A Simplified Model for HF Radio Wave Propagation for Middle East Region

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ABSTRACT

In this work, a simplified mathematical model is proposed which leads to predict the HF radio frequencies that can ensure the annual permanent, reliable connection for different link distances and orientations that lay within the Middle East region. For this purpose, an analytical study for the datasets, generated from the REC533 international model, has been made in order to reach for the conclusions that enable to forecast the frequencies required to maintain a semi-permanent reliable connection between the transmitting and receiving stations. Also, as a case study, Iraq region has been adopted generally, whereas, Baghdad was taken specially to be represented as a central point. The capital Baghdad has been adopted to be as a transmitting/receiving station with many stations lying within big Iraqi cities and some surrounded Arabian and foreign capitals that place within the Middle East zone.

Keywords- Radio wave propagation, High frequency communication, Ionospheric communication.

1. INTRODUCTION

Ionosphere is a name given to a layer or layers of ionized gas in the upper atmosphere extending from almost 60 km above the surface of the earth to altitudes of 1000 km and more [1]. The ionosphere makes up less than one percent of the mass of the atmosphere above 100 km. Even though the ionosphere only contains a small fraction of atmospheric material, it is very important because of its influence on the passage of radio waves. Most of the ionosphere is electrically neutral, but when solar radiation strikes the chemical constituents of the atmosphere, then electrons are dislodged from atoms and molecules to produce the ionospheric plasma. This occurs on the sunlit side of the Earth, and only the shorter wavelengths of solar radiation, (the extreme ultraviolet and X-ray), are energetic enough to produce this ionization. The presence of these charged particles makes the upper atmosphere an electrical conductor, which supports electric currents and affects radio waves [1].

2. PATH GEOMETRY PARAMETERS

The HF ionospheric radio communication systems consist of several operational parameters; these parameters are based on the geometry of the path. Path length and path bearings are examples of these parameters [2].

2.1 Path Length

The path length is the shortest path between the transmitting and receiving locations, which is taken to be the shorter of the great-circle distances between the two points, and which is computed as follows [2]:

$$\cos(\alpha) = \sin(\theta_1)\sin(\theta_2) + \cos(\theta_1)\cos(\theta_2)\cos(\Phi_1-\Phi_2) \quad ..(1)$$

Where:

θ_1 = geographic latitude of the transmitter,
Φ_1 = geographic longitude of the transmitter,
θ_2 = geographic latitude of the receiver,
Φ_2 = geographic longitude of a receiver,
α = path length in radians.

2.2 Bearings

The bearings referred to in the predictions are the true bearings (degrees clockwise from true North) of the transmitter with respect to the receiver and vice versa. Bearings may be entered in degrees or mils. North= 0°, east = 90°, south = 180° and west = 270°.

Having obtained the path length, the bearing of transmitter to the receiver and receiver to transmitter along the great circle path can be evaluated as follows [2]:

$$\cos(b_1) = \frac{\sin(\theta_2) - \sin(\theta_1)\cos(\alpha)}{\cos(\theta_1)\sin(\alpha)} \quad ,.....(2)$$

$$\cos(b_2) = \frac{\sin(\theta_1) - \sin(\theta_2)\cos(\alpha)}{\cos(\theta_2)\sin(\alpha)} \quad ,......(3)$$

Where:

b_1 = bearing transmitter to receiver in radians,
b_2 = bearing receiver to transmitter in radians.

3. INTERNATIONAL HF PROPAGATION MODELS

The predication communication models were becoming an important aspect in the development and planning of radio systems that operated within the frequency band [3]. After World War II, the communications industry turned its attention to other technologies, leading to a period of growth in High-Frequency (HF) radio communications during the 1960s and 1970s [4].

In the late 80's and the beginning 90's, various Ionospheric predication models have been made by U.S.

Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences (NTIA/ITS) like ICEPAC, VOACAP and REC533 models which have ability to predict many parameters for long time at given times of day as a function of frequency for a given HF path and a specified complement of equipment like MUF, FOT, gain, signal to noise ratio... etc. [5].

