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ANALYSIS OF CHILTON IONOSONDE CRITICAL FREQUENCY MEASUREMENTS DURING SOLAR CYCLE 23 IN THE CONTEXT OF MIDLATITUDE HF NVIS FREQUENCY PREDICTIONS

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Abstract

This paper presents a comparison of Chilton ionosonde critical frequency measurements against vertical-incidence HF propagation predictions using ASAPS (Advanced Stand Alone Prediction System) and VOACAP (Voice of America Coverage Analysis Program). This analysis covers the time period from 1996 to 2010 (thereby covering solar cycle 23) and was carried out in the context of UK-centric near-vertical incidence skywave (NVIS) frequency predictions. Measured and predicted monthly median frequencies are compared, as are the upper and lower decile frequencies (10% and 90% respectively). The ASAPS basic MUF predictions generally agree with *fxI* (in lieu of *fxF2*) measurements, whereas those for VOACAP appear to be conservative for the Chilton ionosonde, particularly around solar maximum. Below ~4 MHz during winter nights around solar minimum, both ASAPS and VOACAP MUF predictions tend towards *foF2*, which is contrary to their underlying theory and requires further investigation. While VOACAP has greater errors at solar maximum, those for ASAPS increase at low or negative T-index values. Finally, VOACAP errors might be large when T-SSN exceeds ~15.

1 Introduction

Near-vertical incidence skywave (NVIS) propagation allows HF ionospheric communication over relatively short distances, typically up to ~400-500 km, using frequencies mainly in the range 2-10 MHz. This technique is relevant to military and humanitarian organisations, as well as amateur-radio operators, particularly during emergency situations where the normal power and communications infrastructure may have failed. This technique primarily makes use of waves transmitted at high angles from the ground, such that terrain obstructions (e.g. mountains) have little or no influence on signal strengths. This also renders direction-finding more difficult. However, appropriate choice of operating frequency is important for effective NVIS communication [4].

NVIS propagation is predominantly single hop via the *F2* region (1F2) and, therefore, knowledge of the daily maximum observed frequency (MOF) at a given time supported by this region is key to effective operation. Although the actual MOF cannot be predicted accurately in advance, propagation prediction software such as ASAPS (Advanced Stand Alone Prediction System) and VOACAP (Voice of America Coverage Analysis Program) estimate the monthly median MOF, also termed the maximum useable frequency (MUF), for given HF ionospheric paths.

Much practical literature is available that places emphasis on the ordinary wave (or o-wave) critical frequency *foF2* as the maximum operating frequency that does not penetrate the ionosphere at vertical incidence. Unfortunately, the existence and importance of the extraordinary wave (x-wave) for NVIS communications is largely ignored. Previous work by this author presented theoretical and historical evidence, together with measurement data that highlighted the relevance, as well as limitations, of the x-wave in NVIS propagation [17].

This paper follows with a comparison of manual and autoscaled Chilton-ionosonde critical-frequency data against HF NVIS frequency predictions using ASAPS and VOACAP software for the time period from 1996 to 2010 (essentially covering solar cycle 23). For zero ground distance (i.e. vertical incidence), the ASAPS and VOACAP MUF algorithms attempt to predict the x-wave critical frequency *fxF2*, although discrepancies exist below ~4 MHz. Furthermore, comparisons are made between the upper and lower deciles of the MOF (i.e. those frequencies occurring on 10% and 90% of days in the month) that are relevant in the determination of channel frequency ranges for automatic link establishment (ALE) systems [12]. Comparisons are also made with the respective sunspot indices, and periods when greater prediction errors might occur are identified.

2 HF Propagation Predictions

2.1 Basic and Operational MUF, OWF and HPF

ITU-R Recommendation P.373 provides definitions of maximum and minimum transmission frequencies for ionospheric links that are relevant to HF propagation predictions [9]:

a) The *basic MUF* is simply the highest frequency that propagates by ionospheric refraction alone.

b) The *operational MUF* is the highest frequency that permits an acceptable level of performance for propagation via the ionosphere taking into account system parameters (e.g. transmit power, antenna gains, modulation, noise, etc.).

c) The *optimum working frequency* (OWF) and the *highest probable frequency* (HPF) are those frequencies that are exceeded by the operational MUF on 90% and 10% of the specified period (usually a month) respectively.

