Propagation Models

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Abstract:
The propagation of radio frequency energy at the surface of the Earth poses scientific and regulatory issues for users of the spectrum: decisions are often based on results obtained from propagation models. This paper introduces the context which models have to represent, outlines their role and purpose, as well as introducing several of the more popular models.

1. Introduction

The propagation of radio waves at the surface of the Earth is both the reason for their use in communication systems, and at the heart of spectrum management, as it introduces a need for regulation to protect different services with some degree of geographical proximity. This in turn is very frequency dependent, and can be affected by a diversity of other factors, such, for instance, as the physical terrain or reflection from the ionosphere. There is consequently a host of ITU regulations pertaining to the definitions of relevant terms, to aspects of radio propagation in ionized and neutral media or around obstacles, and on how to model the variety of situations occurring in practice. These recommendations are listed in the Appendix. The purpose of this paper is to touch on the key aspects affecting the propagation of radio waves, so we appreciate the circumstances that need to be modeled, and can then briefly consider the salient features of several of the more popular models.

2. Modes of propagation & propagation loss

(a) *Free space propagation* is the simplest, as the intensity of radiation is then frequency independent and decreases as the inverse square of the distance, D, from the transmitter. The received pfd (W m^{-2}) = $P / (4 \pi D^2) = 10 . \log (P) - 11 - 20 . \log (D)$ in dBW, where P is EIRP (Watts). The EIRP (Watts) is similarly related to the electric field strength, E (V m^{-1}), by $E = \sqrt{(30 . P)} / D = 173 \sqrt{P} / D$, where D is in meters. Finally the received pfd (W m^{-2}) = $E^2 / Z_o \equiv E^2 / (120 . \pi)$, with Z_0 the characteristic impedance of free space.

(b) *Free space loss.* While the translation from EIRP (W) to pfd (W m^{-2}) is frequency independent, the loss in the transition from an isotropic transmitting antenna propagating to an isotropic receiving antenna increases as frequency squared, so

$$P_{rx} = \{P_{eirp} / (4 \pi D^2)\} * \{\lambda^2 / (4 \pi)\}$$

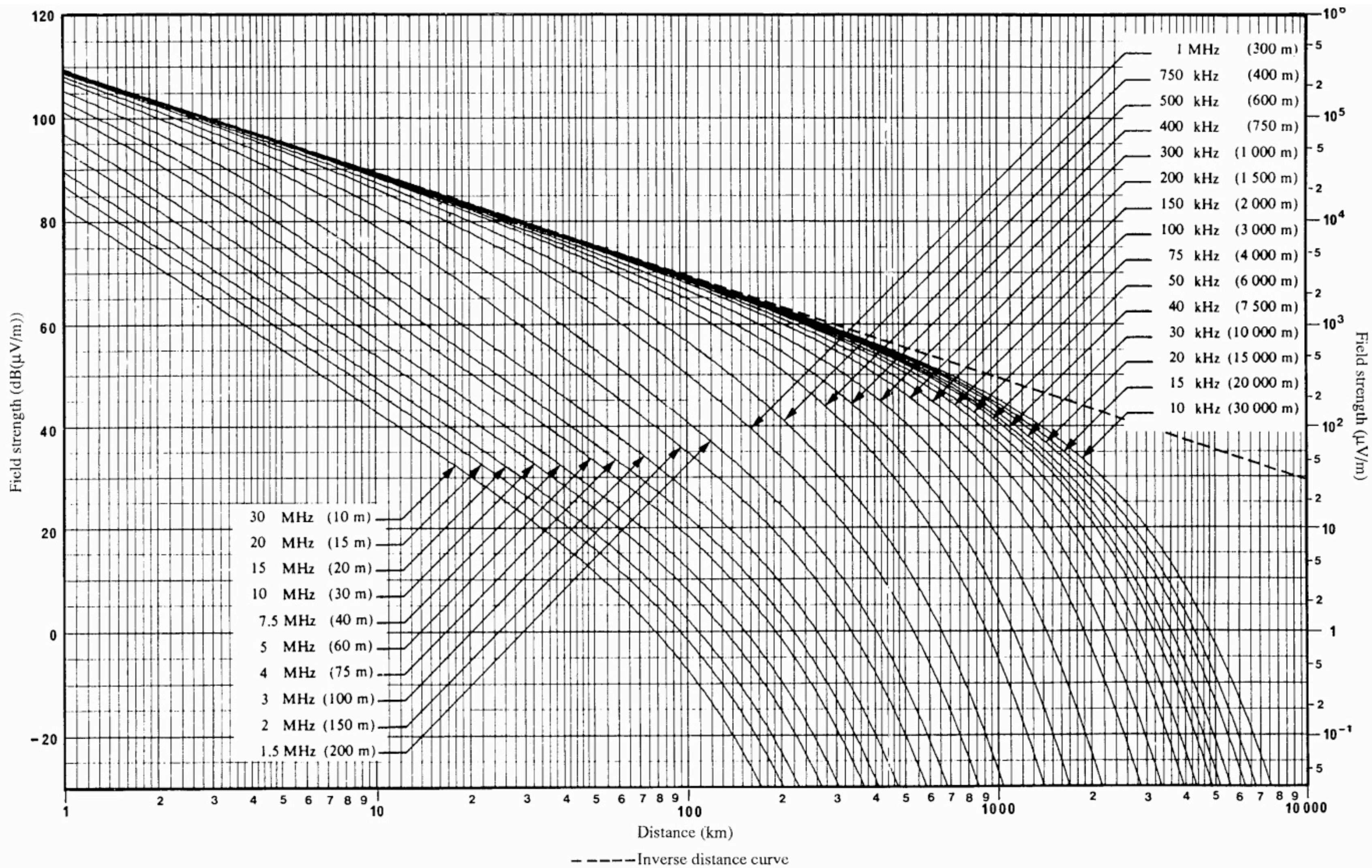

Fig. 1: Ground-wave propagation curves over wet ground as a function of frequency and distance (calculated $\sigma = 10^{-2}$ S / m and $\varepsilon = 30$).

where $\{\lambda^2 / (4\pi)\}$ corresponds to the capture area of an isotropic antenna, at wavelength λ. (It is interesting to note that if the capture area of an isotropic antenna is regarded as a circular disk, then the circumference of that disk is precisely one wavelength.)