In this research, the REC533 model had been selected to calculate the reliable frequencies over the Middle East zone. The REC533 model had been selected because this model represents one of the best and modern HF communication models beside this model meets the main requirements of this study. The REC533 model is a window based implementation of the International Telecommunication Union's (ITU) propagation model (Recommendation ITU-R) [6]. It predicts the expected performance of high frequency communication links, so this model is useful in planning and operation of HF transmissions for the four seasons, different sunspot activities, hours of the day, and geographic location.

4. A SIMPLIFIED HF PROPAGATION MODEL

The current research work aims to construct a simplified HF communication prediction model. The preparation of the simplified model implies big significance; it will be a simple prediction tool for the reliable HF-frequencies that have approximately permanent link between Baghdad (the transmitting station) and many other receiving stations that are distributed within the Middle East region.

The goal of designing the empirical mathematical formula or model is to reach the simple, less expensive and fast way that can be served to forecast the reliable frequencies successful link conditions. Simplicity (less complexity), fast implementation, and reasonable accuracy should be satisfied by the adopted empirical model. These attributes can be achieved since the studied geographic region is limited. This limitation will supply the ability to study the considered region accurately and deeply; so, the limited region will procure the simplicity because most locations in the limited geographic region have approximately the same common peculiarities and characteristics, which make the analytical description easier and accurate. In the other hand, still the determination of simplified model parameters implies a big problem due to the numerous variations, which may be affected by the time (day or night), solar activity, climate variations, terrain effects, besides other parameters that affect the communication operation. The effects of these parameters must be taken into consideration during the construction of the analytical models, which will be used for predicting the most reliable HF-frequencies between the transmitting and receiving stations.

5. THE SUGGESTED EMPIRICAL FORMULA

To achieve an empirical desecration that can give a good prediction of the optimal reliable frequencies, which can assure nearly-permanent radio links between the stations whose position may be cited within the Middle East region, it is important to realize the nature of the HF-frequencies, and their behavior style, in order to determine the proper empirical formula for such kind of variations.

Depending on the results which have been got for the Middle East region (local and regional zones) using the adopted REC533 international model, the performance of HF-link depends essentially on the distance between the transmitting and receiving stations, or in other words it depends on the geographical locations of the both stations.

As mentioned before, the geographical location can be represented by two parameters, they are the longitude and latitude; therefore, the suggested empirical equation must be mainly depends on these parameters. In this work, the suggested empirical formula is taken as a three-dimensional power series (polynomial) equation, which can be represented in the following general form:

$$f_k = \sum_{n=0}^{N}\sum_{i=0}^{n} b_{ni} X_k^{n-i} Y_k^{i} \quad \ldots\ldots \ (4)$$

Where:

f_k: is the predicted optimal reliable frequency.

X_k: is the difference between the longitude of the transmitting and receiving stations (i.e, ΔLong= T_{Long}-R_{Long}; T_{Long} is the transmitter longitude, R_{Long} is the receiver Longitude).

Y_k: is the difference between the latitude of the transmitting and receiving stations (ΔLat= T_{Lat}-R_{Lat}; T_{Lat} is the transmitter latitude, R_{Lat} is the Receiver latitude).

b_{ni}: is the polynomial coefficients.

N : is the polynomial order.

Equation (4) can be expanded and rewritten, as follows:

$$f_k = a_0 + a_1 X_k + a_2 Y_k + a_3 X_k^2 + a_4 X_k Y_k + \ldots + a_q Y_k^N \ \ldots (5)$$

The solution of the previous N^{th} order 2D power series equation has been made by evaluating the adequate order of the polynomial equation and finding the values of its coefficients (a_0, a_1 …a_i).

In the present work, the methods of least square error are used to determine the polynomial coefficients. According to this method, the coefficients values of the best-fitted polynomials must be determined under the condition that the overall difference between the predicted optimal frequencies obtained from the REC533 interna-tional model and the corresponding optimal frequencies obtained from the polynomial equations must be as minimum as possible, i.e.

$$\chi^2 = \sum_{i=1}^{M} (f_i - f_i')^2 \qquad \ldots (6)$$

Where:

f_i: denotes the predicted frequency by using REC533 model at i^{th} station

f_i': denotes the predicted frequency by using the empirical polynomial at i^{th} station

M: is the number of considered stations, the number of stations (M) must, at least, more than the number of coefficients of the polynomial (q).

χ^2: is the sum of the overall squared different between the predicted frequencies.

