

Comparison of propagation predictions and measurements for midlatitude HF near-vertical incidence sky wave links at 5 MHz

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[1] Signal power measurements for a UK-based network of three beacon transmitters and five receiving stations operating on 5.290 MHz were taken over a 23 month period between May 2009 and March 2011, when solar flux levels were low. The median signal levels have been compared with monthly median signal level predictions generated using VOACAP (Voice of America Coverage Analysis Program) and ASAPS (Advanced Stand Alone Prediction System) HF prediction software with the emphasis on the near-vertical incidence sky wave (NVIS) links. Low RMS differences between measurements and predictions for September, October, November, and also March were observed. However, during the spring and summer months (~April to August), greater RMS differences were observed that were not well predicted by VOACAP and ASAPS and are attributed to sporadic *E* and, possibly, deviative absorption influences. Similarly, the measurements showed greater attenuation than was predicted for December, January, and February, consistent with the anomalously high absorption associated with the “winter anomaly.” The summer RMS differences were generally lower for VOACAP than for ASAPS. Conversely, those for ASAPS were lower during the winter for the NVIS links considered in this analysis at the recent low point of the solar cycle. It remains to be seen whether or not these trends in predicted and measured signal levels on 5.290 MHz continue to be observed through the complete solar cycle.

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1. Introduction

[2] Near-vertical incidence sky wave (NVIS) propagation allows HF ionospheric communication over relatively short distances, typically up to ~400–500 km, using frequencies generally in the range 2–10 MHz. This technique is of relevance to military and humanitarian organizations, 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. However, appropriate choice of operating frequency is important for effective NVIS communication [Fiedler and Farmer, 1996]. The arrival of waves from high angles makes direction finding more difficult because bearing errors increase dramatically with decreasing range to the transmitter [Goodman, 1992], although recent research using real-time ray tracing through a tilted ionosphere has led to more reliable determination of transmitter locations for short-range links [Huang and Reinisch, 2006].

[3] NVIS propagation is predominantly single hop via the *F*₂ region (1F₂) and, therefore, knowledge of the daily maximum observed frequency (MOF) supported by this region at a given time is beneficial for effective operation. Although the actual MOF cannot be predicted accurately in advance, propagation prediction software such as VOACAP (Voice of America Coverage Analysis Program) and ASAPS (Advanced Stand Alone Prediction System) estimate the monthly median MOF, also termed the maximum useable frequency (MUF), for given HF ionospheric paths. By working with monthly median predictions, there should also be an expectation of temporal variability. Systems employing ionospheric sounding or real-time channel evaluation (RTCE) are able to further refine the MOF estimate and, consequently, select the best available frequencies for improved operational performance in the short term [Goodman, 1992].

[4] Recently, a comparison was made between signal-to-noise ratio (SNR) measurements and VOACAP SNR predictions for North American NVIS links operating on the 3, 4, 6, 7 and 9 MHz bands during part of the recent sunspot minima [Johnson, 2007]. VOACAP was found to be generally accurate, although some discrepancies in SNR were observed that require further investigation.

[5] Another recent study compared median signal power measurements with VOACAP and ASAPS predictions for

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Figure 1. UK map showing locations of transmitting beacons and receiving stations.

two North American links (one was 490 km and, therefore, an NVIS link) over a 10 month period [McNamara *et al.*, 2006]. On 3.330 MHz, the RMS errors for the NVIS link were similar for VOACAP and ASAPS (~ 3 –9 dB), whereas on 7.335 MHz, the VOACAP RMS errors were less than those for ASAPS during the day (~ 4 dB versus ~ 8 dB). Although these errors might appear large, typical operational systems are designed for at least 90% reliability rather than the median, which is achieved by predictions of the frequency of optimum traffic (FOT) and the optimum working frequency (OWF) in VOACAP and ASAPS, respectively. With this reliability target in mind, performance should be at least 90% [Lane, 2001].

[6] This paper presents signal power measurements taken over a 23 month period between May 2009 and March 2011 for an amateur radio network of three beacon transmitters and five monitoring stations operating on 5.290 MHz, and located in the United Kingdom. This work expands on earlier investigations by comparing the measurements with VOACAP and ASAPS predictions with the emphasis on NVIS links [Walden, 2010].

[7] The beacon transmitters and receiving stations are referred to by their amateur radio call signs and are marked on

the UK map shown in Figure 1. Table 1 gives their geographic coordinates, while the geographic great circle range and bearing for the 15 links are given in Table 2.

[8] Nine of the 15 links have a ground range < 500 km and, therefore, the mode of operation is considered to be NVIS. The measurement data have been obtained from real, practical installations (i.e., buildings and/or vegetation in close proximity), which could be considered representative of impromptu or emergency installations, as potentially used by the military or humanitarian organizations at short notice. Operation at 5 MHz is particularly useful for midlatitude locations during daylight hours at low points in the sunspot cycle when ionization is often insufficient to support NVIS communication at higher frequencies, and significant D region absorption occurs at lower frequencies.

