Fast and accurate calculation of multipath spread from VOACAP predictions

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[1] Improved predictions of multipath spread at HF have been obtained from VOACAP by including the effect of probability distribution functions of the signal power rather than just taking the median signal power. A Monte Carlo calculation method has been adopted that is superior in terms of accuracy and computation speed over the brute force method previously employed. The predictions of multipath spread are generally comparable with the values measured over an 1800 km sub-auroral path. The new method will be useful to those planning or operating digitally modulated radio systems in the HF band since these can be adversely affected by multipath spread.

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1. Introduction

[2] HF radio signals reflecting from the ionosphere can suffer from substantial multipath delay spread (of the order milliseconds) since they may arrive at the receiver via a number of different routes (e.g., 1-hop F and 2-hop F). As well as causing signal fading, large delay spreads can also reduce the data rates achievable with acceptable bit error rates in digitally modulated systems. A number of authors [e.g., *Angling et al.*, 1998; *Warrington and Stocker*, 2003; *Stocker and Warrington*, 2011a] have measured the delay spreads found at various latitudes and some of these values have been incorporated into the appropriate ITU-R recommendation [*International Telecommunication Union Radiocommunication Sector* (*ITU-R*), 2000]. Various models have been produced [e.g., *Watterson et al.*, 1970; *Mastrangelo et al.*, 1997; *Angling and Davies*, 1999; *Warrington et al.*, 2006] that allow the effect of the delay spreads on modems to be simulated and tested [e.g., *Angling and Davies*, 1999; *Jodalen et al.*, 2001; *Warrington et al.*, 2011].

[3] There are a number of methods by which the delay spreads on a given propagation path might be predicted. While raytracing (provided the simulated ionosphere is of sufficient accuracy) would form a physically realistic, albeit somewhat computationally intensive, method, the Voice of America Coverage Analysis Program (VOACAP) [*Lane*, 2001] and ITU-R Recommendation 533 [*ITU-R*, 2009] have generally been used for most studies [e.g., *Rogers*, 2003; *Smith and Angling*, 2003]. However, these methods have some limitations, e.g., they only include the effect of specular reflections, only three hops from each ionospheric layer are calculated, and the underlying databases are monthly and hourly in nature, so predictions cannot be made for individual days. The ITU-R have published a method of calculating the delay spread using such prediction techniques [see *ITU-R*, 2007; *Barclay et al.*, 2009] and this has been incorporated in the software package REC533 (now called ITUHFPROP), but not VOACAP, available from the Institute for Telecommunications Services (ITS) website (elbert.its.bldrdoc.gov). However, this implementation is based on using the median signal power or signal-to-noise ratio (SNR), which, as will be demonstrated in this paper, can often lead to incorrectly predicted values. It should also be noted that the multipath probability (MPROB) value given by VOACAP is not the probability of multipath occurring, but is rather the reliability (i.e., the probability that the SNR exceeds a user-defined required SNR) of the modes meeting the multipath criteria set by the user.

[4] A recent paper [*Stocker and Warrington*, 2011a, 2011b] presented a 'brute force' method of calculating ITU-R multipath spread (IMPS) [*ITU-R*, 2007; *Barclay et al.*, 2009] from VOACAP predictions that included the effect of the SNR probability density functions (pdf). The predictions of spread were compared with observations obtained over several sub-auroral paths with generally good agreement at sunspot minimum, but poorer performance at sunspot maximum because the presence (or otherwise) of high order modes (e.g., 3F2) is not well predicted by VOACAP at that time for these paths. While the method used to calculate the multipath spread from VOACAP predictions has been reasonably well validated, it suffers from very poor computational efficiency and takes too long to run to be used for practical purposes. For example, if four ionospheric modes are present, it can take up to 20 min to calculate the IMPS for a single frequency-hour-month. This time increases rapidly if additional modes are present. In this paper, a Monte Carlo approach has been adopted that provides a solution that is asymptotically approached by the 'brute force' method

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previously employed, but in run times many orders of magnitude smaller. The matlab code implementing this new method is available from the author and will allow the users of prediction programs such as VOACAP to properly determine the expected multipath spreads and the likely effect that these will have on reception.

2. Method

[5] The ITU-R multipath spread (IMPS) is defined in ITU-R Recommendation 842 [*ITU-R*, 2007] and is calculated by finding the largest delay spread including all ionospheric modes that have a power within 10 dB of that of the strongest mode (note that 10 dB is used throughout, but other values are allowable). In the case where there is only one ionospheric mode, then the IMPS (ignoring non-specular reflections) is trivially zero. Where there is more than one ionospheric mode then, if the signal power distributions predicted by VOACAP are ignored, the IMPS can then simply be derived from the median signal power (P_{50}) or SNR for each mode. For example, consider a case where two modes are present, one with a $P_{50} = -150$ dBW and upper and lower decile ranges of 10 dBW (i.e., lower and upper decile signal powers of -160 dBW and -140 dBW, respectively), and the other with a P_{50} of -161 dBW with upper and lower decile ranges of 10 dB. If only the median signal values are considered, then the predicted multipath will be zero since $-150-(-161) = 11$ dB is greater than the 10 dB threshold. However, although this 'median' method is simple to implement and computationally fast, it does not include the effect of the day-to-day signal distributions predicted by VOACAP. If the day-to-day signal distributions are included and the split Gaussian method described below used, the probability of there being multipath will be $\sim$46% (and, clearly, a 54% probability of there being no multipath, as given by the calculation using the medians). The results from the 'median' method are compared with those from the Monte Carlo methods in Section 2.5.

[6] The Monte Carlo approach is divided into two main parts. First, the signal power pdf for each ionospheric mode is determined from the VOACAP predictions and second these distributions are then combined to find the probability distribution of the IMPS.