Note that ITU-R Recommendation P.373 places the emphasis on operational with regard to the definition of OWF and HPF. Furthermore, the basic and operational MUF are median values and not individual values [5].

2.2 Software, Sunspot Indices and Coefficients

ASAPS (Version 5.4) and VOACAP (Version 09.1208) were used for the frequency predictions presented here.

VOACAP Method 9 was used to predict the MUF, HPF and FOT (*frequency of optimum traffic*, which is equivalent to OWF – the original French definition is *frequence optimum de travail*) [11]. The international smoothed sunspot number (SSN) is the solar index used in VOACAP predictions and is a 12-month running-average sunspot number centred on the month of interest.

ASAPS GRAFEX simulations predicted the MUF, OWF and UD (*upper decile*, which is equivalent to the HPF) used in this analysis [8]. In contrast to VOACAP, ASAPS uses the monthly T-index, which is an effective sunspot number based on numerous global ionosonde *foF2* measurements.

In determining the MUF, both VOACAP and ASAPS use global maps of median *foF2* for sunspot numbers of 0 and 100. Interpolation of the *foF2* maps is necessary for other sunspot numbers. VOACAP uses CCIR coefficients for the global *foF2* maps, whereas ASAPS uses IPS-derived maps (URSI coefficients can also be used in VOACAP, which can lead to prediction differences in some regions, particularly in the southern hemisphere and the Pacific basin [5]). Therefore, any conclusions drawn from this analysis can only be considered in the context of UK-centric NVIS propagation.

The VOACAP (Method 9) MUF, FOT and HPF, and the ASAPS (GRAFEX) MUF, OWF and UD actually relate to the basic MUF and not the operational MUF (i.e. system parameters are not considered). Consequently, the analysis presented here also relates to the basic MUF and not to the formal ITU-R definitions described in section 2.1. (Lane discusses the confusion associated with these and other similar terms [11].)

Obviously, knowledge of the basic MUF is not a guarantee of successful link establishment, which requires a full link-budget assessment through consideration of the system parameters. However, it does enable appropriate operating frequency ranges to be identified.

2.3 Zero-Distance MUF

For zero ground distance (i.e. vertical incidence), both VOACAP and ASAPS use the same equation to calculate the *F2* region MUF:

$$MUF = foF2 + \frac{f_H}{2}, \qquad (1)$$

where f_H is the electron gyrofrequency at the reflection point. Detailed equations to calculate the *F2* region MUF for non-zero ground distances can be found in the draft IONCAP Theory Manual [14] and ITU-R Recommendation P.533 [10], from which VOACAP and ASAPS, respectively, are derived.

Equation (1) is an approximation for the x-wave critical frequency *fxF2* when both *fxF2* and *foF2* are significantly greater than f_H [2]. This fact might not be evident to users of HF prediction software and/or HF NVIS techniques. The approximation is not valid for longer distance links and, in this case, the reader is referred to texts covering *quasi-longitudinal* (QL) and *quasi-transverse* (QT) propagation (e.g. [1],[2]).

3 Chilton Ionosonde Measurements

3.1 Autoscaled Data and ARTIST

Critical frequency data measured by the Chilton ionosonde for the time period from 1996 to 2010 was obtained from the UK Solar System Data Centre, RAL Space and used for this analysis. The Chilton ionosonde was located in the UK at 51.6°N, 1.3°W and used a Digisonde DPS-1 for these measurements. Data from 2000 to 2010 had been autoscaled using ARTIST (Automatic Real-Time Ionogram Scaler with True height) software [3]. For 1996 to 1999, manually scaled data was used. The use of both manual and autoscaled data in this analysis did not show any inconsistencies.

On the whole, ARTIST appeared to correctly extract ionogram parameters. Unfortunately, there were occasions when the electron density profile (and correspondingly *foF2*) was underestimated. Additionally, maximum *F* region frequencies were recorded as greater than reality during some sporadic *E* events. For the purposes of this analysis, it was assumed that any ARTIST interpretation errors occurred infrequently and, therefore, the subsequent statistical analysis and extraction of median, and upper and lower decile frequencies is valid.

3.2 Spread *F* Index, *fxI*

The aim of this analysis was to compare the measured *F2* region critical frequencies *foF2* and *fxF2* with HF basic MUF predictions. While *foF2* is a standard ionogram output parameter, *fxF2* is not.

