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Improved Guidelines for Automatic Link Establishment Operations

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1. INTRODUCTION

High frequency (HF) radio systems employing modern automatic link establishment (ALE) protocols can operate much more reliably using lower power and less expensive antennas than conventional manually operated systems. The ALE systems utilize link quality assessment to find the best frequency for current operations from a scan list of candidate frequencies. Such frequency agility is nearly impossible using human operators, especially in the situation of multi-station networks. The underlying advantage of having almost real-time sampling is that the links in the net are set automatically to the frequency yielding the highest signal-to-noise ratio (SNR) under the prevailing ionospheric conditions at that point in time.

Yet, ALE systems can fail to the point where no useful communications is possible. This is generally because of an inadequate frequency scan list or improper antenna selection. Current guidelines suggest that planners use prediction programs to find the available working band of frequencies per radio link by time of day, month and sunspot number [NTIA, 1998]. These ALE handbooks and manuals suggest picking frequencies which fall between the FOT (loosely translated as the *frequency of optimum traffic*) and the lowest usable frequency (LUF) [ALSA Center, 2003]. This guidance for ALE operation is very poor and usually leads to reduced performance. In this paper, new frequency planning guidelines are suggested and compared to measured data on a 7159 km HF link between France and the USA. It is shown that the ALE system will operate effectively on frequencies which are above the predicted MUF. The improved guidelines provide a means of accurately predicting the actual band of frequencies where ALE operation would be optimized. This paper provides the supporting evidence for the use of VOACAP for ALE frequency planning in accordance with the new International Telecommunications Union Recommendation on adaptive HF planning [ITU-R, 2003].

2. BACKGROUND

ALE systems scan a list of pre-selected frequencies within a computer controlled time-schedule and perform a link quality assessment (LQA) on each frequency scan. The assessment is made using bit error rate (BER) for the known transmission. The BER is also directly related to the signal-to-noise ratio (SNR). The frequency having the lowest BER or the highest SNR is then selected for sending and receiving traffic over the HF link.

This process of finding the optimum frequency in near real-time allows the ALE system to find the frequency having the best propagation condition (i.e. highest SNR). HF radio performance is known to be external noise limited. That is the SNR is controlled by the combination of atmospheric, man-made and galactic radio noise. RF noise decreases exponentially with increasing frequency. Therefore, we would expect that the ALE system will find the highest frequency having the lowest BER or best SNR. We also know that the maximum observed frequency (MOF or sometimes called the instantaneous MUF) will vary considerably from day-to-day over the month at the same hour. Typically, this variation in the mid-latitude regions is plus or minus 15% of the monthly median MOF which is also known as the Maximum Usable Frequency or MUF. For example, if the MUF is 10 MHz, the expected range of MOFs would be 8.5 to 11.5

MHz at that hour over 80% of the days of the month. In other words, only 3 days per month would have a MOF equal to or less than 8.5 MHz and only 3 days per month equal to or higher than 11.5 MHz. This is then the range in which we would expect the ALE system to select frequencies provided that they are in the scan list.

3. HF System Performance Prediction Programs

From extensive oblique ionospheric sounding, it is know that the received signal power tends to reach a maximum at the junction frequency (JF). At this frequency the signal power from the high ray and the low ray are the same yielding a 3 dB power increase. The JF varies over the hours of the day and from day-to-day over the days of the month. The long term variation (day-to-day) was first studied by Davis and Groome in 1964 with high latitude effects added in 1965. Neither study was documented at the time but was discussed in some detail by Lucas and Haydon [1966], as follows:

- **An investigation of the distribution of daily values of Maximum Observed Frequency (the MUF at a given hour and day in the month) about their monthly median was carried out. Three points in the distribution over the days of the month were considered; values of the daily MUF exceeded 0.90, 0.50 and 0.10. These points are now referred to as the optimum working frequency (*fre′quence Optimum de Travail or* FOT), the Maximum Usable Frequency (MUF) and the Highest Probable Frequency (HPF). [Davis, R. M. and N. Groome (1964), Variations of the 3000-km MUF in time and space (private communication)]**

- **Data used in this study was derived from measurements at 13 stations representing a range of geomagnetic latitudes from 71° S to 88° N. The variation in frequency about the MUF was represented in tables of upper and lower decile values for low, medium and high Sunspot Number. Each table showed values for a given season, local time in hours 00, 04, 08, etc., and each 10° of geographic latitude from 10° to 80°, north or south.**

- **The study indicated that the distribution of MUF's is wider at night than in the daytime and wider at low latitudes than high latitudes in the daytime. Again in daytime the distribution is wider in summer than winter, except at high latitudes where the reverse is true. The sunspot number dependence is weaker, but in daytime the difference between two ratios seems to increase with sunspot number at latitudes higher than 40° and to decrease with increasing sunspot number at latitudes below 40°. The distribution of frequency variation was mostly a function of the foF2 and not the M(3000)F2 (the factor used to convert the vertical incidence critical frequency to the oblique path MUF); therefore, the distributions are assumed valid for any oblique path. [Davis, R. and N. Groome (1965), The Effect of Auroral Zone Absorption on High Frequency System Loss, (private communication)]**

In 1966, tables of the FOT-MUF-HPF distribution as a function of local time at the transmitter, season, smoothed sunspot number (SSN) and geomagnetic latitude (of the transmit site) were incorporated in the first widely used HF ionospheric radio performance prediction program, ITSA-1 [Lucas and Haydon, 1966]. These are often referred to as the F-Days tables. The value of F-DAY was loosely defined as the probability of ionospheric support (i. e. the fraction of the days that the operating frequency is below the MUF).

