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Maximum Useable Frequency Prediction Using Vertical Incidence Data

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Abstract

The formulation of dependable propagation prediction techniques is of profound importance in the advancement of radio science and such techniques can be of engineering value. In this paper, acompact review of the propagation prediction methods and models for HF communication systems is presented. Propagation prediction challenges and some approaches for meeting these challenges are also described.The comparison between predicted and measured maximum useable frequency (MUF) is used for analysing the accuracy of the ITU-R P.533 and the Ray theory prediction methods in the Southern African region. ITU-R P.533 method was found to generally give a better agreement with the measured datathan did Ray theory method.

Keywords:*MUF, propagation prediction, HF communication, radio science, ionosphere*

1. Introduction

The ionosphere is a region of weakly ionised plasma which ranges from about 50 km to beyond 1000 km altitude within the Earth's atmosphere. This region is important to sky-wave radio propagation and provides the basis for almost all HF communications beyond line of sight (LOS)[1-3]. The ionosphere is also essentialin optimising satellite communication systems since the satellite signals traverse the ionosphere, leading toattenuation, depolarization, refractionand dispersion as a result of scattering and frequency dependent group delay. When an HF radio wave reaches the ionosphere, it can be refracted such that itradiates back toward the Earth at somehorizontal distance beyond the horizon (see Figure 1). This effect is due to refraction but it is often apparentlyconsidered to be a reflection [4].

HF communication is usedfor short and long range tactical and strategic military purposes since its antennas and equipment can be deployed rapidly to provide immediate command post communications without the need for careful site planning, as is the casewith LOS communication. In civilian society, HF is used for international broadcasts by organizations such as the British Broadcasting Corporation and the Voice of America [5]. In Southern Africa, HF exploitation is relatively common and is a primary method for communication since satellite communication infrastructure is not as well improved as in the developed countries.As a result, the use of HF communication is preferred due to its relative simplicity, its capability to provide long range communication at low power without repeater base stations, its ease of development and its low cost [6].

Since ionosphericvariability affect HF radio propagation, the maintenance of an ionospheric link under satisfactory conditions requires that the usable frequency band be known. The highest possible frequency that can be used to transmit over acommunication link under given ionospheric conditions is known as the Maximum Usable Frequency (MUF). Frequencies higher than the MUF penetrate the ionosphere and continue into space. Frequencies lower than the MUF tend to refract back to earth[7,8]. The MUF primarily relies upon the electrondensity of the ionosphereand hence varies according to hour, day, season as well as geographical coordinates where the apparent reflection occurs in the ionosphere. MUF also varies with the geographical location of the transmitter (Tx) and the receiver (Rx) and the solar activity.Several MUF prediction models and programs have been developed since the 1980s and these include MINIMUF [9], MICROMUF [10], EINMUF [11], HFBC84 [12], VOACAP [13] and REC533 [14] among others. Most of these models are used for global description of HF communication parameters and they imply some complexity in their mathematical manipulation. In this paper, a compact review of the propagation prediction methods and models for HF communication systems is presented. The spatial and temporal variation of MUF parameter is also investigated and two prediction methods (Ray theory and ITU-R P.533) are compared to ionospheric measurements to determine the accuracy to which they predict MUF values over the Southern African region.

2. HF Propagation Prediction

Before thedesignimplementation and confirming planning of radio communication systems, accurate propagation characteristics of the communication path should be well known. In the absence of propagation predictions, such parameter estimations can only be achieved by field measurements which tend to be expensive and time consuming. The formulation of dependable propagation prediction techniques is of profound importance in the advancement of radio science and such techniques can be of engineering value.The results deduced from the theoretical models developed should, of course, be measured against experimental results as far as possible to confirm their validity. It is necessary to critically analyse the simplified assumptions of these models to indicate their accuracy and to pinpoint where improvements can be made.

2.1 Approaches to propagation prediction

The aim of radio propagation prediction is often to ascertain the likelihood of suitable performance of a communication system that is dependent upon electromagnetic wave propagation. This is essential in communication network planning. Ionospheric propagation conditions are certainly variable in space and time, thus, different prediction techniquesshould be developed according to the duration chosen for the forecast.