The parameter *fxI* represents the maximum *F* region frequency recorded and provides a measure of the degree of spread *F* associated with the overhead ionosphere [6]. Spread *F* is typically a low- or high-latitude phenomenon that gives rise to range or frequency spread on an ionogram [2]. At times when spread F is uncommon, the median fxI is equal to the median $fxF2$ [7]. On this assumption, fxI was consequently used in lieu of $fxF2$ for this analysis of midlatitude ionosonde data. Additionally, fxI and $fxF2$ have been used interchangeably in this paper, although this is not strictly correct.

3.3 Statistical Analysis of Measurement Data

ASAPS and VOACAP provide hourly predictions and, therefore, the ionosonde measurement data were grouped according to measurement timestamp that had been rounded to the nearest hour (e.g. 1710 UTC becomes 1700 UTC). Sounding rates varied from hourly in 1996 to every 10 minutes in 2010. The median values of $foF2$ and fxI were determined for each hour, as well as the upper and lower decile (10% and 90%) frequencies, on a month-by-month basis.

4 Comparison Methodology

The monthly-median $foF2$ and fxI measurements were compared with the predicted ASAPS and VOACAP MUF. Likewise, the measured lower-decile frequencies were compared with predicted FOT and OWF, and the measured upper-decile frequencies were compared with predicted HPF and UD. For a given year, a matrix of statistical parameters (i.e. mean, standard deviation and rms for each hour of each month) was obtained for the differences between measurements and predictions, which allowed any temporal dependence to be identified. From this matrix, summary statistical data were extracted for a given month, to show the seasonal variation in prediction accuracy when viewed over the complete solar cycle. Furthermore, summary statistical data for the entire 1996 to 2010 analysis period gave an overall assessment of the fidelity of the prediction methods with regard to their underlying theory.

5 Results

5.1 Overall Statistics for 1996 to 2010

Table 1 presents the average differences between the measured and predicted MUF for the period 1996 to 2010 inclusive. ASAPS tended to predict the x-wave critical frequency $fxF2$ and, therefore, is consistent with Equation (1). By contrast, VOACAP was conservative in its MUF prediction for Chilton, which lay between $foF2$ and $fxF2$ (although closer to $foF2$).

The differences between the lower decile measurements and predictions are given in Table 2, and show both ASAPS and, more so, VOACAP as conservative. ASAPS tended to predict the OWF approximately halfway between $fxF2$ and $foF2$, whereas VOACAP tended to predict the FOT as $foF2$.

Measurement (50%)	Prediction	Mean (MHz)	St. Dev (MHz)
fxI	ASAPS MUF	0.09	0.25
$foF2$		-0.65	0.25
fxI	VOACAP MUF	0.48	0.31
$foF2$		-0.25	0.30

Table 1: Average differences between median Chilton measurements and predictions (1996-2010)

Measurement (90%)	Prediction	Mean (MHz)	St. Dev (MHz)
fxI	ASAPS OWF	0.37	0.32
$foF2$		-0.36	0.32
fxI	VOACAP FOT	0.74	0.37
$foF2$		0.01	0.37

Table 2: Average differences between lower decile Chilton measurements and predictions (1996-2010)

Measurement (10%)	Prediction	Mean (MHz)	St. Dev (MHz)
fxI	ASAPS UD	-0.08	0.36
$foF2$		-0.80	0.36
fxI	VOACAP HPF	0.36	0.40
$foF2$		-0.37	0.40

Table 3: Average differences between upper decile Chilton measurements and predictions (1996-2010)

Table 3 gives the differences between the upper decile measurements and predictions. As for the MUF predictions, the ASAPS UD prediction tended towards $fxF2$, whereas VOACAP was once again conservative, predicting the HPF roughly halfway between $foF2$ and $fxF2$.

Guidelines for ALE frequency planning recommend selecting frequencies in the range from just below the lowest FOT (OWF) up to the highest HPF (UD) [12]. On the basis of this and the summary information in Table 1, Table 2 and Table 3, ASAPS appears to be a better choice than VOACAP for preparing ALE frequency scan lists for NVIS links at/around Chilton (and, perhaps more generally, for the UK).

