PRELIMINARY COMPARISONS OF THE IPS HF SKYWAVE PROPAGATION MODEL WITH IONOSPHERIC SOUNDING DATA

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ABSTRACT

The availability of oblique radio sounding data through the ionosphere has offered the opportunity of comparison with the IPS HF radio propagation model. The model is at the core of space weather prediction systems in the Regional Warning Center, Advanced Stand Alone Prediction Service (ASAPS) software and the system to determine the coverage of HF skywave for over-the-horizon - communication or surveillance networks. The ionospheric sounding between New Zealand and the east coast of Australia indicates the maximum first-hop oblique frequency (FMUF) to compare with that produced from real time vertical radio sounding and converted to an oblique equivalent via the propagation model. The relation between the observed and modelled data is examined as a function of ionospheric and solar activity parameterised by the T index, diurnal variation and the ionospheric gradient between the transmitter and receiver.

INTRODUCTION

This work is intended as a preliminary study in use of oblique sounding data to refine the IPS HF propagation model [1] and it's parameterisation for ionospheric activity with the T index [2]. IPS has been running an oblique sounding program for some years using a receiver and antenna located at the head office in Sydney monitoring co-operative external party transmitters over short and medium ranges. Due to equipment maintenance issues and manual intervention to maintain Tx-Rx synchronisation, sustaining a continuous link has proven to be problematic although a significant quantity of data have been archived. As a prelude to creating a system for analysing large amounts of archived data to feedback into model refinement and propagation predictions, this initial comparison has been made between a small number of observations and outputs of the model. The model has existed for many years and is based largely on accepted CCIR and ITU recommendations and methodologies. Data maps are used extensively to anchor calculations around empirical data for the static model. Certain model elements are made more dynamic with regular data updates replacing some of the historical data. The model predicts many parameters such as Maximum Usable Frequency (MUF), Absorption Limiting Frequency (ALF), elevation angles, mode probability, ionospheric reflection height, transmission loss and gain factors, noise background and signal to noise. However this study is limited to comparisons of the first F mode maximum frequencies, the most obvious observable from an oblique ionogram.

METHOD

Ionospheric Oblique Sounding: Chirpsounder

Chirpsounders have been set up at distant ends of an HF circuit to provide a measurement of operating parameters such as received power, propagation modes and signal strength. The ‘chirpcomm’ system used consists of a Barry BR Communication’s TCS-5 transmitter and a RCS-5 receiver and the system component schematic is shown in Fig. 1. The transmitter sends a CW signal, which starts at 2MHz and steps up in frequency, at a rate of 50 kHz/sec for 2-16 MHz sweep and 100 kHz/sec for a 2-32 MHz sweep. At the other end of the circuit the receiver starts sweeping synchronously with the transmitter and tracks precisely the transmitted signal. The transmitter uses a vertically polarized antenna for long distance transmissions while the receiver requires an antenna capable of efficiently receiving HF signals. The RF power output of the transmitter is 100 Watts average chirp with sweep duration of 280 seconds. When the transmitted signal is received and processed, the receiver displays this information as traces of delay time versus frequency as shown in Fig. 2., thus providing a real-time measurement of propagating modes of the HF circuit. The vertical axis for the oblique ionogram is group delay in milliseconds and is given by the difference between the total slant path and the ground range between Tx and Rx, divided by the speed of light in free space.

Sounding has been monitored in Sydney for some time from co-operative transmitters in Belconnen, Canberra for a short path and Auckland, New Zealand for a long path. Both transmitters were run by the respective countries Departments of Defence. Only the long path has been used in this study and it is Tx in Auckland (geog Lat 36.88S, Long 174.75E), Rx in Sydney (geog Lat 33.85S, Long 151.18E) over path length of 2158km with a bearing of 272 degrees geographic.