Propagation predictions can be classified as short-term, medium-term or long-term depending on the period on which they are established [8,15]. Long-term predictions are valid over a period of a month and are developed from ionospheric characteristics, from the prediction of the solar activity index and from statistics of the values of the ionospheric indices measured during previous similar situations[16].Long-term predictions are useful for frequency management, circuit and service planning as well as radio system design and testing. This type of prediction has an important role in the provision of information on the choice of frequency range, Tx location, Tx power and the selection of suitable Tx and Rx antennas. Medium-term predictions are intended atforecasting the generalpropagation conditions and particularly the MUF values during the next week period [8]. Such predictions are meant for the correction and adaptation of long-term ionospheric forecasts with respect to season as well as solar and geomagnetic activities. The fundamental characteristics of these predictions are therefore their more accurate approximationof seasonal variations and their better account of solar and magnetic activities.On the other hand, short-term predictions are generally stipulated over the next 24 hours and are intended at forecastingthe usable frequency band over six hour periods in comparison with the usable frequency band defined over the long term. These short-term predictions aremeant for providing corrections of long-term forecasts on a daily basis over permanent areas[17].As a result, they generally refer to departures from the median behaviour. The short-term ionosphericfluctuations may be specified in terms of hourly, daily and weekly variabilities. There are also second-to-second and minute-to-minute variations but this group of variations broadly falls within the sphere of unpredictable behaviour. These very short-term predictions are generally referred to as nowcasts [18].

2.2 Propagation modeling challenges

Ionosphericpropagation modelingcomes in different forms ranging from empirical to purely theoretical. In some cases, approaches may also include a combination of these forms, although empirical models dominate the field [6,18]. Recent advancements involve allowance for adapting the prediction models to exploit nearreal-time measured data for special applications, leading to real-time ionospheric models.This category of models is driven by a system of solar-terrestrial observations. However, this approach to propagation modelling leads to an improved understanding of ionosphericvariability and hence short-term forecasts.

Most propagation models in use today are largely specified on the basis of semi-empirical relationships derived from observational data. Ionospheric models allow forradio system performance assessment and prediction and are the engines that drive HF system performance models such as IONCAP [19]. Empirical models are usually a set of equations derived from long records of extensive field measurements [20,21]. There is a distinct bias of the empirical models to those areas where more data had been collected. This discrepancy tend to leave the oceanic areas, equatorial regions and in particular, Southern African region under-represented. One of the main impediments of empirical models is that they cannot be used for different environments without modification or adaptation. On the other hand, site-specific models are based on numerical methods such as the ray-tracing method and the finite difference time domain (FDTD) method [22,23]. Their input parameters can be very detailed and accurate but their drawback is the large computational overhead that may be prohibitive for some complex environments. Theoretical models are derived physically assuming some ideal conditions and are generally more efficient than the site-specific models and more site specific than the empirical models [22]. The accuracy of propagation prediction involves many aspects. To meet these challenges, existing prediction methods should be modified and improved, and new procedures and adaptation techniques have to be developed.

3. MUF Prediction Methods

3.1Ray theory method

If the effects of the Earth's magnetic field are ignored then the refractive index n of the ionosphere is given by: [24].

$$n^2 = 1 - \left(\frac{f_p}{f}\right)^2 \qquad (1)$$

where$f$ is the wave frequency and $f_p$is the plasma frequency. To predict the bending of the ray we use a layered approximation to the ionosphere. Thus a ray entering the ionosphere at an angle of incidence ψ_i will be reflected at a height where the ionisation is such that n has the value:

$$n = sin\psi_i \qquad (2)$$

At vertical incidence the reflection condition occurs when n equals zero and from Eq. (1) this occurs where $f = f_p$. If $f = f_v$represents the vertically incident frequency reflected at the level where the plasma frequency is $f_p$then for the obliquely incident wave

$$sin^2\psi_i = 1 - \left(\frac{f_p}{f}\right)^2 = 1 - \left(\frac{f_v}{f}\right)^2 \qquad (3)$$

Therefore:

$$f = f_v sec\psi_i \qquad (4)$$

Thus a frequency f incident on the ionosphere at an angle ψ_i will be reflected from the same true height as the equivalent vertical incidence frequency hence a given ionospheric layer will always reflect higher frequencies at oblique incidence than at vertical incidence [3]. When $sec\psi_i$has its maximum value, the frequency$f$ is called the MUF, hence:

$$MUF = kf_v sec\psi_i \qquad (5)$$

Since $sec\psi_i$changes as the ionosphere changes, it is therefore sufficiently accurate to introduce acorrection factor$k$ (Smith's coefficient)so that the secant law in Eq. (4) becomes Eq. (5) [25,26].$k$is a function of path length (D) and reflection height (h').