By combining equations (4) & (5), we will get:

$$\chi^2 = \sum_{i=1}^{M} \left(f_k - a_0 - a_1 X_k - a_2 Y_k - a_3 X_k^2 - \ldots - a_q Y_k^N\right)^2 \quad \ldots (7)$$

The optimal values of (a_0, a_1, a_2,…a_q) can be determined using the condition:

$$\frac{\partial \chi^2}{\partial a_m} = 0 \quad , \; m = 0 \ldots M \qquad \ldots (8)$$

Because χ^2 should be minimum. By substituting equation (7) in (8), and after a straightforward manipulation, we will get a set of (q) simultan- eous linear equations with respect to (a_i) coefficients, these equations can be represented mathematically as follows:

$$\sum_i f_i = a_0 M + a_1 \sum_i X_i + a_2 \sum_i Y_i + \ldots + a_q \sum_i Y_i^N \quad \cdots (9a)$$

$$\sum_i X_i f_i = a_0 \sum_i X_i + a_1 \sum_i X_i^2 + a_2 \sum_i X_i Y_i + \ldots + a_q \sum_i X_i Y_i^N \quad ..(9b)$$

$$\sum_i Y_i f_i = a_0 \sum_i Y_i + a_1 \sum_i X_i Y_i + a_2 \sum_i Y_i^2 + \ldots + a_q \sum_i Y_i^{N+1} \quad ..(9c)$$

$$\sum_i X_i^2 f_i = a_0 \sum_i X_i^2 + a_1 \sum_i X_i^3 + a_2 \sum_i X_i^2 Y_i + \ldots + a_q \sum_i X_i^2 Y_i^N \quad ..(9d)$$

$$\sum_i Y_i^2 f_i = a_0 \sum_i Y_i^2 + a_1 \sum_i X_i Y_i^2 + a_2 \sum_i Y_i^3 + \ldots + a_q \sum_i Y_i^{N+2} \quad ..(9e)$$

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$$\sum_i Y_i^2 f_i = a_0 \sum_i Y_i^2 + a_1 \sum_i X_i Y_i^2 + a_2 \sum_i Y_i^3 + \ldots + a_q \sum_i Y_i^{N+2} \quad (9k)$$

The above simultaneous equations can be solved by using one of the well-known numerical analysis methods, in this work the Gauss elimination method is used to determine the polynomial coefficients from the above linear equations.

In order to apply the Gauss elimination method to solve the polynomial equation and get up to the suitable pattern of the suggested empirical formula, a computer program (POWF) has been written. The POWF program perform several operations in an effort to reach the best order polynomial that can give a good fitting within the optimal reliable frequencies obtained by analyzing the predicted frequencies obtained from the international propagation model. The operational steps of the POWF program can be clarified in the block diagram shown in figure (1).

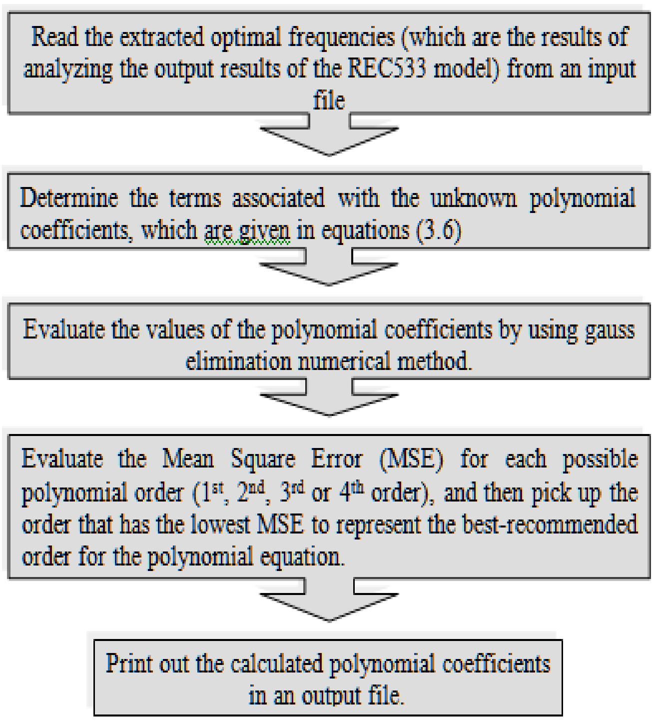

Fig. (1) A diagram illustrates the flow steps of the POWF program

The output file of the POWF program includes different detailed information about the fitted polynomial equations. Such information is supported by a brief comment about the tested connection, the number of the examined stations, the recommended best order of the suggested polynomial equation that has the minimum MSE, the calculated coefficient values for the best order, and a comparison between the frequency values calculated from the REC533 international model and the corresponding frequencies determined by using the simplified model POWF. A sample of the output file has been shown in figure (2).