2.1. Calculating the Signal Power Probability Distribution

[7] In order to calculate the IMPS, VOACAP must be run using 'method 25, all mode tables' since the output then contains the median and upper and lower decile signal powers and time delays of each individual ionospheric mode (note that the currently available implementation of ITU-R Recommendation 533 [*ITU-R*, 2009] does not have an equivalent method, and therefore cannot easily be used). Three approaches of calculating the pdf have been employed. The first ('analytic') method was used in previous work [*Stocker and Warrington*, 2011a, 2011b]. Here, the median and upper and lower deciles of signal power and noise power were combined analytically following the method described in *Lane* [2001] to determine the SNR pdf. However, this method of calculating the IMPS is flawed since it implicitly assumes that there is an independent noise source for each ionospheric mode, whereas, in general, for a given frequency, antenna, time of day and receive site the noise will be the same for all ionospheric modes. The error introduced into the value of the IMPS by analytically combining the signal and noise values using this method is quantified in Section 2.5. In the second technique, signal power pdf, split Gaussian in form (i.e., Gaussians with different standard deviations above and below the median), have been generated separately for each ionospheric mode. In the third method, a skew-normal (SN) distribution [*Azzalini*, 1985] has been used to represent the signal power for each mode.

2.1.1. Split Gaussian Signal Power Distribution

[8] If the signal power distributions are assumed to be split Gaussian in form (i.e., with standard deviations that are different above and below the median) they can be found by taking the median and upper and lower decile values predicted by VOACAP and using equations (1) and (2).

$$P_u = P_{50} + \sqrt{2} \times \frac{dP_{90}}{1.28} \times erf^{-1}(2p_u) \tag{1}$$

$$P_l = P_{50} - \sqrt{2} \times \frac{dP_{10}}{1.28} \times erf^{-1}(2p_l - 1) \tag{2}$$

where P_u is the power above the median and P_l the power below the median value and $0.5 < p_l \leq 1.0$ and $0 \leq p_u \leq 0.5$ are fractional probabilities (e.g., $p_u = 0.5$ results in a value of $P = P_{50}$, i.e., the median). The upper and lower decile ranges, i.e., the separation of the decile from the median, (dP_{90} and dP_{10}, respectively) are converted to the upper and lower standard deviations by dividing them by 1.28 in the above equations. To calculate the density functions, N probability values are generated using a pseudo-random number generator.

2.1.2. Skew-Normal Signal Power Distribution

[9] Following *Azzalini* [1985], the density function of the SN distribution (centered on 0 with a scale of 1) is given by

$$\phi(z;\ \alpha) = 2\phi(z)\ \Phi(\alpha z) \tag{3}$$

where $\phi(z)$ and $\Phi(\alpha z)$ are the density function and cumulative distribution function of a normal distribution, and α is the shape parameter. To find the SN signal power distribution, a split-Gaussian distribution with N elements is generated (see previous section). An expectation-maximization (EM) algorithm is then used to find the MLE and hence the scale, location and shape parameters, although *Azzalini and Capitanio* [1999] note that while this method is reliable, it is also relatively slow. Furthermore, in the matlab implementation used, memory limitations restrict the fit to the first 5000 samples of the N elements. Once the fit parameters have been found, then a SN density distribution with N samples can be generated.

2.2. Finding the ITU Multipath Spread (IMPS)

[10] Once a signal power pdf has been produced for each ionospheric mode (by either method described in the preceding subsection), then for each instance (i.e., for each of the N independently, randomly determined samples) the

Table 1. Example Method 25 Output From VOACAP for a 6.9 MHz Signal on a Path From Nurmijärvi (60.51N, 24.66E) to Bruntingthorpe (52.49N, 1.12W), January 2010[a]

	1.E (Low)	1.E (High)	1.F2
Time del.	6.11	6.15	6.38
Sig. pow.	−134.10	−142.93	−109.24
SNR	20.16	11.33	45.01
Sig low	25.00	25.00	20.81
Sig up	13.31	23.61	4.98

[a]The transmitted power = 100W, 3 MHz noise value = −145 dBW, and vertical monopole antennas were used at both the transmitter and receiver. Only relevant output parameters are shown, time del. is the propagation delay (in ms), sig. pow. is the monthly median signal power (in dBW), SNR is the monthly median SNR (in dBW·Hz), and sig low and sig up are the lower and upper decile ranges of the signal power (in dB), respectively.

strongest mode (P_{max}) and those modes that have a power, P such that

$$P_{\max} - P \leq P_t \tag{4}$$

where the default value of the threshold, P_t is 10 dB [*ITU-R*, 2007] are found. Since the code has been written in matlab, this algorithm needs to be vectorised in order to ensure fast operation. Two methods have been employed to do this, the choice of method depending on how many ionospheric modes are present. For cases up to five modes the occurrence of the various combinations of different modes within the threshold power is calculated. For example, with three modes, there are five combinations, single moded (i.e., where no modes fulfil the condition given in equation (4)), modes 1 and 2 (only) are within the threshold and one or other is the strongest mode, similarly for modes 1 and 3 and modes 2 and 3, and finally modes 1, 2, and 3 (i.e., all three modes fulfil the condition in equation (4), whichever is the strongest mode). For five and six modes there are 27 and 58 combinations, respectively and the increasing number of combinations leads to a significant increase in the complexity of the code and the time it takes to run. Therefore, for six modes or more, a different method is used to calculate the IMPS such that the modes are first sorted in order of delay and then, for each of the N instances, the modes with the highest and lowest delays that meet the condition in equation (4) are found. This dramatically reduces the complexity of the code and, for six modes or more, the execution time (the second method is just marginally faster for six modes). For both methods, the maximum difference in time of flight (or delay time) for the selected modes is then found resulting in the IMPS value.

