Rockwell Collins

Signal-to-Noise Predictions Using VOACAP, Including VOAAREA

A User's Guide

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PREFACE

For thirty years I have worked with high-frequency radio (HF) systems and used the latest HF sky wave system performance models. In that time, I was very fortunate to have been taught by Luther Kelly, George Haydon, Timothy Shaw and Alvin Sylvia of the former US Army Signal Corps Radio Propagation Agency. Merrill Stiles and Edwin Bramel of the Radio Propagation Division within the USA Communications-Electronics Engineering Installation Agency introduced me to the first US Government HF prediction program from the Institute for Telecommunication Sciences. ITSA-1 was being tested at Ft. Huachuca, AZ in 1967. I had the unique experience of being taught by the experts and having the opportunity to put these predictions into practice for circuits throughout Southeast Asia from 1967 until 1972. There, again, I met and was taught by many experts who had worked HF systems most of their lives. I especially remember William Neuendorff at the Pacific Field Office of USACEEIA-Pacific. Through him I learned the intricacies of making measurements at HF.

In the 1970s, I continued to work for the US Army at Ft. Huachuca. Here I had the opportunity to meet and to work with many more experts. In 1975, I met with George Haydon in Boulder, CO where we worked out an initial statement of work for the program which became IONCAP. Under the leadership of Miles Merkel, Chief of the Electromagnetics Engineering Office, we undertook a period of exciting development of modern HF prediction and modeling programs. During the following years I worked with James R. Wait, Doug Crombie, Bill Utlaut, Donald Lucas, John Lloyd, Randy Ott, Larry Teters, Herman Cottony, A. D. (Don) Spaulding, Charles Rush and many others at the Institute for Telecommunication Sciences. George Hagn of SRI International; John Goodman of the Naval Research Laboratory; David Sailors of the Naval Ocean Systems Center; Peter Bradley, chairman of the ITU Working Party 6-1; Alan Christinsin of the US Air Force Communication Service and many others had a profound impact on my development in this rather strange field of ionospheric studies. I am also greatly indebted to the many military personnel of the US Army, US Air Force and US Navy who let me become a member of their teams, instructed me in their operations and worked with me to improve our ability to correctly prepare the signal operations plans for numerous exercises and military operations. My greatest mentor in military HF radio operations was Lt. Gen. Emmet Paige who was the commander of the 11th Signal Group and later commander of USACEEIA and USACC.

During the 1980s, I worked for the Voice of America. Here I had the opportunity to take our recently developed IONCAP program and transform it into an area prediction program. This process was more involved than anyone had first imagined. For one thing, we found that IONCAP had not been completed nor totally debugged. Also, computer memory for area coverage work was sorely strained, to say the least. We were blessed by two factors in the birth of VOACAP. One was that we had a dedicated and talented team consisting of Frank Rhoads at NRL, Greg Hand at ITS and our VOA staff of engineers: Richard Davis, Lorraine DeBlasio, David Loudin, Rina Makhdoom, Allen Richardson, Mike Toia and Hien Van Vo. The other was the rapid evolution of the personnel computer and its ability to handle huge files and to process millions of calculations at such amazing speed. I am very grateful to the management at the Voice of America and the United States Information Agency for their multi-year funding of this development and for authorizing the release of VOACAP to the general public in 1993.

Finally and not in the least, I acknowledge the great assistance I have received from the talented scientists and engineers in industry. I wish I could list all of the names. Let me just say, this HF world is small and the individuals who work in this area work well together as we struggle to make this cantankerous media conform to the demands of the communicators.

Now, I come to this work. I am very pleased that Rockwell Collins saw the need and has funded this effort to document the use of VOACAP. For this I am very grateful, as it has allowed me to bring together so much of what I have learned from the many people mentioned above and to put many obscure but meaningful documents between the covers of this book. Also, my work with Daniel Roesler and David Bliss of Rockwell Collins has brought me full circle. Dan Roesler keeps asking for real examples of where the predictions are correct. The invaluable assistance of David Bliss with his many years in HF communications work has led to the organization of the material in this book. Also, I greatly appreciate his attention to detail in the technical editing of the text.

I think what is so fascinating about this field is that the mysteries of actual events can be predicted by careful modeling of the entire circuit. My hope is that you will find this book useful in unraveling the mysteries of HF skywave propagation and system performance. The book is based on the work of the real experts, to whom I am greatly indebted.

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1. INTRODUCTION

1.1 Signal-to-Noise Ratio

The signal-to-noise ratio (SNR) is the critical parameter used to define the grade of service in high-frequency (HF) radio systems. The SNR delivered to the input of the receiver can be equated to speech intelligibility, character error rate and bit error rate. The Voice of America Coverage Analysis Program (VOACAP) predicts the SNR and other parameters for user-specified HF circuits and conditions. Please refer to Section 1.3, History, for the history of VOACAP and for references to available documentation of VOACAP and its predecessor programs.

VOACAP is based on the Friis Transmission Equation which simply states that the power at the receiver is related to the power delivered to the transmit antenna taking into account the gain of the transmit and receive antennas and the transmission loss (Friis 1946). The approach is fundamentally sound. The thoroughness of the propagation model combined with the time and frequency dependent statistical databases makes VOACAP one of the most accurate prediction models ever created for HF system performance prediction. However, this prediction accuracy can only be achieved when the user has input the correct variables for the radio system to be modeled. Also, it is essential that the user understand the definition of the output predictions when applying them to actual operational plans or system design.

This user's guide is designed to assist us in understanding how the statistical performance factors are calculated in VOACAP starting first with the signal power, then the noise power and finally the signal-to-noise ratio distribution. From these statistics we will see how circuit reliability and required power gain are computed for the circuit in question. Then we cover the actual input parameters needed in order to obtain the desired output and which methods in VOACAP to use for valid predictions. Next, we describe how the various output parameters can be displayed as contours on maps of our choosing using the VOAAREA program. Examples are also given for the use of the HFANT program which allows us to compute a variety of antenna patterns for use in the VOACAP and VOAAREA predictions. Finally, we will find a discussion of lessons learned as well as useful "rules of thumb" we can use with VOACAP. The text is extensively referenced to the source documents for those interested in greater detail or knowing the names of the many contributors to this five-decade long development.

1.2 Frequency and Time

VOACAP has 2 distinct prediction regimes: one deals with frequency and the other is the time-dependent amplitude-probability distribution (APD) of the signal-to-noise ratio. Achievement of satisfactory ionospheric telecommunications is dependent on both of these factors. First, one must find a frequency that will propagate over the desired circuit and which will meet the minimum grade of service desired by the user. VOACAP can be used to find the best frequency bands needed to operate over a particular circuit or area for purposes of designing or planning a communications system. Second, the program can be used to determine the variability of the signal-to-noise ratio on the best frequencies at a given hour over the days of the month.

We will see how this knowledge can be used to determine (1) the required system gain needed for satisfactory performance or (2) the grade of service that an existing communications system will provide. Performance analysis using VOACAP employs both the frequency and the time domains. The signal-to-noise ratio is dependent on the operating frequency with respect to the mode MUF (maximum usable frequency) and the fading characteristics of the path over the days of the month as well as transmitter power, antenna radiation patterns, etc.

1.3 History

In 1985, after considering all of the known high frequency (HF) skywave prediction programs, the Voice of America selected the Ionospheric Communications Analysis and Prediction (IONCAP) program for use in planning and radio station design for the modernization program authorized by President Reagan and approved by Congress. IONCAP had been developed by the Institute for Telecommunication Sciences and was deemed to be the best and most accurate program for developing an area prediction capability for shortwave broadcasting (Lane and Toia 1985). It was soon discovered that IONCAP had a number of discontinuities which were troublesome when using the output in an area coverage contouring program.

The Voice of America, in conjunction with the Institute for Telecommunication Sciences and the Naval Research Laboratory, initiated a multi-year development to create a program from IONCAP which could be used not only for point-to-point circuit analysis but also for global coverage. In 1993, the Voice of America Coverage Analysis Program (VOACAP) (Lane et al. 1993) and (Sweeney et al. 1993) was released to the public[1]. The VOACAP Program Guide (Lane et al. 1993) includes a detailed program flow chart, while the VOACAP User's Manual (Sweeney et al. 1993) provides operating instructions for the earlier DOS-based

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[1] The VOACAP Program Guide (Lane et al. 1993) and the VOACAP User's Manual (Sweeney et al. 1993) are available for purchase from the National Technical Information Service (NTIS), Technology Administration, US Department of Commerce, Springfield, VA 22161, telephone: 703-605-6000 or 800-553-6847; facsimile: 703-605-6900; or via website **http://www.ntis.gov/index.html**. Specific NTIS order-number information is provided in the References Section.

version of VOACAP. At the present time, VOACAP for Windows 95, 98 and NT is available via the Internet at no cost from the Institute for Telecommunication Sciences (ITS) as HFWIN32 at **http://elbert.its.bldrdoc.gov/hf.html**. The source code (Fortran program listing) for VOACAP is also available for downloading via the ITS website URL just provided. The VOACAP Program Guide program flow chart (above) will greatly assist the user who wishes to explore the actual Fortran source-code listing.

VOACAP is a modified version of the Ionospheric Communications Analysis and Prediction (IONCAP) program (Teters et al. 1983). Wherever possible, changes to code (DeBlasio et al. 1993) were made only when they were consistent with the draft IONCAP Theory Manual (Lloyd et al. 1978). In some cases, errors were found which were not addressed by Mr. John Lloyd in the IONCAP Theory Manual. In such cases, noted authorities including Messrs. Donald Lucas and A. D. Spaulding were brought in under contract to oversee the changes to IONCAP which were introduced into the newer VOACAP. In 1993 with the release of VOACAP to the public at the Ionospheric Effects Symposium, chaired by Dr. John Goodman, the development of IONCAP and RADARC was described (Lucas and Headrick 1993).

VOACAP and IONCAP are the end products of many years of scientific and engineering development within the United States Government. Both programs are directly traceable to the following list of computer programs: HFMUFES-4 (Haydon et al. 1976), RADAR (Headrick et al. 1971) (Lucas et al. 1972), ITS-78 (Barghausen et al. 1969), and ITSA-1 (Lucas and Haydon 1966). These computer models were developed based on the manual computational process laid out by the US Army Signal Corps Radio Propagation Agency Technical Report 9 (Laitinen and Haydon revised 1962) which was developed during and in the years after World War II (NBS 1948). The IONCAP program merged ionospheric propagation theory with actual measured data, both for communications and for over-the-horizon radar, in order to provide estimates of system performance. At the time VOACAP was being developed, there were 2 other programs being written independently. One was the Ionospheric Communications Enhanced Profile Analysis and Circuit (ICEPAC) prediction program (Parker 1994) and the other was the computer implementation of the ITU-R Recommendation 533 (Dick et al. 1993). Both of these programs have some relationship with the evolution of IONCAP, but they are very different in other respects. At this time, the Institute for Telecommunication Sciences also includes these programs as well as VOACAP in the HFWIN32, the NTIA/ITS HF Propagation Analysis Package. No attempt is made to address the use of ICEPAC or Rec 533 in this user's guide for VOACAP. Gregory Hand at ITS has attempted to standardize the input and the output parameters as much as possible, but it should not be assumed that the same definition of variables can be applied amongst this suite of programs. The definitions given in this guide ONLY APPLY TO VOACAP and the area coverage version of VOACAP, called VOAAREA.

The evolution from IONCAP to VOACAP is primarily an effort to make IONCAP easier to use, to provide predictions for area coverage and mapping, to clean-up numerous program errors and the inclusion of a more accurate method for predicting radio noise. As such, VOACAP embodies the best known and tested ionospheric theory with the largest set of measured data ever collected (starting with the worldwide network of US Army sounders in 1944 to the US Navy Over-the-Horizon Radar measurements in the 1970s).

The strength of the program and the accuracy of the predictions are directly related to the consistent comparison of theoretical predictions and actual measurements. These comparisons were made on circuits around the world for various epochs of solar cycle, seasons and diurnal variations as well as geographic differences in ionospheric conditions and radio noise levels. Many nations, as well as the USA, contributed to the ionospheric and atmospheric measurement database established during the International Geophysical Year (1957 - 58) on which VOACAP and many other programs depend (Davies 1965).

1.4 Illustrative Rockwell Collins Applications

This past half century was a very productive era of evolutionary HF propagation research and modeling. Lessons learned during this era, as documented in this user's guide, can effectively support modern communications systems and avoid "reinventing the wheel." The original ionospheric-communications prediction models did not anticipate the rapid growth of processor technology and development of HF systems that can adapt to current propagation conditions. Recent analyses of 1983-84 Mitre Corporation data and also of current Rockwell Collins data for adaptive HF performance over multiple routes using multiple frequencies substantiate improved-reliability predictions for such operations, as addressed in Section 9.8. An excellent reference in adaptive HF communications design, authored and edited by experienced Rockwell Collins HF engineers, is HF Radio Systems & Circuits, rev. 2nd ed., 1998, W. E. Sabin and E. O. Schoenike, editors, Noble Publishing Corporation (**www.noblepub.com**), ISBN 1-884932-04-5.

Recently, transmission of "electronic mail" via HF systems opened a new era, allowing seamless integration between existing/emerging terrestrial and HF communications networks. Rockwell Collins continually designs modern land, sea and airborne communications systems for varied applications and is currently participating in several global HF modernization projects [e.g., the USAF/DoD Scope Command, USN BattleForce E-Mail based on STANAG 5066 (BFEM-66), Australian HF Modernization Program, et al.]. For updates on the latest Rockwell Collins HF E-mail developments see **www.hfemail.com**. For a commercial-off-the-shelf program that utilizes the VOACAP elements discussed in this user's guide see **www.propman2000.com**.

2. SIGNAL POWER PREDICTIONS

2.1 Definitions

Signal power ***[S DBW]***[1] is predicted at the input of the radio receiver and is expressed in dB relative to 1 watt (dBW). This value includes the power gain of the receive antenna at all of the arrival angles for the contributing modes but does not include the insertion loss of the transmission line, couplers, etc., between the output terminals of the antenna and the input of the receiver. The actual measurement procedure was set forth by the US Army Radio Propagation Agency (Silberstein 1964) and was updated with newer equipment and procedures by the Voice of America (Davis and Lane 1993). (For prediction purposes, the signal and noise can be interpreted as referred to the output of the RF filter, disregarding any effects of the RF-gain circuitry on the signal-to-noise ratio by the insertion of receiver thermal noise, which is assumed to be negligible compared with the external noise in Chapter 3.)

The signal power model in the Voice of America Coverage Analysis Program (VOACAP) (Lane et al. 1993) is based on measurements of the hourly median signal power at the input to the receiver. These measurements were made in the period from 1944 to the early 1960s. Without the aid of computers, the mathematicians recorded just the hourly median power from strip charts. After the strip charts for that hour were obtained for 30 days, they recorded the monthly median signal power. Then they dropped the 3 highest values and the 3 lowest values to get the upper and lower decile values for the signal power distribution. The database in VOACAP is based on these 3 values of signal power.

The signal power predictions from VOACAP are the best fit to the power database. The differences between the measured values and the theoretical value are the basis of the Transmission Loss Tables (see Table 7 in the IONCAP Theory Manual) (Lloyd et al. 1978). Originally, this table had been called the Excess System Loss Table (Lucas and Haydon 1966). It is this data that forces the theory to match observed values. Thus, VOACAP predicts the monthly median value of the hourly median signal powers at the receiver along with estimates of the upper and lower deciles of the signal power. Methods 20, 21, 22, 25 and 30 provide the distribution around the median signal power ***[S DBW]*** as the dB range, ***[SIG UP]*** and ***[SIG LW]*** (Teters et al. 1983).

It should be noted that the distribution is only considered to be Gaussian on either side of the median with each side having a different standard deviation. The lower decile of the signal power is that value which should be exceeded 90% or more of the days in the month

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[1] Variables as given in the VOACAP output are denoted in *italics* inside of ***[ ]***.

and the upper decile is the power which should be exceeded no more than 10% of the days per month.

This distribution is the predicted long term variation or fade over the days of the month at that hour. The individual values in the distribution are the hourly median values for each day of the month at that hour. The variation within the hour of 1 day is not predicted by VOACAP. As we will discuss later in Chapter 9, Section 9.7, Clobbered with Multipath and Fading, the short term fading is considered when establishing the minimum required signal-to-noise ratio ***[REQ. SNR]*** for the desired type and grade of service. Short term fading also needs to be considered when we wish to calculate the multipath probability, ***[MPROB]***.

2.2 The Circuit MUF

The circuit MUF[2] is a critical parameter in determining the signal power for a given path, month, sunspot number and hour. It is defined as the lowest order mode that exists for those conditions and for which ionospheric support is predicted on 50% of the days of the month. Another way of looking at it is that the circuit MUF mode is the mode on an oblique ionogram which has the highest maximum observed frequency (MOF). If we combine the ionograms for that hour over all 30 days of the month, and find the median of the MOFs, we will have the circuit MUF. Again, during the period of data collection, a database was developed using the median MOF and the upper and lower decile values of the daily MOFs. This database was used to develop a table of expected deviation of the MOFs from the circuit MUF as a function of geomagnetic latitude, season and local time for high, medium and low sunspot activity. This tabulated data is given as Table 6. Distribution of F2 (3,000) MUF in the IONCAP Theory Manual (Lloyd et al. 1978) and is used to calculate the IONCAP output parameter called F Days. F Days is defined as the fraction of days in the month that the operating frequency would be below the MUF predicted at that hour.

The first calculation made by VOACAP within the frequency loop is to find the circuit MUF and the associated lowest order mode. This calculation is iterated up to 5 times in order to get the maximum usable frequency (MUF) to the nearest tenth of a MHz. The MUF value obtained represents the expected junction frequency for the high ray and the low ray discounting magnetic field effects. The value of F Days is set at 0.5 for the predicted MUF. The circuit MUF is, thereby, defined as the highest frequency for the lowest order mode that will be equaled or exceeded on 50% of the days in the month. The lowest order mode is that

[2] The MUF is the median maximum usable frequency for a given path, month, sunspot number and hour. On each day of the month for the circuit hour there is a maximum observed frequency (MOF) for a mode. The median of this distribution is the MUF for that mode.

mode we would see at the bottom right-hand side of an oblique ionogram. It has the mode having the highest MUF and usually the shortest delay time.

This process of computing the MUF is continued for the higher order modes for each of the 4 layers, F2, F1, E and E_S until 3 hop numbers exist for each of the layers. Also, the distribution of the MOFs for each higher order mode is established by an upper and lower decile value. In IONCAP, only the F Days parameter for the lowest order mode was printed out. This meant that if at a frequency below the circuit MUF the most reliable mode was a higher order mode, the F Days value shown on the IONCAP printout was for the circuit MUF mode. We felt this was somewhat misleading, so in VOACAP we established a new parameter which is called ***[MUFday]***. In VOACAP, the value of ***[MUFday]*** is the fraction of the days in the month at that hour that the operating frequency is below the MUF for the most reliable mode (i.e., the mode with the highest reliability of meeting the required signal-to-noise ratio). When the most reliable mode is the same as the circuit MUF mode, then F Day and ***[MUFday]*** are the same value.

It should be noted here that VOACAP does not always print out the MUF mode in the MUF column in Methods 20, 22 or 30. The mode shown in the MUF column is dependent on which mode is the "most reliable mode" at that frequency (i.e., the MUF). VOACAP always prints the frequency for the circuit MUF but it shows the "most reliable mode" at that frequency, which may or may not be the circuit MUF mode. One can easily tell if it is the MUF mode or not by looking at the value for ***[MUFday]***. If ***[MUFday]*** is 0.50, then the indicated mode is the MUF mode. If it is < 0.50, then the mode shown is the most reliable mode at that frequency.

Although this sounds confusing, an example makes it fairly clear as to what is happening. Consider a 1,500-km path during the midday. In this example, let us assume that the circuit MUF is 10.7 MHz and the circuit MUF mode is the 1E mode at a relatively low takeoff angle of 3°. The 1F2 mode requires a much higher angle and the MUF for that mode is below that of the 1E mode. If we use isotropic antennas (i.e., equal gain at all angles), VOACAP will print out the MUF at 10.7 MHz, the circuit MUF mode as the 1E and ***[MUFday]*** as 0.50. Now let us suppose that the system actually used half-wave dipole antennas with a beam maximum at the zenith angle. These antennas could have gains as low as –10 dBi at the 3° elevation angle for the 1E mode. With both the transmit and receive antennas taking away 10 dB from the signal power, it is possible for the 1F2 mode to have a higher reliability than the 1E mode even though the MUF for the 1F2 mode is slightly below the 1E mode. In this case, the MUF will be printed out as being 10.7 MHz, but the circuit MUF mode will be shown as the 1F2 mode with a ***[MUFday]*** value of 0.30. The fact that the ***[MUFday]*** value is < 0.50 tips us off that this is not the circuit MUF mode. If we really want to know what modes are being considered at the circuit MUF, we can always run Method 25 - All Modes.

2.3 Electron Density Profile or Reflectrix

VOACAP is unique in the method it uses to compute the ionospheric path geometry which is essential in determining the path length of flight (for spreading loss), takeoff and arrival angles of the rays used in finding the correct antenna gain values, and the angle of incidence at each layer which affects the absorption losses. The first step in the program is to compute the great circle path length between the transmitter and the receiver. This distance determines the number of control points which will be used in computing the electron density profile. For very short paths, only 1 control point will be used at the path mid-point. For longer paths, a point 1,000 km from each end of the path will be used to sample the critical frequencies from the worldwide E-layer map and the central point will be used to sample the critical frequencies for the F1 and F2 layers. For even longer paths, up to 5 different control points will be considered. The control points for the E, F1 and F2 layers are looked at individually to determine which point has the lowest critical frequency for each of the 3 layers. The computed vertical electron density profile is then made from the composite of the lowest critical frequencies for the 3 layers. This electron density profile is not based on a true vertical incidence profile but on a profile as the ray obliquely traverses the layers over the path.

The program uses a 40-point Gaussian quadrature approximation of the Martyn's integral equation in order to obtain the actual path length for the ray as it is bent passing through the composite electron density profile for the path. This calculation provides a "reflectrix" which is a table in VOACAP that is used to determine the range of takeoff and arrival angles which are permissible for each of the considered modes for the 3 layers. We will discuss what modes are considered in the next section, but for now it is important to understand that VOACAP computes a range of angles for a given ray hop mode. The antenna patterns for the transmit and receive ends of the path are used along with the path losses for each angle in 1° increments to determine the best takeoff and arrival angle which will produce the highest reliability for that mode. This process is described by John Lloyd in the IONCAP Theory Manual, Section 4.4 (Lloyd et al. 1978). A critique of the reflectrix method was published during the development of VOACAP (Reilly 1993).

2.4 Modes Considered

Once VOACAP has determined the circuit MUF mode that establishes the lowest order mode for the path, for example, the circuit MUF mode may be the 1F2 mode, then VOACAP will make computations for the next 2 higher modes, i.e., 2F2 and 3F2. For each mode VOACAP computes the signal power for both the low ray and the high ray. A total of 6 propagation modes will be considered for just the F2-layer. Similar calculations are made for the F1- and E-layers. In this way, a total of 18 modes may be considered in finding the one that is most reliable. If the user chooses to include the sporadic E mode (the last field on the FPROB entry), then 3 additional E_s modes may also be considered, e.g., $2E_s$, $3E_s$ and $4E_s$. Again, this is just an example of the 21 possible modes. The hop numbers will be dependent on the actual path under consideration. This process is repeated for all user specified operating frequencies falling below the circuit MUF and for each hour, month and sunspot number. The only exception is when the path is so long that the Long-Path Model is used. The Long-Path Model attempts to predict a forward scatter mechanism and does not consider hops. Also, for frequencies above the circuit MUF, VOACAP uses the most reliable mode at the MUF and the associated above-the-MUF losses for that frequency.

This process of finding modes in VOACAP is nearly identical as the method used in IONCAP. Several coding errors were found in the original IONCAP method and were corrected using the Theory Manual (Lloyd et al. 1978) and program comment cards as guides. The corrections were made by Frank Rhoads at the Naval Research Laboratory (Rhoads 1993) (DeBlasio et al. 1993).

2.5 Signal Power Distribution

The signal power for a mode is computed over the path at a specified operating frequency based on the mode MUF. A full system calculation is made taking into account the transmitter power, free space loss, ionospheric absorption (both deviative and non-deviative), above-the-MUF losses, ground bounce losses (if applicable) and the additional Transmission Loss. This provides the median signal power value for that mode, frequency and circuit hour.

As we discussed earlier, the MUF has an assumed distribution of MOFs about the median value. IONCAP uses the upper and lower decile values of this distribution.[3] The upper decile or Highest Probable Frequency (HPF) is the frequency where no more than 10% of the hourly MOFs will be higher. The lower decile is often considered to be the FOT and is defined as the frequency where the MOFs will be higher on at least 90% of the days of the month at that hour. The mode signal power values are also computed at the 2 decile values of the MOF. This provides the signal power at the operating frequency when the MOF is above and below the MUF. VOACAP prints out this range of signal power relative to the median signal power as ***[SIG UP]*** and ***[SIG LW]***, respectively, which we discussed in Section 2.1, Definitions.

If we look at 1 hour and 1 operating frequency below the circuit MUF, we can trace the procedure used in VOACAP to compute the mode signal power. Up to 21 modes may have

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[3] The distribution of the MOFs is given in the IONCAP Theory Manual as Table 6. This table shows a dependence on geomagnetic latitude, sunspot number, season and local time at the control point for that mode.

been computed. For each of these modes, the ionospheric losses, ground bounce loss, path spreading loss, time delay, takeoff/arrival angle and antenna gains are computed. This allows us to compute the median hourly signal power in dBW. This is the power that would be available on the days when the daily MUF is equal to the predicted MUF. VOACAP is unique in how it computes the signal power distribution. It is next assumed that the daily MUF is at the upper decile value in the variation of the MOFs over the days of the month at that hour. This MUF is considerably above the monthly median and the chances of having above-the-MUF losses are low. Generally, at this assumed MUF, the signal power is higher than when the daily MUF is at the circuit MUF. This value of signal power is set as the upper decile of the signal power distribution. Then the program assumes that the daily MUF has dropped to the lower decile of the MOF distribution. This often places the operating frequency above-the-MUF where losses become large. At this point, we can have as many as 21 modes computed for the operating frequency for 3 different cases: MUF, MUF at the upper decile and MUF at the lower decile.

Again, let us use an example. Take the case where the MUF is 10.0 MHz and the circuit MUF mode is the 1F2. The operating frequency under consideration at this hour set by the user is 9 MHz. For this condition, the median signal power is good because we are under the MUF and the 1F2 mode is supported by the radiation patterns of the antenna. Now let us look at the MUF which is exceeded only 10% of the time and let us say that value is 14 MHz. When we look at the signal power at 9 MHz, now we find that the 1F2, 2F2 and the 2E modes all contribute to the signal power. Finally, we redo the calculations again for the case where the MUF is exceeded 90% of the days of the month, which in this example is for a frequency of 8.5 MHz. The operating frequency at 9 MHz is above-the-MUF, which is assumed to be at 8.5 MHz. Now, only the circuit MUF mode is considered when computing the signal power and it also incurs considerable losses due to the lack of ionospheric support. So, for this example, the median signal power is good but, its lower decile is very low, perhaps up to 25 dB below the median power because of above-the-MUF losses.

Lucas and Haydon (1966) proposed an empirical correction factor, termed excess system loss, which adjusted the signal power median to the least error with respect to the only available database at the time. This table also contained the upper and lower standard deviation around the expected excess system loss. The ITSA-1 prediction program (Lucas and Haydon 1966) used this expected deviation to develop the distribution of the hourly signal levels around the median value for the days of the month. A similar but slightly different approach was used in ITS-78 and in HFMUFES.

In IONCAP, Lloyd et al. (1978) developed a frequency dependent signal level for each ionospheric mode (i.e., hop). Frequency dependence is based on above-the-MUF loss, deviative and non-deviative absorption terms and E-layer obscuration losses, as well as the expected excess system loss table from ITSA-1 but now called "Distribution of Transmission

Loss." The frequency dependence is also computed for the lower and upper decile ranges of the expected day-to-day variations. This computation is done for up to 21 different ionospheric modes (3 hops per layer, 3 layers, high and low ray plus high and 3 hops from the E_s layer). The median monthly signal power distribution is given by the individual summation in watts for each of the 3 conditions, namely, the median, lower decile and upper decile. In the IONCAP output, the decile range values are given as ***[SIG LW]*** and ***[SIG UP]***, respectively. This range in the signal power can be from a few dB up to a limit of 25 dB for poor propagation conditions.

This description of what happens in IONCAP is a simplification of the actual calculation which was only partially described by John Lloyd in the DRAFT IONCAP theory manual (see Section 9.3, Functional Distributions, and Figure 21. Revised Signal Distribution) (Lloyd et al. 1978). In Chapter 5 we will discuss in greater detail how VOACAP calculates the signal power distribution as well as all of the other system performance factors used in what is called the Short-Path Model. The Short-Path Model is the ray hop method described above and is used automatically for all path lengths < 10,000 km in IONCAP using Method 20. The Short-Path Model can be forced at any distance by using Method 22.

Up to this point, we have only discussed the ray hop method used in the Short-Path Model of IONCAP and VOACAP. In the next section, we will discuss the Long-Path Model used when the path lengths are ≥ 10,000 km. Later on, we will cover how VOACAP uses both models to predict the signal strength in the transition region between 7,000 and 10,000 km.

2.6 Long-Path Model

For distances requiring 3F2 modes or higher, investigators have found that considerable energy becomes "trapped" in the ionosphere in what are called forwarded scatter or ducted modes. Other mechanisms such as M[4] modes come into play. The signal power contributed by these forward scatter and long distance modes is not predicted using the conventional ray hop model in IONCAP (i.e., Short-Path Model). For these long paths, John Lloyd et al. (1978) devised a Long-Path Model for IONCAP. This model includes such factors as the M mode and convergence gain when the path length is > 10,000 km. At that range, the path is more than one quarter around the earth and all possible ray paths begin to converge until the antipode is reached (approximately 20,000 km). It is assumed in IONCAP that 15 dB of convergence gain is achieved at the antipode; however, the antipodal focusing is assumed to begin at ranges of 10,000 km.

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[4] An M mode is 1 starting off with a conventional 1F2 or 1F1 bounce from the ionosphere. However, the earthward bound signal is reflected back upwards from the E or E_s layer. The upward signal is reflected back toward the earth via the F layer. Such a mode can traverse over 6,000 km without an earth bounce. It is sometimes denoted as an "F-E-F" mode.

The Long-Path Model is automatically called in IONCAP at distances ≥ 10,000 km using Method 20. It can be forced into use at any distance by using Method 21. VOACAP is similar but also has a Method 30 which provides for signal power continuity between the Short-Path Model and the Long-Path Model by applying a smoothing function from 7,000 km out to 10,000 km. This Method is described in Chapter 5.

IONCAP's Long-Path Model (Whale 1969) is intended for path lengths ≥ 10,000 km; however, this method may be used for any path by specifying Method 21 (forced long path). The Long-Path Method does not predict normal modes but indicates which layer, F_2, F_1 or E, is the most likely entry (transmit) and exit (receive) region for the ionospheric circuit. The IONCAP Long-Path Method does not force continuity with the Short-Path Model and the 2 methods can give considerably different predictions for the same circuit. VOACAP allows the user to apply a smoothing function for this discrepancy (Method 30).

The Long-Path Model only computes one path between the transmitter and receiver which consists of a possible M region and a conventional bounce region. The mode is given as the entry layer and the exit layer, such that we may have any combination of F2, F1, E and E_s taken 2 at a time. An example ***[MODE]*** designator is "F2E" which indicates that the takeoff angle is controlled by the F2 layer 2,000 km from the transmit site and the arrival angle is controlled by the E layer at the receive site. Also, the Long-Path Model output will include both a takeoff angle ***[TANGLE]*** and a receive angle ***[RANGLE]***. Losses are based on the circuit MUF and may be different from those computed by the Short-Path Model since the control points for the path may be different. The signal power distribution of the Long-Path Model is computed using the circuit MUF and the associated MUFdays distribution to obtain the above-the-MUF losses. The expected day-to-day variation in the signal power is obtained from the Transmission Loss tables for the ionospheric control point. As in the Short-Path Model, the signal power distribution is given by the median, upper decile and the lower decile for the days of the month. A more complete description of the program flow for the Long-Path Model is given in Chapter 5.

2.7 Multipath and Skip Frequencies

Multipath conditions occur when more than one signal arrives at the receiver by a different path. If the signals are of equal amplitude and opposite in phase, they will cancel each other, resulting in a deep fade. If the differential delay time is sufficiently great, the received signal will be elongated in time creating either distortion and/or bit/character errors.

VOACAP uses the multipath probability ***[MPROB]*** calculation from IONCAP to compute the probability that a secondary signal will be outside the user-specified time delay tolerance and within the user-specified power tolerance. At the time of this writing, the calculation is known to be in error and a correction needs to be made. A discussion of this problem with the current code is given in Chapter 9, Section 9.7.

Skip frequencies are those frequencies for which there is no ionospheric support between point A and point B. Often times there will be a skip zone between the transmitter location and where the first skywave coverage begins. This inner skip zone is usually more a function of the antennas being used than an ionospheric phenomenon. We will see in Chapter 9 that near vertical incidence skywave (NVIS) propagation is possible and is predicted by VOACAP if we use high angle-of-fire antennas and the lower frequencies in the HF band.

Skip frequencies can occur at greater distances. These portions of the frequency spectrum which will not reach the desired receive location can occur in the transition region between 1 mode and the next higher order mode. These skip regions are generally located between the 1E and the 1F modes and again at the transition region between the 1F2 and the 2F2 modes. In the VOACAP output, we will find that these skip frequencies have very low signal power, whereas, frequencies just higher and just lower have high signal power and will show a change in mode.

2.8 Sporadic-E Layer Contribution

As we have mentioned earlier in this section, VOACAP has a sporadic E layer model. Again, this model of E_S is taken directly from IONCAP. At this time, it appears that the model may give overly optimistic predictions of signal power. For VOACAP applications, it is recommended that the sporadic E model be deactivated using the FPROB function (see Section 6.9, Fprob). This forces the program to compute sporadic E layer effects using the method in ITSA-1 (Lucas and Haydon 1966).

In Chapter 9, Section 9.6, Sporadic E Won't Go Away, there is a discussion of how we can evaluate the effects of sporadic E layer propagation. Until a correct and validated method is available, we will have to content ourselves with being able to bound the problem of sporadic E layer effects.

3. NOISE POWER PREDICTIONS

3.1 General Discussion

In the HF band, noise power present at a radio receiver is expressed in dB relative to 1 watt (dBW) and for a noise power bandwidth of 1 Hz. It is generally assumed that the controlling radio noise is external to the radio. The 3 major sources of radio noise at HF are atmospheric, man-made and galactic noise (Horner 1962) (CCIR Report 322 1964). Atmospheric radio noise usually predominates during the nighttime and at frequencies typically at 10 MHz or lower. Man-made sources are usually the controlling source of radio noise during the daytime and for frequencies above 10 MHz at night. Galactic radio noise is only detectable near 30 MHz in very quiet regions of the earth. We, again, must remember that the prediction of the radio noise power is just as critical as the prediction of the signal power when it comes to correctly estimating the signal-to-noise ratio that will be available to the receiver.

Noise power measurements were made using short vertical antennas over a fairly extensive ground screen (Chindahporn and Younker 1968). Models of radio noise currently in use do not have a direction of arrival for the noise source although in reality there is generally an azimuthal dependency. Noise tends to have a fairly low angle of arrival in the vertical plane. Atmospheric noise is assumed to arrive via skywave propagation, whereas man-made noise fields generally propagate by groundwave or line-of-sight. Galactic radio noise results from the collection of RF emitting sources in our galaxy.

The noise power models used in VOACAP do not consider the directivity of the specified receive antenna. If the user-specified antenna is one which has an associated frequency dependent efficiency terms, then the noise power is reduced by the efficiency factor of the receive antenna at each of the operating frequencies under consideration. It is assumed that receive antenna is immersed in an omni-directional noise field and that the noise power pickup by the antenna is that of the integrated power pattern (i.e., 3 dBi for an antenna over perfect earth).

The actual noise power calculation in VOACAP assumes that the noise power is slightly higher than that received by the isotropic receive antenna over perfect earth. The data is normalized to the noise power available from a short, lossless vertical monopole. This accommodates the fact that most radio noise arrives at low elevation angles. There is some disagreement as to whether a horizontal half-wave dipole is as susceptible to radio noise power as a monopole antenna. The error seems to be small (2 to 3 dB) and VOACAP uses the higher noise power value which makes the signal-to-noise ratio prediction slightly conservative.

WARNING: The VOACAP user should ascertain what the likely noise sources are for the HF system being modeled. The adequacy of the existing noise models should be determined and adjustments made to compensate for any discrepancies (Cummins et al. 1979). Things that could create problems are: systems with large bandwidths (Spaulding et al. 1962) (Disney and Spaulding 1970); excessive interference by other signals, such as in the broadcast bands; cheap receivers with high levels of internal set or thermal noise; high probability of local thunderstorms or heat lightning; precipitation static caused by flying through clouds and blowing ice particles or sand striking the antenna; high levels of audio noise, such as cockpit noise in a jet fighter or helicopter which can exceed the RF noise for voice communications; and height-gain for airborne systems which can see more of the radio horizon than ground-based systems (Roy 1981). These are just some of the examples of things the modeler must be aware of when using the noise model in VOACAP. Also see the discussion in Chapter 9, Section 9.5.

3.2 Atmospheric Radio Noise

Atmospheric radio noise is generally the summation of all the radiation released from thunderstorm activity around the world. A single lightning strike can send a noise spike that can be detected up to 8 times as it circles the world via ionospheric propagation. In the 1940s, when scientists were trying to map the worldwide occurrence of atmospheric radio noise, there were very few observation points. Although the data were well controlled and the National Bureau of Standards (NBS) calibrated the noise measurement devices that were used, there were not enough stations to allow for world mapping. The NBS (Crichlow et al. 1955) prepared the first set of atmospheric radio noise maps using the noise measurement data and world weather maps showing the probability of a lightning strike (WMO 1956). Worldwide atmospheric noise factor contours at 1 MHz were hand drawn. In 1963, after several revisions, these maps were approved by the International Telecommunications Union (CCIR Report 322 1964). Later, with the advent of computers, these maps were regenerated using mathematical contouring (Lucas and Harper 1965). However, they still retained the judgement used by Herb Crichlow in determining where noise peaks and valleys would occur based on lightning-activity maps when actual noise measurement data was not available. Crichlow's contribution is still used in the current noise model in VOACAP.

Other atmospheric radio mapping routines have been produced. Some generated noise contours using only the noise power measurements. This often places noise "valleys" where noise "peaks" should occur. One notable example is the noise model in early versions of the US Navy Prophet program which had a noise valley over the Amazon river basin where it is well known that atmospheric radio noise is so high that it makes the AM band unusable during the nighttime.

The Voice of America has chosen to use the CCIR Worldwide Atmospheric Noise Maps in CCIR Report 322-3 (1986). These maps retain the original insight of where thunderstorm and lightning activities are located and include some additional measurements made in the former USSR and Thailand (Spaulding and Washburn 1985). In the original noise-data collection these areas were poorly represented. There is some controversy over which of the CCIR maps are best (Sailors 1995) (Lane 1994) (Bradley 1999).

One point that is very important for us to understand about any of the CCIR worldwide atmospheric radio-noise maps is that the measured values were excluded when a local thunderstorm was present. Local noise bursts propagated either by line-of-sight or groundwave were so great that they saturated the detector instrumentation. Therefore, the noise power predictions derived from these maps are for conditions when there are no local thunder storms. In areas such as the Southeastern USA, where heat lightning is nearly an every night occurrence during the summertime, actual noise power spikes may greatly exceed the CCIR-predicted atmospheric noise at the location, time and season.

There are several other points that we should consider when using the atmospheric radio noise predictions. The dependence on sunspot number has never been determined although the data is slanted toward the years with higher sunspot numbers. The time variation of the noise data is based on the day-to-day variation over 4-hour time blocks and 3 months. The resolution of noise data for a given hour and month is poor at best. Also, noise collection procedures tended to average the noise over a period of a few minutes. Actual noise spikes may be much greater than indicated by the maps.

The atmospheric radio noise data is adequate for long term planning. However, the engineer should be aware that, during certain months of high probability of local thunderstorm activity, actual conditions can be much worse than predicted. Ionospherically propagated atmospheric radio noise tends to be vertically polarized and tends to arrive at the receiver at relatively low angles, below 10°. In the CCIR models of noise power, it is assumed that the noise arrives omni-directionally and that the noise power delivered to the receiver by any actual antenna is the same as that which would be delivered by an short lossless whip antenna over perfect earth.

The amplitude probability distribution of the atmospheric noise can be wider than that of man-made radio noise. One must remember that, when planning for 90% reliability, the upper decile of the noise distribution applies. When we begin planning for the HF system, we should always consult the CCIR Report 322 to see how severe the atmospheric noise is in the receive areas by looking at the median maps and the upper decile, D_U, found on the figure adjacent to the world map.

Example for Estimating Atmospheric Radio Noise Using the CCIR Atlas: Let us assume that we are planning to place a receiver in Brasilia (16S; 48W) for operation on 5 MHz in October at 18 LT (21 UT). First, we need to remember that October is a spring month in the Southern Hemisphere. Go to the appropriate map in CCIR 322-3 (1986) and look up the value of F_{AM} at 1 MHz. We should see a value of about 84 dB at Brasilia. Next we need to convert this to the noise factor at 5 MHz. This requires us to look at the Figure of Variation of radio noise with frequency (spring 1600-2000 h). Find the intersection of 5 MHz and the curve that would approximate F_{AM} = 84. The corrected F_{AM} is found by looking at where that intersection falls on the vertical axis of the figure. In this case, we find F_{AM} at 5 MHz = 57 dB (Note: Noise Power = F_{AM} – 204 dBW/Hz). Subtracting 204 from this F_{AM} value yields a median noise power of –147 dBW/Hz. The ratio of the upper decile to the median value of F_{AM} is found on the adjacent figure (data on noise variability and character spring 1600 – 2000 h). Here we locate the intersection of 5 MHz with the D_U curve. Again, looking where this intersection falls on the vertical (dB) axis, we find the D_U at 5 MHz = 13 dB. That means that 10% of the time we can expect the noise power to be as high as -134 dBW/Hz. If we are wanting a circuit reliability of 90%, then we must realize that we will need to protect our system by this additional 13 dB just to account for the variability in noise power. This is a significant design consideration.

3.3 Man-Made Radio Noise

The history of man-made radio noise measurements and their levels would fill a book. Let it be said that most of the controversy was dispelled in 1974 (Disney and Spaulding 1974). The CCIR in Report 258-4 (1986) unanimously recommended these median values, but then added on a number of possible statistical distribution methods with no recommendation as to which one should be used.

Under the sponsorship of the Voice of America, the National Telecommunications and Information Administration - Institute for Telecommunication Sciences (NTIA - ITS) was asked to review the man-made noise issue one more time. The recommendation of this review (Spaulding and Stewart 1987) was a statistical model for man-made radio noise which is now included in the VOACAP radio noise model. The equation given for the man-made noise factor is:

$$F_{AM} = C - D \, \mathrm{Log}_{10} f$$

where: f is the frequency in MHz and
C and D are reference values

In Table 3.1. Values of C and D Needed to Compute the Radio Noise Factor, F_{AM}, as a Function of the Frequency, f, in MHz, we will find the reference values needed to compute the median level of man-made noise factor, F_{AM}.

Table 3.1. Values of C and D Needed to Compute the Radio Noise Factor, F_{AM}, as a Function of the Frequency, f, in MHz

Environmental Category	C	D	P_N at 3 MHz
Business	76.8	27.7	–140.4 (dBW/Hz)
Residential	72.5	27.7	–144.7
Rural	67.2	27.7	–150.0
Quiet Rural	53.6	28.6	–164.0
Galactic Noise	52.0	23.0	–163.0

The noise power at the receiver for a 1-Hz noise power bandwidth expressed in dBW is given by:

$$P_N\,(\mathrm{dBW/Hz}) = F_{AM} - 204$$

For some reason buried nearly half a century ago, reference man-made radio noise values were and are still given for a reference frequency of 3 MHz, whereas, atmospheric noise was referenced to 1 MHz. The reference levels at 3 MHz for the international categories of man-made radio noise are shown in the last column of Table 3.1.

Man-made radio noise was primarily measured where noise levels were rather high. In industrial settings, the measurements were made inside the grounds of the factory, one employing electromechanical devices. City and residential measurements were made near stop lights on busy streets where cars would queue waiting for the light to change. The one general complaint expressed most often is that the reference man-made radio noise levels are too high. Again, the VOACAP user must exercise judgement when selecting the man-made noise environment for use in the predictions. It must be kept in mind that the accuracy of the noise prediction is just as important as the accuracy in the signal prediction when it comes to calculating the signal-to-noise ratio.

Man-made noise is the controlling source in most cases during the daytime when the D-layer absorption diminishes the level of skywave atmospheric radio noise. Even at night, man-made sources can predominate. Examples of this are receivers located in close proximity to arc welders (especially bad in the plastics industry of third-world countries), hospitals with diathermy equipment, cities with many unregulated blinking neon signs, power lines in arid climates (grounding wires on the poles lose their connectivity with the ground), saturation of the receiver by antenna pick up of too many out-of-band and nearby CB transmissions, just to name a few.

Actual measurements in the 1980s in Germany showed that both rural and residential man-made radio noise values were about –154 dBW/Hz. Even measurements made near electrical cranes and electrical railroads did not exceed this value at 3 MHz. However, areas in Germany that appeared to be remote rural were not because of noise being propagated along nearby power lines. The noise source was actually a city several miles away, but the power lines offered a means to conduct the city noise level into remote rural areas where it was reradiated from the power lines.

In Washington, DC, measurements made with a roof-top antenna on a 6-story office building yielded noise power values consistent with residential areas except during rush hour. When traffic levels were high, the radio bands became clogged with emergency radio calls, taxi dispatch messages and truck-driver use of CB radios. The combined power of these extraneous transmissions collected by the roof-top antenna was sufficient to saturate the receiver. At these times, it was better to model the noise power at the business level rather than the residential level.

On Taiwan, throughout the entire island, man-made radio noise levels mysteriously rose by 20 dB in a matter of a few years. It was found that the home industry of making plastic tubing with a small arc welder was the primary source of the increased noise. The problem was resolved by requiring, under the penalty of law, that each arc welder must have an inexpensive but effective RF suppressor installed. Within months of vigorous enforcement of this law, the RF noise level on Taiwan fell back to the previous level.

Voice of America found that, due to congestion in the International Shortwave bands, they needed about 1 mV/m signal strength to be competitive with co-channel and adjacent channel interference. A man-made radio noise level of –145 dBW/Hz at 3 MHz was selected to model the listening environment since at the prime bands of 9 and 11 MHz this noise level required field strengths of 1 mV/m or more in order to achieve 90% reliability at a required signal-to-noise (density) ratio of 73 dB•Hz (Lane and Toia 1985).

Each situation the modeler faces is different and great care needs to be exercised when selecting the reference level of the man-made noise power to be used in VOACAP. So far, we have only addressed the median man-made noise value and its dependence on frequency. Measurements have shown that there is a location as well as a time variability to man-made noise (Disney and Spaulding 1974) and (CCIR Report 258-4 1986). In 1987, A. D. Spaulding recommended to the Voice of America that it is acceptable to use one value for each of the statistical parameters for all 4 categories of man-made noise (Spaulding and Stewart 1987). Subsequently, a typographical error was found in that report and at the request of A. D. Spaulding a correction was published (Lane 1995). The correct values, according to Spaulding, are a lower decile range of 6 dB and an upper decile range of 9.7 dB. These are the values currently used in VOACAP and are approximately the same ranges as recommended for use in IONCAP (Lloyd et al. 1978).

Example: Again let's look at the previous example used for the atmospheric noise discussion. We had computed the median and upper decile of the noise power at 5 MHz in Brasilia for October in the early evening. If we assume that the receive location is in a residential area of the city, then the reference level from Table 3.1 is –144.7 dBW/Hz at 3 MHz. Adjusting this value for 5 MHz using the frequency dependence equation given previously, we obtain a median man-made noise power of –150.9 dBW/Hz. The critical parameter which will effect the reliability is the range to the upper decile (i.e., 9.7 dB). Thus, 10% of the time, the man-made noise power will not exceed a value of –141.2 dBW/Hz. Although this value is 8 dB lower than the value we calculated for the upper decile range of the atmospheric radio noise, it is a significant level for quieter parts of the day and seasons with less thunderstorm activity.

3.4 Galactic Radio Noise

Galactic radio noise is included in VOACAP so that noise power cannot go essentially to 0. However, noise arriving on earth from the Milky Way is hardly a factor in the HF band anymore with the huge increase in RF noise pollution. The original model for galactic noise is taken from ITSA-1 (Lucas and Haydon 1966) and is attributed to an extrapolation of data measured by Cottony and Johler (1952) and later verified by measurement (Crichlow and Spaulding 1965). The same source is quoted in CCIR Report 322 (1964); however, the noise is slightly higher at the 1 MHz intercept 52 rather than 49.5 dB, and the slope with frequency is –23 rather than 22.

