The Ionospheric Effect on HF Wave Propagation in Equatorial Region

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ABSTRACT

A 3D raytracing model was employed to study the effect of the equatorial ionosphere on High Frequency (HF) radio propagation. The ionosphere was generated by Parameterized Ionospheric Model to represent the ionospheric profiles in the equatorial region. The homogeneous ionospheric profile was used for comparison of effect of the ionospheric inhomogeneity on HF ray tracing. The magnetic effect on HF propagation was investigated as well. The effect of ionospheric inhomogeneity was found to be substantial.

1. INTRODUCTION

Ray tracing is a powerful tool and especially useful in applications requiring a detailed knowledge of radio wave propagation through the ionosphere. There are a number of modern radio wave applications that make use of ionospheric propagation, such as the long range communication systems, single station location and HF direction finding systems. These radio wave systems depend critically on realistic ionospheric modelling, and accurate ray tracing through these ionospheric models.

Ray tracing techniques includes two main approaches: numerical solution of Hamilton's equations in the ionosphere and analytic technique. Accurate ray tracing is normally carried out using numerical approach. A well known ray tracing model (Jones and Stephenson, 1975) is based on a completely numerical solution of coupled first order Haselgrove equations. In the numerical solution of Hamilton's equations the ionosphere is typically specified as a set of tabular height profiles on latitude-longitude points. For consideration of long paths this involves large array storage. As its name suggests, analytic ray tracing techniques used explicit equations to define the ionosphere and to determine ray parameters such as ground range, reflection height, phase path, group path and divergent power. This approach, consequently, is considerably less time consuming than numerical ray tracing. Despite its advantage in computational speed, analytic ray tracing does, however, have two main limitations. The first is the absence of explicit equations which include the effects of the Earth's magnetic field on the ray path. The second limitation is the difficulty of including the horizontal gradients in electron density profile within the ionosphere. Besides, it cannot adopt any real time ionospheric measurement (for example ionosonde data) to improve its ray tracing result.

The ionosphere in the equatorial region is not spherically symmetric. Horizontal gradients in the electron density distribution exist of sufficient magnitude to appreciably affect predictions of range, cause substantial ray-path departures from great circle propagation, and move ionospheric reflection positions by significant amounts away from control points obtained by simple predictions. Davis and Rush (1985) have shown these interesting effects of the horizontal gradients for the equatorial anomaly, subauroral trough, sunrise and sunset transition regions, traveling ionic disturbances and other situations. Thus, accurate modeling of the ionosphere is crucial to achieve accurate ray tracing results.

In this paper, the results of ionospheric effect on High Frequency (HF) wave propagation will be presented by using Jones 3D ray tracing numerical model. The ionospheric profiles are generated by the well established Parameterized Ionospheric Model (PIM). The data and methods will be given in the following sections. In section 3, the ionospheric effects on ray tracing results will be discussed. The magnetic effect on ray tracing will be presented in session 4. A quantitative comparison of the effect of ionospheric inhomogeneity and the effect of magnetic field is illustrated in session 5. Conclusions and discussions will be given in the last section.

2. DATA AND METHODS

For 3D ray tracing in the equatorial region, 3D ionospheric profile data is required. The data used to perform ray tracing covers a region from 74°-134°E in longitude, 22S°-30°N in latitude, and a height of 600km. The hourly ionospheric data was generated by PIM using the real time solar indices on 18

March, 2003. The Sun Spot Number (SSN) is 72 (12-month smoothed), radio flux (F10.7) 112.7 and K_p 3.5, which represents a moderate strength of solar activity (The latest peak of solar activity occurred in year 2001 and 2002, SSN~120, F10.7 ~ 200). The date is close to the equinox. The bearing (i.e., azimuth angle) of ray tracing is taken as 45 degrees for all cases. All the ray tracings start from the location at latitude=0° N and longitude = 83° E. This is an arbitrary location just for the purpose of investigation and illustration of the effect of ionospheric inhomogeneity on HF propagation.