[11] Since a Monte Carlo method is used, each time the program is run, a slightly different answer is obtained. By running the program multiple times the standard deviation, σ associated with a single estimate of IMPS (with N = 100000) can be found. An approximate value of σ for the split-Gaussian case is given by the following, empirical, expression

$$\log_{10} \sigma \approx 0.4606 \log_{10} P - 1.5022 \tag{5}$$

where P = probability (%) for values less than 50% and P = 100−probability for values greater than 50%. Since the approximation given by equation (5) breaks down for high values of P, σ should be capped at 0.15 percentage points. If the calculation has been run with *N* instances, then the standard deviation calculated above is modified as follows

$$\sigma(N) = \sqrt{\frac{100000}{N}}. \tag{6}$$

[12] The upper and lower decile ranges can be approximated by 1.28σ. It should be noted that although equations (5) and (6) provide the statistical accuracy associated with the calculation of the various probability values of IMPS using the Monte-Carlo method, other sources of error (e.g., the difference in the type of distribution employed – see following section, and the limitation of the VOACAP prediction method itself) are likely to be significantly larger.

2.3. Example Calculation of IMPS

[13] An example prediction made by VOACAP (version 10.0123W) using method 25 is given in Table 1. For this frequency and time, three modes are predicted (1F2 and low and high angle 1E) with monthly median signal power values of approximately −134, −143, and −109 dBW. Taking the 1F2 mode, the upper and lower decile ranges of signal power are dP_{90} = 4.98 dB and dP_{10} = 20.81 dB, respectively. If the signal power distributions are ignored and the median method of calculation is used then in this case, the propagation is effectively single moded and the IMPS = 0 ms.

[14] The split Gaussian signal power pdf and cumulative distribution functions (cdf) for the three modes given in Table 1 are plotted in Figure 1. The split Gaussian nature of Modes 1 and 3 (low angle 1E and 1F2, respectively) in particular are immediately apparent in both the pdf, where there is a discontinuity in the number of occurrences at the median, and the cdf, where there is a discontinuity in the gradient. This discontinuity arises because although the number of samples above and below the median is, by definition, the same, the samples above the median are distributed over a smaller range of signal power values and hence the number density (or occurrence) is higher. For Mode 2, the upper and lower decile ranges are similar (see Table 1) and therefore there is no discontinuity and the pdf and cdf behave more like a Gaussian.

[15] The skew-normal signal pdf and cdf for the same three ionospheric modes (see Table 1) are given in Figure 2. It is clear that fitting a SN distribution has removed the discontinuities found in Figure 1 and that the SN distribution may be more representative of likely form of the original empirical distributions used by VOACAP to predict the signal powers. However, the properties of the distribution are changed, e.g., for Mode 3, the median signal power predicted by VOACAP is approximately −109.2 dBW, whereas the median of the SN distribution fitted to the split-Gaussian is −112.9 dBW (the deciles are less affected, with the upper decile being changed by 0.3 dB and the lower decile by 1.7 dB). Furthermore, the execution time of the SN method is between three times and nearly seven times longer than that of the split Gaussian method (example execution times are given in Table 2).

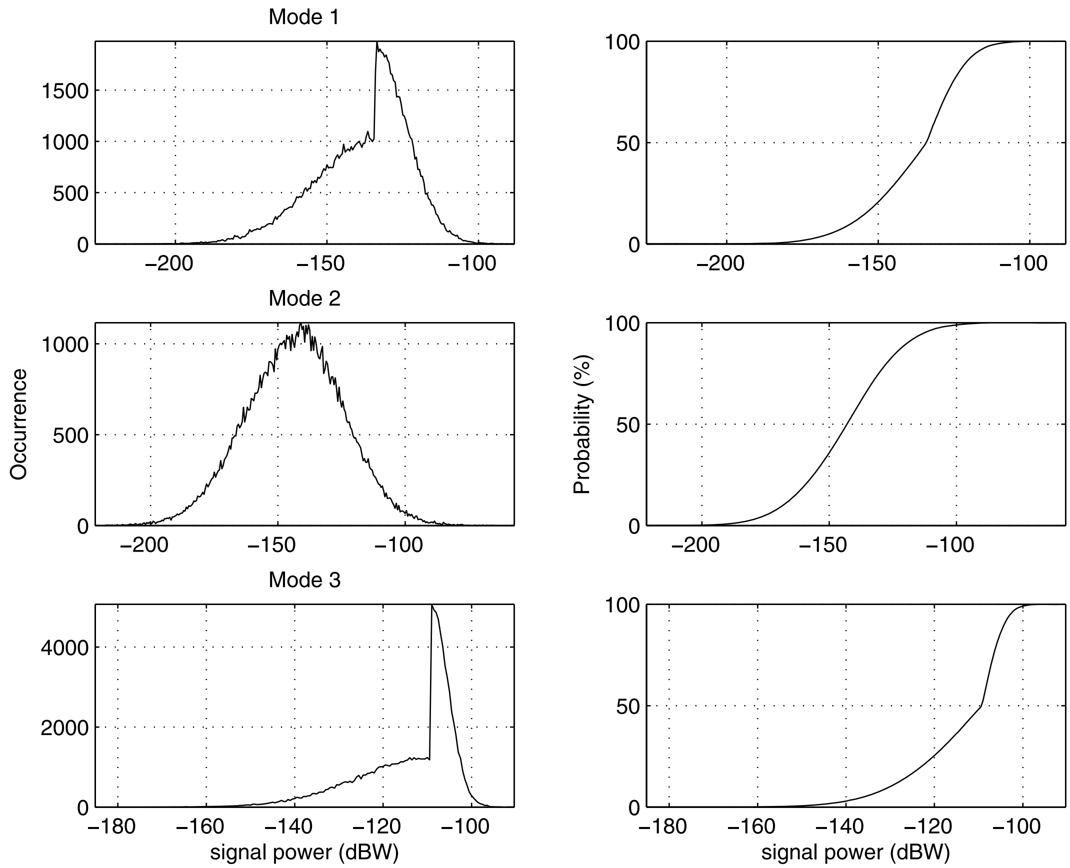

Figure 1. (left) Split-Gaussian probability distribution function and (right) cumulative probability distribution function for the three example modes whose parameters are given in Table 1 (Mode 1 is low-angle 1E, Mode 2 is high angle 1E, while Mode 3 is 1F2). A total of 100000 random values were used to generate each curve.