From Fig. 1, using the law of sines of triangles:

$$\psi_i = \arctan\left[\frac{\sin\left({}^{D}/_{2R_e}\right)}{1 + {}^{h'}/_{R_e} - \cos\left({}^{D}/_{2R_e}\right)}\right] \qquad (6)$$

$$\text{where: } \theta = {}^{D}/_{2R_e} \qquad (7)$$

ψ_i – ray incidence angle, h'– virtual height, D – distance between Tx and Rx, M – path midpoint, R_e– Earth's radius and τ– ray take-off angle.

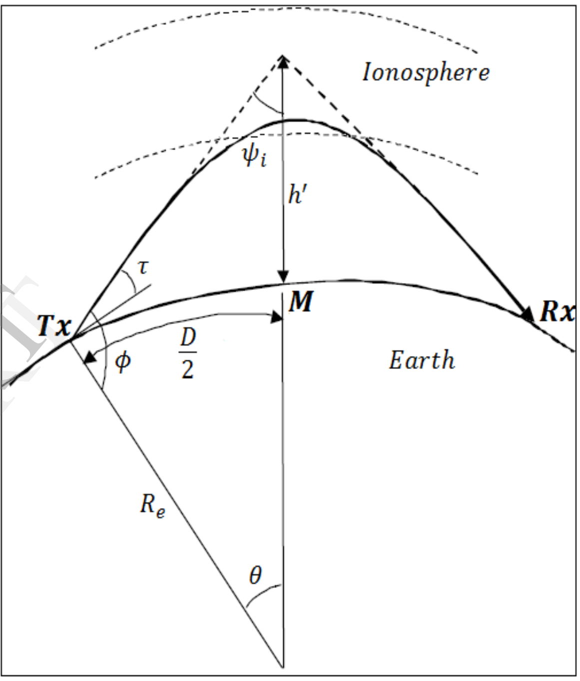

Figure 1. True (solid line) and equivalent (dashed line) trajectories of HF radio waves between two points on Earth through skip mode.

$$MUF = kf_v\left[1 + \frac{sin^2\left({}^{D}/_{2R_e}\right)}{\left[1 + {}^{h'}/_{R_e} - cos\left({}^{D}/_{2R_e}\right)\right]^2}\right]^{\frac{1}{2}} \qquad (8)$$

3.2ITU-R P.533method

Since the early 1990's, ITU made a series of recommendations on methods of predicting the performance of HF circuits. Among these recommendations is the ITU-R P.533. This prediction method has been implemented in computer programs such as Advanced Stand Alone Prediction System (ASAPS) and REC533. However, REC533 also include elements of other several recommendations [27, 28]. Eq.(9)is an empirical formula developed for prediction of monthly median F2 basic MUF through sky wave propagation at frequencies between 2 and 30 MHz for a given path[27].

$$F2(D)MUF = \left[1 + \left(\frac{C_D}{C_{3000}}\right)(B-1)\right] foF2 + \frac{f_H}{2}\left(1 - \frac{D}{d_{max}}\right) \qquad (9)$$

Where:

$$C_D = 0.74 - 0.591Z^2 - 0.09Z^3 - 0.088Z^4 + 0.181Z^5 + 0.096Z^6 \qquad (10)$$

$$Z = 1 - 2D/d_{max} \qquad (11)$$

C_{3000} – value ofC_D for D = 3000 km where D is the great circle distance.

$$B = M(3000)F2 - 0.124 + [(M(3000)F2)^2 - 40.0215+0.005\sin 7.854x-1.9635 (12)$$

$x = foF2/foE$or 2, whichever is larger.

The maximum ground range d_{max} (km) for a single hop F2 propagation mode is given by:

$$d_{\max} = 4780 + \left(12610 + \frac{2140}{x^2} + \frac{49720}{x^4} + \frac{688900}{x^6}\right)\left(\frac{1}{B} - 0.303\right) \qquad (13)$$

Equations (9) to (13) apply for the basic MUF for the extraordinary (x) wave at zero distance, for the ordinary (o) wave at d_{max} and beyond. The o-wave MUF, for all distances, is given by neglecting the last term in f_H from Eq. (9)[29]. The path mid-point is used as the control point for the F2 mode.

