REPORT 266-7 *

IONOSPHERIC PROPAGATION AND NOISE CHARACTERISTICS PERTINENT TO TERRESTRIAL RADIOCOMMUNICATION SYSTEMS DESIGN AND SERVICE PLANNING

(Fading)

(Question 35/6)

(1953-1956-1959-1963-1966-1970-1974-1978-1982-1986-1990)

1. Introduction

Experience has shown that information concerning the mean value of the received signal is not sufficient for planning radiocommunication systems. The variations in time, space and frequency, collectively described as fading, also have to be taken into consideration. Fading has a decisive influence on the performance of radiocommunication systems and on the type of modulation that may be used effectively. It is essential to know the severity and rapidity of fading to be able to specify the power required for transmitters, the necessary protection ratio to guard against interference and, with additional knowledge of the correlation of signals at separate antennas or frequencies, to be able to determine the most efficient and economical diversity or coding systems. A discussion of the importance of fading in connection with frequency utilization, together with a treatment of various aspects of fading, is given in Reports 413, 414 and 415 (Oslo, 1966).

2. General causes of fading

Fading may be caused by several different effects, such as:

- movement of the ionosphere, and multipath changes causing interference fading;
- rotation of the axes of the polarization ellipses;
- variations of the ionospheric absorption with time;
- focusing and temporary disappearance of the signal due to MUF failure [Davies, 1965].

On an 8000 km north-south transmission path, long-term fading has been attributed to atmospheric gravity waves [Röttger, 1973].

As also remarked by Davies [1965], the period of the fading cycle depends largely upon the cause of the fading. As a result, the period for interference and polarization fading may last for a time of the order of a fraction of a second to a few seconds, focusing may last something like 15 to 30 minutes, absorption fading may last for more than an hour; MUF failure is highly irregular and occurs at times of fade-in and fadeout.

Experiments to observe the relative rate of fading of both reflected and scattered signals from the ionosphere have been performed in the USSR over path lengths of about 1000 km [Kerblaï *et al.*, 1974; Kerblaï *et al.*, 1977; CCIR, 1978-82].

Fading tends to be faster on high frequencies than on low, because a given movement in the ionosphere represents a greater phase shift at the shorter wavelengths. Motion of the ionized regions gives rise to selective fading and to a distortion of the modulation envelope of a signal. The motion produces changes in path length, and Doppler shifts of frequency on each of the individual contributing signal components.

3. Sampling periods

For the purpose of communication system analyses, it is not always essential to identify the individual contributory effects; instead, it is possible to observe the resulting time series and characterize the fluctuations of signal levels in time as a random or stochastic process [Brennan, 1961]. Characterization of the time series requires, first, the selection of an observation period T_s, long enough to include a sufficiently large number of fluctuations of the signal level. The choice of T_s, while somewhat arbitrary, is generally made to suit the objectives of the analysis. Thus, for HF paths, samples from a few minutes to an hour in length have been found suitable where the interest was in the fast fading; sampling periods of a month have been used to estimate the random variations of each hourly mean period in a day.

* This Report should be brought to the attention of Study Groups 3, 5, 8 and 10.

It is expedient to consider short-term and long-term fading separately. The short-term fading component includes phase interference between multipath propagation components, and rapid variations of signal strength caused by ionospheric irregularities. The long-term fading component arises from random changes in the short-term median values of the received signal. For example, long-term fading would include variations in the median field strength measured from day to day over a fixed hour. Diurnal, seasonal and solar-cycle variations are of a more systematic nature and are usually not associated with fading.

4. Severity and rapidity of short-period fading

The terms "severity" and "rapidity", as used here, refer to the characteristics of the variations of the received signal amplitude when a steady tone is emitted from the transmitter.

4.1 *Severity of fading*

The signal amplitude distribution function $P(v_0)$ conventionally employed gives the probability of finding the signal amplitude v greater than v_0. It is related to the probability density function $p(v)$ by:

$$P(v_0) = \int_{v_0}^{\infty} p(v)\, dv \qquad (1)$$

Probability density functions, obtained analytically to describe the envelope of a fading signal, differ according to the different assumptions made with respect to the structure of the contributory signals. Among the most frequently used models is the one which assumes that the received signal before detection is composed of a steady sinusoidal component and a random Rayleigh component with a uniform phase probability density [McNicol, 1949; Bramley, 1951]. This leads to the Nakagami-Rice probability density function [Nakagami, 1943; Rice, 1944 and 1945]:

$$p(v) = (2\, v/v_n^2) \exp\left[-(v_1^2 + v^2)/v_n^2\right] I_0\,(2 v_1\, v/v_n^2) \qquad (2)$$

where:

$I_0(x)$: modified Bessel function of zero order,

v : received signal envelope voltage/$\sqrt{2}$,

v_1 : r.m.s. voltage of steady sinusoidal component,

v_n : r.m.s. value of random voltage component.

Figure 1 gives the corresponding signal amplitude distribution function $P(v_0)$. Each curve represents a constant probability $P(v_0)$ that the level v_0 (shown as the ordinate) is exceeded. The abscissa is the ratio v_n/v_1, the parameter that is needed to specify a particular Nakagami-Rice distribution. For instance, if the ratio of r.m.s. random voltage to r.m.s. steady voltage equals 1 (i.e. 0 dB), then a level that is 7.5 dB below the median will be exceeded 90% of the time.

If $v_n/v_1 \gg 1$, then equation (2) reduces to the Rayleigh density function:

$$p(v) = (2v/v_n^2) \exp\,(-v^2/v_n^2) \qquad (3)$$

Figure 1 shows, however, that the actual distribution approximates closely to the Rayleigh distribution provided $v_n/v_1 > 2$ (6 dB).

If $v_n/v_1 \ll 1$, then, in the vicinity of $v = v_1$, equation (2) reduces to the normal or Gaussian distribution function

$$p(v) = \frac{1}{v_n \sqrt{\pi}} \exp\left[-\frac{(v - v_1)^2}{v_n^2}\right] \qquad (4)$$

The signal then varies symmetrically about the median value v_1 with standard deviation $v_n/\sqrt{2}$. Figure 1 shows that the distribution about the median value is almost symmetrical provided $v_n/v_1 < 0.1$ (−20 dB); the distribution may therefore be regarded as approximately normal whenever this condition is satisfied.