[16] For the example given in Table 1, the IMPS values are presented in Table 3 for the analytic [*Stocker and Warrington*, 2011a, 2011b], split Gaussian, and skew-normal methods of finding the signal power pdf. In this case, the results for the split Gaussian and SN distributions are similar with a maximum difference of approximately 2.5 percentage points. This difference is more than the associated statistical errors, suggesting that fewer than 100000 samples could be used with no significant loss of accuracy and a consequent improvement in execution time. The results in Table 3 indicate that while the propagation is predicted to be single moded approximately 73% of the time (for a split-Gaussian pdf), for 26% of the time the IMPS would be greater than 0.2 ms with consequent effects on the robustness of digitally modulated systems. In this case, whatever distribution is used (split-Gaussian or SN), the median value of IMPS is 0 ms and the upper-decile value is 0.27 ms. In general, the result once again illustrates the importance of taking the distribution of powers into account since, as mentioned above, if the medians alone were used to calculate the IMPS, the solution would appear to be single-moded.

2.4. A Comparison of the 'Brute Force' and Monte Carlo Methods

[17] The brute force method of calculating the IMPS from the SNR pdfs predicted by VOACAP has been described in *Stocker and Warrington* [2011a, 2011b]. In brief, the pdf was constructed for each mode with a given number of samples at equally spaced probabilities, e.g., if the number of samples, N_s = 99, the first would be at a probability of 1%, the second 2%, up to the last one at 99% (i.e., the resolution would be 1%). The IMPS was then calculated for all possible combinations of SNR values. The number of combinations is then given by N_s^n, where n is the number of ionospheric modes and therefore, increases in the resolution (and hence N_s) or the number of modes led to rapid increases in the execution time. An example of the performance of the brute force method with increasing N_s is given in Figure 3. As expected, the execution time of the brute force method increases as the resolution is increased. At the lowest resolution shown it is still slower than the Monte Carlo method, but produces a result that underestimates the value given by the Monte Carlo method by over two percentage points. At the highest resolution shown, the IMPS given by the brute force method is at the bottom end of the distribution of values produced by the Monte Carlo method, but this takes approximately 13 h of run time. From the figure, it would appear that increasing the resolution used by the brute force method still further would eventually give a result comparable with the Monte Carlo method, but in a completely unacceptable time. Therefore, the Monte Carlo method not

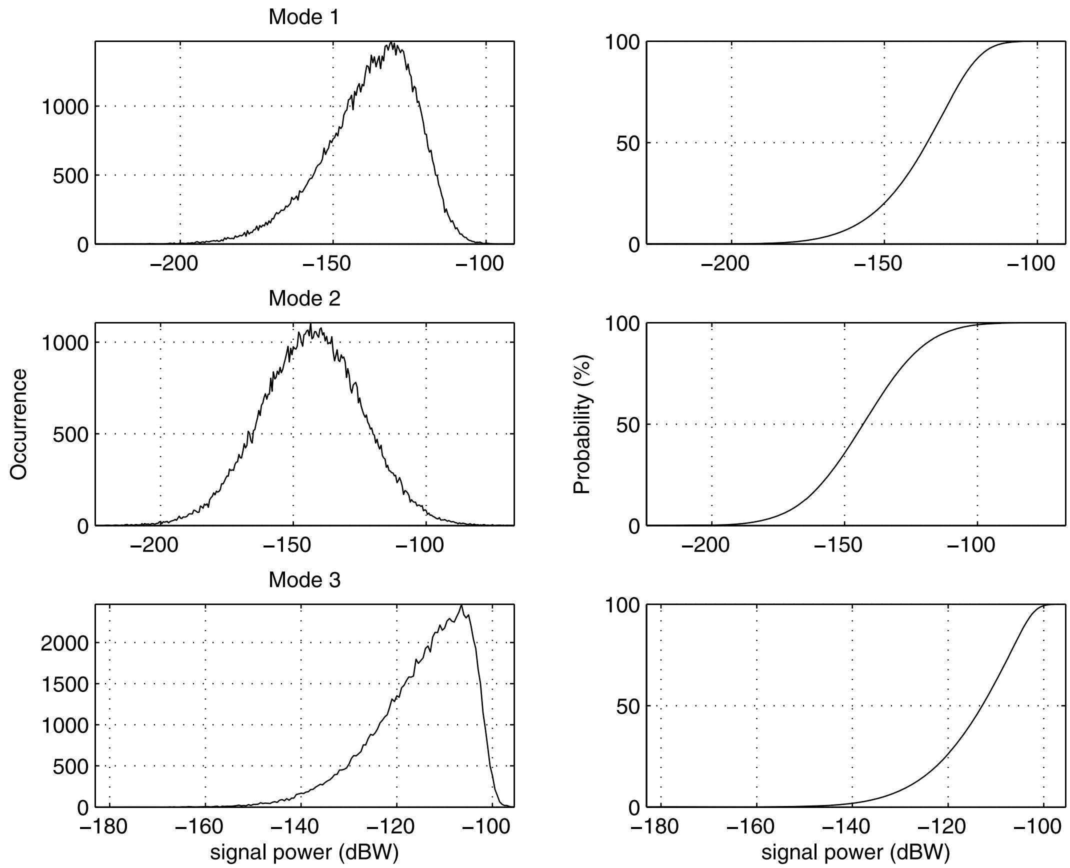

Figure 2. Same as Figure 1, except a skew-normal distribution is used (which is fitted to the first 5000 samples of the split-Gaussian).

only produces a result in significantly less time than the brute force method, but the result is also more accurate.

