

PROPAGATION AT FREQUENCIES ABOVE THE BASIC MUF

(1997-1999)

1 Introduction

Recommendation ITU-R P.373 defines the basic MUF as “the highest frequency by which a radio wave can propagate between given terminals, on a specified occasion, by ionospheric refraction alone”. The Recommendation also recognizes that this does not necessarily define the maximum transmission frequency for those circumstances, since a definition is also given for the operational MUF. The operational MUF is taken to be the highest frequency that would permit acceptable performance at a given time under specified working conditions.

The various mechanisms which may contribute to propagation above the basic MUF (here for convenience referred to as ABM propagation) are described in § 2. However the situation is complicated for two main reasons:

- the definition of the basic MUF implies that this is determined by extraordinary mode propagation, taking no account of any differences in signal amplitude from that of the ordinary mode;
- for ITU-R purposes it is necessary to predict signal intensities; such predictions have their basis in monthly median maps of ionospheric characteristics and the instantaneous values of basic MUF will not be known. Moreover the day-to-day variability in ionospheric characteristics may result in the frequency used for communication being above the basic MUF on some days and below on others.

It may be noted that instantaneous basic MUFs may only be determined from the examination of oblique-incidence ionograms measured along the propagation path. Approximations to such values may be obtained from well-placed vertical-incidence sounders along the great-circle path, assuming ionospheric homogeneity or specific horizontal gradients. Real-time channel-evaluation systems will not generally give a clear indication of the basic MUF.

2 Propagation mechanisms responsible for propagation at frequencies above the basic MUF

Propagation mechanisms and ionospheric characteristics which may give rise to ABM propagation are as follows:

2.1 Ionospheric roughness

The ionosphere is always likely to contain spatial inhomogeneities over the volume responsible for reflection of the bulk of the components contributing to the received signal power. These inhomogeneities can occur at all heights, and all those below the height of ray reflection may be significant. Under benign conditions, spatially random electron-density fluctuations will have intensities that vary with both position and time. Large changes arise for example during the presence of travelling ionospheric disturbances. Theoretical studies have been conducted using model ionospheres representative of average mid-latitude conditions. In these studies the ionospheric fluctuations were taken to be of a turbulent type with spatial correlation function of Kolmogorovian form and a diffraction analysis in terms of stochastic (fluctuational) and coherent components lead to the conclusion that significant signal intensities due to this mechanism arise only over frequencies up to some 60 kHz above the basic MUF, which is a smaller frequency extension (see below) than that typically observed in practice.

Under other conditions, intense but spatially contained ionospheric irregularities may be present, such as those responsible for the phenomenon of spread-F observed on vertical-incidence ionograms. Spreading in either range or frequency may permit propagation by refraction or scatter at frequencies above the basic MUF for the average region of the ionosphere. This phenomenon is observed on some oblique-incidence ionograms where the maximum observed frequency is determined by a “nose extension” beyond the junction frequency of the low- and high-angle rays. Ionospheric irregularities may be expected to have electron densities proportionate to the bulk ionosphere, so that such frequency extensions would be enhanced the greater the basic MUF.

2.2 Ground back- and side-scatter

Off-great-circle propagation, involving two ionospheric hops and intermediate scattering at the Earth's surface, may permit propagation at frequencies beyond the great-circle basic MUF. Such scatter signals often have fading rates greater than 1/s and are received with variable azimuth angles of arrival. Signal strengths gradually decrease to 25-40 dB less than that of the great-circle mode as the propagation paths progressively deviate from the great circle. Scattering coefficients of the Earth's surface may be quite variable, depending upon the nature of the surface and the elevation angle. The ground-scatter coefficient is a function of azimuth and azimuth difference between the down-coming and upgoing rays, the presence of land or sea, the ground roughness, elevation angles and also upon focusing due to ionospheric curvature for grazing-incidence angles. There have been conflicting observations concerning the intensities of signals scattered from the sea as compared with those from land. The intensities of back- and side-scatter signals at frequencies above the basic MUF for the great-circle path will depend on their respective path lengths, and will vary in proportion to their respective basic MUFs. The lowest path loss should normally occur for the beam of intersection of the skip distances around the transmitter and receiver because of skip-distance focusing. However, in practice the directivities of the transmitting and receiving antennas can influence the bearing of the maximum received signal strength. It has been suggested this is the dominant mechanism responsible for ABM propagation for single-hop shorter paths of up to 4 000 km length.

2.3 Higher-order mode back-scatter

As an extension of the two-hop ground back-scatter case, there may be back-scatter from longer ranges, involving multiple-hop propagation. This phenomenon is likely to be more important where there are significant ionospheric horizontal gradients in electron density.

