RECOMMENDATION ITU-R SF.765*

INTERSECTION OF RADIO-RELAY ANTENNA BEAMS WITH ORBITS USED BY SPACE STATIONS IN THE FIXED-SATELLITE SERVICE

(1992)

The ITU Radiocommunication Assembly,

considering

a) that Recommendation ITU-R SF.406 specifies the maximum e.i.r.p. of line-of-sight radio-relay system transmitters operating in the frequency bands shared with the fixed-satellite service (Earth-to-space);

b) that the examination of the compliance of radio-relay stations operating below 15 GHz with Recommendation ITU-R SF.406 requires the calculation of the angle between the direction of the radio-relay antenna beam and the direction towards the geostationary-satellite orbit;

c) that the effect of atmospheric refraction should be taken into account in the above calculation,

recommends

1. that the material contained in Annex 1 should be taken into consideration when planning radio-relay systems;

2. that the method described in Annex 2 should be used for the calculation of the angle between the direction of the radio-relay antenna beam and the direction towards the geostationary-satellite orbit.

Note 1 – For their own protection, highly sensitive radio-relay receivers operating in frequency bands between 1 and 15 GHz shared with space radiocommunication services (space-to-Earth) should avoid directing their antennas towards the geostationary-satellite orbit (see Note 2 of Recommendation ITU-R SF.406). The method given in this Recommendation can also be used for such purpose.

ANNEX 1**

General considerations concerning the intersection of radio-relay antenna beams with orbits used by space stations in the fixed-satellite service

1. Introduction

The exposure of the antenna beams of radio-relay systems to emissions from communication satellites is geometrically predictable when such satellites have circular orbits with recurrent earth tracks but is only predictable statistically for inclined circular orbits of arbitrary periods. A phased system of these recurrent earth-track satellites can be made to follow a single earth-track and such systems are of increasing interest for communication. Geostationary satellites are a special case, since the equator constitutes the earth-track of all equatorial orbits.

* Radiocommunication Study Groups 4 and 9 made editorial amendments to this Recommendation in 2000 in accordance with Resolution ITU-R 44.

** *Note from the Director of the CCIR* – For information, derivation of the formulae and historical development of this Annex are given by references contained in CCIR Report 393 (Düsseldorf, 1990).

At any Earth location from which the satellites of a single-earth-track system could be seen, successive (non-stationary) satellites would follow a fixed arc through the sky, from horizon to horizon. Moreover, except for inclined orbits, this arc would be independent of longitude and be symmetrical relative to North/South.

Subsequent portions of this Annex consider exposure conditions relative to a circular equatorial orbit (including the special case of the orbit of a geostationary satellite) and also the probability of exposure to unphased satellites (non-recurrent earth-track).

Some indication of the extent to which existing antennas of radio-relay systems are directed towards the orbit of a geostationary satellite, has been provided by several administrations. It is shown that although the overall percentage of antenna beams which intersect the geostationary orbit is about 2%, this percentage will be substantially higher if one takes into account the beam extending to ± 2° from its axis, and the effect of refraction. Examination of the compliance of existing radio-relay stations with Recommendation ITU-R SF.406 indicates that the percentage of stations having an antenna-beam direction within ± 2° of the geostationary-satellite orbit is in the order of 10% in some countries. Furthermore, it cannot be assumed that substantial segments of the orbit in any range of longitude are free from illumination by the antennas of radio-relay systems.

2. Some characteristics of the antenna beams of terrestrial radio-relay systems

Line-of-sight radio-relay systems use antennas with gains of the order of 40 dB and half-power beam-widths of the order of 2°. Trans-horizon systems generally use antennas with higher gain and narrower beams, say 50 dB and 0.5°. In either case, path inclinations are less than 0.5° on the average and rarely in excess of 5°. When all of a negatively inclined beam strikes the Earth, there would be no exposure to an orbit. For horizon-centred beams, the upper half could have exposure.

When passive reflectors are used, spill-over also should be considered.

Since the beams are close to the Earth and traverse a considerable thickness of atmosphere, diffraction and refraction should be taken into account in making precise calculations of exposure.