This discrepancy was noted by Spaulding and Stewart (1987) and the new galactic noise model for IONCAP/VOACAP was changed to that recommended by the CCIR Report 258-4 (1986) which is attributed to CCIR Report 322 (1964) and is shown in Table 3.1 of this chapter. The reason for the discrepancy is not clear and the parties who might know are deceased. The variation of the galactic noise has remained the same throughout this period at ±2 dB at the decile range.

As noted earlier, our discussion of galactic noise is mostly historical. Galactic radio noise does not effect most HF radio systems except under rare circumstances as will be discussed in Section 3.5, Controlling Noise.

3.5 Controlling Noise

The method of combining the 3 radio noise sources in IONCAP and older prediction programs assumed that the 3 noise sources were highly correlated. Thereby, one could assume that the lower decile, median and upper decile occurred in unison. In fact, each of the 3 sources of noise is random and independent. The Voice of America sponsored the Institute for Telecommunication Sciences (ITS) to generate a more accurate statistical model for specifying the controlling noise consisting of these 3 sources (Spaulding and Stewart 1987). The CCIR Report 322-3, based, in part, on Spaulding and Washburn (1985) was used to obtain the values and statistical relationships for the atmospheric radio noise. CCIR Report 258-4 (1986) was used as the source of the man-made noise levels and the galactic noise model. As noted under the discussion of man-made radio noise in Section 3.3, A. D. Spaulding chose to simplify the decile ranges for the man-made noise rather than use the variety of complex models proposed in CCIR Report 258-4 (1986). VOACAP employs the new ITS noise model (Spaulding and Stewart 1987).

VOACAP can be run so that the effects of the various noise models can be viewed using Method 25 - ALL MODES (for a discussion of Method 25, see Chapter 7, Section 7.4). In the following paragraphs, we will examine cases where each of the noise sources predominate and the case where atmospheric and man-made noise combine to yield a controlling noise higher than either one. As a word of warning, Method 25 produces a large volume of output so it is wise to look at only 1 frequency, hour and month at a time. The example circuit we will use is as follows:

Transmit Loc.	Rio de Janeiro, Brazil
Receive Loc.	Brasilia, Brazil
Month	October
Hour	1800 LT (2100 UT)
SSN	10
Antennas	Half-wave dipoles at 0.3 wavelengths height
Power	5 kW
Frequency	5, 12 and 19.4 MHz
Man-Made Noise at 3 MHz	–141 dBW/Hz

The Method 25 output for the 5 MHz frequency in the above example is shown in Figure 3.1. Method 25 All Modes Output for the Controlling Noise Example at 5 MHz. It appears that IONCAP authors never completed work on this output format and it is very difficult to read. Essentially, it shows the contributing modes and the most reliable mode, which is a composite of the contributing modes.

At the bottom of Figure 3.1, we see a summary table that has entries for "Noise, S. Power, Signal, Noise, Reliab and SPROB." For our discussion of controlling noise we need to focus on the third line from the bottom of the chart which is labeled "Noise." The first entry we see is 12.7 which is the dB range to the upper decile of the noise power distribution. Next we see –145.1 which is the median noise power in dBW/Hz at 5 MHz in Brasilia at 2100 UT in October (a spring month). Following that is 10.9, which is the dB range to the lower decile of the noise power distribution. After that are 3 numbers which deal with prediction errors and are included in the service probability ***[S PROB]*** calculation <u>which is not recommended for use at this time</u>.

If we remember the example given in Section 3.2, Atmospheric Radio Noise, we had used the maps from CCIR Report 322-3 (1986) to compute the noise power in Brasilia for these same conditions at 5 MHz. The value we obtained for atmospheric noise was –147 dBW/Hz with D_U = 13 dB. VOACAP Method 25, as shown in Figure 3.1, predicts –145.1 dBW/Hz and D_U = 12.7 dB. As we can see, the controlling noise model in VOACAP has included some slight addition (about 2 dB) to the noise level due to the presence of nearly a "business" grade of man-made noise. However, what we are seeing is that the atmospheric radio noise from the high level of thunderstorm activity during the early spring evening is predominating over the city noise. At this frequency, which is well below the circuit MUF, up to 6 modes contribute to the signal-to-noise ratio (SNR). However, the 2 most significant modes are the 1F2 and the 2F2 at takeoff and arrival angles well supported by the dipole antennas. The predicted circuit reliability for 5 MHz, in spite of the high level of noise, is 95%.

Next we look at 12 MHz for this same example. The Method 25 output is shown in Figure 3.2. Method 25 All Modes Output for the Controlling Noise Example at 12 MHz. Again at the bottom of the figure, we find the controlling noise power distribution with the median equal to –153.5 dBW/Hz and the lower and upper decile ranges of 6.0 and 8.4 dB. At 12 MHz, the atmospheric noise has dropped considerably and the heavy residential noise should be controlling. We had specified the man-made noise level at 3 MHz as being –141 dBW/Hz. To find the noise power at 12 MHz, we use the slope of –27.7 (Log f/3 MHz) which yields a median man-made radio noise power of –157.7 dBW. This value is 4.2 dB lower than the VOACAP controlling noise power prediction. So even at 12 MHz, there is a small contribution coming from the atmospheric noise. The decile ranges of 6 and 8.4 dB are nearly that assumed for the man-made noise (i.e., 6.0 and 9.7 dB). Again, we see that there are 6 modes predicted, but at 12 MHz the 1F2 mode is the predominant mode with a circuit reliability of 99%. The signal power at 5 MHz and 12 MHz is nearly the same (–74 to –78 dBW); however, the noise floor at 12 MHz is 8 dB lower than at 5 MHz.

Finally, in Figure 3.3. Method 25 All Modes Output for the Controlling Noise Example at the MUF 19.4 MHz, we look at 19.4 MHz, the frequency equal to the circuit MUF at this hour. The median radio noise power has dropped to –162.2 dBW/Hz with the lower and upper decile ranges of 5.1 and 9.2 dB, respectively. The fact that the decile ranges are so close to the 6 and 9.7 ranges for purely man-made radio noise leads us to surmise that the controlling noise is again mostly man-made. Again, if we compute the man-made noise for 19.4 MHz, the median value is –163.5 dBW/Hz. Although a frequency as high as this might have some galactic radio noise component, the other noise sources would have to be as low as –182 dBW/Hz. As we can see, the man-made radio noise is controlling. At the MUF we find 3 contributing modes, the low ray and high ray of the 1F2 and a very weak 1E mode. The circuit reliability is predicted at 97%. This is high for a frequency at the MUF, but it does tell us that our design has adequate power to operate at very low as well as very high frequencies. In a high noise environment such as central Brazil, it is very advantageous to be able to use the higher frequencies where the noise power is lower. However, we cannot be assured that this circuit will work during periods of local thunderstorm activity.

In concluding this chapter on radio noise, the interested reader is referred to a relatively recent review of the subject conducted for the Department of Defense. It is the proceedings of a 2-day symposium on radio noise which probably represents, at 459 pages, the most comprehensive collection of recent thinking and activity on this subject (Hagn et al. 1984).

SUMMARY 6 MODES FREQ = 5.0 MHZ UT = 21.0

	1.F2	1.E	2.F2	2.E	3.F2	3.E	Most REL 1.F2
TIME DEL.	3.50	3.25	4.23	3.57	5.26	4.03	3.50
ANGLE	23.16	12.81	40.58	27.30	52.37	38.11	23.16
VIR. HITE	223.73	125.30	210.46	126.93	210.02	126.12	223.73
TRAN.LOSS	112.11	133.25	117.17	337.23	128.31	377.76	112.11
T. GAIN	4.74	0.55	6.99	5.66	6.95	6.89	4.74
R. GAIN	4.74	0.55	6.99	5.66	6.95	6.89	4.74
ABSORB	5.68	8.63	3.64	4.99	3.02	3.82	
FS. LOSS	106.84	106.20	108.48	107.01	110.38	108.07	
FIELD ST.	41.32	24.37	34.01	–184.72	22.91	–226.48	42.18
SIG. POW.	–75.12	–96.26	–80.18	–300.24	–91.32	–340.77	–73.84
SNR	70.02	48.88	64.96	–155.10	53.82	–195.63	71.30
MODE PROB	1.00	0.51	1.00	0.00	0.99	0.00	1.00
R. PWRG	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	–4.57
RELIABIL	0.94	0.41	0.87	0.00	0.56	0.00	0.95
SERV PROB	0.56	0.18	0.46	0.00	0.27	0.00	0.56
SIG LOW	7.37	25.00	7.82	7.18	8.46	7.18	7.51
SIG UP	4.69	13.47	4.70	4.68	4.74	4.68	4.85

NOISE = –145 S. POWER = –73.8

SIGNAL = 7.2 8.5 4.7 / 1.7 3 .1 0.6

NOISE = 12.7 –145.1 10.9 / 3.1 4.1 3.2

RELIAB = 11.9 71.3 14.7

SPROB = 21.0 55.3 21.0

Figure 3.1. Method 25 All Modes Output for the Controlling Noise Example at 5 MHz

SUMMARY 6 MODES FREQ = 12.0 MHZ UT = 21.0

	1.F2	1.E	2.F2	2.E	3.F2	3.E	Most REL 1.F2
TIME DEL.	3.47	3.25	4.62	3.57	6.64	4.03	3.47
ANGLE	22.30	12.81	45.60	27.30	60.70	38.11	22.30
VIR. HITE	214.96	125.30	251.59	126.93	291.35	126.12	214.96
TRAN.LOSS	115.85	309.73	124.60	338.92	142.85	380.41	115.85
T. GAIN	4.33	0.49	6.60	5.42	6.12	6.51	4.33
R. GAIN	4.33	0.49	6.60	5.42	6.12	6.51	4.33
ABSORB	1.47	2.17	0.84	1.25	0.69	0.96	
FS. LOSS	114.37	113.80	116.86	114.61	120.01	115.67	
FIELD ST.	45.59	–144.45	34.58	–178.57	16.80	–221.15	45.93
SIG. POW.	–78.86	–272.74	–87.61	–301.93	–105.86	–343.42	–78.31
SNR	74.63	–119.25	65.88	–148.45	47.62	–189.94	75.18
MODE PROB	0.94	0.00	0.72	0.00	0.59	0.00	0.94
R. PWRG	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	–10.62
RELIABIL	0.99	0.00	0.83	0.00	0.32	0.00	0.99
SERV PROB	0.73	0.00	0.42	0.00	0.16	0.00	0.73
SIG LOW	8.91	7.18	16.35	7.18	25.00	7.18	9.36
SIG UP	4.80	4.68	6.74	4.68	10.79	4.68	5.10

NOISE = –153 S. POWER = –78.3
SIGNAL = 7.2 8.5 4.7 / 1.7 3.1 0.6
NOISE = 8.4 –153.5 6.0 / 1.5 2.5 1.4
RELIAB = 7.9 75.2 12.6
SPROB = 17.0 62.4 17.0

Figure 3.2. Method 25 All Modes Output for the Controlling Noise Example at 12 MHz

SUMMARY 3 MODES FREQ = 19.4 MHZ UT = 21.0

				Most REL
	1.F2	1.F2	1.E	1.F2
TIME DEL.	3.77	3.86	3.25	3.77
ANGLE	30.36	32.31	12.81	30.36
VIR. HITE	303.48	327.36	125.30	303.48
TRAN.LOSS	120.91	121.80	312.86	120.91
T. GAIN	5.68	5.89	0.39	5.68
R. GAIN	5.68	5.89	0.39	5.68
ABSORB	0.48	0.45	0.90	
FS. LOSS	119.28	119.49	117.99	
FIELD ST.	43.37	42.27	–143.29	45.87
SIG. POW.	–83.92	–84.81	–275.87	–81.33
SNR	78.28	77.38	–113.67	80.86
MODE PROB	0.50	0.50	0.00	0.50
R. PWRG	1,000.00	1,000.00	1,000.00	–9.20
RELIABIL	0.96	0.95	0.00	0.97
SERV PROB	0.61	0.58	0.00	0.61
SIG LOW	17.11	17.70	7.18	17.36
SIG UP	8.22	8.82	4.68	8.50

NOISE = –162 S. POWER = –81.3

SIGNAL =	7.2	8.5	4.7	/	1.7	3.1	0.6
NOISE =	9.2	–162.2	5.1	/	1.5	4.2	1.7
RELIAB =	9.9	80.9	19.7				
SPROB =	25.3	58.8	25.3				

Figure 3.3. Method 25 All Modes Output for the Controlling Noise Example at the MUF, 19.4 MHz

4. SIGNAL-TO-NOISE RATIO PROBABILITY DISTRIBUTION

4.1 Definitions

In order to understand what the signal-to-noise ratio (SNR) probability distribution represents, we need to define some terms. Time variations in the signal power, usually referred to as "fading," are of 2 types. There is short-term fading, also known as "within-the-hour" fading or minute-to-minute fading. And, there is the variation in the hourly median signal power from day-to-day over the days of the month at a given hour, sometimes denoted as long-term fading.

As we have noted in Chapter 2, the signal power predicted by VOACAP only addresses the long-term fading or variation in the hourly median values at a given hour. The short-term or within-the-hour fading is very important but is not included in the VOACAP prediction of signal power. In the determination of the minimum required signal-to-noise ratio, the user must include protection for short-term fading. Generally, one uses Rayleigh fading[1] or some form of log-normal fading. The fade protection factor should be computed or measured for the required reliability ***[REQ. REL]*** specified in the input to VOACAP. The required signal-to-noise ratio including the short-term fading protection factor is entered in the input to VOACAP as ***[REQ. SNR]***.

The SNR distribution is the critical calculation in estimating the performance of HF radio systems. Communications quality is dependent upon the SNR available in the detector stage of the receiver. Hence, the reliability of a communications system over a circuit is usually expressed as the fraction of time that the actual SNR exceeds the minimum level associated with the grade of service required by the user. In HF prediction programs, the signal and the noise distributions are computed separately and then combined to obtain the joint SNR distribution. It is this distribution that allows us to determine the fraction of time that a required minimum SNR ***[REQ. SNR]*** is equaled or exceeded.

However, before we can discuss the circuit performance, we must go back to Chapter 2, Section 2.5, Signal Power Distribution, where we described the modes to be considered in the composite signal power distribution. Of all the 21 possible modes, VOACAP must decide which one is the most reliable mode. This is the point at which we must begin our discussion of reliability, as that is the term which is used in finding the most reliable mode. We will begin that discussion by describing how VOACAP computes the signal-to-noise ratio distribution over the days of the month in the next section. Once the most reliable mode is identified, the multiple modes signal powers are summed, in watts, to find the composite signal power distribution. At that point, VOACAP can compute the

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[1] A discussion of Rayleigh fading may be found in Chapter 9, Section 9.7.

predicted signal-to-noise ratio power distribution needed to define the circuit-hour statistics as a function of frequency.

4.2 Computation of the SNR Distribution

The signal power delivered to the HF receiver via the ionospheric channel is computed using the transmitter power plus the transmit and receiver antenna gain less the transmission loss. In most prediction programs, one obtains only the monthly median signal power or, if the receive antenna is ignored, the field strength. The signal level has a diurnal, seasonal and sunspot number dependence. It also has variability that is due to the changing ionospheric conditions from one day to the next during the month. The IONCAP family of programs, including VOACAP, includes this all-important variation of the hourly signal power and the noise power over the days of the month at a given hour and frequency.

The median SNR ***[SNR]*** is found by subtracting the median noise power ***[N DBW]*** from the median signal power ***[S DBW]***. Since the individual samples within the distributions are unknown and can be assumed to be independent, then the root-sum square of the signal and noise decile ranges can be used to approximate the upper and lower decile ranges of the joint distribution, such that:

$$(\boldsymbol{SNR10}) = (\boldsymbol{SNR}) + [(\boldsymbol{SIGUP})^2 + N^2_{LW}]^{.5} \qquad \textbf{(1)}$$

$$(\boldsymbol{SNR90}) = (\boldsymbol{SNR}) - [(\boldsymbol{SIGLW})^2 + N^2_{UP}]^{.5} \qquad \textbf{(2)}$$

Where:

SNR	=	Monthly median signal-to-noise (density) ratio in dB•Hz
SNR10	=	Signal-to-noise (density) ratio exceeded 10% of the days
SNR90	=	Signal-to-noise (density) ratio exceeded 90% of the days
S DBW	=	Monthly median signal power (dBW) at the receiver input
SIGUP	=	dB above the median signal power exceeded 10% of time
SIGLW	=	dB below the median signal power exceeded 90% of time
N DBW	=	Monthly median noise power (dBW/Hz) at receiver input
N_{UP}	=	dB above median noise power exceeded 10% of the days
N_{LW}	=	dB below median noise power exceeded 90% of the days

With the use of the above equations, VOACAP can now compute the median, upper decile and lower decile for the monthly distribution of the SNR for a given circuit, sunspot number, month, hour and frequency for each of the 21 possible modes. Next, the program must compute the reliability for each of the possible modes in order to determine which one is the most reliable mode.

Note that when N DBW is defined to be the noise power in 1-Hz of bandwidth, as above, the resultant SNRs are expressions of the ratio of signal power to noise power density. The units of these SNR values, when expressed in decibels, are dB•Hz.

4.3 Reliability

We have said that reliability is the fraction of the days in the month that the predicted SNR equals or exceeds the minimum required SNR ***[REQ. SNR]***. For each of the possible modes predicted for a given circuit hour and specified operating frequency, VOACAP has now computed the predicted SNR distribution in terms of a median, upper and lower decile range. This distribution is assumed to be normal on either side of the median ***[SNR]*** (refer to Chapter 2, Section 2.5). Therefore, the SNR which will be exceeded 0.90 days of the month is:

(SNR90) = ***[SNR] – [SNRLW]***

where

$$[SNRLW] = [(SIGLW)^2 + N_{UP}^2]^{.5}$$

If (SNR90) is equal to the ***[REQ. SNR]***, then the reliability is equal to 0.90 days of the month. If ***[REQ. SNR]*** is higher than (SNR90), then the fraction of days will be < 0.90. Conversely, if ***[REQ. SNR]*** is less than (SNR90), then the fraction of days will be > 0.90.

VOACAP uses a Gaussian cumulative distribution function to compute the reliability. The first test is to determine whether ***[REQ. SNR]*** is equal to, greater than or less than the predicted ***[SNR]***. This determines the appropriate decile range to use in finding the reliability ***[REL]***. The decile range is divided by 1.28 to obtain the standard deviation.

Next the absolute difference between ***[REQ. SNR]*** and ***[SNR]*** is found. This difference is divided by the standard deviation to determine where the ***[REQ. SNR]*** value falls under the predicted SNR distribution. Using formulation of the Gaussian distribution, the absolute difference between the mean and the ***[REQ. SNR]*** measured in standard deviations allows us to compute the fraction of the distribution which is equal to or exceeds the desired value.

For example, if ***[REQ. SNR]*** is 1 standard deviation below the mean, then 84% of the values in a normal distribution will fall at or above this value. If on the other hand, the ***[REQ. SNR]*** is 1 standard deviation above the mean of the distribution, only 16% of the values will fall at or above this value.

4.4 Most Reliable Mode

At this point in our discussion, VOACAP has computed the SNR distribution for each of the possible modes for the circuit hour of interest and for a specified operating frequency. It also has computed the reliability that the ***[REQ. SNR]*** will be equaled or exceeded. This is done for each mode. The most reliable mode is determined by the following criteria:

1) The mode with the highest calculated reliability

2) If the reliability values are within 5%, the mode with the lowest number of hops

3) If the hop numbers are equal, then the mode with the largest median SNR is selected

Except for Method 25, the most reliable mode is the mode printed out under each of the operating frequencies. (Method 25 also shows the most reliable mode as well as all of the other modes which were considered for the circuit hour and frequency.) It is the path characteristics for the most reliable mode which are printed out under the frequency row. These path characteristics consist of the takeoff angle ***[TANGLE]***, ***[DELAY]*** time in milliseconds, virtual height ***[V HITE]***, the probability that the operating frequency is below the MUF for the most reliable mode ***[MUFday]*** (refer to Chapter 2, Section 2.2), and the transmission loss ***[LOSS]***. For extremely long paths when the Long-Path Model is being used in VOACAP, only 1 mode is computed so that it is, by definition, the most reliable mode. Other system parameters are computed based on the contribution from all of the other modes. This calculation will be described next.

4.5 Calculating the SNR Probability Distribution

For the circuit-hour at a given frequency over the days of the month, it is assumed in VOACAP that the signal power contributions of the possible modes add in a linear fashion. For example, at the MUF or junction frequency of the high and low ray paths, the median signal power from each mode would be nearly equal. If these were the only 2 contributing modes, then the received signal power in watts would be doubled or increased by 3 dB. Generally, the presence of additional modes will increase the median signal power by a small fraction of a dB upward to a limit of 6 dB.

The same procedure is used to compute the signal power equaled or exceeded at 10% and 90% of the days in the month. The decile ranges are added to or subtracted from the median signal power to obtain power values in dBW. The resultant upper and lower decile values are changed from dBW to watts, summed, and then converted back to dBW. The difference between that value and the median yields the appropriate values for *[SIG UP]* and *[SIG LW]*. An example for the case where there are 2 contributing modes is given in Table 4.1. Example Signal Power Distribution When Two Modes are Present.

Table 4.1. Example Signal Power Distribution When Two Modes are Present

Variable	Mode 1		Mode 2		Composite Mode	
Median Signal Power	–80 dBW	1.0×10^{-8} W	–78 dBW	1.58×10^{-8} W	–75.9 dBW	2.58×10^{-8} W
SIG LW	12 dB		14 dB		13.1 dB	
SIG UP	6 dB		8 dB		7.4 dB	
S $PWR_{0.90}$	–92 dBW	6.3×10^{-10} W	–92 dBW	6.3×10^{-10} W	–89.0 dBW	13×10^{-10} W
S $PWR_{0.10}$	–74 dBW	4.0×10^{-8} W	–70 dBW	10×10^{-8} W	–68.5 dBW	14×10^{-8} W

Now, we know the signal power distribution for the combination of all possible modes for that circuit-hour and frequency. Next, we find the joint distribution of the signal power and the predicted radio noise power. VOACAP has already computed the combined radio noise (atmospheric, man-made and galactic radio noise) at the receiver for that hour and frequency using the method by Spaulding and Stewart (1987). This was used when we found the most reliable mode. We will recall that the noise power also has median, upper and lower decile values. This allows VOACAP to combine the appropriate noise power values with the predicted signal power distribution to obtain the signal-to-noise ratio (SNR) for the median and the upper and lower decile values (Lane 1995).

These values describe the distribution of the daily SNR values over the days of the month at that hour and are found by using Equations 1 and 2 which we had applied when looking at each of the possible modes. VOACAP assumes that the distribution is normal on either side of the median but that there is an upper standard deviation and a lower standard deviation which may not be equal.

We have already specified a required minimum SNR ***[REQ. SNR]*** with its associated short-term fade, protection factor as input to the program. We also had to specify a required reliability ***[REQ. REL]*** usually set at 90%. VOACAP now locates the ***[REQ. SNR]*** within the predicted distribution of daily SNRs.

Let us return to the example signal power distribution shown in Table 4.1. Assume that the combined noise power distribution for this example is given by a median noise power of –151 dBW/Hz with upper and lower deciles of 9.7 and 6.0 dB. Then, using the equations from Section 4.2, Computation of the SNR Distribution:

Median **SNR** = –75.9 dBW – (–151 dBW/Hz) = 75.1 dB•Hz

From Eq. (1) ***SNR10*** $= 75.1 + [(7.4)^2 + (6.0)^2]^{.5} = 84.6$ dB•Hz

From Eq. (2) ***SNR90*** $= 75.1 - [(13.1)^2 + (9.7)^2]^{.5} = 58.8$ dB•Hz

It is assumed in VOACAP that each side of the distribution is normally distributed. Consequently, we can compute upper and lower standard deviations for the above distribution, such that

$$\sigma = [\ |mean - decile| / 1.28]$$

NOTE: The value of an independent variable in a distribution, expressed in numerical units of standard deviations, can be converted to a percentage of occurrences which will be equaled or exceeded by using a table of probability functions for a Gaussian or Normal distribution, such as the one given in R.S. Burington's Handbook of Mathematical Tables and Formulas (Burington 1995).

For practical purposes, we assume that the median and mean distribution are the same. Also, we will note that the distributions predicted by VOACAP are assumed to be log-normal distributions. In other words, we are predicting the distribution of dB values that we would expect to measure at that hour over the days of the month.

For our example, then, σ_{LW} = 12.7 dB and σ_{UP} = 7.4 dB. Using the Gaussian cumulative distribution function, we can find the probability that an SNR value will be equaled or exceeded, as shown in Table 4.2. Example SNR Probability Distribution and shown graphically in Figure 4.1. Example SNR Probability Distribution.

The probability function in the third column of the table is the reliability that the corresponding SNR will be equaled or exceeded. For example, if the ***[REQ. SNR]*** is 60 dB, then the circuit reliability is predicted to be 88.3% or 26.5 days out of 30 days of the month at that frequency. The relationship between the minimum required signal-to-noise ratio and the reliability will be discussed in more detail in the next chapter.

Table 4.2. Example SNR Probability Distribution

SNR	z = lM – yl / σ	Probability (%)
45	2.37	99.11
50	1.98	97.61
55	1.58	94.29
60	1.19	88.3
65	.80	78.81
70	.4	65.54
75	0	50
80	.66	25.46
85	1.34	9.01
90	2.01	2.22
95	2.69	0.36
100	3.36	.04

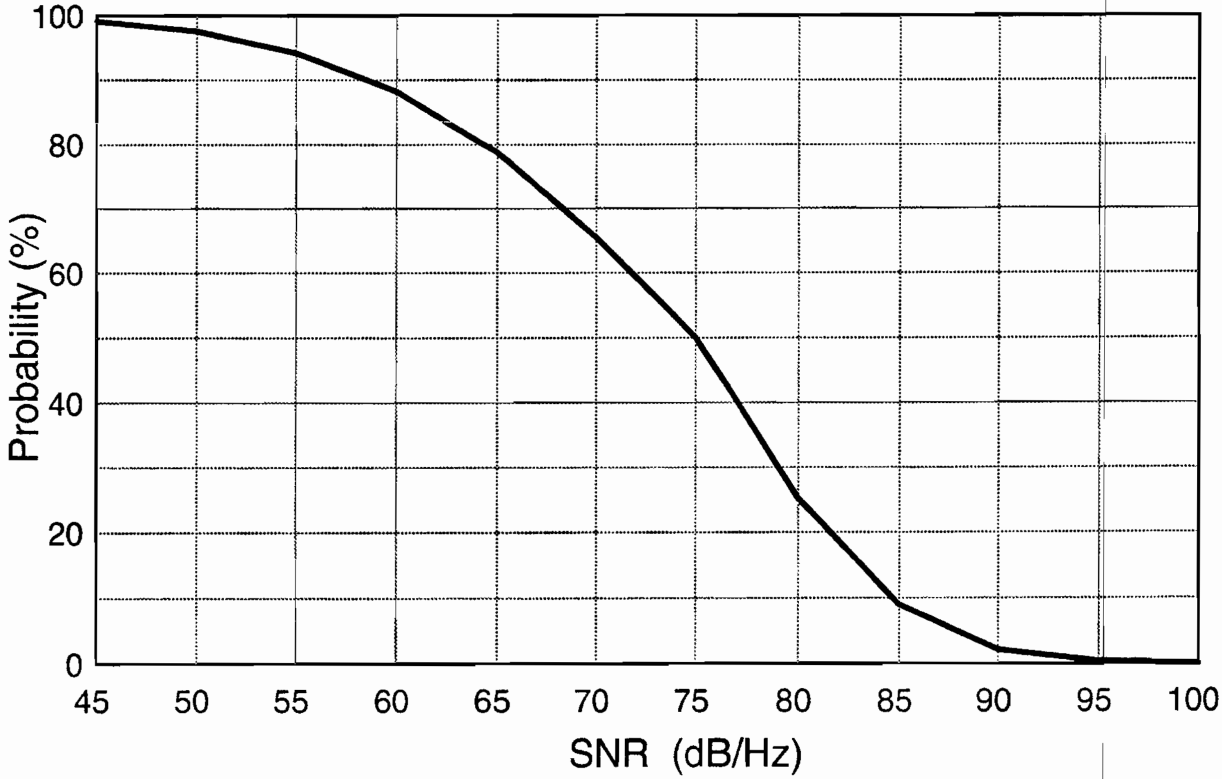

Figure 4.1. Example SNR Probability Distribution

5. REQUIRED SIGNAL-TO-NOISE RATIO AND RELIABILITY

5.1 Definitions

Required signal-to-noise ratio ***[REQ. SNR]*** is a necessary and critical user input to VOACAP as the measure of required communications quality. The prediction program will estimate the fraction of days in the month (i.e., reliability ***[REL]***) that the actual SNR will equal or exceed the ***REQ. SNR***. If this number is wrong, then the predictions of reliability will be meaningless for the system in question.

As with SNR, the ***[REQ. SNR]*** is the ratio of the signal power at the input of the receiver over the external noise power measured in a 1-Hz bandwidth. Generally, this value is based on measurements in the laboratory in the absence of fading or multipath distortion. These requirements under ideal conditions must be adjusted to account for the effects of minute-to-minute fading and time dispersion resulting from multipath. Procedures for developing the appropriate ***[REQ. SNR]*** for a particular system were developed in the 1960s by the US Army Signal Corps (Silva 1964) and the Institute for Telecommunication Sciences (Akima et al. 1969).

Reliability ***[REL]*** is defined as the fraction of the days per month at a given hour and operating frequency for which the actual available SNR should equal or exceed the minimum required signal-to-noise ratio ***[REQ. SNR]***. As we have seen in Chapter 4, the difference between the predicted median ***[SNR]*** and the ***[REQ. SNR]*** is, then, "z" standard deviations above or below the median. Using a Gaussian look up table, we can easily find the area of the distribution which is above our required SNR. The area is expressed as a percentage of the total area under the "bell shaped" curve. It is that percentage we call reliability ***[REL]*** in the VOACAP output.

> **Note:** VOACAP is based on a database from which extremely disturbed ionospheric days have been removed. Therefore, reliability is the expected performance on the undisturbed days of the month. Generally, this is considered to be the case when the geomagnetic index $A_p \leq 27$ or when $K \leq 4$.

Required power gain ***[RPWRG]*** is defined as the dB difference between the ***[REQ. SNR]*** and the actual SNR which is the amount needed to achieve the required reliability ***[REQ. REL]***. If the user has specified ***[REQ. REL]*** at 90% and the predicted ***[REL]*** is 0.90, then the ***[RPWRG]*** must equal 0 dB. If ***[RPWRG]*** is positive, then that number of dB must be added to the system design in order to achieve the desired ***[REQ. SNR]*** at the ***[REQ. REL]***. Conversely, if at that hour and frequency the ***[RPRWG]*** is negative, then that many dB, of SNR, are in excess of the amount needed to just satisfy the system requirements.

[RPWRG] is a very important design tool for the HF radio system. It allows the designer to ascertain whether a system is over-designed or under-designed. The minimum cost system design is the one where ***[RPWRG] = Zero***.

Another useful output parameter from VOACAP is ***[SNRxx]***. This is the SNR which has a reliability equal to the specified ***[REQ. REL]***. In other words, if the user specified ***[REQ. REL]*** is at 90%, then ***[SNRxx]*** becomes SNR90. Any reliability can be specified for ***[REQ. REL]*** from 10 to 90%. Values outside of this range are not meaningful because **the VOACAP database has no data in the regions of the tails of the distribution.**

Note: We should always be consistent when we add a fade protection factor to the ***[REQ. SNR]*** to protect for within the hour fading; it should be for the same required reliability as we have specified for ***[REQ. REL]***.

5.2 Required SNR

The required signal-to-noise ratio ***[REQ. SNR]*** is the single most important variable which the VOACAP user must input to the program. As we noted before, if ***[REQ. SNR]*** is not correct, then the computation of reliability ***[REL]*** and required power gain ***[RPWRG]*** will be incorrect, also. We also have seen that the ***[REQ. SNR]*** is used to determine most reliable mode. Now we need to discuss how we select a ***[REQ. SNR]*** for the system we wish to model.

Note: If we are **only** interested in the signal-to-noise ratio probability distribution, then ***REQ. SNR*** and ***REQ. REL*** can be left at the default settings. These input parameters have little effect on the predicted SNR distribution.

The actual determination of ***[REQ. SNR]*** for a modern HF radio system can be very time consuming and expensive. Historically, the values of ***[REQ. SNR]*** for Morse code, radiotelephony, radioteletype and international broadcasting service are well documented. However, that is not the case for modern high-speed data systems or systems employing automatic link establishment (ALE) techniques.

Let us start with some fairly well known examples which have been long recognized by the radio amateur community and the US Army Signal Corps. First is manual Morse code (telegraphy) (Lane 1975). Typically, the receiver uses a narrow band filter to reduce the noise power. In actual measurements with a receiver bandwidth of 1,200-Hz, trained operators could copy 15 words/minute with at least 90% correct words when the SNR was 0 dB in the bandwidth of the receiver for fading skywave signals and –1 dB for non-fading groundwave or laboratory measurements. For use in VOACAP, we must convert the measured SNR in the bandwidth of the receiver to the ***[REQ. SNR]*** which is always referenced to a 1-Hz noise power bandwidth, so that:

$$[REQ.\ SNR] = SNR + 10 \log B_{Hz}$$
$$= 0\ dB + 10 \log (1{,}200\ Hz)$$
$$= 30.8\ dB \bullet Hz$$

Next, let us consider voice communications over a skywave link. Again, it is well known that trained radio operators can communicate with 90% sentence intelligibility at a SNR of 13 dB[1] in the bandwidth of the receiver (Akima et al. 1969). Most amateur and military HF receivers are set up to operate in a 3-kHz bandwidth for voice communications. Older radios and those used for shortwave broadcast reception require the carrier as well as the upper and lower sidebands and have a bandwidth ranging from 5 to 10 kHz. Using the bandwidth conversion above, we can calculate the ***[REQ. SNR]*** for just-usable voice communications (i.e., 90% sentence intelligibility with trained radio operators) for a 3-kHz single-side-band (SSB) system and a 6-kHz double-side-band (DSB) system:

SSB:

$$[REQ.\ SNR] = 13\ dB + 10 \log (3{,}000\ Hz)$$
$$= 48\ dB \bullet Hz$$

DSB:

$$[REQ.\ SNR] = 13\ dB + 10 \log (6{,}000\ Hz)$$
$$= 51\ dB \bullet Hz$$

In 1994, a comparison between measured values of SNR and subjective aural assessment was published (Lane et al. 1994). Conservative values of required SNR for DSB reception are presented in Figure 5.1. Grades of Radiotelephony Service. Remember that these required SNR values are 3 dB higher than needed for SSB reception in a 3 kHz bandwidth. It is interesting to note that with 39 dB•Hz for DSB reception (or 36 dB•Hz for SSB reception) the listener is unable to recognize the voice signal as being wanted or unwanted. However, a highly trained operator can still copy just-usable telegraphy traffic at 31 dB•Hz.

The aural telegraphy value of 44 dB•Hz for DSB, shown in Figure 5.1, is for 95% correct copy and includes a 3-dB protection for differences between operators (Silva 1964). However, for just-usable voice comprehension, the ***[REQ. SNR]*** must increase to about 51 dB•Hz (DSB) and 48 dB•Hz (SSB). An additional 10 dB is needed to assure 99% sentence intelligibility for 90% of the listeners. Another 10 dB is needed to overcome the annoying level of noise. And, another 10 dB is needed to make the background noise only slightly perceptible. A further 10 dB is needed so that the listener hears no noise at all.

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[1] One dB of fade protection against slow Rayleigh-type fading is included in this required SNR.

This presentation is made because it bounds the full range of values for ***[REQ. SNR]*** from 30 to 90 dB•Hz. Some very sophisticated HF data systems will retain connectivity at ***[REQ. SNR]*** in the 30 to 40 dB•Hz range. These systems either slow the transmission rate, repeat missed packets of data, and/or search for a better frequency during periods of low SNR. Somewhat better throughput is afforded if the ***[REQ. SNR]*** is in the range of 40 to 50 dB•Hz. A voice system will definitely need a ***[REQ. SNR]*** of 48 to 55 dB•Hz, depending on the training of the user. This range will also be needed to achieve a throughput of 60 to 100 words/minute for HF email systems. Generally, ***[REQ. SNR]*** values of 70 dB•Hz or higher are only needed by systems where the user demands a very high rate of data transfer and at 90% reliability or by users who require broadcast quality program reception. These typical values of ***[REQ. SNR]*** are shown in Figure 5.2. Required SNR for Modern HF Systems.

Actual ***[REQ. SNR]*** for modern HF radio systems which use sophisticated signal processing schemes are not expressed in terms which are the same as we have defined for use in VOACAP. Great care must be used to insure that required signal-to-noise ratio is converted correctly to conform to the boundary conditions assumed in VOACAP. We must be careful to determine the point in transmission cycle which is both critical and requires the highest ***[REQ. SNR]***. Often, this is when the system is in the initial message-recognition phase.

Many systems can operate at very low SNR, but in order to recognize that a signal is intended for that receiver the SNR must be much higher. Unless the receiver demodulator knows that there is a signal, nothing will be received.

Other systems require a “handshake” from the receive site in order to pass traffic. In this case, the circuit which presents the lowest SNR at the terminus must be used to define system performance. For example, if a system operates from a base station to an out station using a type of service that requires full-duplex connectivity, the out station with small transmitter power and inferior antennas may present the weaker circuit. In this case grade of service should be based on VOACAP link analyses of the out station to base station.

Only a few reports of performance requirements for digital radio transmission systems are known. The US Army commissioned a study of current HF data communication systems (Systems Technology Associates 1975); however, that report is now almost obsolete. Later, the Office of Telecommunications prepared a theoretical study of PCM/PSK systems for possible use on HF SSB radios (Akima 1976). Unfortunately, that study did not include consideration of signaling rate and bandwidth. A more recent study (Lane and Corrington 1982) of a digital message device group (300 baud signaling rate with information transfer at 180 characters/sec) for the US Army presented ***[REQ. SNR]*** in terms designed for use with IONCAP. In that study, the preamble was found to be the weakest portion of the entire signal. Errors in the preamble resulted in a “lost message”. That study also looked at message repeats which are often used to increase the probability of reception but to the

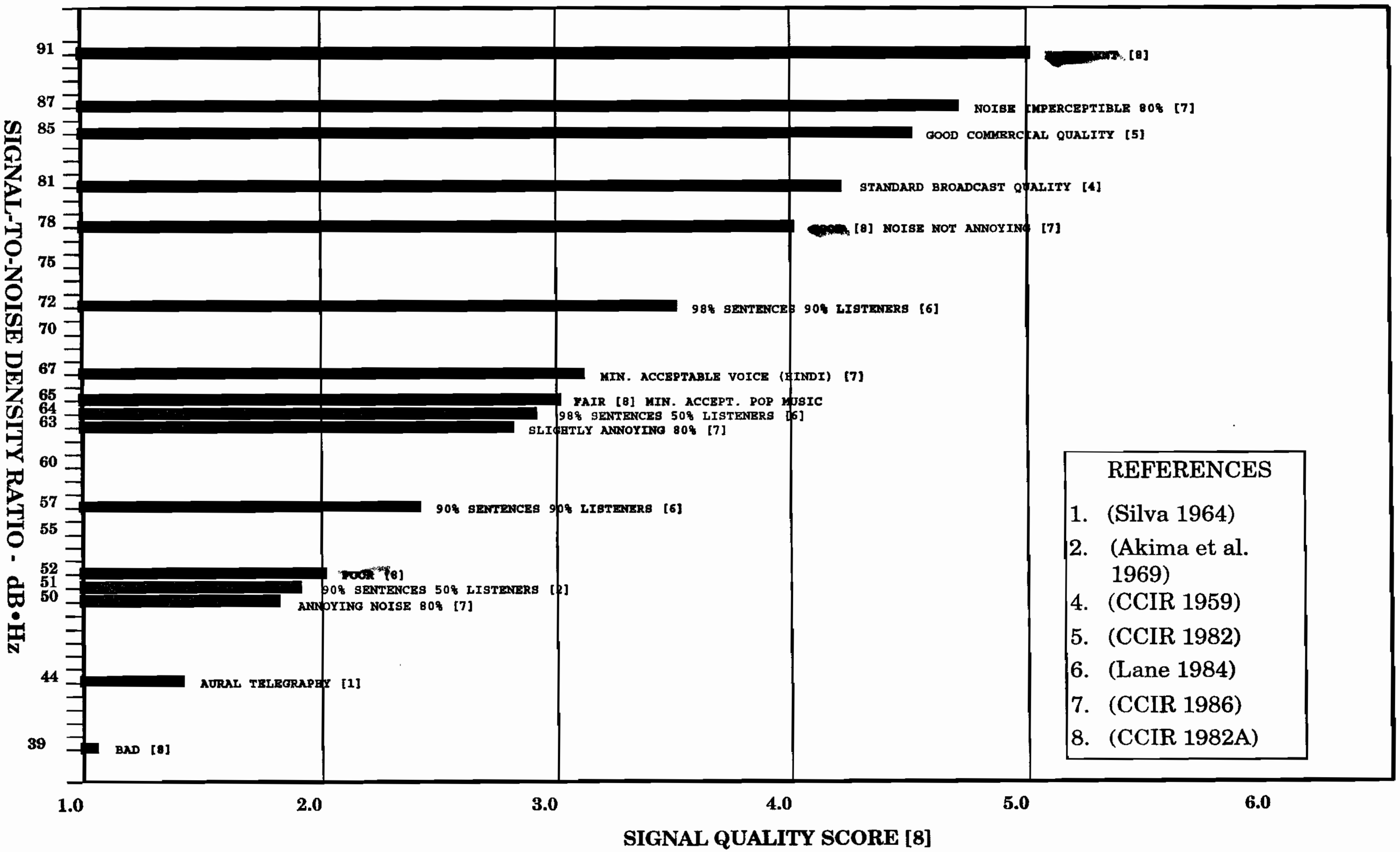

Figure 5.1. Grades of Radiotelephony Service Signal-to-Noise Radio

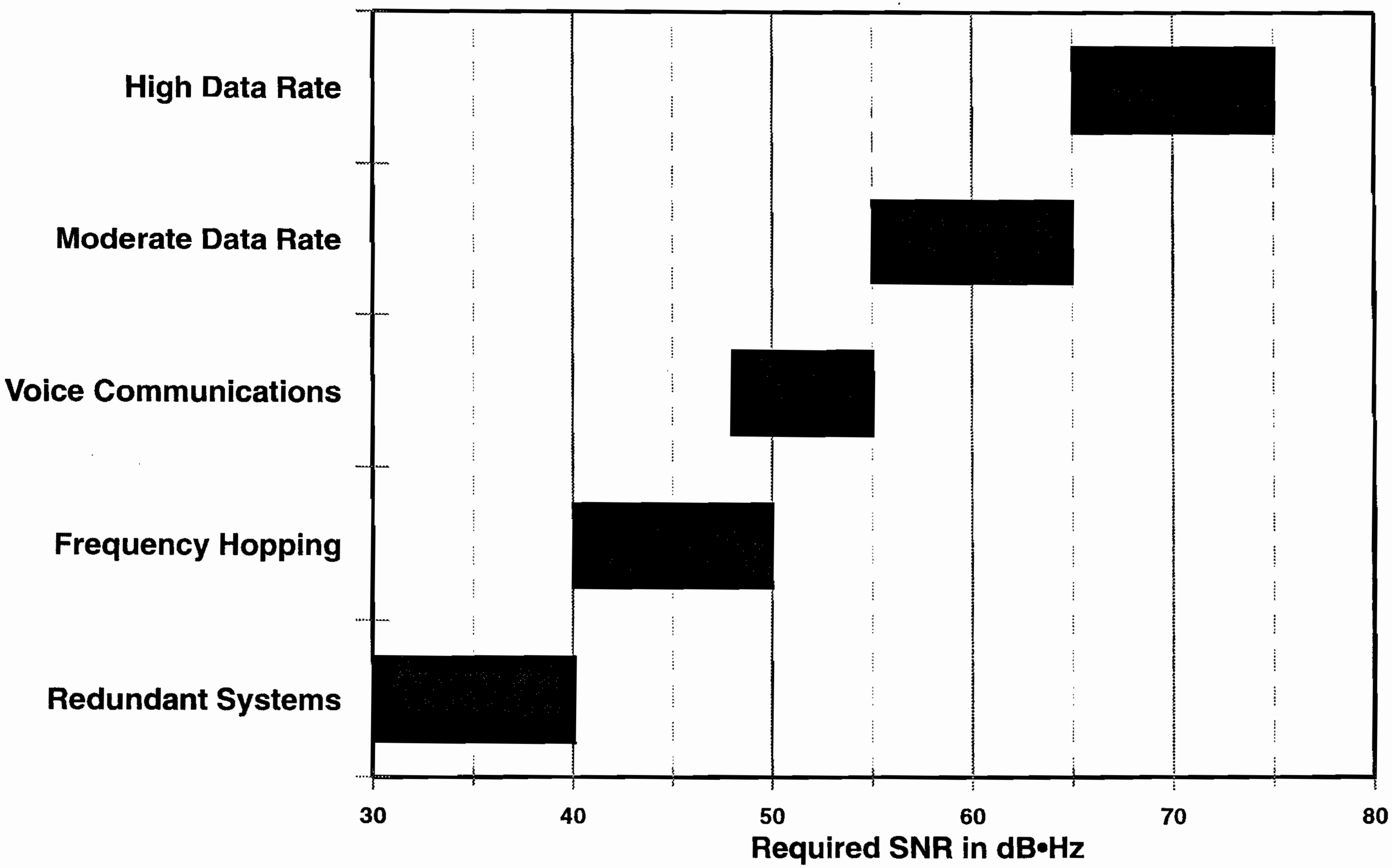

Figure 5.2. Required SNR for Modern HF Systems

detriment of information transfer speed. There is a great need to develop ***[REQ. SNR]*** values for modern, improved-performance HF radio systems (Roesler and Carmichael 2000).

5.3 Circuit Reliability

As with SNR, there are 2 types of reliability we must consider when using VOACAP. The first is the output parameter reliability ***[REL]*** which we discussed in Chapter 4. At that point we needed to compute reliability in order to find the most reliable mode. We will recall that it is based on the probability that the SNR will equal or exceed the ***[REQ. SNR]*** assuming a normal distribution on either side of the median. The other reliability term used in VOACAP is ***[REQ. REL]***, and it is an input parameter the user must specify. It is defined as the desired reliability of achieving or exceeding the ***[REQ. SNR]***. ***[REQ. REL]*** only affects the computation of ***[SNRxx]*** and ***[RPWRG]***, so we will defer our discussion of ***[REQ. REL]*** until we discuss how those output parameters are calculated.

Let us look at an actual prediction methodology. If we remember the example given in Chapter 3, Section 3.5, Controlling Noise, for the circuit from Rio de Janeiro to Brasilia, we had 5 kW of power operating into a half-wave horizontal dipole mounted 0.3 wavelengths above good ground. At Brasilia we had an identical antenna. It has been decided that we will operate at 12 MHz at 2100 hours UT. We wish to know the reliability of achieving commercial quality voice contact at that time during the month of October with a sunspot number of 10. The VOACAP output for these conditions is shown in Table 5.1. VOACAP Output for the Circuit from Rio de Janeiro to Brasilia.

For the time being, we will concentrate on the SNR distribution which is described by the listed values of SNR, SNR LW and SNR UP: 78, 12.6 and 7.9 dB, respectively. If we convert SNR LW and SNR UP to their standard deviation values (i.e., divide each value by 1.28), we obtain values of 9.84 and 6.17 dB. This allows us to construct the log-normal distribution shown in Figure 5.3. Split Gaussian Distribution. From these values, we can also plot the SNR amplitude probability distribution, as shown in Figure 5.4. SNR Amplitude Probability Distribution.

In our example, we had specified a ***[REQ. SNR]*** of 82 dB•Hz for commercial quality voice communications using SSB radios. Our requirement is 7 dB above the predicted median SNR of 75 dB•Hz. This amounts to 1.13 standard deviations above the median. Using a one-tailed, normal distribution table, we find that only 13% of the distribution will be higher than 82 dB•Hz. As we have discussed before, this is the value used by VOACAP to describe the circuit reliability ***[REL]*** and is exactly what VOACAP predicted (see ***REL*** in Table 5.1). We can also see the same value of 13% in the SNR amplitude probability distribution shown in Figure 5.3.

So now we know that the predicted reliability is only 13% or approximately 4 days out of the month. This is not a very satisfactory reliability. We might want to know how many dB we would need in order to have ***[REL]*** = 90% for a ***[REQ. SNR]*** = 82 dB•Hz. VOACAP will make this calculation, but we must set ***[REQ. REL]*** = 90% at the input to the program. In the next paragraph, we will describe how VOACAP uses these values to compute the number of dB needed to achieve 90% reliability.

