

A Critique of the Reliability and Service Probability Calculations for the Ionospheric Communication Analysis and Prediction Program - IONCAP

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A CRITIQUE OF THE RELIABILITY AND SERVICE PROBABILITY CALCULATIONS FOR THE IONOSPHERIC COMMUNICATION ANALYSIS AND PREDICTION PROGRAM - IONCAP

A. D. Spaulding and F.G. Stewart¹

This report presents an analysis and explanation of the system performance calculations performed by the reliability and service probability subroutines of the Ionospheric Communication Analysis and Prediction Program "IONCAP" and an IONCAP derivative termed "VOACAP". A review of the three components needed to properly statistically describe the performance of a communications system or link is presented. These components are needed to account for the short-term and long-term statistical variations of the desired signal and the interference and also the inherent prediction errors. A detailed numerical example is given for illustration and explanation. The functioning of the subroutines that perform the system performance calculations is documented in detail followed by suggestions for modification and improvement.

Key words: IONCAP, VOACAP, reliability, noise, overall operating noise threshold, system performance.

1. INTRODUCTION AND BACKGROUND

This report details the functioning and rationale of the subroutines RELBIL (IF), "reliability," and SERPRB (IF), "service probability," of the Ionospheric Communications Analysis and Prediction Program (IONCAP) (Teters et. al., 1983) and an IONCAP derivative, termed VOACAP, developed for the Voice of America by the Naval Research Laboratory (NRL). In addition, the functioning of the corresponding similar routines in an antecedent HF prediction program termed HFMUFES (Barghausen et. al. 1969) is discussed. All input and output

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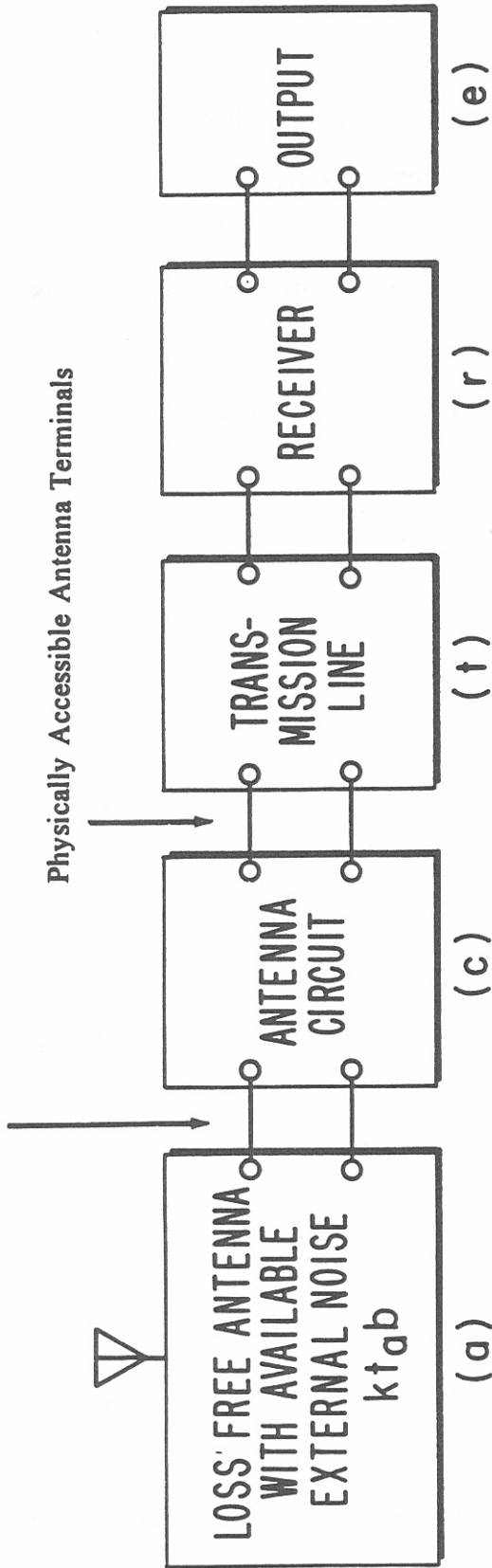
parameters and their source are listed and defined and the mathematical functioning of the calculations performed by the subroutines detailed. Care is taken to explain the precise meaning of "reliability" and "service probability" as used by these HF propagation prediction programs. To this end, Section 2 is an example of a system performance calculation, to show the statistics involved and their use. The example is basically (but expanded) one developed by the authors for CCIR Report 322 (CCIR, 1988) showing the use of atmospheric radio noise data. The example also shows, however, how IONCAP, VOACAP and HF MUFES, and other programs treat system performance determinations. The above subroutines RELBIL and SERPRB are documented in Section 3, and finally a suggested modification is presented in Section 4.

The specifications of system performance involve the statistics of both the received desired signal and the accompanying noise (or interference). Here, we will refer to any undesired emission, intentionally radiated or not, as "noise." We start with basic definitions leading to the three independent components of "system performance." For completeness and understanding, we will start from the very beginning. This, apparently, has not been done before in connection with IONCAP and its functioning in terms of system performance.

The external noise is expressed as an antenna noise factor, so that it can be combined with the noise generated within the receiving system to give an overall operating noise factor, f (CCIR, 1967, 1991; and Barsis et al., 1961). As derived in CCIR Report 413 (CCIR, 1967), the only appropriate point to specify the noise factor f , and correspondingly the input signal-to-noise ratio, R , is at the terminals of an equivalent loss free antenna. Figure 1 shows a diagram of the general receiving system and its operating noise factor. If the receiver is free from spurious responses and all elements prior to the receiver are at a reference temperature T_0 (taken to be 288 K), then f is given by

$$f = f_a - 1 + f_c f_i f_r , \tag{1}$$

S/N, f , and f_e Defined Here



$$L_a = 1, t_a$$

$$L_c, t_c$$

$$L_t, t_t$$

$$f_a = t_a / t_o \quad f_c = 1 + (L_c - 1)(t_c / t_o) \quad f_t = 1 + (L_t - 1)(t_t / t_o) \quad f_r$$

$$f = f_a + (L_c - 1)(t_c / t_o) + L_c(L_t - 1)(t_t / t_o) + L_c L_t(f_r - 1)$$

Figure 1. The receiving system and its operating noise factor, f .

where

f_c is the noise factor of the antenna circuit (its loss in available power, i.e., available output power/available input power),

f_t is the noise factor of the transmission line (its loss in available power),

f_r is the noise factor of the receiver ($10 \log f_r$ is the familiar receiver noise figure, F_r), and

f_a is the antenna noise factor due to external noise.

The antenna noise factor, f_a , is defined as

$$f_a = \frac{P_n}{kT_0 b} = \frac{T_a}{T_0} \quad (2)$$

where

P_n is the available noise power from the equivalent lossless antenna,

k is Boltzmann's constant = 1.38×10^{-23} J/K,

T_0 is the reference temperature (288K),

b is the receiver noise bandwidth (Hz), and

T_a is the effective antenna temperature in the presence of external noise. [Noise intensities are usually given in terms of T_a at higher frequencies, but generally not at HF.]

Different antennas have different f_a 's for a given noise field strength (Hagn, 1984). In general, one converts the specified f_a data (particular to the reference antenna - short vertical monopole above a perfectly conducting ground plane for atmospheric noise, for example) to the corresponding field strength. This field strength is then applied to the antenna of interest to obtain its f_a . IONCAP uses the noise f_a data directly for all antennas. This assumes that the noise is omnidirectional and the actual antenna is equivalent to the reference monopole when losses are removed. In general, since different antennas have different effective length to radiation resistance ratios, they can have different f_a 's. Equation (2) relates available power and f_a . The available power is given, in general, for an antenna by

$$P_n = \frac{(\bar{e} \cdot \bar{\ell}_{eff})^2}{4R_{rad}} \quad , \quad (3)$$

where \bar{e} is the field strength (in a bandwidth b), $\bar{\ell}_{eff}$ is the vector effective length of the antenna and R_{rad} is the radiation resistance of the antenna. For the short vertical monopole over a perfectly conducting ground plan, (2) and (3) give.

$$E_n = F_a - 95.5 - 20 \log f_{MHz} + 10 \log b \quad (4)$$

where

E_n is the equivalent vertically polarized rms field strength (dB (μ V/m)) in bandwidth b (Hz), and

$F_a = 10 \log f_a$ = external noise figure for center frequency f_{MHz} , where f_{MHz} denotes the frequency in MHz.