2.5. A Systematic Comparison of the pdf Generation Methods

[18] In order to systematically test the effect of the different methods of calculating the probability distribution functions, a test set of VOACAP predictions have been used. This consists of predictions for a single path (Nurmijärvi-Leicester) for every month-hour in 2008 for three different frequencies (4.6 MHz, 6.9 MHz, and 8.0 MHz) giving a total of 864 cases. In processing these predictions to find the IMPS, weak modes have been omitted (where a weak mode is defined as one in which the signal power at the 99th percentile is more than 30 dB below the signal power of the 1st percentile of the strongest mode) in order to reduce execution time. The frequency of occurrence for different numbers of modes is given in Table 4. In this test set, there are 298 cases where only one mode is predicted and, as a consequence, where no calculation of IMPS is required (since, given specular reflection, it will be 0 ms). Of the remaining 566 cases, there is a good mix of different numbers of modes, although it should be noted that since the IMPS is currently not calculated for more than 8 modes, where there are more modes than this the weakest ones are omitted until the eight strongest ones remain (i.e., in the test

Table 2. Time (in Seconds) to Calculate IMPS for Different Number of Modes[a]

	Number of Modes						
	2	3	4	5	6	7	8
Split-Gaussian	0.07	0.13	0.22	0.38	1.03	1.07	1.13
Skew-normal	0.48	0.94	1.18	1.63	3.09	3.35	3.61

[a]100000 samples, Matlab R2011b, 64-bit Scientific Linux 5.4, 2.67 GHz Quad-core Intel Xeon X5550, one processor used. The skew-normal was fitted to the first 5000 samples of the split-Gaussian distribution.

Table 3. The Mean Percentage Probability of Different ITU Multipath Spread (IMPS) Values (in ms) for the Example Given in Table 1[a]

	IMPS (ms)			
	0.00	0.04	0.23	0.27
Analytic method	72.82 ± 0.14	1.30 ± 0.03	9.18 ± 0.09	16.69 ± 0.12
Split-Gaussian	73.05 ± 0.14	1.00 ± 0.03	9.45 ± 0.09	16.50 ± 0.11
Skew-normal	70.41 ± 0.40	0.78 ± 0.05	10.25 ± 0.24	18.55 ± 0.36

[a]100000 samples were used in creating the pdf. The errors represent the standard deviations obtained after 1000 runs. The skew-normal was fitted to the first 5000 samples of the split-Gaussian distribution.

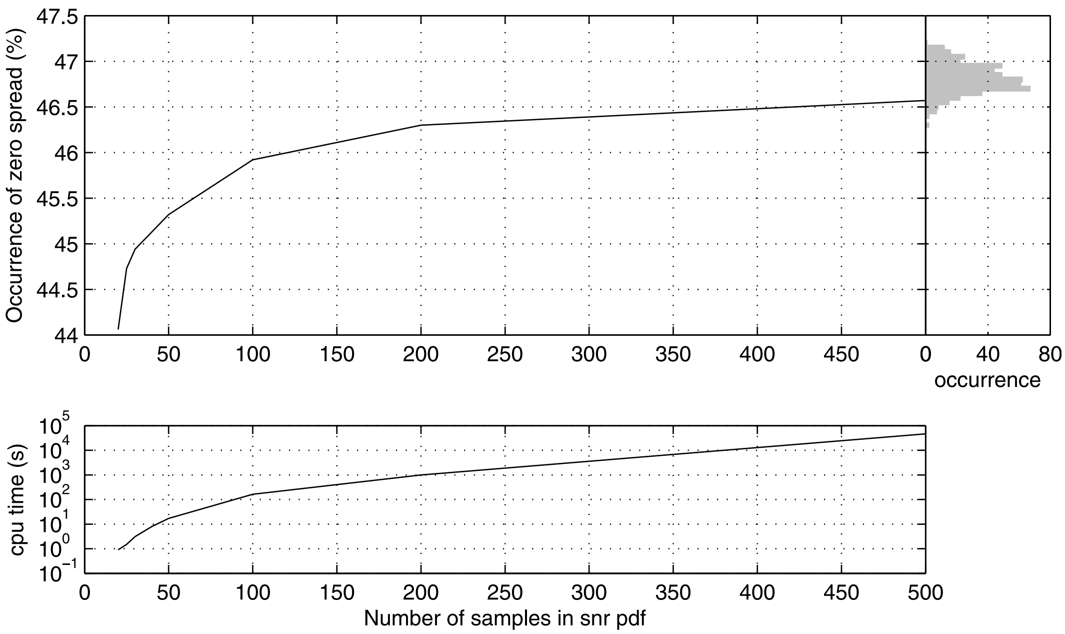

Figure 3. A comparison of the performance of the brute force and Monte Carlo methods of calculating the IMPS for four modes ($SNR_{50}/dSNR_{10}/dSNR_{90}$ of 0/10/10, −10/10/10, −20/10/10, and −30/10/20). (top left) The probability of occurrence of an IMPS = 0 ms as a function of the number of samples in the SNR pdf (N_s) for the brute force method, (top right) a histogram of the number of times the Monte Carlo method produced a given probability of occurrence of IMPS = 0 ms after 500 runs (with N = 100000), and (bottom) cpu time required for brute force method to run as a function of N_s (for comparison, a single run of the Monte Carlo method took ∼0.38 s).