[RPWRG] is defined as the number of dB needed to be added to or subtracted from the system design in order to achieve the user specified ***[REQ. REL]***. In the above example, we have specified that ***[REQ. SNR]*** = 82 dB•Hz and the ***[REQ. REL]*** = 90%. Basically, what we want to do is move the distribution shown in Figure 5.3 to the right such that the decile value of the lower distribution is now at 82 dB•Hz. We can see that the lower decile (i.e., Fraction of Area = 0.1) is at 63 dB•Hz. This is 12 dB below the median, 75 dB•Hz. That value is 7 dB below the desired ***[REQ. SNR]*** of 82 dB•Hz. Thus, we wish to move the distribution 12 + 7 or 19 dB to the right. This means that ***[RPWRG]*** is a positive 19 dB. As we can see in Table 5.1, this is the value actually computed by VOACAP for ***[RPWRG]***.

In practical terms, what does ***[RPWRG]*** really tell us? For one thing, we know that we might want to add 3 dB of power (10 kW rather than 5 kW). We will still need to add 16 dB of gain. This could be done by using different antennas. The dipoles assumed for this example supply 4.3 dBi at 22.3° for the most reliable mode (see Table 5.1 for TANGLE, TGAIN and RGAIN). If we wish to increase the antenna gain from 4 to 12 dBi, we might want to use a log-periodic or yagi antenna rather than the simple dipole.

The above system design changes are expensive, so we might wish to know what SNR is achieved at a ***[REQ. REL]*** = 90%. In VOACAP this output value is named ***[SNRxx]***, where "***xx***" stands for the value the user set for ***[REQ. REL]***. We have already computed this value when we constructed the Split Gaussian Distribution shown in Figure 5.3. In our example, we wish to know the actual SNR at the lower decile of the distribution. This implies that ***[REQ. REL]*** is 90%. If we look at Figure 5.3, we see that a Fraction of Days value of 0.1 is achieved at a SNR of 63 dB•Hz. Again, this is exactly the value computed for ***[SNRxx]*** as shown at the bottom of Table 5.1.

What is the practical meaning of ***[SNRxx]***? For our example, it means that voice quality will be at the "FAIR" level (Signal Quality Score of 3, as shown in Figure 5.1) or better on 90% of the days of the month at this hour. If we set ***[REQ. REL]*** = 50% or the median, we have already seen that ***[SNRxx]*** = 75 dB•Hz. That means that on 50% of the days of the month the voice quality will be adequate at the "GOOD" level where the noise is perceptible but not annoying and sentence intelligibility is 98% for 90% of the listeners. The practical value of ***[SNRxx]*** is that it lets us decide if we wish to lower the design goal or whether we wish to add the more expensive equipment needed to meet the design goal. For our example, voice communications will be maintained but not at the commercial grade for 90% of the days using the 5-kW transmitter and simple dipole antennas.

Table 5.1. VOACAP Output for the Circuit from Rio de Janeiro to Brasilia Using 5-kW, Half-Wave Dipoles, City Level of Noise (–141 dBW/Hz), October, SSN=10

21.0 UT 19.4 MHz = MUF

12.0	FREQ
1F2	MODE
22.3	TANGLE
3.5	DELAY
215	V HITE
0.94	MUFday
116	LOSS
46	DBU
–78	S DBW
–153	N DBW
75	SNR
19	RPWRG
0.13	REL
0.01	MPROB
0.13	S PRB
9.4	SIG LW
5.1	SIG UP
12.6	SNR LW
7.9	SNR UP
4.3	TGAIN
4.3	RGAIN
63	SNRxx

The remainder of this chapter on the system performance parameters for the HF circuit will be of most value to those readers who are interested in knowing the program flow in VOACAP for the short-path (i.e., ray hop) method and the long-path (i.e., forward scatter) method. For those readers, it is suggested that you print out the VOACAP program listing[2] to use while reading the next 2 sections of this chapter. The third (last) section deals with a recent correction made to the reliability calculation in VOACAP. Other readers who are more interested in learning how to best use VOACAP should proceed to Chapter 6.

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[2] The reader is encouraged to download the VOACAP FORTRAN program listing in order to follow the actual program flow in the various subroutines. The source code is free via the Internet at http://elbert.its.bldrdoc.gov/hf.html.

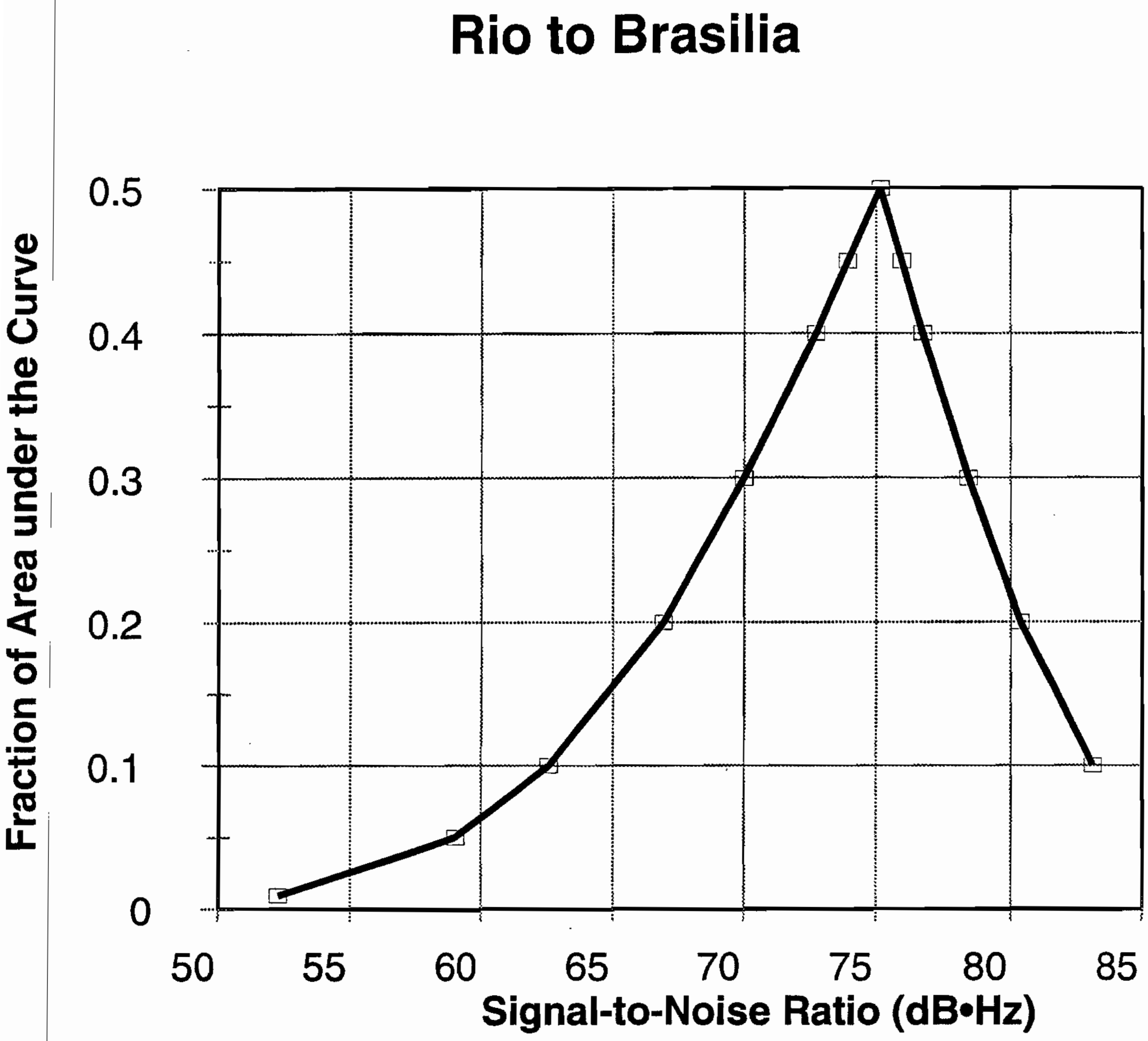

Figure 5.3. Split Gaussian Distribution

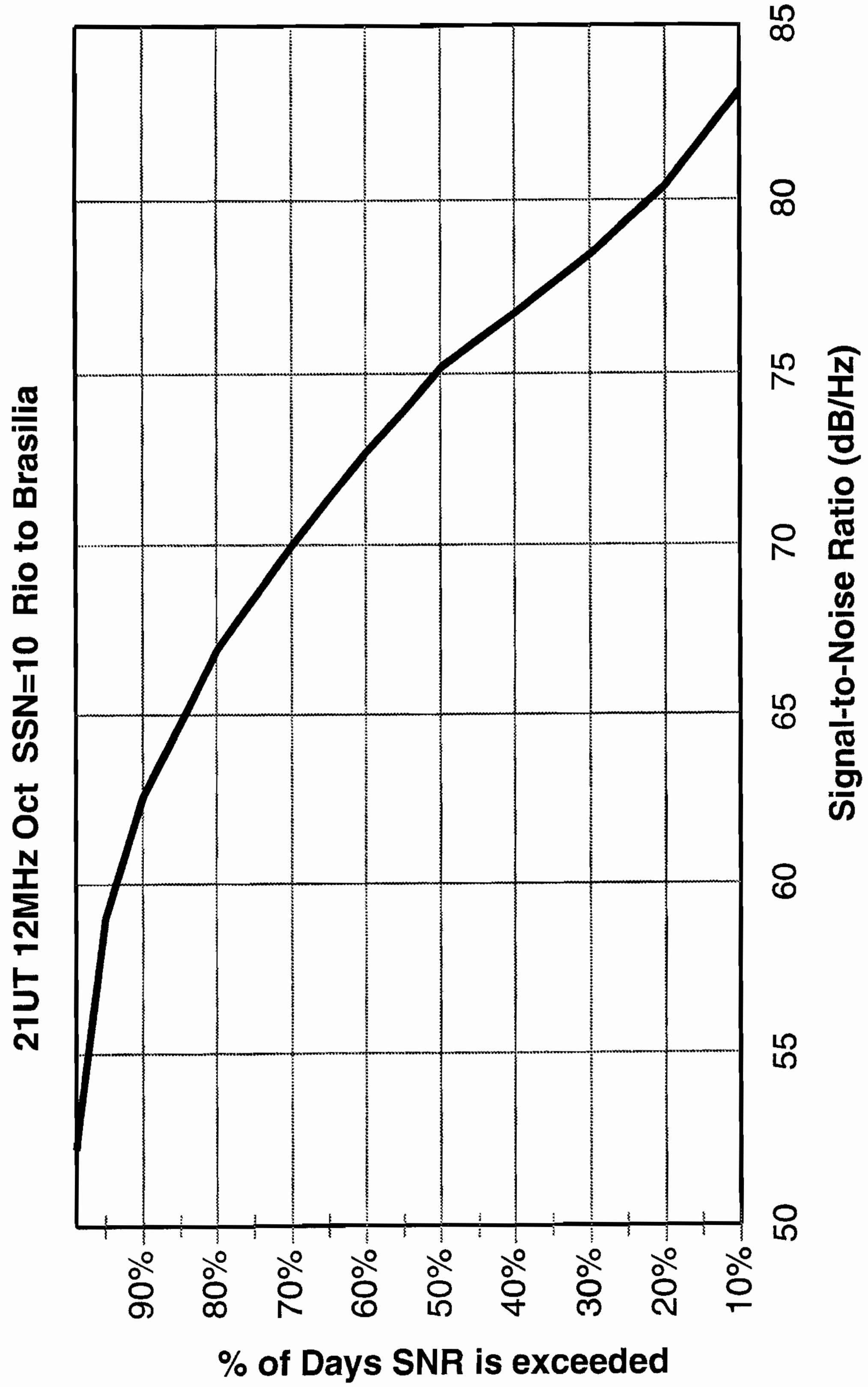

Figure 5.4. SNR Amplitude Probability Distribution

5.4 Short-Path Model in VOACAP

For a given path geometry, sample areas are selected along the path as a function of path length. From the layer's maximum ionization, the semi-thickness, and the height of maximum ionization, a controlling sample-area electron-density profile is generated in subroutine LECDEN.[3] Using a 40-point Gaussian quadrature technique in subroutine GETHP, virtual heights of reflection are calculated at the control area, for a chosen set of vertical-incidence frequencies (i.e., operating frequencies reflected from a vertical angle of incidence).[3] Snell's law is used to calculate a reflectrix, a table of oblique-incidence frequencies, for the above set of vertical incidence frequencies and a selected set of take-off angles. These computations are made in subroutines GENION and FOBBY. The propagation distance is determined by Martyn's theorem and the group path is given by the law of Breit-Tuve, thus giving a complete geometrical solution of the raypath (Goodman 1992). By comparing the results with a rigorous ray-trace model, a correction term is introduced to adjust for the effects of a spherical earth and to yield results comparable to rigorous ray tracing. This is the portion of the code which makes it a quasi-ray-trace model and is unique to the IONCAP family of programs (Reilly 1993).

Routines ALOSFV, SIGDIS, SYSSY, ANOIS1 and NOISY calculate loss parameters. The combined noise distribution for atmospheric, man-made and galactic noise is calculated in GENOIS. Penetration angles and a set of distances for all possible hop modes are computed for each operating frequency specified by the user in subroutines FINDF and PENANG.

Subroutine LUFFY computes the minimum and maximum hop numbers for the specified path from the minimum and maximum distance in the ray-set table. If the operating frequency is above the circuit MUF for the path, the hop number is set to the hop number computed for the circuit MUF. This is the only hop order treated in VOACAP.

VOACAP then enters the hop loop and subroutines REGMOD and INMUF search for modes for the E, F_1, and F_2 layers, in that order. In INMUF, if a layer does not have a mode and if the operating frequency is above the layer MUF at that hop number, an above-the-MUF mode is assumed. If the operating frequency is below the circuit MUF and no mode is found, the program continues to the next layer or hop number. If the frequency is above the circuit MUF, then, using the hop number set in LUFFY, an above-the-MUF mode is calculated for that layer only; no modes are computed for the other layers.

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[3] Subroutines LECDEN and GETHP can be replaced with routines PEN and BENDY to use a parabolic E and F_2 layer. Routine F2DIS calculates the upper and lower distributions for the F_2 layer.

Losses, field strengths and signal-to-noise ratios are calculated in REGMOD for each mode found. Then, for each hop number, a most reliable mode is found in subroutine RELBIL. The most reliable mode is determined by the following criteria: (1) the mode with the highest calculated reliability, (2) if reliability values are within 5%, the mode with the lowest number of hops and (3) if the number of hops is equal, then the mode with the largest median SNR is selected. Subroutines REGMOD, FDIST, INMUF and RELBIL are repeated for each hop number in the hop loop. The most reliable modes are saved.

Subroutine INMOD is then called. If no mode at all has been found and the operating frequency is above the layer MUF for the highest hop number in the hop loop, an above-the-MUF mode is calculated. If the operating frequency is below the layer MUF, the hop number is incremented again and new MUFs are calculated. When the operating frequency is above the new MUF, that MUF mode is used. If no new MUF is found after 2 additional increments of the hop number, no mode is printed out for that frequency. Subroutines ESMOD and ESREG calculate the sporadic E mode and loss parameters if the sporadic E option is specified.

REGMOD and RELBIL are called again, the system parameters are calculated, the most reliable mode is selected, and then the composite mode and required power gain are calculated. Finally, subroutine SERPRB calculates the service probability, and MPATH performs multipath calculations, if this option was specified by the user.

5.5 Long-Path Model in VOACAP

At distances of 10,000 km, unless redirected by user options, VOACAP modifies the ray-trace model in what is called the Long-Path Model. Although the default switchover is at 10,000 km, we can choose to force the Short-Path Model for any distance (**Method 22**[4]) or we can select the following Long-Path Model at any distance (**Method 21**). In addition, by selecting **Method 30**, we have the option of using a smoothing function between the Short-Path and Long-Path Models from 7,000 to 10,000 km and whichever model produces the highest signal power at distances greater than 10,000 km. The following description of the Long-Path Model is developed from several documents (Lloyd et al. 1978), (Lane et al. 1993) and (Rhoads 1993).

As in the Short-Path Model, the long-path calculations are the same up to the entry of the hop loop. The only difference is that an electron-density profile, a reflectrix and a ray-set table are generated at points 1,000 km from both ends of the path for the E layer and at 2,000 km from both ends for the F_1 and F_2 layers rather than at a single controlling point for

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[4] A discussion of the **Methods** available in VOACAP can be found in Chapter 7.

the path. This generates 2 optimum ray paths, 1 entering the ionosphere and 1 exiting the ionosphere. The operations are done in the following subroutines:

Subroutine SANG selects the angles and number of angles that are treated as a function of distance. Then, routines LECDEN, GENION, GETHP, FOBBY and ALOSFV are called for both the transmitter and the receiver ends of the path.

Routines ALOSFV, SIGDIS, SYSSY, ANOIS1, and NOISY calculate loss parameters. For the Long-Path Model, VOACAP uses the circuit MUF distribution to calculate the above-the-MUF losses. The sample area from SELMOD is used to find the additional-loss distribution from stored Transmission-Loss Tables accessed by the program. The combined radio-noise distribution for atmospheric, man-made and galactic noise is calculated in GENOIS for the receiver location.

Subroutines FINDF and PENANG are called twice, once each for the transmit and the receive ends, to calculate penetration angles and area coverages for all permissible hop modes for each operating frequency.

An optimum ray for each end is selected by the following criteria. The ray with the smallest transmission loss is chosen as the highest priority. If 2 rays have transmission-loss values within 3 dB of each other, the fractional parts of their hop numbers are used to determine the optimum ray, as follows. (Here hop numbers can be fractional since the number of hops is determined by dividing the total distance by hop length.) If they differ by more than 0.1, the one with the fractional part nearest an integer, i.e., the most spectral, is selected. Otherwise, if the "gain-minus-loss" values are within 3 dB and the hop-number fractional differences are within 0.1, the one whose takeoff angle is closest to 3° from the horizon is selected. In the program, this is accomplished in 4 subroutines, as follows.

Subroutines SETTMT and SETRCR calculate the take-off angle, virtual height of reflection, true height, hop distance, absorption loss, gain and ground loss for the transmit and receive ends of the path. Then, routines SELTMT and SELRCR select transmit and receive modes based on the following criteria: (1) the mode having the smallest transmission loss, (2) if the transmission loss is within 3 dB and if the fractional parts of the hop numbers (distance divided by hop length) differ by more than 0.1, choose the mode nearest an integer and (3) if transmission loss is within 3 dB and the fractional parts of the hop numbers are within 0.1, choose the ray whose take-off angle is closest to 3°.

For long paths, several physical phenomena can occur which do not exist on short paths. At about 10,000 km, the energy from the transmitter has propagated one-fourth of the way around the world. At this point and beyond, until the antipode is reached, the energy converges into smaller and smaller annular rings, each having greater energy density. To account for this signal build up, a convergence factor is introduced which maximizes at 15 dB at the antipode and then begins to decrease at greater distances.

Subroutine LNGPAT then calls subroutines CONVH, GETTOP, TABS and BABS.

Also, on long paths, more and more energy is scattered away from the distinct reflection points of the normal ray path until the scatter mechanism becomes dominant. Energy can become ducted (e.g. guided between layers) or it can be chordal (i.e., reflected such that it travels on a path which does not come back to earth until it is reflected from the ionosphere 2 or more times). The ionospheric absorption is computed for each of the optimum rays, the one as seen from the transmitter and the one as seen from the receiver. The computed absorption losses for these 2 rays are then averaged. The portions of the path that undergo either the normal D-E absorption or the exotic propagation discussed above are determined by calculating the E-layer penetration frequencies at 1,000 km from each end of the path and at the midpoint. If the penetration frequency at the midpoint is the highest of the 3 and the operating frequency is below it, but greater than the larger of the 2 end frequencies, the length of the path undergoing M-mode[5] or exotic propagation is linearly proportional to the amount that the operating frequency is below the center penetration frequency. All losses are added along with the free-space loss, average ground-reflection losses and the convergence factor and then the received signal power is computed. With the noise power predicted at the receiver location, the complete system performance can be characterized in terms of the signal-to-noise distribution.

RELBIL is called to calculate the one most-reliable mode (not the composite of all possible modes as is done in the Short-Path Method). SERPRB calculates the service probability. SETLUF finds the lowest frequency with a reliability greater than that specified by the user or by the default of 90%.

We will note several differences in the output for the Long-Path Model of VOACAP. The mode will not indicate a hop number but will show the reflecting layer as seen from the transmitter (E, F1, or F2) followed by the reflecting layer as seen from the receiver. For example, we might find the mode designated as ***F2E***. This means that the optimum ray from the transmitter is reflected from the F_2 layer and the optimum ray exiting the ionosphere at the receive end of the path is reflected from the E layer. The takeoff and arrival angles are denoted as ***TANGLE*** and ***RANGLE***, respectively. These angles determine the gain values used for the transmit and receive antennas. Since only 1 optimum transmission ray results from the Long-Path Model, Method 25 (All-Modes method) does not provide information

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[5] The "M-mode" is sometimes referred to as an F-E-F mode and consists of 2 hops with no intermediate ground reflection (the midpoint reflection is from the top of the E layer).

relative to the propagation path computed by the Long-Path Model. Use of Method 25 always forces use of the Short-Path Model in VOACAP.

5.6 Corrected Reliability Calculation

All versions of VOACAP since 1996 contain the corrected SNR distribution. This section is included for those readers who are interested in what the correction is and how it impacts reliability calculations.

In 1994, an error was found in the equations used in VOACAP to compute the SNR distribution (Lane and Davis 1994). This error had been copied from IONCAP (Teters 1983). The same error, according to A. D. Spaulding (1994), had also been made in ITS-78 (Barghausen et al. 1969) and HFMUFES-4 (Haydon et al. 1976). Under tasking from the United States Information Agency's International Broadcasting Bureau, Don Lucas (1995) located the error and has made corrections for VOACAP. The corrected method estimates the SNR distribution in a manner consistent with ITSA-1 (Lucas and Haydon 1966). Subsequently, Greg Hand at ITS has made similar corrections to ICEPAC.

The error contained in ICEPAC, VOACAP, IONCAP, HFMUFES and ITS-78 was that the terms N_{UP} and N_{LW} were reversed in equations (1) and (2) given in Chapter 4, Section 4.2, Computation of the SNR Distribution. This resulted in a "tighter" distribution and an artificially higher reliability prediction. In the original IONCAP program, the "most reliable mode" printed for each frequency column in the output for Methods 20 (for paths less than 10,000 km) and 22 (forced Short-Path Method) is defined as the mode having the highest reliability of all the modes present. If 2 or more modes have reliabilities whose difference is not greater than 5%, then 2 other tie-breaking criteria may be brought into play, as described in Section 5.4.

The correction to VOACAP may change the mode reliabilities in the Short-Path Method (Method 22) such that a different mode can be tagged as the "most reliable mode." When this occurs, the mode indicator (hop number and ionospheric layer) will change as will the virtual height, takeoff angle and delay time. Generally, the required power gain and reliability will not change or change by only a small amount. A benchmark analysis of 52,400 frequency-hours using the Short-Path Method for typical shortwave broadcast operations showed that less than 1% of the predictions had a change in the most reliable mode or the hop number. The Long-Path Method uses a different criteria for determining the entry layer for the ionospheric channel than does the Short-Path Method. The change in the reliability calculation did not cause any changes to occur in the long path entry and exit layer selection.

The error was found to cause up to 6 dB under-prediction of the lower decile of the SNR distribution, with the majority of the cases falling in the range of 2 to 4 dB. The output parameters, reliability ***[REL]***, required power gain ***[RPWRG]*** and the decile ranges of the signal-to-noise ratio, ***[SNR LW]*** and ***[SNR UP]***, are affected by this error. In rare cases the error can change the most reliable mode and its associated characteristics: angle, virtual height and delay time.

The changes made to VOACAP by Donald Lucas (1995) can make the ***[RPWRG]*** increase by as much as 6 dB. Primarily, changes of this magnitude will be found on short paths requiring the use of nighttime frequencies in the 2 to 4 MHz range. For most other situations, the increase in required power gain will be less than 3 dB. The upper and lower decile ranges of the atmospheric radio noise are nearly equal for frequencies above about 10 MHz. Under these conditions, and when the man-made radio noise is low with respect to the atmospheric radio noise, no change in the predicted SNR distribution occurs.

During times when the man-made radio noise is controlling, usually during the local daytime at the receive site or when the receive site is in an urban or industrial area, the change in ***[RPWRG]*** can vary from a few tenths of a dB to upwards of 4 dB. These findings with regard to ***[RPWRG]*** are similar for either the Short-Path (Method 22) or the Long-Path (Method 21).

In summary, the correction to the SNR distribution in VOACAP results in a change in the ***[RPWRG]*** of more than 1 dB in 25 to 40% of the usable frequency-hours for paths of more than 3,000 km. More differences are found in high sunspot years than low. Also, more differences occur for low latitudes than high latitudes. The most significant changes occur for frequencies of less than 10 MHz on circuits with path lengths of less than 3,000 km. The largest difference expected is 6 dB for 2 to 3 MHz on very short paths.

6. HOW TO SET UP THE INPUT FOR VOACAP

6.1 General Point-To-Point Analysis

VOACAP is a user-friendly program with many pop-up screens and Help functions. However, many terms and units used in VOACAP are unique to the HF spectrum and the US Government methodology for HF radio system performance analysis. This section is for those who may not have two decades of experience in the use of IONCAP. Also, a few of the variables in VOACAP are new and not available in IONCAP or other programs.

It is recommended that the reader have VOACAP available on a PC when using this chapter of the manual. The program can be obtained at no cost from ITS via the Internet at **http://elbert.its.bldrdoc.gov/hf.html**.

VOACAP comes with a default program input field and the example circuit will run when RUN I CIRCUIT is entered. We have not chosen that sample for this text as it is not the best example of a full system performance analysis. The program user can easily enter the example used in this text by simply opening each data field "button" and over-writing the existing sample. Input data will be highlighted in **BOLD** print.

Figure 6.1. Opening Screen for VOACAP Point-to-Point Circuit Analysis, shows the format of the initial VOACAP screen when the program is first loaded. The sample data shown in Figure 6.1 is for the example to be discussed in this text. At this point, we are interested in looking at the functions and the data buttons. We will discuss the input data as we proceed.

On the first line under the banner: "VOACAP Point-to-Point data input," we find the functions that allow us to perform filing and program execution (run). There is also a general help file. The "View" and "Save To" functions are of importance once the circuit has been run. The "File" function allows us to open an existing file or to save an input field. Generally, it is more efficient in terms of computer memory to save just the input field. Calculation time is very fast except in the case of running extremely large batch files.

Assuming this is the first time we have run VOACAP, we do not need to worry about using any of the functions on the first line and can begin immediately with the data input buttons. In the upper left hand corner of the screen we find the "Method" button. We can either enter "M" from the keyboard or left-click on the button using the mouse. The Method pop-up screen will open, as shown in Figure 6.2. Pop-Up Screen Showing the 30 Possible Methods Available in VOACAP. We can scroll from Method 1 to Method 30. If we leave the highlighted bar on **"20 = Complete system performance"** and then click on "Accept," Method 20 will be set as the input. Once we select the "Accept" or "Cancel" button, we will return to the initial input screen. For the time being we will be content with using Method 20 without question. Chapter 7 will be devoted entirely to which methods can be used and when, as well as those that should NEVER be used.

The next button is "Year." This is strictly a user label if we want to specify a particular year. Later on we will have to enter the appropriate sunspot number (SSN) which actually affects the output data, whereas Year is simply a label. For our example, we will enter 1999 for the year. Values from 1950 to 2100 may be entered.

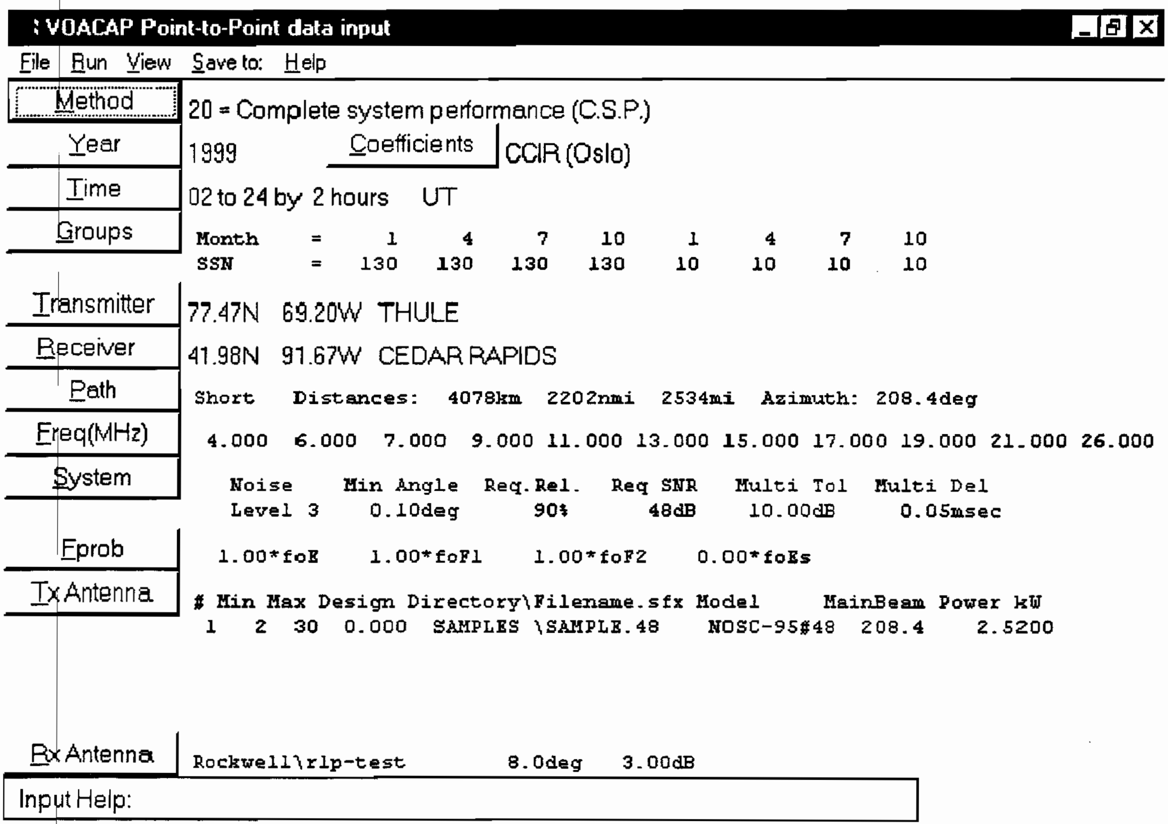
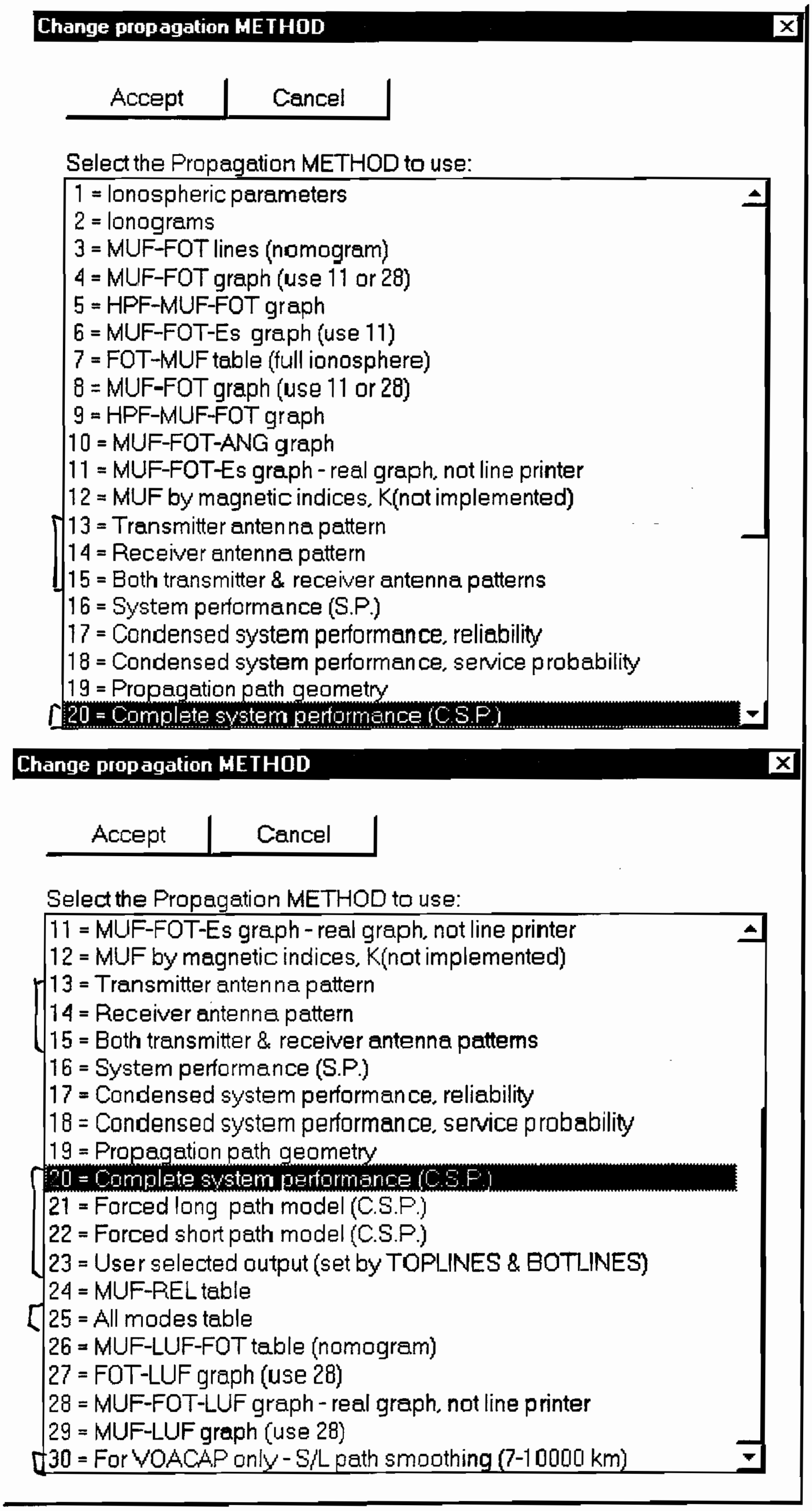


Figure 6.1. Opening Screen Format for VOACAP Poin-to-Point Circuit Analysis



[⇒ only these have been validated for VOACAP

Figure 6.2. Pop-Up Screen Showing the 30 Possible Methods Available in VOACAP

6.2 Coefficients

To the right of the "Year" is the "Coefficients" button. This is a rather significant choice. One can set either "CCIR (Oslo)" or "URSI 1988 (Australian)." The safest choice is "CCIR (Oslo)" and is the one used in this example, as is discussed below.

IONCAP is based on data taken from a full epoch of ionospheric conditions and system performance. The ionospheric coefficients were mapped by the Institute for Telecommunication Sciences in numerous reports. The final data base is best described in the user's manual for ITSA-1 (Lucas and Haydon 1966). In that same year, the International Telecommunications Union (ITU Radio Communications Consultative Committee, CCIR) unanimously accepted this data and published portions of it in CCIR Report 340 in Oslo, 1966 (CCIR Report 340 1967).

During the IGY, there was little data gathered over the ocean areas of the world or in the Southern Hemisphere. This was a known problem and theoretical models were developed to account for areas over the oceans (Rush et al. 1982). This study made use of considerable data obtained from a Japanese ionospheric sounding satellite (Matuura 1979). Nearly a decade later, the Australian Ionospheric Prediction Service (IPS) released considerable data collected in and around Australia (Fox and McNamara 1988). In the following year, the International Union of Radio Science (URSI) released a new series of foF2 maps based on all of these models (Rush et al. 1989). The option "URSI 1988 (Australian)" in the ITS HF models refers to the URSI foF2 maps which replace those in the CCIR Oslo maps. The remainder of the ionospheric maps are those contained in ITSA-1 and the "CCIR (Oslo)" option in VOACAP.

The "URSI 1988 (Australian)" coefficients could introduce errors in VOACAP since the foF2 data is not consistent with the epoch for which other critical parameters were measured. Also, John Lloyd provided a rationale for maintaining this continuity in the IONCAP Theory Manual, see Chapter 2, Ionospheric Parameters Model, Section 2.5, Additional Comments (Lloyd et al. 1978).

For years, there has been a great interest in obtaining near real-time predictions of system performance for HF radio circuits. One reason that programs such as VOACAP have not performed well in this arena is that the daily data was not retained in the original data bases. This is especially true with respect to the critical frequency maps of the ionospheric layers.

When the worldwide maps were made, the only data from the observatories were the median and the upper and lower decile values of the critical frequency for the month. Ideally, we need to map the ionosphere for a particular day. In this case we would know the relationship on a day-to-day basis of observations from each observatory. It became pointless to map the ionosphere based on upper and lower deciles since there was no knowledge of which days were being represented. That is, there was no reason to suspect that the lowest decile values fell on the same day of the month. It is unfortunate that the original data are no longer available. At the time, no one suspected that computers would be invented which could process such huge amounts of data.

A study was made of the daily departures of the foF2 from the monthly median (Jones et al. 1973). However, at this time VOACAP does not consider the expected variation of the critical frequencies about the monthly median value. As we shall see later, this may help explain why the use of daily observations of sunspot numbers DOES NOT improve the predictions from VOACAP.

6.3 Time

Next we enter the time loop. We can either enter a single hour or a set of hours. These hours will be evaluated for each month and sunspot number to be entered later. In Figure 6.3. Time Entry Screen for VOACAP, we see the pop-up screen for the "Time." For our example, we are looking at the even hours throughout the day. Therefore, we enter a beginning hour of **02** and an ending hour of **24** with an increment of **02** hours.

We can also select whether or not we want the hours to represent **Universal Coordinated** Time (UT), also known as Greenwich Mean Time (GMT) or in the military as Zulu time. This is the time most often used as it is common throughout the circuit. However, some users prefer to have the predictions based on local time at the receiver (LMT). For our example, we will use **UT** as the time unit. At this point, we click on the "Accept" button and the time loop will be set in the input for VOACAP.

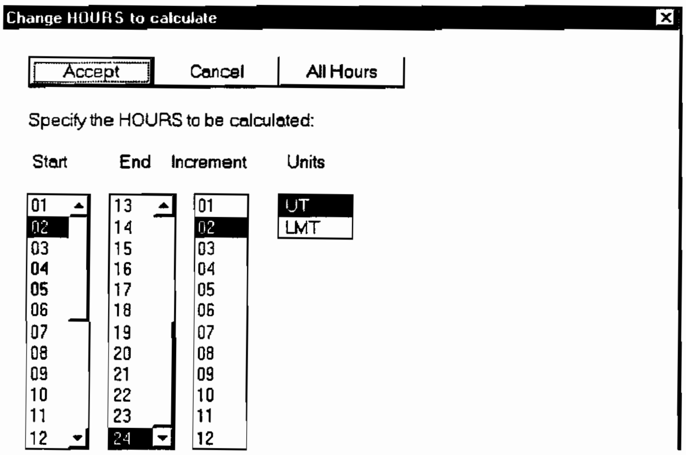


Figure 6.3. Time Entry Screen for VOACAP

6.4 Groups (Month/Sunspot Number)

The next input button is “Groups.” More precisely, this is the point where we can specify the month and sunspot number loops. If we are interested in only a single month or a few months we can enter them here along with their associated sunspot number (SSN). If we are doing a full system performance model over the lifetime of the circuit, we need to look at the seasonal variation and the expected extremes of solar activity. The best representation of the seasonal variation is to use January **(01)**, April **(04)**, July **(07)** and October **(10)**.

If we click on the “Groups” button, the Change Month/SSN parameters screen will appear, as shown in Figure 6.4. Month and Sunspot Number Entry Screen. We can either enter the months and sunspot numbers manually, or select from:

- January as the first month
- Seasons, to use the 4 months listed above or
- All Months

We should be aware that there are many different types of sunspot numbers and numerous places that provide sunspot number predictions for the current solar cycle. However, we must maintain consistency with the atlas of ionospheric characteristics used in VOACAP. This requires us to use the International smoothed sunspot number, R_i.

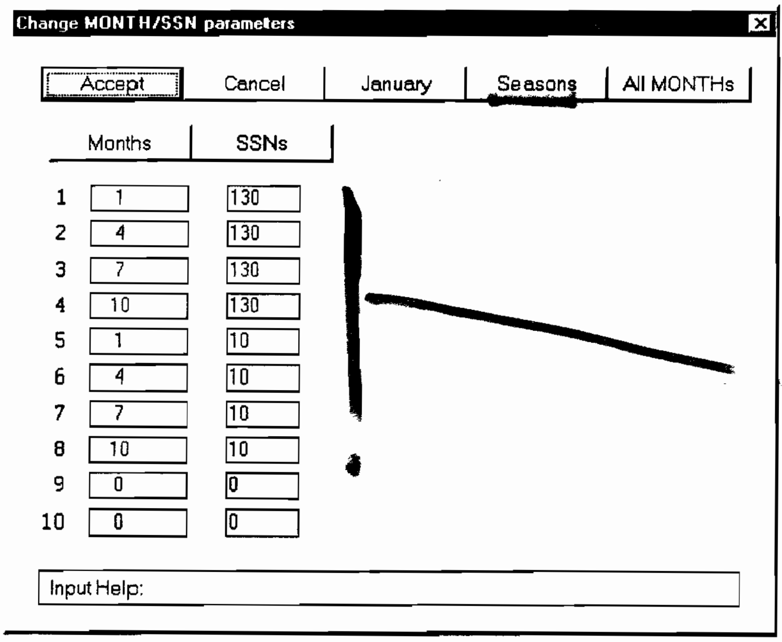


Figure 6.4. Month and Sunspot Number Entry Screen

The correct sunspot numbers to be used in VOACAP (i.e., International smoothed sunspot number R_I), (formerly known as the Zurich smoothed sunspot number, R_Z) can be obtained from the Space Physics Interactive Data Resources (SPIDR) web page:

http://spidr.ngdc.noaa.gov:8080

From the left side of this page, select "Solar." This opens the Solar & Geomagnetic Indices On-Line at National Geophysical Data Center (NGDC) page. Double click on "Indices Information." Select the "Get Data" button and then scroll down to and click on "Sunspot Numbers." This opens the "Current Directory." Scroll to nearly the bottom of the page and select "Smoothed" for sunspot numbers from 1749 to the present. For predicted sunspot numbers in the current solar cycle, select "Sunspot.Predict." For most applications we will be wanting to know the sunspot numbers now or for the future. In this case, we will want to access the NGDC "Sunspot.Predict" list, as just described.

The current sunspot cycle, No. 23, beginning in October, 1996 and expected to end in the year 2007, is predicted to reach a maximum of 116 in August, 2000 with a decile range of ±24 at the time of this writing. This is indicated by the number in parentheses, "( )" under the sunspot number. Thus, the predicted maximum at the time of this writing is expected to fall within a range of 90 to 138 with a confidence level of 90%. Actual values of the International smoothed sunspot number are indicated by (0) under the sunspot number. One will note that the smoothing function uses a running average some 6 months behind the actual date so that the sunspot number for the current month will have some uncertainty to it, as indicated by the decile value in the parentheses below the predicted sunspot number.

It is very important to remember that the worldwide maps used in VOACAP which have a sunspot number dependence are based on monthly median estimates. In order to get the correct coefficients, we must use the smoothed sunspot numbers which were used to develop these worldwide maps. It is tempting to use a daily value or a monthly mean of observed numbers, but it is known that use of these numbers tends to lead to erroneous predictions of system performance from VOACAP. There are agencies that advocate use of these short-term sunspot numbers but they should not do so if they are using VOACAP or IONCAP!

For our example in VOACAP, which is for a full system performance analysis spanning several solar cycles, we will choose a sunspot number of 130 for the solar maximum. Before 1969, 90% of the solar maximums reached a value of 110, but in the more recent cycles, the maximums have been much higher and 130 is more appropriate. For the solar minimum year, we will select a value of **10**, which is typical of most sunspot minimums.

6.5 Transmitter/Receiver

The "Transmitter" button allows us to specify the name and geographic coordinates of the transmitter site. Figure 6.5. Pop-Up Screen for Specifying the Transmitter Location, is the first pop-up screen that we see when we click on the "Transmitter" button. A default location will be shown which we can easily change. For our example, we wish to place the transmitter at Thule, Greenland. Since we know the city, we select the "by City" button. This opens the GEOCITY atlas in VOACAP. Various regions of the world are listed. We will select North America for Greenland. The screen will show city names alphabetically. If we enter "t" from the keyboard for the first letter in Thule, the list will jump to Tacoma, the first city starting with the letter "t." By using the scroll button on the right side of the screen, we can scroll down to **Thule**, as shown in Figure 6.6. Location of Thule Using the NAmerica Geomap Atlas. At this point, we click on the "Accept" button. The name and coordinates for Thule will be input to the VOACAP program.

If by chance we wish to enter a transmitter location that is not in the atlas, we can enter the values in the appropriate boxes. By placing the cursor in the box, instructions for entering data will appear in the "Input Help" box at the bottom of the pop-up screen. If, in the past, we had saved input for this same transmitter site, we can go to the "Transmit???" or the "Circuits???" buttons at the top of the screen and select the appropriate file to get the name and coordinates of the desired transmitter site.

Now we are ready to enter the receiver location. This is easy, as we find exactly the same screens as we did for the transmitter. In this case, we wish to insert the location for Cedar Rapids, IA. This time it is easier to use the "by State" atlas and search for **Cedar Rapids** among those cities listed under Iowa.

6.6 Path

The "Path" button switches the direction of the circuit from the short great-circle route to the long great-circle which is 180° from the short path azimuth. For most situations, we will only be interested in the **Short** distance. We will see that once we have entered the Transmitter and Receiver data, the distance and azimuth are shown to the right of the "Path" button. The great-circle distance is given in kilometers (km), nautical miles (nmi) and statute miles (mi). The azimuth is in degrees from true north as computed for the transmitter looking along the great-circle route from the transmitter to the receiver. Once the circuit is computed, the VOACAP header material will show the azimuth from the receiver toward the transmitter. Suffice it to say right now that the great-circle azimuth from the receiver is not 180° from the azimuth at the transmitter site except when the path follows a common latitude or follows the equator.