Other similar relationships, as noted above, exist for other antennas.

The operating noise factor, f , is used in determining the relationship between the available signal power p_s , the noise power p_n , and the signal-to-noise ratio r ($r = p_s/p_n$):

$$p_s = f r k T_0 b \quad , \quad (5)$$

or

$$P_s = R + F + B - 204 \quad , \quad (6)$$

where

$$P_s = 10 \log p_s \quad ,$$

$$-204 = 10 \log k T_0 \quad ,$$

$$B = 10 \log b, \text{ etc.}$$

In evaluating the operating noise figure, F, for use in equation 6, all of the parameters in (1) need to be considered. However, at HF, the external noise usually dominates, so that, for that case, F is simply given by F_a . Note that (1) provides the means to determine an appropriate receiver noise figure (see CCIR Report 670, 1991). In very quiet receiver locations, the noise figure for some shortwave receivers may be the limiting noise. For F_a , IONCAP (and VOACAP) now use the new noise routines (Spaulding and Stewart, 1987) which appropriately combine atmospheric, man-made and galactic noise.

Equation 6 is used to obtain the required average signal power from the required signal-to-noise ratio, R. The required R depends on the detailed statistical characteristics of both the noise and signal random processes. The determination of this required R can be quite involved, depending on the particular system of interest. This is especially true at HF, since the noise generally is highly non-Gaussian and the signal can have involved fading characteristics (Akima et al., 1969). Once determined, this required R is an input to IONCAP. IONCAP and similar programs determine the available signal power and its statistical variations for the communication circuit

of concern, the noise equivalent vertically polarized field strength and its statistical variations, and use these to determine the likelihood of the required R being achieved. Since this determination of system performance involves predicting the future statistically (and such predictions are subject to errors and unknowns), it is necessary (for a proper statistical description) to define system performance in terms of three independent component parts. These parts are termed (using the original terminology developed some time ago: grade of service, time availability, and service probability (Barsis et al., 1961; Spaulding, 1982 and references therein). We will, of course, relate these system performance "parts" to IONCAP, VOACAP, and HFMUFES, and more modern statistical terminology.

Grade of Service is used to specify the average performance for stationary noise and signal processes and is a measure of "quality." Typical examples are probability of symbol error for digital systems and articulation index for voice systems. The signal-to-noise ratio that results in some required grade of service (e.g., symbol error probability) is the required R and an input to IONCAP. If we knew the signal process and noise process precisely, we could determine the grade of service precisely. If this all remained "constant" into the future, we would have the "answer" and would have no need of IONCAP or similar programs. But, as noted above, we can only statistically estimate the required parameters and are forced, therefore, to a statistical specification of system performance.

Time availability is the percentage of a specified period of time a given grade of service (via R here) or better will be achieved. In IONCAP, the period of time is usually a month-hour. Time availability, when expressed as a fraction of time, is exactly what IONCAP (and VOACAP) term reliability. [In HFMUFES, reliability is given by the time availability (as in IONCAP) times the probability that the chosen frequency will be below the maximum usable frequency.]

Service probability is the probability that a specified grade of service or better will be achieved for a specified time availability. The service probability accounts for the uncertainties (statistically) in the many parameters involved in the calculation of performance. It is simply

the "standard" statistical confidence factor required for any statistical description. The reliability normally calculated by IONCAP, etc., is a median measure. That is, the associated service probability (which is usually ignored) is 0.5. Only one-half of "identical" circuits with the given specifications will have the calculated reliability.

In this introduction, we have explained in a complete way how system performance is specified. The next section will give a simple numerical example to show the relationships between the three components of system performance and how they are determined. After this, we will look at the IONCAP procedures in detail.

2. A SYSTEM PERFORMANCE EXAMPLE

In this section, we want to go through, in detail, a system performance example to show the relationships between the three factors involved in specifying system performance. This example shows how VOACAP computes "reliability" and service probability. We will use a numerical example so that the procedures are easily followed rather than just provide the general equations.

CCIR Report 322-3 (CCIR, 1988) gives two examples of the determination of system performance, mainly to illustrate a use of the atmospheric noise estimates given in Report 322. The first example is for a 50 kHz-100 Hz bandwidth digital system and the second is a 5 MHz-6 kHz bandwidth voice system. It is this second example we will use, but expanded in detail. Before this, however, we want to take a look at distributions used for signal and noise processes and their rationale.

Large data bases of both atmospheric and man-made noise F_a values have shown that the hourly (say) F_a values for both these noise types are log-normally distributed. Typically there are two log-normal distributions involved, one for values above the median value, F_{am} , and another one for values below F_{am} . That is, the decile values (or, corresponding, the standard deviation values) are different for above and below the median values. Spaulding and Stewart (1987) have developed a method of obtaining a log-normal approximation for the sum of log-normally distributed noises (specifically, atmospheric, man-made and galactic). This is an approximation since the distribution of the sum of the two log-normal random variables is not log-normal. IONCAP and VOACAP use this method to obtain the required noise statistics.

Smaller data bases have indicated that the received signal level (hourly average values) is also reasonably represented by log-normal distributions. Again, one for above the median value; and one for below the median value. IONCAP also determines the statistics for these log-normal signal distributions. In general, the short term (within an hour) signal fading distribution is Rayleigh and the long-term fading is log-normal [see CCIR Report 266-7 (CCIR, 1990a) and

references therein]. The short-term fading is involved in the determination of the required signal-to-noise ratio for the required grade of service, as is the short-term noise distribution (usually given by the exceedance probability distribution, termed APD).

What is of most interest is the distribution of the signal-to-noise ratio. In general, the distribution of the ratio of two random variables is quite different from the distribution of the individual variables. Normal distributions are a classic example of this. While the sum of two normal distributions is again normal, the ratio is not. The log-normal distribution, however, is quite unique in that if two random variables are log-normally distributed, their ratio is also log-normally distributed. It is an interesting mathematical exercise to demonstrate this fact. IONCAP (and, of course, VOACAP) make use of this in obtaining the signal-to-noise ratio statistics. It is of interest to note that HFMUFES, in its determination of system performance makes no assumptions as to signal and noise distributions, but computes median and decile values (different upper and lower deciles) and then fits a chi-square distribution to these three "points." This was probably done in order to obtain a continuous distribution rather than the "broken" lognormal ones. Also, the tails (beyond the deciles) of the log-normal distributions are "steeper" than those of the chi-square distribution.

Before going on to the example, we now briefly review the log-normal distribution. If the signal s (watts) is log-normal, then converting to dB, S (dBW) is normal,

$$p_S(y) = \frac{1}{\sqrt{2\pi\sigma_S^2}} e^{-\frac{(y-\mu_S)^2}{2\sigma_S^2}}, \quad -\infty < y < \infty, \quad (7)$$

where

μ_S is the mean value (dBW) and

σ_S is the standard deviation (dBW).

The log-normal distribution for the signal in "real" units i.e., watts, is

$$p_s(x) = \frac{K}{x\sqrt{2\pi\sigma_s^2}} e^{-\frac{(K\ln x - \mu_s)^2}{2\sigma_s^2}}, \quad 0 < x < \infty, \quad (8)$$

$$y = 10 \log x = K \ln x, \quad K = 4.3429.$$

In terms of "real" units, the mean and second moment are given by

$$E[s] = \exp\left[\frac{\mu_s}{K} + \frac{1}{2} \frac{\sigma_s^2}{K^2}\right] \text{ watts, and} \quad (9)$$

$$E[s^2] = \exp\left[\frac{2\mu_s}{K} + \frac{2\sigma_s^2}{K^2}\right] \text{ watts}^2 \quad (10)$$

Note that the mean is not simply the μ_s (dBW) converted to watts.

