50 51 52	51 52 53 54	55 56 57	58 59 60

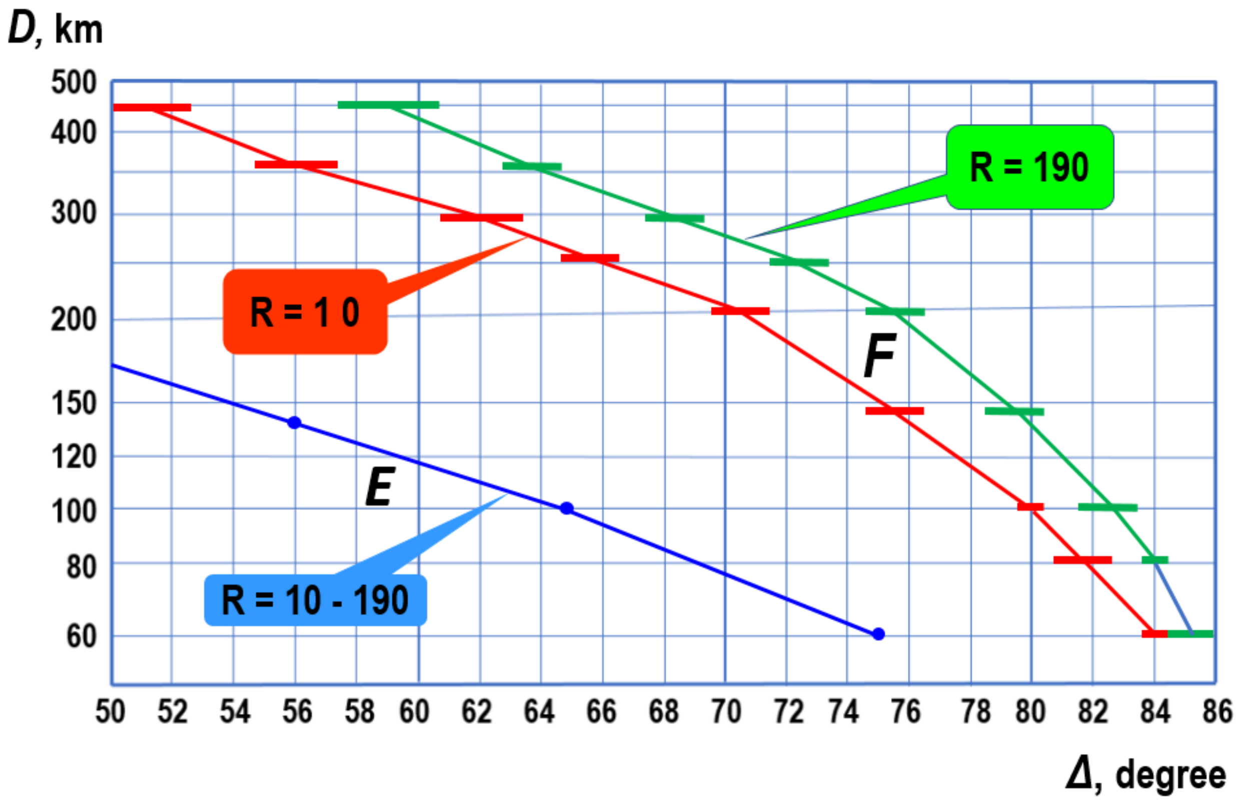

Figure 2. Dependences $D = f(\Delta)$ for reflections from layers E and F under big values of Δ

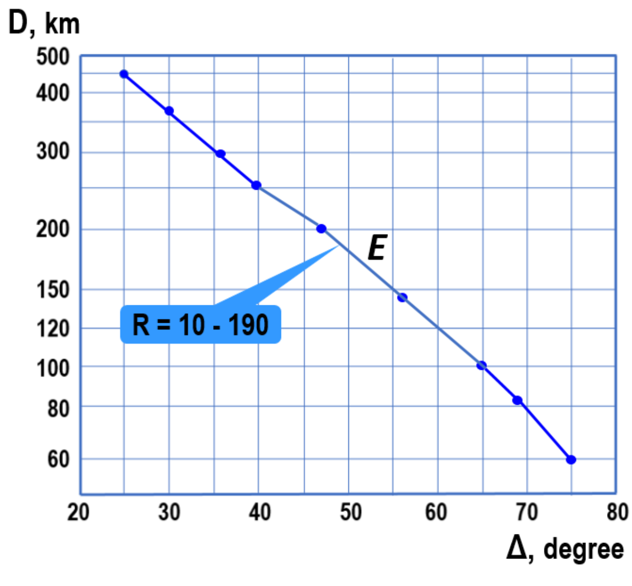

Figure 3. Dependences $D = f(\Delta)$ for reflections from layer E under all calculated values of Δ

As it can be clearly seen from Figure 2, the $D = f(\Delta)$ relationship for elevation angles between 50° and 75° is not unambiguous. As Figure 1 clearly demonstrates, the same elevation angle Δ may occur from a wave reflected under some conditions by layer E from a transmitter located at a distance D_E, and from a wave reflected in other conditions by layer F from a transmitter located at a greater distance D_F.

This circumstance must be taken into account when searching for a transmitter at the place using a mobile HF monitoring station. For example, let a HF/SSL monitoring station measures an elevation angle of 70° in the condition of low solar activity. According to Figure 2, this corresponds to the distance of $\boldsymbol{D_E}$ equal to about 78 km and the distance of $\boldsymbol{D_F}$ equal to about 210 km. In a daytime, the mobile station should start searching for the transmitter in the area of about 78 km from the HF/SSL monitoring station along its DF bearing line, assuming that the reflection occurs from the ***E*** layer. If the desired transmitter is not found here, it is necessary to try finding it in the area of about 210 km from the HF/SSL monitoring station along its bearing line. During morning or evening times, the search should be started from the area of about 210 km from the station on its DF bearing line, assuming that the reflection occurs from the ***F*** layer.

If a RF/SSL monitoring station measures an elevation angle of less than 50°, for example 40°, and the desired transmitter cannot be found at a distance $\boldsymbol{D_E}$ of about 250 km (see Figure 3) along the DF bearing line, this means that there may be a reflection from layer ***F*** of the wave coming from the transmitter, which separates from the monitoring station at a distance exceeding 450 km, i.e. in the Tunisian case - installed abroad.

The calculations also showed that in countries with a relatively small territory, such as Tunisia, all local radio links are characterized by a single-hop propagation of RF radio waves; this fact greatly facilitates implementation of the SSL regime.

Since the ionosphere parameters vary depending on the location on the Globe, the data in Table 2 and Figures 2 and 3 may be slightly different for other countries. However, $\boldsymbol{D} = f\,(\boldsymbol{\Delta})$ relationships obtained for Tunisia may well be used by the communication Administrations of other countries for guidance. To get more accurate data, Administrations can repeat similar calculations using, for example, ITU-R software ITURHFProp [10]. Acceptable accuracy can be considered such that, according to the results of calculations, the mobile station confidently falls into the earth wave zone of the sought transmitter, with its following DF by the earth wave using the homing system. The current value of the averaged sunspots number for operation with Figure 2 can be obtained in the ITU-R Circular [11].

Conclusion

It seems that the material of this article, together with the publication [7], provides comprehensive information for planning and optimizing spectrum monitoring networks operating in the RF range.

Acknowledgment

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