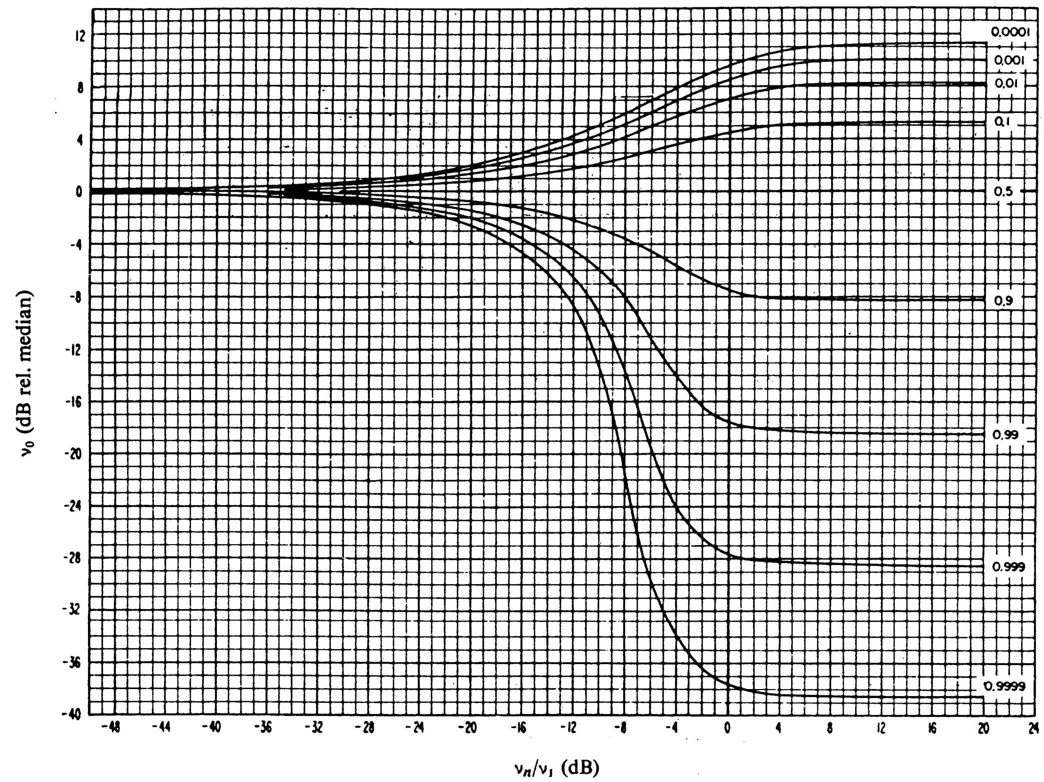

FIGURE 1 – *Distribution function P (ν_0) for the Nakagami-Rice distribution*

(The values of P(ν_0) are shown on the curves)

If the signal strength is expressed in decibels relative to a specified level the distribution referred to in equation (4) is known as the log-normal distribution. Both the normal and log-normal probability density functions may be expressed through one formula, as follows:

$$p(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma_x^2}\right) \tag{5}$$

For the normal distribution, x is to be interpreted as $(\nu - \nu_m)$ while for the log-normal distribution in dB, x is to be interpreted as 20 log (ν/ν_m), where ν_m is the median value of ν; and σ_x is the standard deviation of x.

In addition to the above probability densities, which are bound up with certain theoretical assumptions (stationary processes, random motion of secondary radiators), there are other probability density functions worth considering, because they contain several arbitrary parameters to which values may be assigned to fit the measured data. In this connection, mention may be made of the *m*-distribution [Nakagami, 1960], which is similar to the χ^2 and gamma distributions often used in statistics. The *m*-distribution is close to a Rice distribution when *m* is large and close to a Rayleigh distribution when *m* is near unity.

In reality, the received signal on operational HF radio paths is generally the result of the interaction of several signals. If these signals have arbitrary constant amplitudes and random relative phases the amplitude distribution of the sum of the n individual signals is given by Kluyver's integral [CCIR, 1986-1990a]. Specifically, for n = 2, the distribution is given by

$$p(v) = 1 \qquad \text{for } v < |v_1 - v_n|$$

$$p(v) = \frac{1}{\pi} \arccos \frac{\nu^2 - \nu_n^2 - \nu_1^2}{2\nu_1\nu_n} \qquad \text{for } |v_1 - v_n| \leq v \leq (v_1 + v_n) \qquad (6)$$

$$p(v) = 0 \qquad \text{for } v > v_1 + v_n$$

If both the amplitudes and phases of the individual contributing signals are random, the envelope fading of each of the signals can be described by equation (2). For this case the amplitude distribution of the sum has been calculated by [Sergeev, 1978a].

If n > 2, the distribution of the first case approximates to a Nakagami-Rice distribution and of the second to a Rayleigh distribution. For n = 2, however, the differences are considerable. Table I gives the levels exceeded for a number of specified percentage points for the distribution according to equation (6) together with those for the theoretical distributions discussed earlier [Norton et al., 1955].

An alternative evaluation of the empirical probability density functions of a signal envelope carried out by the method of Dyakov and Kiyanovsky [1981] on single-hop and two-hop paths [Gorshkova et al., 1985] has demonstrated the possibility of describing experimental data by theoretical laws having either one parameter based on distribution shape or none at all. The probability density functions can be adequately described by a family of curves which use a family of ß distributions, having two parameters based on shape. These curves describe practically the entire range of empirical distributions of the signal envelope [Dumbrava et al., 1988].