set, there will be a total of 11 cases where the calculation uses 8 modes). For each case in the test set, the absolute difference in the median IMPS found using split Gaussian pdf and the various other methods, i.e., the 'median' method where only the median signal powers are used, the 'analytic' method [*Stocker and Warrington*, 2011a, 2011b] where, incorrectly, independent noise sources have been included in the pdf for each ionospheric mode, and skew-normal, has been calculated. For the Monte-Carlo methods (i.e., all except the 'median' method), N = 100000 and for the skew-normal method, the first 5000 points have been used to determine the fit parameters. The statistics associated with these differences in IMPS are presented in Table 5. The comparison of the split-Gaussian results and the 'median' method shows the benefit of including the effect of the signal power pdf in the calculation of IMPS, since in over half of cases there is a difference in value found with the difference exceeding 0.9 ms in 10% of cases. As discussed above (Section 2.1), the analytic method presented in a previous paper [*Stocker and Warrington*, 2011a, 2011b] incorrectly introduced an independent noise source for each ionospheric mode. The effect this has on the test cases is illustrated in Table 5, where more than half the time (up to the 73rd percentile) there is no difference in the predicted result, while the difference exceeds 0.3 ms in 10% of cases. This means that the results given by *Stocker and Warrington* [2011a, 2011b] are broadly correct with relatively small errors only affecting a few cases. The effect on the predicted median IMPS of changing the shape of the signal power distribution from split Gaussian to skew-normal is also presented in Table 5. In 90% of cases, there is no difference in the predicted IMPS and even in 5% of cases the difference exceeds only 0.13 ms, so although the skew-normal distribution removes the discontinuity in the signal power distribution introduced by the split Gaussian method, the marginal

Table 4. Frequency of Occurrence of Number of Modes in Test Set of VOACAP Predictions Consisting of All Month-Hours in 2008 for 4.6, 6.9, and 8.0 MHz on the Nurmijärvi-Leicester Path

	Number of Modes									
	1	2	3	4	5	6	7	8	9	10
Frequency of occurrence	298	61	107	65	150	101	71	6	2	3

Table 5. Absolute Difference in Median IMPS Values (in ms) Between Split-Gaussian and Other Methods at Different Percentiles for a Test Set of VOACAP Predictions Consisting of All Month-Hours for 2008 on the Nurmijärvi-Leicester Path

	Percentile			
Method Compared	50	75	90	95
'Median'	0.06	0.63	0.91	1.06
'Analytic'	0.00	0.06	0.30	0.60
Skew-normal	0.00	0.00	0.00	0.13

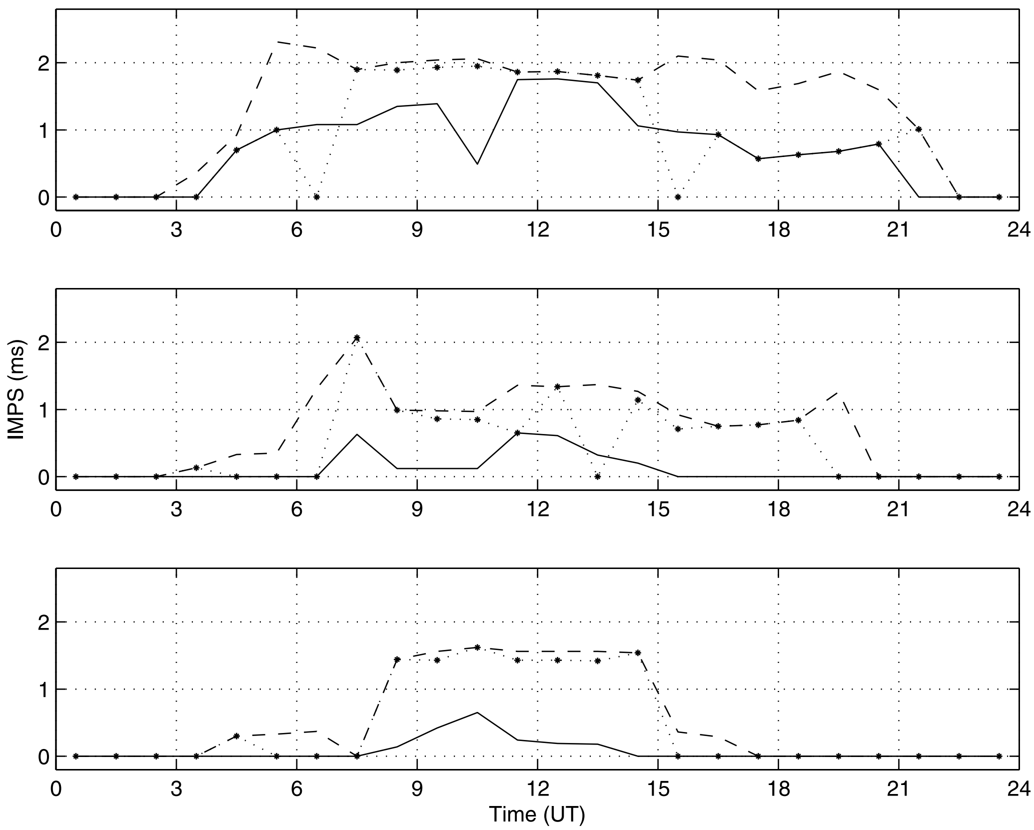

Figure 4. ITU multipath spread (IMPS) derived from VOACAP predictions as a function of time of day for Nurmijärvi-Leicester in April 2008 for three frequencies, (top) 4.6 MHz, (middle) 6.9 MHz, and (bottom) 8.0 MHz. The dotted line, together with the stars, is the IMPS considering the median signal power values only, while the solid (median) and dashed (upper decile) lines are derived from the split Gaussian probability distribution functions. Note that the times are plotted 30 min earlier than that given by VOACAP (i.e., the 1 UT VOACAP prediction is plotted at 0030 UT, 12 UT is plotted at 1130 UT, etc.).

changes in the outcome do not justify the additional code complexity and run time required.