The development of IONCAP changed these definitions, as the F-DAYS values were only used for the lowest order mode for a circuit-hour. This is also called the MUF mode and is very carefully computed using convergence of up to 5 iterations. Modified distributions are assumed for the MUF's about each of the higher order modes (up to 20) depending on the layer; Es, E, F1 and F2 [Lloyd, et al., 1978]. The authors of IONCAP often stated that F-DAYS are not used in IONCAP. However, in VOACAP the 'F-Day' factor given for each of the user defined operating frequencies was changed to show the value actually being used for the most reliable mode (mrm) for that frequency. This new factor is named MUF-DAY in VOACAP [Lane, 2001]. For these reasons, VOACAP is used exclusively in the comparison of predicted frequencies and actual frequencies used on the test link.

4. TEST CIRCUIT

Rockwell Collins operated an ALE link from Toulouse, France to Cedar Rapid, IA (7,159 km path) from 1700 UTC 21 Jun 04 to 0700 UTC 13 July 04 (a total of 21.6 days or 518 hours) using a 1kW transmitter operating into a rotatable log periodic (RLP) antenna approximately 60 feet high. A Barker and Williams (B&W) broadband dipole roof mounted 20 to 30 feet above a courtyard was used for reception. The ALE processor was the Rockwell Collins 309M-1 (MIL-STD-188-141A and FED-STD-1045 compliant). The ALE operation over the days of the test was to process 20 frequencies from 7.7 to 29.7 MHz each hour. The data collected at Cedar Rapids are as follows: highest frequency for linking, frequency with highest SNR, the lowest frequency for linking and the corresponding SNR values for these 3 frequencies. The antennas used were antennas of opportunity. The only action taken to optimize this circuit was that the RLP was rotated to the azimuth toward Cedar Rapids. Neither the RLP nor the broadband dipole are designed for use on a path of this length. Ionospheric conditions during the test period were relatively quiet. There were no flares of C or X class and the 3-hour geomagnetic index Ap was below 27 on all blocks except on 8 occasions with the highest 3-hour index being 48, which is below major storm level.

During each hour of the test 20 frequencies were scanned. One of these frequencies which were recorded was the frequency having the highest SNR. Tables were made for each hour of the day over the 21.6 days of the test. The frequencies were listed in ascending order. The two highest values and the two lowest values (10% of the data in the tails) were discarded. From this list the highest frequency and the lowest frequency for the interdecile range were found, as well as the median value. At some hours the system failed to link up for some of the days per month. In this case, the interdecile range for those days was reduced to one value removed to no values removed according to the number of days of success.

The distribution of the frequencies having the maximum SNR is plotted for the 24 hours of the day, as shown in Figure 1. Also shown as the dashed lines are the plus and minus 15% of the median frequency. The test data seem to show the best agreement during the daylight hours for path mid-point with 85% and 115% rule of thumb for MOF distribution over the days of the month (as used in some HF prediction programs). The distribution of best frequencies widens greatly during the long sunset period on the East-West path. Also there is a brief period around the pre-dawn dip (0900 UTC) where frequencies ranging all the way from 11 to 19 MHz had the highest SNR for 80% of the days. The actual performance of the test circuit is shown in Figure 2, as a function of the fraction of days having a SNR equal to or greater than 40, 45 and 50 dB*Hz. These values correspond to system synchronization, low speed digital traffic and high speed digital or analog voice. As may be seen, the test circuit provided 50 dB*Hz at 90% reliability or better on 8 hours per day and with marginal service on an additional 5 hours per day.

5. COMPARISONS

Standard VOACAP (version 03.1209W), as obtained from the Institute for Telecommunications via the Internet at http://elbert.its.bldrdoc.gov/hf.html, was used to model the test link. The RLP antenna was modeled using ITU-R Recommendation 705 antenna package set to Type05:LPH (15/4.7/18.3/24.4/19.2/19.2/250). This model shows maximum gain of 10.8 dBi at 26 degrees in elevation at 8 MHz and 9.8 dBi at 9 degrees at 27 MHz (highest effective frequency actually found). The broadband dipole was modeled using the HFANT antenna package as a modified Type 23 Horizontal Dipole (0.4 wavelengths/ 9.14 m over average ground).

Both sets of ionospheric coefficients (CCIR, Oslo 1966 [CCIR, 1966]and the URSI-88 [Rush, et al., 1989]) were used in making the comparisons. The NOAA SEC International smoothed sunspot number was 41 at the time of the test. Method 26 was used to obtain the predictions of FOT-MUF-HPF for the circuit MUF mode (lowest order mode) and Methods 22 and 30 were used to obtain predictions of modes, angles and system performance at the actual scan frequencies.