(c) *Ground wave propagation* is concerned with diffraction around a smooth Earth and with ground reflections, factors which are of most relevance to the propagation of low (less than 30 MHz) frequencies. This mode depends on such electrical properties of the ground as conductivity & permittivity, and is the subject of several ITU recommendations, such as ITU-R P.368. The ITU makes the program GRWAVE available on its web pages, which provides estimates for the field strength as a function of frequency and distance under a variety of conditions. An example, which is taken from Fig. 5 of ITU-R P.368-7, is shown here as Fig. 1 for the propagation of radio waves over wet ground. Similar curves are available for propagation over fresh water, the sea, etc.

(d) *Ionospheric reflection* is most relevant in increasing the range of radio wave propagation at frequencies up to ~30 MHz. But there are many modes of propagation making this a complicated topic, which is made yet more complicated still by the high degree of ionospheric variability occurring between day/night-time conditions as well as with the progress of the Solar Sunspot Cycle. Moreover the sporadic E layer in particular can be important to the propagation of frequencies up to 70 MHz (ITU-R P.534).

(e) *Tropospheric factors,* such as variations of radio refractive index and its "normal" change with height, enable radio-wave propagation over a greater than line-of-sight range. This effect is often taken into approximate account by assuming an increased radius for the Earth, e.g. by a factor of 4/3. Moreover temperature inversions can cause ducting, with relatively low attenuation over large distances beyond the horizon. Similarly small-scale irregularities within the troposphere can be responsible for forward

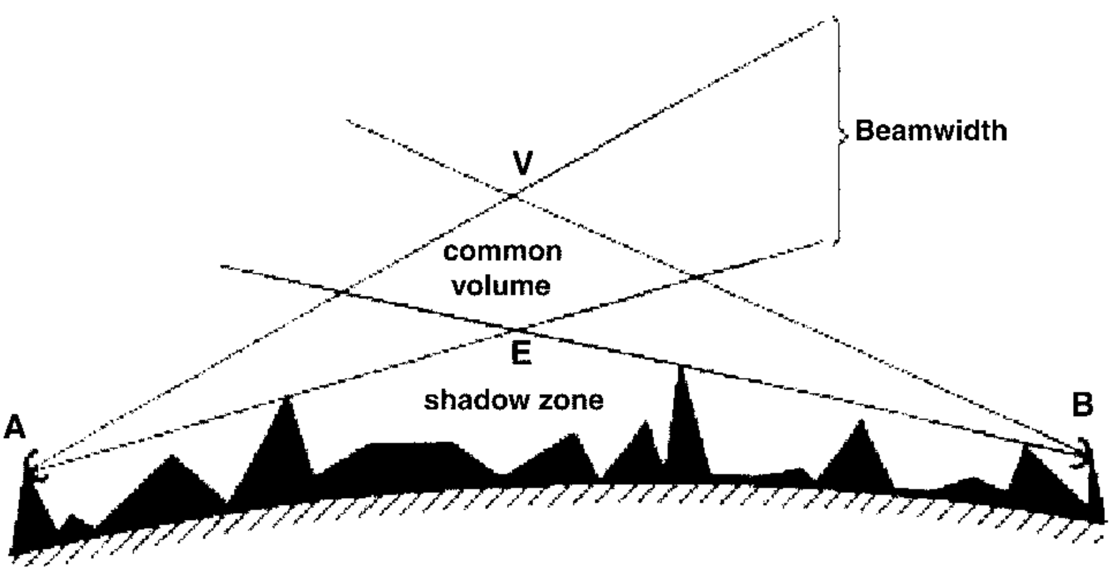

Fig. 2: Profile of a typical tropo-scatter path.

scatter propagation, while rain scatter can sometimes be a dominant mode.

(f) *Obstacles*, such as buildings and terrain features, usually attenuate signals. But in some circumstances knife-edge diffraction can greatly enhance propagation beyond the horizon. There is then always a question as to whether an apparent obstruction is in fact completely obstructing the ray path, as the cartoon in Fig. 3 shows. Such circumstances can be modeled: for example, the *OKUMURA-HATA* model calculates attenuation taking account in a statistical sense of the percentage of buildings in the path, as well as natural terrain features.