5.2 Monthly Variation Over the Period 1996 to 2010

A single, overall statistic is insufficient to describe the many facets that can be observed over a complete solar cycle and further detailed investigation is required. Figure 1 shows the variation in monthly mean difference between the measured Chilton $foF2$ and fxI parameters, and the MUF predicted by ASAPS. Also shown in Figure 1 is the monthly T-index. In general, and in accordance with Equation (1), the ASAPS MUF seems a good prediction of the x-wave critical frequency $fxF2$ (trace labelled ‘ASAPS fxI’). However, there appears to be a cyclical pattern to the frequency difference. During the winter months and particularly when the T-index was low, the ASAPS MUF prediction tended towards $foF2$.

Figure 2 shows the equivalent variation in monthly mean difference between measured $foF2$ and fxI parameters, and VOACAP-predicted MUF, together with the SSN. VOACAP was generally conservative in its MUF prediction for Chilton, being between $foF2$ and $fxF2$ (as summarised in Table 1). Clearly evident in Figure 2 are large discrepancies between

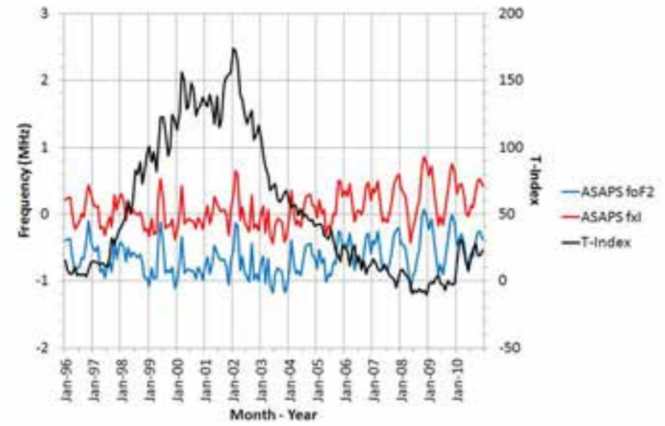

Figure 1: Monthly mean difference between Chilton measurements and ASAPS MUF (T-index also shown)

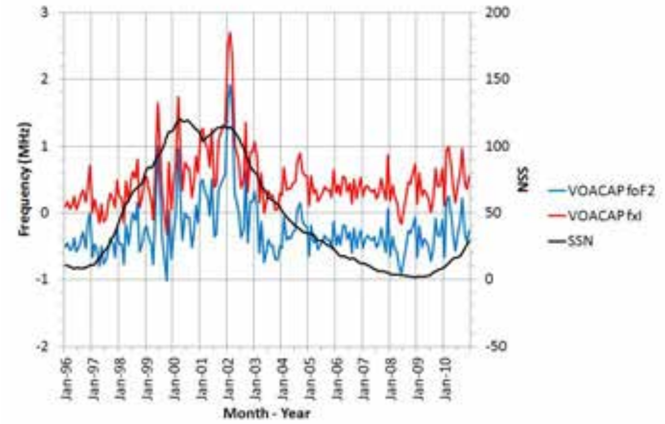

Figure 2: Monthly mean difference between Chilton measurements and VOACAP MUF (SSN also shown)

measurements and predictions at solar maximum. The cyclical pattern observed with the ASAPS predictions in Figure 1 was not apparent with the VOACAP MUF predictions.

Although not shown here, the monthly standard deviations associated with the mean differences between measured and predicted MUF did show a cyclical variation for both ASAPS and VOACAP over the complete analysis period. Values were greater during the winter period and are likely to be a consequence of (and the difficulty in predicting) the *F2* region *winter anomaly*. Generally, the ASAPS and VOACAP standard deviations appeared comparable, except for VOACAP during winter at solar maximum when it was much larger still, which would account for the different overall standard deviations in Table 1 (as well as Table 2 and Table 3). Although the *foF2* maps used by ASAPS and VOACAP are not the same, the differences observed here are most likely due to ASAPS using a monthly effective sunspot number as opposed to one that has been smoothed over a 12-month period. Indeed, it is known that *ersatz* indices based upon ionospheric measurements (e.g. effective sunspot number) outperform direct indices (e.g. SSN). Furthermore, the sunspot number is only a circumstantial index with regard to predicting ionospheric propagation [5].