3. Directions to circular equatorial orbits

It is well known from geometric considerations that the azimuth angle, A (measured clockwise from North) and the angle of elevation, e, of a satellite in a circular equatorial orbit can be expressed by:

$$A = \arctan (\pm \tan \lambda / \sin \varphi) \tag{1}$$

$$e = \arcsin \left[(K \cos \varphi \cos \lambda - 1) / \sqrt{K^2 + 1 - 2K \cos \varphi \cos \lambda} \right] \tag{2}$$

where:

K : orbit radius/earth radius

φ : earth latitude of the terrestrial station

λ : difference in longitude between the terrestrial station and the satellite.

Eliminating λ between these two equations leads to

$$A = \arccos \left\{ \left[\frac{\tan e + K^{-1} \sqrt{\tan^2 e + (1 - K^{-2})}}{1 - K^{-2}} \right] \tan \varphi \right\} \tag{3}$$

If necessary, azimuths and elevations to any single-earth-track inclined orbit system, of given height, inclination and equatorial crossings could be determined by an extension of this analysis. For such systems, however, the orbit directions would depend both on latitude and longitude of the terrestrial station.

An antenna directed at the orbit of a non-geostationary satellite (or other single earth-track orbit) will be certain to have intermittent exposure. For a circular equatorial orbit (other than the orbit of the geostationary satellite) with m satellites, antennas having an interference beamwidth of θ radians will have interference for a fraction of the time given approximately by:

$$P = m\,\theta/(2\pi) \tag{4}$$

For the special case of the orbit of a geostationary satellite, P will be either zero or unity.

4. Unphased satellite systems

In this case it is possible to derive only an average probability of exposure to a satellite. Thus, for a system of n orbits of equal height and equal inclination angle, i, it can be shown that the average probability of exposure is given by:

$$P = [m\,n\,\theta/(8\pi \cos \psi)]\ \{\text{arc cos}\ [(\sin(\psi - \theta/2))/\sin i] - \text{arc cos}\ [(\sin(\psi + \theta/2))/\sin i]\} \tag{5}$$

when $\psi \leq (i - \theta/2)$,

and where:

m : number of satellites in each orbit

ψ : latitude of intersection between the antenna beam and the orbital sphere.

In most of the cases encountered in practice, when $i > \theta$, calculations can be made by means of the following equation:

$$P = \frac{m\,n\,\theta^2}{8\pi\sqrt{\sin^2 i - \sin^2 \psi}} \tag{6}$$

The relative error of the calculations made by means of equation (6) does not exceed 0.25% of those made with equation (5).

For the particular case of the polar orbit, $i = \pi/2$, and the above expression reduces to

$$P = m\,n\,\theta^2/(8\pi \cos \psi) \tag{7}$$

5. Geometric relations between the directions of radio-relay antennas and the geostationary-satellite orbit

The geostationary-satellite orbit is particularly important, not only from the point of view of the exposure of radio-relay systems to beams from satellites, but also because of the limitations imposed by Recommendation 406 on the directions of radio-relay antennas to protect reception by geostationary satellites.

Equation (3) can be expressed as:

$$A = \text{arc cos}\ \frac{\tan \varphi}{\tan\,[\text{arc cos}\,(K^{-1} \cos e) - e]} \tag{8}$$

where:

A : azimuth (or its complement at 360°) measured from the South in the Northern Hemisphere and from the North in the Southern Hemisphere

K : orbit radius/Earth radius, assumed to be 6.63

e : geometric angle of elevation of a point on the geostationary-satellite orbit

φ : latitude of the terrestrial station.

For a given station latitude and for a given angle of elevation the values of the angle A, for the two orbit points, are measured from both sides of the meridian.

5.1 The effects of atmospheric refraction

The usual effect of atmospheric refraction is to bend the radiowave ray towards the Earth; the beam of a radio-relay antenna having an angle of elevation ε, may reach a satellite with an angle of elevation *e* where:

$$e = \varepsilon - \tau \qquad (9)$$

and *e* and ε are algebraic values, and τ is the absolute value of the correction due to refraction.