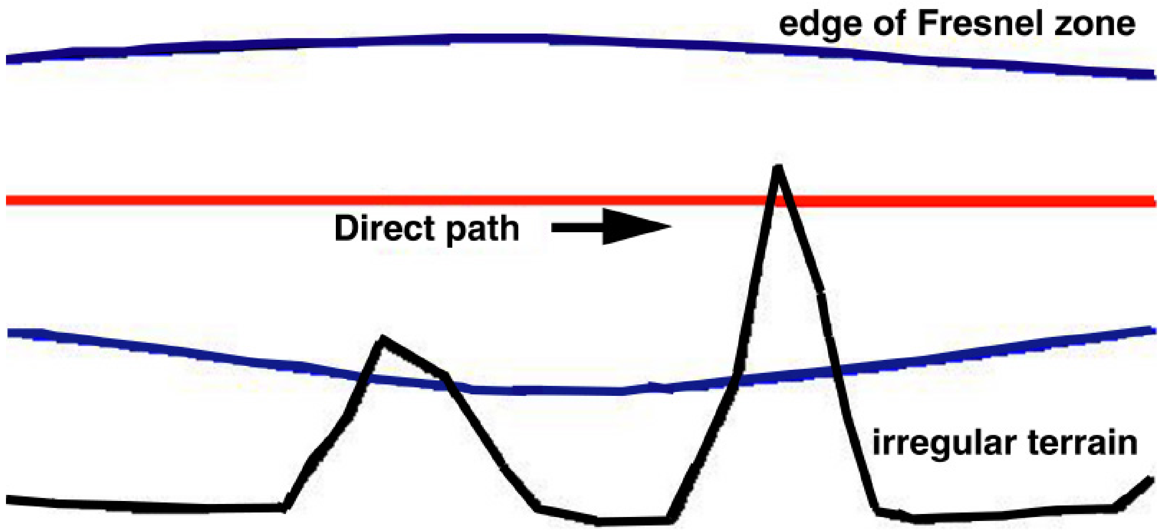

Fig. 3: Is an obstruction obstructing? Ray paths over irregular terrain.

In studying radio-wave propagation between two points A & B, the intervening space can be subdivided by a family of ellipsoids, known as Fresnel ellipsoids, all having their focal points at A & B such that any point M on one ellipsoid satisfies the relation

$$AM + MB = AB + n\lambda/2 \quad ,$$

where λ is the wavelength and n a whole number characterizing the ellipsoid, whereupon n = 1 corresponds to the first Fresnel ellipsoid. As a practical rule, if there is no obstacle within the first Fresnel zone anywhere along a propagation path, diffraction effects can be ignored and free space propagation rules apply: clearance by 0.6 of the Fresnel zone radius is then often taken as a sufficient criterion to assume free space propagation.

The radius of an ellipsoid at a point between the transmitter and the receiver is

$$R_n = \left[\frac{n\lambda\, d_1\, d_2}{\left(d_1 + d_2 \right)} \right]^{1/2}$$

Or, in practical units by

$$R_n = 550 \left[\frac{n\, d_1\, d_2}{\left(d_1 + d_2 \right) f} \right]^{1/2}$$

where f is the frequency (MHz) and d_1 & d_2 the distance (km) between the transmitter and receiver at the point where the ellipsoid radius (m) is calculated.

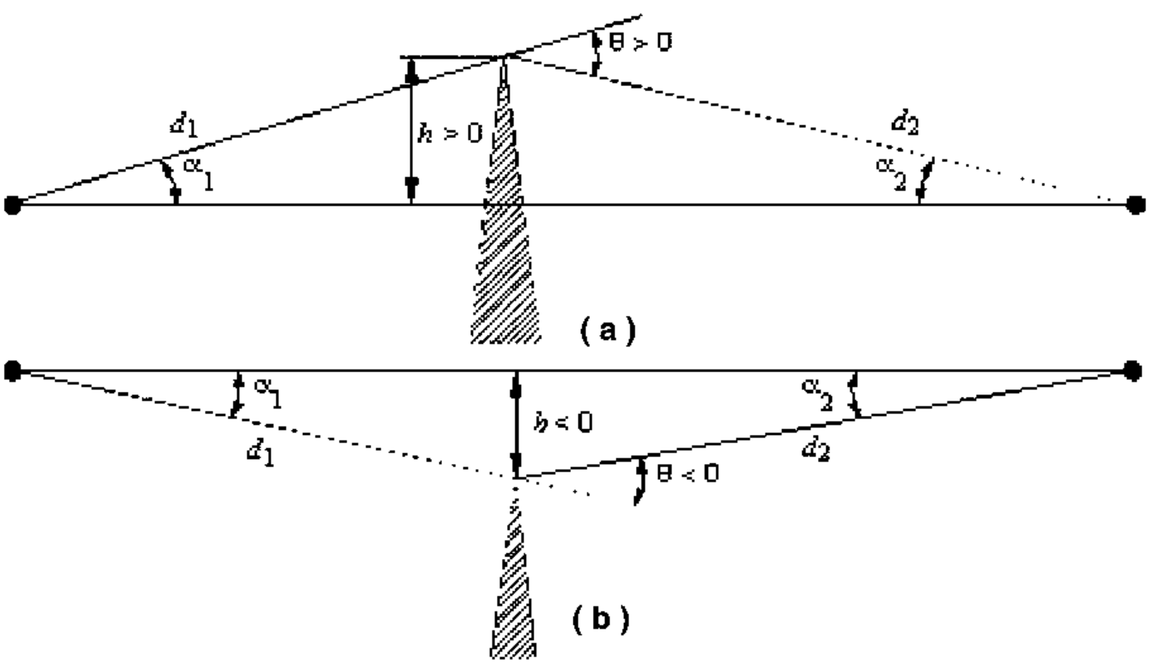

Fig. 4: Schematic for knife-edge diffraction.