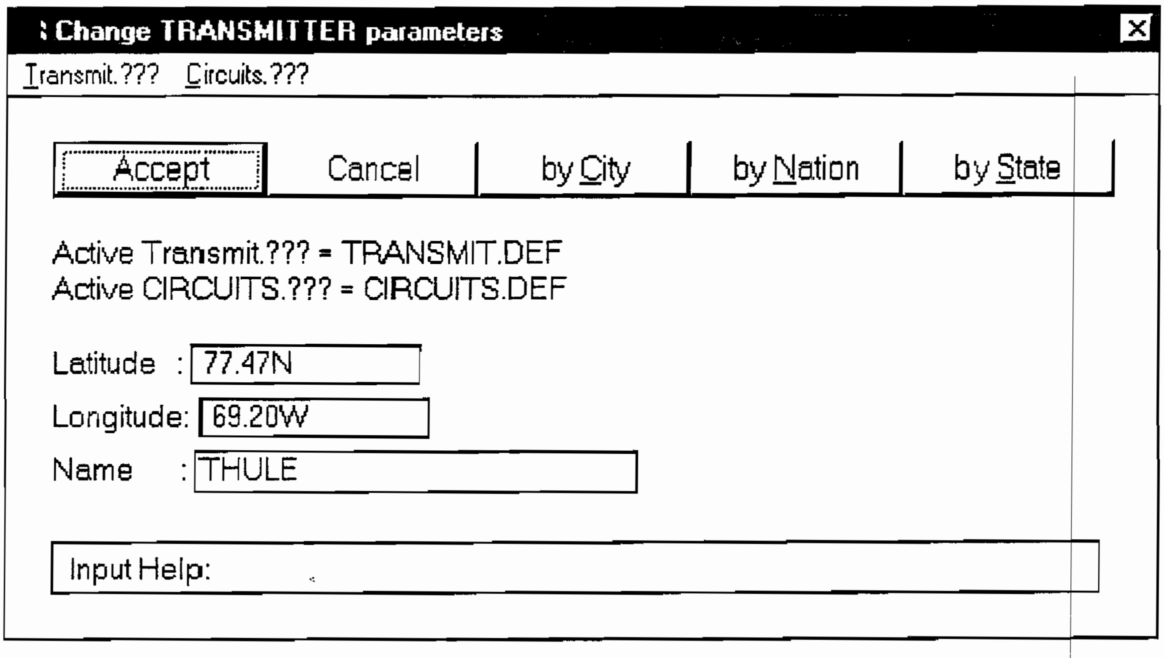


Figure 6.5. Pop-Up Screen for Specifying the Transmitter Location

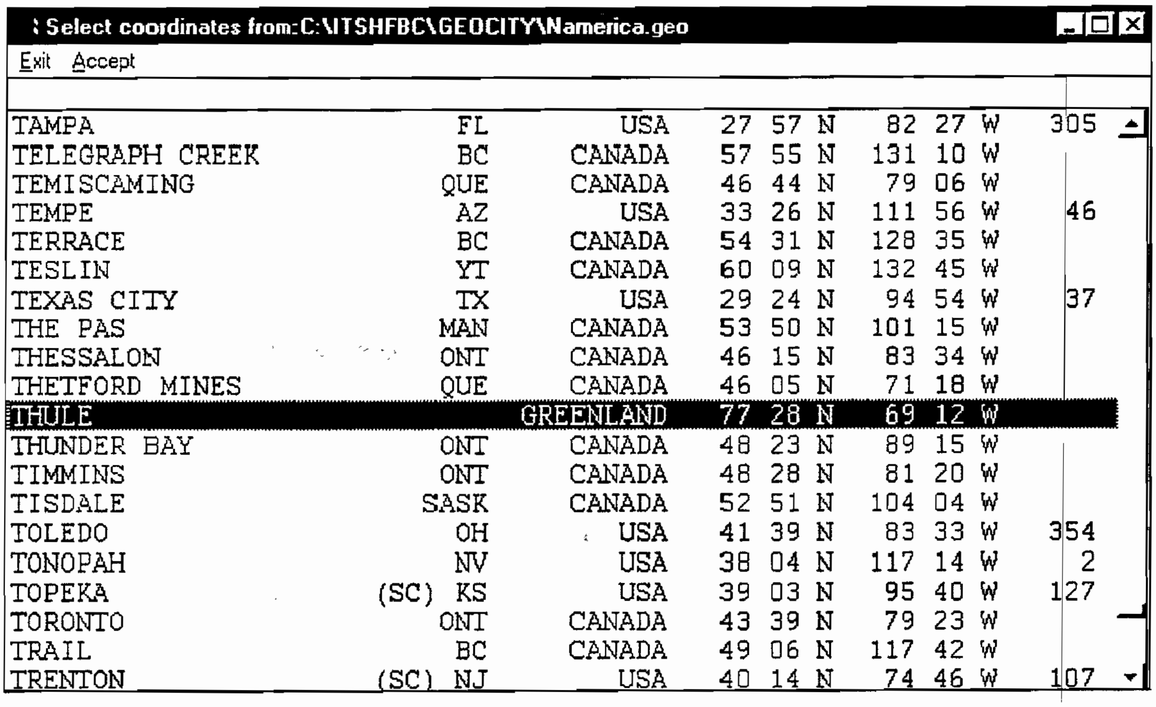


Figure 6.6. Location of Thule Using the NAmerica Geomap Atlas

We may wonder why we might want to use the long-path distance? There are at least two possibilities. One might be if we are interested in self-interference from signals arriving from the back azimuth. Under some conditions on very long paths, the long distance path may have less absorption and actually present a stronger signal at the receiver than if we had used the short distance direction. For example, it has been shown that propagation from Germany to Australia and New Zealand is superior via the long distance path than on the short path during certain hours of the day (Lane et al. 1999).

For those interested in computing great-circle routes, there are several old National Bureau of Standards Technical Notes No. 209 (Brady and Crombie 1964) and No. 303 (Crary 1965). The method used in VOACAP can be seen by looking at the Fortran listing in subroutine GEOM. GEOM is used to find the geomagnetic locations of ionospheric control points, nearness of a control point to a magnetic pole and the conductivity of the ground at the ground bounce locations along the great-circle path.

6.7 Frequency

Next, we need to select the frequencies for the performance data. We can choose from 1 through 11 different frequencies between 2 and 30 MHz.

When we click on the "Frequency" button, a pop-up screen, such as the one shown in Figure 6.7. Frequency Pop-Up Screen, will appear. We have our choice of setting our own frequencies by "zeroing" out all the preset frequencies, or we can select an existing set of frequencies as shown for Default, Default 2 and Default 3. The Default frequencies are the center of the international broadcast bands. Default 2 is a typical complement of frequencies for long-distance HF circuits and Default 3 is typical of the frequencies needed for near-vertical-incidence skywave (NVIS) or short-distance HF links. For our example, we will click on **Default 2** and set these frequencies for our VOACAP analysis.

If one wants to save a set of frequencies for repeated use, they can be set as either Default 2 or Default 3 by clicking the "Set Def" buttons at the top of the pop-up screen.

6.8 System

Now we need to specify the parameters for the system performance analysis. These are very critical and need to be selected with great care. In Figure 6.8. System Pop-Up Screen, we see the pop-up screen for changing the System parameters. These include the man-made radio noise environment at the receive site, the minimum takeoff angle (or angle of arrival), required signal-to-noise ratio, required reliability and the multipath parameters.

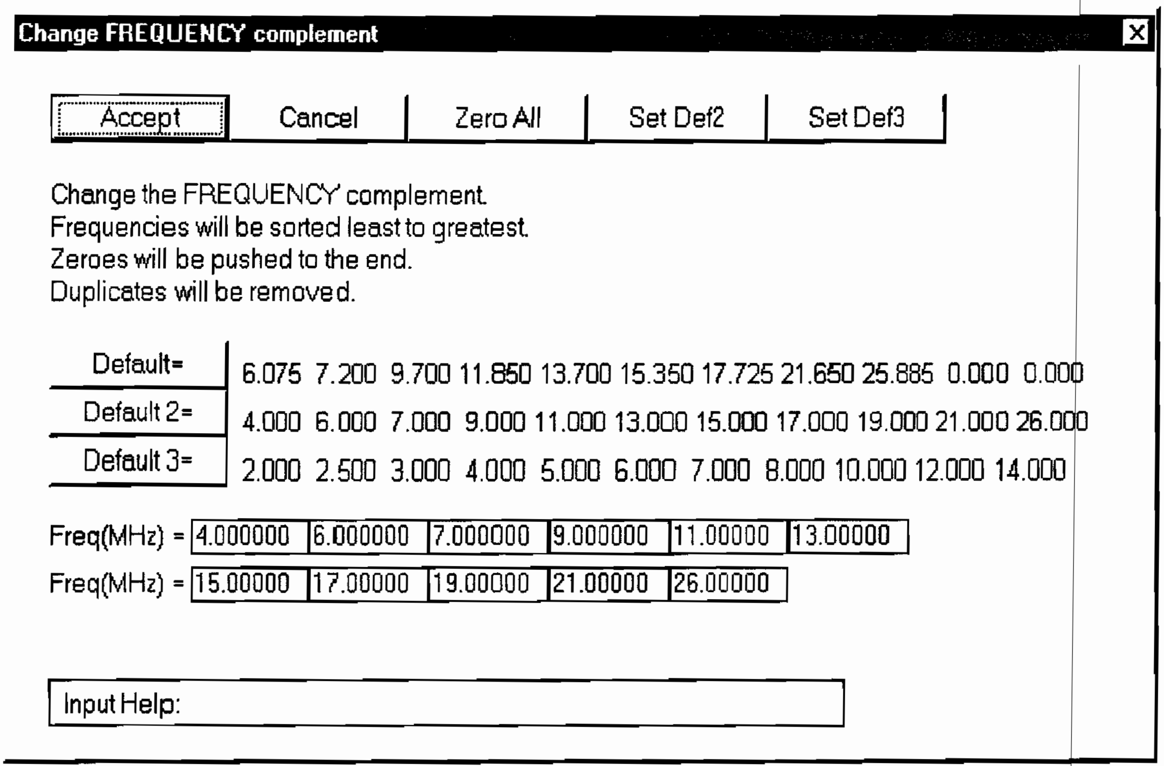


Figure 6.7. Frequency Pop-Up Screen

Man-made radio noise is shown as dBW where the definition of dBW is noise power in a 1-Hz bandwidth in dB below 1 watt–thus, the negative of its true value in dBW/Hz. If we place the cursor in the box for man-made noise, we see that the instructions for setting the noise power appear in the Input Help box at the bottom of the screen, as shown in Figure 6.9. Noise Input Help Instructions.

As we can see, the man-made radio noise values, discussed in Chapter 3, Section 3.3, Man-Made Radio Noise, are given again in the Input Help box. For our example, we are going to select level **3** for Cedar Rapids. This is perhaps too low; but, if the site is away from heavy industry, high-voltage power lines and city traffic, it should be a reasonable level.

Next we need to enter the minimum takeoff or arrival angle. The default value is 0.1°. Values from 0.1° to 40° can be used. The original documentation with IONCAP had initially recommended a value of 3°. The 3° is a rather common lowest angle for arriving skywave signals due to the roughness of the terrain. Based on discussions with Donald Lucas and George Haydon, it was decided at the Voice of America to change default minimum takeoff angle from 3° to 0.1°. This was done for two reasons. The most important is that the minimum takeoff angle is applied to the reflectrix where the possible ionospheric modes are first considered. If we restrict the lowest possible angle, it can

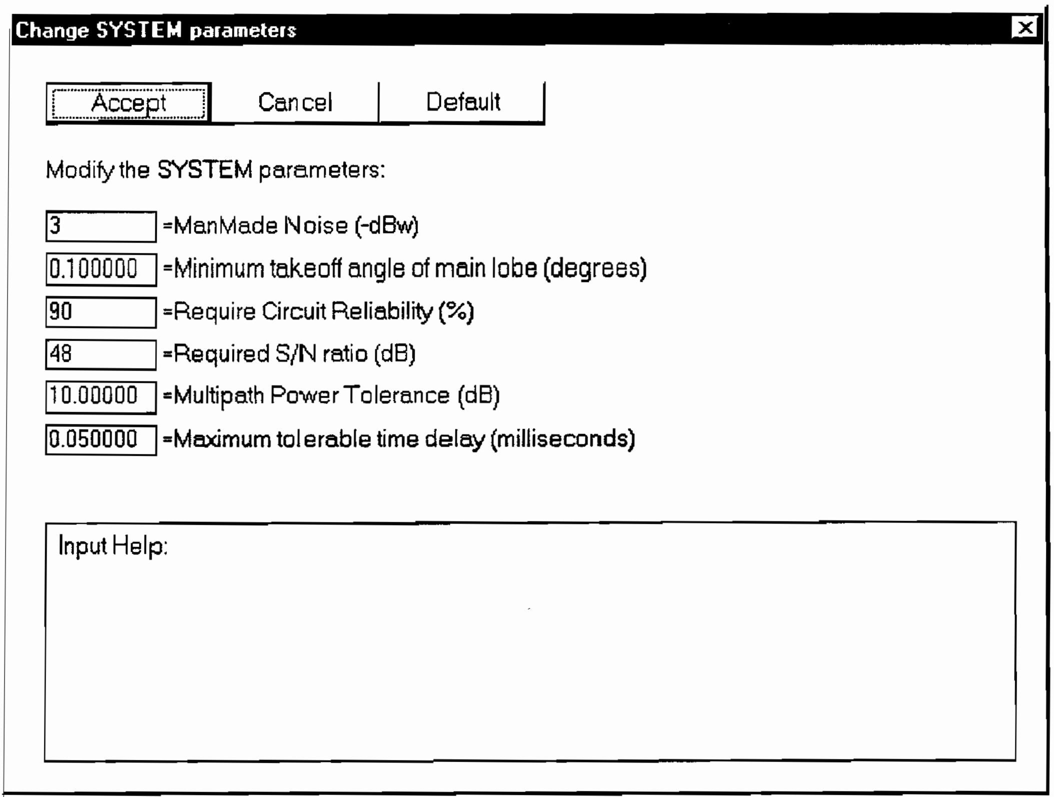


Figure 6.8. System Pop-Up Screen

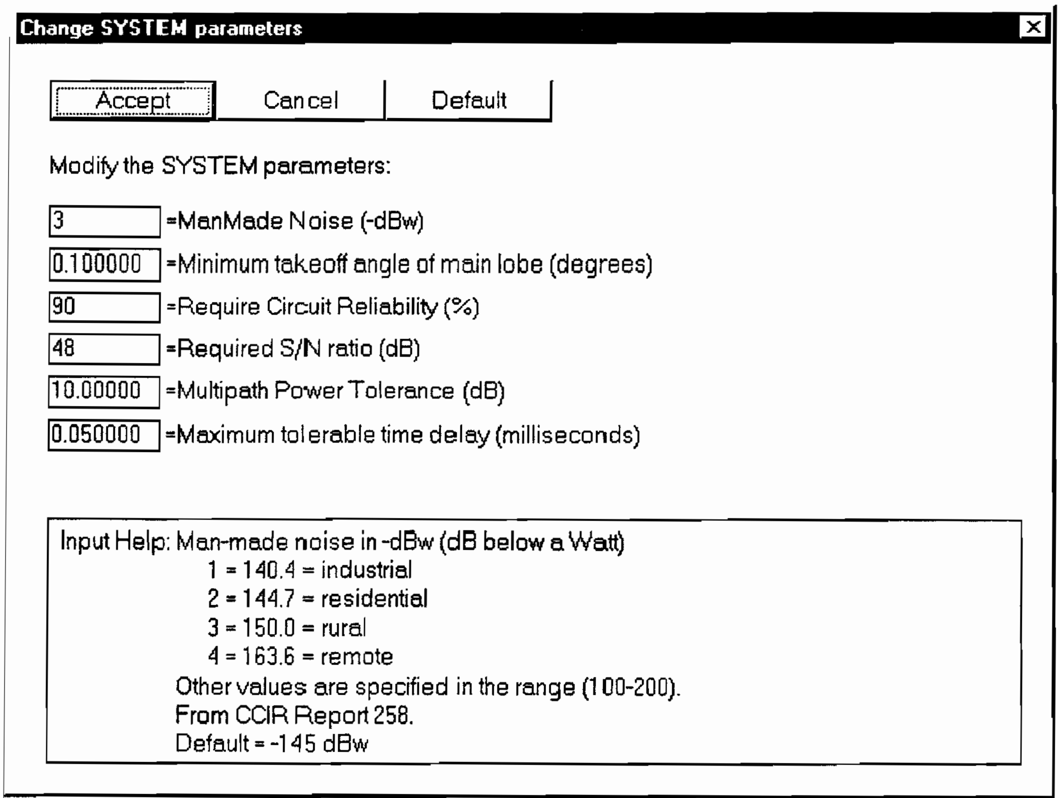


Figure 6.9. Noise Input Help Instructions

change the ionosphere used in the prediction such that low-angle modes can be missed. Secondly, Voice of America goes to great expense to build very large antennas with considerable gain at the very low takeoff angles. However, when we allow VOACAP to consider modes between 0.1° and 3°, we must be very careful to have modeled the antenna pattern very accurately for these angles.

For non-broadcast HF operations (e.g., military, amateur radio, etc.), we may wish to use the 3° minimum takeoff angle. This is especially true if the antennas are not located on flat, unobstructed sites. Also, if we are using an isotrope for a hypothetical antenna, we certainly do not want to have 0 dBi antenna gain at angles below 3°! This can be 10 to 20 dB greater than any practical antenna could develop. Remember that the skywave pattern of an antenna over real earth has no gain (–99 dBi) at 0° elevation. VOACAP uses various values at 0° ranging from –20 to –99 dBi except for the isotrope which has 0 dBi (infinitely more gain than can be achieved).

For our example, we could use either 0.1° or 3° since the path distance is 4,078 km. This distance is beyond the range for 1F2 modes and is at the beginning of the 2-hop region. Therefore, the takeoff and arrival angles on this path will be well above 3° and our choice of minimum takeoff angle is not too critical. Later on, when we look at the antennas on this circuit, we shall also find that they produce very little gain below 3°. Even if a mode did exist at such a low angle, it would not develop enough signal power to become the most reliable mode. We will leave the minimum takeoff angle at its default value of **0.1°**.

The next parameter is the "Required Circuit Reliability." Normally, we will leave this at the default value of **90%** as was discussed in Chapter 5, Section 5.3, Circuit Reliability. This value defines the output variables of Required Power Gain and SNRxx.

Next, we must specify the "Required Signal-to-Noise" ratio (dB•Hz). If we return to Chapter 5, Section 5.2, Required SNR, we will find that for just-usable voice quality the ***[REQ. SNR]*** = 48 dB•Hz or 13 dB in a 3-kHz bandwidth. For our example we will use **48**. Generally, ***[REQ. SNR]*** values for practical HF radio systems will fall in the range of 30 to 90 dB•Hz. Values outside of this range should be reviewed carefully to make sure that they are representative of real conditions and that the units are correct.

Finally, we come to the last two fields for the System input. These have to do with the multipath prediction. The first is the "Multipath Power Tolerance" in dB. As we will recall, VOACAP finds the most reliable mode as well as all other contributing modes. A possible multipath mode will be identified if its median signal power is within the dB power tolerance. In our example we have chosen **10** dB. Therefore, any mode that is within 10 dB of the most probable mode will be flagged as a possible multipath mode.

Next, we specify the "Maximum Tolerable Time Delay" in milliseconds. The modes that have been flagged as possible multipath modes are now checked for delay time. If the delay time is greater than that which is input to the program, the mode will be selected as the multipath mode and its reliability will be printed out as the multipath probability. In our example, we have chosen **0.05** msec. This will allow us to see almost any other mode which is within the 10-dB power tolerance.

6.9 Fprob

At this point, we can use the Fprob function to insert multipliers of the critical frequencies for the 4 ionospheric layers which are mapped in VOACAP. As we will recall, the critical frequency for a layer is determined for the control point found for each layer. The multipliers for these critical frequencies allow us to manipulate the electron-density profile used in calculating the reflectrix table.

VOACAP presents a listing of default multipliers which were recommended by the authors of IONCAP (Teters et al. 1983). However, it is instead recommended that the default multiplier for the sporadic-E layer (foE_s) <u>not</u> be used. Rather than a multiplier of **0.7**, it is recommended that we use a sporadic-E layer multiplier of **0.0**, as is shown in Figure 6.10. Fprob Input. The use of a multiplier of zero for the sporadic-E layer effectively shuts off the sporadic-E model in VOACAP.

> **Note:** Do not use the default multipliers presented for the Fprob set-up screen. The recommended multipliers for the critical frequencies are 1.0 • foE, 1.0 • foF1, 1.0 • foF2 and 0.0 • foE_s. Use of the default multiplier 0.7 • foE_s will artificially increase the signal power by 2 to 4 dB on all paths.

The reason for shutting off the sporadic-E layer when we make circuit performance predictions is that the sporadic-E model was not fully tested prior to the release of IONCAP. During the development of VOACAP, it was found the sporadic-E model from IONCAP increased the composite-signal-power prediction by 2 to 4 dB at any distance and at any location in the world. Based on discussions with several ionospheric scientists at ITS (Boulder, CO), it was felt that the predictions using the sporadic-E model with the default multiplier of 0.7 were overly optimistic, especially at distances greater than 2,000 km, where the occurrence of sporadic-E layer can obscure the more favorable F2-layer propagation.

When the multiplier is set to 0 for foE_s, the signal-power calculation reverts to the values used by ITSA-1 (Lucas and Haydon 1966). The effects of the sporadic-E layer are included in the Transmission Loss Tables so that shutting off the sporadic-E model in VOACAP does not totally exclude consideration of sporadic-E layer effects. We will discuss the possible use of the sporadic-E model in VOACAP in Chapter 9, Section 9.6, Sporadic-E Won't Go Away. However, for our example we will set the multipliers to **1.0**, **1.0**, **1.0** and **0.0**, as shown in Figure 6.10.

The authors of IONCAP gave no instructions or guidance in the use of these critical-frequency multipliers other than the default values discussed above. It is left to others to determine if the use of the multipliers in conjunction with real-time observations could lead to more accurate predictions.

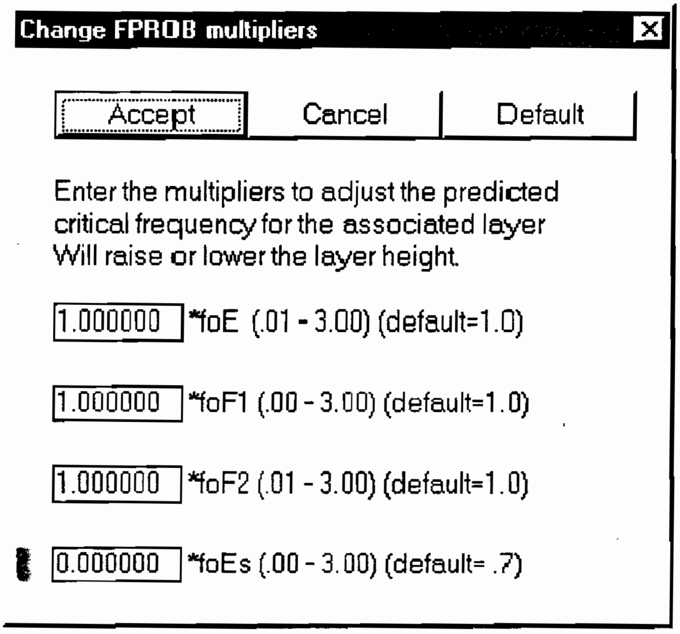


Figure 6.10. Fprob Input

6.10 Transmit Antenna Patterns and Power

Now we come to the most labor-intensive portion of the program, that is, the input of the correct antenna patterns. VOACAP does come with a number of useful programs for computing patterns for common antennas. These are closed-form solutions (meaning that they assume sinusoidal current distributions). Radiation patterns for whips, dipoles, inverted-L, rhombics, sloping vees, horizontal dipole curtain arrays and a common Naval shore station inverted-cone antenna are reasonably accurate. Antenna patterns for yagi antennas and log-periodic antennas require considerable iterations until an acceptable pattern can be obtained. If one has an existing radiation pattern, it can be set up in a file that can be read in and used by VOACAP.

Let us open the first pop-up screen for "TxAntenna." When we click on the "TxAntenna" button (second to the bottom on the left side of the screen), we see the screen shown in Figure 6.11. Pop-Up Screen for TxAntenna Specification. Here we find up to 4 transmit antenna boxes that can be used. The purpose of the 4 transmit antennas is for the case when the circuit uses multiple antennas to cover the required frequency band. VOACAP requires an antenna pattern for all frequencies from 2 to 30 MHz. An example is the case where we have a low-band and high-band rhombic for use on a circuit. Here we would specify the low band from 2 to 10 MHz and the high band for 10 to 30 MHz. If we are using an antenna that only will work from 6 to 18 MHz and no other antenna is available, we should input an isotrope with –99 dB gain from 2 to 6 MHz, then our real antenna from 6 to 18 MHz and then the isotrope with –99 dB from 18 to 30 MHz. This will effectively prevent VOACAP from finding best frequencies outside of the 6 to 18 MHz window. The circuit may not perform well because of this antenna limitation, but that is what we are trying to find out.

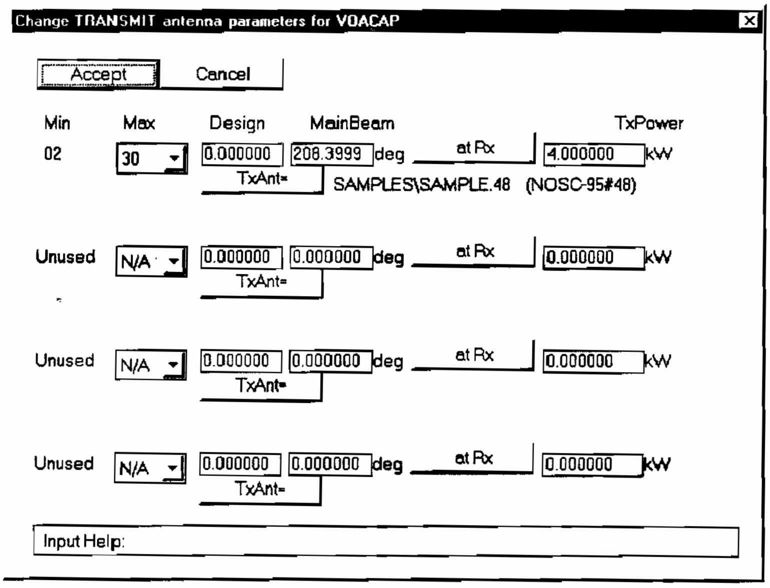


Figure 6.11. Pop-Up Screen for Tx Antenna Specification

With this introduction, let us find what antenna models are in the program. We do this by clicking on the first (at the top) "TxAnt=" button on the "Change TRANSMIT antenna parameters for VOACAP" screen shown in Figure 6.11. In the menu of files, select "SAMPLES." Forty different patterns are available for selection within SAMPLES, as shown in Figure 6.12. Table of Contents for the 40 Types of Antennas Contained in Samples.

The first 12 patterns (00 - 11) are derived from the CCIR Recommendation 705 (now ITU-R Recommendation 705 1995) based on the earlier work of CCIR Study Group 10 (Rossi 1991) and Study Group 3 (Dick et al. 1993). The source code is derived from the computer program from the ITU-R (ITU-R Recommendation P.533 1995).

Sample 12 allows us to obtain the pattern of a horizontal dipole curtain array which has 4 bays and 4 stacks of dipole elements, with the lowest bay at 1 wavelength above ground at the design frequency of the array. This pattern is based on work done at the Institute for Telecommunication Sciences (Kuester 1987). Sample 13 is an example of an HR 4/4/0.5 array using the above technique. To create patterns for other HR arrays using the cited calculation method, a separate program is provided with VOACAP, called HFANT. Patterns created by HFANT can be saved in our Antenna directory under a new folder.

Samples 21 to 30 are subroutines for various antennas taken from the ITSA-1 program (Lucas and Haydon 1966). Samples 31 to 47 are subroutines for antenna pattern calculations taken from the ITS-78 (also in HFMUFES) (Barghausen et al. 1969). We will find some overlap in antennas and some variation in the computed gains between these two sets of subroutines. All of these samples include a typical antenna design. If we wish to use a particular type of antenna with a different design, we must go to the HFANT program and change the design parameter, compute a new pattern and save it under a new name in our Antenna directory. This will be discussed further in Section 6.11, Receive Antenna Patterns.

There is another antenna file available with VOACAP. It is contained in the folder labeled DEFAULT. This folder is available by clicking on the "TxAnt" button. If we select the DEFAULT folder rather than the SAMPLES folder, we find a listing of 33 antennas. Many of these are duplicates of the antennas found in SAMPLES. The first 27 patterns are for antennas specified for use by the ITU for broadcast planning purposes. Only two antenna patterns are of interest to us in the DEFAULT folder. The first is "CONST17.VOA" which is a hypothetical pattern for a typical horizontal dipole array. The pattern has 17-dBi gain at all angles from the zenith down to 3° above the horizon. At angles from 3° down to 0.1°, the gain is reduced based on the reflection loss for a horizontally polarized antenna mounted at a height of one-half wavelength above perfect earth. This pattern is used for new circuits for which the required takeoff and arrival angles are unknown. This nearly omnidirectional pattern allows the engineer to ascertain the angles which the ideal antenna will require. As such, it is useful in the design or selection of antennas for new circuits. The other pattern of interest is "SWWHIP.VOA" (shortwave whip antenna). This is the typical pattern for a short whip antenna attached to small HF receivers which are used inside of dwellings. Although it is a representation of a typical pattern which varies considerably for any given situation, it has been validated with actual measurements and appears to be a better representation of actual situations than the Recommendation 533 shortwave whip which is also given in DEFAULT as CCIR.026.

Select TRANSMIT ANTENNA file from ..\ANTENNAS\SAMPLES

Accept | Cancel | 40 valid antenna files found

Filename	Type	Description
SAMPLE.00	(0)	ISOTROPE :Sample type 00 Constant gain isotrope
SAMPLE.01	(1)	HR 4/4/1 :Sample type 01 Multiband Aperiodic Reflector Array
SAMPLE.02	(2)	HR 2/2/.3 :Sample type 02 Dual-Band Center-Fed Half-Wave Dipol
SAMPLE.03	(3)	HR 4/4/.5 :Sample type 03 Dual-Band End-Fed Half-Wave Dipole
SAMPLE.04	(4)	TR 2/1/.5 :Sample type 04 Tropical Array
SAMPLE.05	(5)	LPH 29/.8/31.1/67.1/7/21.60/450 :Sample type 05 Horizontal Log-P
SAMPLE.06	(6)	LPV 12/4/25/56/2/14/450 :Sample type 06 Vertical Lop-Periodic
SAMPLE.07	(7)	RH155/40.3/68 :Sample type 07 Horizontal Rhombic
SAMPLE.08	(8)	Omni 4dB [HQ 1/.3] :Sample type 08 Quadrant Antenna
SAMPLE.09	(9)	HX .3 :Sample type 09 Crossed-Dipole Antenna
SAMPLE.10	(10)	VM 8/8/120/3 :Sample type 10 Vertical Monopole
SAMPLE.11	(11)	SWWhip for REC533 :Sample type 11 Gain Table versus Elevation
SAMPLE.12	(12)	HR 4/4/1 :Sample type 12 Curtain Array NTIA Report 87-215
SAMPLE.13	(13)	HR 4/4/.5 :Sample type 13 360 degree gain table
SAMPLE.14	(14)	RH155/40.3/68 :Sample type 14 Point-to-Point gain @ 30 fre
SAMPLE.21	(21)	RH67/88/17 :Sample type 21 ITSA-1 Terminated Horizontal Rho
SAMPLE.22	(22)	VM/.25 :Sample type 22 ITSA-1 Vertical Monopole
SAMPLE.23	(23)	HD/.5/.25 :Sample type 23 ITSA-1 Horizontal Dipole
SAMPLE.24	(24)	HY/.5/.25 :Sample type 24 ITSA-1 Horizontal Yagi
SAMPLE.25	(25)	VLP/.25/2 :Sample type 25 ITSA-1 Vertical Log-Periodic
SAMPLE.26	(26)	H/2/4 :Sample type 26 ITSA-1 Curtain

Select TRANSMIT ANTENNA file from ..\ANTENNAS\SAMPLES

Accept | Cancel | 40 valid antenna files found

Filename	Type	Description
SAMPLE.25	(25)	VLP/.25/2 :Sample type 25 ITSA-1 Vertical Log-Periodic
SAMPLE.26	(26)	H/2/4 :Sample type 26 ITSA-1 Curtain
SAMPLE.27	(27)	V23/122/15/1.8 :Sample type 27 ITSA-1 Sloping Vee
SAMPLE.28	(28)	L/21/10 :Sample type 28 ITSA-1 Inverted L
SAMPLE.29	(29)	SR/23/88/17/8 :Sample type 29 ITSA-1 Sloping Rhombic
SAMPLE.30	(30)	IR/70/114/20/4 :Sample type 30 ITSA-1 Interlaced Rhombic
SAMPLE.31	(31)	RH67/88/17 :Sample type 31 ITS-78 Terminated Horizontal Rho
SAMPLE.32	(32)	VM/.25 :Sample type 32 ITS-78 Vertical Monopole
SAMPLE.34	(34)	HY/.5/.25 :Sample type 34 ITS-78 Horizontal Yagi
SAMPLE.35	(35)	VD/.5/.25 :Sample type 35 ITS-78 Vertical Dipole
SAMPLE.36	(36)	H/2/4 :Sample type 36 ITS-78 Curtain
SAMPLE.37	(37)	V23/122/15/1.8 :Sample type 37 ITS-78 Terminated Sloping Vee
SAMPLE.38	(38)	L/21/10 :Sample type 38 ITS-78 Inverted L
SAMPLE.39	(39)	SR/23/88/17/8 :Sample type 39 ITS-78 Terminated Sloping Rhombi
SAMPLE.41	(41)	SLW10/91/0 :Sample type 41 ITS-78 Sloping Long Wire
SAMPLE.43	(43)	HxD3/33/54/450 :Sample type 43 ITS-78 Horizontal X-Dipole Log P
SAMPLE.44	(44)	ATD45/.5/.25 :Sample type 44 ITS-78 Arbitrary Tilted Dipole
SAMPLE.45	(45)	SLR28/80 :Sample type 45 ITS-78 Side-Loaded Vertical Half
SAMPLE.46	(46)	SDR62/150 :Sample type 46 ITS-78 Sloping Double-Rhomboid
SAMPLE.47	(47)	VM/.25/76/2/120 :Sample type 47 ITS-78 Vertical Monopole + Groun
SAMPLE.48	(48)	INVCONE :Sample type 48 NOSC Inverted Cone antenna

Figure 6.12. Table of Contents for the 40 Types of Antenna Contained in Samples

For our example, the antenna at Thule is an inverted-cone antenna which happens to be a special antenna pattern added as **Sample 48**. There are two ways to view the power-gain pattern for this inverted-cone antenna. One way is to open HFANT, click on FILE I New TYPE I NOSC-95. We then click on PATTERN and we can select a number of formats. In Figure 6.14. 11-MHz Vertical Radiation Pattern from HFANT for Sample 48, NOSC-95 Inverted Cone, we see the VERTICAL pattern at a frequency of 11 MHz. We find that the mainbeam is at an angle of 20° above the horizon with a directivity gain of –1.7 dBi. The other way we can see the pattern is to run VOACAP for Method 13. This prints out the transmit power-gain pattern as a table. Values of gain are in dBi and are arranged from elevation angles of 0 to 90° and for frequencies ranging from 2 to 30 MHz. A section of this table is reproduced in Figure 6.15. Method-13 Output for Gain Pattern of Sample Antenna – NOSC Inverted Cone, showing the gain from 2 to 13 MHz for elevation angles of 0 to 50°.

The pattern plot given by HFANT indicates that the plot is a directivity pattern. This is a misnomer because the pattern is actually a power gain pattern, as it includes the efficiency losses of the ground plane in the gain values. The tabular output of Method 13 is power gain and produces the same gain values as HFANT. Method 13 also provides an efficiency table under the bottom frequency line. This table lists the efficiency as 0 dB at all frequencies for the NOSC inverted cone. This is not correct for a monopole type of antenna using a ground plane. Consequently, we can only use Sample 48, the inverted cone, as a transmit antenna. In the case of a receive antenna, we would need to know the efficiency as a function of frequency. As we will recall from Chapter 3, the computed noise power as delivered to the receiver from a short, lossless vertical antenna is reduced by the efficiency value for the receive antenna at each of the specified frequencies. Since the efficiency values for the inverted cone are 0 dB, only the signal power will be reduced by the actual antenna losses. The noise power will erroneously be that provided by a short, lossless vertical antenna with 0-dB efficiency for this inverted-cone table.

After selecting the Sample 48 antenna as our transmit antenna for the example circuit, we need to either specify the mainbeam heading for the antenna or we can have it positioned on the great-circle route azimuth by clicking on the "at Rx" button. The inverted cone is omnidirectional in azimuth so this is not a critical step in this case. However, for a directional antenna, such as a rhombic, the azimuth of the mainbeam is extremely important.

Select TRANSMIT ANTENNA file from ..\ANTENNAS\DEFAULT

Accept | Cancel | 33 valid antenna files found

Filename Type Description

```
CCIR.000     ( 0) ISOTROPE
CCIR.001     ( 1) HR 4/4/1
CCIR.002     ( 1) HR 4/4/.8
CCIR.003     ( 1) HR 4/4/.5
CCIR.004     ( 1) HR 4/3/.5
CCIR.005     ( 1) HR 4/2/.5
CCIR.006     ( 1) HR 4/2/.3
CCIR.007     ( 1) HR 2/4/1
CCIR.008     ( 1) HR 2/4/.8
CCIR.009     ( 1) HR 2/4/.5
CCIR.010     ( 1) HR 2/3/.5
CCIR.011     ( 1) HR 2/2/.5
CCIR.012     ( 1) HR 2/2/.3
CCIR.013     ( 1) HR 2/1/.5
CCIR.014     ( 1) HR 2/1/.3
CCIR.015     ( 1) HR 1/2/.5
CCIR.016     ( 1) HR 1/2/.3
CCIR.017     ( 1) HR 1/1/.5
CCIR.018     ( 1) HR 1/1/.3
CCIR.019     ( 4) TR 2/1/.5
CCIR.020     ( 4) TR 2/1/.3
```

Select TRANSMIT ANTENNA file from ..\ANTENNAS\DEFAULT

Accept | Cancel | 33 valid antenna files found

Filename Type Description

```
CCIR.012     ( 1) HR 2/2/.3
CCIR.013     ( 1) HR 2/1/.5
CCIR.014     ( 1) HR 2/1/.3
CCIR.015     ( 1) HR 1/2/.5
CCIR.016     ( 1) HR 1/2/.3
CCIR.017     ( 1) HR 1/1/.5
CCIR.018     ( 1) HR 1/1/.3
CCIR.019     ( 4) TR 2/1/.5
CCIR.020     ( 4) TR 2/1/.3
CCIR.021     ( 4) TR 1/2/.5
CCIR.022     ( 4) TR 1/2/.3
CCIR.023     ( 4) TR 1/1/.5
CCIR.024     ( 4) TR 1/1/.3
CCIR.025     ( 8) Omni 4dB [HQ 1/.3]
CCIR.026     (11) SWWhip for REC533
CONST17.VOA  (11) Const 17dB transmit antenna used by VOA
INVCONE      (48) INVCONE    :NOSC Inverted Cone antenna
ISOTROPE     ( 0) ISOTROPE
MONOPOLE.VER(32) VM/10.          :Receive antenna for Dave Sailors analysis
SAMPLE.12    (12) HR 4/4/1   :Sample type 12  Curtain Array NTIA Report 87-215
SWWHIP.VOA   (11) SWWhip.VOA used by VOA for receive antenna
```

Figure 6.13. List of Default Antennas

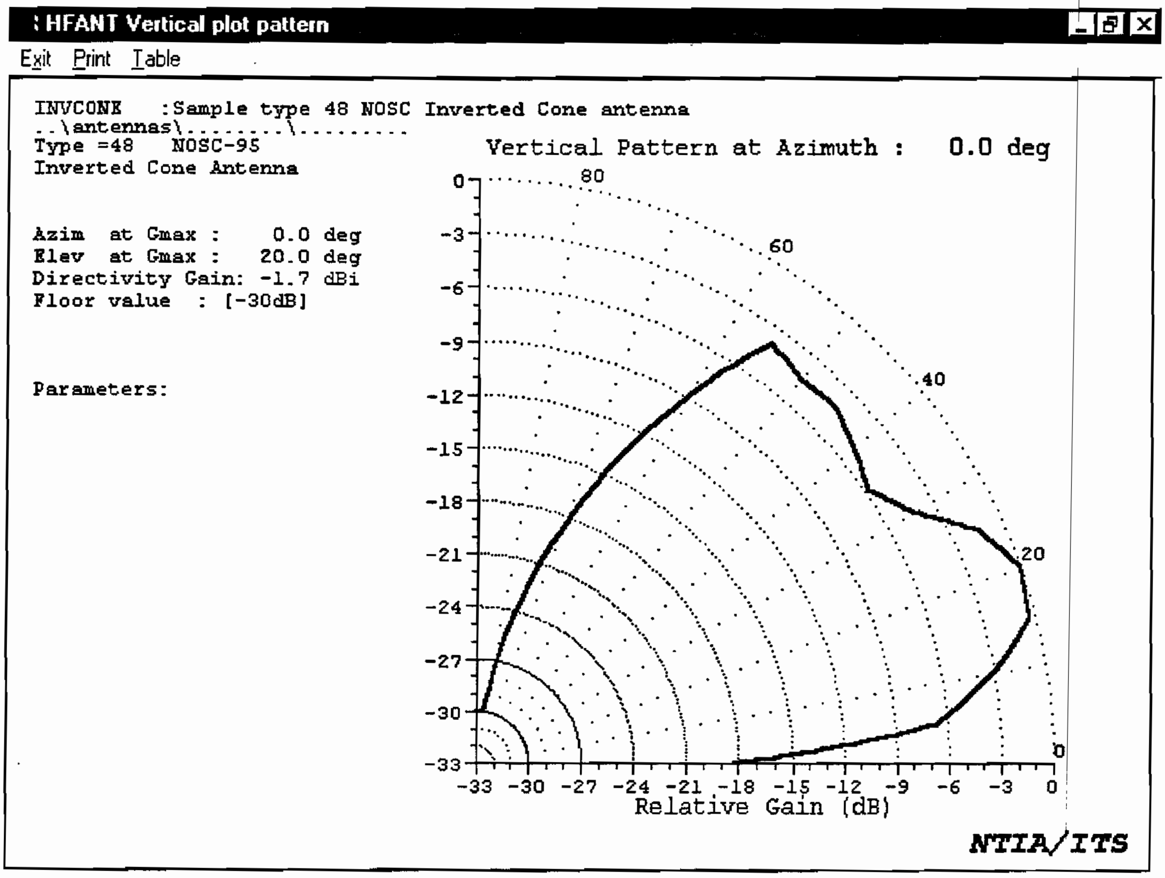


Figure 6.14. 11-MHz Vertical Radiation Pattern from HFANT for Sample 48 - NOSC-95 Inverted Cone

The final entry is for the effective transmitter power, which is entered in a box labeled "TxPower." This is not as simple as it first seems. First of all, we have to consider whether this should be the average power or the peak envelope power. For double-sideband (DSB) radios, we should use the average power. For single-sideband (SSB)* radios, we will use the peak envelope power rating of the transmitter. Next, we need to consider the transmission-line loss between the transmitter and the antenna. For long runs of coaxial cable this can be a substantial loss. Also the use of baluns, multicouplers, switches and tuners, etc. increases the losses. As a general rule of thumb, it is common practice to reduce the power by 2 dB (to a factor of 63%) for losses between the transmitter and the transmit antenna. For actual installations, the real loss should be computed using (coaxial cable) line-loss tables, insertion losses for other equipment in use and 0.05 dB for each connector between the transmitter and the antenna. Since we do not know the exact set up at Thule, we will apply the 2-dB line loss to the 4-kW rating of the transmitter. This gives an effective power of 4 x 0.63 = **2.52 kW** delivered to the antenna. This completes our entries for the transmit antenna file.

Scrollw:C:\ITSHFBC\RUN\VOACAPx.out 8315 bytes

File Edit

A	50	-1.5	-0.5	0.5	0.4	0.1	-1.0	-5.4	-12.1	-10.3	-6.1	-5.2	-8.5
N	48	-1.2	-0.2	0.8	0.8	0.5	-0.5	-4.9	-11.5	-10.7	-6.0	-5.1	-8.5
G	46	-0.9	0.1	1.1	1.1	1.0	0.0	-4.4	-10.8	-11.1	-5.9	-5.0	-8.5
L	44	-0.7	0.3	1.3	1.3	1.3	0.5	-3.9	-10.1	-11.2	-6.1	-5.0	-8.8
E	42	-0.6	0.4	1.4	1.4	1.4	0.9	-3.4	-9.2	-10.9	-6.4	-5.1	-9.3
	40	-0.5	0.5	1.5	1.5	1.5	1.3	-3.0	-8.4	-10.6	-6.7	-5.2	-9.8
I	38	-0.5	0.5	1.5	1.5	1.5	1.4	-2.7	-7.8	-11.0	-7.0	-5.4	-10.0
N	36	-0.4	0.5	1.5	1.5	1.5	1.5	-2.4	-7.3	-11.3	-7.3	-5.7	-10.3
	34	-0.4	0.6	1.5	1.5	1.5	1.4	-2.1	-6.7	-10.6	-7.2	-5.6	-9.9
D	32	-0.3	0.6	1.6	1.6	1.5	1.3	-1.8	-6.1	-8.9	-6.6	-5.3	-9.0
E	30	-0.3	0.7	1.7	1.6	1.5	1.2	-1.6	-5.5	-7.2	-6.0	-5.0	-8.0
G	28	-0.4	0.6	1.6	1.5	1.4	0.8	-1.4	-5.0	-6.2	-4.8	-4.2	-7.4
R	26	-0.5	0.5	1.5	1.4	1.3	0.5	-1.1	-4.5	-5.2	-3.7	-3.3	-6.9
E	24	-0.5	0.5	1.5	1.3	1.0	0.3	-0.9	-3.8	-4.2	-2.8	-2.8	-6.3
E	22	-0.6	0.4	1.4	1.0	0.7	0.2	-0.8	-3.0	-3.3	-2.3	-2.6	-5.7
S	20	-0.7	0.3	1.3	0.8	0.4	0.1	-0.7	-2.2	-2.3	-1.7	-2.4	-5.1
	18	-1.3	-0.3	0.7	0.2	-0.2	-0.5	-1.0	-1.9	-2.1	-1.8	-2.5	-4.1
	16	-1.8	-0.8	0.2	-0.4	-0.7	-1.0	-1.3	-1.6	-1.8	-1.9	-2.6	-3.1
	14	-2.7	-1.7	-0.7	-1.3	-1.6	-1.8	-1.9	-2.0	-2.1	-2.5	-3.1	-3.1
	12	-3.8	-2.8	-1.8	-2.4	-2.7	-2.9	-3.0	-3.1	-3.0	-3.6	-4.1	-4.0
	10	-5.0	-4.0	-3.0	-3.5	-3.8	-3.9	-4.0	-4.1	-3.9	-4.7	-5.1	-4.9
	8	-6.6	-5.6	-4.6	-5.4	-5.7	-5.9	-5.7	-5.5	-5.4	-6.1	-6.4	-6.1
	6	-8.2	-7.2	-6.2	-7.3	-7.6	-7.8	-7.4	-7.0	-6.9	-7.6	-7.7	-7.4
	4	-11.2	-10.4	-9.6	-10.6	-10.9	-11.0	-10.6	-10.2	-10.2	-10.6	-10.6	-10.4
	2	-15.6	-15.2	-14.8	-15.3	-15.4	-15.5	-15.3	-15.1	-15.1	-15.3	-15.3	-15.2
	0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0	-20.0
		2	3	4	5	6	7	8	9	10	11	12	13

Frequency in MHz

Figure 6.15. Method-13 Output for Gain Pattern of Sample 48 Antenna – NOSC Inverted Cone

6.11 Receive Antenna Patterns

Our final data field is for the receive antenna. When we click on the "RxAntenna" button, we obtain the pop-up screen shown in Figure 6.16. RxAntenna Input. We will note that it is very similar to the screen for the transmit antenna with only a few differences. For one thing, we only have the option of a single receive antenna. This is a limitation which ought to be corrected in the future so that more than one receive antenna can be considered for the circuit, as we do for the transmit case.

For our example, we are told that the receive antenna is a rotatable log-periodic antenna with a gain about 3 dB better than that of a broadband dipole. If we click on the "Receive Antenna =" button and open the SAMPLES folder, we do not find the broadband dipole antenna. We do see that "Sample. 23" is for a horizontal dipole antenna in the ITSA-1 program. At this point, we need to go to the HFANT program.

Once we have loaded HFANT, we see the see the "HFANT data input" screen that looks something like the one in Figure 6.17. HFANT INPUT Screen. The first step is to click on the "File" button. Then we click on "New type | ITSA-1 IONCAP | Type 23: Horizontal Dipole." This will change the initial "HFANT data input" screen to exactly the one shown in Figure 6.17.