The extent of bending depends on the climate of the region where the station is situated (refractive index, gradient of the index, etc.), on the altitude of the station and the initial angle of elevation ε; the variation of τ as a function of ε is particularly rapid at a low negative value of ε.

The value of τ may exceed several tenths of a degree, and this is particularly important for stations at medium or high latitudes, where a slight change in the angle of elevation results in a considerable change of the azimuth to each of the two corresponding points on the geostationary-satellite orbit. Moreover, this correction varies in time with atmospheric conditions. At a given point of latitude and for a given angle of elevation, the azimuth to the orbit will in time scan a certain angular zone.

To apply Recommendation ITU-R SF.406, whereas a mean value of refraction will provide substantial protection, to provide full protection it is desirable to consider the maximum and minimum values of bending due to refraction, so as to determine the azimuths of the extremities of this angular zone. This can be done on a statistical basis. Equation (8) may be used to determine the extreme azimuths of the angular zone, on the basis of extreme angles of elevation e_1 and e_2.

It is not always easy to determine the bending τ as a function of the climate, the altitude of the station and the angle of elevation ε, since the assumption of a reference atmosphere of exponential type is not always applicable and the probability of the formation of atmospheric ducts is by no means negligible, especially in certain hot maritime areas.

Where a hypothetical atmosphere of exponential type is admissible and where the ground index, *N*, and the gradient Δ*N* of the index between 0 and 1 000 m are related, the curves showing correction τ as a function of the angle of elevation ε can be calculated. Determining the maximum and minimum corrections τ_1 and τ_2 is then equivalent to the assessment of the maximum and minimum of *N* (or Δ*N*) corresponding to the particular case under consideration.

The influence of the altitude of the station is very difficult to assess. For positive angles of elevation, the radio beam quickly leaves the atmosphere, the bending τ is relatively slight and the influence of altitude is probably reduced. On the other hand, for negative angles of elevation, a beam crossing the horizon passes twice through the densest layers of the atmosphere; the bending τ is thus greater and its variation with altitude at constant angle of elevation is likely to be much greater. However, there are no accurate data in this connection.

Provisionally, and to provide protection under all conditions, one should adopt the following rules:

5.1.1 in those geographical areas where propagation data are available which will enable the amount of bending to be determined on a statistical basis, the maximum bending (for instance the bending not exceeded for 99.5% of the time) and the minimum bending should be derived from these data;

5.1.2 where such data are not available, the following approximation may be used. Limits of refractive index assuming an exponential reference atmosphere can be calculated from the sea-level radio refractivity, N_0, and the gradient, Δ*N* (as found in worldwide charts). A range for N_0 between 250 and 400 (Δ*N* at sea level between –30 and –68, respectively) is representative of minimum and maximum values throughout a large part of the world and throughout the year. Establishing these limits permits the calculation of curves for τ_1 and τ_2 as a function of angle of elevation of the antenna and station height.

The refraction correction, τ, can be calculated by the following integration:

$$\tau = -\int_{n_1}^{n_2} [\cot \varepsilon / n(r)] \, \mathrm{d}n \qquad (10)$$

This integration is performed under the condition of Snell's law for polar coordinates, which follows:

$$n(r) \cdot r \cdot \cos \varepsilon = n(r_1) \cdot r_1 \cdot \cos \varepsilon_1 \quad (11)$$

where:

$n(r) = 1 + a \cdot \exp [-b(r - r_0)]$

r_0 : Earth radius (6 370 km)

$r_1 = r_0 + h$ (h: station height)

ε_1 : elevation angle at the station

n_1 : refractivity at the station height

n_2 : refractivity at the orbit

$a = N_0 \times 10^{-6}$

$b = \ln [N_0/(N_0 + \Delta N)]$

$N_0 = 400$ and $\Delta N = -68$ for maximum bending

$N_0 = 250$ and $\Delta N = -30$ for minimum bending.

This integration has been carried out and the calculation results are presented in Fig. 1.

Numerical formulae which give a good approximation to this function are described in Note 1 of Annex 2, § 4, to this Recommendation.