There is a handy approximation for calculating the path length just achieving a clearance of 0.6 of the first Fresnel zone over a smooth Earth, for a given frequency, f (MHz), and antenna heights h_1 & h_2 in meters. This is given approximately by

$$D_{0.6} = \frac{D_f \,.\, D_h}{D_f + D_h}$$

where the frequency dependent term is

$$D_f = 0.0000389 \, f \, h_1 \, h_2$$

and the asymptotic term defined by the radio horizon is

$$D_h = 4.1 \left(\sqrt{h_1} + \sqrt{h_2} \right)$$

Figure 5 plots the attenuation, compared to free-space propagation, introduced by a knife-edge obstacle. The attenuation J (ν) is shown, in dB, as a function of the parameter ν. This parameter ν can be derived in a number of ways (see e.g. recommendation ITU-P.526), with one convenient expression being:

$$\nu = \sqrt{(2 \,.\, d / \lambda) . \alpha_1 . \alpha_2}$$

where d is the total length of the path, λ the wavelength, and α_1 and α_2 are the angles between the top of the obstacle and one end, as seen from the other end. As an example, if the obstacle is mid-way between transmitter and receiver, assumed to be at the same elevation, then $\alpha_1 = \alpha_2$. If the distance between transmitter and receiver d = 1640 wavelengths, then the values of ν along the abscissa of Figure 5 would correspond to degrees. In this particular example, with $\nu = 1$, the free-space line of sight between the transmitter and receiver would be 2 degrees below the top of the knife edge, and yet the signal is only attenuated 14 dB below the free-space propagation value; if propagation had been over a smooth, spherical earth without the knife edge, the attenuation might have been much higher. Note also that if $\nu \sim -1.2$, the presence of the knife-edge actually introduces an ENHANCEMENT over free-space propagation, by about 1.4 dB. Note also that if the free-space line of sight just skims the top of the knife-edge, the attenuation is 6 dB (a factor of 4 in power) rather than the perhaps intuitive 3 dB. Figure 6 shows the propagation loss in the presence of a representative amount of clutter, or obstacles, for different antenna heights.

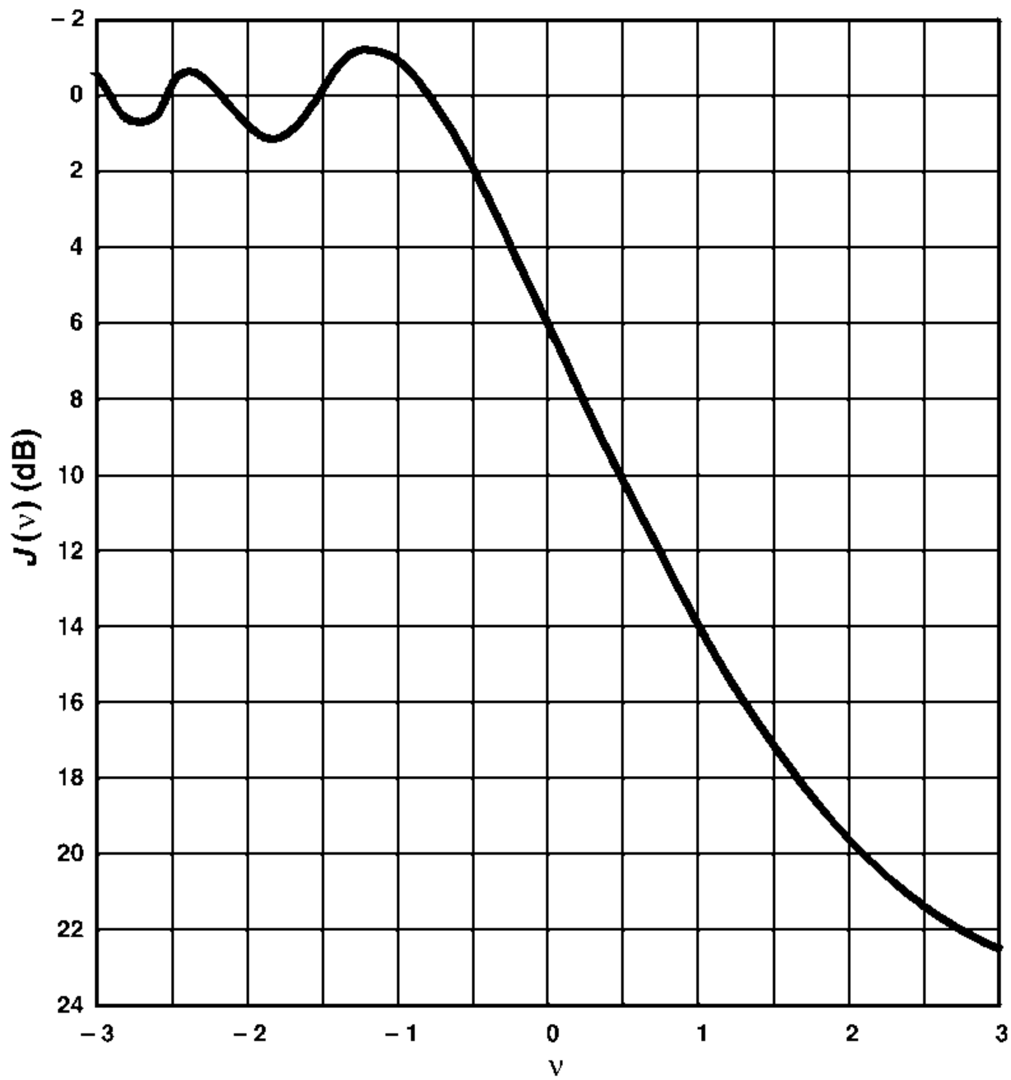

Fig. 5: Attenuation at a knife-edge.