The first comparison is to test the premise: 'Is the predicted distribution of hourly MOF values(FOT, MUF and HPF)) correlated with the distribution of hourly best frequencies found by the ALE protocol over the 21.6 days of the test?' Linear regression analysis was used to make the comparison. There are two input functions which affect the value of the predicted MUF. The first is the set of foF2 coefficients to be used for mapping the ionosphere; the recommended CCIR Oslo 1966 [Lane, 2001] and the newer URSI-88 daily coefficients. Since this is a trans-Atlantic path, one might suspect that the URSI coefficients would be more accurate for the test path since they have data for ocean areas. The other input parameter to VOACAP is the minimum (takeoff/arrival) angle to be considered when finding the lowest order ionospheric mode. The recommended value is 0.1 degrees when the low angle gain of the antennas is accurately modeled [Lucas and Haydon, 1986]. The default value [Teters, et al., 1985] is 3 degrees when not much is known about the horizon clearance. In the case of the test path, the broadband dipole was nearly 'buried' by surrounding buildings. Therefore, a minimum angle of 6 degrees was assumed to account for blockage in the near-field of the receive antenna.

The first comparison was made for the best fit of the MUF predictions using the CCIR Oslo and the URSI-1988 ionospheric coefficients as compared to the distribution of the frequencies found to have the highest measured SNR. The results of the linear regression analysis are shown in Table I. The scatter of predicted MUFs and median best frequencies are shown for the CCIR coefficients in Figure 3 and for the URSI coefficients in Figure 4. For the test circuit it is clearly shown that the CCIR coefficients provide the best fit. The correlation coefficients for the FOT, MUF and HPF at the three values of minimum angle using the CCIR coefficients are shown in Table II. As shown, the MUF predictions show a correlation coefficient of 86% when compared to the ALE frequency having the highest SNR. The HPF and the FOT show lesser degrees of correlation (see Fig.s 5 and 6).

The system performance predictions using VOACAP are for use of one frequency per hour over all days of the test or the month. The ALE equipment found and used the best frequency per hour over the days of the month. Therefore the predicted performance and the actual performance are for two very dissimilar operating conditions. However, it is of interest to see how much better the ALE system performed compared to conventional predictions. In Figure 7, the actual reliability of achieving a SNR of at least 40 dB*Hz is compared to the same prediction from VOACAP (Method 30, minimum angle 0.1 and CCIR coefficients).

Under the assumption that the poor performance at some hours of the day was the result of inadequate antenna gain at the low angles needed to support the 2F2 mode, vertical half rhombic antennas were modeled for use on this circuit. The design of this simple wire antenna was for a center height of 50 feet and 400 foot leg length terminated in 500 Ohm resistor (VOACAP ITS-78 Type 45: Side loaded Vertical Half-rhombic 7.2/121.9). This design will produce a power gain at the needed 4 degrees elevation from 4 dBi at 10 MHz to 10 dBi at 20 MHz. The predicted increase in the reliability of achieving 40 dB*Hz SNR is shown in Figure7 in comparison to that predicted for the actual RLP and B&W dipole.

6. DISCUSSION

The test circuit was a circuit of opportunity using existing antennas and a'shotgun' list of 20 frequencies. Conventional HF operation on a path of 7159 km using 1 kW and mismatched antennas (medium range transmit with a short range receive antenna) would not be expected to work very well. But the ALE operation was quite good for a circuit which was not optimized. Yet there was a long period of poor operation on almost every day of the test.

The median frequency used by the ALE controller was accurately predicted (r^2 = 86%) by the hourly MUF prediction from VOACAP with the original CCIR coefficients and the minimum angle set at 0.1 degrees. There was reasonable correlation with the HPF (r^2 = 76%). As might be expected, the actual FOT was lower than the predicted FOT. The regression correlation coefficients are shown in Table II.

The CCIR [1966] Coefficients provide greater correlation to the measured frequencies than do the URSI (1988) Coefficients [Rush, et al., 1989], as shown in Fig.s 3 & 4.. The probable reason for this is that URSI foF2 coefficients are from a different solar cycle than the CCIR ionospheric atlas used in the development of VOACAP. No attempt was made to re-calibrate VOACAP with the introduction of the new coefficients. Mixing data from different solar cycles were strongly discouraged by Lloyd, et al. [1978]. The VOACAP predicted MOF distribution (FOT-MUF-HPF) more closely matches the actual ALE frequency usage than the ± 15% rule of thumb.

The more surprising result at first glance is that correlation coefficients for the minimum angle at 0.1 and 6 degrees are higher than for the case of minimum angle at 3 degrees. This is explained when we look at the plot of the MUF values in comparison with the measured median frequency having the highest SNR (see Fig. 8). MUF values for 0.1 degrees tend to follow the measured best frequencies during daylight (2F2 mode); whereas, MUFs for 6 degrees tend to agree with measurement better during the nighttime (3F2 mode). The values of the MUF for 3 degrees tend to go back and forth between the extremes of the 0.1 and 6 degree cases. Unfortunately, raising the minimum angle above 3 degrees can result in modifications in the electron profile for the path which are erroneous. Use of the minimum angle should be only for diagnostic purposes and not for system prediction [Lane, 2001].