If the signal s is log-normal and the noise n is log-normal, and s and n are uncorrelated, then s/n is log-normal, so that S/N (dB) is normal with,

$$\begin{aligned} \mu_{S/N} &= \mu_s - \mu_n, \text{ and} \\ \sigma_{S/N}^2 &= \sigma_s^2 + \sigma_n^2. \end{aligned} \quad (11)$$

We now use example II from CCIR Report 322, except much more completely. In Report 322, only time availabilities and service probabilities above 0.5 (50%) are considered, and we want to consider the entire range to better match IONCAP. Our example is:

Determine the performance of an A3E telephony double-sideband system with reception at Geneva, Switzerland, under the following conditions:

Frequency	: 5 MHz
Time of day	: 2000-2400 local time
Season	: Summer
Bandwidth	: 6 kHz
Propagation	: ionospheric (resulting in a fading signal)
Grade of Service	: marginally commercial.

The problem is to assess the probability that a given signal-to-noise ratio R will provide the specified grade of service or better for any given percentage of time and to determine the statistical confidence (service probability) of our estimate. We will assume that the noise is atmospheric (rather than a combination of atmospheric, man-made and galactic) and both the signal and noise have statistical variation. CCIR Report 266-7 (CCIR, 1990a) specifies a standard deviation of 8 dB for the long-term fading of our ionospheric signal, which results in an upper decile (and lower decile) for the signal, D_s , of 10 dB (1.28×8). Also, based on the variation noted in Report 266-7 for the standard deviation of the long-term signal fading distribution, a value of $\sigma = 2$ dB will be used. Of course, IONCAP would give us the signal statistics if we were using IONCAP, but here we are interested in explaining system performance without the intricacies of IONCAP. However, rather than use upper and lower decile values of 10 dB (via CCIR Report 266-7), we will use an upper decile value of 12 dB and a lower decile value of 8 dB. This arbitrary choice is to better match IONCAP and to enable us to notice a difference in the above-the-median and below-the-median distributions.

While the required R , R_m , is an input to IONCAP, we will derive the required R_m here to indicate how our required signal-to-noise ratio might be obtained, at least for this example. Recommendation 339-6 (CCIR 1990b) gives a median required carrier power to noise power in a 1 Hz bandwidth of 64 dB (Rayleigh fading signal, non-diversity reception) for marginally

commercial A3E emissions. For our bandwidth, this gives a median required signal-to-noise ratio R of 26 dB. For analogue systems, the performance requirements are based on white Gaussian noise. In general, a given voice understandably can be achieved with a smaller R in impulsive (e.g., atmospheric) noise than in white Gaussian noise (Spaulding, 1982). The impulsiveness of the noise for our situation is detailed in Report 322-3 (CCIR, 1988). The results given in Spaulding (1982) for an AM voice system in atmospheric noise indicates that we can safely reduce the required R by about 6 dB (at least, assuming no noise limiting). We, therefore, will specify a required R_m of 20 dB, with a standard deviation for R_m , σ_R , of 3 dB.

The atmospheric noise statistics are obtained from CCIR Report 322 (or the computer routines that exactly reproduce the results in CCIR Report 322-3, such as GENFAM in IONCAP and VOACAP). We obtain for Geneva for June, July, August, 2000 - 2400 h and a frequency of 5 MHz : $F_{am} = 56$ dB, $\sigma_{Fam} = 4.1$ dB, $D_\mu = 4.8$ dB, $D_\ell = 5.1$ dB, $\sigma_{D\mu} = 1.3$, and $\sigma_{D\ell} = 1.6$ dB. Since the signal-to-noise ratio R is log-normally distributed, the decile values are [see (11)],

$$\begin{aligned} D_{R\mu}^2 &= D_{S\mu}^2 + D_\mu^2, \quad R > R_m, \\ D_{R\ell}^2 &= D_{S\ell}^2 + D_\ell^2, \quad R \leq R_m, \end{aligned} \tag{12}$$

since the signal and noise processes are independent. The deviation of R about its median R_m is $D = R_m - R$ ($D_{R\mu} = 12.9$, $R > R_m$; $D_{R\ell} = 9.5$, $R \leq R_m$).

The standard deviation of the decile for R are obtained similarly, i.e.,

$$\begin{aligned} \sigma_D R_\mu^2 &= \sigma_{D\mu}^2 + \sigma_{D_S}^2, \quad R > R_m, \text{ and} \\ \sigma_{D_{R\ell}} &= \sigma_{D_\ell}^2 + \sigma_{D_S}^2, \quad R \leq R_m. \end{aligned} \tag{13}$$

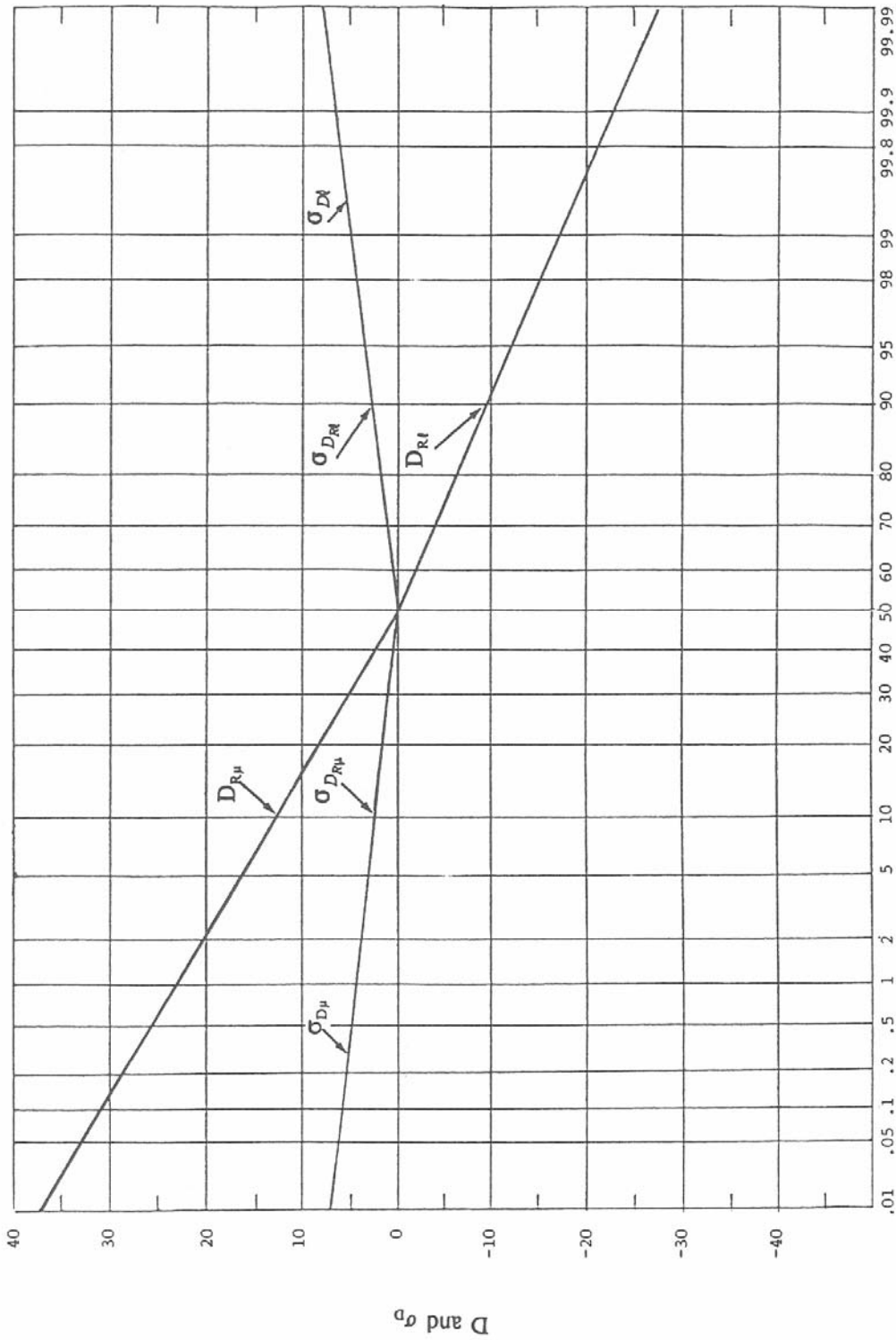
This gives that $\sigma_{D_R} = 2.4$ dB for $R \leq R_m$ and 2.6 dB for $R > R_m$. D and σ_{D_R} are shown on Figure 2. Figure 2 is plotted on normal probability coordinates, so that cumulative log-normal distributions plot as straight lines. Note that D (and σ_{D_R} are log-normally distributed and Figure 2 gives a graphical display of