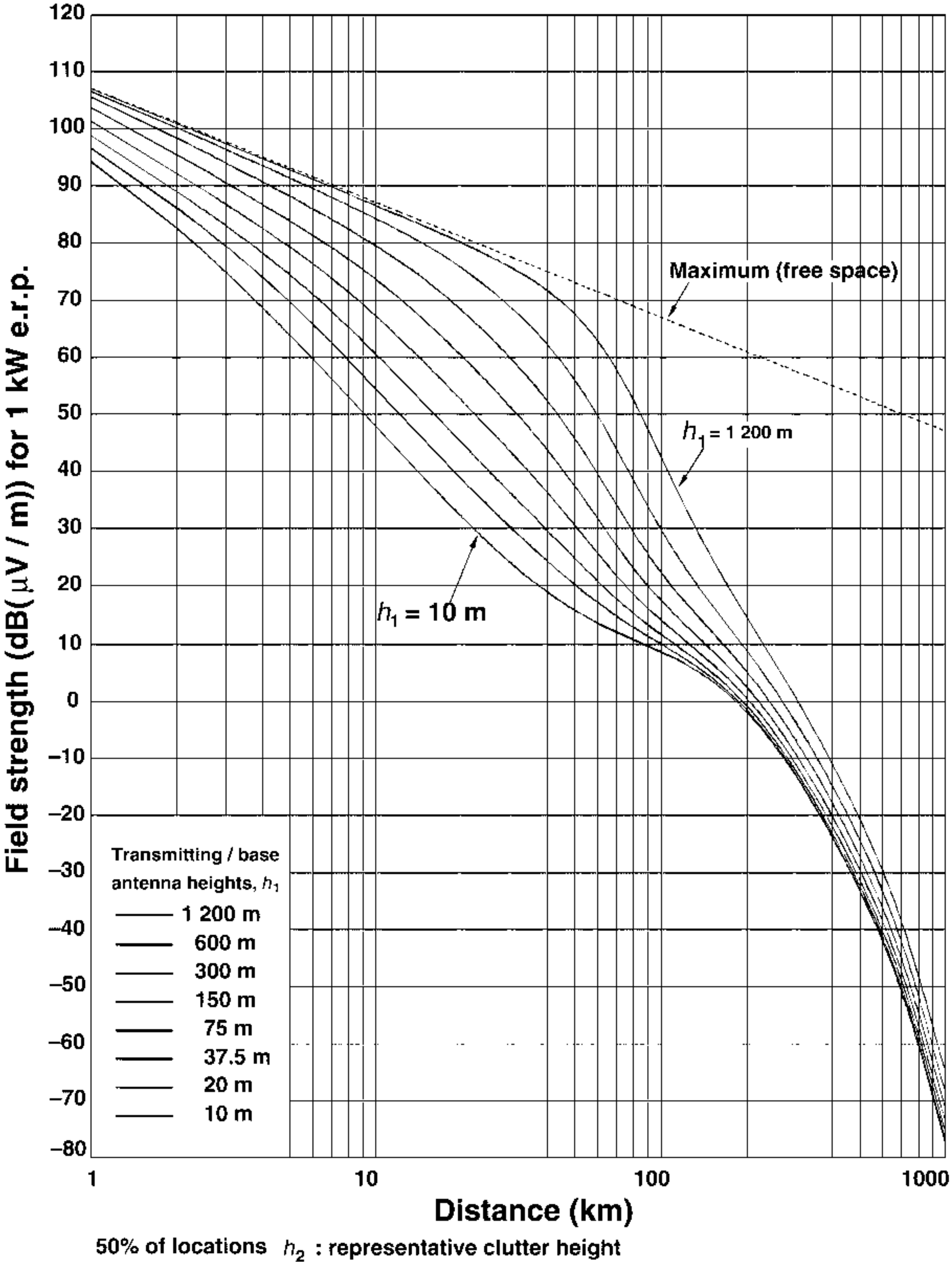

Fig. 6: Field strength versus distance, for a frequency of 2 GHz. The indicated field strength will be exceeded for 50% of locations at a given distance. A transmitter power of 1 kW erp is assumed, and curves are shown for transmitter antenna heights of from 10 to 1200 meters. A representative clutter height along the path is assumed.