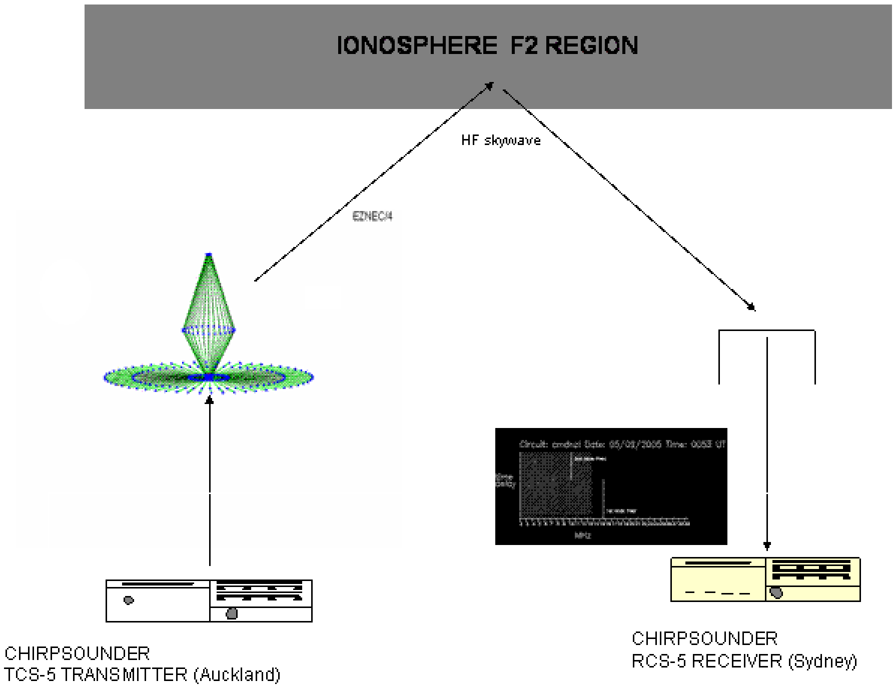

Fig. 1. Schematic of the Chirpsounder oblique sounding system

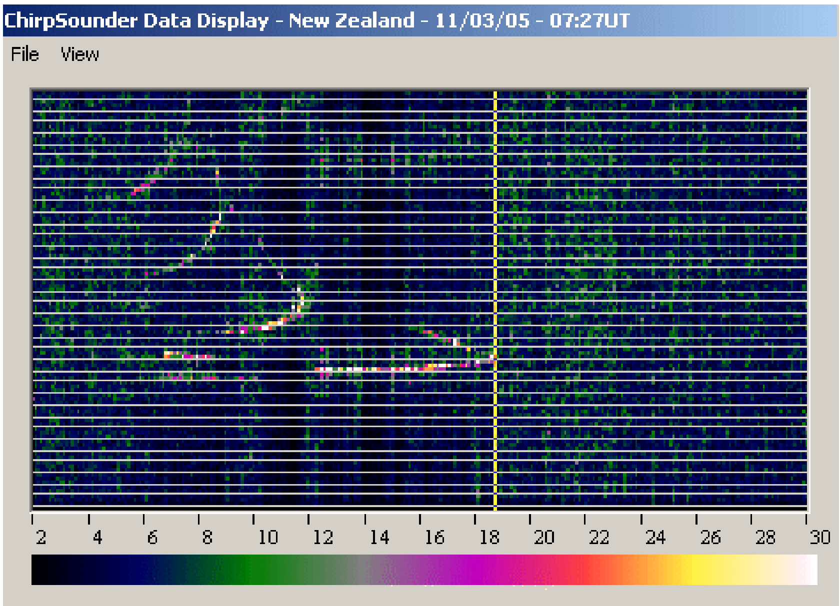

Fig. 2. Auckland to Sydney oblique ionogram in the IPS viewing software. The abscissa is sounding frequency in MHz and the ordinate axis is group delay in milliseconds. The 1FMUF near 18.5MHz is indicated.

The observed first F mode maximum frequencies for the oblique ionograms (1FMUF) were manually read off the IPS chirpsounder display in Fig. 2. for comparison with the synthesized oblique ionograms described below. The measured 1FMUF was also read from the web display described below for comparison with first mode predicted frequency.

IPS model: First Mode Predicted Frequency from Real-Time Data

Dynamic manifestations of some elements of the model are available over the internet with regularly updated data replacing some of the mapped parameters and two of these have been chosen to compare with oblique soundings. The first examined here is the predicted first F mode maximum usable frequency (1FMUF) shown in Fig. 3. and at the website http://www.ips.gov.au/HF_Systems/1/2/5. If the chirpsounder is active then the oblique ionogram is overlain in this display but as the transmitter was offline for maintenance at the time Fig. 3. was taken, the ionogram is not shown. Autoscaling of these ionograms [3] in the future would enable real-time automated comparisons.

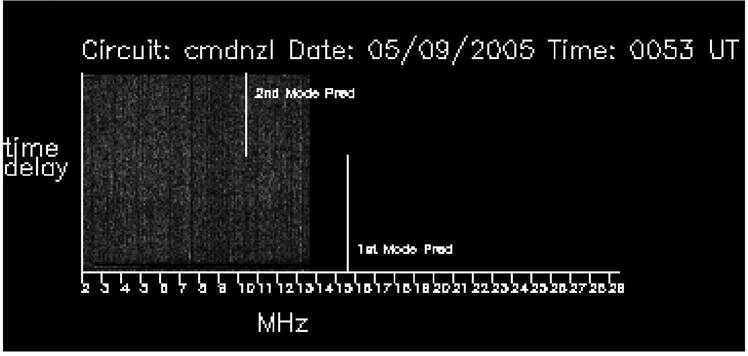

Fig. 3. The model derived first and second mode predicted frequencies superimposed on the chirpsounder display.

Equation (1) shows the method of calculating [1,4] the 1FMUF and 2FMUF values which are "1st Mode Pred" and "2nd Mode Pred" values in Fig. 2,

$$\text{FMUF} = A\,[(\text{fxF2} + B) \times M(d)\text{F2} + C] \tag{1}$$

where A,B and C are constants dependent on circuit range and number of hops
fxF2 = the extraordinary ray vertical critical frequency for the F2 layer
M(d)F2 = F-mode obliquity factor, dependent on hop length and characteristic M(3000)F2

but with changes;

- the IPS World Maps of fxF2 and M(3000)F2 in the ‘static’ model are replaced with real-time foF2 and T-index data converted to real-time fxF2 and M(3000)F2.
- an empirical ‘decile’ scaling factor is applied to the fxF2 value in the FMUF formula. This scaling factor of 0.90 has been determined to offset autoscaling problems for the percentage of time the foF2 trace is mis-scaled as fxF2 and hence fxF2 is underestimated.

IPS Model: Synthesised Oblique Ionograms

The synthesized oblique ionograms are generated by a frequency conversion from vertical (f_v) to oblique (f_o) is given by (2)

$$f_o = f_v .\, k .\, \sec(\varphi) \tag{2}$$

where k is a distance-dependent correction factor for the curvature of the earth and ionosphere, and φ is the angle of incidence with the ionosphere for either the 1-hop or 2-hop mode, being zero for vertical incidence. The vertical axis for the oblique ionogram is group delay in milliseconds and is given by the difference between the total slant path and the ground range between Tx and Rx, divided by the speed of light in free space. The slant path (L) for one half of one hop is calculated by the cosine formula (3)

$$L^2 = R^2 + (R+h_v)^2 - 2R.(R+ h_v).\cos(d/2R) \tag{3}$$

where
R = earth radius,
h_v = virtual height at frequency f_v on vertical ionogram,
and d = hop length (= ground range (D) for 1-hop and D/2 for 2-hop).

