IONOSPHERIC PROPAGATION DEGRADATION PROBABILITIES FOR EARTH-SPACE LINKS

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ABSTRACT

Radio signals propagating between a spacecraft and ground experience various changes due to the presence of the ionosphere: Faraday rotation, propagation delay, refraction, dispersion, absorption and scintillation, with the first four of these directly dependent upon the columnar total electron content (TEC). Long-term radio-service planning requires quantification of the probabilities that user specified tolerable propagation effect levels are met. ITU-R reliability expressions for HF are extended to Earth-space propagation. Formulae are quoted giving propagation degradation probabilities under multiple-effect conditions when these may be regarded as independent of one-another or when fully correlated.

INTRODUCTION

To a first order Earth-space links are established by line-of-sight trajectories, with the various ionospheric effects representing a corruption of the free-space signals. The relative importances of these separate features, also in relation to corresponding tropospheric factors which may often dominate, will depend on frequency, geographical region and service application. For example, high-speed communication systems are principally affected by dispersion, absorption and scintillations, whereas for navigation and surveillance systems, propagation delay and refraction effects are likely to be of paramount concern. Often though significant impairments may arise simultaneously from more than one of these phenomena.

Long-term radio-service planning requires quantification of these degradations under different operating conditions. The need is then not just to derive median conditions, but also to determine the probabilities that user specified tolerable propagation effect levels are met. This means that not only must the propagation effects themselves be quantified, but also that acceptance probabilities must be specified. Past measurement data that are sufficiently extensive as to be representative need to be employed in system predictions, either on the assumption that the future will be like the past, or with incorporation of judicious trend factors. Acceptance probabilities by nature have to be subjective factors in which users balance risk with expense or importance to which they attach the service.

The Radiocommunication Sector of the International Telecommunication Union (ITU-R) has adopted in its Recommendation P. 842 [1] formulae to calculate the reliability of an HF radio system. In this context reliability is taken as the probability that a required signal/noise ratio is achieved at a receiver, and is evaluated using long-term ionosphere, propagation and noise models to determine the likelihoods of propagation support and of meeting specified required signal/background ratios. The present paper extends the ITU-R reliability expressions to Earth-space and space-space propagation where by analogy the term 'propagation degradation probability' (or PDP) is introduced to quantify system performance [2]. Evaluation of PDP is shown to require knowledge of median and decile values of the separate effects, and the extent to which these are currently known is discussed. The need is stressed for additional data collection and analyses both to refine the median values and to derive the required reference variability factors.

HF RELIABILITY AND COMPATIBILITY

ITU-R Recommendation P.842 [1] defines the terms reliability and compatibility as the probabilities of satisfactory signal reception at HF in the presence of the natural and interference backgrounds, and when co-channel and adjacent channel signals are present respectively. For a particular radio circuit and in the presence of natural noise alone the reliability is known as basic circuit reliability (BCR). When also interference is allowed for, the corresponding quantity is referred to as circuit reliability (CR). Formulae to compute these terms are given. BCR and CR are estimated in terms of predicted prevailing mean amplitudes and day-to-day variabilities of a wanted signal, and a background consisting of natural noise, man-made noise and interference, as appropriate. The required signal/background level must be specified. Compatibility is similarly determined from the mean amplitudes and variabilities of a wanted signal and a co-channel or adjacent channel unwanted signal. In this case, the protection ratio between wanted and unwanted signals must be chosen.

The determination of the signal components of BCR for a point-to-point HF radio circuit is a two-stage process. Firstly the probability of ionospheric signal support has to be evaluated using reference maximum usable frequency (MUF) day-to-day variability statistics, and then given that propagation is possible, the probability has to be assessed that a required signal/noise ratio is met. The ITU-R has adopted separate reference decile-to-median ratios (fractional decile deviation values) of maximum usable frequency for different geographical areas and seasonal groupings [3]. Decile day-to-day deviations of signal strength from the monthly median values used in Recommendation P. 842 are given separately as a function of the ratio of transmitting frequency to predicted MUF for paths with mid-points below or above 60° geomagnetic latitude. Upper decile deviation values lie in the range 6-13 dB and lower decile deviation figures are between 5-17 dB. These values are combined on an rms basis with the corresponding within-the-hour signals and with the day-to-day and within-the-hour variations of the background, so that thereby the upper and lower decile deviations, D_uSN and D_lSN respectively of the signal/background ratio, are given. For natural noise alone and with monthly median signal/noise ratio S/N, then, following Bradley and Bedford [4], for a required signal/noise ratio S/N_r and with all quantities expressed in decibels, the BCR as a percentage is given as:

$$\begin{aligned} BCR &= 130 - 80/(1+(S/N-S/N_r)/D_lSN) \text{ or } 100, \text{ whichever is smaller} \qquad \text{for } S/N \geq S/N_r \\ &= 80/(1+(S/N_r - S/N)/D_uSN) - 30 \text{ or } 0, \text{ whichever is greater} \qquad \text{for } S/N < S/N_r \qquad (1) \end{aligned}$$