2. Measurement System

2.1. Beacon Transmitters

[9] The beacon transmitters operated on 5.290 MHz and were time and frequency locked to GPS. The conducted output power was nominally 10 W (i.e., this was the design level rather than a calibrated level). The transmission interval was 15 min with GB3RAL transmitting at 0, 15, 30 and 45 min past the hour. GB3WES and GB3ORK transmit 1 min and 2 min later than GB3RAL, respectively. Each beacon transmission lasted 1 min and consisted of a call sign identification in Morse code (7 s), power reduction of carrier from 10 W down to $160 \mu\text{W}$ in 6 dB steps that was repeated twice (2×8 s), followed by a full-power carrier transmission (5 s). The remaining 30 s consisted of a sequence of $500 \mu\text{s}$ pulses at full power with a pulse repetition frequency of 40 Hz that could allow delay and multipath propagation measurements to be made [Talbot, 2005a, 2005b]. The transmit antennas were inverted vee dipoles.

2.2. Receiving Stations

[10] All of the monitoring stations used direct conversion receivers, although a superheterodyne receiver with the AGC disabled was used by one for a period of time. The demodulated audio signal was sampled by a PC sound card. The receivers were calibrated using either a low-power crystal oscillator or commercial signal generators. The receive antenna designs at stations differed but included an active broadband loop, an active tuned loop, resonant half-wave inverted vee dipoles and a nonresonant, asymmetric dipole.

Table 1. Geographic Coordinates for Beacon Transmitters and Receiving Stations

Station	Geographic Coordinates
Beacon	
GB3RAL	51.56°N, 1.29°W
GB3WES	54.56°N, 2.63°W
GB3ORK	59.02°N, 3.16°W
Receiving station	
G3SET	53.39°N, 0.57°W
G3WKL	52.10°N, 0.71°W
G4ZFQ	50.73°N, 1.29°W
G8IMR	50.91°N, 1.29°W
GM4SLV	60.29°N, 1.43°W

Table 2. Geographic Great Circle Range (Bearing) From Beacon Transmitters to Receiving Stations

Station	G3SET	G3WKL	G4Zfq	G8IMR	GM4SLV
GB3RAL	210 km (14°)	70 km (33°)	92 km (181°)	74 km (180°)	968 km (0°)
GB3WES	189 km (133°)	302 km (154°)	435 km (168°)	418 km (167°)	639 km (6°)
GB3ORK	646 km (164°)	785 km (167°)	929 km (172°)	911 km (171°)	170 km (34°)

2.3. Monitoring Software

[11] The beacon-monitoring software measured the peak received signal level during the 5 s full-power carrier transmission. The average noise level (adjusted for 1 Hz bandwidth) was measured over ± 25 Hz about the beacon frequency during the minute before the GB3RAL transmission. If the peak signal exceeded the average noise level by 15 dB, then the measured audio frequency was recorded; otherwise zero was recorded. This procedure helped identify transmitter outages (whether intentional or accidental), as well as preventing noise peaks or interference being falsely recorded as real signals. The measured frequencies showed a stable, diurnal variation (that related to the receiver local oscillator drift), which also indicated the reception of valid signals rather than noise or interference.

3. HF Propagation Modeling

3.1. VOACAP (Version 09.1208) and ASAPS (Version 5.4)

[12] VOACAP Method 20 (complete system performance) with the CCIR coefficients was used for predictions [Lane, 2001]. (The VOACAP software refers to CCIR coefficients even though the CCIR organization no longer exists, having been succeeded by the ITU-R). Although VOACAP incorporates a sporadic *E* model, this was turned off because it has not been validated and its use might lead to overly optimistic results. Table 3 presents the smoothed international sunspot number (SSN) used as input to the VOACAP predictions (months with no SSN recorded in Table 3 were not considered in this analysis). VOACAP predicts the median signal level (among other output parameters), which was used in this analysis.

[13] ASAPS is derived from Recommendation ITU-R P.533 [International Telecommunication Union, 2009] and uses the smoothed monthly T index (an effective sunspot number based on global ionosonde measurements of *foF2*) as input to predictions [IPS Radio and Space Services, 2009]. Table 4 presents the monthly T indices used in these ASAPS predictions. (If no T index is given in Table 4, then this month was not considered in the analysis.) The T index for some

Table 3. Smoothed International Sunspot Number (SSN) Used in VOACAP Predictions

Year	Month											
	01	02	03	04	05	06	07	08	09	10	11	12
2009	–	–	–	–	2	3	4	5	6	7	8	8
2010	9	11	12	14	16	16	17	17	20	23	27	29
2011	31	33	37	–	–	–	–	–	–	–	–	–

Table 4. IPS Monthly Smoothed T Indices Used in ASAPS Predictions

Year	Month											
	01	02	03	04	05	06	07	08	09	10	11	12
2009	–	–	–	–	4	–2	–3	–7	0	–2	–3	–2
2010	12	29	31	21	13	7	18	24	28	19	19	23
2011	23	32	52	–	–	–	–	–	–	–	–	–

months was below zero indicating that measured ionospheric conditions were actually worse than expected for a nonzero SSN in that month (SSN can never be less than zero). Predictions using *ersatz* indices (such as the T index) are known to outperform predictions using direct indices (such as the SSN). Furthermore, the sunspot number is only a circumstantial index with regard to predicting ionospheric propagation [Goodman, 1992]. In view of the antenna types used, the “Approximation” algorithm was used to determine the polarization coupling loss. The median signal level is not a direct output from ASAPS, so this was calculated using the known transmit power, the predicted path loss, and the predicted combined antenna gains for the links.