The ALE system will find the frequency having the highest SNR. When propagation conditions are good and the propagating frequency band over the path are at the MUF or higher, the SNR will be dominated by the much lower noise at these higher frequencies. But when the MOF is below the monthly MUF, antenna radiation patterns become much more important and often frequencies below the FOT are needed. Prediction of the lowest needed frequency in the scan list should be dependent on SNR predictions and not the system independent FOT prediction. The FOT predicted by VOACAP using Method 26 is only dependent on the length and ionospheric parameters for the path; whereas, the lower frequencies used by the ALE system were for the 3F2 mode with higher angles than the predicted FOT for the 2F2 mode.

VOACAP did not accurately predict the observed SNR distribution. The fraction of the days over the test with a SNR ≥ 40 dB*Hz varied from 27 to 100%, but the VOACAP predicted reliability for the same SNR was from 6 to 62%. This disparity is directly related to the assumed fixed frequency operation in the VOACAP SNR model and the actual ALE operation on any one of 20 frequencies at that hour over the days of the month. However, this does not prevent us from using the model to diagnose: why did the test circuit fail to provide good service for 16 hours per day? (see SNR ≥50dB curve in Fig. 2) Method 22 (Forced Short Path) was used to find the predicted ray hops and the takeoff/arrival angles for each frequency and hour. The predictions show that the test path is at the transition distance between the 2F2 and the 3F2 modes. The 2F2 mode is supported by the higher frequencies and much lower angles than is the 3F2 mode. During the daylight hours, the 2F2 mode at frequencies above 15 MHz will be supported at angles of 7 to 8 degrees. At these angles the RLP will provide 7 dBi and the B&W dipole approximately 0 dBi. At night the 2F2 mode drops below the effective horizon for the antennas and the 3F2 mode predominates at angles of 8 to 10 degrees for frequencies of 7 to 13 MHz. At these lower frequencies the RLP provides 4 to 7 dBi and the BW dipole produces from 0 to -3 dBi.. Thus, in the twilight hours, we can expect a large range of frequencies supporting the ALE link. The time that the 2F2 daylight mode will fail is dependent on the daily solar and geomagnetic conditions. VOACAP also predicts that severe upset should occur during the 3F2 mode predawn dip. From 07 to 09 UTC the MUF for the 3F2 mode falls to approximately 8 MHz and then below 8 MHz at 10 UTC. This corresponds to the hours where the reliability for the test circuit dropped to its lowest levels. The daytime absorption of the D-layer accounts for the overall poorer reliability during the day than at night.

It is predicted that if the antennas for the test circuit had been simple vertical half rhombic antennas with good clearance angles to the horizon the 2F2 mode could be used even at night. The gain for these antennas in addition to the lower loss of the 2F2 mode indicates that much higher reliabilities are possible than wereactually achieved on the test circuit (Fig. 7).

7. CONCLUSIONS AND RECOMMENDATIONS

- The ALE system performance was far better than VOACAP conventional predictions. Yet antenna short-comings prevented the ALE system from providing 24 hour per day service, especially for the predawn and the daylight hours where gain is needed at the lower angles.

- The URSI-88 ionospheric coefficients available for use in VOACAP did not provide for more accurate FOT-MUF-HPF predictions. It is recommended that VOACAP be set to use the original CCIR-1966 coefficients. A high degree of correlation between the predicted MUF and the median ALE frequency having the highest hourly SNR was demonstrated when the CCIR coefficients were employed in VOACAP

- Frequency scan lists for an ALE link should be populated with frequencies that follow the diurnal MUF variation for the path-month/season. In addition there should be a frequency assigned which approximates the highest of the hourly HPF values and one which falls slightly below the lowest of the hourly FOT values. At this time the FOT-MUF-HPF diurnal values should be those provided by VOACAP with CCIR 1966 Coef. and a minimum angle set to 0.1 degrees.

- The statistical model for computing the SNR distribution in VOACAP should be restructured for ALE applications. IONCAP, and now VOACAP, has the statistical data within the program to predict the SNR distribution for the case of multiple frequency usage in ALE operation. Until this development is completed, it is suggested that ALE circuits be designed using VOACAP Method 30 with minimum angle of 0.1 deg. and CCIR-1966 coefficients such that each hour of the day has at least one frequency with 50% reliability for a required SNR equal to the link up value which in this test case was 38 dB*Hz. This should assure that the circuit will at least link up on those days during the month when the propagation conditions are poor and the lower frequencies are needed. On days when the MOF values are higher much better circuit performance should be anticipated.

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Teters, L.R., J. L. Lloyd, G. W. Haydon and D. L. Lucas, [1983] Estimating the Performance of Telecommunication Systems Using the Ionospheric Transmission Channel; {Volume II} Ionospheric Communications Analysis and Prediction Program User's Manual, Institute For Telecommunication Sciences NTIA Report 83-127.

Table I. Correlation Coefficients (r^2) for predicted MUFs vs measured frequency having the highest SNR for both the CCIR and URSI ionospheric coefficients and minimum angles of 0.1, 3, and 6 degrees.