TABLE I

Distribution	ν_n/ν_1 (dB)	Level (dB) relative to median, exceeded for the following percentage of time			
		1%	10%	90%	99%
2 waves of constant amplitudes and random relative phase	0	3.01	2.90	-13.10	-33.07
	-3	2.88	2.78	-9.87	-12.42
	-6	2.55	2.46	-6.23	-7.01
	-9	2.12	2.04	-3.97	-4.32
	-12	1.68	1.61	-2.59	-2.78
Nakagami-Rice	0	7.02	4.48	-7.53	-17.55
	-3	6.02	3.79	-6.28	-15.49
	-6	4.91	3.03	-4.57	-11.10
	-9	3.86	2.33	-3.17	-6.96
	-12	2.95	1.75	-2.18	-4.47
Rayleigh		8.22	5.21	-8.18	-18.39
Normal and log-normal		$2.326\sigma_x$	$1.282\sigma_x$	$-1.282\sigma_x$	$-2.326\sigma_x$

Frequently in radio propagation studies, the monthly median value of the signal-to-noise ratio is known, but the probability distribution of the instantaneous value is required. The median values of signal strength, expressed in decibels, for a specified time interval (e.g. 1 h) on a series of days are normally distributed, with a standard deviation of σ dB. That is, these median values are log-normal. If the distribution of the instantaneous values about the median value during each individual time interval is Rayleigh, then the total probability distributions for all the periods can be obtained from these two distributions [Spaulding, 1982]. Figure 2 [Picquenard, 1974] shows the level below which the signal falls for given percentages of the total time, for values of σ up to 20 dB. For sky-wave propagation with no interference, σ can be found from the equation for σ_{S-N} of Sailors *et al.* [1977]. For strong signal-to-noise conditions with interference present, the equation for σ_{S-N} from the same reference can be used for σ.

Spaulding [1982] has presented computational algorithms to determine the total amplitude fading distribution for a signal composed of one or more components, each of which has Rayleigh short-term fading and log-normal long-term fading of hourly median values.

Measurements in band 6 (MF) [Spaulding, 1982], tend to show that the hourly day-to-day median values of field strength, for a given night-time hour are log-normally distributed, but that the within-the-hour short-term fading can depart from the usually assumed Rayleigh distribution.

The properties of the sky-wave field-strength distribution in the LF and MF bands show that the log-normal and the Rayleigh distributions apply only in marginal cases and that the 30 min and 60 min recording intervals follow a different distribution law when performed over several years and during various seasons [Täumer and Sulanke, 1967 and 1968].

A review of information in CCIR and other publications and new analyses of available data carried out in the United Kingdom, give values of the decile deviations of signal field strength from the median values arising from within-the-hour variability. These results yield a lower decile deviation from the hourly median field strength of about 6 dB and an upper decile deviation of about 5 dB, indicating greater consistency with the log-normal distribution than with the Rayleigh or Nakagami-Rice distributions on average.

The fading distribution obtained by averaging individual experimental estimates over 2 - 3 minute periods, depends on the ray structure of the signal. As the number of rays increases, the distribution approaches Rayleigh. Also, as the observation time increases up to 30 minutes the Rayleigh distribution is approached [Sergeev, 1978b; Sergeev and Fiks, 1982]. During longer analysis intervals (30 to 60 min), the distribution seems to follow the log-normal law rather than Rayleigh. The fading range is often defined as the difference (in dB) between the signal levels exceeded for 10% and 90% of the time, and values of 13 ± 3.2 dB [Grosskopf, 1953] and 16.6 ± 3.2 dB [Konopleva, 1964] have been given for long-distance HF paths. The value does not appear to vary greatly with path length in the range 1500-6000 km, with time of day or with season [Konopleva, 1964]. For a shorter path (650 km) and a 10-minute analysis interval, a log-normal law with a fading range of about 11 dB has been reported [Gibson, 1989].

It is of interest to note that, although the form of the measured distributions may differ from the Rayleigh distribution, the observed fading range is of the same order as the value of 13.4 dB expected for the Rayleigh distribution. However, at high signal levels the fading range has been observed to fall below the Rayleigh value, possibly due to a strong constant component term arising from a specular reflection, and distributions of the Nakagami-Rice type will apply under these conditions. The deviations of the deciles of (2 to 10) minute medians from the hourly median were also studied in the USSR. For radio links operating at f/MUF $<$ 0.85 these deviations are 5 to 7.5 dB at medium latitudes and 6.5 to 10 dB at northern latitudes [Kosikov, 1957; Khmelnitsky, 1975]. Studies have shown that the degree of fluctuation in the within-the-hour mean relative to the hourly median depends on the averaging period. For a 3000 km middle-latitude path, decile deviations from the mean hourly value of 6, 5 and 2 dB have been found for averaging times of 1, 2 and 15 min respectively [Malygin and Sergeev, 1982; Sergeev *et al.*, 1985].

Atmospheric noise data are given in Report 322. These are based on a global network of standardized measurements in which mean values were determined for a quarter-hour period each hour taken as representative of the hour in which they were made. The assumption inherent to the measurement programme is that excluding dawn/dusk transitions and local storm periods, in general there is no significant within-the-hour variation in the noise.

Information on man-made noise is given in Report 258. Mean noise power is quoted as a function of frequency for business, residential and rural environmental categories, together with the corresponding decile deviations from the hourly median field strength arising from within-the-hour variability at a fixed location. Upper decile values appropriate to HF are as given in Table II. Whereas the variability is somewhat less for rural areas at a frequency of 5 MHz, there is little difference among the other results. The median of all these values, which is also the median for residential areas, is 10.0 dB.

TABLE II – *Upper decile deviations from the hourly median field strengths for man-made noise (dB)*

Frequency (MHz)	Environmental category		
	Business	Residential	Rural
5	11.0	10.0	5.9
10	10.9	8.4	9.0
20	10.5	10.6	7.8

4.2 *Rapidity of fading*

The rapidity of fading can be characterized in different ways [McNicol, 1949; Ratcliffe, 1956; Price, 1957; Rice, 1958]. One description of fading which is useful for a number of purposes is given by the channel auto-correlation function in time or by the corresponding power spectrum.