File Identification: Local Communication Between Baghdad and Many Other Iraqi Cities

Number of Stations (M) : 140

The Best Polynomial Order : 3

The Minimum Overall Frequency : 1.446

Coefficients Set : a0 = 5.153 a1 = 0.089 a2 = -0.006 a3 = 0.101 a4 = 0.050

a5 = 0.104 a6 = -0.010 a7 = 0.001 a8 = 0.001 a9 = 0.003

A Comparison Between The Actual and Fitted Frequencies :

M	Longitude	Latitude	Z(Inter.)	Z(Poly.)
1	45.48	35.50	6.00	5.79
2	45.60	33.73	5.00	5.25
3	47.78	30.50	7.00	6.78
4	45.25	31.30	5.00	5.49
5	42.27	32.15	6.00	5.98

Fig. (2) Sample of the output file for the POWF program

The polynomial representation has been employed for the considered local and regional studied zones. The calculations, results, and comparison between the polynomial fitting results and the corresponding international model frequency results will be demonstrated in the following sub-sections.

5.1 The Local Zone

By using the suggested polynomial, the optimal reliable frequencies have been calculated for different stations located inside the local zone; these stations are distributed over Iraq territory from north to south and east to west. The polynomial coefficients have been determined by using POWF program. The following entries were used: the optimal reliable frequencies for thirty (30) different stations, as shown in figure (3), about one hundred forty (140) optimal reliable frequencies (where for each considered station about five selected frequencies was considered. The certain optimal frequency of the station is a reliable frequency whose S/N ratio is more than the threshold value (T=73 dB) for above 95% of the days of year.

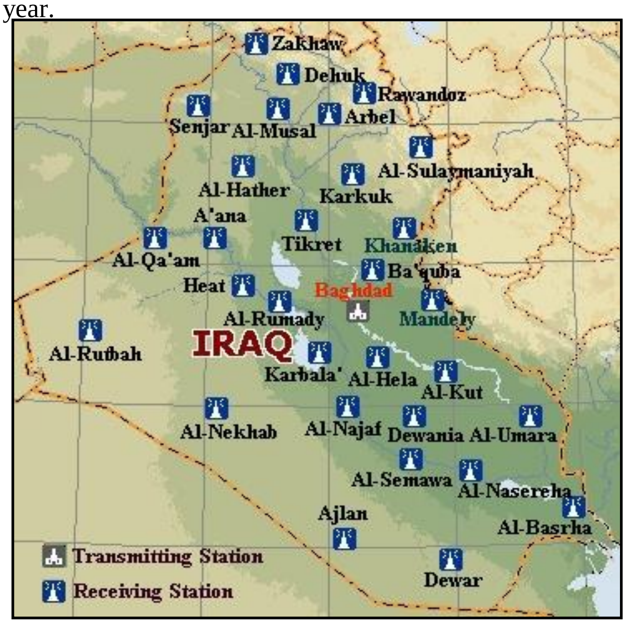

Fig. (3) The local transmitting and receiving stations

The result of executing POWF was a polynomial equation of the third order with overall error value equal to 1.446 and the polynomial coefficients are:

$a_0 = 5.153$ $a_1 = 0.089$ $a_2 = -0.006$
$a_3 = 0.101$ $a_4 = 0.050$ $a_5 = 0.104$
$a_6 = -0.010$ $a_7 = 0.001$ $a_8 = 0.001$
$a_9 = 0.003$

By substituting the geographical location (i.e., Longitude (X) and Latitude (Y)) for the each considered communication station in equation (5), the reliable frequencies will be determined. The frequencies determined by using polynomial representation have been presented in figure (4) by using contour graphical presentation. It can be noticed from figure (4) that the distribution of optimal reliable frequencies determined by using polynomial form is very close to the frequencies distributions generated by using the international REC533 model (as shown in figure (5)).