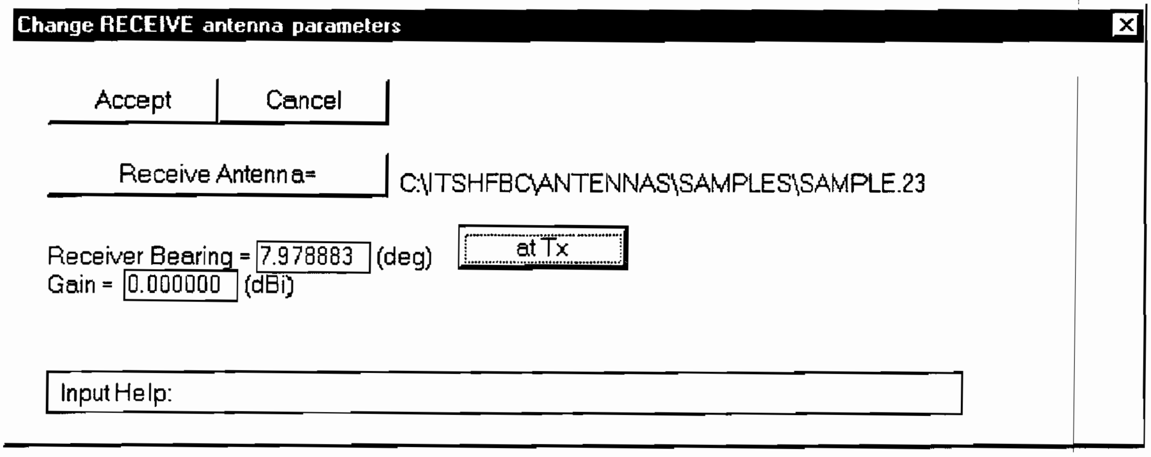


Figure 6.16. Pop-Up Screen for RxAntenna Specification

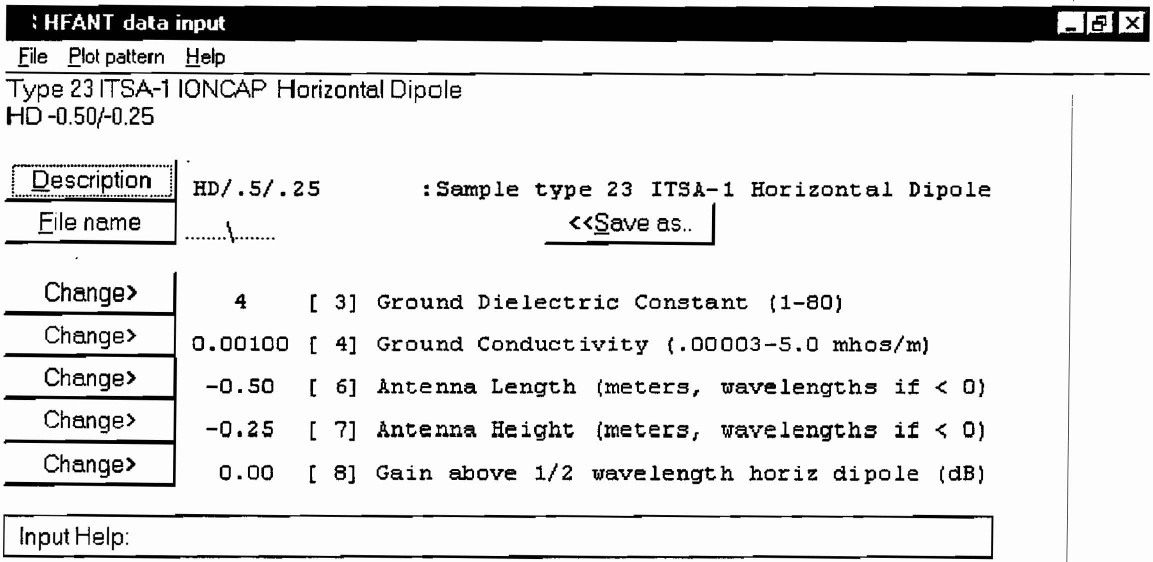


Figure 6.17. HFANT Data Input Screen

Now we can change the input parameters for the horizontal dipole. We will assume that the antenna at Cedar Rapids is mounted over poor earth, which is the default setting for ground dielectric constant and ground conductivity. We will leave the antenna length at "–0.50" since this will force the program to assume that the antenna is one-half wavelength at each of the possible frequencies between 2 and 30 MHz. The rotatable log-periodic antenna we are trying to model is somewhat higher than one-quarter wavelength. At mid-band (14 MHz) and at a height of 50 feet, the rotatable log-periodic antenna is 0.71 wavelengths high. So, for a first approximation of the estimated pattern, we will change the Antenna Height from "–0.25" to **–0.71**. We click on the "Change>" button next to the antenna height field. This opens the "Change Antenna Height above Ground" pop-up screen, as shown in Figure 6.18. Change Height Screen - HFANT, and we enter –0.71 in the blank field. This will raise the dipole height to 0.71 wavelengths above poor ground. We have been told that the rotatable log-periodic antenna produces about 3 dB more gain than a dipole antenna, so we will change the "Gain above ½ wavelength horiz dipole" in the screen shown in Figure 6.17 from 0 to a value of **3.00** dB.

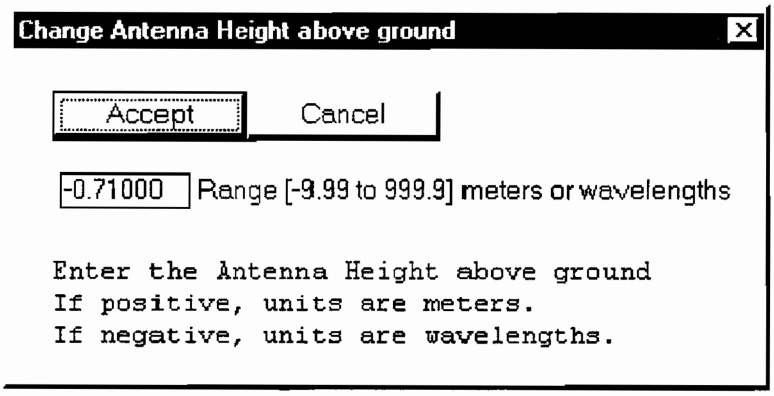


Figure 6.18. Change Height Screen - HFANT

Next, we should check the pattern to see if it is reasonable. At the top of the screen we see a function called "Plot pattern." We can select a number of different plots. Since we are modeling a point-to-point circuit, we are most interested in the case of the mainbeam in the vertical plane on the azimuth toward the transmit site. So we select "Vertical." This brings up the "Plot Parameters" pop-up screen, shown in Figure 6.19. Plot Parameters Screen - HFANT. We select the **–1.0000** default for the mainbeam azimuth and we change the frequency to the mid-band frequency of 14 MHz.

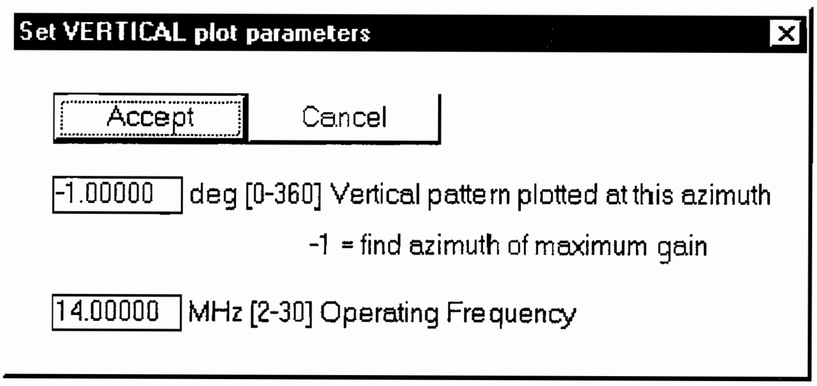


Figure 6.19. Plot Parameters Screen - HFANT

When we press the "Accept" button on the "Set Vertical plot parameters" screen, we see the antenna pattern plot as shown in Figure 6.20. Vertical Radiation Pattern for the Half-Wave Dipole at 0.71 Wavelengths Height Above Poor Ground. The mainbeam is at 19° above the horizon with a gain of 9.7 dBi. This is a reasonable approximation of the mainbeam for a tactical rotatable log-periodic antenna. The higher-order side lobes are not well represented, but the gain at elevation angles from 40° to 90° does show the envelope of the higher-order sidelobes typical of the rotatable log-periodic antenna.

The pattern shown is not as accurate as we would like, but often one only knows the type of antenna being used and nothing about its actual design. Use of the pattern we have constructed should be considered as a first approximation. We have determined that it reasonably represents the pattern of a typical tactical rotatable log-periodic at mid-band frequencies.

Next, we should click on the Exit function on the pattern plot. This will return us to the HFANT data input screen. Since we would like to use this pattern in our VOACAP analysis, we need to save the pattern. The first step is to give the pattern a file name. We will click on the "File" name button. This opens the Antenna file. For our example, I have created a folder titled "Rockwell." I have opened that folder and created a file name of "rlp-test." Next we will click on the "<<Save as.." button. This will save the antenna parameters we have entered into HFANT to approximate the rotatable log-periodic antenna at the following address, which is accessible by VOACAP: Antennas\rockwell\rlp-test. The HFANT data input screen should now look like the one shown in Figure 6.21. Screen Showing the Antenna Pattern "Saved As" Rockwell\rlp-test.

At this point, we can return to VOACAP and our "Point-to-Point Data Input" screen, as shown in Table 6.1. Again, we click on the "Rx Antenna" button. This brings up the screen shown in Figure 6.16. Now, when we click on the "Receive Antenna=" button, we will find our new folder, ROCKWELL, in the Antenna Directory. When we open that folder, we find the "rlp-test" file. We click on it and then click on the accept button. Now the Point-to-Point data input screen should show all of the parameters as they appear in Figure 6.1. Output for Thule to Cedar Rapids for 0200 UT Jan = 130.

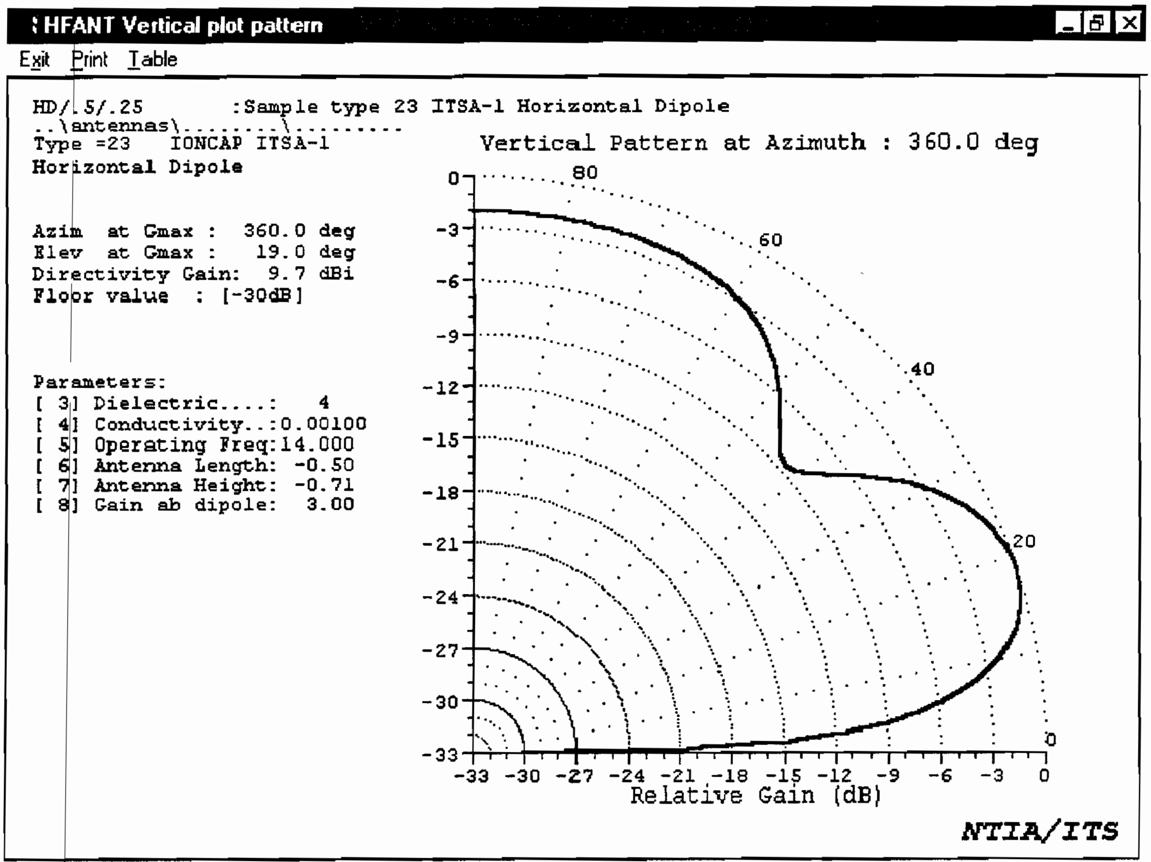


Figure 6.20. Vertical Radiation Pattern for the Half-Wave Dipole at 0.71 Wavelengths Height Above Poor Ground

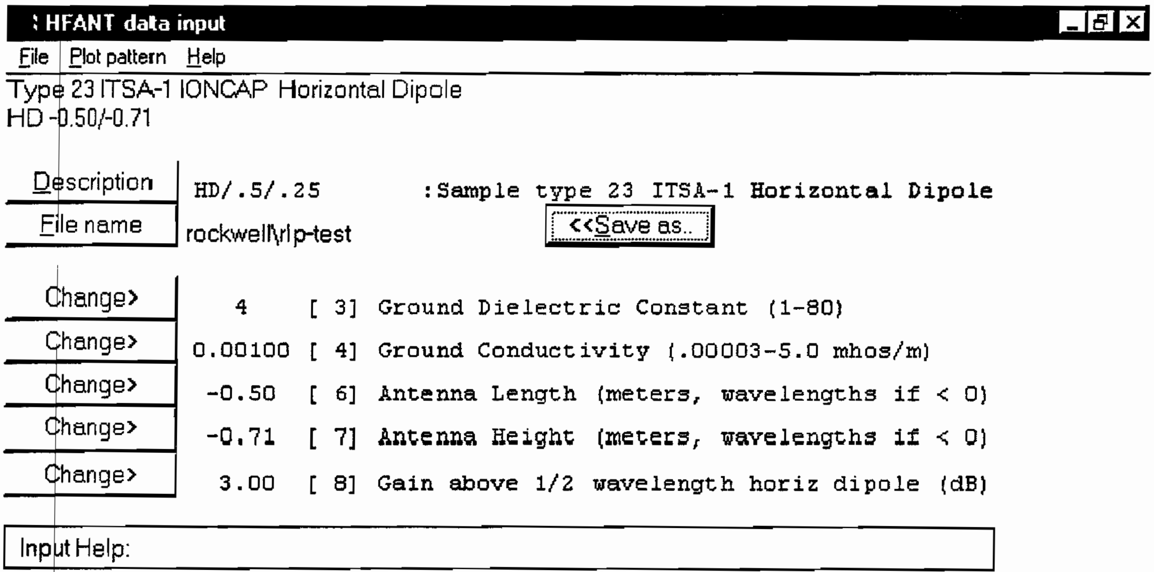


Figure 6.21. Screen Showing the Antenna Pattern “Saved as” Rockwell\rlp-test

6.12 Circuit Analysis

Now that we have entered all of the needed circuit information into VOACAP, we are ready to run the Method-20 circuit analysis. If we refer to Figure 6.1, our input page should now be identical with that shown for the "VOACAP Point-to-point data input." At the top of that screen, we see a function called "Run." If we click on that function, we will find options of Circuit, Graph or Batch. We are only interested in **Circuit** at this point. Since we have more than one circuit-month in our input data stream, we cannot use "Graph." If we do, we will get the heading for the first month/SSN and the graph for the last month/SSN in the loop. **This can be very misleading. Do not run Graph if you have more than one circuit-month.** If we had been saving circuit information into a batch file, we could now call that file and run the entire batch of circuits. This is a useful function if we are running a very large number of circuits.

Once we click on "RUN I Circuit," the program will execute and run our data input stream. We will get 48 pages of output for our example, corresponding to the 12 hours (2 per page) for the months of Jan, Apr, Jul, and Oct for SSN =130, and then a repeat for the year with SSN = 10. The first hour block is for 02 UT in January with a SSN = 130. This data is reproduced in Figure 6.22. VOACAP Method-20 Output for Thule to Cedar Rapids for 0200 UT Jan =130. On the top line, we see the "2.0" which stands for the hour. The first column of data is listed under "16.3" which is the predicted maximum usable frequency (MUF) at that hour. Then, we enter the frequency loop we specified in the input, namely, 4.0 ... 26.0 MHz. The last column contains the labels for each of the rows in the hour block. A brief description of each of the terms is given in Table 6.1. Definition of Terms in the VOACAP Output.

If we go through the 48-page output, several things stand out about this circuit. For the most part the path is controlled by the 2F2 mode (i.e., 2 hops from the F2 layer). Occasionally, the best mode is the high ray of the1F2 mode at a frequency very near the MUF. When we see mode switching such as this, we can expect that this will be a difficult circuit, as it will be very frequency-sensitive. Also, this is a high-latitude path, where we can expect great variation in ionospheric conditions from day-to-day within the month. The full solar cycle shows a dependence on frequencies from 4 MHz to 21 MHz. We will need to look at the hours when 4 to 6 MHz are required as our estimated radiation pattern for the rotatable log-periodic antenna is very optimistic at those frequencies. As we look through the predictions we do not see many hours of reliable voice communications.

However, if we look at the predicted SNR distribution, we gain a better appreciation of the expected performance of this circuit. At each hour for the 4 seasons and extremes of the solar cycle, we select the best frequency. This is defined as the frequency that is predicted to have the highest median and smallest SNR LW for the hour. In other words

2.0	16.3	4.0	6.0	7.0	9.0	11.0	13.0	15.0	17.0	19.0	21.0	26.0	FREQ
	1F2	2F2	2F2	2F2	2F2	2F2	2F2	1F2	1F2	1F2	1F2	1F2	MODE
	4.0	12.4	11.0	10.9	11.5	13.1	18.2	0.8	3.2	3.2	3.2	3.2	TANGLE
	14.5	14.6	14.4	14.4	14.5	14.6	15.3	14.2	14.4	14.4	14.4	14.4	DELAY
	502	320	291	290	301	334	444	372	468	468	468	468	V HITE
	0.50	1.00	1.00	0.99	0.90	0.61	0.32	0.68	0.44	0.27	0.14	0.01	MUFday
	164	138	138	138	139	142	163	179	169	177	187	222	LOSS
	3	9	12	13	13	11	–9	1	–2	–9	–18	–51	DBU
	–128	–101	–102	–103	–105	–108	–129	–145	–135	–143	–153	–188	S DBW
	–169	–149	–153	–155	–158	–162	–165	–168	–170	–172	–173	–176	N DBW
	42	48	51	52	53	54	36	23	35	29	20	–12	SNR
	31	14	11	10	11	20	38	48	39	46	54	87	RPWRG
	0.32	0.48	0.61	0.65	0.66	0.61	0.28	0.00	0.19	0.15	0.08	0.00	REL
	0.00	0.29	0.42	0.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	MPROB
	0.15	0.21	0.27	0.29	0.32	0.27	0.13	0.06	0.12	0.09	0.06	0.01	S PRB
	22.8	10.1	10.9	11.8	14.3	24.5	25.0	21.2	23.9	25.0	25.0	25.0	SIG LW
	16.9	7.2	7.2	7.4	7.9	10.6	25.0	11.2	18.2	23.3	25.0	25.0	SIG UP
	24.6	13.4	13.6	14.3	16.4	25.9	26.5	23.0	25.7	26.7	26.8	26.8	SNR LW
	17.7	10.3	9.8	9.6	9.6	11.6	25.4	12.1	18.9	24.0	25.6	25.6	SNR UP
	–11.9	–1.6	–3.3	–3.4	–3.3	–3.0	–4.2	–18.2	–13.6	–13.6	–13.6	–13.6	TGAIN
	0.9	9.0	8.2	8.2	8.4	8.9	9.7	–14.7	–1.1	–1.1	–1.1	–1.1	RGAIN
	17	34	37	38	37	28	10	0	9	2	–6	–39	SNRxx

Figure 6.22. VOACAP Method-20 Output for Thule to Cedar Rapids
for 0200 UT Jan = 130

we are looking for the tightest distribution with the highest median. Since we specified ***[REQ. REL]*** to be 90% at the input to VOACAP, ***[SNRxx] = [SNR] – [SNR LW]***. These values of SNR and SNRxx have been extracted and are shown for the high and low SSN years in Table 6.2. Thule-to-Cedar Rapids VOACAP Analysis.

We can see that the best hours are from 2000 - 1000 UT during the high-sunspot years and from 2200 - 1200 UT during the low-sunspot years. The lowest SNRxx occurs at 1600 UT (or 10 AM local time) in Cedar Rapids from spring through the summer months. This appears to be due to excessive ionospheric absorption during the mid-day period. We may also expect that there will be extremely poor performance during the low-sunspot years when frequencies as low as 4 MHz are needed during the pre-dawn dip. This is because of possible limitations of the rotatable log-period antenna at frequencies below 6 MHz. It may be necessary to install a secondary antenna for the low-sunspot period which can support frequencies between 4 and 6 MHz.

Table 6.1. Definition of Terms in the VOACAP Output

LABEL	UNITS	DEFINITION
FREQ	MHz	MUF followed by up to 11 user-specified frequencies
MODE	# of hops and layer	Ionospheric path for the most reliable mode
TANGLE	degrees	Takeoff and Arrival angle of the most reliable mode
DELAY	msec	Time delay of the arriving signal via Mode shown
V HITE	km	Virtual height of the most reliable mode
MUFday	factor	Fraction of days in the month for which the Mode MUF is above the operating frequency
LOSS	dB	Transmission loss for the path
DBU	dB>1 μV/m	Field strength as would be detected from a short, lossless vertical antenna for a surface wave
S DBW	dBW	Signal power delivered to the input of the receiver
N DBW	dBW	Noise power in a 1-Hz bandwidth delivered to the receiver from a short, lossless vertical reduced by the actual receive antenna efficiency
SNR	dB/Hz	Signal-to-noise density ratio as measured in a 1-Hz bandwidth
RPWRG	dB	Required power gain: dB needed (+) or excess (–) to achieve 90% circuit reliability
REL	factor	Circuit reliability: fraction of days in the month for which the SNR will equal or exceed the Req. SNR
MPROB	factor	Reliability of a secondary mode which is within the power range and exceeds the delay time specified by the user
S PRB	factor	Service probability, this term was supposed to be a confidence factor for the circuit reliability but was never completed in the basic IONCAP code
SIG LW	dB	Lower decile range for the signal power
SIG UP	dB	Upper decile range for the signal power
SNR LW	dB	Lower decile range for the SNR
SNR UP	dB	Upper decile range for the SNR
TGAIN	dBi	Transmit antenna gain at TANGLE
RGAIN	dBi	Receive antenna gain at TANGLE or RANGLE (for long path)
SNRxx	dB•Hz	SNR at the specified Req. Rel. (xx)

During the high-sunspot year, we can expect to achieve order-wire-quality voice communications on at least half of the days per month at all hours. However, as the sunspot number falls, the number of hours of where the circuit reliability is 50% drops to 4 two-hour blocks or 8 hours. For conventional HF equipment, the reliability is too low for operators to establish contact even at the 50% level. We need to consider ways to maintain the link and then adjust the signaling rate for the current circuit quality. Adaptive frequency technology is very attractive because we can see that the best frequency varies rapidly from hour to hour for this path and that the most reliable mode may switch, also. Frequency diversity can produce about 4 dB of improvement. But this is not enough gain to compensate for the extremely low SNRxx values at most hours.

Next, we should consider systems which establish link contact using a redundant code with a very slow signaling rate. Once a link has been established, the signaling rate can be adjusted to the prevailing link quality. Such systems can link-up at required signal-to-noise density ratios of about 33 dB•Hz. Since such systems use repeats and multiple contact attempts, they provide for time diversity. Generally, such systems should maintain contact at required signal-to-noise ratios in the 30 to 34 dB•Hz range. However, little to no useful communication can be carried over the circuit at such low signal-to-noise ratios.

As we can see in Table 6.2. SNRxx (SNR exceeded on 90% of the days) is close to 24 dB•Hz over the full solar cycle (SSN = 10 and 130). Yet, the median of the SNR distribution over the solar cycle is over 40 dB•Hz at all hours and over 50 dB•Hz for some hours. Let us calculate the fraction of days where we can expect SNR $\geq$ 33 dB•Hz (the condition where link establishment can be maintained). The method for making this calculation was described in Chapter 4, Section 4.5. We will recall that we need to find the number of standard deviations, denoted as "z," that we are away from the median. First, we find the dB difference between the median SNR and 33 dB•Hz. Then, we divide that difference by the lower standard deviation, which is the difference between the median SNR and the low-decile value, SNRxx, as follows:

$$z = \frac{(\text{Ave SNR} - 33)}{(\text{Ave SNR} - \text{SNRxx})/1.28}$$

For the high-SSN year,

z = .64 or 74% (using a Gaussian distribution table)

For the low-SSN year,

z = .55 or 71% (as above)

NOTE: The value of z, expressed is numerical units of standard deviations, can be converted to a percentage of occurrences which will be equaled or exceeded by using a table of probability functions for a Gaussian or Normal distribution, such as the one given in R.S. Burington's Handbook of Mathematical Tables and Formulas (Burington 1955).

Thus, we see that even with sophisticated modern radio equipment, this circuit will experience complete outages for more than several hours on 8 to 9 days per month throughout the lifecycle of the system. The system gain shortfall for this circuit is 33 minus 24 or 9 dB. This is a considerable shortfall, as it amounts to an order of magnitude increase in transmitter power to 40 kW rather than 4 kW. However, if this circuit is just one link in a network where re-routing over other links is possible during the 8 to 9 days per month when this circuit is unavailable, it could provide useful service in the overall network on 21 or more days per month.

This discussion has been centered on signal-to-noise ratio and how to interpret these predictions. There are many other useful output variables as we can see in Table 6.1 that can be used in our overall analysis of system performance. But, that is a subject for another book.

Table 6.2. Thule-to-Cedar Rapids VOACAP Analysis

	Jan 130		APR 130		JUL 130		OCT 130		SSN=130	SSN=130
HOUR	SNR	SNRXX	SNR	SNRXX	SNR	SNRXX	SNR	SNRXX	Ave SNR	Ave SNRxx
2	53	37	47	21	47	21	50	23	49.25	25.50
4	48	30	48	22	48	22	51	25	48.75	24.75
6	49	32	49	23	48	23	51	25	49.25	25.75
8	53	37	50	25	47	21	55	28	51.25	27.75
10	53	33	44	27	44	17	48	29	47.25	26.50
12	49	34	45	19	42	15	47	22	45.75	22.50
14	49	23	42	16	46	19	47	20	46.00	19.50
16	52	25	44	18	43	17	46	19	46.25	19.75
18	53	27	44	17	42	15	47	20	46.50	19.75
20	55	34	49	23	41	15	51	24	49.00	24.00
22	52	36	44	19	44	18	52	26	48.00	24.75
24	53	40	47	22	45	18	51	26	49.00	26.50
SUM	619	388	553	252	537	221	596	287		
AVE	51.58	32.33	46.08	21.00	44.75	18.42	49.67	23.92	48.02	23.92

	JAN 10		APR 10		JUL 10		OCT 10		SSN=10	SSN=10
HOUR	SNR	SNRXX	SNR	SNRXX	SNR	SNRXX	SNR	SNRXX	Ave SNR	Ave SNRxx
2	56	39	44	20	42	22	48	26	47.50	26.75
4	54	36	42	16	42	18	46	24	46.00	23.50
6	47	33	41	22	41	21	46	27	43.75	25.75
8	52	36	45	29	44	32	49	34	47.50	32.75
10	51	39	43	28	41	25	47	35	45.50	31.75
12	56	39	41	24	40	20	45	28	45.50	27.75
14	47	27	40	17	38	11	45	23	42.50	19.50
16	48	26	36	10	39	13	40	18	40.75	16.75
18	48	25	36	10	43	17	42	16	42.25	17.00
20	49	34	26	0	42	15	48	22	41.25	17.75
22	51	37	44	18	44	18	48	29	46.75	25.50
24	54	40	45	20	41	19	48	27	47.00	26.50
SUM	613	411	483	214	497	231	552	309		
AVE	51.08	34.25	40.25	17.83	41.42	19.25	46.00	25.75	44.69	24.27

7. SELECTION OF THE BEST VOACAP METHOD

7.1 What are Methods?

At one time, IONCAP was set up using computer cards. The user needed to insert a Method card at the front of the data deck so that the program would call the proper subroutines and select the correct output format. If we refer to page 138 in the original IONCAP User's Manual (Teters et al. 1983), there are 30 Methods listed. It is important to note that VOACAP **does not** duplicate all of the original IONCAP methods. If we refer to Chapter 6 and Figure 6.2. the VOACAP Methods are shown as they are displayed when we click the "Method" button on the start-up screen for VOACAP. To the best of anyone's knowledge, Methods 1 to 19 are based on the original IONCAP code. No changes were made by the Voice of America to the computer code when these methods were called.

In the development of VOACAP, the interest was focused on **"Complete System Performance."** Great care was taken to insure that the coding and logic are consistent for all of the methods which involve Complete System Performance. In the original IONCAP, this was not the case. These errors in coding and logic were corrected in VOACAP so that there is consistency among methods.

The VOACAP Methods which have been checked, corrected and verified are **13, 14, 15, 20, 21, 22, 23, 25** and **30**. Therefore, only these methods will be discussed within this text. The other methods are provided, as found in IONCAP, for those users who may have an interest in these procedures. However, caution is urged when using the output of the unverified methods. **Values of FOT and LUF are highly suspect. It is recommended that methods that supposedly predict these values NOT BE USED.**

7.2 Methods 13, 14 and 15

Methods 13, 14 and 15 are available so that we may inspect the antenna gains for the antennas specified in the input for VOACAP. The power gain patterns are presented as a matrix, as was shown in Figure 6.15. Gain values in dBi are presented as a function of elevation angle and frequency for the azimuth specified in the antenna input for the Tx Antenna and Rx Antenna. **Method 13 provides the pattern for the transmitter antenna, Method 14 is for the receive antenna and Method 15 provides both patterns.**

The procedure for obtaining the pattern is to enter the method by using the "Method" Button and clicking on Method 13, 14 or 15. We must enter all circuit data before we can compute the pattern with these methods as the program will be computing the "off-azimuth" by taking the difference between the great-circle route azimuth for the path and the azimuth we have entered for the antenna. Once all of the data are entered, we can click on the "Run" function at the top of the input screen and select "Circuit." The program will execute and the pattern will be shown. To print out the full pattern, you will need to use legal size paper and select landscape mode for your printer.

We should always compute the antenna patterns with Method 15 when we are first analyzing a circuit. We want to see that the patterns we have generated appear to be reasonable compared to the actual antennas we are attempting to model. It is easy to input a wrong pattern or a wrong azimuth. A quick check of the pattern will help us to catch this mistake. Also, we should to see that the mainbeams appear to be at appropriate elevation angles for the circuit distance. Further, we should always look at the gains at 0° and 2° to see if too much gain is occurring at these low angles. If the gain values seem too optimistic for the antenna height and ground conditions, we should use a minimum takeoff angle of 3° when we enter the System data.

Once we have checked the pattern, we need to go back to the "Method" button and select the type of Complete System Performance method we desire to use for the circuit analysis. A discussion of the available performance-prediction methods in VOACAP follows.

7.3 Method 20, Automatic; and Method 22, Forced Short-Path Model

Method 20 - Automatic is an original method in IONCAP which is no longer needed in VOACAP unless we are using the batch mode where some paths may be short and others very long. This method will use the Short-Path Model for all circuits less than 10,000 km and the Long-Path Model for any circuit that is 10,000 km or longer. The Short-Path and Long-Path Models were discussed in Chapter 5 and in detail in Sections 5.4 and 5.5, respectively. These models refer to ray-hop versus forward scatter propagation mechanisms. We must not confuse these models with options of "short" and "long" when we input data for the "Path" button. Under "Path" we are referring to the short and long great-circle route distance as discussed in Section 6.6.

Once we have entered circuit data and have selected the "short" or "long" great-circle route distance, VOACAP will show the great-circle distance for the path and the great-circle route azimuth at the transmit location. If the path distance is less than 7,000 km, we can use either Method 20 or **Method 22 - Forced Short-Path Model**. Both methods will give identical outputs as was discussed in Section 6.12. If the path distance is 7,000 km or greater, we should consider using Method 30. But before we discuss the Long-Path Model and smoothing functions, there is one more method which uses the forced Short-Path Model. That is Method 25.

7.4 Method 25, All Modes Table and VOAAREA

The All Modes Table of Method 25 will only function for the Short-Path Model. As we have previously discussed, the signal power distribution is the combination of all of the propagating modes (up to 21 different modes). If we wish to see the individual modes that make up the signal power distribution, we should run Method 25. Also, this is the only method that will show the noise power distribution. For examples of Method 25 output, see Section 3.5.

For the most part, we use Method 25 to troubleshoot a circuit that is not performing as predicted. By running very fine frequency increments, we can use the time delay and frequency predictions from Method 25 to construct the monthly median oblique ionogram for that hour. It is also useful in determining what modes might be causing excessive amounts of multipath interference.

> **Warning:** Method 25 produces a full page of output for each frequency-hour. Therefore, we might not want to include many hours or months in the analysis.

There is another technique we can use to diagnose problems on a particular circuit and this is VOAAREA (refer to Section 8 of this User's Guide). VOAAREA is special version of VOACAP which permits us to map a particular frequency-hour on a selected portion of the earth's surface. This area-coverage program, which is part of the current ITS HF Propagation package of programs, lets us see where the propagation modes begin and end. Also, we can see what is happening off-azimuth from the great-circle route. These features are useful in finding problem areas of failing modes, multipath fading and "hot spots" falling off-azimuth from our circuit. Any of these raise concerns of instability and possible errors in the predictions. When possible, we should operate on a frequency that is stable (i.e., a single mode and near the FOT). However, there are times when we may wish to see if side scatter might fill in a target area when, for some reason, we cannot use the direct great-circle route.

7.5 Method 21, Forced Long-Path; and Method 30, Smoothed Long-Path/Short-Path

VOACAP has 2 different propagation models, namely, a ray-hop model for shorter distances and a ducted or forward-scatter model for the longer distances. When operating the program using the normal method (i.e., Method 20) the ray-hop model is used for all distances less than 10,000 km. For paths of 10,000 km or greater, the Long-Path Model is used. If the program user is interested in paths of nearly 10,000 km, some ambiguity exists as to which model should be used. The models are **NOT** forced to yield similar results at the boundary distance so that discontinuities in predicted performance parameters can occur at distances just under 10,000 km and right at 10,000 km. This is an artifact of the parent program, IONCAP. A smoothing function to eliminate the discontinuity in predicted signal level between the 2 propagation models has been incorporated in VOACAP and can be accessed by using the new Method 30.

Both IONCAP and VOACAP allow the user to force a particular propagation model to be used for paths at any distance. Method 21 forces the use of the Long-Path Model which simulates the ducted or forward-scatter mechanisms that can prevail usually at distances having 3 or more hops. Method 22 forces the use of the conventional ray-hop model. In VOACAP and VOAAREA, the user can request area coverage plots using Methods 20, 21 or 22. Method 20 may produce "cliffs" or strange looking coverage plots at the discontinuity occurring at 10,000 km. Method 21, the Long-Path Method, produces unrealistic coverage plots at the shorter distances where the ray-hops should occur. Significant errors occur in the regions of mode transitions (e.g., between the $1F_2$ and the $2F_2$). Method 22, the Short-Path Method, may produce overly pessimistic performance estimates at the distances beyond the third ionospheric hop.

VOACAP version 95.08 (August 1995) and subsequent versions have the Method 30 which allows the user to obtain smoothed signal power predictions for ranges of 7,000 km or greater.[1] At these distances, both Method 21 (Long-Path Model) and Method 22 (Short-Path Model) are run. Where appropriate, a distance-weighted smoothing function is applied. Method 30 was generated by making changes to subroutine LUFFY taken from VOACAP version 93.04. The long path/short path smoothing function is applied if the path distance is ≥ 7,000 km. The parameter which is smoothed is the predicted signal power which is expected to occur or be exceeded on 90% of the days of the month at that hour. This parameter is obtained from the median signal-power prediction ***[S DBW]*** minus the dB range to the lower decile of the signal power ***[SIG LW]*** for the specified hour. The smoothing algorithm is as follows:

1) Run Method 22.

1) Is the great-circle path distance ≥ 7,000 km? If yes, run Method 21 also.

3) If Method 22 only, continue process using Method 22 and end.

4) If Method 21 and 22 exist, compute lower decile of signal power from median less range in dB to lower decile for both methods.

5) If the lower decile of signal power for Method 22 ≥ the value from Method 21, continue the Method 22 process and end.

6) If the path distance ≥ 10,000 km, continue the Method 21 process and end.

---

[1] IONCAP and ICEPAC do not have the smoothing function. Rec. 533 uses a different smoothing function than VOACAP.

7) If the path distance < 10,000 km, perform the following smoothing function:

$$S_{smooth\ .9} = 10\log\left[(W) \cdot (10^{.1(S_{LP}).9} - 10^{.1(S_{SP}).9}) + 10^{.1(S_{SP}).9}\right]$$

where:

$S_{smooth\ .9}$ = Smoothed signal power in dBW for 90% of the days

W = [(D – 7,000)/3,000], the weighting factor

D = Great-circle route distance in km

SLP .9 = Signal power (dBW) at 90% reliability from Method 21, Long-Path

SSP .9 = Signal power (dBW) at 90% reliability from Method 22, Short-Path.

1) Use the statistics obtained from Method 21 to compute performance factors for the smoothed case (i.e., range ≥ 7,000 but < 10,000 km and Method 21 signal power at 90% reliability is greater than the Method 22 signal power at 90% reliability).

Some points to consider when using Method 30 are discussed below:

The Short-Path Model (Method 22) is the more rigorous solution, using a quasi-ray trace model for multiple ionospheric reflections. It includes all of the ionospheric and earth bounce losses; therefore, Method 22 should represent the worst-case transmission loss for any path length.

The Long-Path Model (Method 21) may predict that higher signal powers are possible via ducted or forward-scatter mechanisms at distances normally associated with 3 or more ionospheric hops (e.g. around 7,000 km). It is assumed that the weighting factor is 0 at 7,000 km and is 1 at 10,000 km. The short path signal power in watts is linearly increased by the weighting factor times the difference in watts of the signal levels from the Long- and Short-Path Methods. This smoothing function is applied in the transition regions from 7,000 to 10,000 km.

Under certain conditions, the Long-Path Model may predict lower signal powers than the Short-Path Model. This is due to a number of reasons, but most are related to the different ionospheric control points used by the models. The Short-Path Model is considered to be more rigorous and its values are used at all distances when the Long-Path Model provides lower signal-power values.

The VOACAP prediction is more accurate at the lower decile of the signal-power distribution than at the median value. This is true because the signal-power distributions are often non-

Gaussian and/or bi-modal. The lower-decile value is based on actual measurements and not on an assumed distribution function. Consequently, the smoothing function is applied to the lower decile of the signal power distribution. The median- and upper-decile values of the signal power are computed using the signal distribution from the method providing for the largest lower-decile value. Also, the most reliable mode information, given in the output, is used from the method providing the higher signal power on at least 90% of the days (i.e., lower-decile value). In the case where Method 21 is controlling, the takeoff and arrival angles at the transmit and receive terminals are given as ***[TANGLE]*** and ***[RANGLE]***. When Method 22 prevails, these angles are the same value.

Other parameters in addition to the signal power are also smoothed. The smoothed signal power is used to compute the median field strength ***[DBU]***, the median signal-to-noise ratio ***[SNR]***, the required power gain ***[RPWRG]***, reliability ***[REL]***, lower- and upper-decile ranges of the SNR (***[SNR LW]*** and ***[SNR UP]***) and the signal-to-noise ratio at the reliability specified by the user ***[SNRxx]***.

7.6 Comparison of Measurements and Predictions

The Voice of America conducted a comparison of Methods 21, 22 and 30 with measured data obtained by professional, shortwave listeners who monitor VOA broadcasts (Richardson 1995). The circuit paths were selected in the range from 7,054 to 9,469 km in length. Of these circuits, 73% are in the 7,000 to 8,500 km range. The data consist of subjective scoring on a 5-point scale system (where 5 is excellent and 1 is nil), as described in Section 5.2. VOA monitors score signal, degradation and overall reception quality. Frequencies are monitored once per half-hour in short-duration auditions (30 seconds typical). The half-hour observations are averaged to derive the hourly observation for that day. The hourly observations for the month are then rank ordered and the lower-decile extracted. A database of 51 circuit hours comprising 608 observations was obtained during April and May, 1995 for use in this comparison.

VOACAP input parameters conform to the VOA Engineering Standard (Lane and Toia 1985) except the actual transmitter carrier power and transmit antenna are used. A transmission line loss of 1.5 dB is assumed. The receive antenna is the "Shortwave Whip" antenna used by VOA to approximate the performance of the antenna attached to a shortwave receiver. This pattern is found at the end of the Default file of the Antenna Directory. The sporadic-E model in VOACAP is not used. Background noise at the receive location is assumed to be a combination of atmospheric and residential man-made noise (i.e., –145 dBW in 1-Hz bandwidth at 3 MHz). ***[REQ. REL]*** is set at 90% so that the output term ***[SNRxx]*** will be for the hourly median signal-to-noise density ratio which is exceeded on 90% of the days of the month. For this comparison, VOACAP Methods 21, 22 and 30 were used. The output variable ***[SNRxx]*** is converted to its equivalent signal-quality value for comparison with actual monitor scores (see Figure 5.1).

The standard 5-point quality and impairment scale for aural assessment of sound broadcasting has been shown in Chapter 5 to equate to an equivalent carrier-to-noise density ratio for DSB-AM broadcasts (Lane et al. 1994). This relationship was obtained using linear regression analysis with a correlation coefficient (r^2) of 95% and is given as follows:

$$S = 0.077\ CNR - 2.04$$

where:

S = Signal quality score (1 through 5)

CNR = Carrier-to-Noise density ratio in dB•Hz

Using the above equation, the lower decile ($S_{.9}$) of the monthly monitor scores for a given circuit-hour is computed from the predicted $CNR_{.9}$. For DSB applications, ***[SNRxx]*** from VOACAP it is the same as the hourly median carrier-to-noise ratio (CNR) which is exceeded on 90% of the days over the month. Values computed to be > 5 are truncated to 5; likewise, values < 1 are truncated to 1.

The premise of the comparison is that the difference between the predicted quality and the observed quality should be 0. The mean difference and the standard deviation of the differences are computed. This gives the bias and variance of the predicted quality to that observed. The lower decile for the monitored broadcast hour is used. The number of observations for the month for these data range from 6 to 18 with 12 as the typical value. All days were used (i.e., disturbed days not excluded). Samples containing severe interference (i.e., degradation of 1 or 2) are excluded.

The results of the difference comparison obtained from the 51 monthly circuit-hours are shown in Table 7.1. Difference Between Observed and Predicted Quality with 90% Confidence Interval. The Signal Quality (S) refers to only the signal strength, whereas the Overall Quality (O) includes the additional factors of interference, noise and propagation (fading) in determining an overall score for a given reception. The observed S and O are 0.1 to 0.2 units better on average than predicted using Method 21 (forward scatter model). For Method 30 (smoothing algorithm), the observed S and O are 0.3 units better. For Method 22 (ray-hop), the observed S and O are 0.4 units better than predicted. The confidence levels at 90% for these differences range from ±1.2 to 1.3 units on the 5-point scale.

One unit on the signal quality score equates to a difference in ***[SNRxx]*** of 13.0 dB. In terms of predicted signal-to-noise ratio, the prediction models in VOACAP agree with mean observation within 1 to 5 dB. The variance is rather large due to the coarseness of the monitor scores (e.g. monitors score in whole number units of signal quality; 1, 2, ... or 5). The measurement data for this comparison indicates fairly good levels of reception for the long paths. This probably explains why the less conservative forward-scatter model in Method 21 gave the best agreement with this data.

Table 7.1. Difference between Observed and Predicted Quality with 90% Confidence Interval (Richardson 1995)

Parameter/ and Method	S, Signal Quality	O, Overall Quality
Lower Decile, M21	0.1± 1.3	0.2 ± 1.2
Lower Decile, M30	0.3± 1.3	0.3 ± 1.2
Lower Decile, M22	0.4 ± 1.3	0.4± 1.2

In all cases, the predicted lower decile of the signal quality was lower than that observed. The ray-hop calculations in Method 22 (short-path) predicted larger variations around the monthly median signal value than were observed. The long-path predictions of Method 21 indicated slightly less path loss at these distances. The results from the smoothing function of Method 30 gave results that fell closer to Method 22 because the majority of the path lengths in this comparison were less than 8,500 km.

The measurement period in this study is for very low sunspot activity. Generally, ionospheric propagation is more stable from one day to the next during this portion of the solar cycle. It is not clear that the same comparison results would be obtained when the sunspot number is higher and geomagnetic conditions are less stable.

In an earlier study at VOA (Lane et al. 1994), a database of 81 monthly circuit-hours involving 1,614 monitor scores was used to compare with VOACAP Method 20 predictions where all paths were less than 10,000 km in length. This comparison showed that the mean difference between predicted and observed Signal score was –0.1 ± 1.5 and for the Overall score was –0.1 ± 1.4. The circuits were taken from Europe, Asia and Africa so that they represented both mid-latitude as well as high latitude. It is interesting to note that this comparison showed that VOACAP was overly optimistic by 0.1 Signal unit or 1.3 dB when using the ray-hop method (i.e., Method 20 for distances less than 10,000 km). The later comparison (Richardson 1995) showed that the VOACAP Short-Path Model under-predicted by 0.4 Signal units or 5.2 dB on paths which were greater than 7,000 km. Between 1994 and 1995, the error in the calculation of the signal-to-noise ratio distribution in IONCAP was found and corrected in VOACAP. As we saw in Chapter 5, Section 5.6, this correction resulted in a reduction of the lower-decile value of the signal-to-noise ratios by 2 to 4 dB. Therefore, if we were to re-run the earlier comparison (Lane et. al., 1994) with the corrected VOACAP, we would find that the predictions would be conservative by 1 to 3 dB, which is very close to the later comparison described in detail above.

A much smaller comparison was made using Method 30 for an 8,976-km path traversing the high latitudes (Lane et al. 1999). This path from Germany to San Bruno, CA, crosses over Greenland. Several hours of broadcasts were monitored during the entire month of October, 1998. For the 2-hour period when the broadcast was aimed at Eastern North America, the mean difference between predicted and observed was –0.3 Signal units. When the broadcast was slewed toward Western North America during the next 2-hour period, the mean difference was approximately 0 (the predicted SNRxx was 51 which was 1 dB below the scoring system in use by the Croatian Information Service). This comparison using Method 30 is very interesting because Method 22 predicted SNR values from 20 to 30 dB lower than Method 21. The smoothing function of Method 30 was almost entirely influenced by the Long-Path Model.

The conclusions which can be drawn from these comparisons are listed below:

VOACAP predictions and coverage maps provide a good estimate of the signal quality level being heard at least 90% of the time. Employing the smoothing algorithm of Method 30 between the "long path" and "short path" signal-power calculations for circuit distances greater than 7,000 km is preferable to using Method 20 or 22 (ray-hop) alone.

At 90% circuit reliability using the Method 21 Long-Path Model for circuits ranging from 7,000 to 10,000 km in length, the difference between the actual and predicted Signal quality amounts to 1 to 2 dB of carrier-to-noise ratio or 0.1 units on the Signal quality scale. The difference using the smoothing algorithm Method 30 is about 4 dB or 0.3 units. The difference using the ray-hop model of Method 22 is 5 dB or 0.4 units on the Signal quality scale. The actual Signal quality is slightly better than what is predicted using any of these methods.

In the case of very high latitude paths, Method 30 should be run as well as Method 22. The difference in location of control points for the Long-Path Model and Short-Path Model may produce great differences (e.g., 20 to 30 dB) in the predicted SNR. Longer paths with multiple modes are more likely to propagate than shorter paths at these high latitudes, which may depend on a single mode of propagation.

8. THE USE AND APPLICATION OF VOAAREA

8.1 Introduction

8.1.1 General

VOAAREA was introduced in Section 7.4 of this User's Guide. VOAAREA is a companion program to VOACAP in the suite of HF prediction programs available from the US Department of Commerce, National Telecommunications Information Administration's Institute for Telecommunication Sciences (NTIA ITS, Boulder, CO) at **http://elbert.its.bldrdoc.gov/hf.html**. This program allows us to use VOACAP to compute the circuit parameters to a grid of points (AREA). Then, for the desired VOACAP output parameter, we can plot the coverage over the set of points using a world mapping routine and a contouring program. A map is only valid for 1 hour in the month at a specified sunspot number and frequency. Originally, the Voice of America developed this program for planning short-wave broadcasts. VOAAREA is well-suited for this purpose and is also applicable to many other HF radio applications such as: broadcast-in-the-blind, radio net operation and ground and air mobile communications, etc. There are a number of areas where the program needs to be expanded to cover the more general HF radio communications rather than just broadcasting. We will discuss these needed improvements as we progress through the use and application of VOAAREA.

8.1.2 Assumptions

VOAAREA assumes that we will have 1 transmit location and many receiver sites. It is also assumed that we have made 1 or more VOACAP point-to-point analyses within the area of interest. Coverage maps may be used to demonstrate typical, worst-case or best-case scenarios. Maps can be used for diagnosing strange or unusual circuits where actual performance is quite different than had been predicted. They are also useful for locating where mode changes and skip zones occur. In military applications we can use coverage maps to see if we can deny signals entering enemy territory.

Other assumptions which have been brought forward by the original broadcast application of VOAAREA are that the receive or remote locations all have identical radiation patterns for that frequency. Also, the required signal-to-noise ratio ***[Req. SNR]*** must be the same for all receive locations. Time must be specified as universal time (UT) so that the coverage is for that specific hour at the 0° longitude.

8.1.3 Example Problem

We will use an example problem which we will model using VOAAREA. It will be more informative if we actually input the data to VOAAREA as we follow the set-up procedures given in Section 8.2, Set-Up Procedures. The example we will explore involves high speed data transmission between San Diego, CA and Cedar Rapids, IA. The particular time of interest is for service at 1800 hours UT in February, 2000. It is assumed that the radios are adaptive and have automatic link establishment (ALE) capability. The specifics of the example problem are listed below:

Transmit Location:	San Diego, CA
Receive Locations:	All of continental USA centered on Cedar Rapids
Transmitter Power:	400 W delivered to the antenna
Transmit Antenna:	Rotatable Log Periodic Array pointed at Cedar Rapids
Receive Antennas:	Vehicular mounted short-whip antennas
Type of Service:	High Speed data with Req. SNR = 65 dB•Hz
Month and SSN:	February with sunspot number of 110
Hour:	1800 hours UT

8.2 Set-Up Procedures

8.2.1 Opening VOAAREA

When we open VOAAREA, we find a screen such as shown in Figure 8.1. Start-Up Page for VOAAREA. It appears to be quite similar to VOACAP but there are numerous and subtle differences which we will discuss. The top bar has the buttons for the "File," "Run," "Save To" and "Help" functions. At this point, we will ignore them as they will be discussed after we have set up the input file.