[14] The transmitter power delivered to the antenna was taken to be 9 W, assuming a cable loss of 0.5 dB, which was considered reasonable for the types and lengths of cables used. Both the VOACAP and ASAPS predictions have been interpolated to 15 min intervals to coincide with the beacon transmit interval. This might not be wholly correct but highlights the uncertainty associated with these predictions. The original database from which VOACAP is derived had median measurements at 2-hourly intervals [Lane, 2001]. For ASAPS, the predictions are considered applicable ± 30 min about the hour [IPS Radio and Space Services, 2009].

Table 5. Summary of Antennas and NEC-2 Simulated Average and Peak Gains

Station	Antenna	Description	Peak Gain (dBi)	Average Gain (dB)
GB3RAL	dipole	inverted vee with apex at 3 m above concrete building	–0.7	–7.8
GB3WES	dipole	inverted vee with apex at 9 m	+4.1	–3.3
GB3ORK	dipole	inverted vee with apex at 6.5 m	+3.4	–4.3
G3SET	dipole	inverted vee with apex at 8.3 m	+4.0	–3.5
G3WKL	dipole	asymmetric, nonresonant 41.5 m long (feed at 13.8 m) with majority of antenna at 10 m above ground	+0.9	–7.0
G4Zfq	dipole	inverted vee with apex at 9.5 m	+3.3	–3.8
G8IMR	active loop	tuned 0.48 m diameter loop at 4 m above ground	–31.3	–36.7
GM4SLV	active loop	broadband 1 m diameter loop at 1 m above ground	–11.2	–17.1

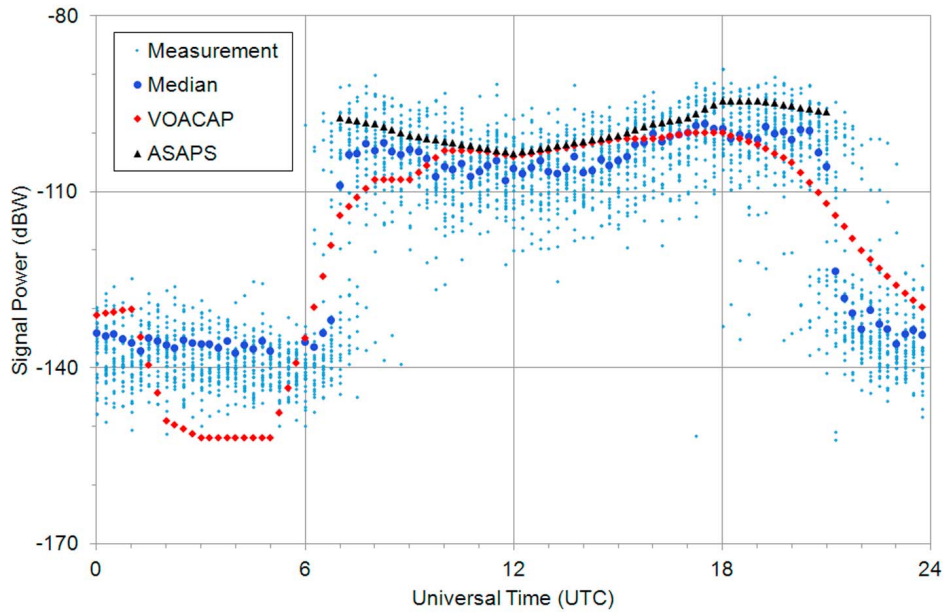


Figure 2. Measurements and predictions for GB3RAL-G3WKL March 2010.

3.2. Antenna Models

[15] The 3D antenna radiation patterns for each station were used as additional input to the VOACAP and ASAPS predictions and were obtained through simulation using Numerical Electromagnetic Code version 2 (NEC-2) software with the Sommerfeld-Norton ground implemented (EZNEC software was used, which is available from <http://www.eznec.com>). As an initial assumption, all station grounds were

modeled as “average” ($\epsilon_r = 13$, $\sigma = 0.005$ S/m), except for GB3RAL, which was modeled as “extremely poor” ($\epsilon_r = 3$, $\sigma = 0.001$ S/m) because the antenna was located at a low height above the flat roof of a multistorey concrete building [Straw, 2003]. The actual ground characteristics are unknown. However, simulation by the author of a half-wave dipole at 5 m above ground indicates that the potential error in gain owing to the use of incorrect ground characteristics could be