The maximum f_o for the 1st hop F mode, the FMUF, was taken for the available synthesized 2000km and 2500km path length synthesized oblique ionograms at http://www.ips.gov.au/HF_Systems/1/3 and an interpolation found the predicted FMUF at the required 2158km path length.

The T index

The T index is a standard method to parameterise ionospheric activity and support for radiowave propagation [2] and is used a main driving parameter in the model. Maximum frequencies for ionospheric reflection are measured by vertical ionosonde soundings and foF2 is essentially the MUF for the circuit. The sunspot number can be compared with foF2 measurements used as a predictor of these and the MUFs for any other circuit in the region. However conditions in the ionosphere are affected by more than just the sunspot number (e.g. geomagnetic storms) and the solar EUV radiation does not always vary in exact accord with the sunspot number. An actual ionospheric index such as the T index is derived from observed values of maximum ionospheric frequencies and T has also been shown to be closely correlated with measures of solar activity such as Zurich twelve month running mean sunspot number (R_{12}) and monthly mean 10.7 cm solar radio noise flux (Φ) [5].

To derive the T index, it is necessary to make extensive observations of foF2 over several solar cycles and to then plot the foF2 against the sunspot number to obtain a relationship between them. Given some recent observations of foF2, the relationship can be used to derive a value of the T index. It is necessary to repeat the process for each time of the day and for each month of the year and each point on earth to produce maps. IPS has accumulated monthly median world maps of foF2. A world map of foF2 exists for each UT hour (24) and month (12), and for two levels of ionospheric effective sunspot number (the IPS T index) T = 0 and T = 100, giving 24 x12 x 2 = 576 maps. These maps were constructed from over 30 years of ionospheric data. By interpolation or extrapolation these maps provide a relationship between foF2 and T index at any location. Each vertical sonde provides 5 minute real time automatic foF2 values each hour. The median of each stations foF2's is then used to compute an observed T index. If the regional ionosphere exactly matched the median map all T indices from the stations would be the same. For each sonde the observed station foF2 is converted into an observed effective sunspot number. This gives an irregular grid of T index values and an interpolation technique is used to produce regular grid of T indices for a given UT hour, compared with medians in Fig. 4. Hence regional and local T indices can also be produced. Median maps are then used to convert regular grid of T indices back into a regular grid of foF2 values, also shown in Fig. 4.

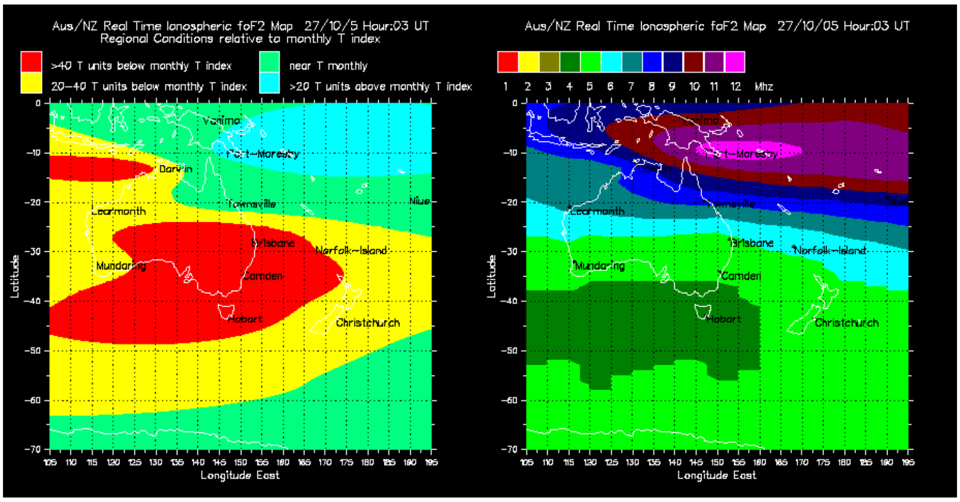

Fig. 4. Regional maps of ionospheric T index difference between current observed hourly conditions and predicted monthly conditions for the Australian region. (left) http://www.ips.gov.au/HF_Systems/1/6/1 and foF2 (right) http://www.ips.gov.au/HF_Systems/1/4

The strength of the T index in measuring ionospheric support during a period of reduced propagation support due to weak solar activity coupled with enhanced solar wind and geomagnetic activity is shown in Fig. 4.

Performing the interpolation in T index adds robustness as it can utilize inherent structure in the median map if a low number of stations are contributing to the map for a given hour. If the number of observed values is high and well spaced interpolation could be performed directly with the foF2 values. This study considers variations in daily Australian/NZ regional T indices and hourly NZ and southern Australian region T indices (http://www.ips.gov.au/HF_Systems/6/4/2) for effect on oblique sounds variance from model predictions. The effects of gradients in hourly T index between the New Zealand and south Australian regions are also examined.

Data Sampling and Ionospheric Conditions

Manual oblique sounding FMUF observations and corresponding model predictions were taken over mid and late July 2005 when the monthly global T index was 31. The link was down in mid July (11th-19th) due to sharply weakening ionosphere rendering re-synchronisation of Tx and Rx difficult. A few days in early August (1st - 5th) were also used before the Auckland transmitter was closed for maintenance and the August monthly T index was 25. 109 observations were taken in all. Significant daily variations occurred however and so for greater resolution in T index, the Australian region daily index was used, shown in Fig. 5. The daily activity was above the monthly average early in July and below it late in the month so a wide sample of the independent parameter was obtained. The very low correlation of daily T index with time of day (-0.09) confirms these two parameters are independent of each other and their effects do not need to be de-convolved when examining dependence of the difference between measured and modelled frequencies on them.