For comparison, a horizontally homogeneous ionosphere is used. The vertical ionospheric profile is given by a parabolic distribution. The formula is:

$$f_N^2 = f_c^2\left[1.-\left(\frac{h-h_{\max}}{Y_m}\right)^2\right] \text{ if } f_N^2 > 0 \qquad (1)$$

$$f_N^2 = 0. \text{ otherwise}$$

where f_N is the critical frequency (or plasma frequency) varying with altitude h, f_c the maximum critical frequency in Mhz, Y_m the semi-thickness of the ionosphere in kilometer, h_{max} the height of maximum electron density in kilometer.

3. IONOSPHERIC EFFCTS ON RAY TRACING RESULTS

The equatorial ionosphere has special features compared to the ionosphere over temperate region. Figure 1 is the contour of critical frequency at the altitude of 390km (which corresponds to the maximum electron density height for the daytime in PIM) in equatorial region at UT=09, 18 Mar 03. UT=09 is local time 2~3PM, corresponding to the highest ionization period for the day. It shows the location of two maximum centers at about latitude 3° south and 22° North, which is equatorial anomaly. The peak values are above 12Mhz. These two maximum centers are located asymmetrically by the geo-magnetic equator, which is at about 10° north of geo-graphic equator in this region. The equatorial anomaly occurs due to fountain effect. The movement of electrons in ionosphere is affected by magnetic field and electric field. The combined effect of the electric and magnetic fields on the electrons causes them to rise upwards. As they rise, they encounter the horizontal lines of the force of the Earth's magnetic field. The electrons move down these field lines and re-enter the main body of the ionosphere, giving rise to large clumps of electrons at latitudes 10° to 20° from the magnetic equator. It is observed from Figure 1 that the two centers are not well symmetric and large gradient from south to north exists. Gradients also exist for the east-west direction. Those gradients will greatly affect the ray paths that propagate in the ionosphere.

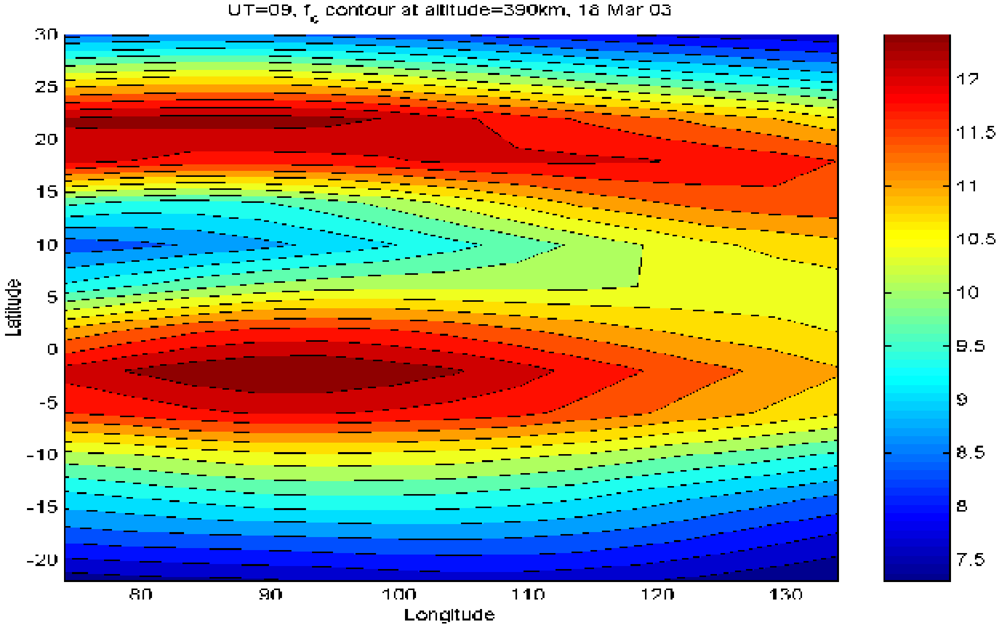

Fig. 1: Contour plot of critical frequency at altitude=390km, UT=09, 18Mar 03.