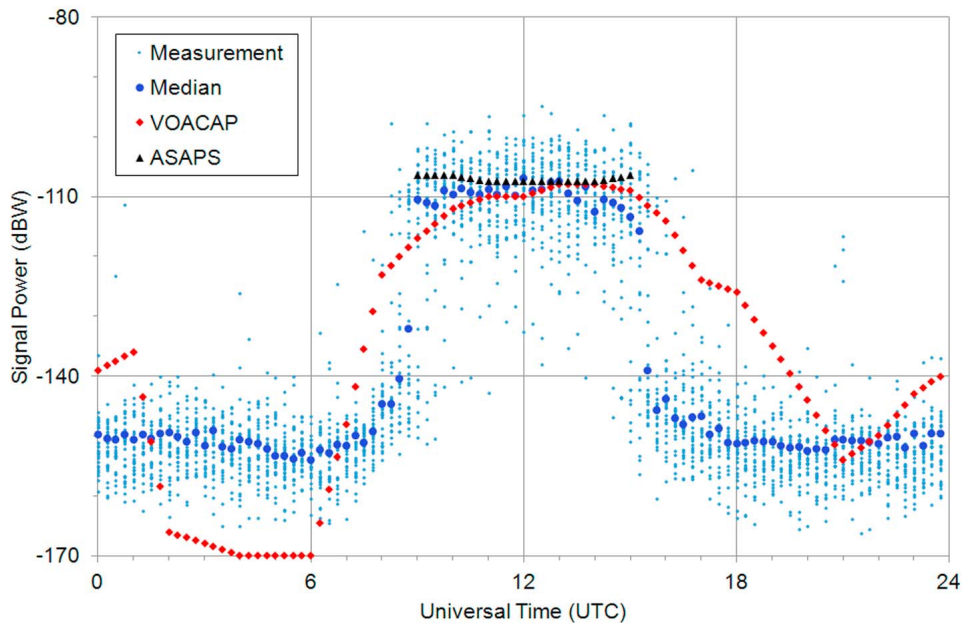


Figure 3. Measurements and predictions for GB3ORK-GM4SLV November 2009. (Figure 3 in the original IES2011 paper [Walden, 2011] is incorrect in that it is for the GB3WES-GM4SLV link in November 2009. The author apologizes for any confusion this might cause.)

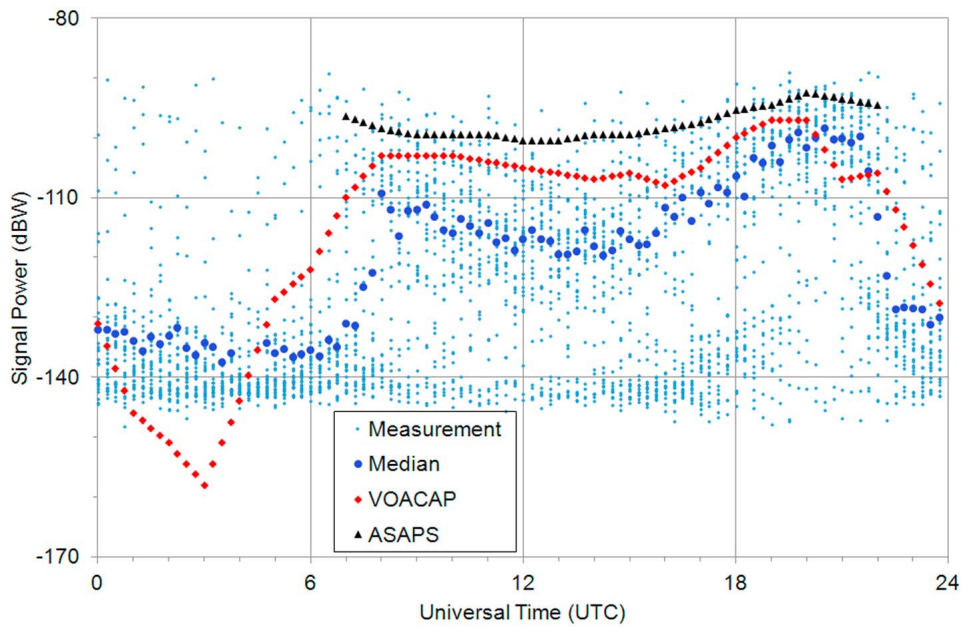


Figure 4. Measurements and predictions for GB3RAL-G3SET August 2009.

expected to be within ± 2 dB. The simulated dipole gain values are consistent with previously published measurements of field-deployed antennas [Hagn, 1973]. The active tuned loop at G8IMR was modeled as a passive antenna with the amplifier gain incorporated into the calibration. The broadband active loop at GM4SLV had a nominal antenna factor of 0 dB, which was converted into an equivalent free-space gain and subsequently modeled above a ground. Table 5 summarizes the antenna characteristics and their simulated average and peak gains. The NEC-2 simulations assume a

plane earth, so the effects of obstructions (e.g., buildings and vegetation) have not been included in the VOACAP and ASAPS predictions.

4. Data Analysis and Comparison Methodology

[16] The signal measurements were considered for analysis if there was a nonzero frequency component (i.e., measured SNR > 15 dB). “Since VOACAP is based on a database from which extremely disturbed ionospheric days have been