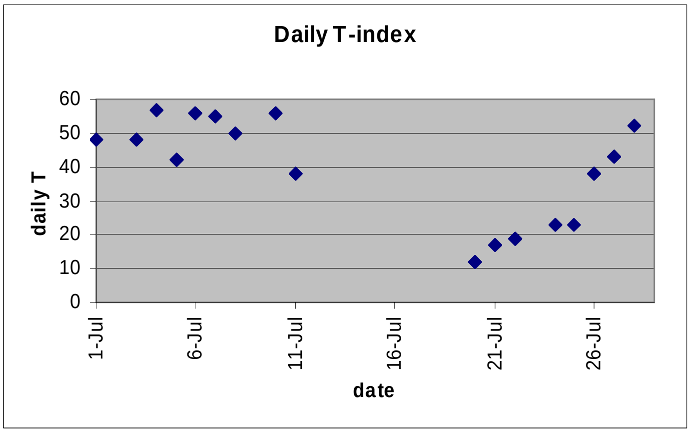

Fig. 5. Australian region daily T index for days in July and August 2005 when oblique sounding FMUF readings were compared. Correlation = -0.09.

The manual oblique FMUF readings were taken during daylight hours to remove diurnal effects in this preliminary study. For even finer T resolution near the end of the study, hourly indices for 28th July to the 5th of August were used. The irregularly spaced sequence of hourly T indices are shown in Fig. 6. A polynomial trendline has been fitted to highlight the variation in hourly T across the period. The moderately good trendline fit indicates, even with irregular sampling periods, the hourly

T variation follows a moderately smooth variation over scales over tens of T units and several hours. As a rule of thumb, ionospheric activity and support is similar for points within 10 T units of each other.

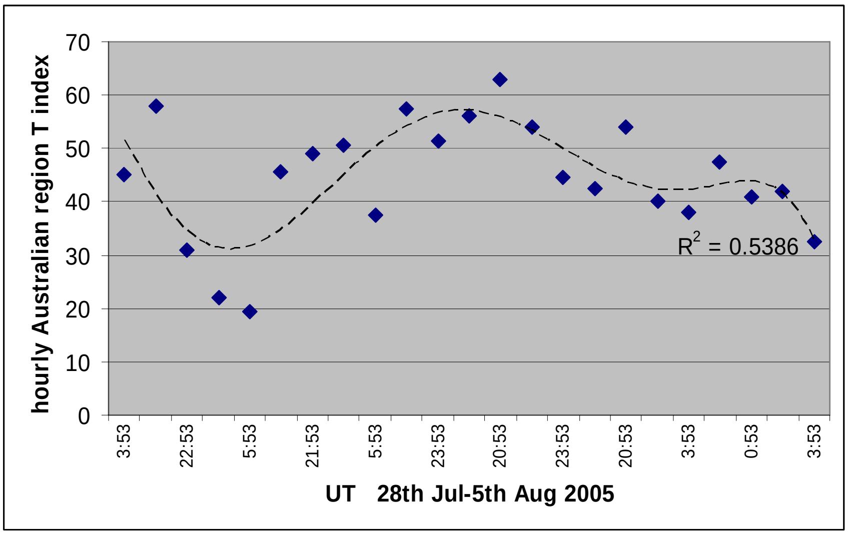

Fig. 6. Regional hourly T index for 28th July to 5th August 2005 when oblique sounding FMUF readings were taken.

Method Summary

1. The initial programme was to take manual readings three or four times a day of chirpsounder FMUF from the web to compare with the model 1st F mode predicted maximum frequency and also chirpsounder FMUF in the IPS display software to compare with the synthesized oblique maximum frequency. The two comparisons were taken independently by different observers as a double blind test to lessen subjectivity. A 0.3MHz offset in the IPS display software compared with the chirpsounder CRT and web display was compensated for to the readings are equivalent.
2. The pairs of frequencies were first viewed as time series for a general comparison.
3. The absolute difference between observed and modelled frequencies in MHz were then compared with the independent parameters time of day and daily T index for the modelled 1st mode maximum frequency.
4. The percentage difference in observed and modelled frequencies was also studied as a more sensitive dependent variable than absolute difference.
5. Later in the experimental programme, after initial comparisons with daily T index, the sometimes large variation of hourly T within a day was noted. For greater refinement, the percentage difference between observed FMUF with modelled 1st F mode maximum frequency was compared with hourly Australian region T index values.
6. Further refinement was achieved by comparing the percentage difference in frequencies with the gradient of area T index from either end of the circuit, southern Australian and New Zealand areas.

RESULTS

Oblique Sounding Compared With Predicted First Mode Frequencies

The first comparison is of the measured FMUF on the web display with modelled 1st F mode maximum frequency. The condensed time series of readings is shown in Fig. 7. as an initial comparison. Generally the observed frequencies are higher than the modelled predictions and the two series show a solid correlation. However the offset is certainly not consistent and the observed frequencies are occasionally less than the measured. This suggests correlation of the difference with other independent parameters and warrants further investigation of the dependence on time and ionospheric activity.

