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| Radiocommunication Study Group 3 | |
| Draft Revision to RECommendation ITU-R P.834-6 | |
| Effects of tropospheric refraction on radiowave propagation | |
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Introduction

Study Group 3 proposes a revision of Recommendation ITU-R [P.834-6](http://www.itu.int/rec/R-REC-P.834/en) concerning the prediction of the effective path length, also defined as tropospheric excess path length, on Earth‑space paths.

Summary of changes

In Annex 1, Chapter 6, the title of effective path length is changed to excess path length to align it with the text of the recommendation and there are some editorial changes in this chapter.

The model provided from equation (2) in page 7 up to page 8 has been updated to include:

– a new refractivity coefficient (k2);

– separate mapping functions;

– correction from dry to hydrostatic component;

– correction of gravity constant in equation (23e);

– inclusion of model parameters as an integral part of the recommendation;

– definition of the interpolation procedure along the horizontal and in height.

Keywords

Tropospheric excess path length, Earth-space link, GNSS, numerical weather product, digital maps.

draft revision to RECOMMENDATION ITU-R P.834-6

Effects of tropospheric refraction on radiowave propagation

(Question ITU-R 201/3)

(1992-1994-1997-1999-2003-2005-2007)

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Annex 1

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# 6 Excess radio path length and its variations

Since the tropospheric refractive index is higher than unity and varies as a function of altitude, a wave propagating between the ground and a satellite has a radio path length exceeding the geometrical path length. The difference in length can be obtained by the following integral:

 (15)

where:

*s* : length along the path

*n* : refractive index

*A* and *B* : path ends.

Equation (15) can be used only if the variation of the refractive index *n* along the path is known.

When the temperature *T*, the atmospheric pressure *P* and the relative humidity *H* are known at the ground level, the excess path length *L* can be computed using the semi-empirical method explained below, which has been derived using the atmospheric radio-sounding profiles provided by a one-year campaign at 500 meteorological stations in 1979. In this method, the general expression of the excess path length *L* is:

 (16)

where:

0 : elevation angle at the observation point

*LV* : vertical excess path length

*k* and  (0, *LV*) : corrective terms, in the calculation of which the exponential atmosphere model is used.

The *k* factor takes into account the variation of the elevation angle along the path. The  (0, *LV*) term expresses the effects of refraction (the path is not a straight line). This term is always very small, except at very low elevation angle and is neglected in the computation; it involves an error of only 3.5 cm for a 0 angle of 10 and of 0.1 mm for a 0 angle of 45. It can be noted, moreover, that at very low elevation for which the  term would not be negligible, the assumption of a plane stratified atmosphere, which is the basis of all methods of computation of the excess path length, is no longer valid.

The vertical excess path length (m) is given by:

*LV*  0.00227 *P*  *f* (*T*) *H* (17)

In the first term of the right-hand side of equation (17), *P* is the atmospheric pressure (hPa) at the observation point.

In the empirical second term, *H* is the relative humidity (%); the function of temperature *f*(*T*) depends on the geographical location and is given by:

*f* (*T*)  *a* 10*bT* (18)

where:

*T* is in C

*a* is in m/% of relative humidity

*b* is in C–1.

Parameters *a* and *b* are given in Table 2 according to the geographical location.

TABLE 2

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| --- | --- | --- |
| Location | *a* (m/%) | *b* (C–1) |
| Coastal areas (islands, or locations less than 10 km away from sea shore) | 5.5  10−4 | 2.91  10−2 |
| Non-coastal equatorial areas | 6.5  10−4 | 2.73  10−2 |
| All other areas | 7.3  10−4 | 2.35  10−2 |

To compute the corrective factor *k* of equation (16), an exponential variation with height *h* of the atmospheric refractivity *N* is assumed:

*N*(*h*)  *Ns* exp (– *h* / *h*0) (19)

where *Ns* is the average value of refractivity at the Earth surface (see Recommendation ITU‑R P.453) and *h*0 is given by:

 (20)

*k* is then computed from the following expression:

 (21)

where *ns* and *n*(*h*0) are the values of the refractive index at the Earth surface and at height *h*0 (given by equation (20)) respectively, and *rs* and *r*(*h*0) are the corresponding distances to the centre of the Earth.

For Earth-space paths with elevation angles, θthe tropospheric excess path length, *L*(), (m) can be expressed as the sum of hydrostatic and wet components, *LH*() and *LW*().