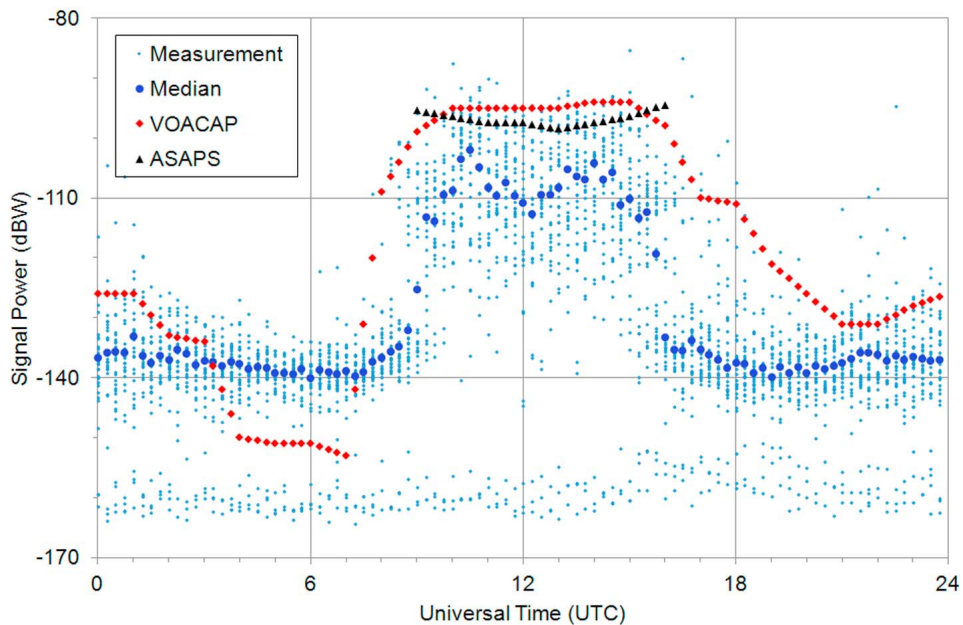


Figure 5. Measurements and predictions for GB3RAL-G4ZFQ January 2010.

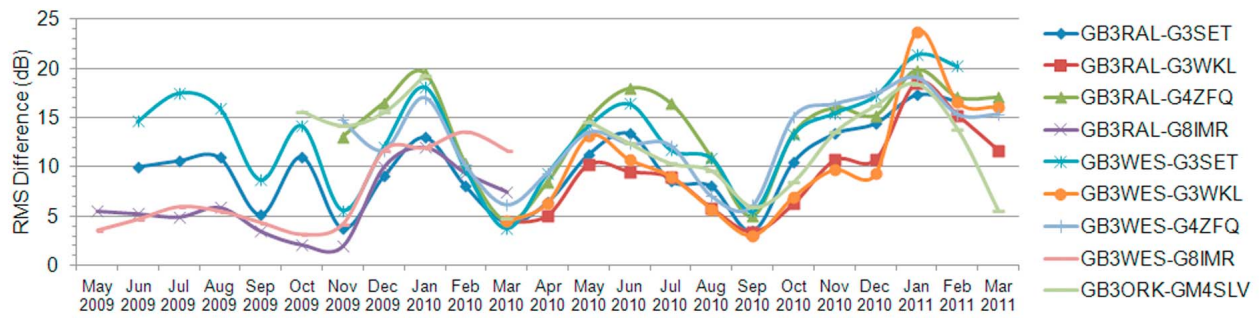


Figure 6. RMS difference between measurements and VOACAP predictions for $MUF_{day} > 0.03$.

removed,” measurements from periods when the planetary index, K_p , was > 4 were also removed [Lane, 2001]. Sporadic E propagation was not considered, partly because of the lack of ionosondes covering the whole of the UK (although the Chilton ionosonde data might be useable for the GB3RAL to G3WKL/G4ZFQ/G8IMR links) but primarily because of the significant additional processing required. The measurement median values were determined only if there were sufficient samples for meaningful calculations and for these values, the RMS and mean differences from the predictions were calculated. The use of a single metric for comparison was not thought suitable because this would have obscured the nuances observable in the measurements. Both VOACAP and ASAPS provide as output a measure of the likelihood of ionospheric support (MUF_{day} and $Probability$, respectively), which is simply the proportion of days in a month when propagation is predicted to occur (the value of MUF_{day} and $Probability$ lies in the range 0–1). For this analysis, comparisons were limited to times when MUF_{day} and $Probability$ were > 0.03 (i.e., at least 1 day in the month). Note that VOACAP outputs a signal prediction even when $MUF_{day} = 0$. Additionally, smaller time correlation windows were considered (0900–1500 UTC and even 1100–1300 UTC).

[17] The measurements in this paper represent the peak signal level in a 5 s interval every 15 min (note that the recent U.S. NVIS investigation using automatic link establishment (ALE) systems only sampled once every hour [Johnson, 2007]). Fading will have been present on the signals and measuring the peak signal might have introduced a bias to the data samples. An earlier UK NVIS study

observed both rapid fading with deep fades, as well as shallow, slow fading, depending on the time of day and month [Burgess and Evans, 1999]. In the presence of rapid fading, the peak measurement is expected to bring the sample closer to the actual median level. Although this method might yield samples in error, it is initially assumed that the samples have a normal distribution about the actual median and, therefore, the comparison with VOACAP and ASAPS median signal levels is still valid. However, the possibility of a nonzero mean error has not been ruled out.

[18] Potential errors in this analysis might be attributable to calibration errors (absolute level and impedance mismatches), sound card nonlinearity and antenna model inaccuracies. The latter might comprise the use of incorrect ground characteristics (permittivity, conductivity and roughness), the presence of secondary conductors affecting the gain and radiation pattern (e.g., other antennas, telephone cables, mains wiring, support structures, etc.), and vegetation and buildings in close proximity. Intermittent faults and transmitter/receiver outages can cause problems and also affect the overall statistics.