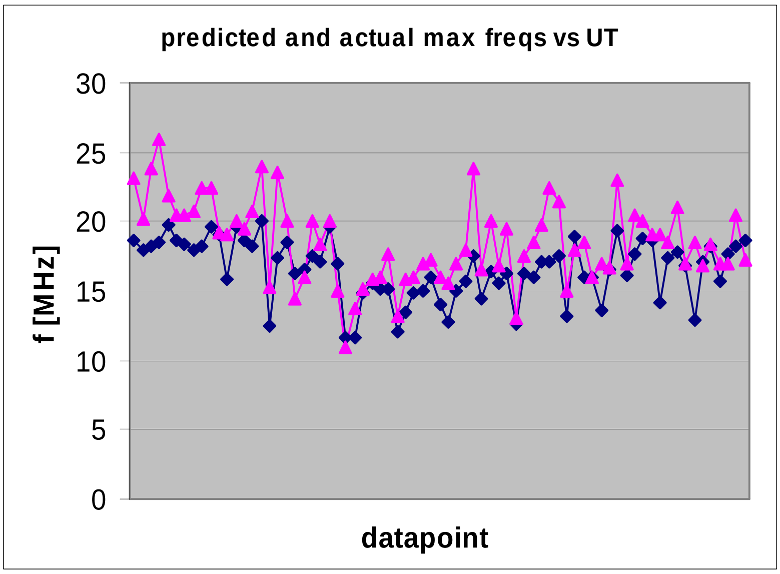

Fig. 7. The series of observed (triangles) and modelled 1st mode (squares) maximum F layer oblique frequencies on the Auckland to Sydney path. Note, the data have been concatenated so gaps are removed and sampling appears regular.

The comparison of the absolute difference between frequencies as a function of time of day for daylight hours is shown in Fig. 8. It is to be noted that this does not examine diurnal variation, to remove one more variable.

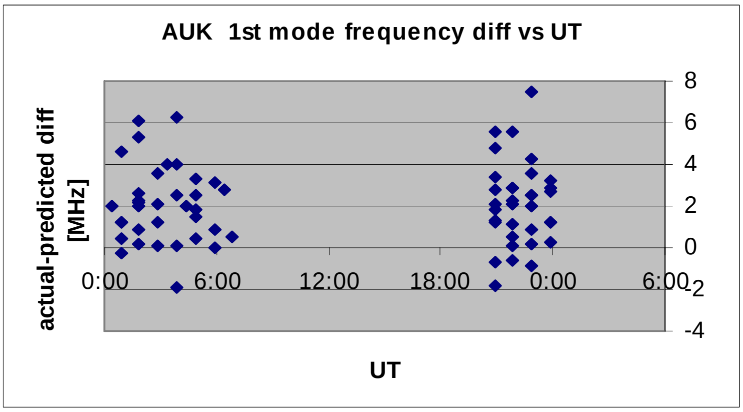

Fig. 8. Absolute difference [MHz] of observed and modelled 1st mode maximum frequencies as a function time of day. Note, comparisons only in daylight hours. Correlation = 0.06.

It can be seen there is no correlation of the frequency difference with time, at least during daylight hours, with as much as 8 MHz variation in the differences for a given hour. The majority of observed frequencies being greater then measured is also shown. The other major independent parameter upon which the difference between observed and modelled frequencies might depend is the T index. Fig. 9. shows absolute frequency difference versus daily T index. An increase in frequency difference to T = 50 can possibly be visually discerned but the correlation is not statistically significant (0.19) over the full T range. An attempted linear best fit shows a very low coefficient of determination (R^2 = 0.0373) so there is no solid dependence. A wide spread of frequency differences can be seen for some T values. Re-sampling the data for daily T less than 50 significantly improves the fit (R^2 = 0.22) so a weak dependence could be claimed. The results imply there is too much variation within a day for a daily index to provide sufficient resolution.

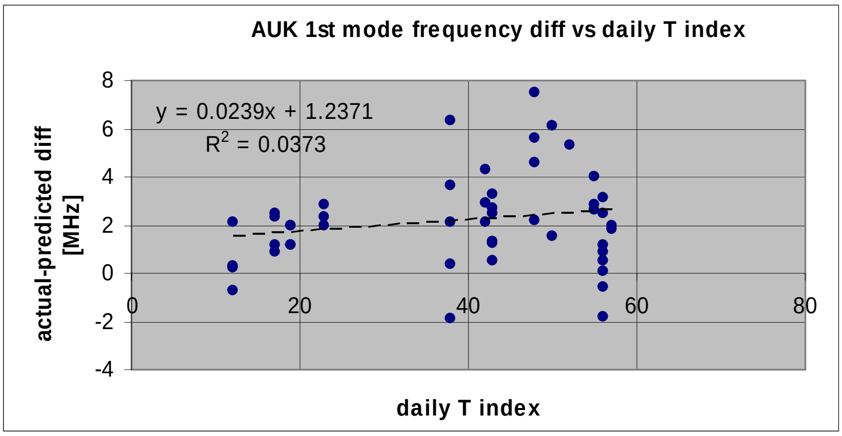

Fig. 9. Absolute difference [MHz] of observed and modelled 1st mode maximum frequencies as a function daily T index. Correlation = 0.19.

The frequency difference was refined to a percentage of the observed maximum frequency as a ratio is a more sensitive dependent parameter than an absolute difference. Fig. 10. shows the ratio dependence with time, to be compared with Fig. 8. The correlation is very slightly improved but still insignificant, confirming no dependence with time across daylight hours.

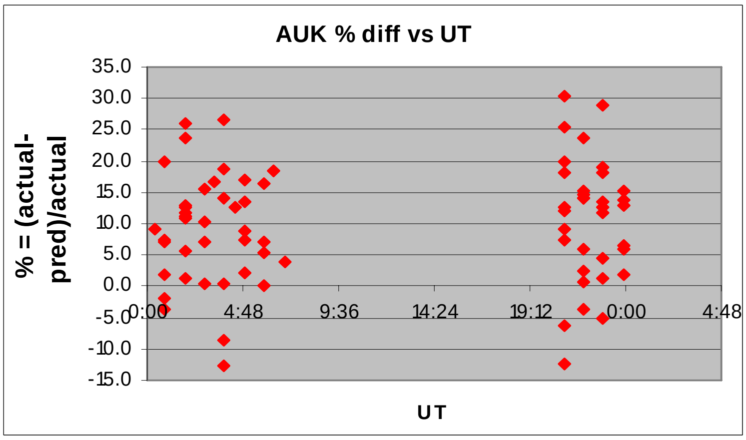

Fig. 10. Ratio of observed and modelled 1st mode maximum frequencies difference as a percentage of the measured frequency as a function time of day. Correlation = 0.08 c.f. fig 8