Ray tracing was performed in the ionosphere shown in Fig 1 and the homogeneous ionosphere obtained using Eq 1 to compare the effect of ionospheric inhomogeneity on HF wave propagation. One of the ray tracing results is shown in Fig 2. The operating frequency is 10Mhz with a bearing of 45 degrees. The maximum critical frequency for the homogeneous ionosphere is taken as the maximum value in the inhomogeneous profile close to the geo-location of 0° N in latitude and 83° E in longitude. The dotted lines represent the ray paths in inhomogeneous ionosphere, while the solid lines show the ray paths in homogeneous ionosphere. We found that the ground ranges of ray paths in inhomogeneous ionosphere are much greater than those in homogeneous ionosphere. The lower the take-off angles, the greater the difference between the ground range of ray path in inhomogeneous and homogeneous ionosphere. For rays with long ground range, the difference between homogenous and inhomogeneous ionosphere may be as large as a few hundred kilometers.

We observed strong gradients in both north-south and east-west directions in Fig 1. When the ray path propagates with the bearing of 45 degrees, it experiences strong irregular reflection from the inhomogeneous ionosphere layers. The effect of ionospheric inhomogeniety severely affects the ray path and leads to large ray path difference from the one observed in homogeneous ionosphere. As we know, the inhomogeneous ionosphere is much more realistic than the homogeneous one. Thus, in summary, the effect of ionospheric inhomogeneity must be taken into account during ray tracing; otherwise, large raytracing error will be expected.

4. THE EFFECT OF MAGETIC FIELD ON HF WAVE PROPAGATION

When electro-magnetic wave propagates in the magnetic and electric field, its ray path is affected by the two fields. When geomagnetic field is disturbed by solar activities, the ionosphere is disturbed and radio ray path will be disturbed as well. Currently, we only consider how a constant geomagnetic field with moderate strength affects the ray path. In order to account for the disturbances of the geomagnetic field, real time measurements of geomagnetic field, ionospheric variations and so on are required and will be considered in subsequent study.

The effect of earth's magnetic field leads to significant non-planar ray path. Fig 3 is the plot of the ray paths in inhomogeneous ionosphere with and without magnetic field. We found that the ray paths and ground ranges with and without field are quite different.

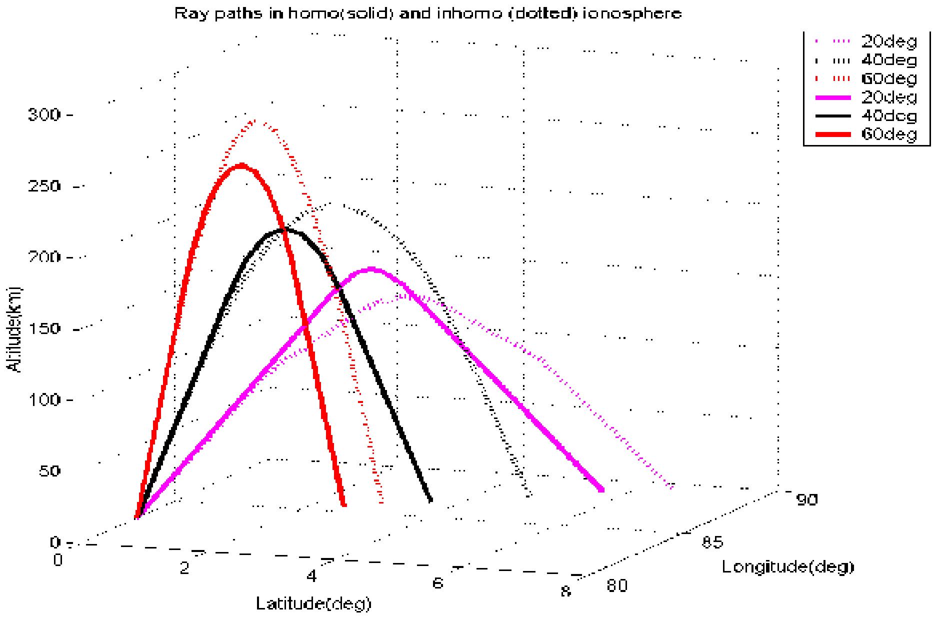

Fig. 2: The ray paths of operating frequency 10Mhz with different take-off angles (20, 40 and 60 degrees) in homogeneous (solid) and inhomogeneous (dotted) ionosphere at UT=09, 18 Mar 2003. azim_0 = 45deg