5. Comparison of Measurements and Predictions

[19] Figures 2–5 below show typical signal measurement characteristics, together with their corresponding VOACAP and ASAPS median signal predictions, that have been observed over the 23 month analysis period. Figure 2 shows very good correlation between median measurements and predictions for the GB3RAL-G3WKL link during March 2010. Differences tend to increase at the start and end of

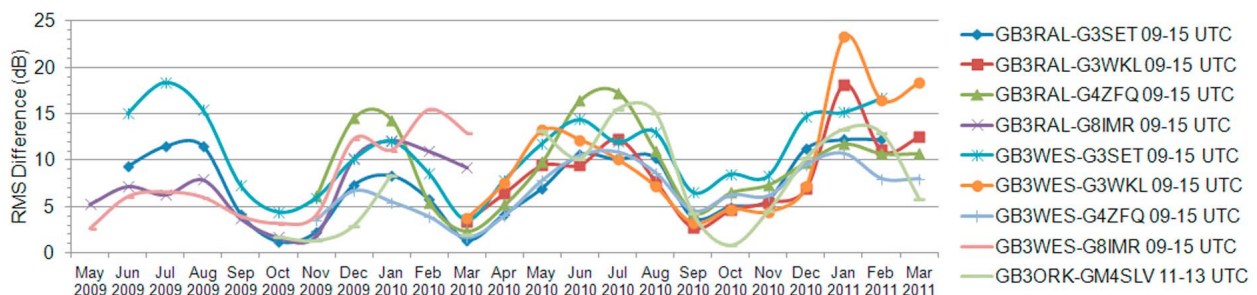


Figure 7. RMS difference between measurements and VOACAP predictions for window about 1200 UTC.

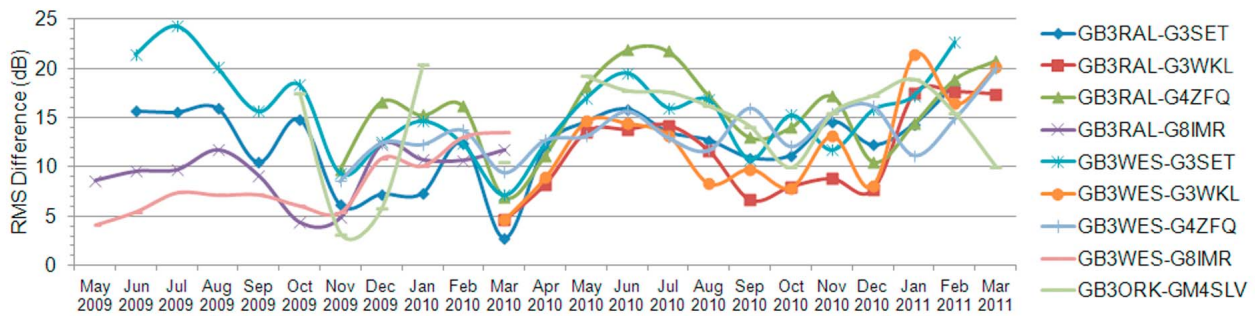


Figure 8. RMS difference between measurements and ASAPS predictions for *Probability* > 0.03.

NVIS propagation, which corresponds to a low VOACAP *MUFday* or ASAPS *Probability*. Similarly good correlation is seen in Figure 3 for the GB3ORK-GM4SLV link during November 2009. In both cases, the measurements showed a small spread in signal levels during the day.

[20] By contrast, Figure 4 shows the measurements and predictions for the GB3RAL-G3SET link during August 2009. During the day, the signal level measurements show a much larger spread than seen in Figures 2 and 3, and median signal levels differ significantly from predictions, although the trends are similar. However, measurements and predictions show much better agreement during the evening. Large differences are also shown in Figure 5 for the GB3RAL-G4ZFQ link during January 2010, although the measurements show a smaller spread than in Figure 4.

[21] Common to all four plots is evidence of “above-the-MUF” propagation during the night when valid signal measurements were recorded (i.e., SNR > 15 dB), even though VOACAP *MUFday* and ASAPS *Probability* were zero (i.e., propagation was not predicted) and measured critical frequencies at the Chilton ionosonde (51.6°N, 1.3°W) were below the operating frequency. Propagation was most certainly not NVIS, but might have been a two-hop, ground (or sea) side scatter mode [McNamara et al., 2008]. Median signal levels were generally 30–40 dB down on typical daytime levels such that the links might have been more efficiently realized on a lower frequency where true NVIS propagation would actually have been supported.

[22] In isolation, the measurements showing large differences from predictions could be viewed as being in error. However, viewing the statistics from all nine NVIS links together is illuminating. Figure 6 shows the RMS

difference between median signal levels and VOACAP predictions when *MUFday* > 0.03, whereas Figure 7 shows the RMS differences from VOACAP about 1200 UTC (either 0900–1500 UTC or 1100–1300 UTC depending on measurements and predictions). A trend is apparent, especially in Figure 7. Low RMS differences were observed around September, October, November, and also March. By contrast, larger RMS differences were seen during the day around the summer months (~April–August) and during winter (~December–February). No trends were apparent in measurements for the North American 490 km link, presumably, because the analysis period was only 10 months long [McNamara et al., 2006]. Note that during 2003, the SSN was greater than that given in Table 3 (SSN ~55–81).

[23] Figure 8 shows the RMS differences between measurements and ASAPS predictions for *Probability* > 0.03. These are generally higher than the VOACAP equivalent (see Figure 6). Figure 9 shows the RMS differences from ASAPS predictions about 1200 UTC, where lower values were seen during autumn and spring, although this is less distinct than the VOACAP equivalent (see Figure 7). Although the ASAPS predictions show greater RMS differences than VOACAP during the summer, these are lower during the winter.