$$Prob [D > D_0] = \int_{D_0}^{\infty} p_D (y) d y , \quad (14)$$

where $p_D (y)$ denotes the log-normal probability density function of D [see (7)]. The values of D for any percentage are also obtainable via the standard normal deviate t , i.e.,

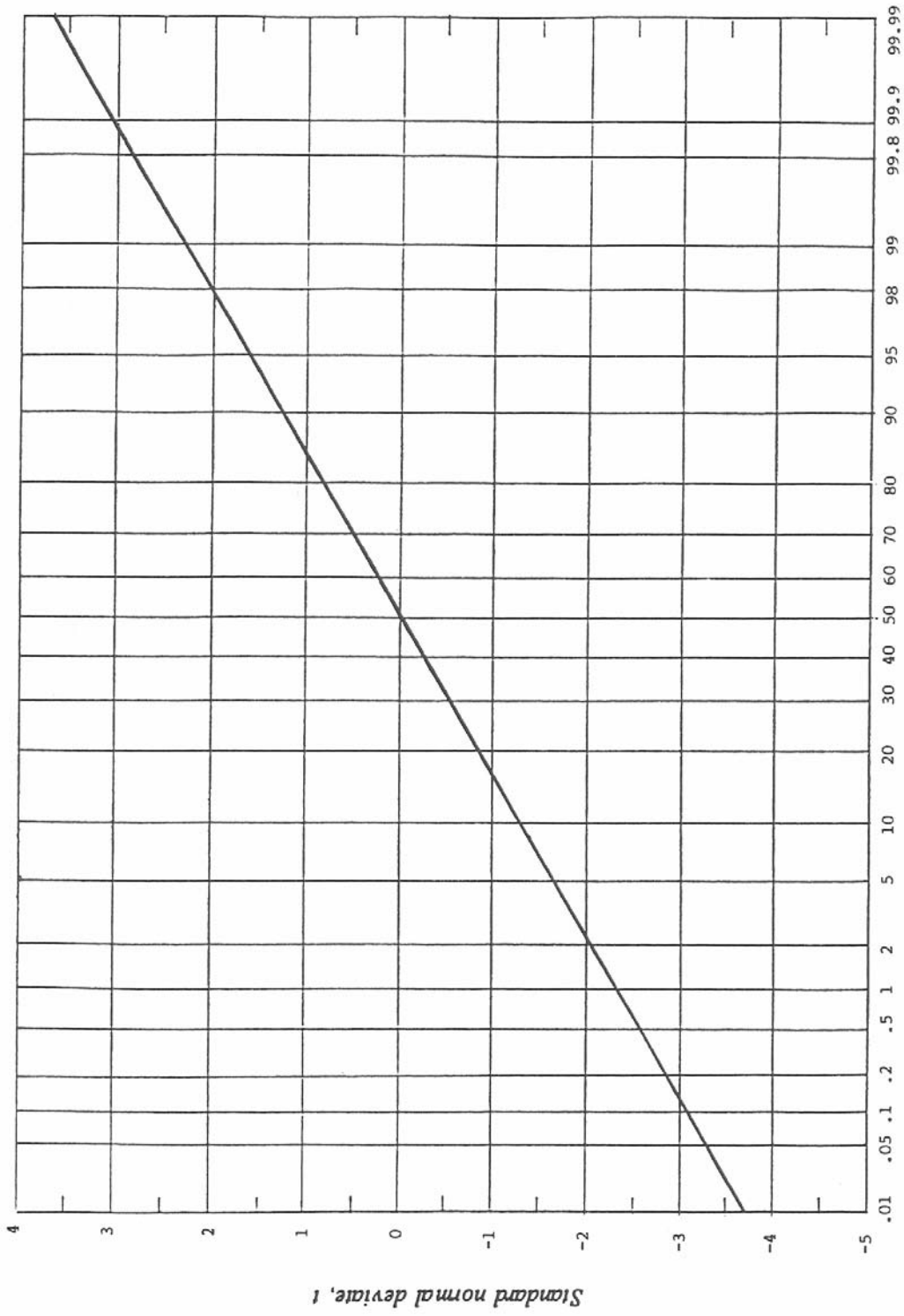
$$D = t \left(\frac{D_R}{1.28} \right) , \quad (15)$$

$D_R/1.28$ being the standard deviation of D . The standard normal deviate is shown, for future reference, on Figure 3. When IONCAP computes these (D and σ_D), it does not do it graphically, of course, but uses simple algorithms. The FUNCTION routine FNORML (YPX) is for the cumulative normal distribution and the normal standard deviate is handled via what amounts to a table lookup using the data statement TME (in subroutine RELBIL(IF), for example). The deviation, D , now accounts for the long-term statistical variations of both the signal power and the noise power. IONCAP uses D of Figure 2 to compute reliability. That is, IONCAP determines $R_m - R$, using for R the calculated median available signal-to-noise ratio (termed D_{50R}). For example, if the median available signal-to-noise ratio were 35 dB and our required R_m is 20 dB, then $D = -15$ dB. Figure 2 gives that the percent of time that -15 dB is exceeded is 98% (or a probability of 0.98). This says that $Prob [R \geq R_m] = 0.98$, which is termed reliability in IONCAP and VOACAP. This results as follows:



Percent of time D (or σ_D) is exceeded (Prob $[D \geq D_0] \times 100$)

Figure 2. Exceedance probability ($\times 100$) for the deviation D and its standard deviation σ_D



Probability (X100)

Figure 3. Cumulative distribution of the standard normal deviate.

$$Prob [R \geq R_m] = \int_{R_m}^{\infty} p_R(r) dr , \quad (16)$$

$$\text{where } p_R(r) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r-D50R)^2}{2\sigma^2}} . \quad (17)$$