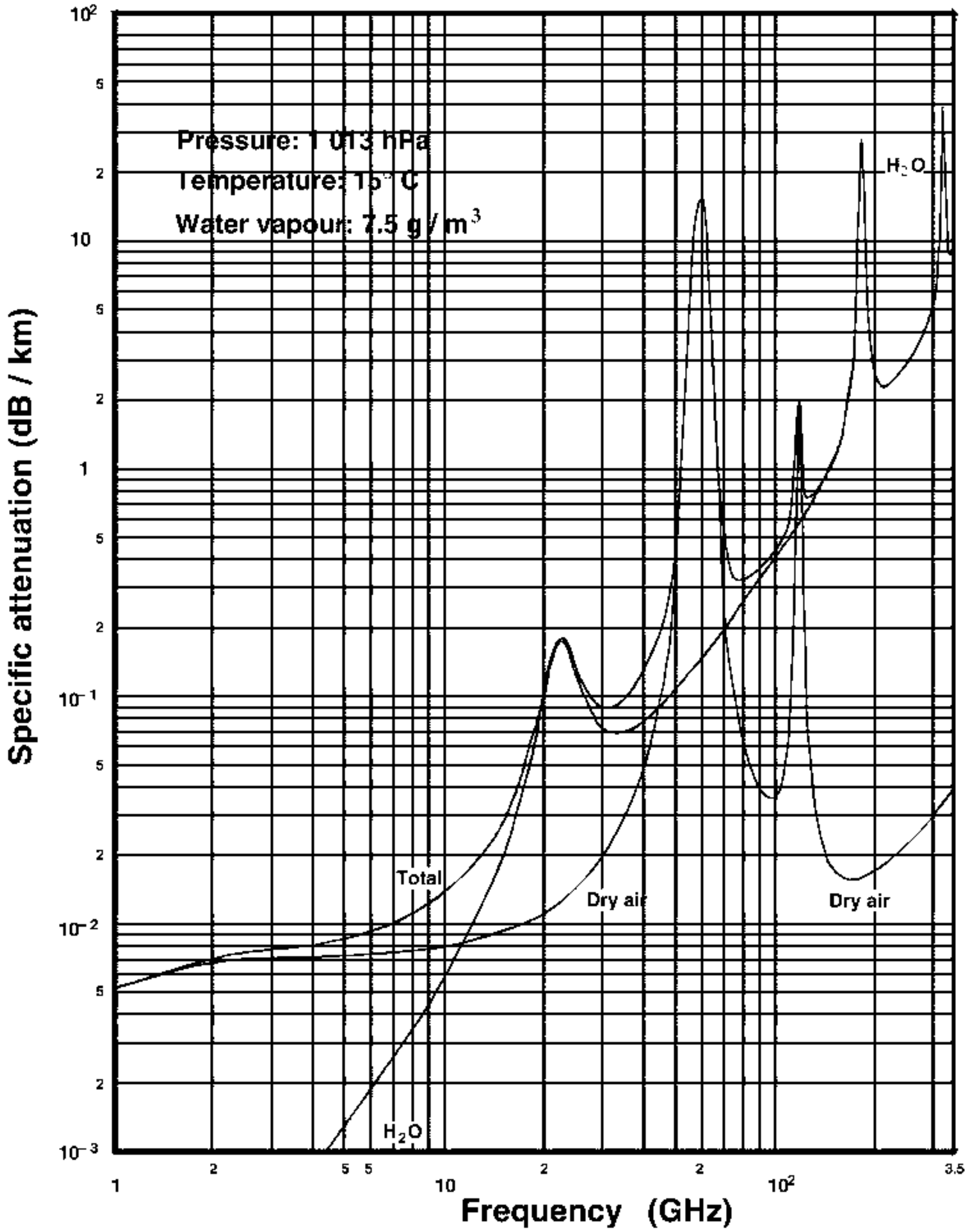

Fig. 7: Specific attenuation by atmospheric gases over the frequency range 1 to 300 GHz.

Recent implementations of propagation models, such as NRAO's TAP model (see below), often incorporate dual knife-edge propagation, where the signal diffracted over one knife-edge is subsequently diffracted over a second edge along the path. In some circumstances this can be the dominant propagation mode between two points.

(g) *Atmospheric attenuation,* which starts to be relevant at frequencies above about 5 GHz, depends primarily, but not exclusively, on the water vapor content of the atmosphere. This of course varies according to location, altitude, path elevation angle etc., and can add to the system noise as well as attenuating the desired signal. Moreover precipitation also has a significant effect. Figure 7 shows the attenuation introduced by propagation loss; for example, Figure 7 shows that at ~183 GHz (one of the water vapor lines), the atmospheric attenuation reaches nearly 30 dB per km. Conversely, at ~2 GHz, the attenuation is only ~0.007 dB/km and can safely be ignored.

3. Propagation models

ITU Recommendations give many "approved" methods and models. Two of the more popular are the Okumura-Hata model and the Longley-Rice model. Let's introduce these.

(i) *Okumura-Hata*
In essence this model calculates the expected electric field strength as a function of frequency at a distance, d, from a transmitter due to normal propagation, using a statistical estimate of obstacles such as buildings. It is used by evaluating equation 1

$$E = 69.82 - 6.16 \log f + 13.82 \log H_1 + a(H_2) - (44.9 - 6.55 \log(H_1))(\log d)^b \quad (1),$$

where E is the electric field strength in units of dB (μV / m) for 1 kW e.r.p., f is the frequency in MHz, H_1 the base-station effective antenna height above ground (m) in the range from 30 to 200 m, H_2 the mobile-station antenna height above ground (m) in the range 1 to 10 m, and d is the distance between them in kilometers. Further,

$$a(H_2) = (1.1 \log f - 0.7)\, H_2 - (1.56 \log f - 0.8)$$

and $b \equiv 1$ for $d \leq 20$ km, but is given by

$$b = 1 + (0.14 + 0.000187 f + 0.00107 H_1')\,(\log(0.05 d))^{0.8}$$

when $d > 20$ km, in which

$$H_1' = H_1 / \sqrt{1 + 0.000007 H_1^2} \,.$$

Nevertheless, the Okumura-Hata model has other features, including an ability to deal with diffraction effects over obstacles. A particular evaluation of equation 1 is illustrated in Fig. 8.

(ii) *Longley-Rice Model*
The Longley-Rice model makes predictions for transmission loss along tropospheric paths. It has been adopted by the FCC, so there are many software implementations available commercially. This model includes most of the relevant propagation modes [multiple knife & rounded edge diffraction, atmospheric attenuation, tropospheric propagation modes (forward scatter etc.), precipitation, diffraction over irregular terrain, polarization, specific terrain data, atmospheric stratification, different climatic regions, etc.