With certain theoretical assumptions (normal distribution of the components of the velocities of the secondary radiators), a normal curve is to be expected for the auto-correlation function:

$$R(\tau) \approx R(0) \exp(-\tau^2/2\tau_0^2) \qquad (7)$$

where τ_0 is called the correlation (or coherence) time-constant of the fading channel. The corresponding power spectral density is proportional to $\exp(-\tau_0^2 f^2/2)$, a Gaussian shape with standard deviation of $1/\tau_0$. The latter is also known as the correlation (or coherence) bandwidth of the fading channel.

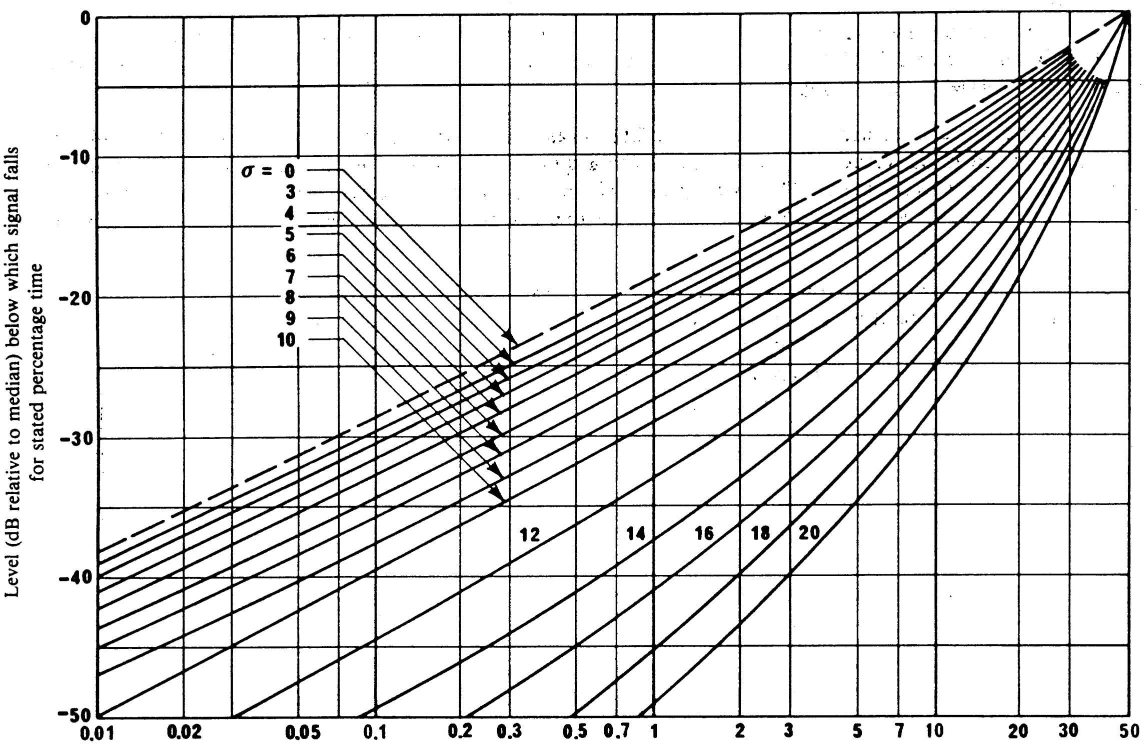

FIGURE 2 – *Level below which signal strength falls when instantaneous signal strength has a Rayleigh distribution but daily median values have a log-normal distribution, with standard deviation σ dB*

However, it is questionable whether the assumption for the velocity distribution of the secondary radiators is always justified. Therefore, the possibility of other velocity distribution functions should also be taken into consideration. These other velocity distributions can lead to other forms of the auto-correlation function as well as different Doppler spreads.

Other parameters have often been used for characterizing the rapidity of fading. There is, first of all, the fading rate defined as the number of positive crossings per unit time through any specified level.

When the signal fades according to equation (2), the fading rate through the level v is given by:

$$N(\nu) = (f_n \nu \sqrt{4\pi}/\nu_n) \exp[-(\nu_1^2 + \nu^2)/\nu_n^2]\, I_0 (2\nu_1 \nu/\nu_n^2) \tag{8}$$

where

f_n: r.m.s. frequency of fading obtained from:

$$f_n^2 = \frac{\int_0^\infty f^2 G(f)\, df}{\int_0^\infty G(f)\, df} = \frac{1}{4\pi^2 R(0)} \left. \frac{d^2 R(\tau)}{d\tau^2} \right|_{\tau = 0} \tag{9}$$

In equation (9), $R(\tau)$ is the autocorrelation function, $G(f)$ is the power spectrum of the fading process and f is measured from the mid-band frequency [Rice, 1948].

In the special case of the Rayleigh distribution, we can introduce the median value ν_m obtaining [Rice, 1958]:

$$N(\nu) = 2.95\, f_n\, (\nu/\nu_m) \exp(-0.693\, \nu^2/\nu_m^2) \qquad (10)$$

where, if $\nu = \nu_m$, it follows that $N(\nu_m) = 1.47\, f_n$. Results similar to these can be derived for various distributions of signal fading, such as the normal and log-normal distributions (equation (5)) or others. The main result is the proportionality of $N(\nu_m)$ to f_n.

Fading rates through the field-strength level exceeded for 90% of the time, were measured in the Federal Republic of Germany by recording on station WWV (15 MHz). The fading rates varied between 6 and 16 per min, the mean value being 11.25 per minute.

The rapidity of signal interference fading depends on the characteristics of the propagation modes which are determined to a large extent by the ratio of the working frequency to the maximum usable frequency [Sergeev, 1974, 1975; Malygin *et al.*, 1982]. Experimental data for middle-latitude paths of ranges up to 3000 km lead to values of the fading correlation time constant τ_0 of 2 to 18 s depending on working frequency and season [CCIR, 1982-86a]. The smaller figures are associated with times when there are multiple ray paths (for example, magneto-ionic splitting or with the Pedersen ray present). For multi-hop paths up to 6000 km range with complex ray structures, τ_0 = 3 to 4 s, with no dependence on working frequency.