With the change of variable $x = r - D50R$,

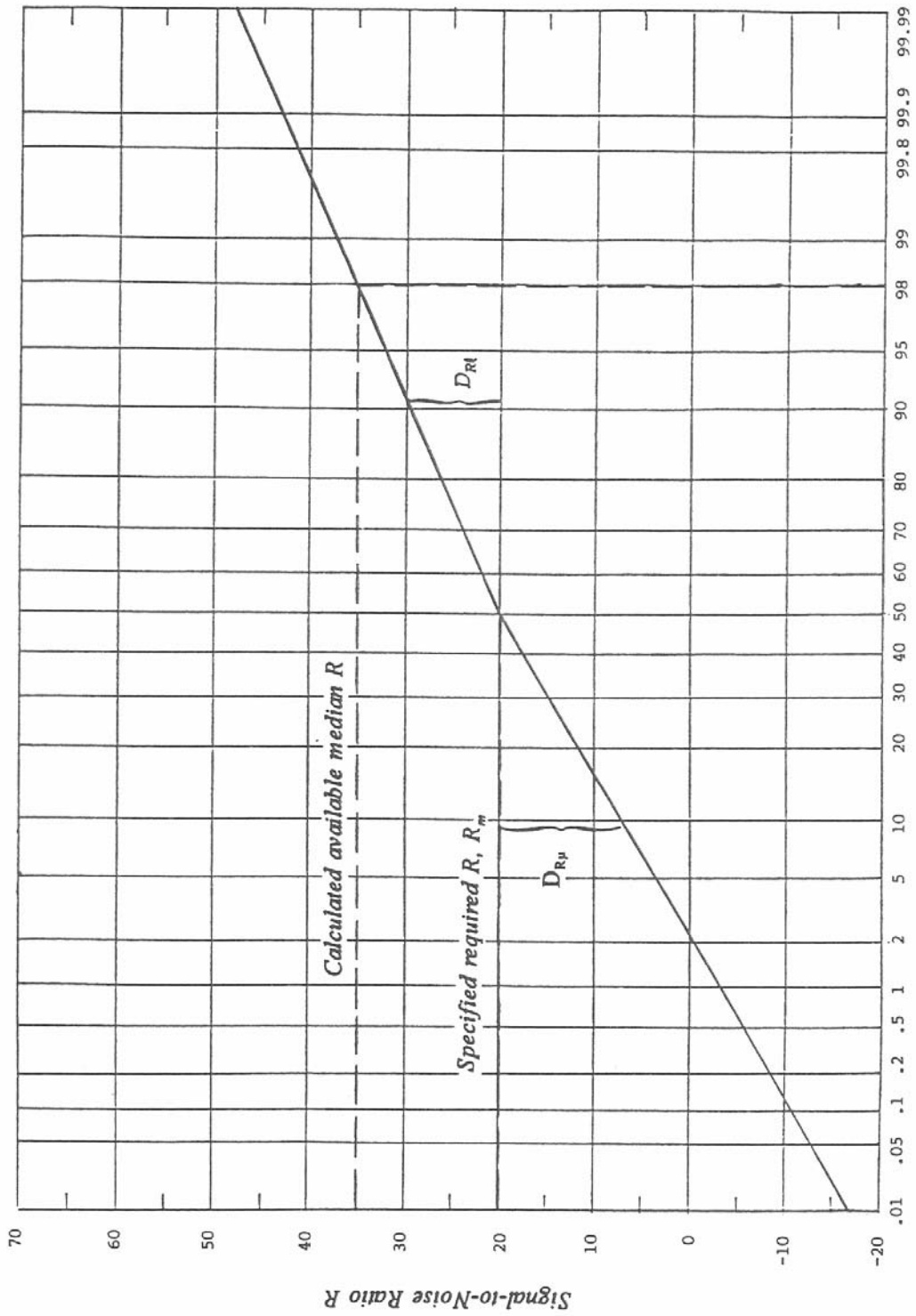
$$\begin{aligned} \int_{R_m}^{\infty} p_R(r) dr &= \frac{1}{\sqrt{2\pi\sigma^2}} \int_{R_m-D50R}^{\infty} e^{-\frac{x^2}{2\sigma^2}} dx \\ &= Prob [D \geq R_m - D50R] \end{aligned} \quad (18)$$

IONCAP actually computes this as

$$\int_{R_m-D50R}^{\infty} p_D(x) dx = 1 - \int_{-\infty}^{R_m-D50R} p_D(x) dx .$$

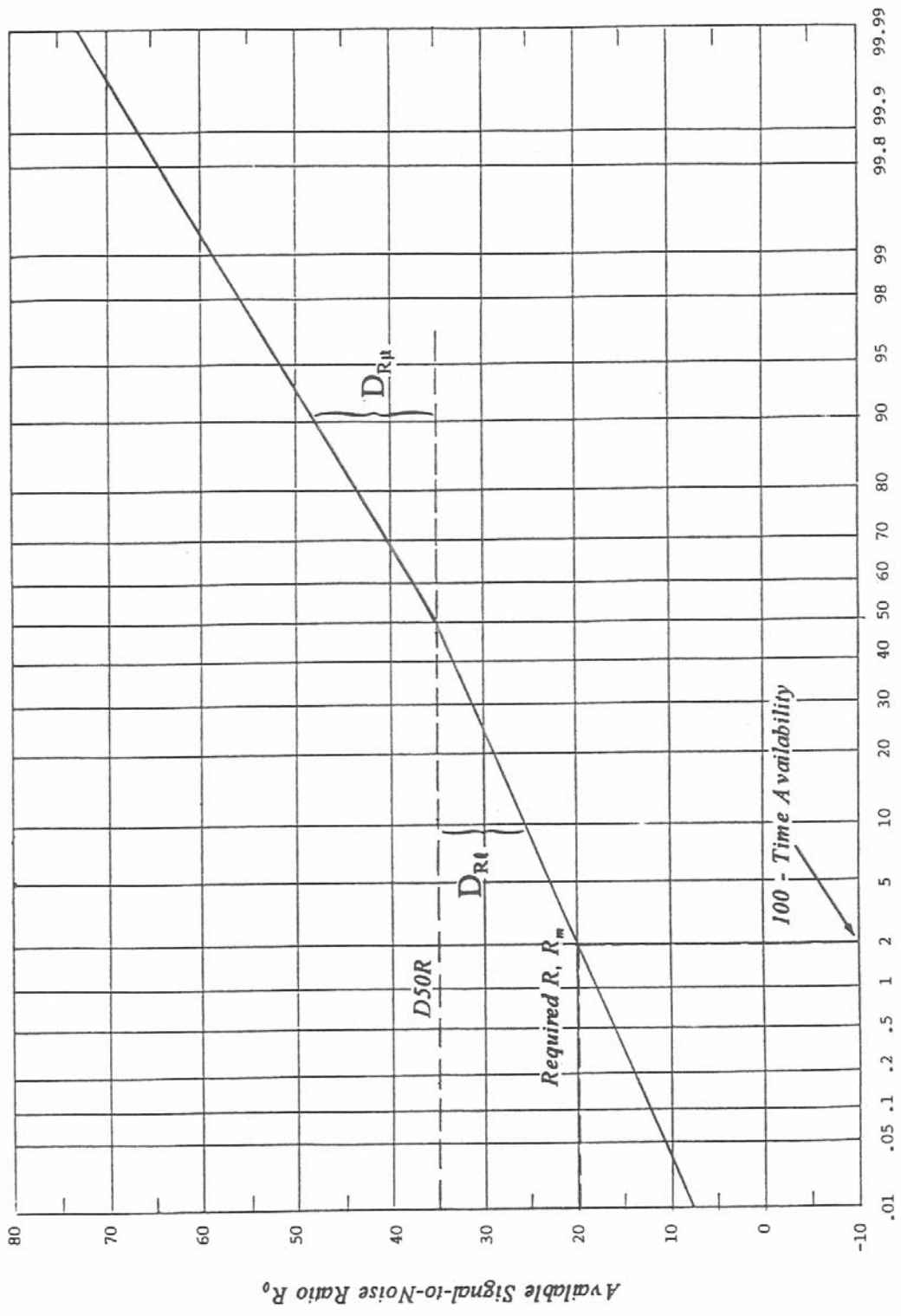
Figure 4 shows the same as Figure 2, but plotted relative to the required R_m so that time availability is easily obtained for any given available median R . For example, from Figure 4 if the available SNR was 30 dB, the time availability would be 91% (reliability of 0.91) or if we required a reliability of 0.80, a SNR of 26 dB would be required. Note that Figure 4 is not a cumulative distribution of the available R . For completeness, Figure 5 shows the cumulative distribution of R for the case of the median R ($D50R$) being 35 dB. The signal power for any R is obtained from (6) namely

$$S = F_{am} + R + B - 204 \text{ dBW} . \quad (19)$$



Time Availability (IONCAP Reliability X 100)

Figure 4. The deviation D plotted relative to the required signal-to-noise ratio R_m .