3. Comparison of Predictions With Observations

[19] VOACAP has been used to predict the propagation on a sub-auroral path from Nurmijärvi, Finland (60.51°N, 24.66°E) to Bruntingthorpe, U.K. (52.49°N, 1.12°W) in April 2008 (a smoothed sunspot number of 3 was employed). The input parameters were chosen to broadly represent those employed in a recent experiment [see *Stocker et al.*, 2009], e.g., a transmitted power of 100 W, vertical monopole antennas at transmitter and receiver (although note that this is a gross approximation for the transmit antenna), and a value of -145 dBW for the 3 MHz noise. The predicted IMPS with a 10 dB threshold has been calculated and plotted in Figure 4 for several frequencies using both the 'median' method and the split Gaussian method. In the cases presented, the values of IMPS calculated directly from the median signal power values usually fall between the median and upper decile values calculated from the signal power pdfs, although occasionally they are below the median value (e.g., for 4.6 MHz at 0630 UT and 1530 UT). As discussed previously, this indicates that the value produced by the 'median' method can be significantly different from the value of IMPS calculated from the signal power pdfs. The diurnal behavior of predicted IMPS is as expected, with greater spread during the day when there are multiple propagation modes and lower spread at night, when there are fewer propagation modes. As the frequency increases, the interval where the spread is high becomes shorter – a result that is consistent with what would be expected. Note that at frequencies higher than 8.0 MHz (not shown), the median IMPS is no more than 0.3 ms, while the upper decile is usually below 0.6 ms.

[20] The observed values of the IMPS (with a 10 dB threshold) derived from measurements collected in April 2007, 2008, and 2009 on the Nurmijärvi to Bruntingthorpe path are presented in Figure 5. The system used to collect these measurements is described in more detail in *Stocker et al.* [2009]. The important considerations are that a 100 W Barker-13 BPSK modulated signal was radiated for 2 s every 20 s. The carrier frequency was changed at 20 s intervals with six different frequencies from 4.6 MHz to 14.4 MHz in use, giving an observation on a given frequency every 2 min. A spaced array consisting of 8 antennas was deployed at the receiver allowing the direction (both azimuth and elevation) of the received signal to be determined. The transmitted Barker-13 sequence allowed both signal recognition and, since the clocks at transmitter and receiver were synchronised using GPS, the measurement of the absolute time of

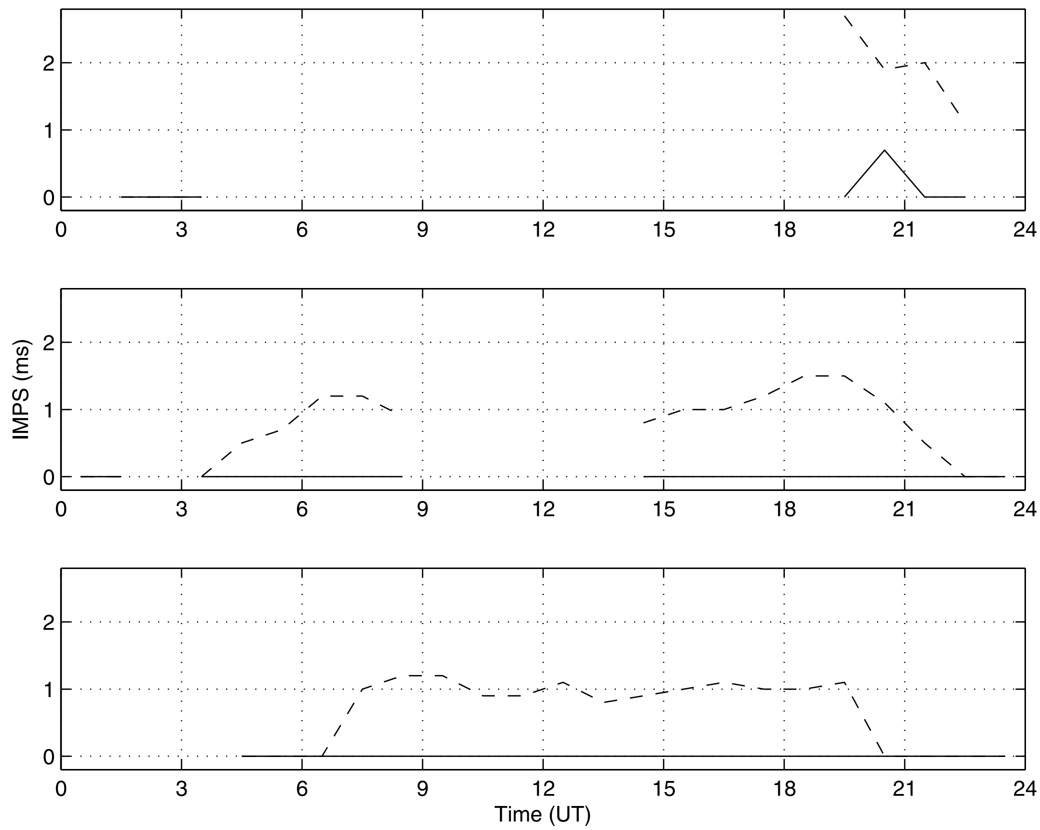

Figure 5. The median (solid line) and upper decile (dashed line) IMPS measured for Nurmijärvi-Leicester in April (observations from 2007, 2008 and 2009 are combined). Only observations with an SNR (in 3 kHz bandwidth) of greater than 6 dB have been included. The frequencies are (top) 4.64 MHz, (middle) 6.95 MHz, and (bottom) 8.01 MHz.