8.2.2 Layers

The "Layers" button is the first button on the top left side of the input screen for VOAAREA. When we click on the "Layers" button, we obtain the pop-up screen shown in Figure 8.2. Map Overlays and Colors. At this point, we can select the colors for the grid lines, country boundaries and the mainbeam of the transmit antenna. We can also select to have the CIRAF zones plotted. These are of importance to international broadcast services. The procedure for plotting the city names is unclear. If the transmit antenna is non-directional, we will want to specify the azimuth as "–1" when we enter the transmit antenna data. This will produce an "X" at the transmit location and no mainbeam will be plotted on the map. Generally, the default parameters for the plot layers are satisfactory.

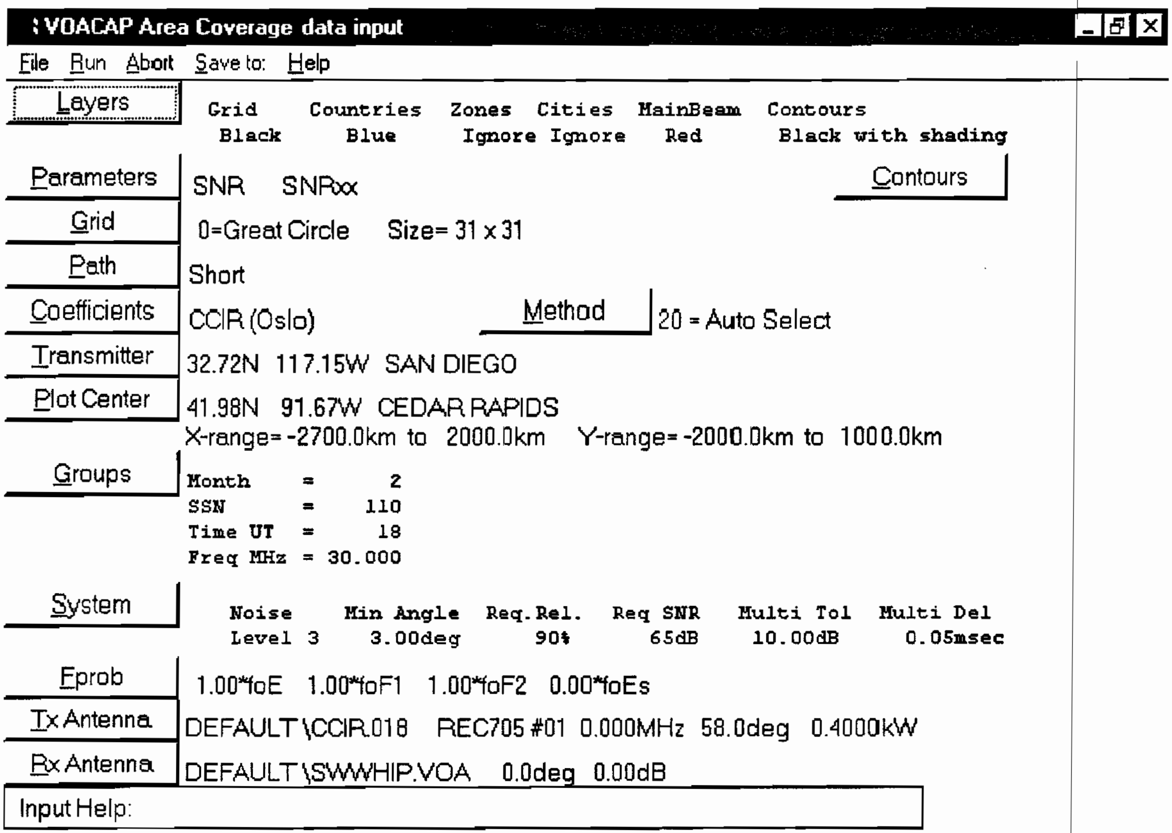


Figure 8.1. Start Up Page for VOAAREA

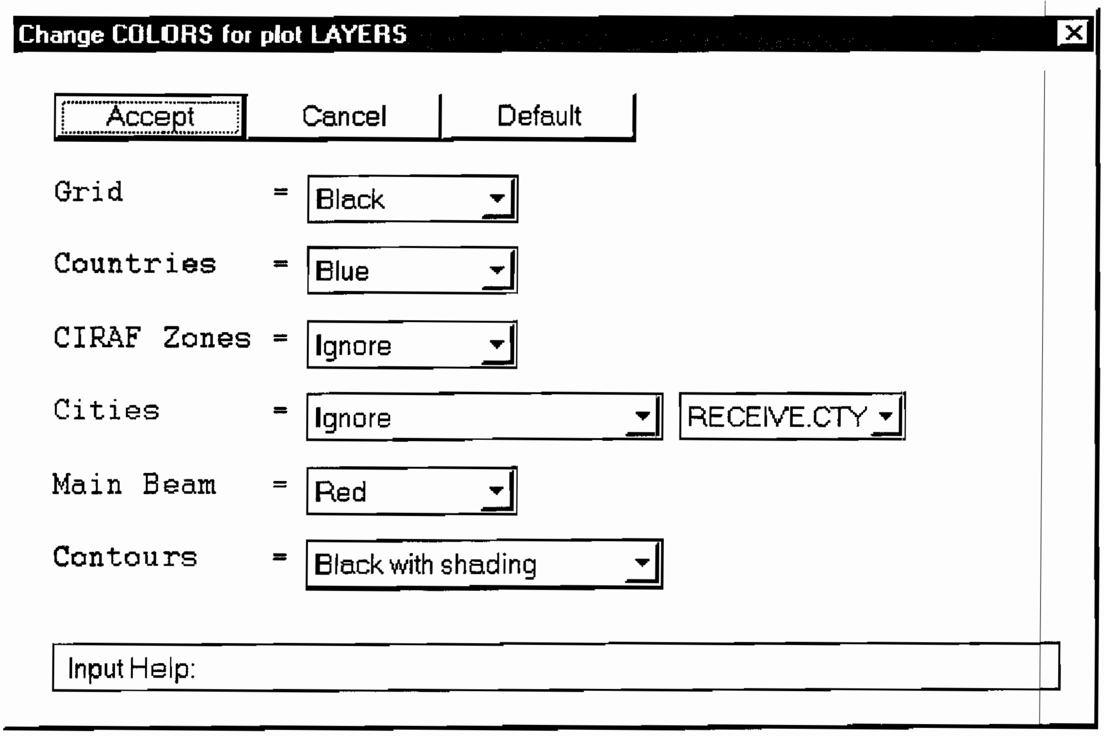


Figure 8.2. Map Overlays and Colors

8.2.3 Parameters

The next input button is the parameters definition. Here, "Parameters" refer to output variables available for plotting from the VOACAP point-to-point prediction. Figure 8.3. VOACAP Prediction Output Parameter, is a partial listing of parameters. One parameter which should never be selected is the **"Service Probability."** This function is meaningless because, at the time VOACAP was written, the correlation functions that were needed to define service probability were not known. Service probability should not be confused with the ITU definition of service probability for broadcast reception. In VOACAP, service probability is an attempt to compute a confidence factor associated with the reliability prediction. There is also a parameter shown as PWRCUT which is an undefined parameter for a particular user of the program. It is recommended that this parameter not be used until the developer publishes the definition of percent power cut.

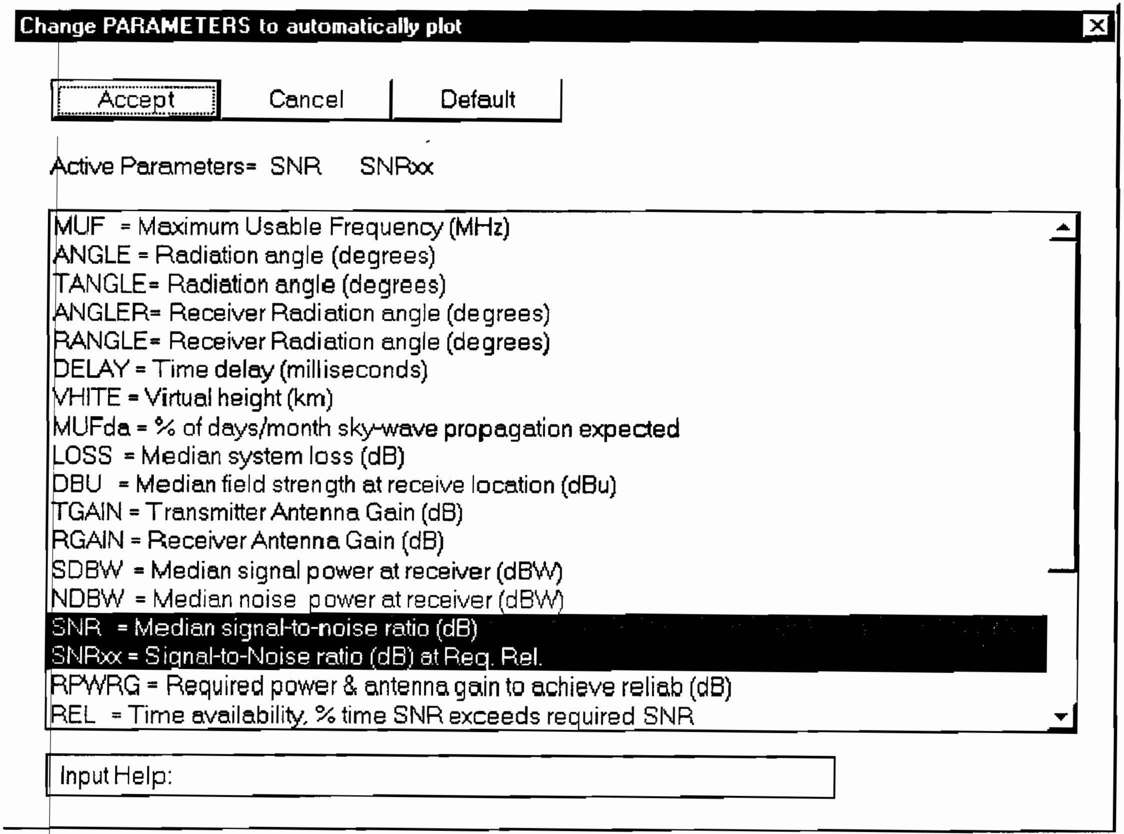


Figure 8.3. VOACAP Prediction Output Parameter to be Plotted

For our example analysis, we will select both **SNR** and **SNRxx**, representing the median signal-to-noise ratio and the lower decile of the signal-to-noise ratio distribution, respectively, where xx = 90%, typically (refer to Chapter 4, Section 4.3). The former represents an estimate of the performance of a frequency-agile, automatic-link-establishment system. The latter is representative of the performance of a fixed-frequency service.

8.2.4 Contours

The "Contours" button is available for users who plan to make many maps for the same parameter. Use of this function allows us to set the contour levels and colors so that they will be consistent for all maps in the series. If we are only going to make a single map, we can wait until after we see the map prepared using the "Auto" or built-in contour setting algorithm and default colors. If we want, we can then use the "User defined" function to select contour levels and colors and re-plot the map. However, if we do this after we have run VOAAREA, the program will return to the "Auto" defined contours.

Because we are interested in making more than 1 map in this example analysis, we should set the "Contours" at this time. This way, we will not have to repeat this function after each map. The initial pop-up screen when we click on the "Contours" button is shown in Figure 8.4. Initial Screen, Contour Levels and Colors. It displays the parameters we have previously selected. In our example, we had selected SNR and SNRxx. The initial values shown for the contours and colors are the default values. We now click on the SNR button and obtain a second pop-up screen which looks like the one shown in Figure 8.5. Selected Parameter Fields.

> **NOTE:** It is essential that we click on the "Values assigned are:" button and select the "USER defined" function. If we do not do this, the contour levels and colors will revert to the "Auto" selection.

Since we are attempting to model a high-speed data system which needs approximately 65 dB•Hz signal-to-noise ratio for minimally satisfactory service, we will want to see contours both greater and lower than this value. For this example, we will assume that SNR values greater than 80 dB•Hz serve as our upper limit for contours; and we will add contours at –10 dB increments. Values below 40 dB•Hz are of little interest since high-speed data transfer is not normally possible at such a low SNR. There are 14 different colors as well as white to choose from. The selected colors for this example are shown in Figure 8.5. Using this scheme, regions which are the color red will provide highly reliable service, yellow will be for minimally satisfactory service, green will be for marginal service requiring multiple repeats, grey will be for regions where link establishment can be maintained but little to no traffic will be passed and white will be regions where no contact is predicted.

When we have completed the entries of contour levels and color selection, we must click on the "Accept" button. We then repeat the same process for the SNRxx parameter. When we have set the values for both parameters, we should see the pop-up screen exactly as shown in Figure 8.4.

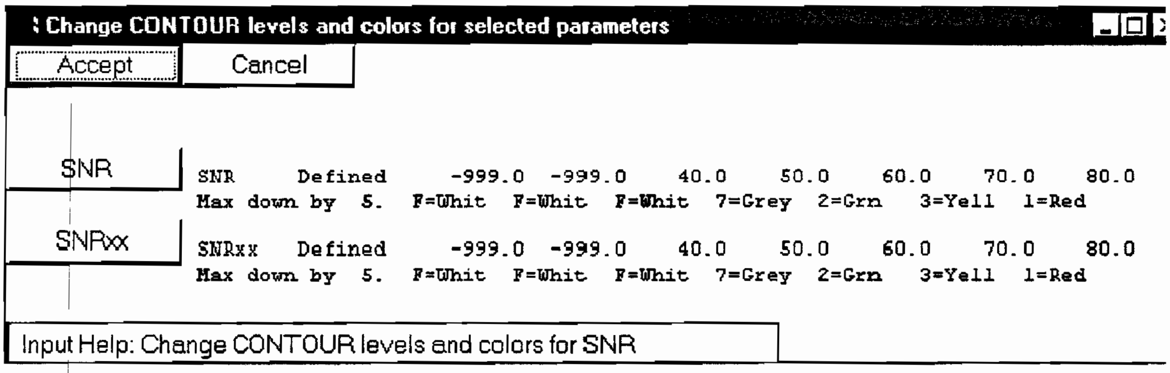


Figure 8.4. Initial Screen for the Definition of Contour Levels and Colors to be Used for the Selected Parameters

8.2.5 Grid

The next function we must set is the number of Grid points and the type of map we wish to display using the "Grid" button. The pop-up screen for selecting the grid type and the grid size is shown in Figure 8.6. Point-to-Point Mapping Circuits Selection. The default values are generally acceptable for what we will want. The map projection will be a great-circle segment of the earth and the number of grid points will be 31 x 31 for a total of 961 points. VOACAP will be used to compute the circuit parameters from San Diego to each of these 961 points. More points may be desired if the map covers a very large portion of the earth and fewer points are needed to map small areas. Other map projections are for a rectangular plot of latitude and longitude and quadrants of the earth's surface.

8.2.6 Coefficients

Our choices for the ionospheric coefficients are the CCIR (Oslo) or URSI 1988. The recommended coefficients for use with VOAAREA are the CCIR (Oslo) coefficients. (For a discussion of the ionospheric coefficients, see Chapter 6, Section 6.2.)

8.2.7 Method

The methods in VOAAREA are the same as in VOACAP, but there are only 4 to choose from. The pop-up screen for the "Method" button and the 4 possible methods are shown in Figure 8.7. VOACAP Methods Permitted in VOAAREA. For maps having circuits of less than 7,000 km, we should use Method 20. If it turns out that the distance from the transmitter to 1 or more of the grid points is greater than 10,000 km, then the method will automatically switch to the Long-Path Model. For maps with circuits greater than 7,000 km, we should use Method 30. (For a discussion of these methods, see Chapter 7.)

For our example, we are looking for coverage in the continental United States. Therefore, we can use the faster-running Method 20.

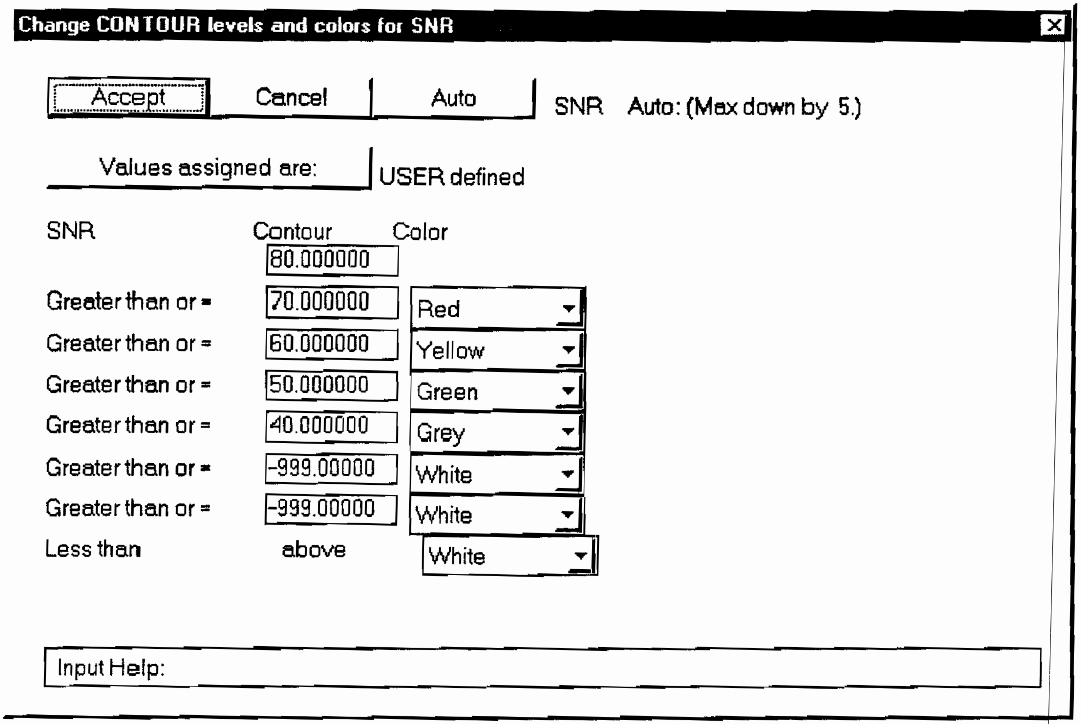


Figure 8.5. Screen for the Selected Parameter with Fields for the User to Define the Contour Level and the Color to be Plotted

8.2.8 Transmitter

For our example, the transmitter is located in San Diego, CA. (For a discussion of how to set the transmitter location, see Chapter 6, Section 6.5.)

8.2.9 Plot Center

The "Plot Center" button allows us to determine the center of the map and the area of the earth's surface to be mapped. The pop-up screen for entering this map-specific data is shown in Figure 8.8. Centering and Determining Map Area. There are no definitive rules for setting up a map. We must decide what looks the best to us and we do this normally by trial and error.

For our example, we have a transmitter on the west coast broadcasting toward the east with the intention of covering much of the central USA. Therefore, we can start our map by setting the plot center to the receive location of interest, namely Cedar Rapids, IA. We can obtain the needed coordinates for Cedar Rapids by using the "by City" button as described in Chapter 6, Section 6.5. Since the map is now centered on Cedar Rapids, we need to set the distances to the edges of the map. The X-range allows us to set the left and right edges and the Y-range allows us to set the north and south edges. The map we have chosen for our example is for the left edge to be 2,700 km to the west of Cedar Rapids and the right edge at 2,000 km to the east of Cedar Rapids. Likewise, we have set the south edge to be 2,000 km south of Cedar Rapids and the north edge 1,000 km to the north of Cedar Rapids.

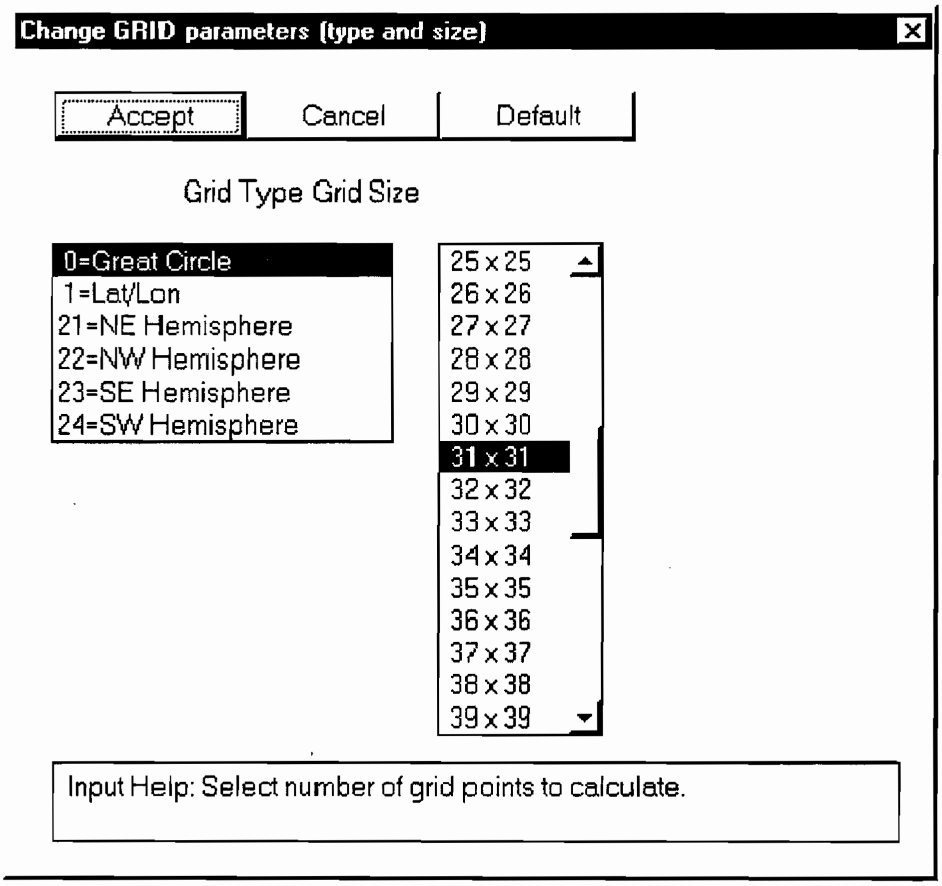


Figure 8.6. Select the Number of Point-to-Point Circuits to Use for Mapping

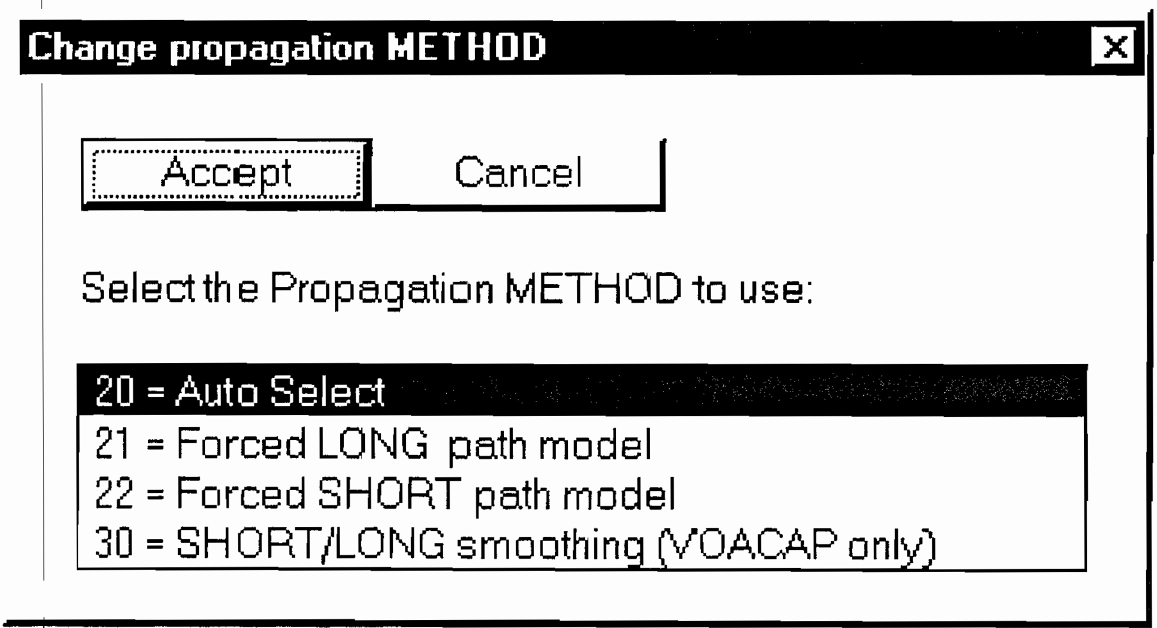


Figure 8.7. VOACAP Methods that are Permitted for Use in VOAAREA

At this point, we should look at the map to see that it actually covers the area we wish to show. This can be done easily by accepting the data as shown in Figure 8.8. This returns us to the initial screen as shown in Figure 8.1. We now click on the "Run" function at the top of the screen. The first option we see on the drop-down screen is "map only." Select this and the program will plot the map we have specified on the screen. We see that we have most of continental USA shown on the map. Cedar Rapids is shown by the "spoked wheel" symbol. If we wish to change the border colors, we can return to the "Layers" button or, if we wish to resize the map, we can return to the "Plot Center" function. When we have the map we are satisfied with, we can then continue setting up the communications parameters for the VOACAP computations.

8.2.10 Groups

The "Groups" button allows us to set the months, sunspot numbers, times and frequencies we wish to map. Each set of these parameters will produce a separate coverage map. The set-up screen for the "Groups" function is shown in Figure 8.9. Set of Parameters to be Mapped. For our example, we are interested in February, 2000 with a sunspot number of 110, 1800 hours UT and a frequency of 30 MHz. We have selected 30 MHz based on a VOACAP point-to-point analysis which showed 30 MHz as providing the highest SNR at that hour in Cedar Rapids.

8.2.11 System

The "System" button is the same as the "System" button we have used in setting up VOACAP. (For a discussion of the System parameters, see Chapter 6, Section 6.8.)

8.2.12 Fprob

The "Fprob" button is the same as the "Fprob" button we have used in setting up VOACAP. (For a discussion of the Fprob parameters, see Chapter 6, Section 6.9.)

8.2.13 TxAntenna

The program allows us to specify a single transmit antenna in a manner similar to that in VOACAP. The pop-up screen for the transmit antenna is shown in Figure 8.10. Transmit Antenna Selection Screen. In our example, we wish to evaluate the coverage by a tactical rotatable log periodic array (RLPA). We have selected a single dipole element with a curtain reflector to represent the pattern of a typical RLPA[1]. This particular antenna is found in the

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[1] The approximation of the RLPA pattern used in this example is not the same as used in Chapter 6, Section 6.11. There are many different ways to approximate radiation patterns using HFANT and the user should explore various possibilities until satisfied with the resultant pattern.

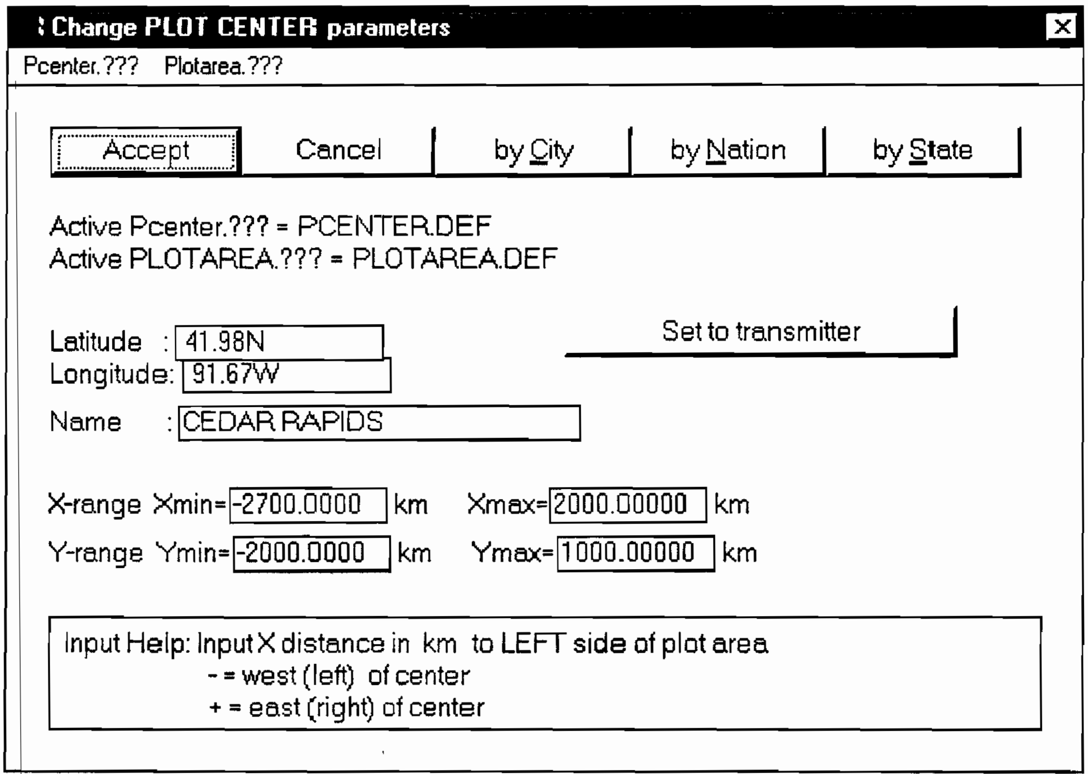


Figure 8.8. Information Needed to Center the Map and to Determine Area Included in the Map

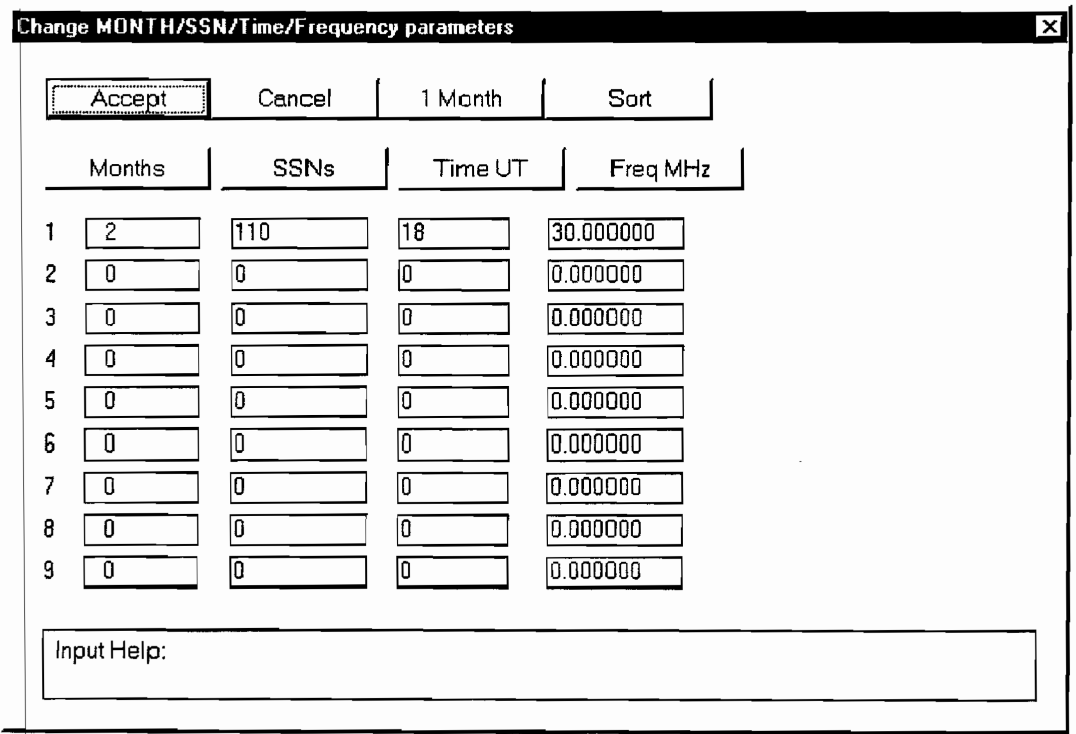


Figure 8.9. Set of Months, Sunspot Numbers, Hours and Frequencies to be Mapped with Each Set Being on a Separate Map

Antennas\DEFAULT folder as CCIR.018. In order to see the design parameters of the CCIR.018 antenna, we need to run HFANT. Here, we click on the "File" button and select "Open." This opens Antennas where we can click on the DEFAULT folder and then click on CCIR.018. This produces the screen shown in Figure 8.11. HFANT Input Screen for CCIR.018 Antenna. If we wish to see the radiation pattern, we need to click on "Plot pattern" and select "Vertical." A typical radiation pattern at 10 MHz is shown in Figure 8.12. HFANT Radiation Pattern for Default CCIR.018 Dipole with Curtain. Once we are satisfied with the radiation pattern, we return to VOAAREA and enter the desired antenna pattern file using the Transmitter Antenna button as shown in Figure 8.10. We also need to enter a mainbeam bearing for the transmit antenna. For our example, we wish to have the pattern directed toward Cedar Rapids. We need to refer to our VOACAP point-to-point analysis to find the great-circle route azimuth. We also need to enter the power delivered to the transmit antenna at this time. Note in this example we are assuming that the transmitter power is adjusted to provide 400 watts or **0.400 kW** at the input to the transmit antenna (see Section 8.1.3, Example Problem). This completes our specification of the transmit antenna.

> **Note:** If a mainbeam bearing of **"–1"** is entered rather than a bearing in degrees from north, then it is assumed that the transmit pattern is non-directional and no great-circle line will be displayed on the map.

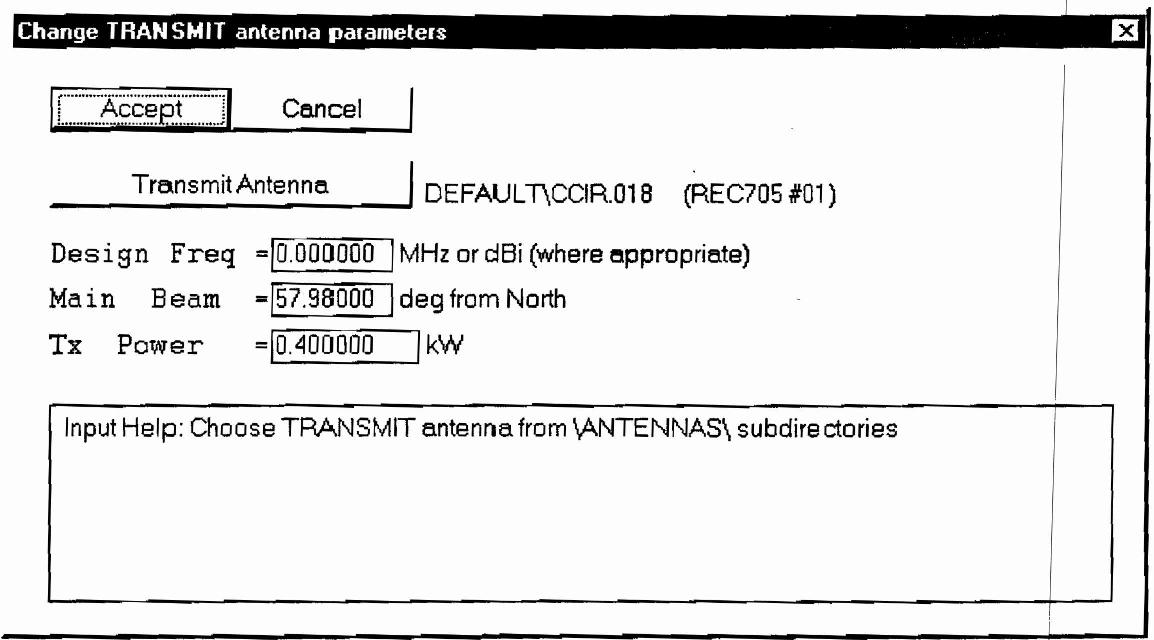


Figure 8.10. Transmit Antenna Selection Screen

HFANT data input

File Plot pattern Help

Type 01 ITU-R Rec705 Multiband Aperiodic Reflector Array
HR 1/1/0.25

Description	HR 1/1/.3
File name	DEFAULT\CCIR.018 <<Save as..

Change>	4	[3]	Ground Dielectric Constant (1-80)
Change>	0.01000	[4]	Ground Conductivity (.00003-5.0 mhos/m)
Change>	1	[6]	# Elements in same ROW (1-9)
Change>	1	[7]	# Elements in same STACK (1-9)
Change>	0.25	[9]	Height above ground (0.10-9.99)
Change>	0	[10]	Slew Angle (+/-30 degrees)
Change>	0.25	[11]	Reflector Distance (0.15-0.35 wavelengths)
Change>	0.83	[12]	Reflector Wire Spacing (0.10-9.99 meters)
Change>	4	[13]	Reflector Wire Diameter (1-9 millimeters)

	Frequency Ratio (Operating/Design)			
	.7	1.0	1.4	
Maximum Antenna Gain	12.31	11.99	11.69	2 MHz Operating
Directivity Calc. (dB)	11.81	11.06	10.40	30 MHz Frequency

Input Help:

Figure 8.11. HFANT Input Screen for CCIR.018 Antenna in the Default Folder

HFANT Vertical plot pattern

Exit Print Table

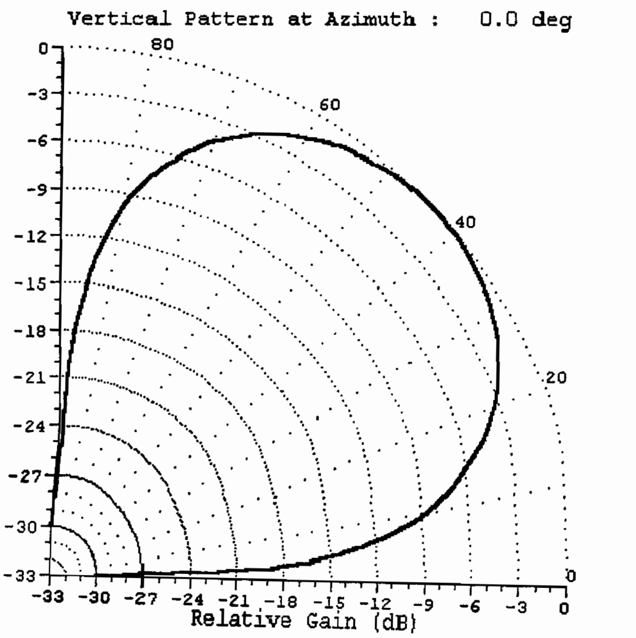
```
HR 1/1/.3
..\antennas\DEFAULT\CCIR.018
Type = 1    ITU-R Rec705
MULTIBAND APER.REF. ARRAY
Reflector : Aperiodic Screen

Azim  at Gmax :    0.0 deg
Elev  at Gmax :   43.0 deg
Directivity Gain: 11.7 dBi
Floor value  : [-30dB]

Parameters:
[ 3] Dielectric....:    4
[ 4] Conductivity..:0.01000
[ 5] Operating Freq:10.000
[ 6] # Row   Elems.:    1
[ 7] # Stack Elems.:    1
[ 8] Design    Freq:10.000
[ 9] Ht. abv Ground:  0.25
[10] Slew Angle....:    0
[11] Reflector Dist:  0.25
[12] Ref Wire space:  0.83
[13] Ref Wire diam.:    4
```

MAXIMUM GAIN TABLE (dBi)

	Frequency Ratio		
	.7	1.0	1.4
2MHz	12.3	12.0	11.7
30MHz	11.8	11.1	10.4



NTIA/ITS

Figure 8.12. HFANT Radiation Pattern for Default CCIR.018 Dipole with Curtain

8.2.14 RxAntenna

The input screen for the receive antenna is displayed, as shown in Figure 8.13. Input Screen for the Receive Antenna, when we click on the “RxAntenna” button. Here we find a serious limitation in the existing version of VOAAREA. We can only specify a single receive antenna and a fixed azimuth. In our example, we can accept this limitation as we will be using a non-directional pattern for a short whip antenna (Antennas\DEFAULT\SWWHIP.VOA). If we wish to model a horizontal, half-wave dipole antenna, then the pattern we specify on the input screen will be the pattern used at every grid point in the coverage map. (It would be advantageous if VOAAREA could be modified such that we could enter a “–1” for the bearing. This would then force the program to compute the pattern at each grid point with the mainbeam pointed toward the transmit location.)

Once we have entered the file location (Antennas\DEFAULT\SWWHIP.VOA) for the receive antenna pattern, we have completed the set-up procedure and can now proceed to plotting coverage maps.

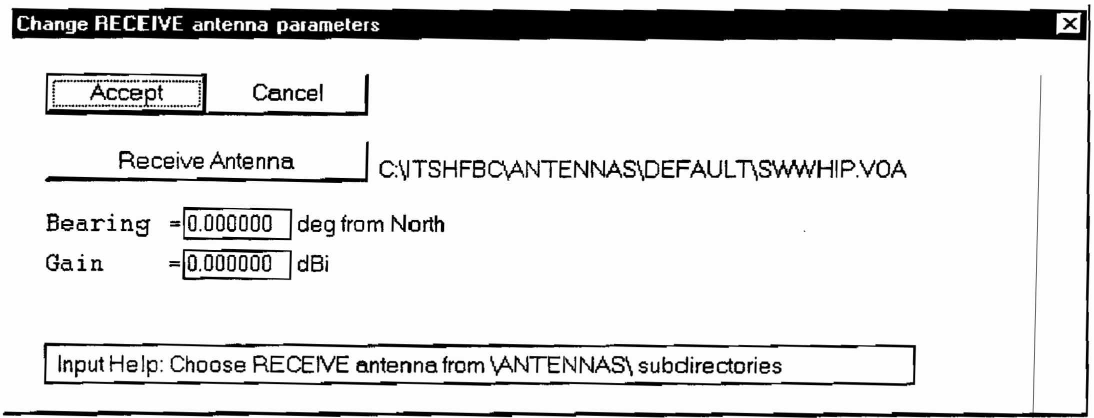


Figure 8.13. Input Screen for the Receive Antenna

8.3 Plotting Maps

8.3.1 Run

To plot a map, we must use the “Run” function button on the top line of the VOACAP Area Coverage data input screen, as shown in Figure 8.1. The “Run” function provides us with a number of options, of which we will only use a few routinely. The full matrix of “Run” functions is shown in Table 8.1. We have already discussed the “Map Only” option. This produces the map outline we specified in the Plot Center data field, less any coverage parameters. Since we have now completed all data fields for producing a coverage map, we will select the “Calculate” operation. Again, we obtain a number of options which are shown in Table 8.1. Generally, we will only use 2 of these options, namely, “Save/Calculate” or “Save{Temp.VOA}/Calculate.” We can refer to the “Help” function to review the purpose of the other options. If we are planning to make only 1 map, or this is the first map in a series, we may only wish to see what the map looks like without saving it, use "Save{Temp.VOA}/Calculate." I recommend doing this on the first map because it often takes several iterations before you are satisfied with the contour colors and the appearance of the map. When we have the map set up to our satisfaction, we can use the "Save/Calculate" option so that we can save the map for later use.

Table 8.1. Run Functions Matrix for VOAAREA

RUN I	Map Only	
	Calculate I	Save/Calculate
	Combine	Save/Calculate/Screen
	Plot Results	Save/Calculate/Print
	Set up Printer	Save{Temp.VOA}/Calculate
		Calculate
		Calculate/Screen
		Calculate/Print
		Batch

8.3.2 Save{Temp.VOA}/Calculate

Let us assume this is our first map so we choose the "Save{Temp.VOA}/Calculate" option. The output data will be saved in the Temp.VOA file. This file will be overwritten every time we reuse this option. At this point, we will see that the program is executing and a count of the number of grid lines which are completed is given. For our example, there are 31 grid rows to be computed. When the calculation is complete and the data has been stored in the Temp.VOA file, the program will return to the initial data-input screen. We can now perform the plot function by selecting "Run I Plot Results." This will bring up the VOACAP Plot Area Coverage Data Input screen. We then perform "File I Open Temp.VG1." This opens the temporary file we just stored in the AREADATA directory. The AREADATA screen is shown in Figure 8.14. VOAAREA Data File. Before we can plot the map, we must select 1 of the 2 parameters we stored from the VOACAP output. To do this, we select the "Parameters" button which brings up the screen shown in Figure 8.15. Pop-Up Screen for Parameter Selection. At this time, we wish to see the median SNR plotted on the map, so we want to select *the data line having the title: SNR = Median signal-to-noise ratio (dB) −135.70 68.50.* To do this, we place the cursor on the SNRxx line and left click with the mouse. This will leave only the SNR line highlighted in blue. We then click on the "Accept" button at the top of the screen. This returns us to the AREADATA screen shown in Figure 8.14 with the exception that now only the SNR is shown to immediate right of the "Parameters" button.

Now we can plot the map by "Plot to I Window." We should see a map that looks like the one shown in Figure 8.16. Median SNR Coverage, 30 MHz. We see a fairly narrow band of coverage over Cedar Rapids at 30 MHz. This plot is representative of our best estimate of the SNR that can be attained over the days of February SSN = 110 at 1800 hours UT if the system can adapt to the best frequency near the daily maximum observed frequency for the 1F2 mode on the circuit between San Diego and Cedar Rapids. This can be done using automatic link evaluation techniques or with sounders. The width of the lay down is dictated by the relatively broad beam width of the transmit dipole array at San Diego. We can see that the coverage is better to the south than to the north of Cedar Rapids. This is a result of the MUF being lower on circuits to the higher latitudes. We see no 2F2 coverage very far to the east of Cedar Rapids. This is primarily due to the fact that the eastern USA is entering into early afternoon on a winter day and the circuit MUF for the 2F2 mode is lower than 30 MHz. If our intent is to communicate only with Cedar Rapids, then operating near the 1F2 MUF is our best choice as it will restrict the spill-over region where we could be intercepted and will diminish the chances that we will experience interference or intentional jamming.

8.3.3 Save/Calculate

Assuming that we like the map as presented in Figure 8.16. we want to save this file for future use. To do this, we close the map and then close the Plot Set-Up screen which returns us to the original set-up screen as shown in Figure 8.1. At this point, we execute the following operation "Run I Calculate I Save/Calculate." This opens the Area Data Input directory. I have created a folder in that Directory titled "Rockwell." We open that folder and then create a name for this file using up to 7 characters. I used the file name: Rockwell\sd-cr30 which stands for San Diego - Cedar Rapids at 30 MHz. Click on the "Save" button and the program will confirm the name you have chosen. After we accept the file name, the program computes the output data and stores it under our new file name.

8.3.4 Plot Results

Now we want to look at the coverage using a conventional HF radio system where the operating frequency at 1800 hours UT is always 30 MHz. We do this by selecting "Run I Plot Results." We have now returned to the AREADATA screen shown in Figure 8.15. We again click on the "Parameters" button and highlight the SNRxx data line and "Accept" that data. We now experience a defect in the current version of VOAAREA. Rather than retaining our defined contour levels and colors we specified at the initial Area Coverage data input screen, the program reverts to the Auto Defined contours. In order to regain our original map colors and contour levels, we must click on the "Contours" button. This will bring up a screen where we can specify "User Defined" and re-enter the data we had originally used during the initial set up. Once we have redefined the contours, we can plot the SNRxx map, as shown in Figure 8.17. SNR_{90} Coverage.

Plot results for:..\AREADATA\DEFAULT\TEMP.VG1

File Plot to Help

```
File name :      DEFAULT\TEMP.VG1
Model/Ver :      VOACAP Version 98.0821W
Grid size :      31x31   Type :  0=Great Circle

Title        SAN DIEGO [HR 1/1/.3 ] 400W 58deg 18ut 30.000MHz Feb 110ssn

Layers       Grid    Countries   Zones   Cities   MainBeam   Contours
              Black    Blue       Ignore BLACK     Red        Black with shading

Parameters   SNR    SNRxx

Contours     SNR      Defined      -999.0  -999.0    40.0    50.0    60.0    70.0    80.0
             -135.7/   68.5     F=Whit  F=Whit  F=Whit  7=Grey  2=Grn   3=Yell  1=Red
             SNRxx    Defined      -999.0  -999.0    40.0    50.0    60.0    70.0    80.0
             -162.5/   50.9     F=Whit  F=Whit  F=Whit  7=Grey  2=Grn   3=Yell  1=Red

Input Help: Change TITLE of plot
```

Figure 8.14. VOAAREA Data File for Making a Coverage Map

The coverage shown in Figure 8.17 is very different than that shown in Figure 8.16. We must remember that SNRxx is the signal-to-noise ratio which will be exceeded on 90% of the days per month at that hour and frequency. It can be expected that on at least half of the days per month the maximum usable frequency on a daily basis at 1800 hours UT will be < 30 MHz. If we use an operating frequency of 30 MHz on those days, we can expect that the SNR will be very low because of MUF failure. Consequently, we find that the SNR we can expect on 90% or more of the days is only 40 - 50 dB•Hz, which is very marginal for voice communications. Conversely, the adaptive system, which would find the best frequency on each day at 1800 hours, was predicted to produce 60 - 70 dB•Hz at Cedar Rapids. At that SNR level, we can maintain a good quality of high-speed data transmission.