5.2 Use of a graphical method for determination of azimuths to be avoided

A graphical method which takes into account the influence of the actual local horizon can be used to determine azimuths to be avoided. The approximations it makes limit its application to stations located below about 70° latitude. Its azimuthal accuracy is approximately 0.1° with better results for low angles of elevation.

This method, illustrated in Fig. 2, is based on the consideration of the apparent orbit of a geostationary satellite, taking into account the effect of refraction, the latitude of the terrestrial station, antenna elevation angle and the influence of the local optical (real) horizon.

To plot the apparent (refracted) orbit, it is necessary to raise the trace of the geometric orbit at each point by a quantity τ , which is a function of the geometric orbit elevation and the station height.

This can be done by plotting the point whose elevation is ε and azimuth is $C(\varepsilon - \tau(\varepsilon))$, where $C(\ )$ is given by equation (14) of Annex 2 and $\tau(\ )$ is $\tau_{max}(\ )$ or $\tau_{min}(\ )$ in Note 1 of Annex 2.

The method may be summarized as follows:

5.2.1 On Fig. 2 draw a straight line passing through the origin and the point corresponding to the latitude of the station in question. (This implies an approximation of the orbit by a straight line in this small region.) The reference azimuth (0° on Fig. 2) for a zero geometric angle of elevation is calculated using equation (8).

5.2.2 Draw a horizontal line corresponding to the angle of elevation ε planned for the antenna.

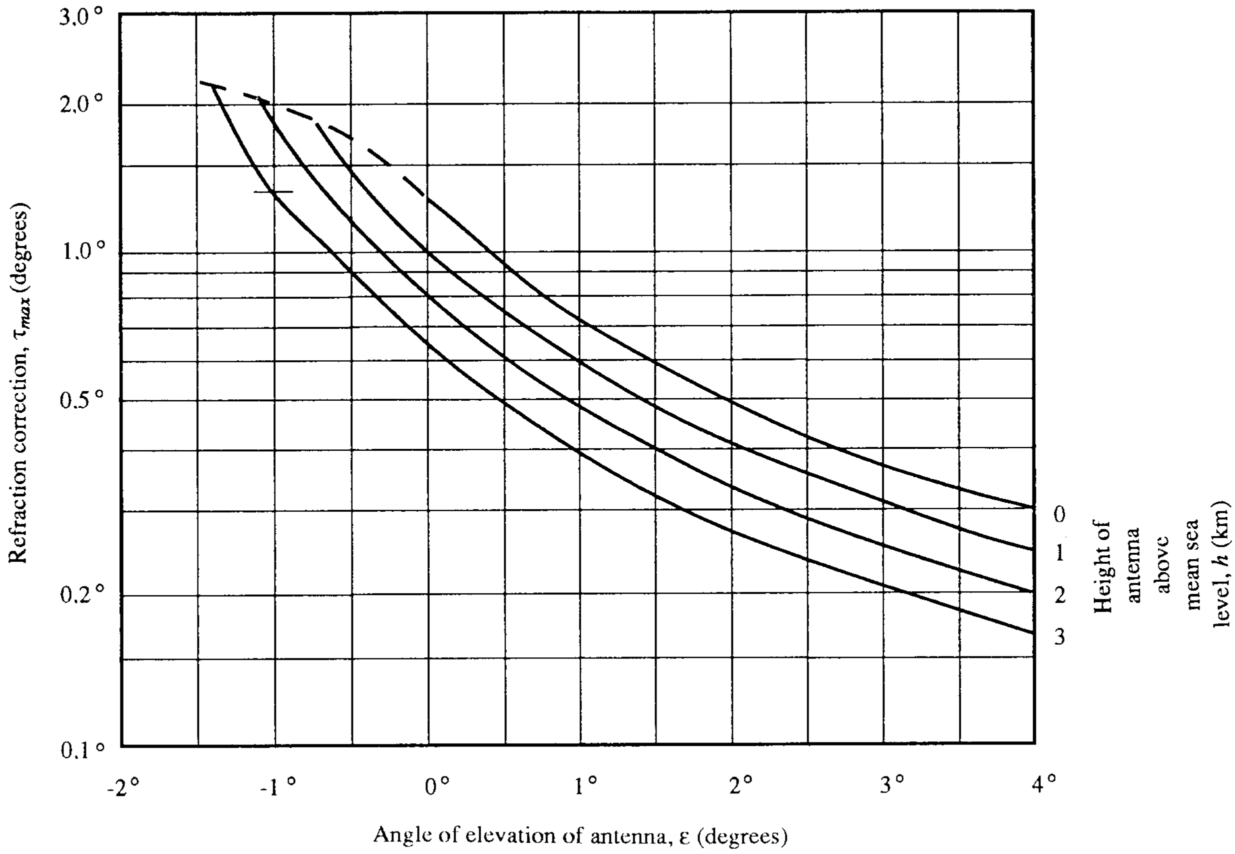
5.2.3 Raise the trace of the geometric orbit at each point by the quantity τ (a function of e) to account for the maximum and minimum refraction expected. This means that there will be two new traces, one corresponding to minimum bending and the other to maximum bending.