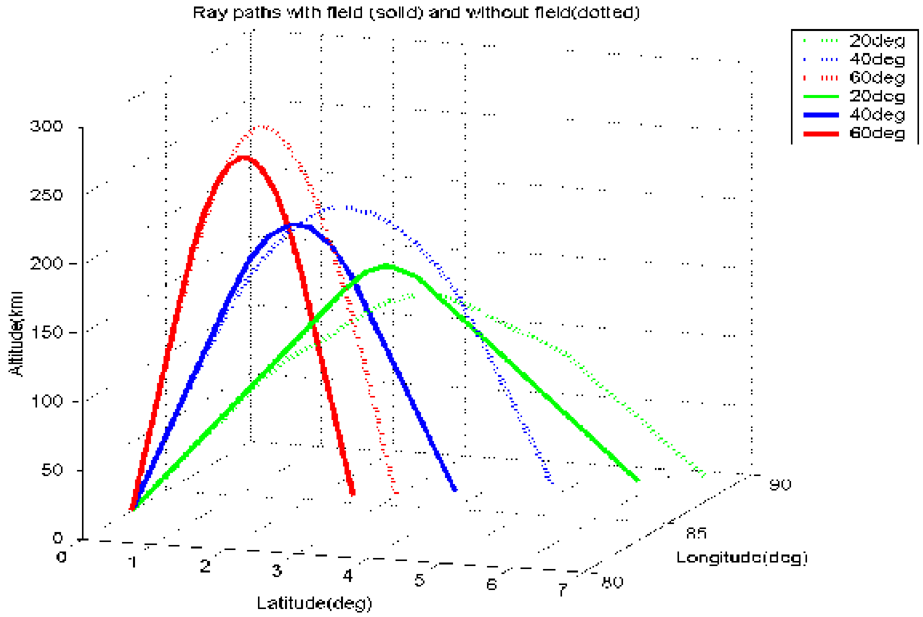

Fig. 3: The 3D ray paths with/without magnetic field at UT=09, 18 Mar 03, operating frequency = 10Mhz, $azim_0$ = 45deg. Solid lines: with field, dotted lines: without field.

Interestingly, the directions of the ray paths with magnetic field tilt away from the direction of the ray paths without magnetic field. Their ground ranges are different for the three elevation angles. The ground ranges without magnetic field are larger than those with magnetic field. The most significant difference occurs in bearing changes as the ray path propagates. Fig 4(a) shows the bearings with respect to ground ranges for three take-off angles: 20, 40 and 60 degrees, at UT=09, 18 Mar 03, with operating frequency = 10Mhz, and initial azim=45degrees. For the ray with take-off angle of 60 degree (red solid line), the bearing when magnetic field is considered gets the largest shift. When the ray enters the ionosphere, its bearing shifts away from the initial value of 45 degrees to a value that is larger than 48 degrees. Then it negotiates back to a direction that is near to the original, and remains at about 2.5 degrees away from the original bearing. The corresponding line (red dotted line) without magnetic field is bent to the left of ray propagation direction by about half degree only. The ground ranges of the two rays (red solid and dotted lines) are very close. The shift of the bearing with take-off angle of 40 degrees is much less than that of take-off angle of 60 degrees. The bearing of the ray with magnetic field shifts less than 2 degrees while the bearing of the ray without magnetic field shifts less than half degree (blue lines). Their ground ranges are different now. The shift of the bearing with take-off angle of 20 degrees is much less than those with take-off angles of 60 and 40 degrees. The bearing of the ray with magnetic field shifts by less than 1 degree, while the bearing of the ray without magnetic field is almost unchanged (green lines). However, their ground ranges are a bit different.

Fig 4(b) shows the shift of the ray path bearing with respect to altitude with and without magnetic field in a vertical plane. The curves in this figure are very interesting, especially the one with take-off angle of 60 degrees with magnetic field. When the ray enters into the ionosphere (solid red line), it is bent to the right of the original propagation direction as altitude increases. When it reaches the maximum height of about 250km, it is bent to the left until it reaches the ground again. The whole path in the vertical plane is asymmetrical. The corresponding one without magnetic field (dotted red line) is shifted as well to the right side. However, the curve in vertical plane is nearly symmetrical and the shift is much smaller (within 0.5 degree). The reasons leading to the bearing shift needs further study.