Coefficients	0.1 degrees	3 degrees	6 degrees
CCIR Oslo 1966	86.0%	66.9%	85.7%
URSI	72.5%	48.7%	69.7%

Table II. Correlation Coefficients (r^2) for predicted FOT, MUF and HPF (CCIR ionospheric coefficients) vs. distribution of frequencies having the highest SNR over the 80% days of the test

Frequency	0.1 degrees	3 degrees	6 degrees
FOT vs.Low Best	53.3%	45.7%	62.4%
MUF vs Median Best	86.0%	66.9%	85.7%
HPF vs High Best	76.3%	60.3%	74.4%

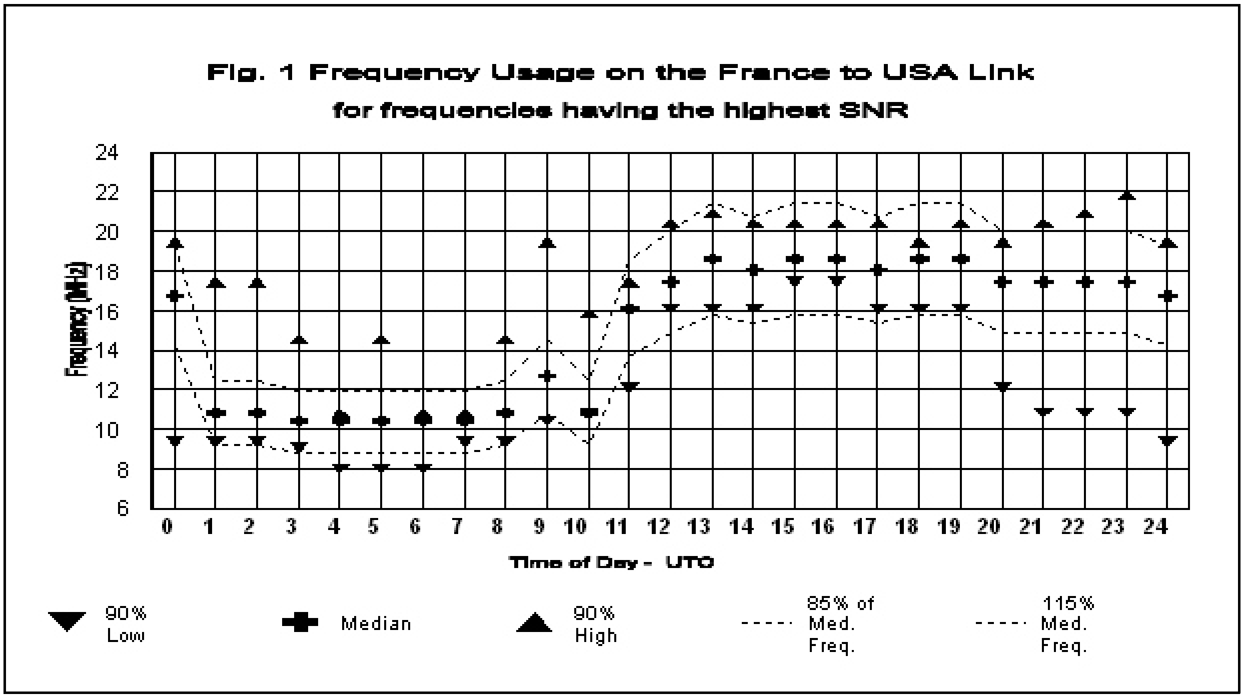
Fig. 1 Frequency Usage on the France to USA Link
for frequencies having the highest SNR
Frequency (MHz)
24
22
20
18
16
14
12
10
8
6
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time of Day - UTC
90% Low
Median
90% High
85% of Med. Freq.
115% Med. Freq.