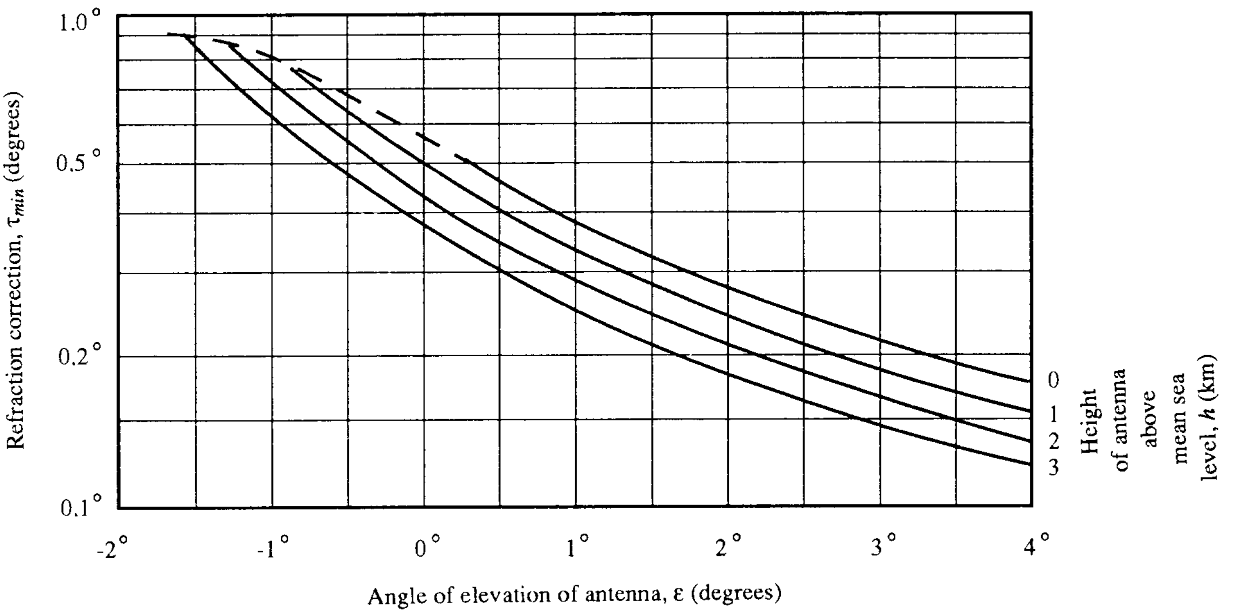
5.2.4 Draw the local horizon in the region of the azimuth concerned. For preliminary studies, the method can be simplified by replacing the real local horizon by a mean, approximate horizon.

5.2.5 Using a compass set to a radius of 2°, find on the straight line of the constant angle of antenna elevation, the centre of a circle tangential to the trace corresponding to minimum bending: one of the azimuth limits is thus defined. Subtract this deviation from the centre azimuth determined using equation (8).