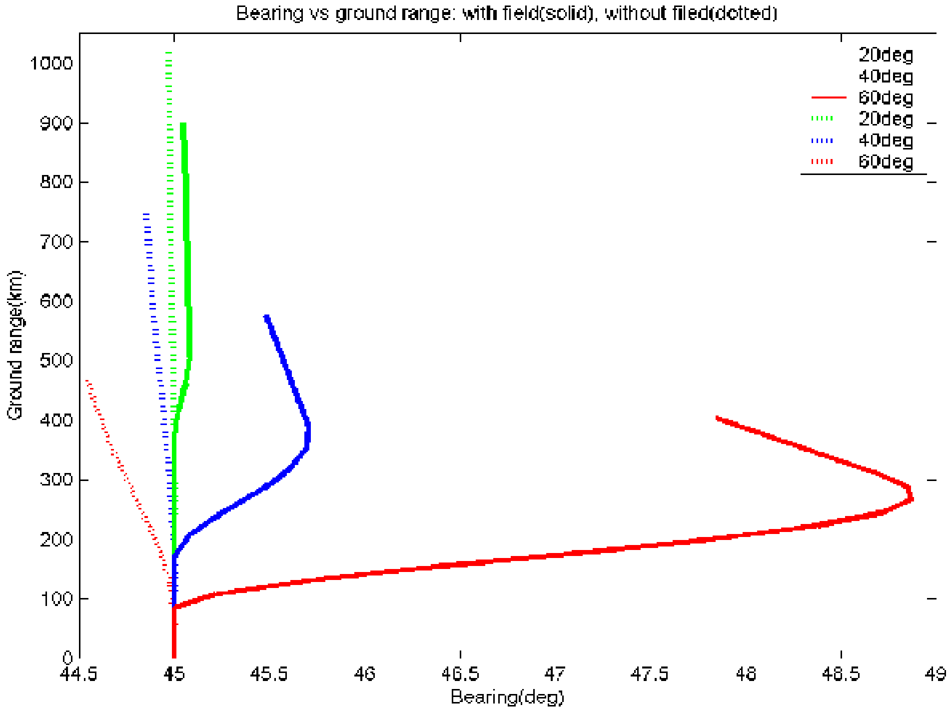

Fig. 4(a): The shift of bearing against ground range with and without magnetic field, when f=10Mhz, initial bearing = 45 degrees and UT=09 on18 Mar 03.

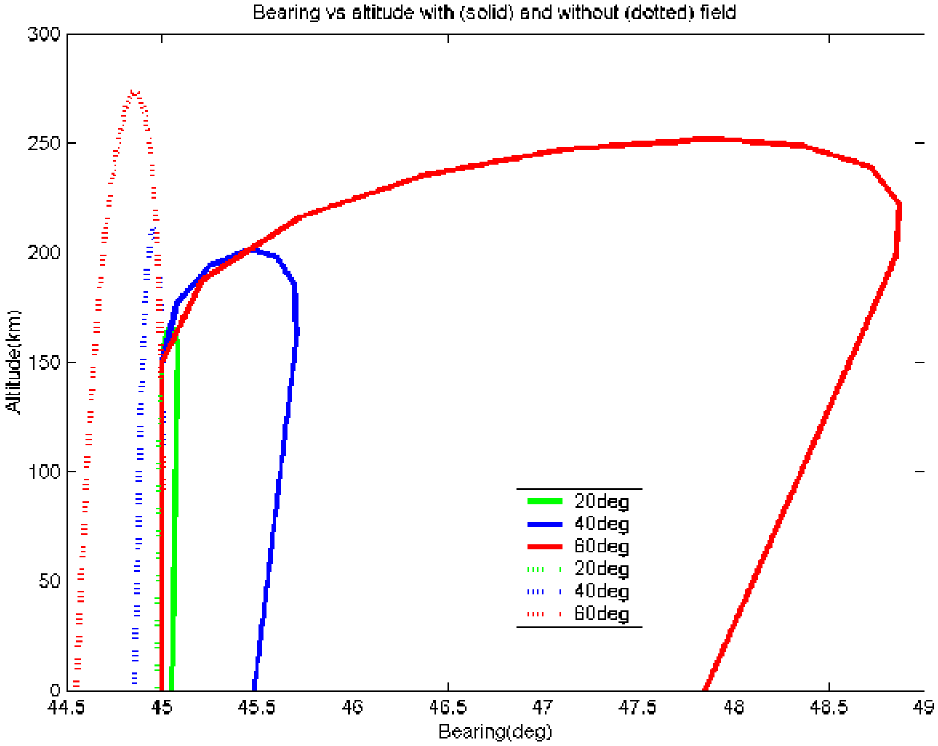

Fig. 4 (b): The shift of bearing against altitude with and without magnetic field, when f=10Mhz, initial bearing = 45 degree and UT=09 on18 Mar 03.