2.4 Ducted modes

In some instances low-angle radiation may be able to enter into ducts formed by particular electron-density height profiles. In such cases, propagation may be possible to long ranges and at higher frequencies than given by the great-circle basic MUF. This mechanism, combined for instance with off-great-circle ground back- and side-scatter, may contribute to ABM propagation.

2.5 Chordal-hop propagation

Tilts in the ionosphere, most notably on either side of the magnetic equator, but also in the sub-auroral troughs, may permit ray paths which proceed from refraction in one region to another without an intermediate ground reflection. Trans-equatorial propagation of this kind has been observed to extend to frequencies well into the VHF range, often accompanied by a scatter-mode signal associated with the presence of ionospheric irregularities. Such signals, especially when combined with ground back- and side-scatter, may give rise to significant propagation above the basic MUF.

2.6 Direct ionospheric scatter

Signal energy may be scattered from any of the ionospheric regions, both along the great-circle path and at other orientations. In high, auroral and equatorial latitudes strong ionisation density gradients may permit significant F-region scatter, but where there are no such strong gradients, scatter from the E-region is likely to be more important, and in this case would be limited to ranges of about 2 000 km. The ionospheric scatter mode is discussed in detail in ex-CCIR Report 260-2 (1974) (now formally deleted). That Report indicates, at least for frequencies above 30 MHz, that the signal intensity varies as the inverse 7.5 power of the frequency.

Ionospheric side-scatter from F-region irregularities located in the auroral regions has been reported by several workers. In some cases the non great-circle signals are attributed to direct scatter from ionospheric irregularities in the absence of an ordinary type of ionospheric reflection. In other cases they are considered to result from multi-hop modes with the strongest scatter signals being generated by ionospheric irregularities and involving a focusing mechanism. On trans-equatorial paths azimuthal deviations of up to $\pm 50^\circ$ have been observed that are confirmed as due to direct scattering from F-layer inhomogeneities near the Earth's magnetic equator. The dominant scatter signals have been attributed to weak field-aligned irregularities, or to specular reflection at horizontal gradients of electron density.

2.7 Sporadic-E propagation

The occurrence of sporadic-E ionisation may permit propagation, either by partial reflection or scatter, to significantly high frequencies. This mode may not be recognized, and is in any case not included in most prediction procedures. Thus it may be considered as a further contributor to propagation above the expected basic MUF, on path lengths up to 2 000 km.

2.8 Auroral scatter

Field-aligned irregularities in the auroral regions, associated with geomagnetic disturbances, give rise to a special kind of sporadic-E. Over propagation paths near the auroral regions such E-region irregularities can give direct back-scatter of signals at frequencies up to 100 MHz or higher. These signal components have been modelled in terms of both weak scattering and critical reflection. Reflections from such irregularities have to obey particular conditions of specularity. The volume scattering function has been approximated by an exponential frequency function. Although multi-hop propagation has been observed, the effect will generally be limited to path lengths less than 2 000 km.

2.9 Meteor scatter

Propagation utilizing reflection or scatter from transient meteor ionization is addressed in Recommendation ITU-R P.843. With the appropriate geometrical circumstances, short duration propagation events may occur well into the VHF range for path lengths less than 2 000 km.

3 Measurement data already collected and needed

Much of the limited measurement data which exist comprise examples of variations of signal intensity with frequency, or with time as the basic MUF changes, over specific paths. Measurements over a range of paths with lengths between 400-2 580 km are described by Hagn *et al.* [1993].

Existing measurement data alone, together with present information, are insufficient for the establishment of comprehensive models which would include the dependence on path length, location, time, etc.

More, and new types of measurement information are urgently needed. Particularly there is the requirement to establish the dependencies and pattern of changes in propagation mechanisms in the different geographical regions with time-of-day, season, solar epoch and degree of ionospheric disturbance.

4 Statistical models of signal intensity at frequencies above the basic MUF

The ITU-R data banks (Recommendation ITU-R P.845) include observations of signal intensity at frequencies above the basic MUF, although the values of basic MUF corresponding to each measurement are unknown and could not have been determined without special additional measurements. Ideally, simultaneous oblique soundings should be carried out over the propagation paths involved, but generally that has not been possible. Accordingly, results have to be considered on a statistical basis.

It may be noted that the day-to-day variation within a month of the basic MUF at a given hour will have an inter-decile range of 30% to 40% of the median basic MUF. Frequencies used for communication within this range will on some days be below the basic MUF and on other days above. However, long-term prediction models must take as a starting point the monthly median basic MUF. Thus the modelling of these circumstances will seek to combine the signal intensity for a refracted path at a frequency just below the monthly median basic MUF with the contributions to ABM propagation described above, and then to include the statistics of day-to-day variability. Supposing that on a given occasion a propagation mechanism exists yielding weak signals above the basic MUF, then day-to-day changes in basic MUF mean that the various formulae discussed below for above-the-MUF loss in terms of monthly median basic MUF must include an unspecified element to allow for the fact that some days the basic MUF is below the monthly median value.