4. Results and Discussion

In this section two basicMUF prediction methods, ITU-R. P.533 (Eq. (9)) and Ray theory (Eq. (8)), are compared to ionosonde MUF measurementsfor single hop F2 propagation. The ability of the prediction methods to forecast the spatial and temporal variation of the MUF parameter is analysed.Hermanus(34.42°S, 19.22°E)and Grahamstown (33.19°S, 26.31°E) ionosonde station data sets for 2010were used. The data sets correspond to a period of low sunspot activity.

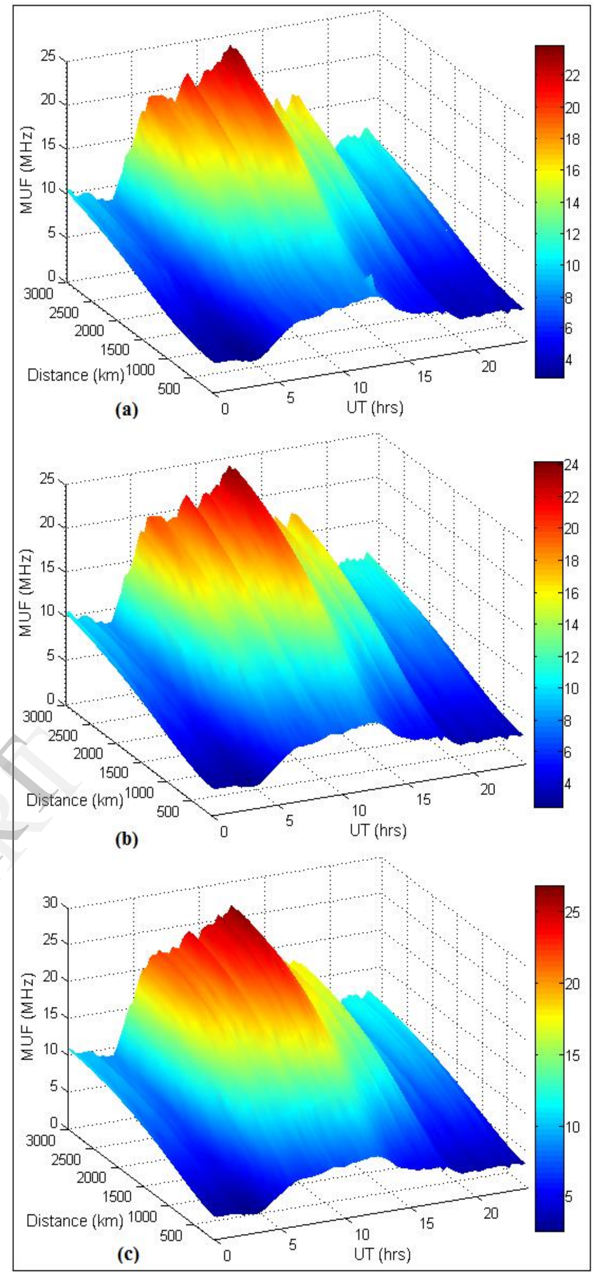

Figure 2. Spatial and temporal variation of (a) Measured MUF (b) ITU-R P.533 predicted MUF (b) Ray theory predicted MUF for Hermanus, day 32.

Figure 2 shows the general variation of measured and predicted MUF in space and time. The MUF increases with path length, with maximum MUF occurring at 3000 km path length. The predicted spatial and temporal variation of the MUF, in Figure 2(b) and 2(c),closely follow the measured data trend in Figure 2(a).

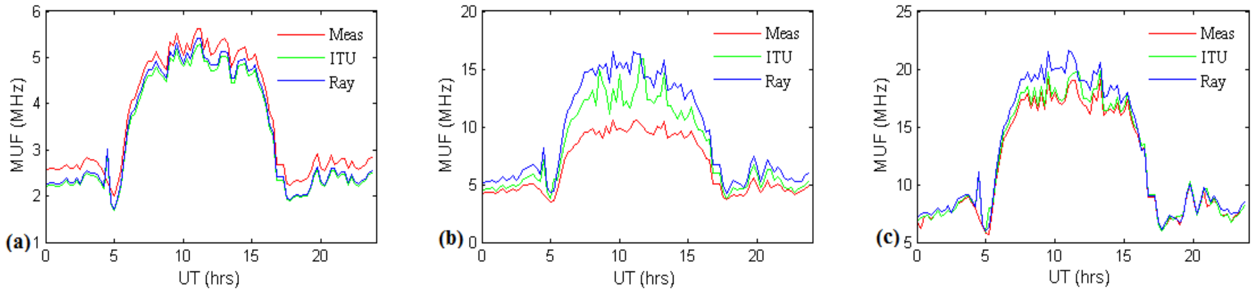

Figure 3.Daily variation of MUF for paths (a) 100 km (b) 1400 km (c) 3000 km with Grahamstown as path midpoint, day 166