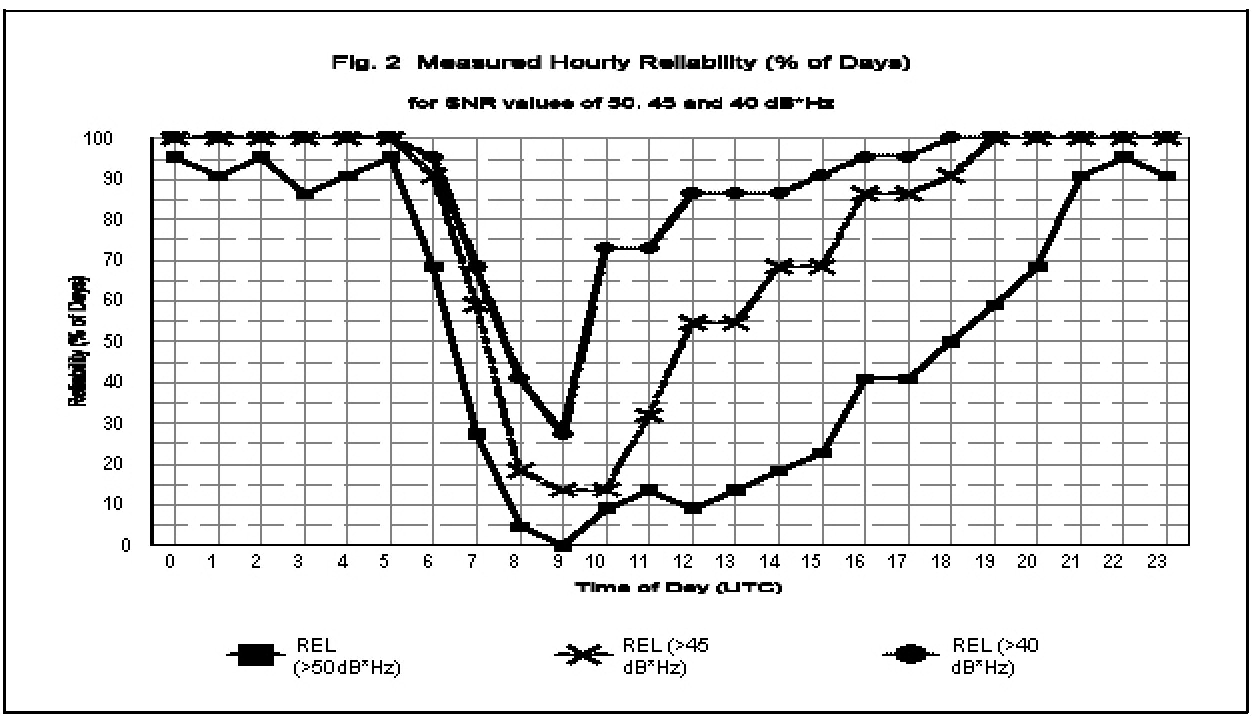
Fig. 2 Measured Hourly Reliability (% of Days)
for SNR values of 50, 45 and 40 dB*Hz
Reliability (% of Days)
100
90
80
70
60
50
40
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time of Day (UTC)
REL (>50dB*Hz)
REL (>45 dB*Hz)
REL (>40 dB*Hz)

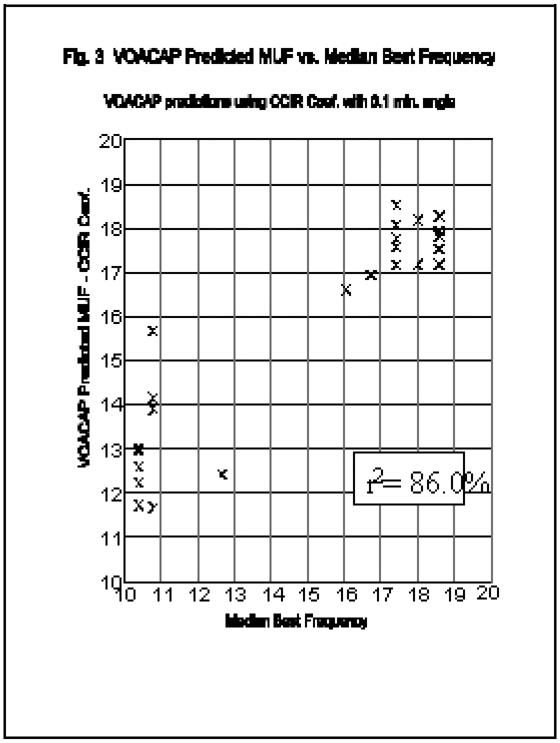
Fig. 3 VOACAP Predicted MUF vs. Median Best Frequency
VOACAP predictions using CCIR Coef. with 0.1 min. angle
VOACAP Predicted MUF - CCIR Coef.
Median Best Frequency
r² = 86.0%

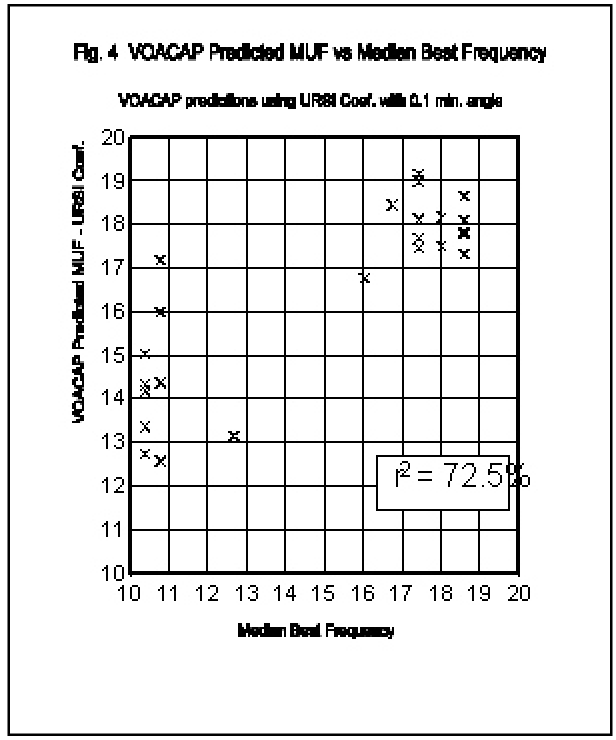
Fig. 4 VOACAP Predicted MUF vs Median Best Frequency
VOACAP predictions using URSI Coef. with 0.1 min. angle
VOACAP Predicted MUF - URSI Coef.
Median Best Frequency
r² = 72.5%