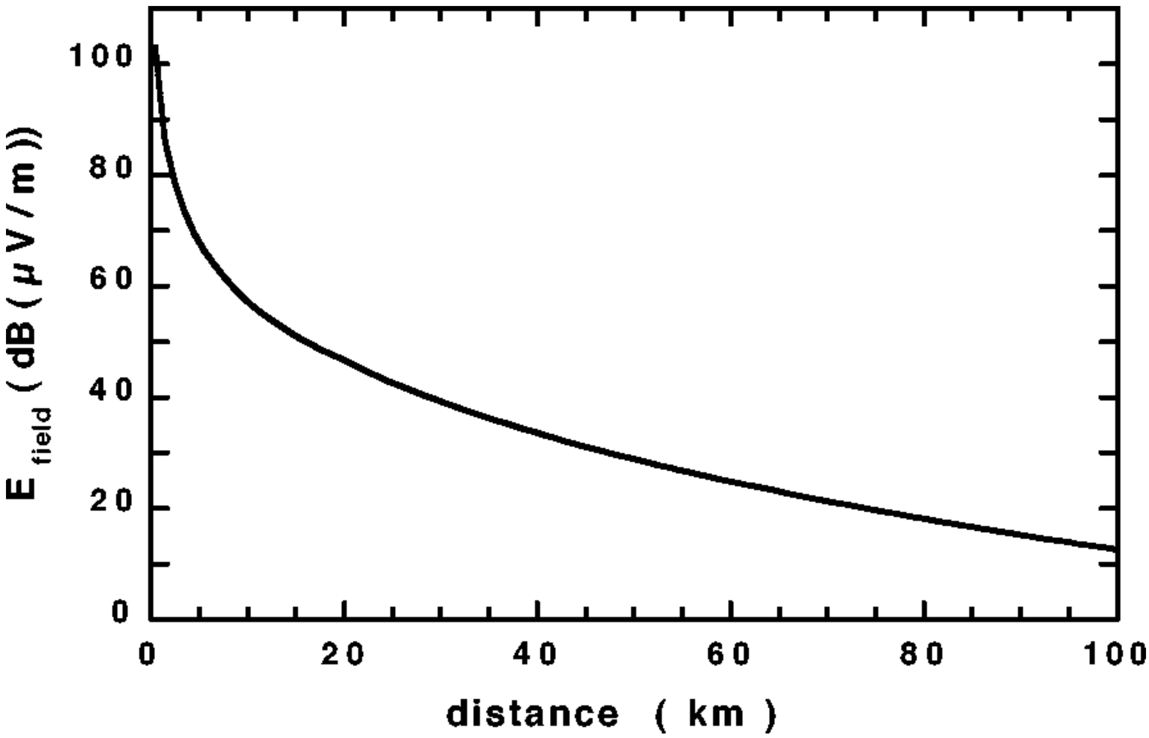

Fig. 8: illustrates the evaluation of equation 1 of the Okumura-Hata model for f = 380 MHz, H_1 = 30 m, H_2 = 10 m, as a function of distance.

(iii) *NRAO's TAP Model*

The Longley-Rice model predicts long-term median transmission loss over irregular terrain relative to free-space transmission loss. The model was designed for frequencies between 20 MHz and 40 GHz and for path lengths between 1 km and 2000 km. NRAO's program predicts tropospheric radio transmission loss over irregular terrain (the Longley-Rice Model) within a Terrain Analysis Package (TAP). This is a commercial implementation of the Longley-Rice Model, from SoftWright, which is based on Version 1.2.2 of the model, dated September 1984. Note also that the version 1.2.2 does not utilize several other corrections to the model proposed since the method was first published (see A. G. Longley, "Radio propagation in urban areas," OT Rep. 78-144, Apr. 1978; and A. G. Longley, "Local variability of transmission-loss in land mobile and broadcast systems," OT Rep., May 1976).

4. Problems with models

All models have limitations. Thus, for example, the Longley Rice Model does not allow for the ionosphere, which limits its applicability at lower frequencies. So some skill is needed in choosing the right model for a given set of circumstances. Clearly models need good input data (e.g. terrain models), but even so their accuracy is necessarily limited, and their results may need statistical interpretation. The resolution of the tabulation of terrain models can seriously affect results; with too coarse a resolution, the roughness and existence of sharp terrain features (such as might support knife-edge diffraction modes) may be significantly underestimated. Their applicability can also be affected with respect to radio astronomy concerns by such tricky questions as "What is the height of a radio telescope?" Is it at the top of a large dish, the bottom of the dish, at the focal point, or where? Moreover different models may give different answers.

Any model that is deployed to give results which need to be accepted by other spectrum users clearly needs to have fairly universal acceptance. Thus general acceptability may often be more important than absolute accuracy.

So where does this leave us? In spite of the difficulties propagation models have come a long way from those initially deployed. Nor can we live without them. They provide us with the best *a priori* guide we have as to whether a given terrestrial transmission will cause interference to a radio telescope, and are also the best guide we have as to whether a given size of coordination zone will be adequate. If greater precision is required in a specific case, or even just to give a high level of confidence to propagation over a given path, an experimental determination of the propagation characteristics may be necessary.