[24] The summer differences might, in part, be related to the $\cos \chi$ -dependent absorption model used in the predictions, where χ is the solar zenith angle. This $\cos \chi$ dependency has been observed on the North American 490 km link measurements on 7.335 MHz [McNamara et al., 2006]. However, the predicted MUF for the summer months of 2009 and 2010 are close to 5.290 MHz such that deviative absorption could have played a greater role in signal

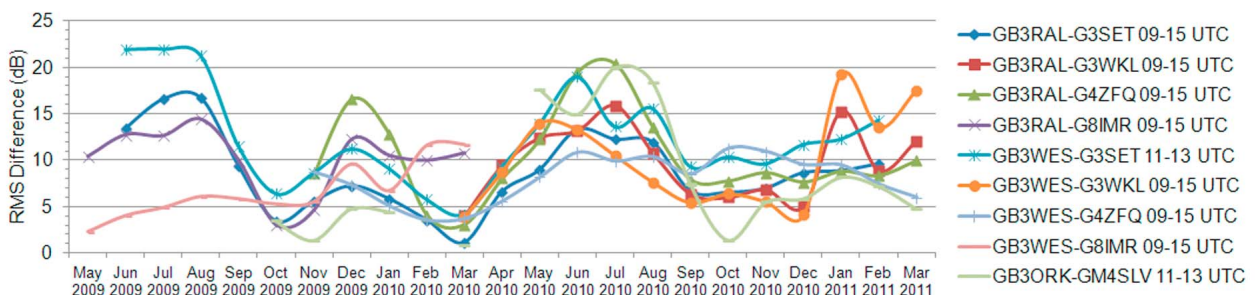


Figure 9. RMS difference between measurements and ASAPS predictions for window about 1200 UTC.

Table 6. Range of Mean Differences Between Measurements and Predictions for All Links Over Measurement Period

	VOACAP (<i>MUFday</i> > 0.03)	ASAPS (<i>Probability</i> > 0.03)	VOACAP (~1200 UTC)	ASAPS (~1200 UTC)
Mean (dB)	–4 to –12	–8 to –14	–6 to –11	–6 to –12

attenuation than was predicted [Davies, 1990]. Additionally, sporadic *E* propagation (E_s) might also have influenced the statistics. The likelihood of E_s at midlatitudes is known to be greater during summer daylight hours [Davies, 1990]. Indeed, the summer daytime measurements typically showed a greater spread in signal levels compared to other times of the year, which could indicate the presence of multiple propagation modes (i.e., 1F2 and 1E_s). The probability of ionospheric support via E_s for a given frequency reduces as the frequency increases and, therefore, the effect of E_s on these measurements at 5 MHz is more obvious (and more so below) than at higher frequencies.

[25] The greater absorption during December, January, and February is consistent with the “winter anomaly” when there is anomalously high absorption [see, e.g., Davies, 1990, Figure 7.8]. It is known that “days of enhanced absorption in one longitude sector are days of low absorption in other longitude sectors” [Davies, 1990]. Scale factors were used with earlier absorption models to accommodate the winter anomaly and, on individual days, these factors might vary between less than 1.0 and as much as ~2.0 [Davies, 1965]. Additionally, there is an asymmetry in the winter anomaly between northern and southern hemispheres that might be due to different meteorological processes occurring around the mesopause [Schwentek *et al.*, 1980]. The presence of an asymmetry suggests that accurate prediction of absorption losses using long-term HF prediction software might be difficult at these times.

[26] Table 6 presents the range of mean differences (associated with the RMS differences shown in Figures 6–9). It would appear that both VOACAP and ASAPS generally overestimated the median signal level for the NVIS links on 5.290 MHz. Of course, this assumes that the input parameters were valid.

[27] The NEC-2 simulations used in this analysis could be optimistic. For example, antenna zenithal gain reductions of about 4–6 dB were observed for ionospheric sounder measurements in California and Thailand forests [Hagn, 1973]. However, significant additional antenna losses at high elevation angles (on top of those simulated) are not thought likely because none of the antennas were located in dense forests (e.g., the GB3RAL antenna was located on top of a flat roof, the GM4SLV loop was located in a grass field and the others were located about residential properties with a low density of trees and bushes, and some or no neighboring properties). Any antenna gain reduction effects are likely to manifest themselves at lower elevation angles (i.e., affecting longer-distance, non-NVIS links more).

[28] It is fair to say that VOACAP is suited for predictions of high-reliability links (i.e., 90%) and, therefore, “actual performance should be much better than the predicted reliability or [SNR90]” [Lane, 2001]. However, Lane also states that “a reliability of 50% might result in a situation where no success is achieved over the month or one in which great success is achieved or anything in between” (available from <http://www.voacap.com/itshfbc-help/voacap-faq.html>).

These statements lead to the interpretation that the measurements were actually consistent with the VOACAP (and, one assumes, ASAPS) predictions.

[29] Table 7 presents the range of overall RMS differences for all nine NVIS links for the analysis period. These values are slightly higher than those obtained for the North American 490 km NVIS link on 3.330 MHz and 7.335 MHz, which might be due to a number of factors including different operating frequencies, different sunspot indices, and different geomagnetic locations for the links [McNamara *et al.*, 2006]. Overall RMS differences would be lower if predictions for each link were adjusted according to Table 6 for zero mean difference over the analysis period. However, summer and winter predictions would still remain optimistic.