flight of the signal. However, it is important to note that since the sounding technique employed a transmitted pulse width of 0.5 ms (the Barker-13 sequence chip rate was 2000 baud), in general, ionospheric modes that have a TOF within 0.5 ms cannot be distinguished and, consequently, derived values of IMPS are either 0 ms or 0.6 ms or greater. In Figure 5, this means that the measured median values tend to be 0 ms (except briefly at 2030 UT for 4.64 MHz). Furthermore, the measurements at 4.64 MHz in Figure 5 are strongly affected by D region absorption with insufficient observations from about 0430 UT (before which the median and upper decile value of IMPS are both 0 ms) to 19 UT. Unfortunately, this period coincides with when VOACAP predicts the largest values of IMPS. The observations at 6.95 MHz are also affected by D region absorption from approximately 9–14 UT. The diurnal variation and frequency dependence of the measured IMPS shows a broad similarity to the VOACAP predictions, i.e., larger during the day and smaller at night, and smaller for larger frequencies. There is a good agreement between the predicted and observed upper-decile values of IMPS for 6.95 MHz. However, for 8.01 MHz, the daytime predicted values ($\sim$1.5 ms) are larger than those observed ($\sim$1 ms) because the difference in the predicted time of flight of the 2F2 and 1E modes (these are the modes largely determining the delay spread at these times) is larger than that observed. Furthermore, the observed multimoded propagation

Table 6. Observed (Obs) and Predicted (VOA) Values of the Upper Decile of ITU Multipath Spread (ms) at a Threshold of -10 dB for 2007–2009[a]

	4.64		6.95		8.01		10.39		11.12		14.36	
	VOA	Obs	VOA	Obs	VOA	Obs	VOA	Obs	VOA	Obs	VOA	Obs
Winter day	1.5	–	1.4	0.9	0.7	0.7	0.6	0.6	0.2	0.0	0.2	0.0
Winter night	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	–	0.0	0.0
Summer day	1.8	–	1.6	–	1.7	–	0.4	0.0	0.6	0.0	0.6	0.0
Summer night	0.3	1.2	0.1	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Equinox day	2.0	–	1.5	1.1	1.4	1.1	0.3	0.6	0.3	0.3	0.4	0.0
Equinox night	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[a]Split Gaussian distributions of the signal power with N = 100000 samples have been used in calculating the predictions. Winter is defined as November–January, Summer is May–July, and Equinox the remaining months. Day is defined as 09–15 UT, and night 21–03 UT. A dash indicates that there were insufficient observations to determine the experimental value.

continues later than that predicted because the 2F2 mode is observed for longer than it is predicted, although for April 2007 (when the sunspot number was 10) the predicted 2F2 mode is present until 18UT. *Stocker and Warrington* [2011a] identified a number of cases where the VOACAP predictions of IMPS differed from those observed, e.g., where the presence of off-great circle modes or sporadic E in the observations were not reflected in the predictions (the former because VOACAP cannot predict off great circle propagation, the latter because the sporadic E model was switched off).

[21] The observations and predictions are compared by time of day and season in Table 6. These data are in the same format as previously presented by *Stocker and Warrington* [2011a], but have been recalculated using the signal power rather than the SNR (since the latter method included an independent noise source for each mode) and with an increase in the maximum number of modes included in the calculation of IMPS from five to eight (the 'brute force' method previously used was limited to five modes because of run time considerations). As a consequence, a few of the values have changed, although the broad conclusions are the same, i.e., that there is a broad agreement between the predictions and observations. However, for the lower frequencies, the predictions of daytime IMPS tend to be higher than those observed for all seasons. For 6.95 MHz, this appears to be because the predicted *E* region modes are not detected during the day because the time of flight of the 1E/2E modes are within 0.5 ms of the much stronger 2F2 mode and, consequently, the IMPS is reduced. For 8.01 MHz during some equinoctial months, the predicted high angle 2F2 mode is not observed and again, this reduces the measured value of the IMPS.

4. Conclusions

[22] A new, Monte Carlo, method of calculating the ITU multipath spread (IMPS) predicted by VOACAP has been presented. This method is significantly more accurate than that described by the ITU [*ITU-R*, 2007] since the day-to-day distribution of mode signal power is properly taken into account (rather than just taking the median signal power) and is several orders of magnitude faster than the 'brute force' method recently reported by *Stocker and Warrington* [2011a]. It is also noted that the method of *Stocker and Warrington* [2011a, 2011b] was in error since what were effectively independent noise sources were included for each ionospheric mode. The effect of the shape of the signal power distribution has been investigated by looking at two forms, namely the split Gaussian and skew-normal. In 90% of cases the choice of distribution has little effect on the derived value of IMPS and since the split Gaussian distribution has the advantage of faster execution time then, despite the discontinuity at the median, it has been used in comparing the predictions with the observations. The predictions have been compared with measurements taken at sunspot minimum on a sub-auroral propagation path and while there are some discrepancies, in general the predicted behavior is close to that observed. There are some limitations to the prediction methods used in programs like VOACAP and ITUHFPROP, since they rely on month-hour databases, predictions for individual days cannot be produced, they ignore polarization fading, and they only account for on-great circle, specular reflection (both ionospheric and ground). Therefore, in regions where strong scattering occurs (e.g., in the auroral zones), the predictions of the time-of-flight and hence IMPS may then be inaccurate. Evidence of this was presented by *Stocker and Warrington* [2011a] where on a sub-auroral path, off-great circle scattering from the auroral zone was frequently observed but not predicted. The new code will benefit a wide range of HF radio users, but it is anticipated will be of particular use to those planning and operating digitally modulated systems where multipath spread has a significant effect on system performance. However, it is important to note that currently neither VOACAP nor ITUHFPROP predict Doppler spread effects and that this, together with delay spread, can have significant effects on the performance of digitally modulated signals.

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