Low correlation of frequency difference with daily T index (Fig. 9.) and a possible significant variation of ionospheric propagation support and T index on time scales shorter than a day suggested using finer scales. The last seven days of the campaign recorded percentage difference as a function of hourly Australian region T index, shown in Fig. 11. The correlation of 0.5 is significantly improved over the daily T index dependence correlation of 0.19. The coefficient of determination for a linear fit ($R^2 = 0.25$) is slightly improved over that for the under-50 daily T index ($R^2 = 0.22$) but it does encompass all T values and significantly better than for all daily T values ($R^2 = 0.04$). This suggests a generally increasing divergence of the modelled 1st mode maximum frequencies from the observed values with increasing hourly ionospheric activity. It should be noted that the sounding path is across only one corner of the region for which the hourly T index is compiled for so there is still some spatial smoothing compiling the T and it is not completely local to the sounding path.

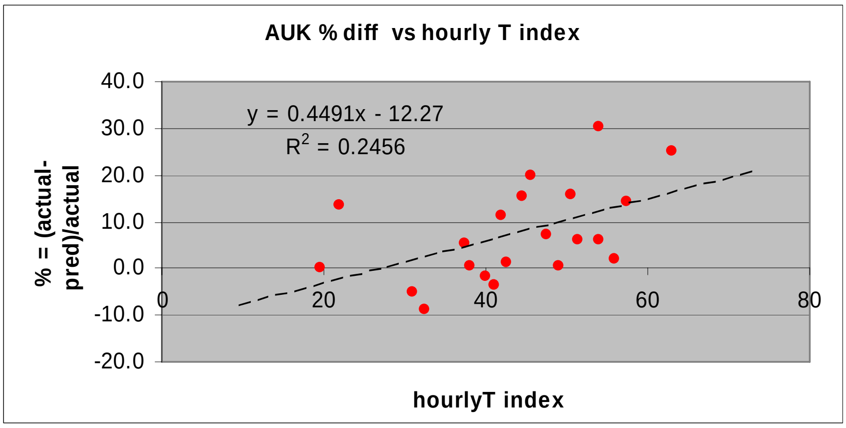

Fig. 11. Ratio of observed and modelled 1st mode maximum frequencies difference as a percentage of the measured frequency as a function of hourly T index during daylight hours over seven days. Correlation = 0.50

In the absence of further independent parameters to test against, a direct comparison was made of predicted 1st mode and measured maximum frequencies, and is shown in Fig. 12. This is for all readings and so masks dependence on any underlying parameters. The correlation of 0.75 is significant and coefficient of determination for a linear fit ($R^2 = 0.57$) suggests a linear relation is appropriate. Visually, two populations may be discerned above and below ~17MHz with that above having a steeper gradient. However, the full data set shall be considered in its entirety. If the linear fit is not constrained to go through the origin, allowing for a systematic offset, it has a gradient of near unity (1.03) and an offset of +1.43MHz for the measured frequency. If the intercept is constrained to pass through the origin then measured frequency = 1.11 x predicted frequency. Readings close to the origin (0 MHz) were not obtained and are also not possible due to the absorption limiting frequency (ALF) during the daytime. At this stage there is a belief that some of this 11% or 1.43MHz difference is due to the empirical ‘decile’ scaling factor (<0.9) applied to the fxF2 value in the FMUF formula (1). Hence, averaged over a reasonable sample of conditions, the predicted values appear to correlate reasonably well with observed maximum FMUFs on this path but a significant deviation occurs due to prevailing ionospheric conditions. A more refined spatial and temporal parameterisation was used by examining the local area hourly T index at either end of the sounding path and dependence on the frequency difference with the T gradient, shown on Fig. 13.

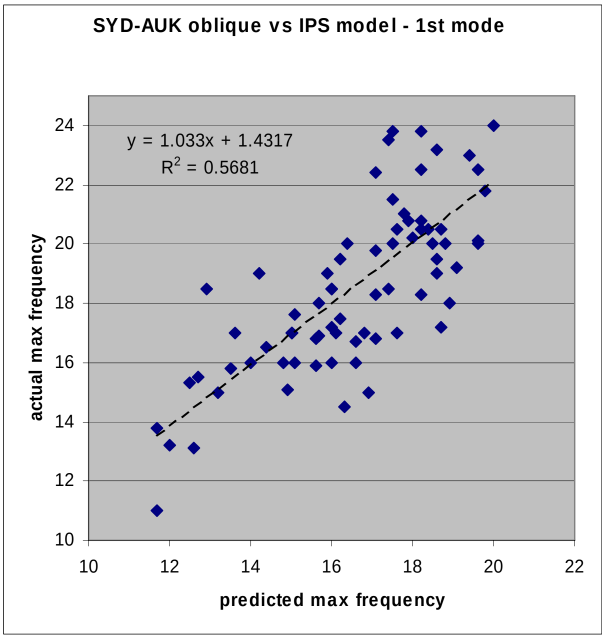

Fig. 12. Observed versus modelled 1st mode maximum frequencies for all readings taken. Correlation = 0.75. If the intercept is constrained to 0 then y=1.11x.

The T gradient is defined as positive if the southern region T is greater than the New Zealand T. Although there is sampling bias with a concentrated number in the low T (0-10) range there is a significant (anti) correlation of -0.69 for the T gradient direction defined. The linear best fit has a marginal coefficient of determination (R^2 = 0.47) but vindicates the visual trend suggesting the frequency difference is zero around a T difference of 15 units. If the T gradient is zero a difference of 10% is implied, with actual frequencies greater than predicted, agreeing with previous results (Figs. 7 and 12). As the model assumes a midpath reflection point, any significant (T>10) ionospheric gradient would be expected to reduce the predictive capability of the model. The small 10% systematic offset may partially explained by the model under-prediction already explained.