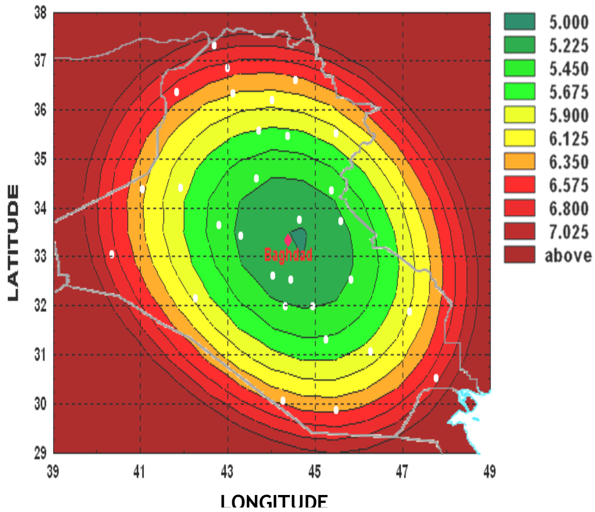

Fig. (4) The predicted optimal reliable frequency distribution generated from using the fitted polynomial for the local zone

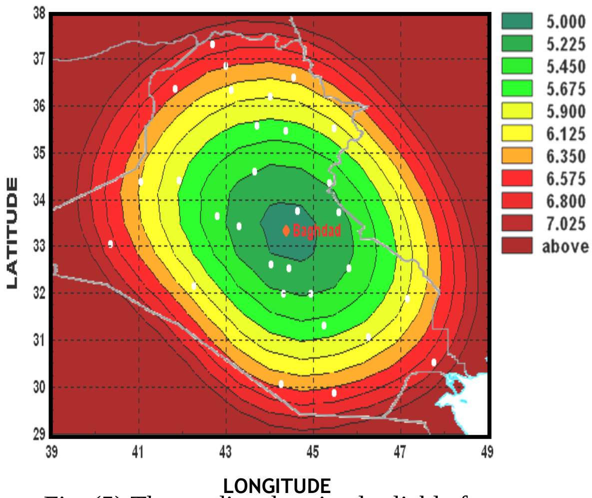

Fig. (5) The predicted optimal reliable frequency distribution extracted from the international model for the local zone

5.2 The Regional Zone

Under the following conditions, the calculations of the reliable frequencies have been made for the regional communications zone by using the empirical polynomial representation, which was determined, by using POWF program. The calculations have been performed for sixty nine (69) different stations distributed over the Middle East zone that surround the central station located in Baghdad, as shown in figure (2.9). Three hundred eighty five (385) optimal frequencies were selected and used for each HF-link. As in the case of local zone, the chosen frequencies have been made to those frequencies, which have an annual probability of successful link exceeding 95%.

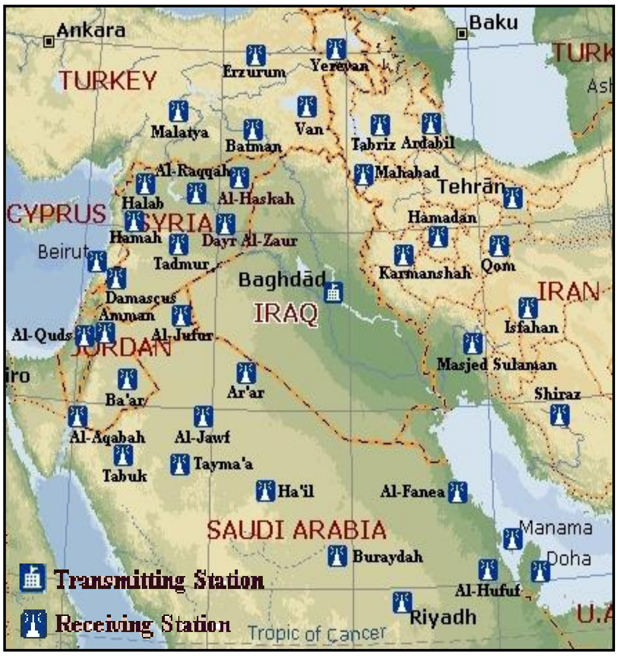

Fig. (6) The regional transmitting/receiving stations

The calculation of the polynomial coefficients for the regional zone have yielded the following results; the proper order of the best fitting is the second order (2^{nd}), with MSE equal to 1.796, and the polynomial coefficients are:

$a_0 = 5.546$ $a_1 = -0.016$ $a_2 = -0.016$

$a_3 = 0.035$ $a_4 = 0.012$ $a_5 = 0.052$

By using the determined polynomial, the distribution of the optimal reliable frequencies of the regional was determined. The frequency distribution has been presented in the form of the contour diagram; as shown in figure (7). In figure (8), the frequency distribution extracted from the analysis of REC533 results is presented in contour form, it is obvious that the results extracted by using the simplified (polynomial) representation is very similar to that produced by using the international REC5333 model.

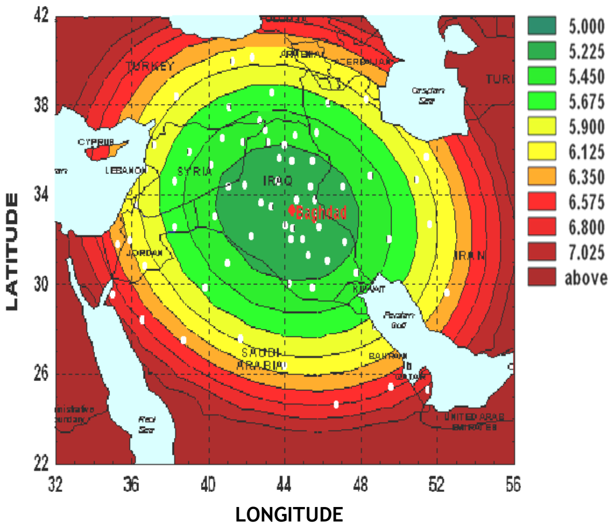

Fig. (7) The predicted optimal reliable frequencies produced by the polynomial representation for the regional zone

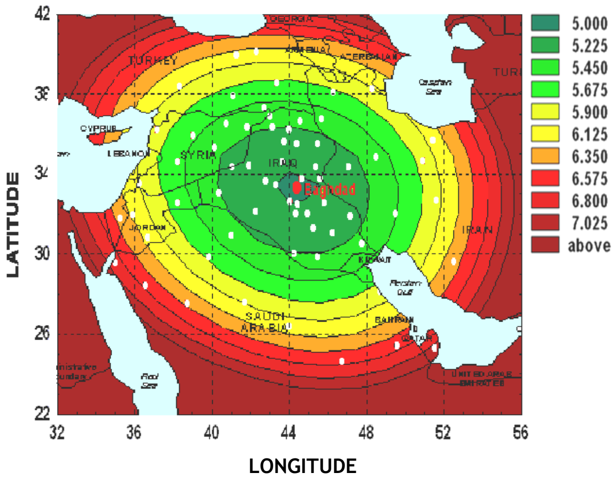

Fig. (8) The predicted optimal reliable frequencies produced by using the international REC533 model for the regional zone.

6. THE OVERALL SIMPLIFIED HF PROPAGATION MODEL

In this section, the final structure of the simplified HF propagation model will be investigated. The suggested model contains the two recommended formulas, which are obtained from studying the HF-communication for the local and regional zones, respectively.

The presented simplified propagation model allows predicting the annual permanent reliable frequencies between the transmitting station (Baghdad) and any other station located within the local or regional zone (i.e. it covers all stations placed in the Middle East zone or within the geographic zone extended about 2000Km around the capital Baghdad).

A computer program (SHEPM) was designed and implemented to perform the determinations of the simplified model. Figure (9) shows the steps of the computer program.