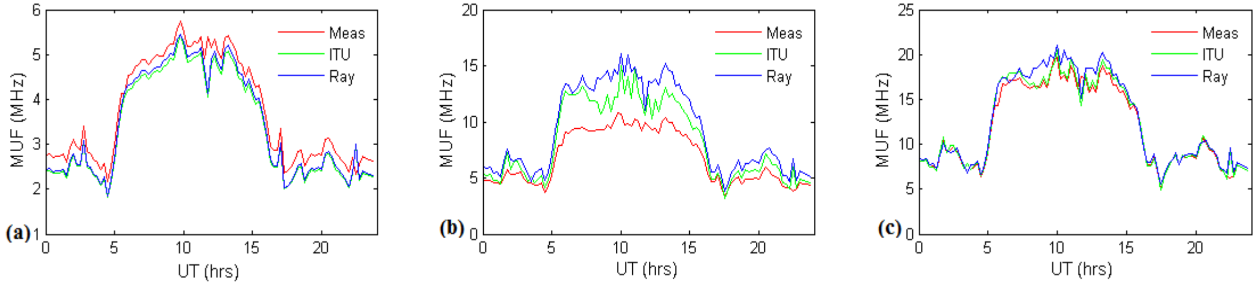

Figure 4. Daily variation of MUF for paths (a) 100 km (b) 1400 km (c) 3000 km with Hermanus as path midpoint, day 166

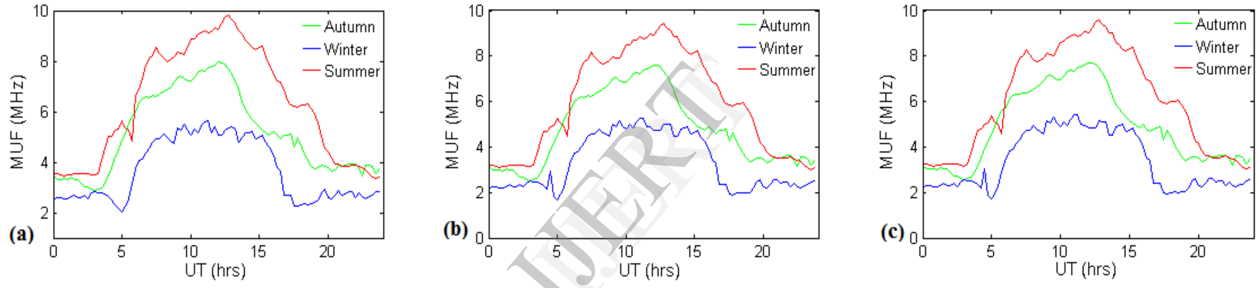

Figure 5. Seasonal variation of MUF for (a) Measured data (b) ITU-R P.533 (c) Ray theory for Hermanus

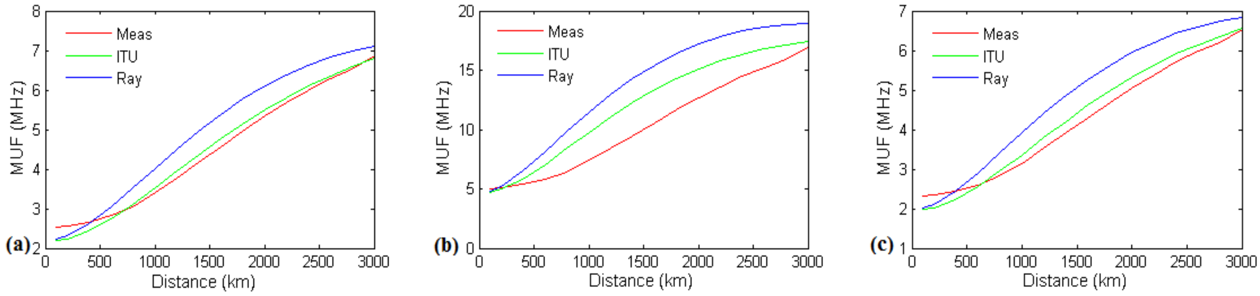

Figure 6. Variation of MUF with distance at (a) 0000hrs (b) 1200hrs (c) 1800hrs for Hermanus, day 166