In summary, we may draw the conclusion that magnetic field affects more significantly those ray paths with high take-off angles, after considering cases of other operating frequencies. That is, the higher the take-off angle, the greater is the bearing shifts. This is because the ray is almost perpendicular to the magnetic field lines when ray is transmitted with high take-off angles. Thus, the magnetic and electric forces in the ionosphere bend the rays much more than those with low take-off angles, which are almost parallel to the magnetic field lines and hence suffers less ionospheric dispersion.

5. THE QUANTITATIVE STUDY OF THE EFFECTS OF THE IONOSPHERIC INHOMOGENEITY AND MAGNETIC FIELD ON RAY TRACING

Next, let us make some comparison on statistical results with regards to the rays' ground ranges for different take-off angles and operating frequencies. The scenarios to be compared are as follows:

i) Ionosphere is homogeneous.
ii) Ionosphere is inhomogeneous.
iii) Ionosphere is inhomogeneous with magnetic field.

From the comparisons, we hope to assess the relative effects of the magnetic field of the earth and inhomogeneity on ground ranges. At the same time, we can evaluate the effects varying with operating frequencies and take-off angles. The data employed stops at a frequency of 10Mhz because rays with higher frequency penetrate the ionosphere when take-off angle is high (such as 60, 70 degrees, etc).

First, I will illustrate the effect of inhomogeneity of the ionosphere on ground range and how it varies with frequency and take-off angels. The total comparison is plotted in Figure 5. The Y axis stands for the average ground range difference, the X axis the total number of data points used to compute the ground range difference (the data sequence is arranged in this way: at each frequency, the ground-range difference is arranged in the descending order of elevation angel and the frequency set is arranged in ascending order.). We observed that the average ground range difference between the ray in homogeneous and inhomogeneous ionosphere for all the frequencies and take-off angles (the purple curve in Fig 5) is much larger than the ground range difference (dark blue curve) between the ray in inhomogeneous ionosphere with and without magnetic field. Furthermore, we observed an oscillation pattern in the purple curve. Each jagged shape corresponds to the data with elevation angle changing from 70 to 10 degrees at certain frequency. We may infer from it that the ground-range difference increases with the decrease of elevation angle when the ray is in inhomogeneous ionosphere. Moreover, the amplitude of the oscillation of ground-range difference becomes larger and larger with the increase of frequency when the ray is in inhomogeneous ionosphere. Thus, we group the data according to frequency and take-off angle, respectively, to analyze the error trend separately.

The plot of the ground range difference between the ray in homogeneous and inhomogeneous ionosphere without magnetic field, and ground range difference between the ray in inhomogeneous ionosphere with and without magnetic field with respect to take-off angles is presented in Fig 6(a). We noticed that the ground range difference between the ray in homogeneous ionosphere and inhomogeneous ionosphere (the purple curve) is much larger than that between the ray in inhomogeneous ionosphere with and without magnetic field (the dark blue curve). This implies that the effect of ionospheric inhomogeneity is much more important than the effect of magnetic field on HF wave propagation. This is especially for the low take-off angle, where the impact of the ionospheric inhomogeniety on ray propagation is even larger. It may be as large as 400km.

The plot of the ground range difference between the ray in homogeneous and inhomogeneous ionosphere without magnetic field, and ground range difference between the ray in inhomogeneous ionosphere with and without magnetic field with respect to different frequencies is presented in Fig 6(b). Again, the ground range difference between the ray in inhomogeneous ionosphere with and without magnetic field (the dark blue curve) is very small compared to the ground range difference between the ray in homogeneous ionosphere and inhomogeneous ionosphere (the purple curve). A quasi-linear trend (the purple curve) is observed in this figure. Thus, we may conclude that the ionospheric inhomogeneity affects the ground range much more than the magnetic field. It will result in much larger error in ray tracing if inhomogeniety of the ionosphere is not taken into account.