[30] On the whole, VOACAP shows slightly lower RMS and mean differences between measurements and predictions than ASAPS for the midlatitude NVIS links on 5.290 MHz for this 23 month analysis period at the recent low point of the solar cycle. However, subjective and somewhat beyond the scope of this paper, ASAPS showed very good agreement for some of the 500–1000 km link predictions (2F2 mode), where VOACAP predictions exhibited larger differences. Obviously, this warrants further investigation.

6. Conclusions

[31] Analysis of NVIS beacon measurements on 5.290 MHz over a 23 month period and comparison with VOACAP and ASAPS median signal predictions has shown some interesting trends and differences. Low RMS differences were observed for September, October, November, and also March. However, greater RMS differences were seen during the spring and summer months (~April to August), which might be due to sporadic *E* and, possibly, deviative absorption influences, that are not well predicted by VOACAP and ASAPS. Similarly, the measurements showed greater attenuation during December, January, and February, consistent with the anomalously high absorption associated with the winter anomaly. The VOACAP summer differences were generally lower than those for ASAPS. Conversely, those for ASAPS were lower during winter. It remains to be seen whether or not

Table 7. Overall RMS Differences Between Measurements and Predictions for All Links Over Measurement Period

	VOACAP (<i>MUFday</i> > 0.03)	ASAPS (<i>Probability</i> > 0.03)	VOACAP (~1200 UTC)	ASAPS (~1200 UTC)
Overall RMS (dB)	7 to 15	9 to 16	7 to 12	7 to 13

these trends in predicted and measured median signal levels on 5.290 MHz continue to be observed through the complete solar cycle.

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References

- Burgess, S. J., and N. E. Evans (1999), Short-haul communications using NVIS HF radio, *Electron. Commun. Eng. J.*, 11(2), 95–104, doi:10.1049/eej:19990205.
- Davies, K. (1965), *Ionospheric Radio Propagation*, Natl. Bur. of Stand. Monogr., vol. 80, Natl. Bur. of Stand., Washington, D. C.
- Davies, K. (1990), *Ionospheric Radio*, Peter Peregrinus, London, doi:10.1049/PBEW031E.
- Fiedler, D. M., and E. J. Farmer (1996), *Near-Vertical Incidence Skywave Communications: Theory, Techniques and Validation*, Worldradio, Sacramento, Calif.
- Goodman, J. M. (1992), *HF Communications: Science and Technology*, Van Nostrand Reinhold, New York.
- Hahn, G. H. (1973), On the relative response and absolute gain toward the zenith of HF field-expedient antennas—Measured with an ionospheric sounder, *IEEE Trans. Antennas Propag.*, 21(4), 571–574, doi:10.1109/TAP.1973.1140544.
- Huang, X., and B. W. Reinisch (2006), Real-time HF ray tracing through a tilted ionosphere, *Radio Sci.*, 41, RS5S47, doi:10.1029/2005RS003378.
- International Telecommunication Union (2009), Method for the prediction of the performance of HF circuits, *Recomm. ITU-R P.533-10*, Geneva, Switzerland.
- IPS Radio and Space Services (2009), ASAPS for Windows V5.3 tutorial, Sydney, N. S. W., Australia.
- Johnson, E. E. (2007), NVIS communications during the solar minimum, paper presented at MILCOM 2007, Armed Forces Commun. and Electron. Assoc., Orlando, Fla.
- Lane, G. (2001), *Signal-to-Noise Predictions Using VOACAP—A Users Guide*, Rockwell-Collins, Cedar Rapids, Iowa.
- McNamara, L. F., R. J. Barton, and T. W. Bullett (2006), Analysis of HF signal power observations on two North American circuits, *Radio Sci.*, 41, RS5S38, doi:10.1029/2005RS003347.
- McNamara, L. F., T. W. Bullett, E. Mishin, and Y. M. Yampolski (2008), Nighttime above-the-MUF HF propagation on a midlatitude circuit, *Radio Sci.*, 43, RS2004, doi:10.1029/2007RS003742.
- Schwentek, H., W. Elling, and M. Peres (1980), Asymmetry in the winter-anomalous behaviour of absorption at midlatitudes in the northern and southern hemispheres, *J. Atmos. Terr. Phys.*, 42(6), 545–552, doi:10.1016/0021-9169(80)90064-1.
- Straw, N. D. (2003), *The ARRL Antenna Book*, 20th ed., Am. Radio Relay League, Newington, Conn.
- Talbot, A. (2005a), Design and construction of the 5 MHz beacons GB3RAL, GB3WES and GB3ORK—Part one, *RadCom*, 81(6), 85–87.
- Talbot, A. (2005b), Design and construction of the 5 MHz beacons GB3RAL, GB3WES and GB3ORK—Part two, *RadCom*, 81(7), 88–89.
- Walden, M. C. (2010), A comparison of measurements and propagation simulations for mid-latitude HF NVIS links at 5 MHz during sunspot minima, paper presented at the Nordic Shortwave Conference HF 10, Nord. Radio Soc., Fårö, Sweden.
- Walden, M. C. (2011), Comparison of propagation predictions and measurements for mid-latitude HF NVIS links at 5 MHz, paper presented at the 13th International Ionospheric Effects Symposium IES2011, Off. of Nav. Res., Alexandria, Va.

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