Besides day-to-day variability, the ionosphere also experiences within-an-hour changes. These changes can result in propagation being maintained by conventional means for part of an hour and in ABM propagation taking place for other parts of the hour. This situation is particularly the case when travelling ionospheric disturbances are present. Skip-distance focusing and fading associated with the interference between low- and high-angle rays can arise, but all such effects have to be treated statistically using hourly median basic MUF estimates.

The approaches adopted will give a probability estimate that signal intensity will occur, and this may be appropriate for the assessment of compatibility. However it may be inadequate for the prediction of circuit performance where the channel-transfer function in terms of fading rate, the time-delay spread, and the frequency spread and shift may be different for frequencies below and above the basic MUF.

5 The definition of ABM loss

The reduction in signal intensity at frequencies above the monthly median path basic MUF, as compared with the intensity for a refracted path at a frequency just below the basic MUF, is referred to as the ABM loss.

6 Existing loss formulae

The various formulae which have been proposed for ABM loss are described by Hagn *et al.* [1993].

6.1 The Phillips-Abel model

This model [Phillips, 1963], based on measurements made in the United States of America, is the only currently available model which can be considered to relate to instantaneous values of the basic MUF, although in its implementation it is usually assumed to apply in terms of the monthly median basic MUF. The model assumes that the ionosphere is composed of a number of ionisation patches within the region of reflection, each of which would yield a different path basic MUF. These MUFs are assumed to be spatially normally distributed with standard deviation σ . Phillips indicated for a path length of about 3 000 km that σ ranged between 1 MHz and 4 MHz dependent on the degree of ionospheric disturbance. Subsequent measurements by Wheeler and Hagn yielded values of σ between 0.9 MHz and 3 MHz. Received signal power is taken to be given in terms of the spatial probability of wave reflection.

In this model, ABM loss L_m (dB) is given as:

$$L_m = 10 \log p$$

where:

$$p = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x/a} \exp(-x/2\sigma) d(x/a) \quad \text{and } x = f - f_b$$

Note in particular that this formulation indicates that L_m depends on the difference between the working frequency, f , and the basic MUF, f_b .

Modified versions of the Phillips-Abel formulation are implemented in current US HF propagation prediction procedures IONCAP [Teters *et al.*, 1983] and VOACAP [DeBlasio *et al.*, 1993]. ABM loss is separately determined for each active propagation mode using the above formulae in terms of the corresponding monthly median basic MUFs and supposing that the spatial variability parameter σ is the same as the standard deviation of the daily basic MUFs.

6.2 The Suessmann model

The model of Suessmann [1990] is based on assumed two-hop ground-scatter and analysis of measurement data contained in Data Bank D1 of Recommendation ITU-R P.845, leading to the expression for ABM loss on paths up to 4 000 km range of:

$$L_m = 20 + 40 [M(d) + 1 - f_b/f] \quad \text{dB}$$

where $M(d)$ is the MUF-factor for path length d .

6.3 The Hunt model

Using separate analyses applied to Data Bank D1 Hunt [1991] formulated the expression for ABM loss for path lengths up to 9 000 km of:

$$L_m = 36 (f/f_b - 1)^2 \quad \text{dB}$$

with a maximum value of 62 dB.

6.4 The Gibson-Bradley model

This model [Gibson and Bradley, 1991 and Gibson, 1993], unlike other available models, relies on theoretical calculations in terms of two-hop ground back- and side-scatter, rather than comparisons with measurement data. The calculations involve finding an expression for the HF scattering cross section of the Earth's surface per unit area as a function of the elevation angles of the incident and scattered waves and the azimuthal scattering angle. Scattered power is integrated from all elements of the surface for which the operating frequency is less than the lower of the basic MUFs of the two paths between transmitter and scattering element and between receiver and scattering element, and is referenced to the power at a frequency just below the great-circle basic MUF. The dependence of scattering cross section on different scattering surfaces, second-order processes and the effects of differing antenna gain may all be taken into account. It is suggested that whereas use of the monthly median basic MUF in the various equations leads to evaluation of the monthly median ABM loss, alternatively upper or lower decile basic MUFs within the day-to-day variability give the corresponding decile ABM losses.

For a 2 000 km path with $f/f_b = 1.4$ the Gibson-Bradley model gives $L_m = 80$ dB whereas the Suessmann model yields a figure of 53 dB for such a situation. Differences of this order should be resolvable using measuring equipment instrumentation having adequate dynamic range.

6.5 The Recommendation ITU-R P.533 model

For ranges up to 7 000 km, Recommendation ITU-R P.533 predicts the value of L_m for each of the propagation modes considered, prior to performing a power summation to obtain the overall field strength. The criteria for the consideration of each potential mode are indicated in the aforesaid Recommendation, and for these modes L_m is given by:

$$L_m = 0 \quad \text{dB}$$

when $f \leq f_b$ for the mode being considered.