Regarding the analysis of the upper and lower deciles, similar observations to those for the MUF were made between the measurements and ASAPS and VOACAP predictions, in line with the overall statistics detailed in Table 2 and Table 3 respectively. A cyclical pattern was observed for the ASAPS OWF and UD differences, with the UD tending towards *fxI*, while the OWF prediction was conservative (generally between *foF2* and *fxI*). The VOACAP HPF prediction was conservative and the FOT prediction tended to *foF2* (or even lower during solar maximum).

5.3 Variation Over Single Year

Figure 3 shows a 3D representation of the MUF difference matrix against time and month for measured *fxI* and ASAPS predictions for 2008. The spring/summer months showed lower frequency differences (and also negative differences in this example) compared with the autumn/winter measurements and were consistent with the monthly mean values shown in Figure 1. Additionally, the night-time frequency differences during autumn/winter were higher than during the day. The equivalent 3D representation for VOACAP against *fxI* measurements is shown in Figure 4, where similar characteristics were also observed.

The minimum for solar cycle 23 occurred during 2008 and, correspondingly, maximum frequencies for vertical incidence were low at this time. Figure 5 compares the median Chilton *foF2* and *fxI* measurements against ASAPS MUF predictions for 2008. As outlined previously, the ASAPS MUF prediction tended to the x-wave critical frequency. However, below ~4 MHz, the ASAPS MUF prediction tended to *foF2*. For 2008, VOACAP showed a similar tendency. Maximum vertical incidence frequencies that are below ~4 MHz typically occur at night-time during winter (more so around solar minimum), which also corresponds to the maximum differences observed in Figure 3 and Figure 4.

This appears at odds with the underlying theory and Equation (1). A possible reason for this might be due to the fact that in the development of IONCAP, “there was very little data below 4 MHz but there was some for short paths that did go down to 2 MHz”. The developers of IONCAP modelled a fit to these cases and it is understood to have given good results for NVIS situations [13]. (Presumably, this also applies for REC533 and ASAPS.)

Another consideration might be absorption since it is known that the x-wave suffers greater absorption in the ionosphere than the o-wave, particularly at the lower frequencies as the electron gyrofrequency is approached [2]. While ionospheric absorption reaches a maximum at about local noon (in the absence of ionospheric disturbances), research has shown that the local noon absorption for the o- and x-waves is comparable at ~5-8 MHz [16]. However, the significant MUF prediction differences occur during the night when absorption is minimal. Consequently, absorption can be ruled out as a practical reason for these errors and, therefore, this discrepancy in low frequency basic MUF prediction warrants further investigation.

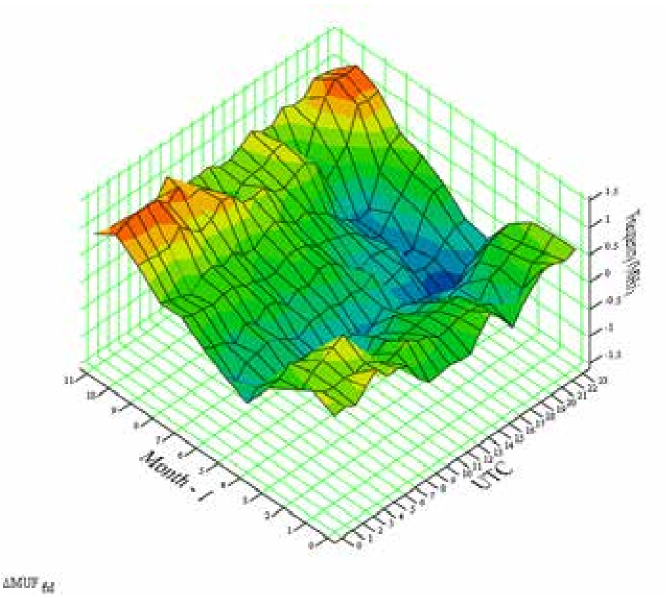

Figure 3: 3D representation of difference between median Chilton *fxI* and ASAPS MUF against time and month for 2008 (note: January-December = 0-11)