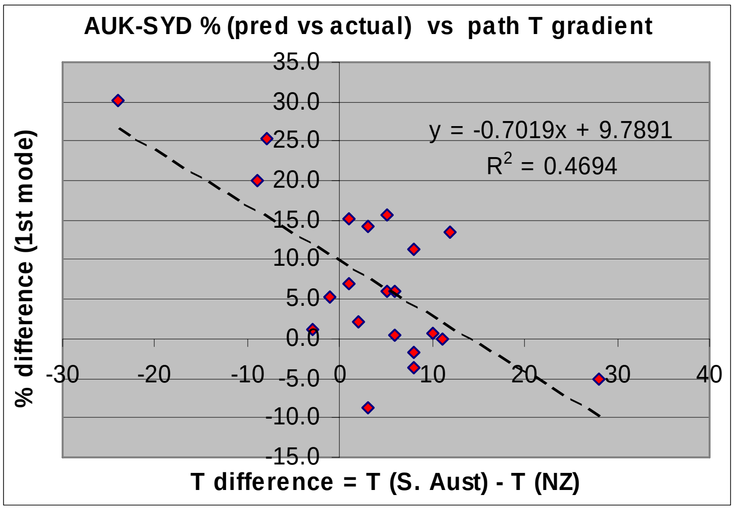

Fig. 13. Observed versus modelled 1st mode maximum frequencies for hourly T index readings. Correlation = -0.69

Oblique Sounding Compared With Synthesized Oblique Ionograms

In a similar manner to the previous section, the synthesized ionogram method maximum frequencies were examined and similar results obtained. Fig. 14. shows the measured and synthesized maximum frequencies as a time series. Similar to Fig. 7. the observed frequencies are greater than the modelled, although perhaps not as regularly as the previous 1st mode predicted frequencies.

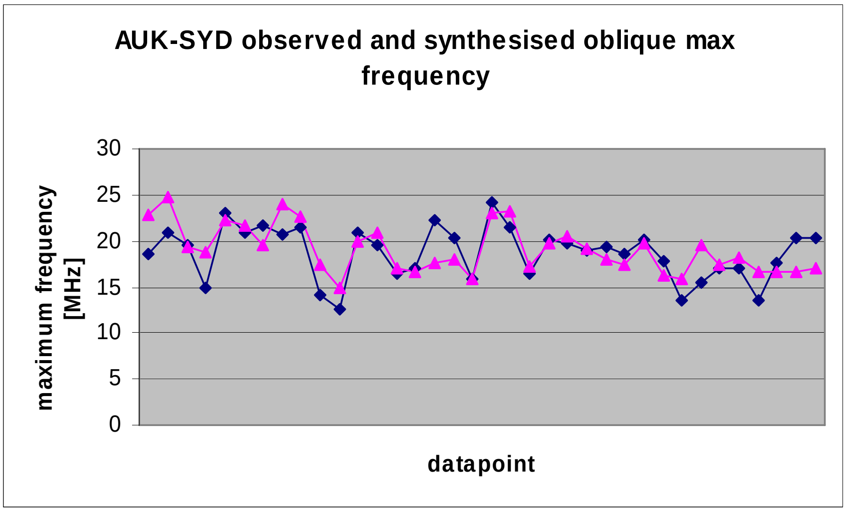

Fig. 14. The series of observed (triangles) and synthesized (squares) maximum F layer oblique frequencies on the Auckland to Sydney path.

The percentage difference in measured and modelled frequencies again show no correlation with time within daylight hours in Fig. 15. (compare with Figs. 8 and 10). There is a more even spread of negative and positive frequency differences than Figs. 8 and 10, suggesting the synthesized frequencies may be closer to observed FMUF than the predicted 1st mode maximum frequencies.

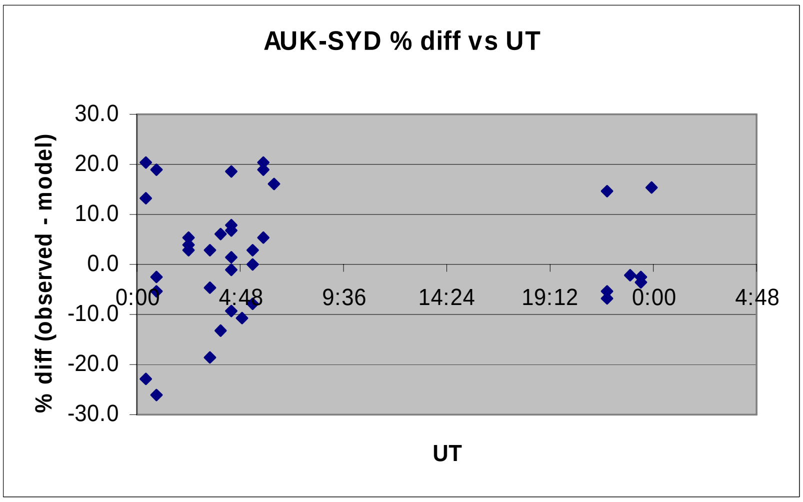

Fig. 15. Percentage difference between synthesised oblique ionogram and observed maximum frequencies as a function of time for daylight hours. Correlation = 0.04.

The frequency difference in shows a greater correlation with daily T index than time, shown in Fig. 16. Comparison with Figs. 8 and 10 suggests the correlation is slightly better than for the predicted 1st mode FMUF. The linear best fit, albeit with a low coefficient of determination ($R^2 = 0.11$) suggests the synthesized frequencies best fit the actual frequencies around T = 40.