Appendix: ITU Recommendations on Radiowave propagation

P.310 Definitions of terms relating to propagation in non-ionized media

P.311 Acquisition, presentation and analysis of data in studies of tropospheric propagation

P.313 Exchange of information for short-term forecasts and transmission of ionospheric disturbance warnings

P.341 The concept of transmission loss for radio links

P.368 Ground-wave propagation curves for frequencies between 10 kHz and 30 MHz

P.369 Reference atmosphere for refraction

P.370 VHF and UHF propagation curves for the frequency range from 30 MHz to 1 GHz broadcasting services

P.371 Choice of indices for long-term ionospheric predictions

P.372 Radio noise

P.373 Definitions of maximum and minimum transmission frequencies

P.434 ITU-R reference ionospheric characteristics and methods of basic MUF, operational MUF and ray-path prediction

P.435 Sky-wave field-strength prediction method for the broadcasting service in the frequency range 150 to 1600 kHz

P.452 Prediction procedure for the evaluation of microwave interference between stations on the surface of the Earth at frequencies above about 0.7 GHz

P.453 The radio refractive index: its formula and refractivity data

P.525 Calculation of free-space attenuation

P.526 Propagation by diffraction

P.527 Electrical characteristics of the surface of the Earth

P.528 Propagation curves for aeronautical mobile and radionavigation services using the VHF, UHF and SHF bands

P.529 Prediction methods for the terrestrial land mobile service in the VHF and UHF bands

P.530 Propagation data and prediction methods required for the design of terrestrial line-of-sight systems

P.531 Ionospheric propagation data and prediction methods required for the design of satellite services and systems

P.532 Ionospheric effects and operational considerations associated with artificial modification of the ionosphere and the radio-wave channel

P.533 HF propagation prediction method

P.534 Method for calculating sporadic-E field strength

P.581 The concept of "worst month"

P.616 Propagation data for terrestrial maritime mobile services operating at frequencies above 30 MHz

P.617 Propagation prediction techniques and data required for the design of trans-horizon radio-relay systems

P.618 Propagation data and prediction methods required for the design of Earth-space telecommunication systems

P.619 Propagation data required for the evaluation of interference between stations in space and those on the surface of the Earth

P.620 Propagation data required for the evaluation of coordination distances in the frequency range 100 MHz to 105 GHz

P.676 Attenuation by atmospheric gases

P.678 Characterization of the natural variability of propagation phenomena

P.679 Propagation data required for the design of broadcasting-satellite systems

P.680 Propagation data required for the design of Earth-space maritime mobile telecommunication systems

P.681 Propagation data required for the design of Earth-space land mobile telecommunication systems

P.682 Propagation data required for the design of Earth-space aeronautical mobile telecommunication systems

P.683 Sky-wave field strength prediction method for propagation to aircraft at about 500 kHz

P.684 Prediction of field strength at frequencies below about 150 kHz

P.832 World Atlas of Ground Conductivities

P.833 Attenuation in vegetation

P.834 Effects of tropospheric refraction on radiowave propagation

P.835 Reference standard atmospheres

P.836 Water vapour: surface density and total columnar content

P.837 Characteristics of precipitation for propagation modelling

P.838 Specific attenuation model for rain for use in prediction methods

P.839 Rain height model for prediction methods

P.840 Attenuation due to clouds and fog

P.841 Conversion of annual statistics to worst-month statistics

P.842 Computation of reliability and compatibility of HF radio systems

P.843 Communication by meteor-burst propagation

P.844 Ionospheric factors affecting frequency sharing in the VHF and UHF bands (30 MHz-3 GHz)

P.845 HF field-strength measurement

P.846 Measurements of ionospheric and related characteristics

P.1057 Probability distributions relevant to radiowave propagation modelling

P.1058 Digital topographic databases for propagation studies

P.1059 Method for predicting sky-wave field strengths in the frequency range 1605 to 1705 kHz

P.1060 Propagation factors affecting frequency sharing in HF terrestrial systems

P.1144 Guide to the application of the propagation methods of Radiocommunication Study Group 3

P.1145 Propagation data for the terrestrial land mobile service in the VHF and UHF bands

P.1146 The prediction of field strength for land mobile and terrestrial broadcasting services in the frequency range from 1 to 3 GHz

P.1147 Prediction of sky-wave field strength at frequencies between about 150 and 1700 kHz

P.1148 Standardized procedure for comparing predicted and observed HF sky-wave signal intensities and the presentation of such comparisons

P.1238 Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz

P.1239 ITU-R Reference ionospheric characteristics

P.1240 ITU-R Methods of basic MUF, operational MUF and ray-path prediction

P.1321 Propagation factors affecting systems using digital modulation techniques at LF and MF

P.1322 Radiometric estimation of atmospheric attenuation

P.1406 Propagation effects relating to terrestrial land mobile service in the VHF and UHF bands

P.1407 Multipath propagation and parameterization of its characteristics

P.1409 Propagation data and prediction methods required for the design of systems using high altitude platform stations at about 47 GHz

P.1410 Propagation data and prediction methods required for the design of terrestrial broadband millimetric radio access systems operating in a frequency range of about 20-50 GHz

P.1411 Propagation data and prediction methods for the planning of short-range outdoor radio-communication systems and radio local area networks in the frequency range 300 MHz to 100 GHz

P.1412 Propagation data for the evaluation of coordination between Earth stations working in the bidirectionally allocated frequency bands

P.1510 Annual mean surface temperature

P.1511 Topography for Earth-to-space propagation modelling

P.1546 Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz

P.1621 Propagation data required for the design of Earth-space systems operating between 20 THz and 375 THz

P.1622 Prediction methods required for the design of Earth-space systems operating between 20 THz and 375 THz

P.1623 Prediction method of fade dynamics on Earth-space paths