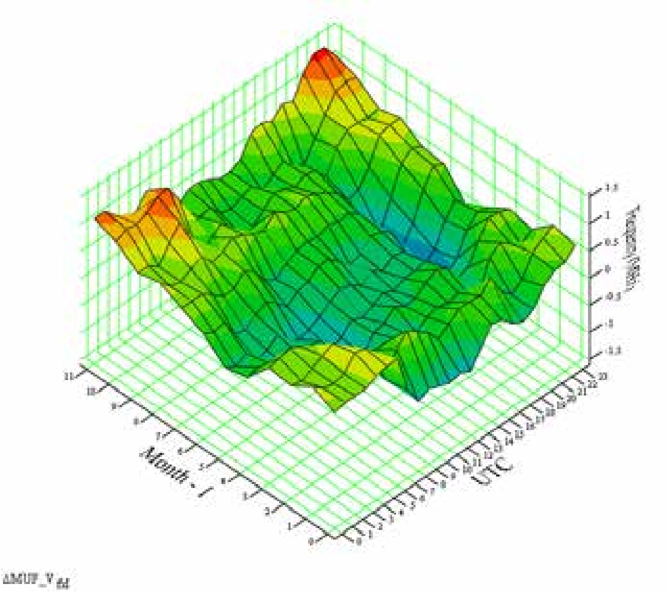

Figure 4: 3D representation of difference between median Chilton *fxI* and VOACAP MUF against time and month for 2008 (note: January-December = 0-11)

Earlier research (before the acronym 'NVIS' became commonplace) investigated the optimum orientation of linearly-polarised antennas (e.g. horizontal dipole) for short-range tactical HF links at or close to the geomagnetic equator [15]. In this region, vertically-incident o- and x-waves are linearly polarised and one of the key recommendations from this research was for dipoles to be aligned N-S for excitation and reception of the o-wave (the use of polarisation diversity with dipoles aligned for the x-wave was also recommended for when the o-wave faded or became inferior in strength). The emphasis on the o-wave for tactical reasons leads this author to speculate that these guidelines have become

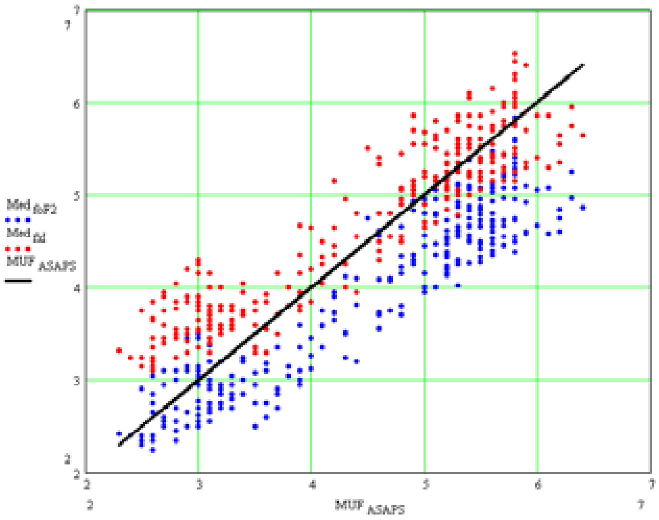

Figure 5: Comparison of median Chilton measurements against ASAPS MUF for 2008

'globally' accepted and might have subsequently influenced predictions at lower frequencies. Obviously, this too requires further investigation.

5.4 MUF Differences and Solar Indices

Figure 6 shows how the measured and ASAPS-predicted MUF differences vary with T-index over the period from 1996 to 2010. In general, the ASAPS MUF prediction was within ~10% of *fxF2* (showing consistency with Equation (1) and the underlying theory), except at low or negative T-index values.

Although conservative in its MUF prediction for Chilton, VOACAP appeared relatively consistent except for high SSN (i.e. > ~100), as seen in Figure 7. Visually, the spread in VOACAP prediction differences in Figure 7 is greater than those for ASAPS in Figure 6 (VOACAP had greater overall standard deviations than ASAPS in Table 1, Table 2 and Table 3). An alternative and interesting view of the VOACAP MUF differences can be seen in Figure 8, which shows the data plotted against the difference between the T-index and the SSN (labelled T-SSN). If T-SSN was greater than ~15, then the VOACAP predictions started to diverge from trends.