It is of note that for a particular transmitter-receiver path, separate reliability and compatibility values are derived because of changes in signal propagation and background levels for the different hours, months and solar epochs. So in choosing system parameters, eg transmitter power and types of antennas to achieve a desired service performance, there must also be subjective specification of what that desired service performance is. This is referred to as service probability. The service probability might for example be derived from just night-time predictions over only a few months of a particular year, or it might embrace all hours over a full sunspot cycle, depending on the operational requirement.

PDP FOR EARTH-SPACE PATHS

In the case of Earth-space or space-space paths the situation is somewhat different in that the need is to determine the probabilities that user specified tolerable propagation effect levels are met, rather than signal/noise values being achieved as at HF. Nonetheless, formulae to determine position within the associated probability distributions are the same in the two cases. So, instead of, but by analogy with BCR, here the term propagation degradation probability (PDP) is judged more appropriate for space paths.

Expressions are provided enabling estimates of the probabilities of occurrence of user-specified values to be derived in terms of their median quantities and day-to-day variabilities. For an effect ε we may write, by analogy with (1):

$$\begin{aligned} PDP_\varepsilon &= 130 - 80/(1+(\varepsilon_m-\varepsilon_r)/D_l\varepsilon) \text{ or } 100, \text{ whichever is smaller} \qquad \text{for } \varepsilon_m \geq \varepsilon_r \\ &= 80/(1+(\varepsilon_r - \varepsilon)/D_u\varepsilon) - 30 \text{ or } 0, \text{ whichever is greater} \qquad \text{for } \varepsilon_m < \varepsilon_r \qquad (2) \end{aligned}$$

where ε_m is the median value, $D_l\varepsilon$ and $D_u\varepsilon$ are reference lower and upper decile deviations from the median for effect ε and ε_r is the required value that must not be exceeded. In particular, with the reference decile deviations assumed given, (2) requires knowledge of both the median and required values. The justification of this formulation, particularly for the distribution tails, is considered to be totally valid in relation to other prediction uncertainties.

AVAILABLE REFERENCE TEC MEDIAN AND DECILE-DEVIATION INFORMATION

At this stage it would appear premature to seek to specify reference absorption and scintillation values under all conditions for use with the above technique, so here attention is restricted to a survey of TEC-dependent features. For many years a large number of research groups have been measuring and quantifying vertical TEC to various heights in different parts of the world. Median values are being generated with the objective of developing a universally adopted reference TEC base covering all required geographical regions and time frames [5]. Alternative methods of determining TEC by electron-density height-profile integration are offered, using either the International Reference Ionosphere (IRI) produced by a COSPAR-URSI Task Group [6] or the models NeQuick [7] and COSTTEC [8] developed within COST251. The IRI model applies only for heights up to 2000km whereas NeQuick, still under revision within COST271 [9] and with its allied models COSTprof and NeUoG-plas now includes a plasmasphere topside [10]. Use of the IRI or NeQuick models enables median TEC to be given separately for ray paths in different geographical regions, and to show the dependence on time-of-day, season and epoch of the solar cycle, for the near full range of conditions for which they apply.

There are two independent approaches to TEC determination, the one involving profile integration as mentioned above, and the other from direct measurement of spacecraft signals. The latter method enables full allowances for electron content at the greater heights, but available data lack universal coverage. There are a range of approaches which aim to normalise globally available TEC models derived from electron-density height profile integrations with direct spacecraft measurements conducted at just a few locations over limited periods of time. Various methods of combining the two data sets are being investigated within COST271 [11]. These include use of incoherent-scatter radar standardisation of GPS TEC-derived values, ionospheric tomography and occultation techniques. It seems then likely that improved median TEC specifications will emerge in due course, in particular providing more realistic figures with greater spatial resolution than hitherto.