100 X Prob [$R \leq R_0$]

Figure 5. The cumulative distribution of the signal-to-noise ratio R

So far, we have seen how the short-term characteristic of the signal and noise processes (noise pdf and signal short-term fading pdf, usually Rayleigh for ionospheric signals) are used to obtain a required median R for a specified grade of service and how the long-term statistics are then used to obtain time availability (or Reliability). However, we have not yet considered the very important prediction uncertainties. Since we are attempting to predict the future, these uncertainties must be accounted for. Up to now (Figure 4) we only have a statistical confidence of 0.5, which means that only one-half of such circuits will meet this design criteria. In general, if we want more confidence, we must increase R to overcome our lack of knowledge (the uncertainties).

The uncertainties to consider are given by the following standard deviations:

- σ_s - standard deviation in the expected median received signal power. We have specified D_s and σ_D for the signal's long-term fading distribution, but there still is a prediction error for the expected value, due to, for example, errors in the ionospheric propagation prediction method used. We will use 5 dB for σ_s ;
- σ_R - uncertainty in the required R , 3 dB as discussed earlier;
- σ_{Fam} - 4.1 dB (from Report 322-3 as noted earlier); and
- σ_D - standard deviation of D (Figure 2), which is a function of the time availability.

The resulting total standard deviation, σ_T , is obtained, since the errors are uncorrelated, from

$$\begin{aligned}\sigma_T &= (\sigma_S^2 + \sigma_R^2 + \sigma_{Fam}^2 + \sigma_D^2)^{1/2} \\ &= (50.8 + \sigma_D^2)^{1/2}\end{aligned}\tag{20}$$

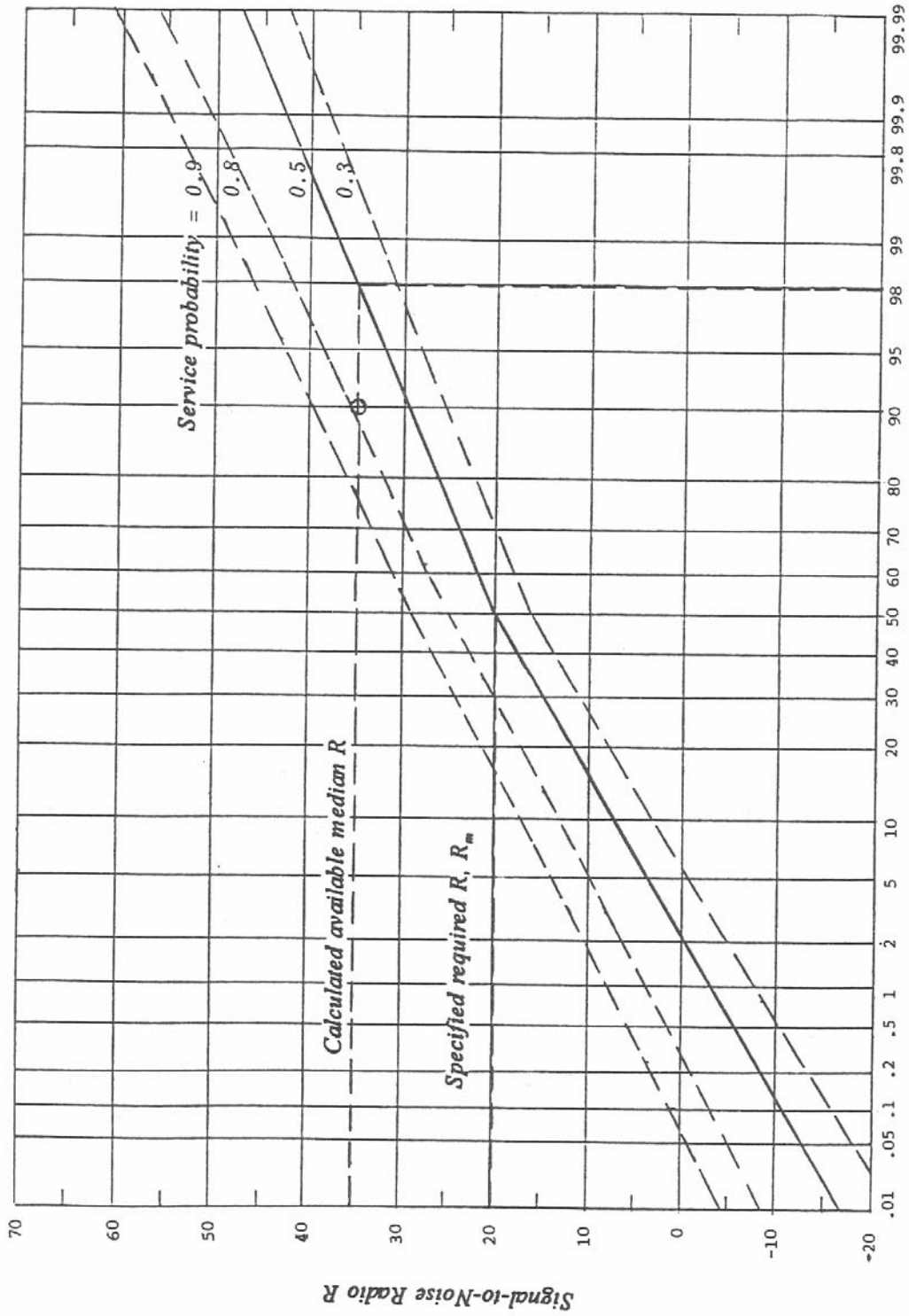
Since only log-normal distributions are involved and if we denote our (new) required signal-to-noise ratio by R_r , R_r can be determined from

$$t = \frac{R_r - R}{\sigma_T}, \tag{21}$$

where, as before, t is the standard normal deviate.

Equation 21 says $R_r = R + t\sigma_T$, i.e., $t\sigma_T$ is the "extra" signal-to-noise ratio (and also specifies the increased required signal power) to be added to increase our confidence (service probability). For 50% confidence, $t = 0$ and $R_r = R$ and we have Figure 3. Figure 6 shows the results for confidence levels (service probabilities) of 0.3, 0.5, 0.8, and 0.9 using (21). Figure 6 is like Figure 4 (and contains Figure 4 as a special case, confidence = 0.5) and is obtained using $D = R_m - R_r = R_m - (R + t\sigma_T)$. Note, now if our calculated available R is 35 dB as before, we have a reliability of 0.76 with a confidence of 90%, or a reliability of 0.88 with a 80% confidence, or a reliability 0.9955 with a 30% confidence, etc.

IONCAP does not compute reliability for a given confidence level (other than 0.5) although this makes sense statistically and probably would be a useful addition. IONCAP does have a service probability subroutine, but this is used differently. Another input to IONCAP is a "required reliability" and this is usually set to 0.9 (the default value). This required reliability is used to determine the LUF (lowest usable frequency) and to determine the required power gain or loss (RPWRG) needed to just achieve this required reliability. In IONCAP, the LUF is defined as the lowest frequency with a reliability greater than or equal to the required reliability. Also, IONCAP computes the service probability for this one required reliability (via the service probability subroutine). It does this for each mode and outputs the maximum. It does not



Time Availability (IONCAP Reliability $\times 100$)

Figure 6. The deviation $R_m - (R + t\sigma_r)$ plotted relative to the required signal-to-noise ratio R_m for various confidence levels (service probabilities)

compute the service probability for the combination of modes. In our example, Figure 6, if the required reliability was 0.9 (90% time availability), IONCAP would compute a service probability of 0.77 for our calculated available R of 35 dB. This is accomplished by noting that the "additional R" ($t\sigma_T$) at the 90% availability point is 5.5 dB, so that t is 0.72 which corresponds to a service probability of 0.77 (Figure 3).