On a certain proportion of days, HF paths in the tropics may show much more rapid fading than paths confined to higher latitudes [Osborne, 1952; Yeh and Villard, 1958; Bennington, 1960; Koster, 1963]. This phenomenon is associated with equatorial F-scattering and usually occurs, starting about 2000 h local time, for some two to four hours. It is likely to affect transmission paths with a reflection point in the F-region between magnetic latitudes ± 15°. Seasonal and sunspot-cycle variations occur, but may differ in nature with the path orientation. Long-distance paths appear to be affected more at the equinoxes and at sunspot maximum [Humby, 1959]. Besides increased fading rates, brief frequency changes of 20 to 30 Hz have been reported and there is a possibility that a lower frequency may be affected, but not a higher frequency [Davies and Barghausen, 1964]. More data are needed before a more exact account of the various fading characteristics can be given.

5. Long-period variations

In the case of long-period variations, the random component is usually analysed by taking hourly median values and evaluating the amplitude distribution over a long period. For simplicity, a log-normal distribution of the long-period variations is usually assumed, and often gives a good approximation to the actual distribution. A very full analysis, carried out in the Federal Republic of Germany [Grosskopf, 1953; 1955a and b] on long-period variations, showed that distribution curves for a sun-rotation period were closely log-normal for 50% of the 28 rotation periods examined; 25% could be split into two log-normal distributions, each valid over a different range of field strengths. The remainder could only be described in terms of the log-normal distribution if split up into more than two ranges.

Results for the spread of long-term variations have been analysed in a number of countries. Expressed in terms of the standard deviation σ_x of the log-normal distribution (equation (5)), the analyses mentioned above gave an average result of 8 dB, with some indication of greater values at night than in the daytime. USSR experiments at HF over paths of 1500, 3000 and 6000 km, for all seasons and times of day, have given values within the range 5 to 10 dB [Konopleva, 1964]. Any systematic change with season or between day and night appears relatively small. Results obtained in the United Kingdom for Accra-United Kingdom, Bombay-United Kingdom and Colombo-United Kingdom paths showed values in the range 5.5 to 7 dB. In certain regions, higher values may be obtained, e.g. a value of 10 dB or more may be found for paths crossing polar areas with high absorption.

Analyses of Bradley and Vernon [1982] based on theoretical studies and examination of measured data, suggest that latitudinal variability of the decile deviations exceeds the dependence on frequency. Different data are shown to be inconsistent, with some measurements giving a reduction in decile deviations with increase of frequency whilst others give an increase.

Studies of long-term fading have been undertaken in the USSR [Khmelnitsky, 1970a, 1975; Bogdanov and Segal, 1967; Blagoveschensky, 1981] for radio links operating at frequencies not too close to the MUF (up to 0.85) at medium and northern latitudes. At middle latitudes the deviations of deciles are equal to 4 to 5 dB over paths less than 3000 km and 6.5 to 10 dB over paths greater than 3000 km. At northern latitudes the deviations of deciles are 7.5 to 12 dB and 12.5 to 15 dB, respectively.

Other studies carried out on paths at medium and low latitudes have shown that the highest standard deviation σ is observed at frequencies close to the MUF (up to 12 - 15 dB). During the winter period an increase is found at the lower values of MUF at distances of 4,000 - 5,000 km; the standard deviation is variable, ranging from about 1 - 15 dB. On paths of length less than 3,700 km and for values of f/MUF from 0.3 to 0.85, $\bar{\sigma}$ = 3.4 dB; for values of f/MUF from 0.85 to 1.15, $\bar{\sigma}$ = 5.2 dB; for distances of 3,700 - 7,500 km and for values of f/MUF from 0.3 to 0.85, $\bar{\sigma}$ = 4.8 dB [CCIR, 1986-90b].

The results of HF field strength measurements in China during 1983 and 1984 on five paths (with distances from 1,000 to 7,000 km, frequencies 5 to 15 MHz) show that the average value of the monthly standard deviations of long-term fading (day-to-day fluctuations) is 4.4 dB [CCIR, 1986-90c].

In the USSR, a method has been developed for the calculation of the amplitude distributions of slow fades and their characteristics taking into account the fluctuations in MUF [Chernov, 1989]. An analytical expression has been obtained for the density distribution, which may have from one to three maxima depending on the real parameters of the MUF fluctuations and the fluctuations in signal levels in conditions when the MUF is far from the operating frequency.

A study was undertaken in the Federal Republic of Germany, ——— based on about 40 000 hourly monthly medians and their decile deviations of HF signal strength measurements. These include both single-hop and multi-hop paths covering all latitudes [CCIR, 1982-86b]. Long-term fading does not appear to vary greatly with path length, with time of day, with season, or with sunspot number. There is, however, a significant dependence on the ratio of the wave frequency to the monthly median basic MUF.

The Supplement to Report 252 provides representative values of the lower and upper decile deviations from the monthly median signal field strength arising from day-to-day changes. Figures have been determined from measured data and are quoted separately for path ranges less than and greater than 2500 km, as a function of midpath local time, season and midpath geomagnetic latitude. Information about long-period variations in the LF and MF bands is contained in Report 432.

Report 322 gives values of the corresponding decile deviations of atmospheric noise power as a function of frequency, season and local time.

No information is currently available on the day-to-day variability of man-made noise, but some changes might be expected with patterns of activity, e.g. reduced noise on rest days.

6. Fading allowances for service planning

A service planning method which makes use of a compatibility analysis will require:

- comparison of the strength of wanted signals with noise to establish whether a desired reception quality is achieved in the absence of interference; and
- comparison with co-channel and adjacent-channel interfering signals to determine if these are harmful.

Monthly median estimates need augmentation with appropriate fading allowances. These have to be considered separately depending on whether the background is atmospheric noise, man-made noise or an interfering signal, but in each case they depend on:

- the within-the-hour and day-to-day fading of the wanted signal;
- the within-the-hour and day-to-day fading of the background;
- the correlation between the wanted signal and background strengths; and
- the fraction of the time for which the desired reception quality must be achieved.