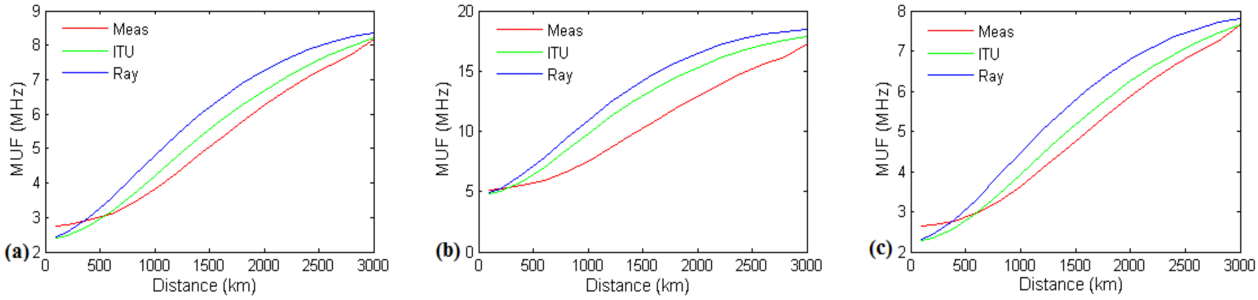

Figure 7. Variation of MUF with distance at (a) 0000hrs (b) 1200hrs (c) 1800hrs for Grahamstown, day 166

Figures 3-7 show MUF predictions deduced from the two propagation prediction methods (Eq. (8) and (9)) for varying path lengths. In the figure legends “Ray” corresponds to Ray theory predictions, “ITU” corresponds to ITU-R P.533 predictions and “Meas” corresponds to measured data.

From Figure 3 and 4, both prediction methods predict closer to the measured data at 100 km path length. However, at 1400 km path, both prediction methods predict large diurnal MUF variation between 0700hrs and 1600hrs. Both methods tend to have a higher bias during this time of the day for Grahamstown as well as Hermanus. At 3000 km path length, both prediction methods tend to over-predict between 0800hrs and 1500hrs. ITU-R P.533 method shows a significant improvement in MUF prediction over the Ray theory method (which is around 5MHz and 2MHz too high at 1400 km and 3000km path respectively).The over-prediction could due to the fact that in some cases, 2 or 3 hop modes involving a combination of E and F2 layer reflections, as well as perigee modes, determine the MUF rather than 1 F2 mode[24,30]. Although ITU-R P.533 method is a significant improvement over the Ray theory method in this case, there is still room for improvement, probably by means of incorporating a correction factor to the prediction equations.

Figure 5 shows the seasonal variation of predicted and measured MUF. From Figure 5(a) and 5(b), it can be deduced that the two propagation prediction methods are able to closely predict the seasonal variation with considerable accuracy.Figure 6 and 7 show the dependence of MUF on path length. Both prediction methods predict better at short path lengths less than 500km as well as at around 3000km. In all the cases considered here, ITU-R P.533 method generally predicts better than the Ray theory method. The two methods however, follow closely the variation of MUF with path length. It should also be noted that for short paths, most of the modes should be one hop. For intermediate length paths, composite mode propagation may exist [30].

5. Conclusion

This paper presented a brief review of HF propagation prediction methods that rangefrom long term to sophisticated nowcasts. HF propagation modeling challenges were briefly discussed and some methods to meet these challenges were described, in the context of Southern African region.An analytical study was also done using two HF propagation prediction methods (ITU-R P.533 and Ray theory) to determine how well they predict MUF values over the Southern African region.It was deduced that ITU-R P.533 method, in general,performs better as a MUF prediction method than the Ray theory method. However, the two methods tend to over-predict at longer path lengths, during day time. For further research, a more comprehensive test of the ITU-R P.533 prediction method is desirable, using a larger data set from Southern Africa. This may identify possible improvements which can be made to the prediction methods.

6. References

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