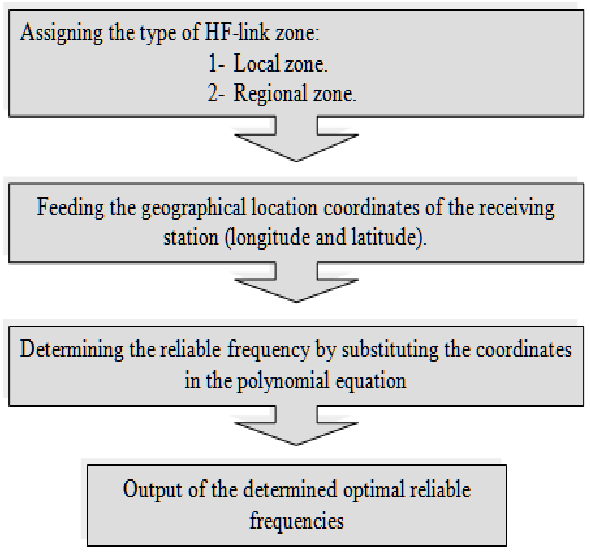

Fig. (9) Block diagram illustrates the steps of the suggested simplified HF propagation model.

7. THE RESULTS OF THE SIMPLIFIED HF PROPAGATION MODE

In order to examine the suggested model, the reliable frequency predictions for both the local and regional zones were made. For the local zone the calculation has been done for the area defined by the longitude range extended from (40.0°- 48.0° E) and latitude extended (29.0°- 37.25° N). Figure (10) presents the distribution of the determined reliable frequencies; the results have been presented by using the graphical representation, whereas figure (11) presents the distribution by using the surface mesh diagram.

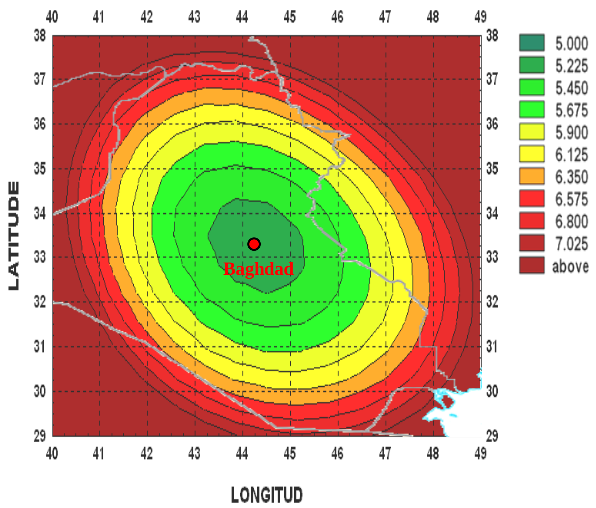

Fig. (10) The contour diagram of the distribution of the optimal reliable frequencies over the area of the local zone

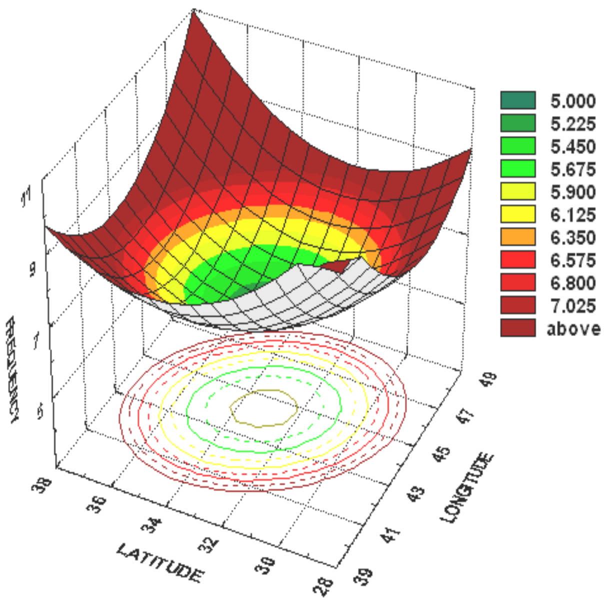

Fig. (3.9) The surface mesh diagram of the distribution of the optimal reliable frequencies for the local zone area

For the regional zone the frequencies for the geographic area extended between (35.0°E to 52.5°E) for longitude, and between (24.5°N to 42.5°N) for latitude.

As in the case of local zone, the results are presented by using the contour diagram (figure 12) and the surface mesh diagram (see figure 13).