FIGURE 1

Refraction correction for angle ε





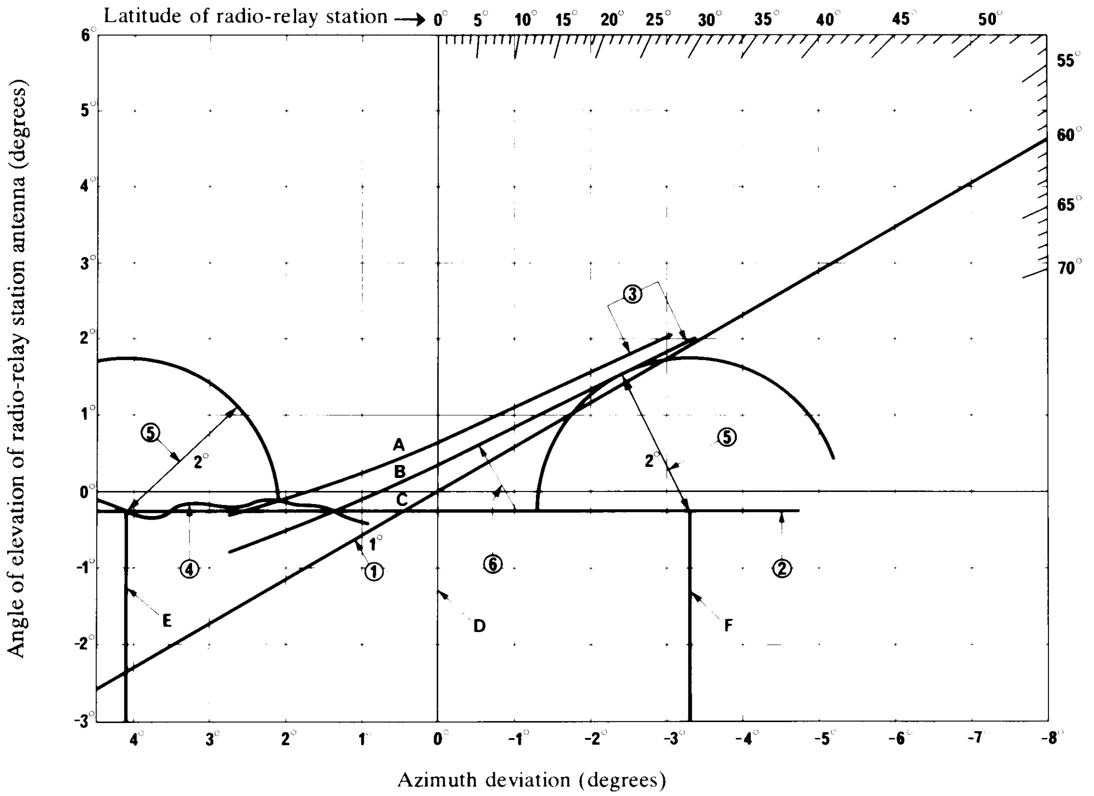
N_0 = 400 and ΔN = –68 for maximum bending

N_0 = 250 and ΔN = –30 for minimum bending

D01-sc

FIGURE 2

Sample determination using graphical method



Radio-relay station altitude: 1 km
Latitude: 60°
Angle of elevation ε: −0.25°

A: maximum refraction
B: minimum refraction
C: no refraction

D: reference azimuth: 74.68° (from equation (8))
E: upper limit 74.68° + 4.1° = 78.78°
F: lower limit 74.68° – 3.3° = 71.38°

D02-sc

Similarly, on the straight line of the constant angle of antenna elevation, find the centre of a second circle such that its closest point of intersection with the maximum bending trace is just above the horizon; the second azimuth limit is thus defined. Add this deviation to the centre azimuth.

5.2.6 This graphical construction can also be used to find the actual angular separation between an existing antenna azimuth and the orbit; this will be the compass radius corresponding to the shortest distance between the point of the antenna direction on the line representing the beam angle of elevation ε, and the nearest orbit trace. The maximum radiated power should be determined using Recommendation ITU-R SF.406.

5.3 Analytical method

Calculation of the separation angle is most easily carried out using a computer implementation of the analytical calculation method described in Annex 2. Also, it may be preferable to use the analytical method, rather than the graphical method, for stations at high latitudes because various approximations used in the graphical method are no longer valid under this condition.