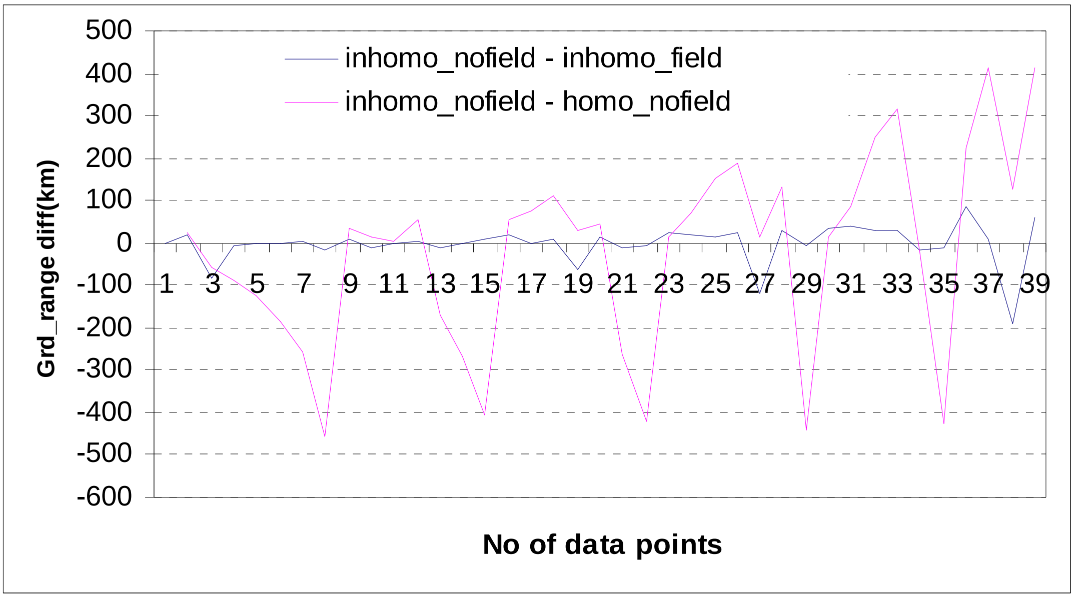

Fig. 5: The ground range differences between the ray in homogeneous and inhomogeneous ionosphere and the ray in inhomogeneous ionosphere with and without magnetic field.