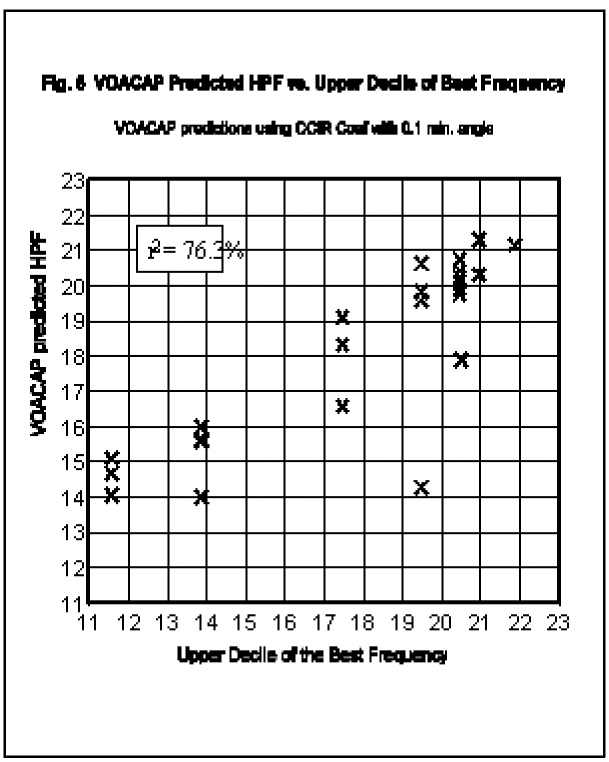
Fig. 5 VOACAP Predicted HPF vs. Upper Decile of Best Frequency
VOACAP predictions using CCIR Coef with 0.1 min. angle
VOACAP predicted HPF
Upper Decile of the Best Frequency
r² = 76.3%

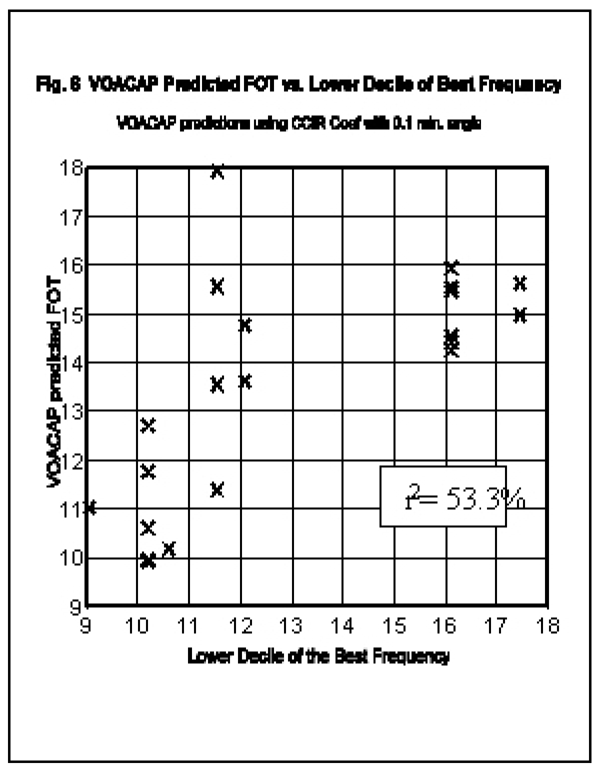
Fig. 6 VOACAP Predicted FOT vs. Lower Decile of Best Frequency
VOACAP predictions using CCIR Coef with 0.1 min. angle
VOACAP predicted FOT
Lower Decile of the Best Frequency
r² = 53.3%