With the monthly median wanted signal/background for satisfactory reception given, it is convenient firstly to evaluate the enhancement or fading allowance $F_{b,90}$ necessary to achieve the desired reception quality for 90% of the time in the presence of within-the-hour and day-to-day fading of both the signals and background. Fading allowances for other percentages of the time may then be expressed in terms of $F_{b,90}$.

On the assumption that both the within-the-hour and day-to-day fading of the wanted signals and the background are uncorrelated, $F_{b,90}$ may be approximated [CCIR, 1982-86c] by:

$$F_{b,90} = \sqrt{S^2_{wh} + S^2_{dd} + B^2_h + B^2_d} \quad \text{dB} \tag{11}$$

where:

S_{wh}: wanted signal lower decile deviation from the hourly median field strength arising from within-the-hour changes (dB);

S_{dd}: wanted signal lower decile deviation from the monthly median field strength arising from day-to-day changes (dB);

B_h: background upper decile deviation from the hourly median field strength arising from within-the-hour changes (dB);

B_d: background upper decile deviation from the monthly median field strength arising from day-to-day changes (dB).

The First Session of the World Administrative Radio Conference for the Planning of HF Bands Allocated to the Broadcasting Service (WARC HFBC (1)) Geneva, 1984, adopted for short term signal fading the upper decile deviation of 5 dB and the lower decile deviation of −8 dB. For long-term signal fading the decile deviations were taken as a function of the ratio of operating frequency to the basic MUF as given in Table III.

TABLE III – *90% and 10% deviations from the predicted monthly median value of signal field strength (dB), arising from day-to-day variability*

Corrected geomagnetic latitude (1)	< 60°		⩾ 60°	
Transmitting frequency/predicted basic MUF	90%	10%	90%	10%
⩽ 0.8	−8	6	−11	9
1.0	−12	8	−16	11
1.2	−13	12	−17	12
1.4	−10	13	−13	13
1.6	−8	12	−11	12
1.8	−8	9	−11	9
2.0	−8	9	−11	9
3.0	−7	8	−9	8
4.0	−6	7	−8	7
⩾ 5.0	−5	7	−7	7

(1) If any point on that part of the great circle which passes through the transmitter and the receiver and which lies between control points located 1000 km from each end of the path, reaches a corrected geomagnetic latitude of 60° or more, the values for ⩾ 60° have to be used.

In principle, fading allowances should also take account of fading rate which can affect reception quality, but data to permit this are not yet available. The fading allowance $F_{b,x}$ for x% of time is conveniently given in terms of $F_{b,90}$ by:

$$F_{b,x} = c \cdot F_{b,90} \qquad \text{dB} \tag{12}$$

Values of c for x in the range 50% to 90% for a log-normal distribution of signal/background ratio, a Rayleigh distribution and intermediate composite distributions, are very similar, approximating to the values of Table IV.

TABLE IV – *The parameter c*

x (%)	c
50	0
60	0.18
70	0.36
80	0.63
90	1

7. Correlation of signals in space, time, frequency and polarization

The study of correlation between two received signals as a function of their separation in position, time, frequency or polarization can provide useful information for the design of a communication system in the presence of fading.

An alternative [Stein, 1966] to the use of increased transmitter power, etc., is the utilization of techniques of modulation and reception which are less vulnerable to fading. Most widely known are multiple-receiver combining techniques classified as diversity reception. Depending upon the mechanism of the propagation, there are a variety of ways for obtaining signals for which the periods of fading occur independently of one another, such as:

– space (spaced antenna) diversity,
– frequency diversity,
– angle-of-arrival diversity,
– polarization diversity,
– time (signal repetition) diversity,
– multipath diversity (Rake).

Of these, the last two have been considered primarily for digital transmission.

It is not within the scope of this Report to discuss the details of channel characterization and diversity methods. It can be remarked, however, that most diversity analyses have been based upon slow, non-selective fading. However, in recent years, increasing attention has been directed to fast, non-selective types of fading. Very useful data on multipath ionospheric propagation have been obtained by Balser and Smith [1962] using oblique-incidence pulse sounders, which have pulse lengths of the order of 10 to 100 microseconds.

From typical data, it is deduced that any attempt to transmit serial digital streams over long distances via the ionosphere, at a rate exceeding 100 to 200 pulse/second, without specific anti-multipath measures, will tend to result in a severe intersymbol interference problem [Stein, 1966].

Operators attempt to minimize undesirable multipath effects by using frequencies near the MUF. Another approach has been the use of highly directive automatically adjustable antenna arrays, such as the MUSA [Polkinghorn, 1940], which discriminate against certain multiple-hop paths in favour of others.

For characterizing the degree of approximation to slow non-selective fading, the *spread factor* is a useful parameter [Stein, 1966]. For information pulse length T, fading is essentially non-selective if the multipath spread T_M satisfies

$$T_M \ll T \tag{13}$$

Similarly, if the Doppler spread (the width of the received power spectrum with an unmodulated carrier) is B_D, the requirement for essentially slow fading is

$$T \ll 1/B_D \tag{14}$$

Then, to approximate slow non-selective fading, T should satisfy both equations (13) and (14), and, therefore, the spread factor L, where

$$L = B_D T_M \tag{15}$$

is required to be

$$L \ll 1 \tag{16}$$

7.1 *Diversity reception*

Considering now diversity, Stein [1966] lists among the common linear methods (which are applicable both to digital and to distortionless reception of analogue transmission):

- combination of selected signals,
- combination of signals having the maximum ratio of strengths,
- combination of signals on an equal gain basis.

Stein also discusses more sophisticated methods: decision-oriented diversity for digital transmission, in which signal fidelity is abandoned as an irrelevance, and instead minimum error-rate is established as the sole goal.

It should be mentioned that limited tests in the United Kingdom of space-diversity reception of single-sideband telephone transmission indicated only a small advantage under the conditions of the test. The correlation bandwidth was too low; the "instantaneous" amplitude of the reduced carrier was a poor indicator of the speech-band transmission. On the contrary, diversity is very effective with double-sideband amplitude-modulated telephony (carrier transmitted), and on typical telegraph signals.