Change PARAMETERS to plot

Accept | Cancel | Default

Active Parameters= SNR SNRxx

Name	Description	Minimum	Maximum
MUF	= Maximum Usable Frequency (MHz)	11.10	37.81
ANGLE	= Radiation angle (degrees)	5.45	84.52
DELAY	= Time delay (milliseconds)	0.84	16.93
VHITE	= Virtual height (km)	125.30	637.60
MUFda	= % of days/month sky-wave propagation expected	0.00	97.60
LOSS	= Median system loss (dB)	142.30	343.90
DBU	= Median field strength at receive location (dBu)	-181.20	24.10
TGAIN	= Transmitter Antenna Gain (dB)	-18.94	11.02
RGAIN	= Receiver Antenna Gain (dB)	-15.01	0.00
SDBW	= Median signal power at receiver (dBW)	-317.90	-113.70
NDBW	= Median noise power at receiver (dBW)	-182.20	-182.20
SNR	= Median signal-to-noise ratio (dB)	-135.70	68.50
SNRxx	= Signal-to-Noise ratio (dB) at Req. Rel.	-162.50	50.90
RPWRG	= Required power & antenna gain to achieve reliab (dB)	14.10	227.50
REL	= Time availability, % time SNR exceeds required SNR	0.00	58.20
MPROB	= Probability additional mode in multipath tolerances	0.10	50.00
SPROB	= Service probability, required reliabilty will be met	0.00	24.60
DL	= Lower decile NOISE power (dB)	5.70	5.70

Input Help:

Figure 8.15. Pop-Up Screen for Selecting the Desired Parameter for Plotting.

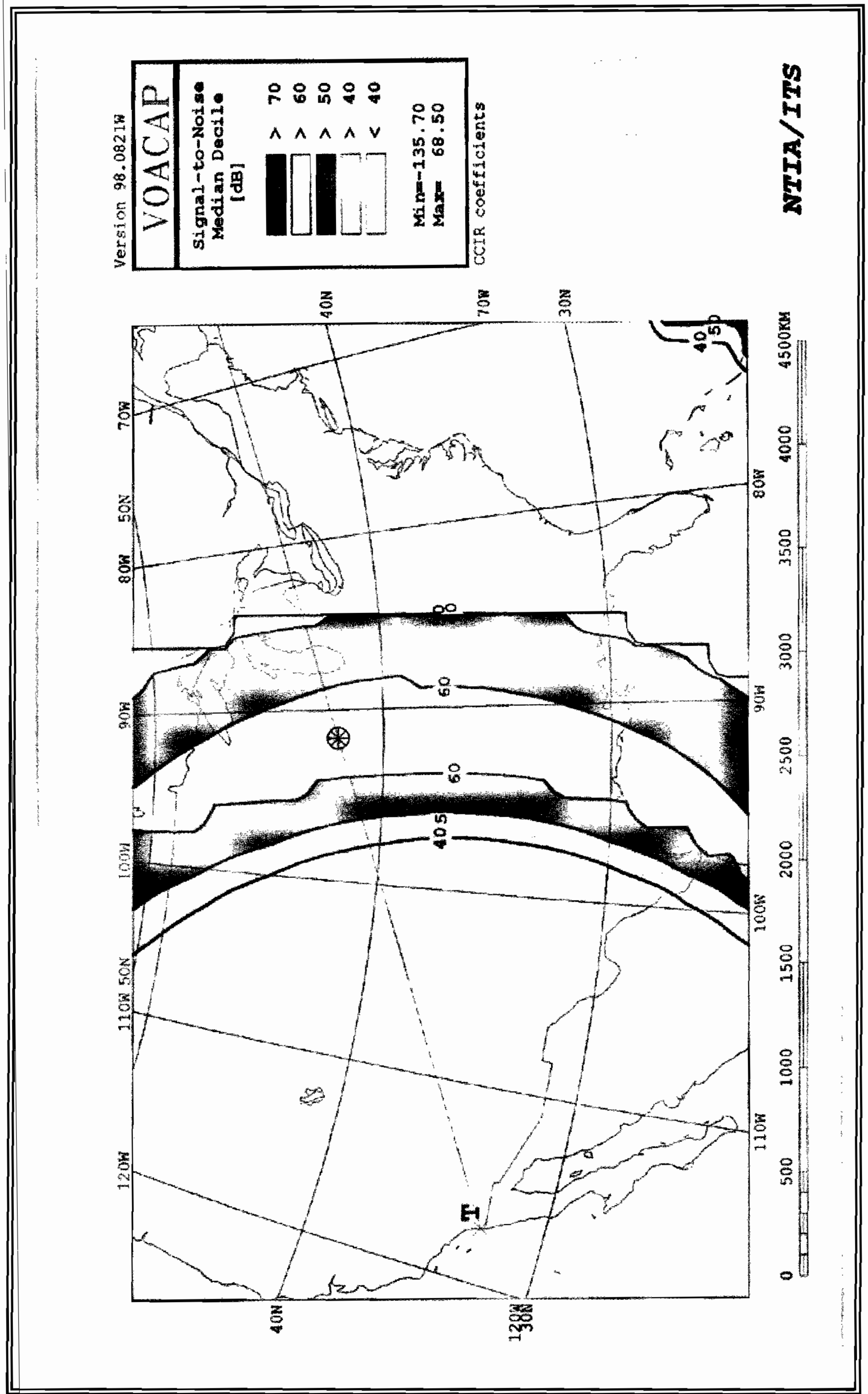


Figure 8.16. Median SNR Coverage from San Diego [RLPA 12 dBi] 400 W 58∞
18 UT 30 MHz Feb 110 SSN

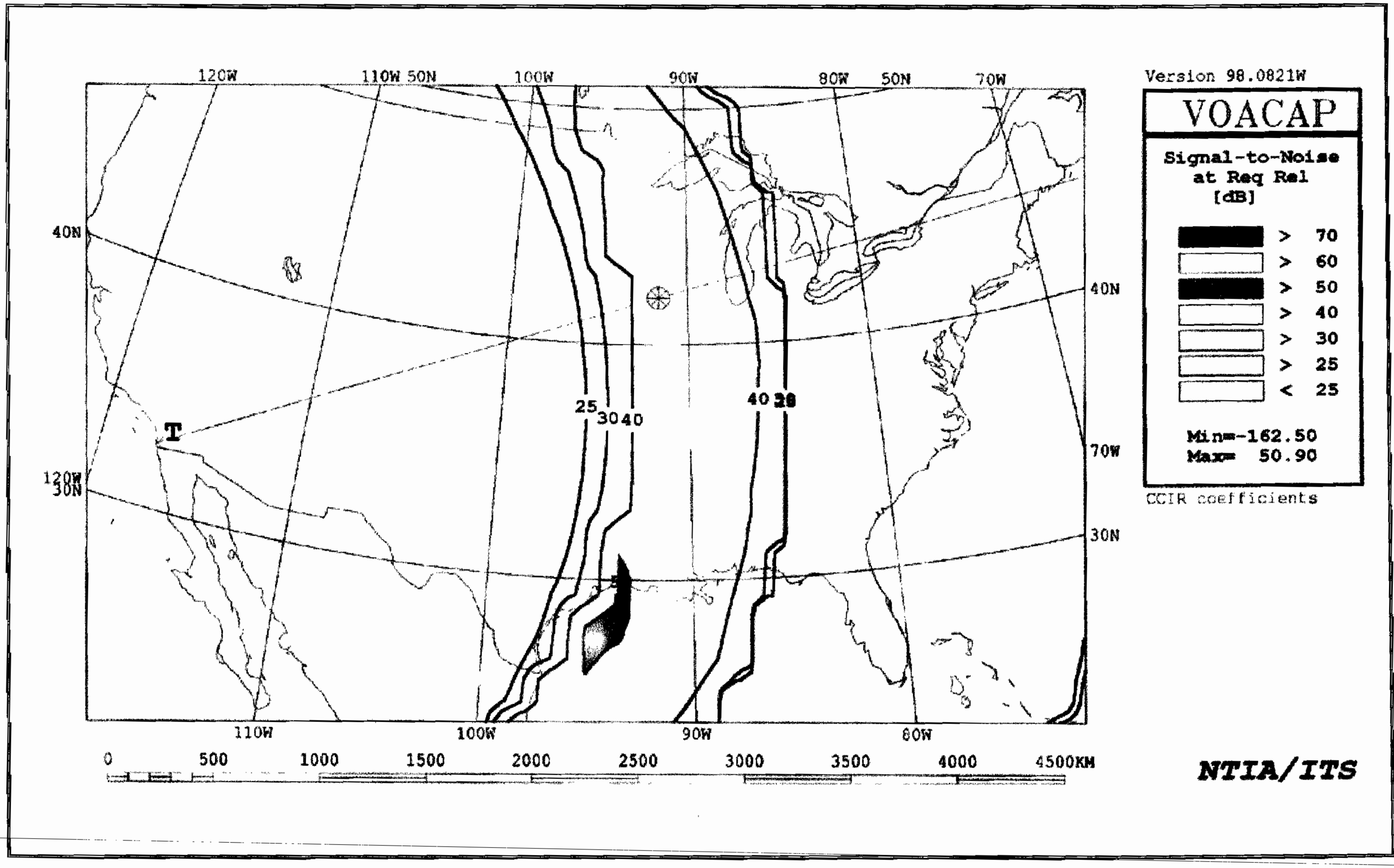


Figure 8.17. SNR$_{90}$ Coverage from San Diego [RLPA 12 dBi] 400 W 58°
18 UT 30 MHz Feb 110 SSN

8.3.5 MUF Map

If, in our example, we had wished to cover more than just Cedar Rapids, we would want to see what the frequency requirements are for coverage of the entire continental USA. We can easily do this by plotting the MUFs for each circuit from San Diego to all 31x31 grid points. We need to return to the input screen by closing all of the open windows. Then we perform the following operation: "RUN I Plot Results." This opens our data file as shown in Figure 8.14. We then click on "Parameters," which opens the screen shown in Figure 8.15. We need to deselect the SNR and SNRxx data lines and then click on the top entry which is "MUF = Maximum Usable Frequency (MHz) 11.10 - 37.81." We now accept the MUF data. Now we want to define the contours by clicking on the "Contours" button. We chose to specify contours starting at greater than 28 MHz and ending with 8 MHz and we used the colors of the rainbow. Once we accept the contours for "User Defined," we can see the MUF map by clicking on the "Plot to" button. The MUF map is shown in Figure 8.18. Circuit MUFs Relative to Transmission. As we can see, most of the USA can be covered if we can operate on frequencies between 12 and 30 MHz. In order to see how well our radio system works over the USA, we need to run SNR coverage maps at frequencies within this range.

The easiest way to obtain these maps is to return to the data input screen shown at Figure 8.1. We select the "Groups" button and change the frequency and then perform "RUN I Save/Calculate." We need to name each file and save it. When we want to make a map, we open the file, select the SNR parameter and then use the "Plot to" button. Coverage maps for 15, 19, 22 and 26 MHz are shown in Figures 8.19. Median SNR Coverage, 15 MHz through 8.22, Median SNR Coverage, 26 MHz. These maps show the coverage via the 1F2 mode starting close in to San Diego at 15 MHz and working out to the mid-west by 26 MHz. We see 2F2 coverage beginning at 19 MHz over Cedar Rapids and extending out across eastern USA. At 22 MHz, Cedar Rapids is at the outer reaches of the 1F2 mode and relatively strong coverage over central USA via the 2F2 mode. Coverage at 26 MHz pushes the 1F2 coverage out further as well as brings the 2F2 coverage out to the East Coast. Note the large skip region between the 1F2 and 2F2 modes at 26 MHz. Also at 26 MHz, we see some broken areas of coverage at 70 dB•Hz or higher (red). This is the result of some 1F1 coverage at this local noon-time transmission.

8.3.6 Combine Maps

The coverage maps of SNR show that a frequency adaptive (i.e., automatic link establishment) radio system will cover most of the USA if we can operate over frequencies from 12 to 30 MHz. VOAAREA will allow us to concatenate maps by using the "RUN I Combine" operation shown in Table 8.1. This operation opens the screen shown in Figure 8.23. Screen for Combining Coverage Maps.

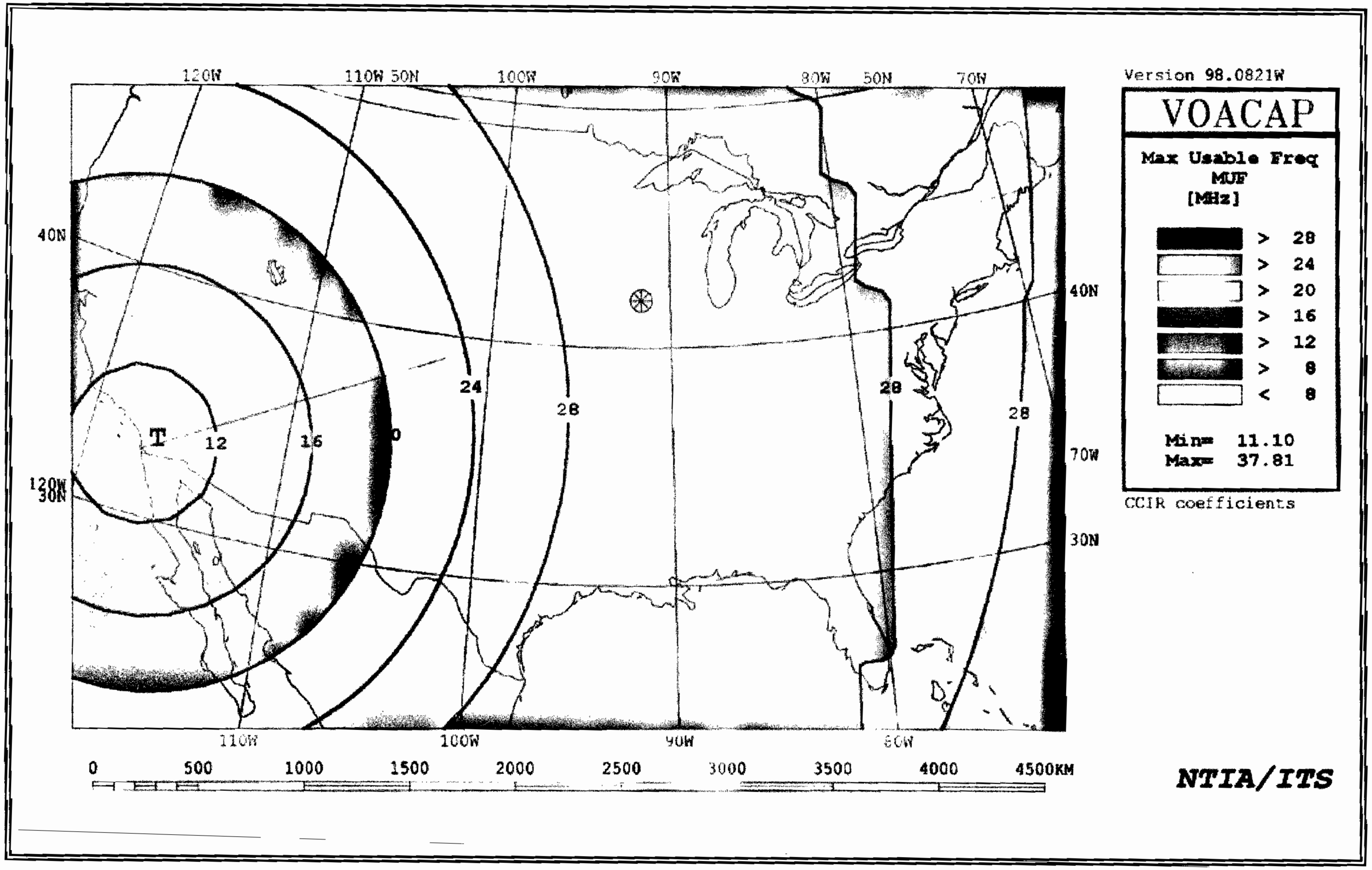


Figure 8.18. Circuit MUFs Relative to Transmission from San Diego 18 UT Feb 110 SSN

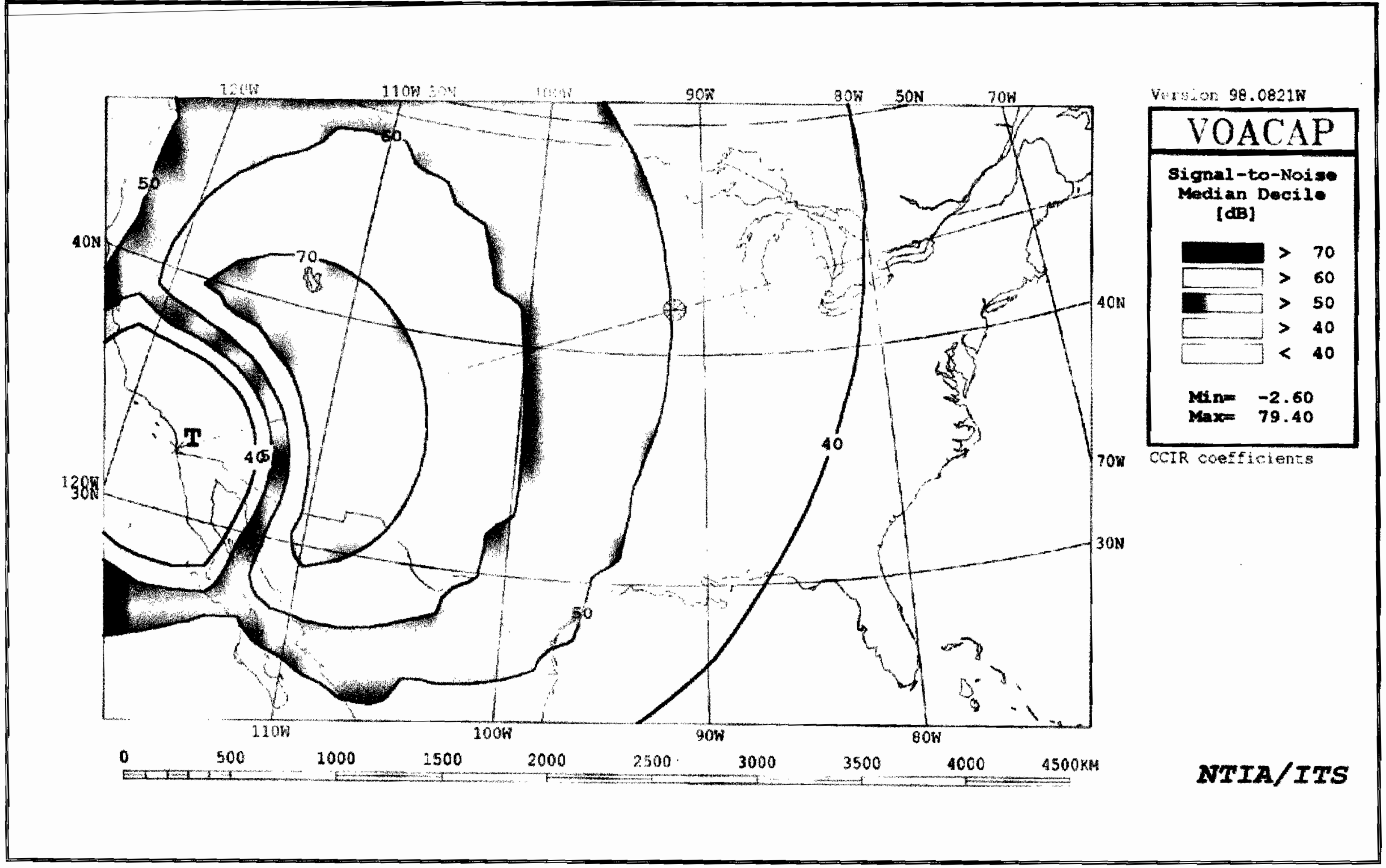


Figure 8.19. Median SNR Coverage from San Diego [RLPA 12 dBi] 400 W 58°
18 UT 15 MHz Feb 110 SSN

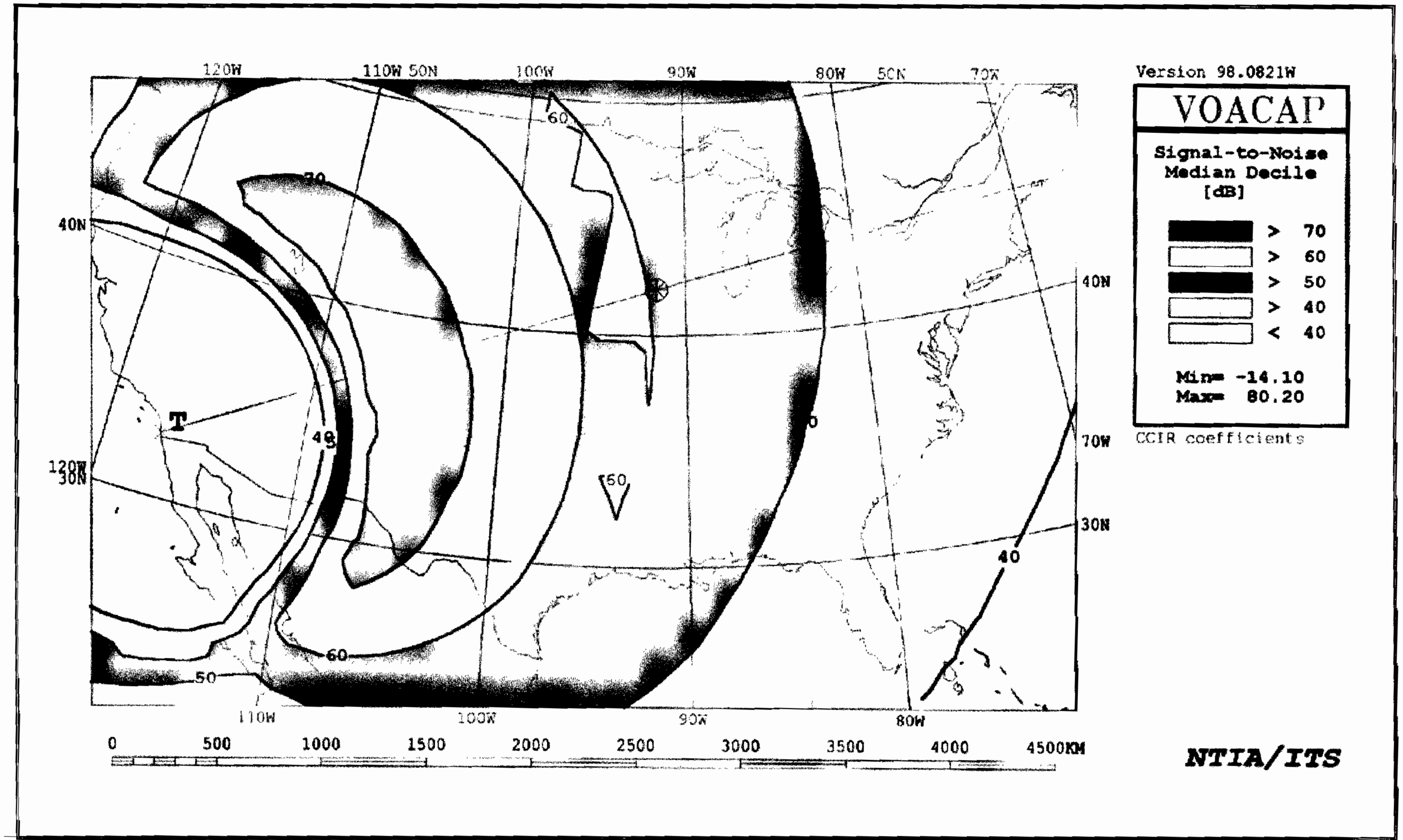


Figure 8.20. Median SNR Coverage from San Diego [RLPA 12 dBi] 400 W 58°
18 UT 19 MHz Feb 110 SSN

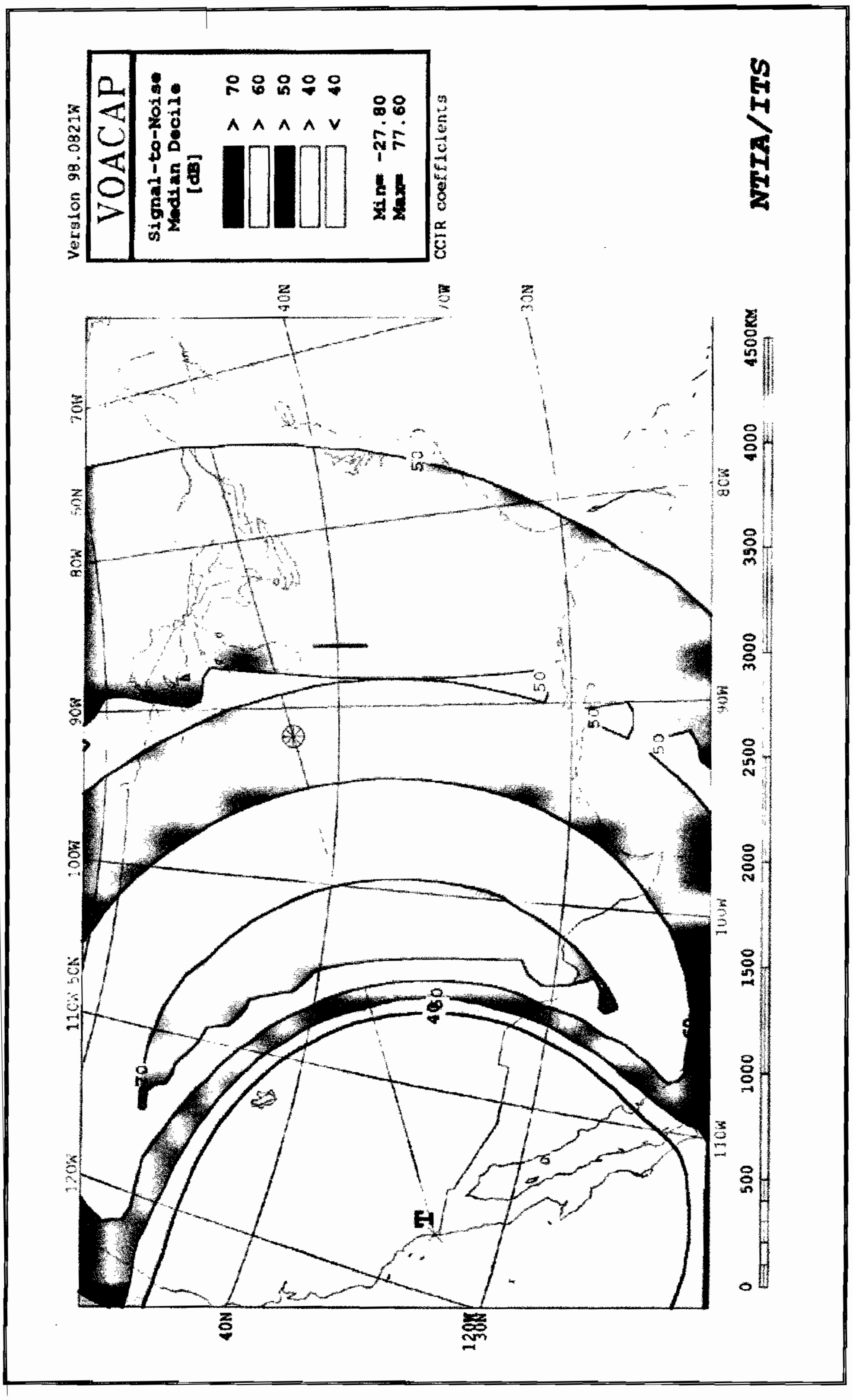


Figure 8.21. Median SNR Coverage from San Diego [RLPA 12 dBi] 400 W 58°
18 UT 22 MHz Feb 110 SSN

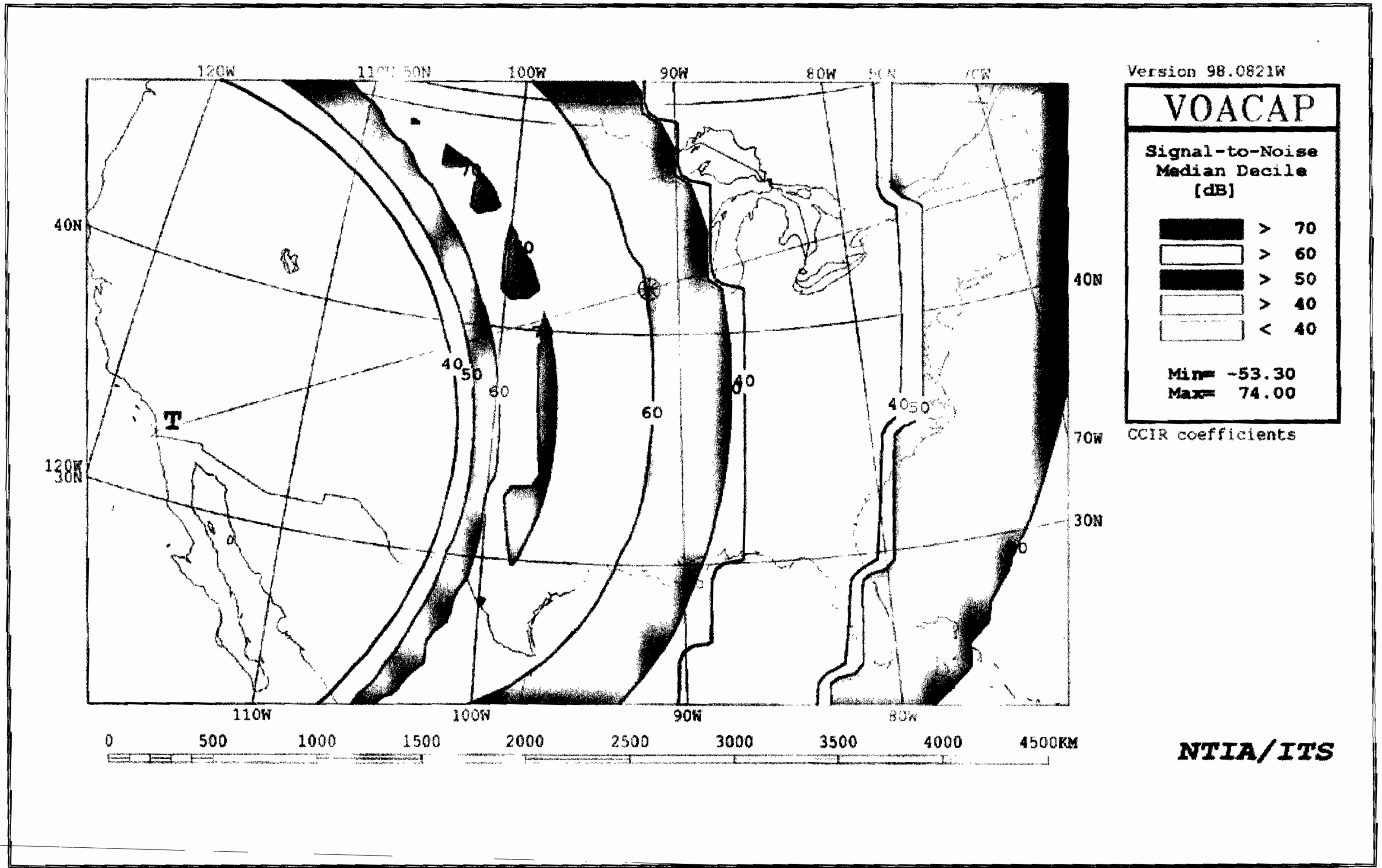


Figure 8.22. Median SNR Coverage from San Diego [RLPA 12 dBi] 400 W 58°
18 UT 26 MHz Feb 110 SSN

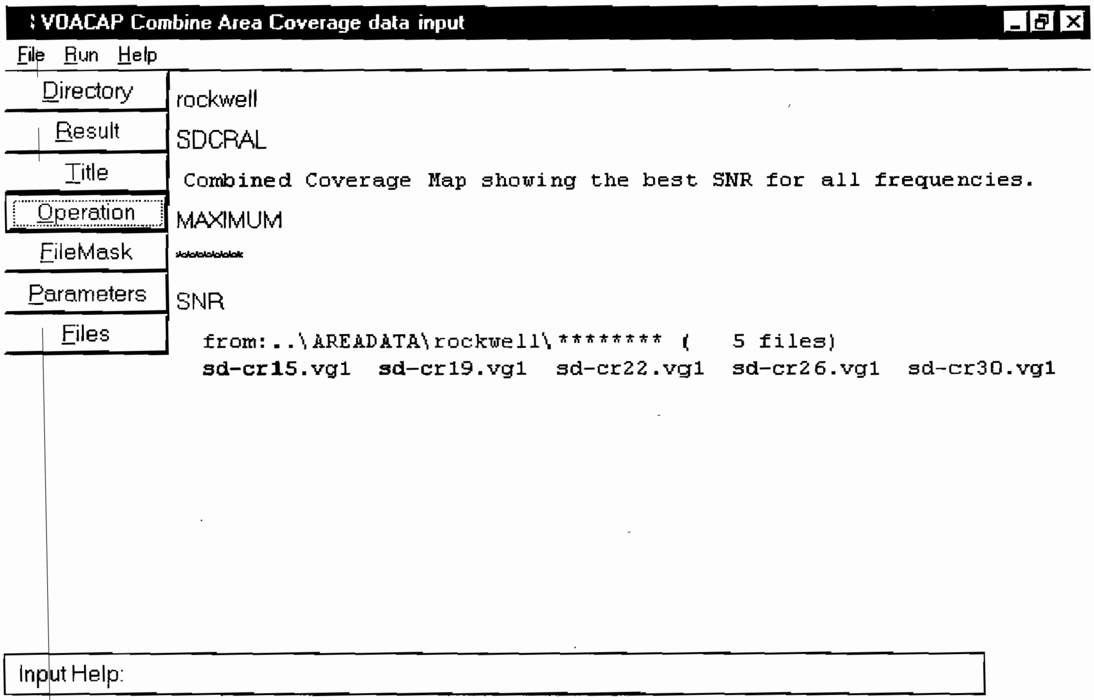


Figure 8.23. Screen for Combining Coverage Maps

We start from the bottom of the screen and work up. First, we select "Files," which opens the data directory. We need to open the Rockwell folder and select the data files for each of our maps at 15, 19, 22, 26 and 30 MHz by depressing the "Control" button, moving the cursor over each file and left clicking with the mouse. When all 5 files are highlighted in blue, we click on "Save." Now we will see our 5 files listed next to the "Files" button.

We next select "Parameters," highlight SNR and then click on the "Accept" button.

Now we need to decide on the "Operation" we wish to perform in the concatenation process. Our options are shown when we click on the "Operation" button, which results in the screen shown in figure 8.24. Listing of Available Combine Operations. Since we wish to see the best SNR at each location over the USA assuming that each receive station can be accessed on 1 of at least 5 frequencies between 15 and 30 MHz, we should select "Maximum," as shown in Figure 8.24. At each of the 31 x 31 grid points, VOAAREA will select the maximum SNR from the 5 different frequency files we identified.

Next, we can enter a title for our combined map. At this point, we are ready to "Run" the combine operation. We perform the following function: "Run I Save/Combine." We will wish to open our Rockwell folder and name the combine file. In this case, I used Rockwell\SDCRAL. When we have saved and accepted the file name, the combine operation executes. When the program is finished, we are returned to the Combine screen and we should now see every entry as it is shown in Figure 8.23.

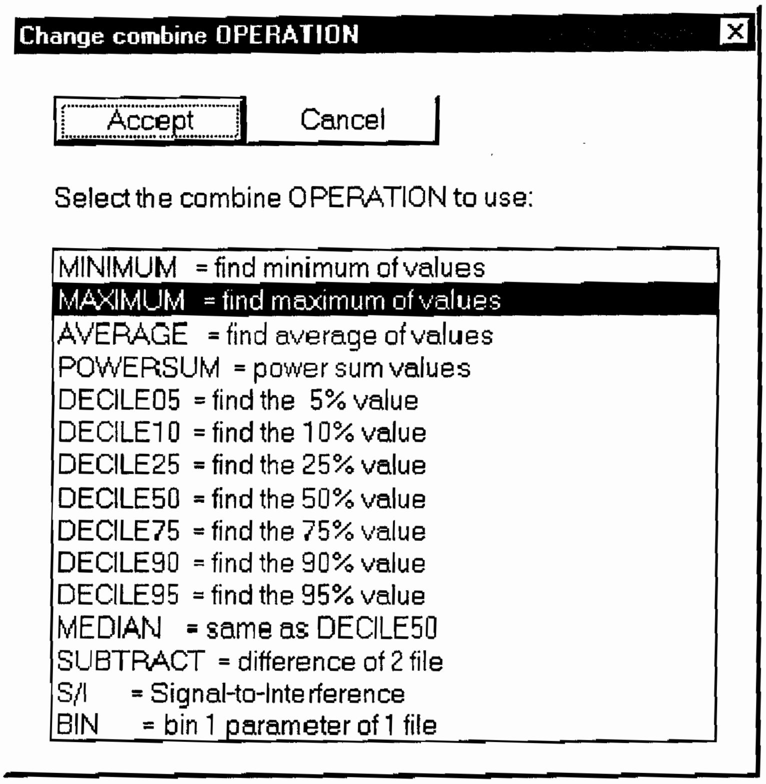


Figure 8.24. Listing of Available Combine Operations

To plot the map, we execute "Run I Plot Results." This allows us to select our new file SDCRAL. The file data is shown on the plot data screen we have seen before. All we need to do is select the "Plot to" button and "Window." The resultant map should appear as shown in Figure 8.25. Highest Median SNR Coverage from Combined Maps at Five Frequencies.

From this combined map, we can see that data transmission from San Diego using 400 W into an RPLA will provide excellent service to remote units operating with whip antennas in the western half of the USA and secondary coverage (slower transmission rate) to the entire eastern USA. There is a pronounced skip zone around San Diego. In order to fill in that region, we will have to change our antennas so that we have high angle of fire at frequencies as low as 11 MHz.

8.4 Other Applications

There are many applications for VOAAREA other than the ones discussed in this chapter. For relatively small areas, we can assume that reciprocity exists on the circuits such that we can model the system as though the outstations are transmitters and the receive location is fixed. We might want to make that assumption if the remote stations have lower transmitter power than the base station. In order to make that assumption, it is necessary for the atmospheric noise to be relatively consistent over the entire area of the radio net. In our example problem we cannot assume reciprocity for atmospheric noise since the radio noise level in Maine, for example, is not the same as in San Diego. Hopefully, someone will upgrade VOAAREA so that we can model many transmitters to one receiver.

If we want to see the controlling radio noise level over an area, we can make a map of noise power. At this time, we can only see the median radio noise expressed in dBW in a 1-Hz noise power bandwidth. We can adjust the assumed level of man-made noise and see if that changes the combined noise level over the area of interest. If it does not, then we can assume that atmospheric radio noise is controlling.

Another useful feature of VOAAREA is that it enables the user to develop the antenna and frequency requirements for area coverage. First, we plot a MUF map for each of the hours of interest and the 4 seasons at the high and low sunspot number. This gives us our frequency requirements over the area for a full solar cycle. Then, we construct maps of required power gain ***[RPWRG]*** and takeoff angle ***[TANGLE]*** for the proposed transmitter power, using an isotropic radiator for transmit with **minimum angle** set to **3°**. The ***[RPWRG]*** map provides the gain needed by the transmit antenna to meet our required signal-to-noise ratio ***[Req. SNR]***. The takeoff angle map tells us the angle at which the gain is needed. If we have set the "Plot Center" of our maps at the transmit location, then we can easily find the azimuthal angle for desired transmit antenna pattern for the area we wish to cover. These maps allow us to develop the transmit antenna pattern requirements. Once the transmit antenna is specified, we can then make new ***[RPWRG]*** maps for that antenna. If we have negative required power gain over the desired coverage region, we can reduce the transmitter power by that number of dB.

On any of the maps we produce using the output to "Window," we can move the cursor to a point of interest and left click on the mouse. This will print out the data for this receive location just below the map heading on the screen. It is important to note that the distances and azimuths are computed from the "Plot Center" of the map and not necessarily the transmitter location.

VOAAREA can be used to see the impact of changing the "Fprob" multipliers or the choice of ionospheric maps. I often use VOAAREA to assess the possible impact of sporadic E propagation. Maps are useful in seeing where mode changes occur or where there are steep changes in signal power. These are areas of uncertainty and the predictions from VOACAP are not as accurate as they are in areas of little change in signal power.

Mapping of coverage allows us to play propagation tactics. We may wish to deny signals into certain areas or to minimize our signal lay-down. Propagation can drift off the mainbeam azimuth because of favorable propagation conditions in other directions. This can produce interference in areas which we might think would be immune because of our antenna azimuth.

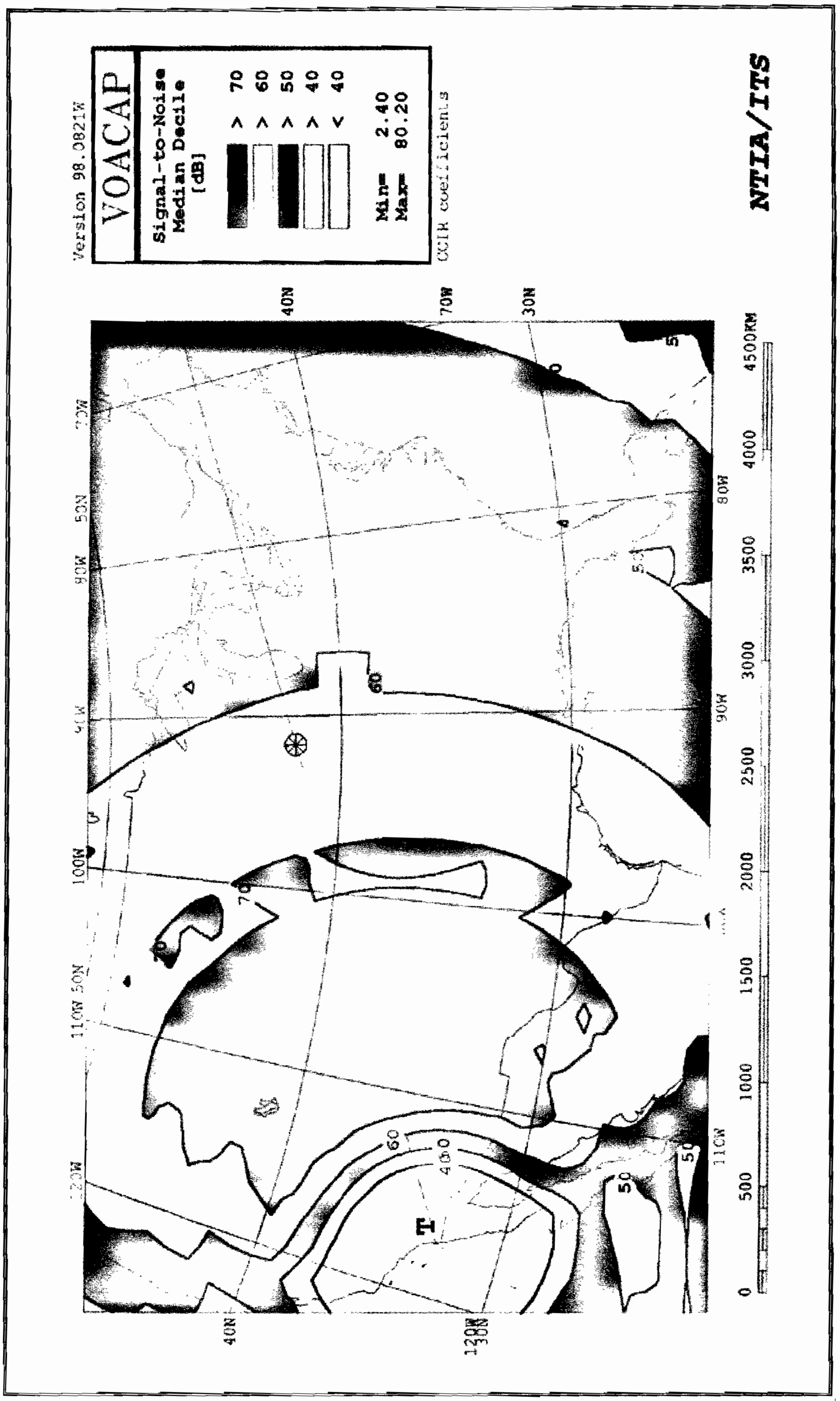


Figure 8.25. Highest Median SNR Coverage from San Diego [RLPA 12 dBi] 400 W 58∞ 18 UT [from Combined Maps at 15, 19, 22, 26 and 30 MHz] Feb 110 SSN

VOAAREA can be used to assess the impact of interference on a desired coverage map by specifying the location and system parameters for the interfering station or jammer. The procedures for doing this are beyond the scope of this book and the supporting documentation for signal-to-interference ratios and the methodology of computation have not been published at this time.

9. TRAPS AND ERRORS: HOW TO DETECT AND AVOID THEM

9.1 MUF, FOT and LUFs

With the advent of IONCAP, terms such as MUF, FOT and LUF were supposed to disappear. It didn't happen, and these terms are even more hopelessly confused than ever. The first version of IONCAP did not include any of these values. However, the sponsors of the program prevailed and the terms were reinserted in the final version. **AVOID THEM!**

The maximum usable frequency (MUF) is a term that everyone seems to understand, but no one can agree on its definition. In IONCAP, the MUF is the junction frequency of the high and low rays. It really is not the maximum usable frequency in terms of communications. In fact, it is a representation of the median of the MUF values at that hour for the month. So half of the days will have a maximum frequency that is higher than the MUF. Historically, HF radio operators have shied away from using frequencies at the MUF or higher because they did not know on which days propagation would be supported at these higher frequencies. Today's adaptive HF technology is such that systems can operate "above the MUF" on those days when the ionosphere will support these frequencies.

When we are using VOACAP, we must remember that each of up to 21 possible propagation modes has its own MUF. The MUF that is shown on the first frequency column of the output is the circuit MUF and is generally the MUF of the lowest-order mode. On rare occasions at the circuit MUF, the most reliable mode is not the MUF mode. In that case, the most reliable mode is shown at the frequency representing the MUF.

At the MUF, communications may or may not be supported. In the example of the Thule to Cedar Rapids circuit in Chapter 6, the MUF was determined by the 1F2 mode, whereas the communications were supported at most hours by the 2F2 mode at a higher takeoff and arrival angle.

The FOT is not a validated prediction in VOACAP. The FOT has various meanings. It is originally from the French, *Frequence Optimum de Travail,* which has been translated into the Optimum Working Frequency or OWF. Nowadays, FOT is often called the frequency of optimum traffic. Again, HF users tend to disagree on its definition. Many decades ago, it was simply taken as 0.90 to 0.85 times the MUF. Later on, it was taken to be the highest frequency that would provide ionospheric support on 90% of the days per month. Then it took on a systems value when people defined it as the highest frequency for which one could obtain 90% circuit reliability. Along with this definition of the FOT came the term Working Band. It was assumed that any frequency between the

FOT and the lowest usable frequency (LUF) would have a circuit reliability of 90% or higher.

Then IONCAP came along and things got confused again. Each of the possible modes in IONCAP can have an FOT and an LUF. Between the LUF and the FOT of the next higher order mode there may be a skip region. These skip regions can be very pronounced between the 1E and the 1F2 modes and the 1F2 and the 2F2 modes. Oblique ionograms often show these skip regions. These frequencies in the skip region should be avoided as no signal will reach the intended receiver. If we look at the coverage maps produced by VOAAREA, we can clearly see the skip regions for a given frequency. We must keep in mind that in VOACAP these "FOTs" and "LUFs" are dependent on the required SNR, the transmitter power, transmit antenna pattern and receive antenna pattern as well as path losses and radio noise. If we use the Complete System Performance methods discussed in Chapter 7, we will not have to worry ourselves with these terms as we will be using the predicted SNR distribution to determine which frequencies provide an acceptable grade of service.

9.2 What Time Is It?

There is such a great temptation to make VOACAP into a real-time prediction model. I have heard arguments as to whether VOACAP gives predictions that are centered "on the hour" or "on the half-hour." The answer is quite simple: who knows? Back in the 1950s and '60s when the data for these models were collected, signal data was averaged over 2-hour blocks, transmission loss values were averaged over 3-hour blocks and the noise data was averaged over 4-hour blocks. Predicted values for an hour in VOACAP are derived by interpolation from these averaged blocks of data. Also, bear in mind that the original data were collected in 3-month blocks representing a season, so it is quite a stretch of the imagination to think that VOACAP gives an accurate representation for a given hour in a given month. The program does an amazingly good job (as discussed in Chapter, Section 7.6, Comparison of Measurements and Predictions), but there can be an hour or so offset between what actually happens and what is predicted due to the averaging done with the original data.