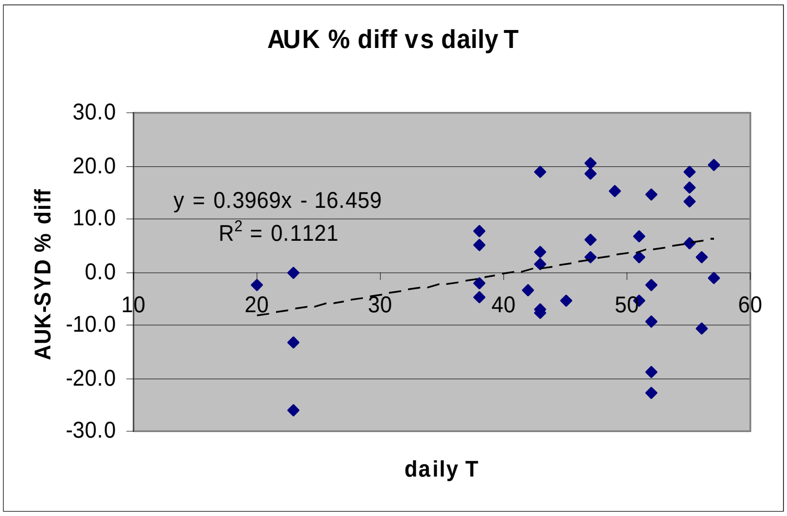

Fig. 16. Percentage difference between synthesised oblique ionogram and observed maximum frequencies as a function daily T index for daylight hours. Correlation = 0.33.

A direct comparison of synthesized and measured FMUFs is shown in Fig. 17. The correlation of 0.66 is significant and linear best fit plausible with a moderate coefficient of determination ($R^2 = 0.44$). The ratio of 0.6 and offset of 7.83MHz in measured frequency suggests the overall fit to measured frequencies is not quite as good as the 1st more predicted FMUF.

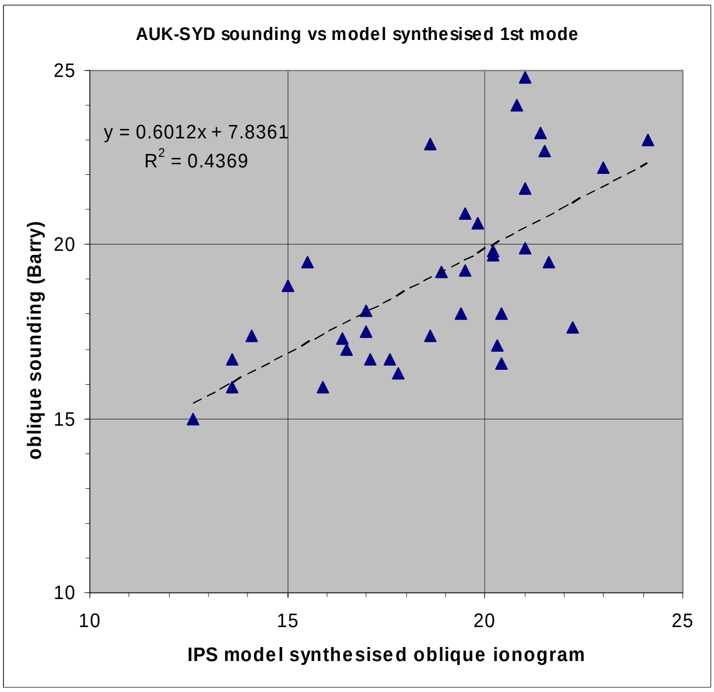

Fig. 17. Observed and synthesised oblique ionogram maximum frequencies compared for daylight hours. Correlation = 0.66. Compare with Fig. 12.

DISCUSSION AND CONCLUSIONS

The preliminary data support the conclusion that the IPS model, parameterised by the T index, provides on average a reasonable prediction of FMUF on an oblique propagation path. This capability is enhanced by the injection of near real time vertical sounding data to the model predictions. Differences in the predicted and observed frequencies are not related to local time within daylight hours and are yet to be tested for diurnal variation. The accuracy of the prediction is moderately correlated with the daily T index and more strongly correlated with the hourly T index. The minimum error appears to occur for T index values in the range 20 to 40, at least near solar minimum in mid 2005. This is not entirely unexpected as these are average activity values where the model would be expected to perform best. For higher T values the model appears to under-predict by as much as 30% and if the T is low the mode appears to over-predict maximum frequency, again by as much as 30%. Direct comparisons of measured and oblique maximum frequencies show moderate levels of correlation with the modelled 1st mode predicted FMUF perhaps being closer to the measured values than the synthesised oblique ionogram values. The synthesised values may have systematic errors in range interpolation as the best fit ratio is 0.6 and this needs to be explored further. Similarly the predicted 1st mode frequency systematic offset may be due to the empirically introduced decile factor to account for problems in autoscaling vertical ionograms during solar maximum. Anecdotal evidence suggests that during solar minimum this decile may be set to unity as autoscaling performs better and the predicted 1st mode FMUFs then average to a good estimation of the measured values on this long single hop F path. The effect of an ionospheric gradient on the path has been demonstrated to affect prediction accuracy which again is not entirely unexpected as the reflection point would be expected to shift from the path midpoint which the model assumes. The nature of the under or over prediction of the frequency with direction of gradient and a small systematic offset is yet to be fully explained. This preliminary study indicates the IPS model performs reasonably well in predicting an average single hop F mode path FMUF for reasonable ionospheric conditions. Future programmes are intended to more fully test the model over various length and direction paths with a more automated analysis of a larger amount of data and utilising the temporal highest resolution possible in T index. This will hopefully lead to refinement of model prediction and perhaps incorporation of real time oblique soundings into regional ionospheric predictions.

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