ANNEX 2

Analytical method for calculating separation angles between radio-relay antenna beams and the geostationary-satellite orbit

1. Introduction

The analytical calculation method in this Annex consists of:

– preliminary calculations in § 2, where the main beam is classified into a total of 8 zones;

– preliminary determination of the separation angle in § 3, where an initial estimation of the separation angle is given in preparation for detailed calculations in § 4;

– detailed calculations of the separation angle are carried out in § 4, where an accurate value of the separation angle is finally obtained.

Parameters necessary for the calculation are:

B : separation angle to be avoided (within 2° for 1-10 GHz and 1.5° for 10-15 GHz)

L : latitude of the station (absolute magnitude)

A_0 : azimuth of the antenna main beam (measured either clockwise or anti-clockwise from the South in the Northern Hemisphere and from the North in the Southern Hemisphere $0 \leq A_0 \leq 180°$)

ε_0 : elevation of the antenna main beam

$\tau_{max}(\varepsilon)$: maximum atmospheric bending corresponding to elevation angle ε (see Note 1)

$\tau_{min}(\varepsilon)$: minimum atmospheric bending corresponding to elevation angle ε (see Note 1)

ε_{m1} : the minimum value of elevation angle towards the local horizon at maximum atmospheric bending, as seen from the antenna height of the station, over the azimuthal range between $A_0 - B$ and $A_0 + B$ (see Note 2)

ε_{m2} : the minimum value of elevation angle towards the local horizon at minimum atmospheric bending, as seen from the antenna height of the station, over the azimuthal range between $A_0 - B$ and $A_0 + B$ (see Note 2).

In addition, the following formulae are defined:

$$F(E) = \text{arc cos } (K^{-1} \cos E) \quad (12)$$

where K is orbit radius/Earth radius, assumed to be 6.63

$$S(A, E) = \text{arc sin } [\sin L \cdot \cos (F - E) - \cos L \cdot \sin (F - E) \cdot \cos A] \quad (13)$$

where $S(A, E)$ is the angle (degrees) between the beam and the orbit (see Note 3)

$$C(E) = \text{arc cos } [\tan L / \tan (F - E)] \quad (14)$$

where $C(E)$ is the azimuth in degrees of the orbit corresponding to the refracted elevation angle E. It should be noted that F in formulae (13) and (14) is calculated from E by using formula (12)

$$\alpha = \sin L / \sqrt{(1 - K^{-2})^2 + (K^{-1} \sin L)^2} \tag{15}$$

$$\beta = \sqrt{1 - \alpha^2} \tag{16}$$

where arc sin α is the angle between the horizon and the line normal to the geostationary-satellite orbit in the azimuthal direction where the geostationary-satellite orbit crosses the horizon, without taking account of atmospheric refraction, as seen from the latitude L.

It should be noted that when $S(A, E)$ is positive, the beam is above the orbit and when $S(A, E)$ is negative, the beam is below the orbit.

The following calculations are carried out on the assumption that the local horizon is flat, its altitude being equal to the lowest altitude over the local horizon in the azimuthal range of $A_0 - B$ to $A_0 + B$. If the local horizon is not flat, the conclusions of the calculations should be interpreted as follows:

– if the calculation shows that the separation angle is at least B degrees, the conclusion is correct even when a complicated skyline of the local horizon is taken into account;

– if the calculation shows that the separation angle is less than B degrees, the graphical method described in Annex 1 may be used for a further investigation. The graphical analysis may show that, in some cases, the separation angle is at least B degrees because of a complicated skyline of the local horizon.

2. Preliminary calculations

Figure 3 shows apparent geostationary-satellite orbits and horizons as seen from the station. GSO_{max} and GSO_{min} are the apparent geostationary-satellite orbits at maximum and minimum atmospheric bending, respectively. HOR_{max} and HOR_{min} are the apparent horizons at maximum and minimum atmospheric bending, respectively. H_1 is the crosspoint of GSO_{max} and HOR_{max} and H_2 is the crosspoint of GSO_{min} and HOR_{min}. Between H_1 and H_2, it seems reasonable to assume that the horizon consists of a straight line connecting H_1 and H_2.