For E-modes (up to a maximum range of 4 000 km) and as adapted from Wheeler [1966], when $f > f_b$:

$$L_m = 130 \left[\frac{f}{f_b} - 1 \right]^2 \quad \text{dB, or 81 dB whichever is the smaller.}$$

For F2-modes (up to a range of 7 000 km), when $f > f_b$:

$$L_m = 36 \left[\frac{f}{f_b} - 1 \right]^{1/2} \quad \text{dB, or 62 dB whichever is the smaller.}$$

The model does not specifically include ABM loss for ranges greater than 9 000 km.

Note that again here L_m is dependent on the ratio of the working frequency, f , to the basic MUF, f_b rather than on frequency difference.

7 Factors to be considered in further development of ABM loss formulations

7.1 The magneto-ionic mode to be assumed for the determination of the basic MUF

Recommendations ITU-R P.533 and ITU-R P.1240 utilize the predicted monthly median o-wave mode for the determination of E-region basic MUF. At very short distances the F2-region basic MUF is given for the x-wave; for path lengths of 4 000 km and beyond the o-wave basic MUF is quoted, and for intermediate distances a composite mode basic MUF applies. (The relationship between o-wave and x-wave basic MUFs depends on magnetic latitude, path orientation and length). These may represent the best available frequency references for ABM loss formulations, but this supposition should be confirmed.

7.2 Amplitude reference

ABM loss is assumed to be 0 dB at frequencies below the monthly median basic MUF for the mode. Thus, following Recommendation ITU-R P.533, it seems appropriate to predict ABM loss empirically with respect to the predicted field strength or signal intensity for the monthly median basic MUF, and to suppose that all other transmission loss and gain factors, such as for example those associated with ionospheric absorption and antenna performance, are frequency insensitive. This amplitude reference seems appropriate for formulations based on the presently used concepts, but other references may be preferable if models are formulated in different ways. For example, signal amplitude drops when o-wave mode support ceases as frequency is increased and propagation is maintained by means of the x-wave. A case could perhaps be made for taking as the amplitude reference that at a frequency somewhat below the o-wave basic MUF for which there is no skip-distance focusing.

7.3 Frequency-scaling factor

As noted above, the Recommended procedure uses the ratio of the basic MUF to the working frequency, whereas the Phillips-Abel method uses the frequency difference. The various separate mechanisms described in § 2, seem likely either to depend on the ratio of the frequencies, or to vary with absolute frequency independent of the basic MUF for the path. Thus at HF it seems appropriate to base a composite formulation on the ratio of frequencies. If methods are prepared for compatibility assessments at VHF, then it may be more correct to use a formulation which does not include the basic MUF for the path.

7.4 Path-length dependence

Present methods do not include a dependence upon path length. However it seems likely that different mechanisms will predominate for path lengths less than 2 000 km, where E region modes are important, as compared with those for longer path lengths, where the ratio of path MUF to 4 000 km MUF may be important.

7.5 Allowances for transmitting and receiving-antenna gain

Many of the mechanisms described in § 2 become more important for low elevation angles. Thus propagation above the basic MUF may be less important when high elevation angle antennas are employed. This effect could be included in a general way by modifying the distance dependence for ABM loss for short path lengths, with the assumption that appropriate antennas will be employed for the wanted path.

Apart from the mechanism due to ionospheric roughness, for which the frequency ratio extension may be rather limited, and the mechanism due to direct ionospheric scatter, most of the phenomena discussed are likely to involve off-great-circle propagation. Further studies are needed to determine whether the antenna gain along the great circle, the maximum antenna gain, or some function of the antenna gain, should be used.

8 Quality of ABM signals for reliability and compatibility considerations

Some of the mechanisms described in § 2 do not require significant ionospheric roughness or irregularities, but depend upon normal propagation in conjunction with ground back- and side-scatter. In these cases it is likely that the channel-transfer function will be rather similar to that for propagation at frequencies below the basic MUF, although the presence of multiple propagation paths will always tend to create a “smeared” transfer function.

On the other hand, particular propagation mechanisms may be very significant in certain scenarios, for example at equatorial and high latitudes, and in magnetically disturbed conditions. In these cases, the transfer function may contain rapidly varying and large time and frequency spreads. Then it may be expected that the quality of speech and particularly of music would suffer, especially for double side-band modulation with envelope detection. The performance of digital modulation systems will depend upon the modulation design and the signalling rate.

Thus, dependent on the sensitivity of the modulation method to these effects, it may be appropriate to formulate the determination of the maximum frequency for planning a wanted service upon the basic MUF, while interference assessment for compatibility purposes may involve a higher frequency which will include ABM propagation.

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