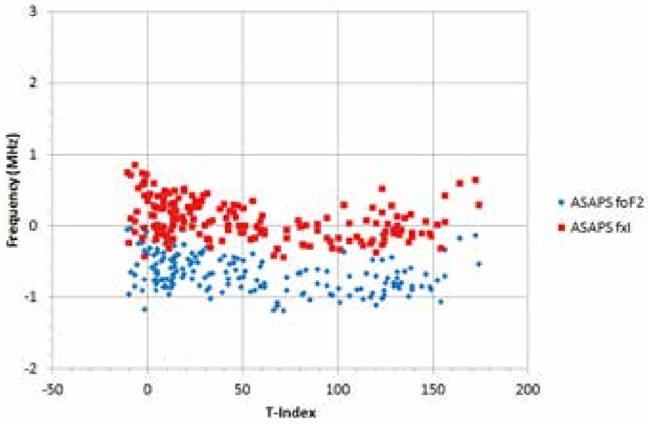

Figure 6: Monthly mean difference between Chilton measurements and ASAPS MUF against T-index

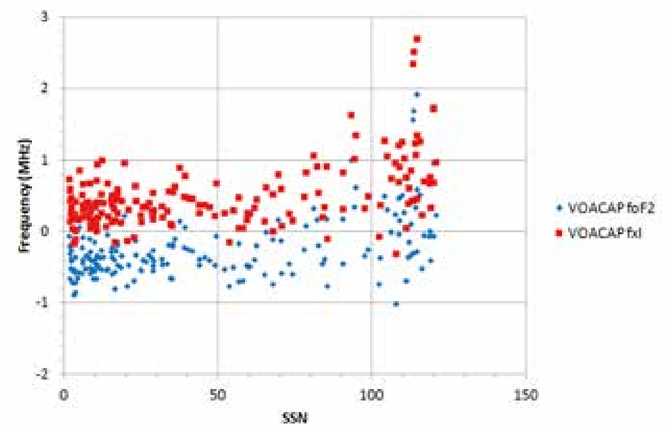

Figure 7: Monthly mean difference between Chilton measurements and VOACAP MUF against SSN

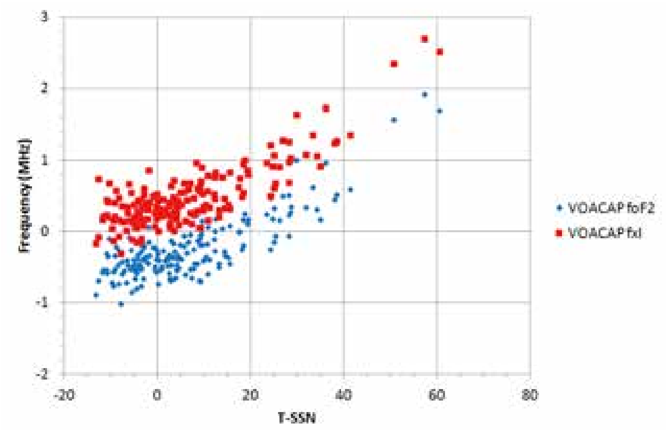

Figure 8: Monthly mean difference between Chilton measurements and VOACAP MUF against T-SSN

This might be a useful guide to identifying periods when VOACAP predictions are likely to be inaccurate (or pessimistic) for Chilton/UK NVIS basic MUF predictions, assuming real-time access to the IPS T-index is available.

6 Summary

It is important to note that any conclusions drawn here are specific to Chilton (more generally the UK) because the ASAPS and VOACAP predictions depend on non-identical global *foF2* maps. Therefore, absolute and relative prediction errors on a global basis will vary depending on the geomagnetic location being considered.

For the time period 1996 to 2010, the ASAPS basic MUF predictions generally agreed with the Chilton ionosonde *fxI* measurements and were consistent with Equation (1) here. By contrast, the VOACAP predictions were conservative, particularly around solar maximum. Similar observations were made for the respective upper decile (10%) predictions, whereas both ASAPS and VOACAP lower decile (90%) predictions were conservative (VOACAP more so). For the UK, ASAPS appears to be a better choice for preparing ALE frequency scan lists. Below ~4 MHz during winter nights around solar minimum, both the ASAPS and VOACAP MUF predictions tended towards *foF2*, which is contrary to their underlying theory and requires further investigation. While VOACAP had greater errors at solar maximum, those for ASAPS increased at low or negative T-index values. Finally, VOACAP errors might be large when T-SSN exceeds ~15.

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