The above example explains the system performance measure outputs of IONCAP (and, of course, VOACAP). The next sections give the inputs and outputs and the precise expressions used in the subroutines RELBIL(IF) and SERPRB(IF).

3. IONCAP SUBROUTINES RELBIL (IF) AND SERPRB (IF)

The previous section has given a system performance example to explain, in detail, the meaning of "reliability" and "service probability." This example also showed how IONCAP (and VOACAP) obtains its system performance results. In this section we want to document the functioning of the IONCAP (and VOACAP) subroutines RELBIL(IF) for reliability and SERPR(IF) for service probabilities, specifying all input parameters, and where each is obtained (from what IONCAP subroutine), the output parameters, and the means used to calculate each of these.

3.1 Subroutine RELBIL (IF)

This routine computes the reliability for each mode at a particular frequency (indexed by IF). IONCAP uses 6 modes and VOACAP uses a variable number of modes with a maximum of 20. The most reliable mode is selected. The signal distribution for the sum of all modes is determined and the reliability for this combination determined. The required power gain needed to achieve the required reliability is also determined.

Input:

IF	=	index, pointing to one of 13 frequencies in array FREL().
RSN	=	required signal-to-noise ratio in a 1 Hz bandwidth, in dB.
LUIFP	=	given required reliability (default = 0.9).
TLOSS(K)	=	median transmission loss for mode K (REGMOD, ESMOD).
TLLOW(K)	=	lower decile of transmission loss distribution for mode K (REGMOD, ESMOD).
TLHGH(K)	=	upper decile of transmission loss distribution for mode K (REGMOD, ESMOD).

FLDST(K)	=	field strength for this mode (REGMOD, ESMOD).
SIGPOW(K)	=	signal power at the receiver for mode K (REGMOD, ESMOD).
RCNSE	=	total noise and antenna efficiency at receiver (GENOIS).
DL	=	lower decile of the noise level (GENOIS).
DU	=	upper decile of the noise level (GENOIS).
SN(K)	=	signal-to-noise ratio for mode K (REGMOD) (ESMOD for sporadic E layer).
HN(K)	=	number of hops in raypath for mode K (REGMOD, ESMOD).
HP(K)	=	virtual height of reflection for mode K (REGMOD, ESMOD).
B(K)	=	radiation angle for this mode (REGMOD, ESMOD).
LAYTYP(K)	=	array of characters describing the layer type for Mode K. E,F1,F2,...(Block DATA).
PROB(K)	=	the probability that the current frequency will exceed the MUF for mode K (REGMOD, ESMOD). This is termed "F days".
TIMED(K)	=	time delay for mode K (REGMOD, ESMOD).

Output:

RELY(K)	=	reliability for current frequency and mode K.
RELIAB(IF)	=	reliability for the sum of the modes for this frequency.

DBLOSL(IF)	=	lower decile of the field strength distribution for the sum of all modes on this frequency.
DBLOSU(IF)	=	upper decile of the field strength distribution for the sum of all modes on this frequency.
DBU(IF)	=	median field strength of the sum of all modes for this frequency.
SNDB(IF)	=	median signal-to-noise ratio of the sum of all modes for this frequency.
NDBW(IF)	=	signal power of the sum of all modes for this frequency.
SNRLW(IF)	=	lower decile signal to noise ratio for the sum of all modes that go for this frequency.
SNRUP(IF)	=	upper decile of the signal-to-noise ratio for the sum of all modes that go for this frequency.
ANGLE(IF)	=	take off angle of the strongest mode that goes at this frequency.
CPROB(IF)	=	probability that the current frequency will go (PROB(K)).
DELAY(IF)	=	time delay of the strongest mode for this frequency.
DBLOS(IF)	=	transmission loss of the strongest mode for this frequency.
VHIGH(IF)	=	virtual height of the strongest mode for this frequency.
MODE(IF)	=	alpha numeric description of the strongest mode for this frequency E, E2, 2E, 2F2, etc.

NHP(IF)	=	number of hops for the strongest mode for the frequency.
NYNOIS(IF)	=	total noise = RCNSE.
SNPR(IF)	=	signal-to-noise ratio required for the specified reliability for sum of all modes and this frequency.

Subroutine procedures:

For each mode, if HP(K) > 70 km,

$$D10R = (DL^2 + DSLF^2)^{1/2},$$

$$D50R = SN, \text{ and} \tag{22}$$

$$D90R = (DU^2 + DSUF^2)^{1/2},$$

where DU, DL are the upper and lower deciles of the noise, DSUF, DSLF are the upper and lower deciles of the transmission loss (TTLOW and TTHGH) and SN is the median signal-to-noise ratio.

The reliability (Prob [available signal-to-noise ratio > required signal-to-noise ratio, RSN]) is calculated for each mode via (18). The normalized ($\mu_s = 0$, $\sigma_s = 1$, in (7)) cumulative normal distribution (standard normal deviate) is used (termed Z here) via subroutine FNORML (Z), i.e.,

$$\begin{aligned}
 \text{if } RSN \leq D50R, Z &= \frac{RSN - D50R}{(D10R/1.28)} \\
 \text{if } RSN > D50R, Z &= \frac{RSN - D50R}{(D90R/1.28)}
 \end{aligned}
 \tag{23}$$

Specifically, reliability for the Kth mode is given by (see (8)),

$$RELY(K) = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^z e^{-\frac{y^2}{2}} dy . \quad (24)$$

After the reliability for each mode is calculated, the most reliable mode is determined. The most reliable mode is selected on the following basis:

1. Reliabilities are compared.
2. If two or more mode reliabilities are "close" (within 0.05) then the one with the minimum number of hops is selected.
3. If two or more have the same number of hops (and the "same" reliabilities), then the one with the maximum predicted median signal-to-noise ratio is selected.

After the selection of the most reliable mode, the distribution for the power from the sum of all modes is obtained. This is done by obtaining the power (in watts) at the decile and median points and adding these "powers". This is not strictly correct mathematically. As noted before (9), the mean power (which adds) is not the median dB value converted to watts. Also, the sum of two (or more) log-normally distributed random variables is not log-normally distributed.

In (Spaulding and Stewart, 1987) a technique was developed to take this into account. Making a change in the addition of the modes probably would have little effect; however, this has not been verified. The decile and median value for the sum are obtained as (using 6 modes):

$$XDSLW = \sum_{K=1}^6 10^{\left(\frac{SIGPOW(K) - TLOW(K)}{10} \right)}$$

$$XSIGS = \sum_{K=1}^6 10 \left(\frac{SIGPOW(K)}{10} \right)$$

$$XDSUP = \sum_{K=1}^6 10 \left(\frac{SIGPOW(K) + TLHGH(K)}{10} \right)$$

with the decile and median values then given by:

$$\begin{aligned} \text{lowerdecile} = DBLOSL &= 10 \log XSIGS - 10 \log XDSLW , \\ \text{median} = NDBW &= 10 \log XSIGS \end{aligned} \tag{25}$$

and

$$\text{upperdecile} = DBLOSU = 10 \log XDSUP - 10 \log XSIGS .$$

Also, the field strengths are summed as,

$$DBU = 10 \log \sum_{K=1}^6 10 \frac{FLDST(K)}{10} \tag{26}$$

The reliability for the sum of the modes is calculated as in (23) and (24), now using the signal median and decile values given by (25).

Finally, the subroutine calculates the required power gain needed to achieve the specified reliability, LUF_P. This is accomplished by determining the D (15) (Figure 2) for the required reliability and using the standard normal deviate as shown in (15). A table of standard normal

deviates (DATA TME) is used. Why this is done rather than simply using the subroutines FNORMAL (YPX) is unknown. In the routine, the appropriate D for above-the-median is given by $TMX * D90R$ and by $TMX * D10R$ for below-the-median, with $TMX = t/1.28$ as in (15). The required power gain is then given by

$$\begin{aligned} \text{SNPR(IF)} &= - (D50R + TMX * D90R) + \text{RSM, above median,} \\ &= - (D50R - TMX * D10R) + \text{RSM, below median.} \end{aligned}$$

3.2 Subroutine SERPRB(SPROB)

This subroutine computes the service probability for the specified reliability. It does this as shown in the system performance example, but only for the one specified reliability. It does this for each mode and determines the maximum service probability. It does not use the sum of the modes (as in RELBIL).