Normally in ionospheric propagation, the single most important limitation is multipath spread T_M. A bandwidth, Δf, may be defined in terms of the reciprocal of T_M:

$$\Delta f = 1/T_M$$

which is similar to "coherence bandwidth", "flat-fading bandwidth" or "selective-fading bandwidth" [Stein and Jones, 1967]. Multipath spread in ionospheric propagation stems from:

- O- and X-ray transit-time differences,
- high and low ray transit-time differences,
- multi-mode transit-time differences,
- irregularity (spread F, etc.) transit-time differences,
- pulse broadening in normal reflection due to dispersion.

Pickering [1975] calculated both multipath and Doppler spread for the HF ionospheric channel. The results of these calculations led to the generation of the "Doppler reduction factor" which is comparable to the "multipath reduction factor" of Bailey [1959] and of Salaman [1962] and can be used to determine the appropriate operating frequency on a given HF link.

Early investigations of space-, polarization- and frequency-diversity were carried out prior to 1940. However, the mathematical techniques for the investigation of the theoretical and empirical aspects of diversity reception have largely been developed since 1947 [Briggs *et al.*, 1950; Booker *et al.*, 1950; Glazer and Farber, 1953; Ratcliffe, 1956].

Based upon a simple, though not completely satisfactory, model of scattering from an inhomogeneous and time-varying ionosphere, a spatial correlation function $\rho(d)$, normalized to unity at $d = 0$, may be derived to show the dependence of CW signals at two antennas spaced at a distance d [Bramley, 1951, Grisdale *et al.*, 1957; Brennan, 1960; Khmelnitsky, 1960] viz.:

$$\rho(d) = \exp\left[-d^2/2\,x^2\right] \tag{17}$$

The parameter x is a function of the structure size of the ionospheric inhomogeneities, of the path length, and the frequency. At a separation $d = x$, the correlation is 0.61 and at $d = x\sqrt{2}$, it is 0.37. At even the shorter of these distances, experience and theory have shown that, for all practical purposes, substantially all the benefits of diversity have been obtained. For example, with two independently fading signals ($\rho = 0$), the diversity improvement was 14 to 15 dB at 99.9% reliability level. For $\rho = 0.61$, the diversity improvement was 13 dB. For this reason, it appears justifiable to identify the distance $d = x\sqrt{2}$ as the "diversity separation distance" or "correlation distance".

In the United Kingdom, tests made in the frequency range 6 to 18 MHz over distances of 2000 to 17 000 km indicate that the structure size, x, was between 150 and 400 m, implying diversity separation distances of 210 to 560 m (10 to 25 λ). These findings were confirmed by recordings made in the Federal Republic of Germany on station WWV (15 MHz). In addition, it was shown that the separation distances required, when specular reflection at the ionosphere is predominant, are much greater than when a substantial random component is present.

In other United States measurements below HF, the average correlation distance at 540 kHz was 29.4 $\lambda \pm 17.1\ \lambda$ [Brennan and Phillips, 1957], while at 85 kHz [Bowhill, 1957], two distinct fading periods were observed, one of 7 min and one of 1.5 min. The correlation distance was determined to be 5 km for 7 min fading and 1 km for the 1.5 min fading.

Polarization diversity in the frequency range 6 to 18 MHz was studied in the United States of America and the United Kingdom. The antennas were at the same location, but arranged to respond to waves with mutually perpendicular polarization. The result was that the diversity action was about the same as that obtained with an equivalent space separation of 240 to 480 m [Grisdale *et al.*, 1957].

Experiments in Australia and New Guinea with nearly-vertical incidence broadcasting in the MF and HF bands have indicated that a polarization-diversity system would significantly reduce fading and distortion.

7.2 *Frequency correlation*

For the transmission of information, a band of frequencies is always required. It can be shown that, for analysis, it suffices to understand what happens to a pair of spaced tones transmitted simultaneously [Stein, 1966]. In practice, with sufficient tone spacing, the cross-correlation of the fading fluctuations at the two tone frequencies decreases toward zero. The lack of correlation in the fading of spaced tones is called *selective fading*.

An early investigation of selective fading by the use of multi-tone signals on a transoceanic path was reported in the classic paper by Potter [1930]. Other work was accomplished in the 1950's [Briggs, 1951; Price and Green, 1958].

The correlation frequency constant (correlation radius) of selective fading is generally in inverse proportion to the maximum delay between multipath rays. On middle-latitude paths up to 3000 km, the fading correlation frequency constant is between 250 and 7500 Hz depending on the ratio of wave frequency to basic MUF, reaching a maximum when that ratio is in the range 0.6 to 0.8 [Malygin and Sergeev, 1984]. However, for a 650 km path the correlation coefficient is typically 0.67 for frequency separations up to 10 kHz [Gibson, 1989].

Other studies have been carried out in China (1983 and 1984) on five paths. Analysis of the long-term fading of field strengths of different frequencies ($\Delta f \geq 900$ kHz) transmitting simultaneously shows that the average value of the correlation coefficients is 10%, with 18.4% for the same paths and 3.1% for different paths, with standard deviations of 35.1, 36.7 and 32.5% respectively. The statistical test shows that fading for different paths may be considered as being basically uncorrelated, while for the same paths there exists some correlation [CCIR, 1986-1990c].

7.3 Correlations pertinent to fading allowances for service planning

There is a need to improve the approximate expression (11) for the fading allowance $F_{b, 90}$ to take into account correlation between the wanted signal and background strengths. Information is needed for the day-to-day fading; also data relating to the correlation of signals and noise are required. Day-to-day signal fading is probably correlated over larger separations, both spatially and in frequency, than within-an-hour fading. Preliminary measurements [Gibson, 1989] indicate a high correlation coefficient (> 99.9%) for day-to-day variations at frequencies separated by up to 10 kHz, but have not yielded significant correlation for receiving sites separated by 20-100 km.