The excess path length along a vertical path, *LHv* and *LWv* can be projected to the elevation angle, θ, greater than 3°, using two separate mapping function for the hydrostatic and wet components, *mH*() and *mW*():

  m (22)

The hydrostatic vertical component at the Earth surface, *LHvs*, can be derived using:

 m (22a)

The wet vertical component at the Earth surface, *LWvs*, can be derived using:

 m (22b)

where:

*ps*, *es*: air total pressure and water vapour partial pressure at the Earth surface (hPa)

*Tms*: mean temperature of the water vapour column above the surface (K)

λ: vapour pressure decrease factor

*Rd* : *R*/*Md* = 287.0 (J/kg K)

*R*: molar gas constant = 8.314 (J/mol K)

*Md*: dry air molar mass = 28.9644 (g/mol)

*k*1 = 77.604 (K/hPa)

*k*2 = 373 900 (K2/hPa)

*gms*= *gm*(*hs*)

*gm*(*h*)=9.784 ⋅ (1 – 0.00266 ⋅ cos (2 ⋅ lat) – 0.00028 ⋅ *h*)

= gravity acceleration at the mass centre of air from height *h* (m/s2)

*lat*: Latitude of the location (radians)

*hs*: height of the Earth surface above mean sea level (a.m.s.l., km).

For receivers located at a height, *h* (km), different than the surface height, *hs*, the hydrostatic and wet vertical component, *LHv*(*h*) and *LWv*(*h*), are given by:

 m (23a)

 m (23b)

where:

The values of the input meteorological parameters at height *h*, *Tm*(*h*), *e*(*h*) and *p*(*h*), can be derived from values at the Earth surface, *Tms*, *es* and *ps*, using the following equations:



                K (24a)

                hPa (24b)

                hPa (24c)

where:

α*m*: lapse rate of the mean temperature of water vapour from the Earth surface (K/km).

*T*s = air temperature at Earth surface (K) = 

α = lapse rate of air temperature (K/km)  

 = *Rd* /1000 = 0.287                J/(g K)

*g* = gravity acceleration at Earth surface [m/s2] = 



All the input parameters of the model, *ps*, *es*, *Tms*, λ, and α*m*, can be derived by assuming the meteorological parameters are characterized by the seasonal fluctuation:

 (25)

where:

*Xi*: *ps*, *es*, *Tms*, λ or α*m*Index *i*, 1 designates *ps*, 2 designates *es*, 3 designates *Tms*, 4 designates *,* 5 designates α*m*

*a*1*i*: average value of the parameter

*a*2*i*: seasonal fluctuation of the parameter

*a*3*i*: day of the minimum value of the parameter

*Dy:* day of the year (1, 2, ... , 365.25),  
1 = 1 January, 32 = 1 February, 60.25 = 1 March.

The coefficients *a*1, *a*2 and *a*3 of the parameters *ps*, *es*, *Tms*, λ, and α*m*, and the height of the reference level, *href*, at which these coefficients have been calculated, are an integral part of this Recommendation and are available in the form of digital maps provided in the file R-RECP.834-7-201504-I!!ZIP-E.

The data is from 0° to 360° in longitude and from +90° to −90° in latitude, with a resolution of 1.5° in both latitude and longitude. The excess path length at any desired location and at any height above the surface, *h*, can be derived by the following method:

a) Determine the coefficients *a*1i, *a*2i and *a*3i, of the five parameters, *ps*, *es*, *Tms*, λ, α*m*, and the reference height, *href*, from the maps at the four grid points closest to the desired location.

b) Calculate the values of the five parameters, *ps*, *es*, *Tms*, λ or α*m*, at the reference height, *href*, for the day of the year *Dy*, , ,  and  at the four closest grid points, using equation (25) with the coefficients *a*1i, *a*2i and *a*3i of each grid point.

c) Calculate the value of the three parameters, *p*(*h*), *e*(*h*) and *Tm*(*h*), at the height *h* at the four closest grid points using equations (24a), (24b) and (24c) with the values of , ,  and , and with the values of *href* of each grid point.

d) Calculate the values of *LHv*(*h*) and *LWv*(*h*), at the height *h* at the four grid points closest to the desired location, using equations (23a) and (23b) with the values of *p*(*h*), *e*(*h*) and *Tm*(*h*) of each grid point.

e) Calculate the values at height *h* of *LHv*(*h*) and *LWv*(*h*), at the desired location by performing a bi-linear interpolation of the four values of *LHv*(*h*) and *LWv*(*h*) at the four grid points as described in Recommendation ITU-R P.1144.

e) Calculate the value of tropospheric excess path length at the height *h* at the desired location, *L*(*h,*), using equation (22).