Input:

LUFP	=	the required reliability expressed as a percentage. The default value is 90.
RSN	=	required signal-to-noise ratio.
DR	=	standard deviation of the required signal-to-noise ratio(prediction error set to 2dB).
SN(K)	=	signal-to-noise ratio for mode K (REGMOD) (ESMOD).
HP(K)	=	virtual height of reflection for mode K (REGMOD, ESMOD).
DU	=	upper decile of the total noise (GENOIS).
DL	=	lower decile of the total noise (GENOIS).

SIGM	=	standard deviation of the median noise (prediction error) GENOIS).
SIGU	=	standard deviation of the noise upper decile (prediction error) (GENOIS).
SIGL	=	standard deviation of the noise lower decile (prediction error) (GENOIS).
TLLOW(K)	=	lower decile of transmission loss distribution for mode K (REGMOD, ESMOD).
TLHGH(K)	=	upper decile of transmission loss distribution for mode K (REGMOD, ESMOD).
ADS	=	standard deviation of median excess system loss (prediction error) (SIGDIS).
SUS	=	standard deviation of upper decile of excess system loss (prediction error) (SIGDIS).
SLS	=	standard deviation of lower decile of excess system loss (prediction error) (SIGDIS).

Output:

SPRO(K)	=	service probability for mode K for the required reliability.
SPROB	=	Maximum of SPRO(K) for modes K=1, NMMOD.

Subroutine procedures:

The median signal-to-noise ratio deviation is computed for each mode with HP>70km for the required reliability level (see (12) and Figures 2 and 4),

$$\begin{aligned}
D50S &= (DN^2 + DS^2), \\
DN &= TMX * \frac{DU}{1.28}, \text{ LUFP} \geq 50\% , \\
&= TMX * \frac{DL}{1.28}, \text{ LUFP} < 50\% , \text{ and} \\
DS &= TMX * \frac{TLLOW(K)}{1.28}, \text{ LUFP} \geq 50\% , \\
&= TMX * \frac{TLHGH(K)}{1.28}, \text{ LUFP} < 50\% .
\end{aligned}
\tag{28}$$

Note the following

1. If the required reliability is 90% (0.9) then DN and DS are decile values.
2. In the subroutine RELIB, TMX was given by $t/1.28$, t being the standard normal deviate, while in this subroutine, TMX is t directly. TMX (here) is the "t" corresponding to the required reliability (i.e., $TMX = 1.28$ if the required reliability = 90). As in subroutine RELBIL, TMX is obtained from the data list TME, the standard normal deviate (Figure 3), $0.5 \rightarrow 0.0$, $0.55 \rightarrow 0.1257$, \dots , $0.9 \rightarrow 1.2815$, $0.95 \rightarrow 1.6649$, with selection made to the nearest 5% value of the required reliability (LUFP).
3. In subroutine RELIB, D above the median is obtained from the noise upper decile and the upper decile of the transmission loss, TTHGH. In this subroutine, D above the median is obtained from the noise upper decile and the lower decile of the transmission loss, TTLOW. This inconsistency needs investigation.

The "additional" required signal-to-noise ratio for the required reliability is calculated from the prediction errors and added to the D50S above. This sum is denoted D10S;

$$D10S = D50S + (SIGM^2 + ADS^2 + DR^2 + DNO^2 + DSO^2)^{1/2}, \quad (29)$$

where

$$\begin{aligned} DNO &= TMX * \frac{SIGU}{1.28}, \quad LUFP \geq 50\%, \\ &= TMX * \frac{SIGL}{1.28}, \quad LUFP < 50\%, \quad \text{and} \\ DSO &= TMX * SUS, \quad LUFP \geq 50\%, \\ &= TMX * SLS, \quad LUFP < 50\%. \end{aligned}$$

Finally, the service probability for mode K for the specified required reliability is computed using the standard normal deviate cumulative distribution subroutine FNORML(Z),

$$SPRO(K) = 1 - FNORML(Z), \quad (30)$$

with

$$\begin{aligned} Z &= \frac{RSN - (SN(K) - D50S)}{D10S}, \quad LUFP \geq 50\% \\ &= \frac{RSN - (SN(K) + D50S)}{D10S}, \quad LUFP < 50\%. \end{aligned} \quad (31)$$

The output then is the maximum service probability of the modes (6 in IONCAP and up to 20 in VOACAP).

4. SUMMARY AND SUGGESTED NEXT STEPS

This report has presented a detailed investigation of the reliability and service probability calculations performed by IONCAP and its derivative program VOACAP. A specific systems performance example was used to explain the precise meaning of "reliability" and "service probability." The means of calculation used and definitions for all input and output parameters of the subroutines RELBIL and SERPRB were documented in detail.

IONCAP (and VOACAP) uses log-normal distributions for the interfering noise and the received signal. This is a quite reasonable assumption and matches data reasonably well, and results in the signal-to-noise ratio being log-normally distributed. The distribution of the signal-to-noise ratio is needed to compute "reliability" and the statistical uncertainties in all the parameters used to estimate the signal-to-noise ratio distribution are needed to determine our statistical confidence in the estimate of reliability.

We have seen that "reliability" as calculated by IONCAP and VOACAP is simply the time availability expressed as a fraction (rather than a percentage) and has a statistical confidence (service probability) of only 50%. That is, the always present errors (uncertainties) of prediction are not taken into account. They are "known" however, and used in the service probability routine to compute a statistical confidence for the input required reliability, usually specified as 0.9. The following items should be addressed to improve the reliability (and other calculations) in IONCAP, and, of course, VOACAP.

1. It makes sense statistically to compute reliability for a given (input) statistical confidence which can be specified by the user. This would, however, be a rather major change in IONCAP, especially in the reliability subroutine. The existing service probability routine could not be used directly, and "combining" the two routines would appear to be somewhat involved. Also, the existing service probability routine needs investigation and correction. The above description details the procedures of subroutine SERPRB. Note that in order to obtain a meaningful result from FNORML (Z), the input variable Z must

be a standard normal deviate (as in (21)). However, Z (31) cannot be a standard normal deviate. For example, the denomination DIOS is not a standard deviation (but apparently the sum of two standard deviations) and the numerator is not the variable of concern (RSN) minus its mean value.

2. The received signal distribution needs attention. The signal distribution is essentially obtained by the transmission loss distribution. We saw that the subroutines RELIB and SERPRB use the transmission loss decile values opposite of each other. This is an error that needs investigation and correction. It was also noted that the combining of the distributions for each mode to obtain the distribution of the sum is not done correctly in RELIB. Whether improvement here would make much difference is, of course, not now known.
3. Another probable problem with the received signal is "excess system loss." This factor was apparently "added" to make predictions better match a very limited set of data. Much better values can now be obtained as much larger data bases are available. Given the questions concerning the excess system loss values, the prediction errors given as a standard deviation for the medium excess system loss and standard deviations for the excess system loss decile values, used in SERPROB, are probably guesswork and not too meaningful. In any case, the whole excess system loss question needs modem attention.
4. The CCIR (Revision 1 to Document 6A/TEMP/7-E) is proposing a simple method of computing "circuit reliability." This method needs analysis and contrasting with the IONCAP method. The proposed CCIR method, for example, takes no note of statistical confidence. It is hoped that this detailed investigation and precise definitions of reliability and service probability, in general, as well as used by IONCAP and VOACAP, will be useful and serve as a basis to now make needed improvements.

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