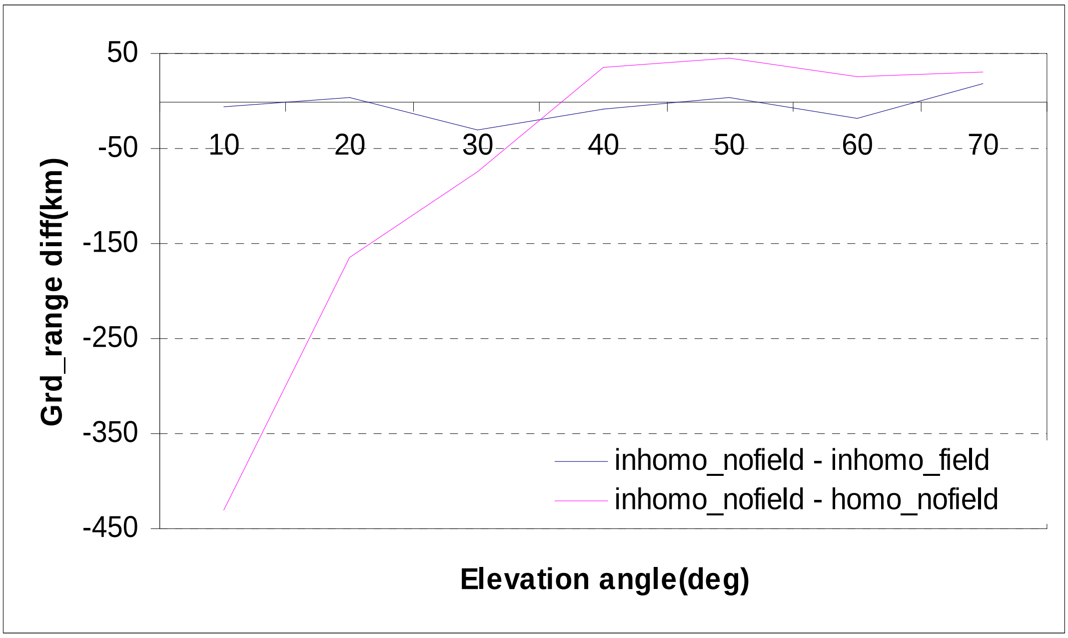

Fig. 6(a): Ground range differences between the rays in homogeneous and inhomogeneous ionosphere without magnetic field (purple), and ray in inhomogeneous ionosphere without magnetic field and with magnetic field (dark blue) with respect to take-off angles.

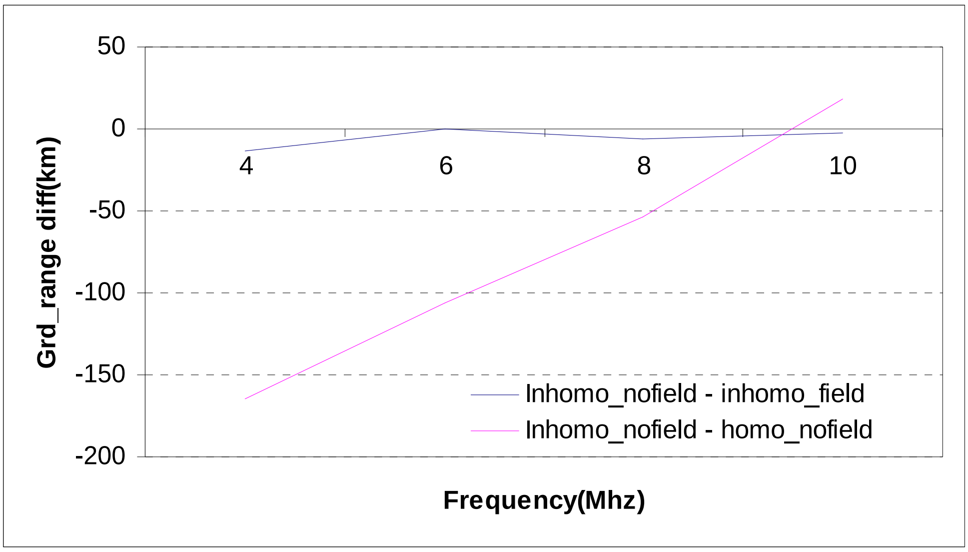

Fig. 6(b): Ground range differences between the rays in homogeneous and inhomogeneous ionosphere (purple), and ray in inhomogeneous ionosphere without magnetic field and with magnetic field (dark blue) with respect to frequency.

6. COCLUSIONS AND DISCUSSIONS

We have used a 3D-raytracing model to study the ionospheric effect on HF ray propagation in the equatorial region, and an ionospheric model PIM to generate 3D and inhomogeneous ionospheric profiles for realistic raytracing. Three scenarios of ionosphere are used as the propagation media for comparison, (1) homogeneous ionosphere (parabolic), (2) inhomogeneous ionosphere, (3) inhomogeneous ionosphere with magnetic field. Simulations are carried out under the three ionospheric conditions. We draw the following conclusions. Ionospheric inhomogeneity plays the most important role in increasing raytracing accuracy. It explains most of the average-ground-range difference between the ray in inhomogeneous and homogeneous ionosphere, with or without the inclusion of the magnetic field. By considering ionospheric inhomogeneity, we expect a reduction in ground range error by few tens of kilometres. On a separate note, we found that the magnetic field affects the ray path severely inside the ionosphere, especially when the take-off angle of the ray is high. It can cause a bearing shift as large as a few degrees.

However, a 3D inhomogeneous ionosphere generated by PIM represents only an average state of the ionosphere. With the availability of real time local ionospheric data, PIM modeling can include the local disturbances within the ionosphere, the geomagnetic fluctuations of the magnetic field lines and other real time ionospheric variations. , This will lead to more accurate ray tracing results, which we hope to achieve in our future work in this area.

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