The accuracy of the proposed model has been tested using radiosonde, GNSS and radiometric measurements to determine *Lvs* and the worldwide uncertainty is between 2 and 6 cm. Where a higher accuracy is needed, concurrent local measurements of air total pressure and water vapour pressure can be used as inputs to the model.

The mapping function of the hydrostatic and wet components, *mh*() and *mw*() are given by:

                 (26a)

                 (26b)

where:



*b*h = 0.0029

*b*w = 0.00146

*c*w = 0.04391

 (26c)

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| --- | --- | --- | --- | --- |
| Hemisphere | *c*1 | *c*10 | *c*11 | ψ |
| Northern | 0.062 | 0.001 | 0.005 | 0 |
| Southern | 0.062 | 0.002 | 0.007 | π |

 (26d)

 (26e)

The coefficients *A*0*h, A*1*h, A*2*h, B*1*h, B*2*h, A*0*w, A*1*w, A*2*w, B*1*w* and *B*2*w* are an integral part of this Recommendation and are available in the form of digital maps in the file R-RECP.834-7-201504-I!!ZIP-E.ZIP. Calculate the values of the parameters *ah* and *aw* at the desired location by performing a bi-linear interpolation of the four values of these coefficients at the four grid points as described in Recommendation ITU-R P.1144.



For the case of an Earth-space link with elevation angles, θ, greater than 20°, the mapping functions given by equations (26a) and (26b) can be approximated by:

                 (26f)

In the application of this model it is recommended to use either equations (26a) and (26b) or equation (26f) consistently along all the elevation angles.



# 7 Propagation in ducting layers

Ducts exist whenever the vertical refractivity gradient at a given height and location is less than −157 N/km.

The existence of ducts is important because they can give rise to anomalous radiowave propagation, particularly on terrestrial or very low angle Earth-space links. Ducts provide a mechanism for radiowave signals of sufficiently high frequencies to propagate far beyond their normal line-of-sight range, giving rise to potential interference with other services (see Recommendation ITU-R P.452). They also play an important role in the occurrence of multipath interference (see Recommendation ITU-R P.530) although they are neither necessary nor sufficient for multipath propagation to occur on any particular link.

## 7.1 Influence of elevation angle

When a transmitting antenna is situated within a horizontally stratified radio duct, rays that are launched at very shallow elevation angles can become “trapped” within the boundaries of the duct. For the simplified case of a “normal” refractivity profile above a surface duct having a fixed refractivity gradient, the critical elevation angle  (rad) for rays to be trapped is given by the expression:

 (27)

where d*M*/d*h* is the vertical gradient of modified refractivity  and *h* is the thickness of the duct which is the height of duct top above transmitter antenna.

Figure 2 gives the maximum angle of elevation for rays to be trapped within the duct. The maximum trapping angle increases rapidly for decreasing refractivity gradients below −157 N/km (i.e., increasing lapse rates) and for increasing duct thickness.

## 7.2 Minimum trapping frequency

The existence of a duct, even if suitably situated, does not necessarily imply that energy will be efficiently coupled into the duct in such a way that long-range propagation will occur. In addition to satisfying the maximum elevation angle condition above, the frequency of the wave must be above a critical value determined by the physical depth of the duct and by the refractivity profile. Below this minimum trapping frequency, ever-increasing amounts of energy will leak through the duct boundaries.

The minimum frequency for a wave to be trapped within a tropospheric duct can be estimated using a phase integral approach. Figure 3 shows the minimum trapping frequency for surface ducts (solid curves) where a constant (negative) refractivity gradient is assumed to extend from the surface to a given height, with a standard profile above this height. For the frequencies used in terrestrial systems (typically 8-16 GHz), a ducting layer of about 5 to 15 m minimum thickness is required and in these instances the minimum trapping frequency, *fmin*, is a strong function of both the duct thickness and the refractive index gradient.

In the case of elevated ducts an additional parameter is involved even for the simple case of a linear refractivity profile. That parameter relates to the shape of the refractive index profile lying below the ducting gradient. The dashed curves in Fig. 3 show the minimum trapping frequency for a constant gradient ducting layer lying above a surface layer having a standard refractivity gradient of −40 N/km.

FIGURE 2

Maximum trapping angle for a surface duct of constant  
refractivity gradient over a spherical Earth



For layers having lapse rates that are only slightly greater than the minimum required for ducting to occur, the minimum trapping frequency is actually increased over the equivalent surface-duct case. For very intense ducting gradients, however, trapping by an elevated duct requires a much thinner layer than a surface duct of equal gradient for any given frequency.

FIGURE 3

Minimum frequency for trapping in atmospheric radio ducts  
of constant refractivity gradients



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