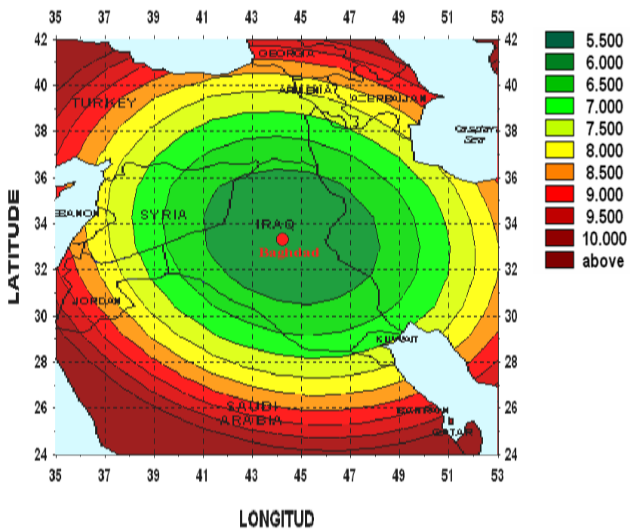

Fig. (12) The contour diagram of the most reliable frequency distribution for the regional zone.

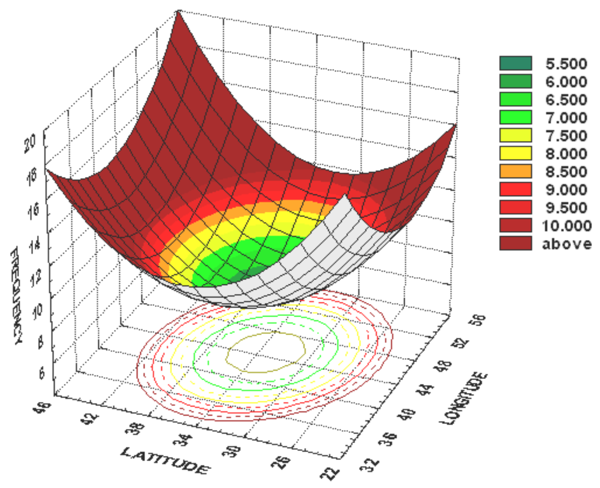

Fig. (13) The surface mesh diagram of the distribution of the optimal reliable frequencies for the local zone area

8. DISCUSSION AND CONCLUSION

In this research, the calculations of the most reliable frequencies between the transmitting and receiving stations using a suggested simplified mathematical model have been made to describe the spatial distribution of the predicted reliable frequencies. The suggested model enable the user to predict the most reliable (permanent) frequencies which can offer a reliable connection between Baghdad and any receiver station located within the Middle East zone.

For the local zone, the most reliable frequencies have been recalculated between Baghdad and the counties and cities that distributed within the Iraq territory by using the suggested simplified model. The calculated results gave good fitting when they have compared with the frequencies calculated according to the REC533 international model.

In the regional zone, the most reliable frequencies have been recalculated between Baghdad and many other locations that are distributed in the studied zone by using the suggested mathematical model. The calculated reliable frequencies show a semi-circular contour distribution shape which is very similar to the frequency contour distribution established by using the analysis results of the international propagation model.

In the last stage of this work, a simplified HF propagation model has been accomplished to predict the most reliable frequencies between Baghdad and different locations placed in the Middle East zone. In this model, the frequency calculations depend on the geographical coordinates (longitude & latitude) for the transmitting/receiving station. Since, the capital Baghdad has been adopted in this work as a fixed central transmitting/receiving station, so the suggested model for the HF-reliable frequency was based on the longitude and latitude values of the other station.

The calculations of the annual reliable frequencies have been made for two regions, the first one has a coverage lies between the following geographical coordinates, longitude from (40.0^o - 48.0^oE) and latitude (29.0^o - 37.25^oN), which is approximately represent the geographical Iraq area coordinates. The results of this calculation have been illustrated in figures (10) and (11), which indicate that the frequency contour and surface mesh distribution gave the same configuration like those shown in figures (4) and (5), which represent the contour diagrams of the most reliable frequencies calculated in the preceding stages.

The second calculated area has a coverage defined by the longitude range (35.0^oE to 52.5^oE) and the latitude (24.5^oN to 42.5^oN), these coordinates have been chosen to cover the Middle East area resemble to the area adopted in the study of the regional zone. The calculated most reliable frequencies for this region have been demonstrated in figures (12) and (13), the contour and surface mesh frequencies distribution. The contour diagram has a semi-circular shape which is similar to the shape of the contour diagram calculated by the analysis results of the predictions of REC533 international model.

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