Efforts are also currently being expended by several groups aimed at characterising TEC temporal variability. For use in estimating Earth-space propagation degradation probabilities by the above techniques, what are needed are the ratios of upper decile to median TEC and of lower decile to median TEC arising from day-to-day variability at a given location, time-of-day, season and solar epoch. Moreover, it seems probable that these decile TEC would better come from limited direct measurements, rather than from profile integration, because in the profile case although the variabilities of the separate ‘anchor values’ such as layer peak densities and heights are generally well known, the correlations in the changes among them are not established. In the absence of adequate direct information, it is here suggested that provisionally TEC fractional decile variability be taken as twice the foF2 (or maximum usable frequency, MUF) fractional variability for which reference values already are available [3,12]. (This relationship ignores day-to-day changes in equivalent ‘slab thickness’). Tables give upper and lower fractional deviation values of MUF for three bands of solar activity, three seasons and 10° geographical latitude bands independent of longitude for each 4 hours of Local Time. A particular feature of these results is that decile-to-median ratios tend to be more stable with space and time than median values, yielding TEC D_u in the range 1.18-1.94 and with D_l between 0.2-0.84.

PDP FOR SPACE-SPACE PATHS

Ionospheric effects may be estimated from ray-tracing results through an appropriate ionospheric model such as NeUoG-plas to derive the corresponding TEC values on satellite-to-satellite paths [13]. At this time it is not clear how median TEC may be characterised, but some amalgamation of separate results to give representative figures will no doubt be necessary. Despite variability between cases, it ought to be possible to provide results whereas none are currently available. Likewise, the study of TEC variability on space-space paths remains to be carried out.

COMBINING PDP VALUES FOR DIFFERENT PROPAGATION EFFECTS

Signals received over an HF point-to-point ionospheric path experience time spread and frequency dispersion as well as attenuation due to passage through the ionosphere. Hence, particularly in the case of digital transmissions, circuit performance criteria have to take account not only of the probability of achieving a user-specified required signal/background ratio, but also specified time spreads and frequency dispersions that must not be exceeded. Bradley and Muhtarov [14], first proposed via ITU-R contribution [15], have developed formulae to combine the BCR values for each of these effects on the assumption that they are independent of one-another. For effects ε_1, ε_2 and ε_3 we have that the combined BCR is:

$$BCR = BCR_{\varepsilon 1} \, . \, BCR_{\varepsilon 2} \, . \, BCR_{\varepsilon 3} \tag{3}$$

Adaptation of this formulation may also be applied to evaluations for Earth-space and space-space paths when considering independent effects such as absorption and scintillation, leading to:

$$PDP = PDP_{\varepsilon 1} \, . \, PDP_{\varepsilon 2} \, . \, PDP_{\varepsilon 3} \tag{4}$$

but in the case of effects directly dependent on TEC, these have to be regarded as completely correlated, and the PDP is taken as the smallest of those separately evaluated for the different effects.

COMBINING PDP VALUES FOR DIFFERENT TIMES AND PATHS

Propagation degradation probabilities may be determined as wanted. Estimates may be used either to predict the performance of an established circuit, or to permit the design specification to meet stated performance objectives. In either case values are likely to need combining for different times and different satellite locations. This means that criteria to be achieved may well involve multiple effect tolerances for stated fractions of days, hours, months and years, as well as for a certain percentage of satellite positions. An example of a performance specification might be that the group delay must not exceed 0.2μs for more than 5% of the nights between March 2003 and September 2005 for a polar-orbiting satellite over 90% of the world ocean area. The formulae given above permit these types of figures to be derived. On the other hand, it can be appreciated that for some applications, having regard also to uncertainties in ionospheric predictions, a single all-embracing effect estimate achieved say for 95% of occasions and covering all times and satellite locations combined might be favoured. This is a matter of user choice.

CONCLUSIONS

The concept of basic circuit reliability (BCR) developed to characterise the probability that the signal/noise ratio for an HF circuit attains a required threshold is extended to Earth-space and space-space paths giving the propagation degradation probabilities (PDP) that acceptable levels are achieved of the different propagation effects related to total electron content (TEC) such as refraction, dispersion and Faraday rotation, as well as arising from ionospheric absorption and scintillation. Formulae are quoted to evaluate PDP when multiple tolerance criteria must be met, both for uncorrelated and fully correlated effects. Available median TEC models are outlined. The particular need is identified for the production of reference decile deviations of TEC from the monthly median values, and it is concluded that such information will best come from analyses of direct measurement data, rather than from electron-density height profile integration. In the mean time, first-order estimates are shown to be possible from existing international foF2 decile deviation values.

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