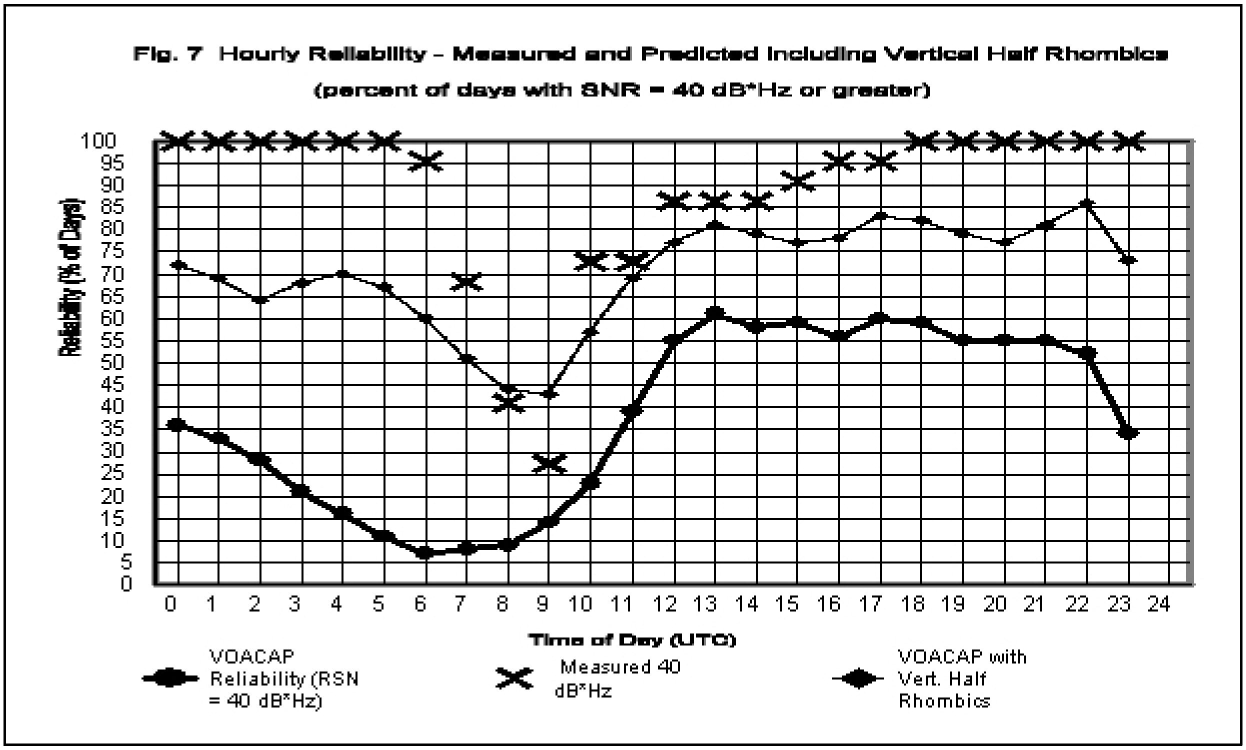
Fig. 7 Hourly Reliability - Measured and Predicted Including Vertical Half Rhombics
(percent of days with SNR = 40 dB*Hz or greater)
Reliability (% of Days)
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Time of Day (UTC)
VOACAP Reliability (RSN = 40 dB*Hz)
Measured 40 dB*Hz
VOACAP with Vert. Half Rhombics

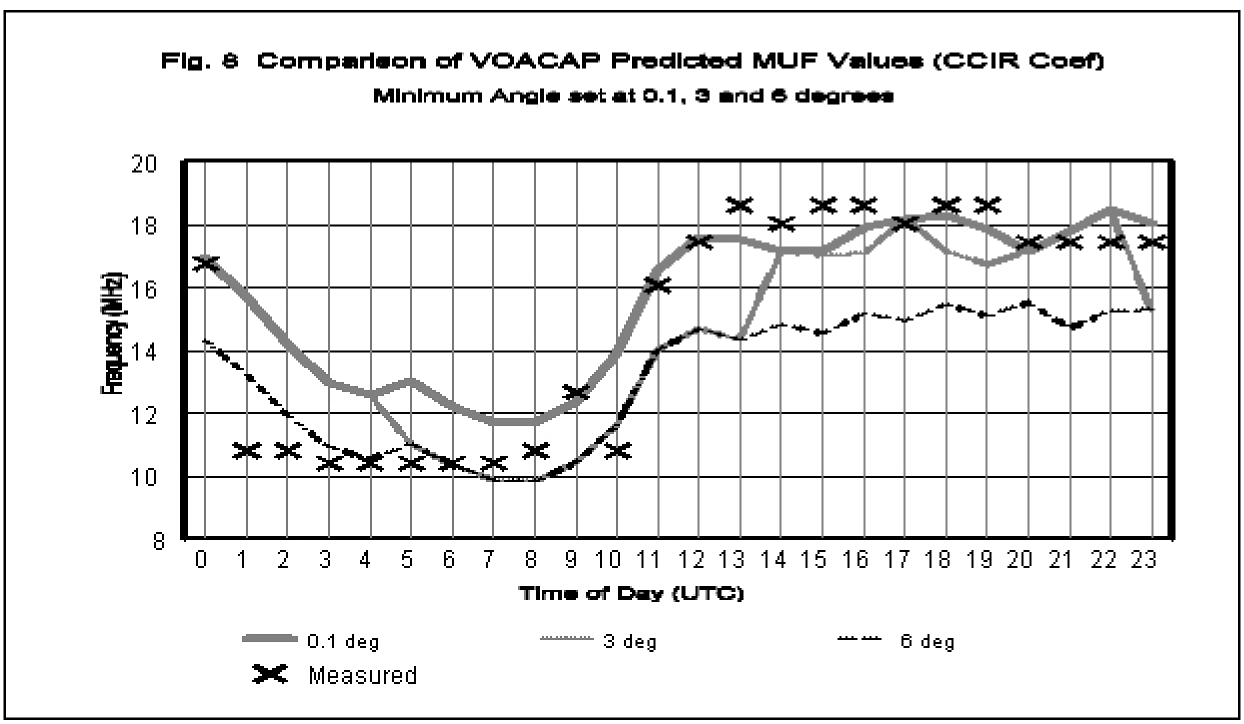
Fig. 8 Comparison of VOACAP Predicted MUF Values (CCIR Coef)
Minimum Angle set at 0.1, 3 and 6 degrees
Frequency (MHz)
20
18
16
14
12
10
8
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Time of Day (UTC)
0.1 deg
3 deg
6 deg
Measured