7.4 *Signal characteristics pertinent to coding*

For modern digital communications applications, diversity schemes are invariably employed in conjunction with coding of the signals. The basic form of coding is the forward-error-correction coding, or FEC coding [Wu 1971; Diffie and Hellman 1976; Fang 1975]. For FEC coding, several common assumptions about the ionospheric channel characteristics are made. The received signal is usually modelled as having an additive white Gaussian noise (AWGN) component, a shallow, instantaneous fade (< 4 dB) and an occasional deep fade (> 4 dB).

Several parameters are of primary importance: the number of bits in deep fade duration, n_1, and the number of bits in instantaneous fade duration, n_2, both of which are related to channel data rate and the dynamics of the ionosphere. The FEC coding/time diversity techniques for this type of channel basically fall into two categories. In the first category, interleavers are used to disperse the bits transmitted during a deep fade so that every bit error seems to be independent of others. An FEC code strong enough to correct most of these errors is then applied. In the second category, an FEC code which is strong enough to correct most of the errors in the time duration without a deep fade is used to ensure a satisfactory channel during the fade-free period. Further details are given by Wu [1971], Diffie and Hellman [1976], and Fang [1975].

8. Characterization of channels for modulated signals

There has been a rigorous mathematical development of theory which encompasses the characterization of channels as time-varying filters [Zadeh and Desoer, 1963]. Such an empirical development for characterization of radio channels requires a more complete identification of the total radio environment than has been possible with the limitations in the design of propagation experiments carried out so far. Although much of the theoretical background has been developed by a number of investigators [Green, 1963; Bello, 1963 and 1964], much remains to be done.

Others have contributed to this field [Turin, 1956; Brennan, 1959; Barrow, 1963; Staras, 1956; Pierce and Stein, 1960; Wozencraft, 1961; Baghdady, 1961; Bello and Nelin, 1963].

A number of models have been used for channel characterization and Report 549 deals in detail with HF ionospheric simulators. Watterson *et al.* [1970] describe one model and its experimental confirmation. Their paper also included a comprehensive list of references. The abstract of their paper is reproduced here, as an example of work on this subject:

"Specially designed HF ionospheric propagation measurements were made and analysed to confirm the validity and bandwidth limitations of a proposed stationary HF ionospheric channel model. In the model, the input (transmitted) signal feeds an ideal delay line and is delivered at several taps with adjustable delays, one for each resolvable ionospheric modal component. Each delayed signal is modulated in amplitude and phase by a gain function for each baseband tap and the delayed and modulated signals are summed (with additive noise) to form the output (received) signal. Statistical specifications for the tap-gain functions involved three hypotheses: (1) that each tap-gain function is a complex-Gaussian process that produces Rayleigh fading, (2) that the tap-gain functions are independent, and (3) that each tap-gain function has a spectrum that in general is the sum of two Gaussian functions of frequency, one for each magneto-ionic component. Statistical tests were performed on day-time and night-time measurements confirming the validity of the three hypotheses, and thereby the validity of the model. For practical applications, the model can be considered valid over a bandwidth equal to about one fourth of the reciprocal of the effective (weighted) time spreads on the ionospheric modal components. The model should be useful both in theoretical analyses of communication system performance and for channel simulator designs."

Another approach has been made by considering propagation path models which makes more precise the quantitative assessment of the possibilities for information transmission [Konopleva and Khmelnitsky, 1970; 1972]. The accuracy of this method of assessment and the possibility of basing the calculations on real channel characteristics, with regard to the variation in both wanted signal [Khmelnitsky, 1970b] and unwanted signal [Khmelnitsky, 1969] parameters should be verified using circuits of various orientations and lengths.

In Spain, measurements made of the impulse response of an HF channel [CCIR, 1982-86d] have led to the conclusion that this approach is valid for characterizing these types of channels and could even be applied to the analysis of channels in other frequency bands.

9. Further studies desirable

Continued studies, along the lines of § 7 and 8 above, particularly as applied to ionospheric paths in various parts of the world, are desirable.

For example, among the physical causes of fading, it is felt that focusing and defocusing effects [Fok, 1950; Liakhova, 1965; Rawer, 1952; Kerblaï, 1963] merit more intensive study. Since these phenomena show considerable regularity, it may be that their description can be improved over that given by present random statistical models.

With regard to improving knowledge of the severity and rapidity of fading, different theoretical approaches to the important practical problem of longer-lasting fades and field increases associated with ionospheric irregularities are needed to supplement the random statistical theory approach. Auto-correlation methods should be helpful in studying phenomena which can be described as being between regular and random.

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REPORT 892-2 *

COMPUTATION OF RELIABILITY FOR HF RADIO SYSTEMS

(Question 35/6)

(1982-1986-1990)

1. Introduction

The basic parameter given by most HF propagation prediction methods is the predicted signal power or field strength. However, as is pointed out, for example in Report 729 and in the Supplement to Report 252, signal-strength data are not sufficient to fully quantify the performance of a radio service.

A parameter of an HF radio system which may be used as a figure of merit is the predicted reliability. Reliability, in general, is defined as the probability that a specified performance will be achieved by the system. More specific definitions of the different types of reliability are given in Appendix I. A term related to reliability, circuit compatibility, is discussed in Report 657.

Predicted reliabilities are valuable in antenna-design optimization, selection of preferred combinations of frequencies, and necessary transmitter powers to achieve a desired performance. Hence accurate methods are required to estimate reliabilities and to apply these estimates in assessing radio system performance. This Report outlines the various computational methods in use. Almost all of these methods require assumptions or approximations since there are insufficient data available regarding correlation among the various modes which may simultaneously exist over a given circuit.

The reliabilities discussed in this Report form a hierarchy as illustrated in Figure 1. Mode reliability is discussed in § 3, circuit reliability in §§ 4 and 5, reception reliability in § 6 and service reliability in § 7. Path and communications reliabilities, which are relevant to HF networks, are discussed in § 9.

* This Report is brought to the attention of Study Groups 3, 8 and 10.