Likewise, it is pointless to discuss which day of the month the program is predicting. However, there is one sponsor of this program who demanded daily data. I think I should be shot for writing this, but you can interpolate right down to the day by specifying the day you want using the "Groups" button on the VOACAP input screen (see Section 6.4). When entering the numerical value (1 to 12) for the month, you can use a decimal followed by the day in the month (e.g. June 18 becomes 6.18). Don't do it unless you are trying to impress the boss or a customer. As we discussed earlier, one can represent system performance by running January, April, July and October. It certainly makes sense to run a particular month if that is the month of interest. VOACAP predicts the distribution of data over a month so it MAKES NO SENSE AT ALL TO RUN A PARTICULAR DAY.

There is one way by which one can improve the accuracy of VOACAP for a particular day and hour. That means is by monitoring real circuits and comparing the actual performance to the predicted performance. This tells us where we are within the predicted signal-to-noise ratio distribution. We can then use that knowledge to improve our prediction on a similar circuit. Several methods of "real-time" predictions or "now-casting" are commercially available which make use of real-time monitoring to augment the predictions.

9.3 Antenna Pattern - Not Mine

One of the easiest mistakes to make in setting up VOACAP is in the antenna specification. **ALWAYS RUN METHOD 15.** This will force us to look at the patterns we have generated for the transmit and receive antenna. So often, I have heard myself or someone else exclaim, "That's not mine!"

Remember that VOACAP always has a default antenna specified so the program will run even if we forget to enter the antenna we want. We can forget to place the antenna on-azimuth or we can enter a wrong azimuth for the antenna. Also, some antennas, especially from the ITS-78 antenna package, can produce very unrealistic patterns. We always need to look at a pattern and determine if it seems reasonable before we use it. This is especially true for the elevation angles between 0° and 3°. Unless we are using a very special type of antenna, gain values at these angles should be much less than that of an isotrope. If not, we must use a "Min. Angle" of 3.0° using the "System" button on the input screen for VOACAP. This will prevent unrealistic antenna gain values at these very low angles from being used by the program. The take-off angle is further discussed in the next section.

9.4 Horizon Obstructions and Minimum Takeoff Angle

Here is where the fun begins. We need to gather our notebook, compass and clinometer and go outdoors. Before we head out, we need to run VOACAP to get the great-circle route azimuth for our circuit and we need to correct this azimuth from True North to a Magnetic Azimuth based on the magnetic pole. Most topographical maps will have the correction factor for a particular region. We write down the magnetic azimuth in the notebook and we are ready to go to the site. We go to the antenna location or proposed location and use the compass to find the desired great-circle azimuth. A good site should have no far-field obstructions above 1°. Here we are looking for mountain ranges, tall buildings, etc., which obscure the distant horizon. The clinometer will let you measure the clearance elevation above horizon.

An excellent reference dealing with antenna siting is the National Bureau of Standards Technical Note 139 (Utlaut 1962). It gives some guidelines in determining losses in directivity gain which may be associated with obstacles in the Fresnel zone. We need to note any obstructions within the Fresnel zone which are 1/8th wavelength or higher and their distance away from the antenna. Roughness in the foreground of the antenna will effect the gain contributed by the ground reflection. We also need to note the type of ground under and immediately in front of the antenna so that we can represent it in terms of conductivity and dielectric constant (see typical soil types listed in the Help function under ground conditions in HFANT).

For the more-distant obstructions, a general rule of thumb can be applied that no loss in antenna gain will occur at angles 3° above the measured elevation angle to the obstruction. Thus, if we have a very tall mountain range that presents a 2° obstruction angle relative to the horizontal, we can expect our antenna gain calculations for flat earth to be correct down to an elevation angle of 2° + 3° = 5°. Up to 6 dB of loss will occur between 2° and 5°. No propagation is possible at angles less than 2° for this example. In this case, we would probably use a minimum takeoff angle of 3° for our VOACAP analysis. However, we will have to be alert if angles of between 3° and 5° are needed for the most reliable mode. If this is the case, we should rerun VOACAP with a minimum angle of 5° and compare the VOACAP predictions. If we note significant differences between the predictions for a minimum takeoff angle of 3° and 5°, we probably will have a real problem on this circuit. If possible, find a better site. If not possible, you may have to engineer both ends of the circuit to work the higher-order mode (a mode with a higher takeoff angle) to accommodate the presence of the obstacle. We can input minimum takeoff angles up to 45°. However, we must remember that this prevents VOACAP from considering any propagation modes at the blocked angles. This is changing the ionospheric parameters used on the path. This is not realistic and we should be very careful when using large minimum takeoff angles. It is best to run the path with and without the obstacle to see what differences occur in the predictions. If results are very different, a better approach is to model the effect of the obstacle on the antenna pattern and then use that antenna pattern file in VOACAP with the minimum takeoff angle set at 3°.

While we are at the site, we should look for other antennas or metallic structures that may couple with our antenna and distort the pattern. Another excellent reference for antenna siting, tuning and mutual coupling is found in the Defense Communications Agency Addendum No. 1, MF/HF Communications Antennas (DCA 1966). Also, the

ARRL Antenna Book is a good source of practical information about construction and tuning of HF antennas (ARRL 1982 or newer editions).

9.5 Too Much Noise

When we use VOACAP, we must remember that the noise is assumed to be a constant field strength from all directions. The noise power delivered to the receiver by the receive antenna is equal to the power picked up by a short, lossless vertical antenna. The power gain of the receive antenna is used to compute the signal power. This is a reasonable assumption as long as the receive antenna is 100% efficient. If the receive antenna is less than 100% efficient, then the efficiency as a function of frequency needs to be included in the efficiency table under the receive antenna pattern (Method 14). For antennas, such as the vertical monopole, inverted-L, rhombic and vee, HFANT will compute the efficiency and place it in the efficiency table. VOACAP uses the efficiency values in dB to reduce the noise power at each frequency. If we are using a receive antenna pattern that we have generated external to HFANT, we must be aware of the need to consider efficiency properly. One way is to input the directivity pattern rather than the power pattern of the antenna. The other way is to include the efficiency values in a table to be read in with the pattern.

Another case of “too much noise” is using a man-made noise power level higher than actually exists. If you have the opportunity to visit the receive site, take along a portable shortwave receiver. Tune to quiet places in the HF band, turn the volume up and listen to the noise. Do this both in the daytime and again at night. Man-made noise has a distinct signature. It sounds like static with a great deal of repetition. Power line noise usually has a buzzing sound, whereas atmospheric noise tends to be a hissing sound that slowly fades in and out. If the man-made radio noise is drowning out all but the strongest signals, you have a problem site and probably need to use Industrial level of man-made noise in VOACAP. If you cannot detect much of any man-made noise, then you should use a man-made noise level of Rural in VOACAP even if the site is not in a rural region.

I participated in a man-made radio noise survey in Germany during 1977 in and around Bremerhaven, Germany. Bremerhaven is a large city having a busy port area with electromechanical cranes and electrified railroads. Our measurements showed a man-made noise level at –155 dBW/Hz at 3 MHz. This is a little quieter than Rural! Earlier measurements made at Bremerhaven for the US Navy by Stanford Research Institute (Hagn 1972), indicated noise power levels ranging from –150 to –138 dBW/Hz at 3 MHz depending on location. The average of all locations was –146 dBW/Hz.

One must be careful when using noise-power measurements. Automated systems that measure noise can often be contaminated by interfering radio signals. The measurements made by Hagn were made with automatic recording systems while the measurements we made were done with a human operator who discarded measurements with obvious interfering signals. What is not totally clear is which measurements should be used to model man-made noise, as interfering signals are a fact of life.

In the absence of actual man-made radio noise measurements, I use the following rules of thumb:

1) Rural locations away from high-voltage power lines and small cities with low vehicle traffic **- 155 dBW/Hz**
2) Large cities with heavy traffic **- 145 dBW/Hz**
3) Industrial locations, large ships or aircraft **- 140 dBW/Hz**
4) Indoor locations or roof-top locations on buildings with fluorescent lights, induction heaters, medical equipment, etc. **- 136 dBW/Hz**

There are special situations where you may choose to raise the noise level over normal ambient conditions. Precipitation static can be extremely troublesome for aircraft flying through ice crystals or vehicles operating in a blowing snowstorm. Sandstorms also create precipitation static. Sufficient static energy can be stored on an insulated antenna to be lethal to either personnel who touch the antenna or receivers that do not have surge protectors. Local thunderstorms including heat lightning can raise noise levels 20 dB or more above that predicted by the CCIR 322 atmospheric radio noise maps in VOACAP.

9.6 Sporadic-E Won't Go Away

Sporadic-E (E_S) propagation comes in various forms and can be a boon or a bane depending on what you want. One thing for sure is that when sporadic-E propagation conditions exist, VOACAP predictions may or may not be accurate. I am not trying to be funny, but the truth is that the authors of IONCAP gave us the ability to shut off the E_S model or to "crank it up" to where it is the only mode possible. It is nice to have such authority. But if we find our predictions are not accurate, we are at fault for not having set the sporadic-E model to the correct levels for the actual conditions. So let us explore what is known about E_S propagation and what we may do with VOACAP to assess its effect on our circuit performance predictions.

The MUF for the E_S mode can easily be the circuit MUF, a condition called blanketing E_S. During this period, only E modes are possible as energy does not reach the F region of the ionosphere. Circuits of 2,500 km or less generally benefit from this condition. For longer circuits, absorption from the D layer and losses due to multiple ground bounces diminishes the SNR to unusable levels. Blanketing E_S occurs along the US east coast in late spring and early summer. If we monitor the DoD sounders in this area, we can see the daytime variation of the E_S MUF. It will vary by several MHz from one 15-minute sweep to the next. Also from day-to-day during the month at a given hour, the E_S MUF will show an even greater variation. It is this variability that makes E_S predictions so difficult. But, before we get into the predictions, let us discuss the three different types of E_S.

If we refer to pages 15 - 16 of the User's Manual for ITS-78 (Barghausen et al. 1969), we will find the following definitions for the three types of E_S:

Auroral E_S - Occurs mainly at night at geomagnetic latitudes greater than about 60°, with a maximum near 69°. Its seasonal, diurnal, and solar cycle patterns are not clear. It occurs more frequently during periods of high magnetic activity and follows the sudden commencement associated with a solar flare.

Temperate E_S - Characterized by a pronounced maximum during the summer solstices (June-July in Northern Hemisphere and December - January in the Southern Hemisphere). A seasonal minimum occurs during the vernal equinox; this minimum changes abruptly at 60° geomagnetic latitude. The diurnal pattern exhibits peaks during mid-morning hours and near sunset. It is primarily observed during the day-light hours and shows a complicated dependence on the sunspot cycle.

Equatorial E_S - A regular daytime occurrence without seasonal dependence. It is highly transparent (partly reflecting) and reaches high (≈ 50 MHz) frequencies. Values of foE_S around 10 MHz are regularly observed by ionosondes near the geomagnetic dip equator. The reflection properties depend on the direction of propagation; higher reflection coefficients are to be expected for north-south paths.

The causes of the sporadic-E layer are beyond the scope of this work. For those who are interested, articles by Dr. David Whitehead at the University of Queensland suggests that the mystery is now solved (Whitehead 1997). There are three good references that can be used to locate geographic regions and times of day where Sporadic-E modes are expected to occur (Smith 1957), (Leftin et al. 1968) and (Smith 1976). The maps by Margo Leftin, et al., were used in the IONCAP sporadic-E model and are still available in VOACAP using the "Fprob" button on the input screen (see Chapter 6, Section 6.9).

The recommendations on how to evaluate for the effects of sporadic-E propagation with IONCAP are not very satisfying. The use of critical-frequency multipliers is not mentioned in the theory manual (Lloyd et al. 1978). It is first mentioned in the User's Manual on pages 24-25 (Teters et al. 1983). Here it is stated that the multipliers allow "the user to adjust the heights of the E, F1, F2, and E_S ionospheric layers." The predicted critical frequencies, as derived from the worldwide maps of each of the 4 layers, are multiplied by the factor specified by the Fprob function on the input screen of VOACAP or the FPROB card of IONCAP. The permissible ranges for the factors for each layer are given by the Help function in VOACAP when the "Fprob" button is clicked. The IONCAP default multiplier for the E_S critical frequency is 0.7. The only explanation for the use of 0.7 is it "allow(s) for median losses." In private communication with John Lloyd, I was told that he had settled on this value as it tended to give the best agreement with data collected by over-the-horizon radar results. This work was never published to my knowledge.

Comparison tests were made by the US Army by running IONCAP with the multiplier for the foE_S set at 0.7 and 0.0. The results showed that the SNR distribution was raised from 2 to 4 dB by using the IONCAP default value of 0.7. To be on the conservative side, the US Army chose to remove the effects of E_S by using the multiplier set to zero. This lets the program revert to using the unmodified Table 7 Transmission Losses from ITSA-1 (Lucas and Haydon 1966), which included sporadic-E-layer losses.

In discussions with Margo Leftin and George Haydon at ITS in 1986, it was concluded that the sporadic-E model in IONCAP, using the default multiplier of 0.7, was not accurately predicting the effects of sporadic-E and did not seem to be using Leftin's E_S maps correctly. Unfortunately, no one has attempted to review and correct this portion of the IONCAP code. The IONCAP theory manual (Lloyd et al. 1978) is sufficiently vague to be of little use in deciphering the model, especially the area in which Lloyd removes the sporadic-E losses from Table 7 Transmission Losses and then adds them back in based on his E_S absorption model. What we do know is that if we include the E_S layer at the Fprob value of 0.7 as recommended on page 25 of the IONCAP User's Manual (Teters et al. 1983), the SNR distribution over several seasons and sunspot numbers will be increased by a factor of 2 to 4 dB at distances greater than 2,500 km. This does not seem to be reasonable since the Table 7 Transmission Losses include the effects of E_S losses (less loss for paths ≤2,500 km and greater for longer path lengths).

Therefore, it is recommended that the Fprob multipliers be set at 1.0, 1.0, 1.0 and 0.0 for use in VOACAP. This will shut off the E_S model in VOACAP and the Table 7 Transmission Losses will be used.

If we wish to evaluate cases where we suspect E_S modes are present, we can rerun VOACAP for the case where the E_S probability is set at 0.7 or we can set E_S at 1.0 and zero out all other modes. It is not clear whether or not these options will predict E_S modes correctly, but it will allow us to see where the E_S modes exist and the takeoff angles which are most effective in launching E_S propagation. The frequency variability of E_S modes is so great within the hour and from day-to-day that little confidence can be placed in the prediction of the best frequencies for E_S propagation.

The sporadic-E model does seem to reflect the general expectations as to when E_S modes should occur during the day and over the seasons. The Fprob multiplier also changes the most reliable frequency by many MHz. Let us look at an example for a circuit along the east coast of the USA. The circuit is from Ft. Bragg, NC to Daytona Beach, FL using 1 kW and half-wave dipole antennas at one quarter-wave above poor ground. We will look at all frequencies between 2 and 30 MHz on this 679-km path at 1800 UT for the month of June with the SSN = 110. First, we will look at the best frequency, which is the one having the highest median SNR and SNRxx where xx = 90%. The Fprob multipliers are set at (1.0/1.0/1.0/0.0), (1.0/1.0/1.0/0.7) and (0.1/0.0/0.1/1.0). This represents the original E_S model from ITSA-1 (recommended for general use with VOACAP), the IONCAP default setting, and the case of blanketing E_S, respectively. The results are shown in Table 9.1.

In the summer day, the predictions by VOACAP with the sporadic-E model shut off gives the most conservative estimate of performance. Using the default multiplier of 0.7 for foE_S raises the median SNR by 3 dB and the SNR exceeded 90% of the time by 7 dB. The best frequency remains the same and the most reliable mode at 8 MHz is the 1F2 mode. When we shut off the F2, F1 and E layers and set the multiplier for foE_S to 1 simulating blanketing E_S, the most reliable frequency is 10 MHz and the maximum frequency for 90% reliability (i.e., the so-called FOT) is 14 MHz.

Whereas, on a winter day, the sporadic-E layer contributes little to the SNR such that the predicted performance is nearly identical using the foE_S multiplier set at either 0 or 0.7. However, if we remove the regular layers and force sporadic-E layer propagation, the best frequency drops.

For planning purposes on this circuit, I would use the predictions with the Fprob multipliers set to 1/1/1/0 which uses the sporadic-E losses associated with the Table 7 Transmission Loss in VOACAP. These predictions are more conservative. If sporadic-E propagation occurs, the performance should improve even if we still remain on 8 MHz during the summer day. Alert operators and an ALE system would find the higher frequencies which can occur during periods of blanketing E_S and the performance may improve by 8 dB. This is not a general conclusion, as sporadic-E propagation can be detrimental to a circuit. For example at a distance approaching 2,000 km, the takeoff angle will be nearly 0°. Since most antennas cannot support very low angle modes, the $1E_s$ mode would not be possible forcing VOACAP to use the $2E_s$ mode with 4 passes through the D-layer. The preferable mode would, of course, be the 1F2 or 1F1 mode. However, if the sporadic-E MUF is higher than the 1F2 or 1F1 MUF, obscuration losses can prevent any useful energy reaching the F layer. HF circuits with path lengths of approximately 2,000 km can be very difficult to maintain in areas where sporadic-E propagation is prevalent.

Table 9.1. Predictions for Three Different Settings of the Fprob Multipliers for Short Path Along the USA East Coast at 18 UT for Summer and Winter

Jun (SSN = 110)

	1/1/1/0 No Sporadic-E	1/1/1/.7 Default E_S	.1/0/.1/1 Blanketing E_S
Best Frequency	8 MHz	8 MHz	10 MHz
Median SNR	65 dB	68 dB	73 dB
SNRxx (90%)	51 dB	58 dB	59 dB

Jan (SSN = 110)

	1/1/1/0 No Sporadic-E	1/1/1/.7 Default E_S	.1/0/.1/1 Blanketing E_S
Best Frequency	14 MHz	14 MHz	8 MHz
Median SNR	75 dB	75 dB	75 dB
SNRxx (90%)	61 dB	62 dB	62 dB

9.7 Clobbered with Multipath and Fading

Skywave propagation will usually involve more than one mode or path between the transmitter and the receiver. This condition is called multipath. Previously, when we were discussing the signal power distribution in Chapter 2, we welcomed secondary modes as they added up to increase the monthly median signal power at the receiver. It turns out that additional signals are not always beneficial at a given instant. They create something called interference fading, which can be quite extreme. Two signals of equal amplitude and 180° phase difference will cancel each other out and no signal will be received. Such extreme fading is generally found in the Medium Wave band where the ground wave signal and a skywave signal can beat against each other. At HF, the ground wave mode drops off so rapidly with distance that there is usually a skip zone between the end of the ground wave range and the beginning of the skywave coverage. But HF skywave propagation can often consist of many different modes and from reflections that are off-path or from ionized clouds or blobs in the upper ionosphere. This leads to considerable short-term fading which has a minute-to-minute variability of many dB.

In addition to interference fading there is polarization fading. This type of fading deals with the instantaneous E-field vector of the arriving wave front with respect to the orientation of the receive antenna. A horizontal-dipole antenna will pick up maximum energy when the arriving E-field vector is horizontal and little energy when the E-field is vertical. The opposite is true for the vertical monopole.

Measurements of HF skywave signals experiencing both interference and polarization fading have shown good agreement with the Rayleigh distribution. A general discussion of fading is given in US Army Technical Manual 11-486-6 (Department of the Army 1956). Also, the National Bureau of Standards published two excellent surveys of the fading phenomena, (Salaman et al. 1961) and (Salaman 1962).

Let us remember that VOACAP provides us with the distribution of the hourly median signal power for a given month, hour and frequency. Now we want to assess the variation in signal power we can expect within the hour. To do that we can apply the Rayleigh distribution, such that:

$$T = 100e^{-.693\,(E/E_m)^2}$$

where:

T = percent of time the signal power will exceed the instantaneous value within the hour.

e = 2.7182818

E = the instantaneous field intensity

E_m = the hourly median field intensity

from (Department of the Army 1956), page 1-11.

If we plot T as a function of 20 $\mathrm{Log}_{10}(E/E_m)$, we obtain a chart as shown in Figure 9.1. Rayleigh Distribution. Here we can see that 90% of the time during the hour the instantaneous signal power will equal or exceed a value 8.2 dB below the hourly median. For 10% of the time, the instantaneous power will be at least 5.3 dB above the median. Thus, we can expect that for 80% of the hour, the instantaneous signal power will be within a 13.5 dB range.

Based on these statistics we can establish the maximum power differential we will need between the primary propagation mode and a secondary mode in order not to experience deleterious multipath fading more than a certain percentage of the time within the hour. If both modes are undergoing Rayleigh fade characteristics, the worst case will be when the stronger mode is at its lower limit and the multipath mode is at its strongest level. If we wish to protect the strongest mode so that multipath conditions do not occur more than 10% of the time, we can take the square root of the sum of the squares of the lower decile of the wanted signal and the upper decile of the unwanted signal to find the required power differential, such that:

$$PMP = \sqrt{8.2^2 + 5.3^2} = 9.8 \text{ dB}$$

where:

PMP = maximum power tolerance

Thus, we need approximately 10-dB power differential between the most reliable mode and the summation of the secondary modes in order not to have a condition where the secondary modes may be as high or higher than the primary mode for more than 10% of the hour. Secondary modes having higher signal power within 10 dB of the primary mode have the potential of causing interference fading for more than 10% of the hour. We have to qualify the above statement because we cannot say for certain that both modes will be present at a given hour on a particular day in the month. However, there is a potential for them to occur simultaneously and hence, there is the *potential* of severe multipath fading.

So far we have ignored the fact that signals arriving at the receiver by different paths must have differing time delays. Time delay differences tend to smear out the signal detected by the receiver. For AM voice, the effect sounds like an echo when the time-delay differential is great enough. Some AM broadcast stations will use an echo box to give an "interesting" sound, but most often, broadcasters do not want the echo sound. For digital radio systems, significant time smearing of the signal can make accurate detection of the message impossible. VOACAP will give us an estimate of the time delay for each of the modes; therefore, we can determine if the time difference is sufficiently great to cause an increase in the error rate or even missed messages. For analog radio-teletype systems, the recommended default for time delay is 0.85 ms and the default for maximum power tolerance is 10 dB.

As we learned in Chapter 6, Section 6.8, the multipath criteria is entered into VOACAP using the "System" button on the data input screen. Then, for those modes having greater delay times, the program determines the probability that the signal power will be above the "multipath power tolerance in dB." VOACAP uses the "maximum tolerable time delay" to flag modes that can cause unacceptable elongation of the detected signal.

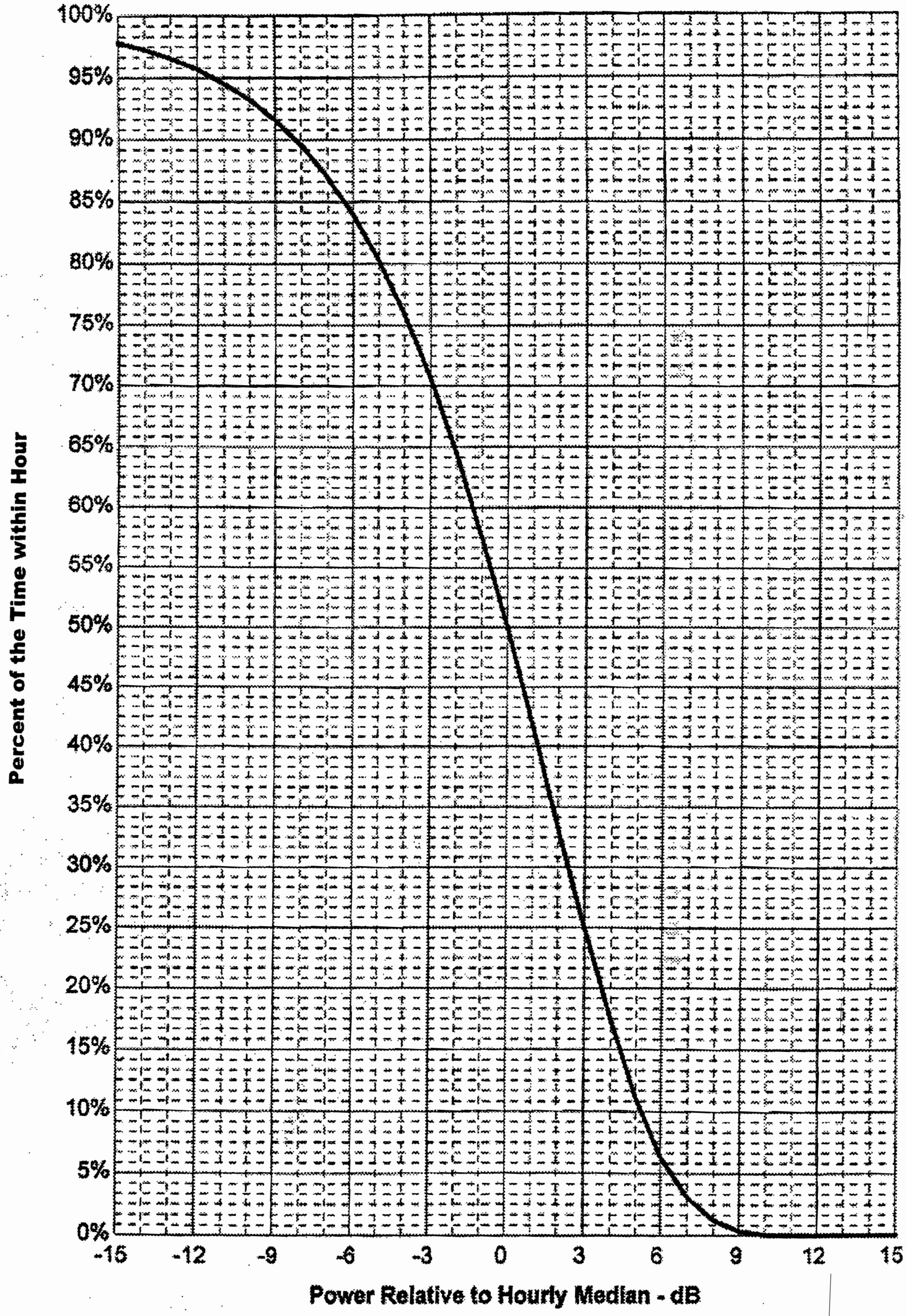


Figure 9.1. Rayleigh Distribution
Short-Term (Minute-to-Minute) Fading

Next, VOACAP looks to see if the flagged modes are within the "maximum power tolerance." If so, then the program will print out the reliability of the strongest of the multipath modes and it is labeled as MPROB (multipath probability). **THIS IS NOT MULTIPATH PROBABILITY!** Sadly, this is what was done in IONCAP in 1978 and it has never been corrected. We can use this indicator to let us know that multipath is possible, but we must run the ALL MODES (Method 25) in order to see what modes are present and then manually calculate the multipath probability. Hopefully, a correction of this existing error will be made by the Institute for Telecommunication Sciences in the near future.

There is one more trap we need to avoid if we are worried about multipath effects on our system performance. VOACAP uses a rather crude map of the earth consisting of only two components: regions of poorly conducting earth and sea water. In the space between these two regions, linear interpolation is used to find the conductivity. Therefore, coastal regions, including a considerable distance inland, will have VERY GOOD earth when VOACAP makes the determination of the conductivity for a ground bounce location. The result is that VOACAP may over-predict the signal power of multiple bounce modes for circuits of very short length. For example, it is not uncommon to see the 3F2 mode predicted to cause multipath on a circuit of only 100 km in a coastal region. If we are very close to the ocean, we might expect some off-path contribution from a 3F2 mode; but, if we are inland and the bounce area is really poor ground, the 2F2 or 3F2 modes should not be significant or a source of multipath interference. For paths of several thousand kilometers or more, the ground bounce area will be quite large and the earth conductivity model in VOACAP is perfectly adequate.

9.8 What About Radio Nets?

VOACAP allows us to predict the circuit reliabilities for each link in a radio net but not the net reliability. The worst trap that I have seen people fall into when it comes to radio nets is computation of NET RELIABILITY. Let us take a very simple net consisting of three stations: 1 net control and 2 remote stations. For simplicity, let us also assume that each station can re-send a message to a station that has not acknowledged receipt and that the circuit reliability for send and receive on each link is equal. (Normally that is not the case, as the remote stations often have inferior radios and antennas compared to the net-control station.) Assume that it is given that the reliability for the net-control station reaching either of the remote stations is 75% and the reliability of the remote stations being able to contact each other is 50%. What is the probability that the remote stations will successfully receive the message at that hour and month?

The answer I see so often is 96.9%. The rationale is that the net control station has only a 25% chance of not reaching either remote station. The chances that the message will reach one of the remote stations is 1 – (.25 x .25) or 93.8%. Now, if only one remote station receives the message, it has a 50% chance of re-sending the message successfully to the other remote station. Thus, the net reliability is thought to be 1 – (.25 x .25 x .5) or 96.9%. **THAT IS NOT THE CORRECT ANSWER!** The correct answer is 75%.

We must remember that circuit reliability is the percentage of days in the month at that hour for which the SNR will equal or exceed the required signal-to-noise ratio. The days when outages occur are highly correlated on circuits within the same geographic area. If the correlation is 1, then both remote stations will receive the message on 75% of the days and both will miss the message on 25% of the days. But, this situation is only true where the links in the net are nearly identical, which can occur if the links are nearly parallel to each other or if the geographic area of the net is very small, say less than 750 km.

In a study made to look at the number of sounders needed in the world to map the ionosphere in real time, it was found that hourly foF2 values between stations separated by 650 km in an east-west direction or 850 km in a north-south direction have a correlation coefficient of 0.85 (Rush 1976). We can suppose that if the critical frequencies fall in unison we will suffer MUF outages throughout the net. But, if the foF2 values rise in unison, we will have more modes available and outages should be more or less uncorrelated. The same is true if the foF2 at one control point rises and falls at the control point of a different link. Continuing this rationale, we might suspect that ½ (0.85) or 0.425 of the time outages will be correlated and 0.575 of the time they will be uncorrelated. Again, this assumes that the control points are separate by about 750 km. If this applies to our example above, then:

$$Rel_{net} = 1 - [\ .525((.25)(.25)(.50)) + .475(.25)\ ] = 0.865$$

The above discussion is presented to remind us that multiple circuits within a radio net do not necessarily raise the reliability of getting a message through the network. There is some advantage as we saw in the example where the net reliability rose from 75% to 87% if the links are separated sufficiently such that outages on the links are not highly correlated. The exact correlation coefficients to use are not known. The ones presented above can be used for a first approximation.

Another problem that can crop up in planning radio net operations is the use of whip antennas on mobile units. The whip is useful for very short distance communications, usually less than 30 km or whatever the limit is for ground wave propagation in that area. In jungle or forested regions, ground wave may be limited to **10 km or less** (Hagn and Vincent 1974). The same is true in desert areas during sand storms or arctic regions when there is blowing snow. In these cases, the radio wave propagates at the air/dielectric interface presented by the forest canopy, blowing sand or ice crystals (Staiman and Tamir 1966).

These blackout effects occur even at VHF. During the tank battles of the Israeli/Arab war, so much sand was in the air that communications between tanks was impossible; however, the frantic radio conversations could be heard as far away as Greece. In Vietnam, long-range reconnaissance patrols using man-pack radios with whips would be hit by the Viet Cong just as the team lost radio contact with their base. This phenomenon of the ground wave signal rising to the top of the dielectric presented by the foliage, sand or snow is well known and has been called the "lateral wave" (Tamir 1967) (Dence and Tamir 1969).

The effects of the lateral wave were first noted by troops operating in the jungles of the Pacific islands of World War II. In a then-classified study conducted by the US Army in Panama, the solution to the problem was discovered (Chief Signal Officer, War Department 1943). It was found that high-angle skywave propagation would penetrate the overhead dielectric both for the upward signal and for the down-coming signal. Sadly, we had to redo these tests in Panama in 1963 because we had forgotten what we had learned 20 years earlier (USAELRDL 1964). This prompted the Department of Defense Advanced Research Projects Agency to initiate a multimillion dollar research study of effects of vegetation on radio wave propagation. This massive effort was summarized in 1972 (Doeppner et al. 1972) and was the topic of a 3-day workshop held at Ft. Huachuca (Wait et al. 1974). A prediction model for lateral-wave propagation was written at the Institute for Telecommunication Sciences (Ott and Wait 1973).

The solution to the lateral-wave problem was to use HF skywave which was later called Near-Vertical-Incidence Skywave or NVIS (Perlman 1974).[1] At first it was thought that this was a novel and exciting form of propagation since it covers the immediate area which had always been thought of as the "skip zone" (Bell 1975). However, we can use VOACAP to show the efficacy of using the skywave mode even for very short distances of a few kilometers as long as we can use the frequencies as low as 2 MHz.

In situations where whip antennas must be used, the lateral-wave effect can be mitigated by having the operators bend the whip so that a portion of it is parallel with the ground. This will increase the gain toward the zenith angle by as much as 10 to 20 dB

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[1] The first mention of NVIS that I have found was by Sol Perlman at Ft. Monmouth. Early works by George Hagn at Standford Research Institute used terms such as "propagation at near-vertical incidence" as far back as 1966 (Hagn et al. 1966).

(e.g. –10 to –20 dBi rather than –40 dBi for a vertical whip). This solution works only over NVIS circuits of very short length, say 100 to 200 km.

During a Solid Shield exercise in the 1970s, an amphibious landing was conducted along the panhandle of Florida. The US Air Force was responsible for the frequency coordination and maintenance of C^3I for the operation. The frequency coordinator was with the landing group. Excellent ground wave communication was maintained between the ships and the landing force until the beachhead headquarters was moved 15 km inland. At that distance, the ground wave signal was buried in the noise. Fortunately, the signal operations plan was based on HF predictions. The ships and the ground forces switched to NVIS mode as soon as the ground wave mode failed. The ship whips were tilted over the side and the landing forces put up their half-wave dipole antennas. Communication was immediately restored on the NVIS frequencies.

9.9 Airborne Operation

VOACAP can be used for analyzing HF radio circuits for ground-to-air and air-to-ground operating with some caution. Skywave propagation has been successfully used between ground stations and high-altitude aircraft for many years. More recently, it has been demonstrated that the near-vertical-incidence skywave can provide reliable communications with helicopters even when flying along the “nap of the earth” (Tupper and Hagn 1978). Generally, we do not know the antenna pattern for the airborne platform and, even if we do, we don’t know the instantaneous orientation of the pattern with respect to ground station. Typically, the airborne antenna pattern can be approximated by using an isotropic pattern reduced to –10 or –20 dBi.

Radio noise at the airborne platform is another problem. The aircraft may be very noisy, where the audio noise is more of a problem than the RF noise. Also, high-altitude aircraft have a much larger view of the earth than antennas located on the ground. This means that for planes flying over or near populated regions, line-of-sight to urban areas and other sources of man-made radio noise will increase as a function of the aircraft altitude. Work by the US Navy has shown this altitude dependence on man-made noise (Roy 1981). The same applies to local thunderstorms; however, I have never seen any measurements of this.

If you are really planning for airborne operations where the aircraft will be dropping people or equipment by parachute, then the radio communications between the ground controller and the pilot become absolutely critical as the aircraft approach the drop zone. So often this is when the HF skywave link fails, usually, because the radios are not tuned to the very low frequency needed for NVIS propagation. Actually, it is pointless to attempt HF skywave at this range since the aircraft will be above the radio horizon and line-of-sight communications is possible. A fairly simple way to estimate when the range at which the aircraft will be above the radio horizon (Lane and Riddell 1977) is as follows:

$$D_{mi} = \sqrt{2H_{ft}}$$

where:

D = ground distance to the aircraft in miles

H = altitude of the aircraft in feet

Some care should be exercised when using the above equation for locations in rough terrain where it may be necessary for the aircraft to be 3° above the radio horizon before true line-of-sight conditions occur. An approximation of the relationship for a 3° clearance angle is made from a derivation documented by the US Army (Lane and Masen 1977), as shown below:

$$\text{Log } H_{ft} = 2.3424 \text{ Log } (D_{mi}) - 0.3424$$

These two equations for unobstructed radio horizon and 3° above the radio horizon for rough terrain are plotted for various distances and altitudes in Figure 9.2. Distance to Radio Horizon as a Function of Aircraft Altitude.

Again remember, if the ground controller is using a whip, advise the radio operator to tilt the whip so that the antenna beam will be directed toward the aircraft. Also, it is advisable to use the highest frequency setting common to both the ground and the aircraft radios where the noise power will be the lowest. In an actual situation, we had aircraft coming into the drop zone from Pope Air Force Base. We lowered the skywave frequencies all the way down to 4 MHz as the aircraft approached the drop zone. As the aircraft broke the radio horizon, we switched to 17 MHz. Communications was maintained with the aircraft from takeoff until drop time. In the last few minutes, as the planes were vectored into the drop zone, the communications quality according to the pilots was as "good as FM."

9.10 Measurements Do Not Equal Predictions

One of the most disappointing things in making predictions is when they don't reflect what actually happens on the circuit. But, before you decide the prediction program is no good, there are a number of things to check. First of all, remember that the predictions are quite accurate and if the difference between prediction and reality is large SOMETHING IS REALLY WRONG.

Let us break the problem down into two conditions: one is where the actual performance is MUCH BETTER than predicted, and the other is when the actual performance is MUCH WORSE than predicted.

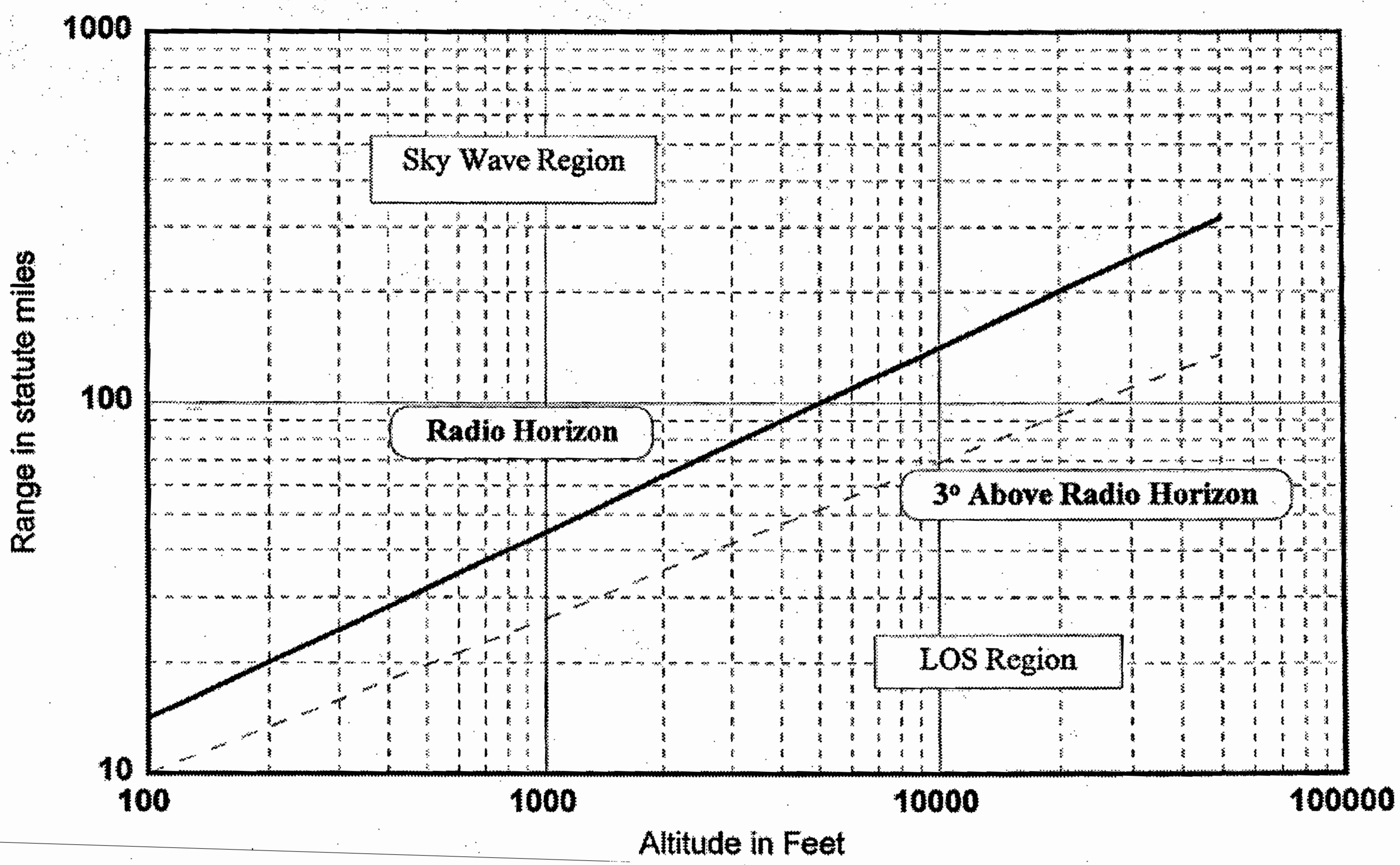

Figure 9.2. Distance to Radio Horizon as a Function of Aircraft Altitude

9.10.1 Much Better Performance

The actual performance SHOULD be much better than the predicted Reliability or ***[SNRxx]***. Remember these terms are the lower decile of the actual distribution. We need to look at the full SNR distribution when we make the comparison with measurement. (See Chapter 4, Section 4.5) However, it is worthwhile to check our VOACAP-prediction parameters, as follows.

Did we overestimate the man-made radio noise? (See Chapter 3, Section 3.3 and Chapter 8, Section 8.5)

Did we overestimate the Required SNR? (See Chapter 5, Section 5.2)

Did we set one or both of the antennas off azimuth? Look at the computed radiation patterns using Method 15 and the off-azimuth information in the VOACAP output header material.

Did we input the correct transmitter power? I remember one disgruntled user who had input 0.001 kW for an actual transmitter power of 100 W!

If we haven't found the problem by now, we need to question how the measurements were made. For instance, a number of successful contacts between transmitter and receiver is not the same as passing continuous digital traffic with an error rate of less than 1 in 10,000!

Be skeptical of Signal-Power measurements. One paper published in a prestigious scientific journal showed that VOACAP seriously under-predicted the signal power from a beacon that operated on a constant frequency 24 hours per day. For many hours the beacon frequency was above the circuit MUF. At that time the actual measurements truncated to a value some 20 to 30 dB above the VOACAP Signal Power prediction. First of all, the investigators were measuring signal plus noise power, although they reported it as signal only. The value they took from VOACAP was the predicted signal power. Secondly, their receive system had a threshold where values would be truncated to internal noise of the receiver; they did not specify what that level was but it was fairly obvious where it fell by looking at their measurement data. Their charts showed fair agreement when the frequency was below the MUF, but when the frequency was above the MUF, their power measurements (signal plus noise) were much higher than the predicted signal power. It was really unfair to compare apples and oranges and then fault the prediction program.

Is the path length over 7,000 km and did we use Method 30? (See Chapter 7, Section 7.5 and 7.6)

If none of these conditions apply, run VOAAREA (see Chapter 8) and look at the coverage maps. Are there regions near our receive site that have high levels of coverage? It is possible that the program over-predicted the impact of a mode change or that we are actually receiving our signal from a non-great-circle route? One example I remember clearly was extremely troublesome. This was a broadcast from Radio Canada to the Caribbean. Their antenna placed a –20 dBi null on the azimuth toward Washington, DC and their frequency was 2 MHz above the circuit MUF for Washington, DC. Yet, for a month of measurements as well as monitor scores, we could receive this broadcast at the EXCELLENT level while the predicted level was NIL. At that hour, VOAAREA showed that Radio Canada had a very strong 1-hop bounce to the east of Washington, DC. It was during sunrise so the more easterly location was experiencing a rising MUF. It is quite clear that the signal we detected in Washington, DC was not via the great-circle route from Canada but was side scatter from the F2 region to the east of Washington, DC.

The last possibility, but quite likely, is the presence of sporadic-E modes. The beneficial effects of sporadic-E modes are usually on paths of less than 2,000 km. However, they can launch an "N mode" (E_S plus F2 modes), especially if the first ground bounce is from sea water. Sporadic-E effects may be very consistent for a few days, weeks or even a month but then go away. They may extend across the entire HF band and into the VHF band for several hours each day. See Chapter 9, Section 9.6 for a discussion on how to evaluate E_S propagation using VOACAP.

9.10.2 Much Worse Performance

This is the most common problem that we will hear about or experience. For one thing, it is easier to determine that it is much worse than much better. One example, that comes to mind as I write this, involved two military units. One was from the Army and the other from the Air Force. They had been in the field for a week with no "commo" achieved, yet my predictions had shown 90% reliability for secure TTY 24-hours per day on a circuit of only 500 km. The officer in charge of this field exercise called me and complained bitterly. I suggested to him that I suspected that one of the units had not put up their dipole kit and was using a van-mounted whip antenna. As it turned out, I was correct (not too remarkable as I knew the unit involved). As soon as they both were using horizontal dipole antennas, the NVIS path worked. That vertical whip produced about 25 dB less gain than the dipole at the required takeoff angle for that path length (Hagn et al. 1966).

I bring up this example as it is typical of what can go wrong between what you think the operations personnel will do and what they actually do. Most often, we will find that what we modeled in VOACAP is not what actually happened. We will not get too worried if it is only for one or two days in the month, but we begin to worry when the deciles and monthly median do not agree.

Antennas are always suspect. Poorly maintained antennas can change input impedance resulting in tremendous transmission-line losses. Other antennas or structures can be built next to an antenna, which distorts the pattern or changes its impedance characteristics. Antennas are usually set up using a magnetic compass to determine the placement of the structure. So many times I have found that the antenna was placed on an azimuth based on the wrong declination correction between True North and Magnetic North. In one case, the individual with the compass stood underneath a large metallic water tank while laying in the antenna!

If the antennas are right, then suspect that the frequencies in use may be different than the ones predicted by VOACAP. A good operation always keeps a log of the frequency usage and that lets us check the operational frequencies versus the predicted best frequencies. Systems operating on a fixed frequency schedule and without human monitoring may be experiencing severe interference which is adversely affecting the grade of service.

Minimum takeoff angle is another possible cause for discrepancies between prediction and actual reception. One classic misinterpretation of measured data was when the investigator placed his receive antenna in a parking lot surrounded by two- and three-story buildings. The goal was to compare BBC broadcasts with Radio Moscow. Radio Moscow was found to produce much greater signals in the eastern USA from Bulgaria than did the BBC from England. This, of course, flew in the face of predictions and suggested to the investigators that Radio Moscow (Bulgaria) was winning the dB war by devious means. When we used VOACAP to revisit this historic experiment we found that the arriving signals from BBC were at 3° to 5° above the horizon for a 2F2 mode and the Radio Moscow signals should arrive at angles around 10° for a 3F2 mode. My conclusion was that the buildings in the foreground of the whip (in the parking lot) blocked the arriving 2F2 BBC signals significantly more than the 3F2 signals coming in at 10° from Radio Moscow. When we put the minimum takeoff angle at 5° in VOACAP, we predicted that Radio Moscow would provide a better grade of service than the BBC on a shorter but coincident path. The reverse was true if we used a minimum takeoff angle of 0.1°.

Radio noise or interference can be much higher than we predicted. Generally, the radio operator can tell you if the circuit is out because of "noise," either natural ("QRN") or man-made ("QRM"). In Washington, DC, I found that the combined power of low VHF (taxi cabs) and CB (truck drivers) radio transmissions during the rush-hour traffic was sufficient to saturate our receiver. The result was that the out-of-band signal power being picked up by our roof-top antenna was causing the receiver AGC to shut down. The effect on the wanted signal was reduced audio power.

A solar flare can knock out the entire HF band for many hours in the daylight area and the effects, if near sunset, on the path can last for most of the night. There are a number of observatories that post notices of solar flares and the associated geomagnetic storms which can degrade HF circuit performance from a few minutes to days.

A Sporadic-E layer can obscure F-layer modes, resulting in low signals or no signals.

Operating on frequencies "above the MUF" can result in very poor performance. I remember a case where a Defense Communications System link between Okinawa and the Philippines had not had a frequency change for several months. The circuit worked during the day but failed miserably at night as the operating frequency went far above the MUF. It turned out that the Philippines station was short of personnel during the night shift and no one was calling for frequency changes shown on the propagation predictions. The funny thing about this story is that the management decision had been that the Army antennas on Okinawa were not properly designed!

Always check to see if the receiver is attached electrically to the antenna. I had to travel from Arizona to Kentucky to "fix the ionosphere" one time when a unit that was supposed to be passing radio telephone traffic had been unable to hear any signal from Germany in Ft. Campbell after attempting contact for 3 weeks. When I got there, I found that the center pin in the coaxial cable connector to the receiver was missing! In other cases, I have found the terminating resistors in a sloping "V" antenna were burned out (this often happens during an electrical storm). Once we found that the amplifiers used with a loop array became very noisy every time it rained. The best story is the time that the operations personnel had built a barbecue pit above the buried coaxial cable from the receive antenna to the receiver. The pit fire finally melted the coax and "propagation" suddenly failed.

The point of this entire section is to remind us to continuously check what actually happened compared to what we thought would happen when we made the predictions.

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