The azimuths A_{m1} of point H_1 and A_{m2} of point H_2 are given by:

$$E_{m1} = \varepsilon_{m1} - \tau_{max}(\varepsilon_{m1}), \qquad A_{m1} = C(E_{m1})$$

$$E_{m2} = \varepsilon_{m2} - \tau_{min}(\varepsilon_{m2}), \qquad A_{m2} = C(E_{m2})$$

where E_{m1} and E_{m2} are the refracted elevation angles.

Since Fig. 3 is relatively complicated, it is necessary to classify main beam directions into various cases.

2.1 Preliminary elimination

In the following cases, it can be easily concluded that the separation angle is at least B degrees.

a) $A_{m1} + B \le A_0$: The separation angle is at least $A_0 - A_{m1}$ degrees.

b) $A_0 < A_{m1} + B$ and $\varepsilon_0 \le \varepsilon_{m2} - B$: The separation angle is at least $\varepsilon_{m2} - \varepsilon_0$ degrees.

For other cases, more detailed calculations are necessary, which follow.

2.2 Classification of main beam directions

The main beam direction is on or above the horizon, when one of the following conditions is met:

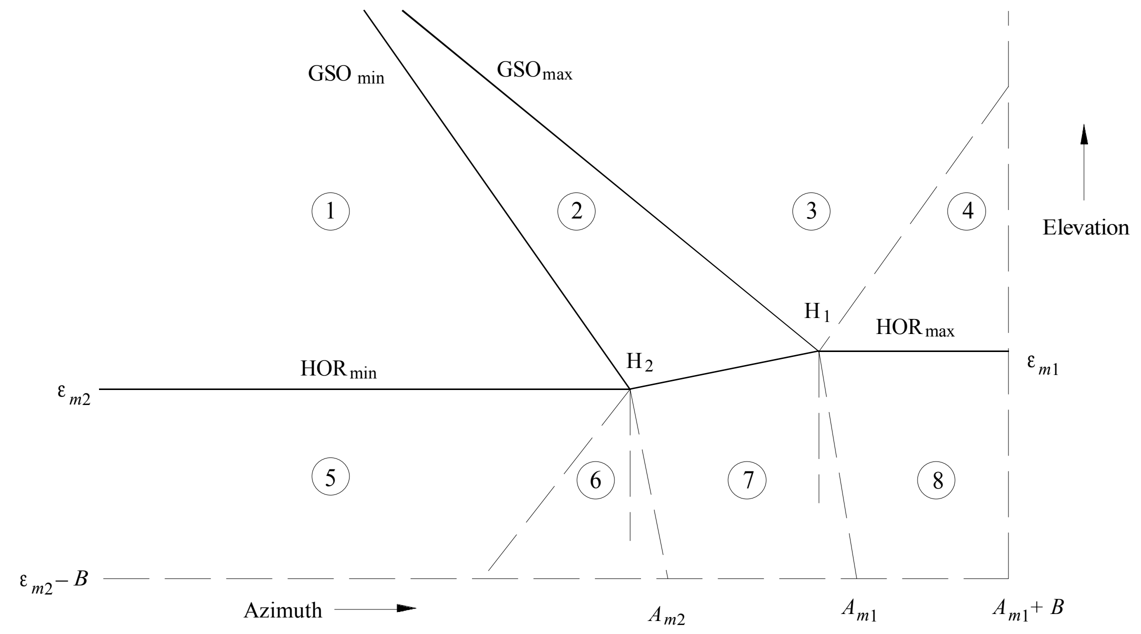
a) $A_{m1} \le A_0$ and $\varepsilon_{m1} \le \varepsilon_0$

b) $A_{m2} \le A_0 < A_{m1}$ and $(\varepsilon_{m1} - \varepsilon_{m2})(A_0 - A_{m1}) \le (\varepsilon_0 - \varepsilon_{m1})(A_{m1} - A_{m2})$

c) $A_0 < A_{m2}$ and $\varepsilon_{m2} \le \varepsilon_0$

FIGURE 3

Classification of main beam directions



GSO_{max} : apparent geostationary-satellite orbit at maximum atmospheric bending

GSO_{min} : apparent geostationary-satellite orbit at minimum atmospheric bending

D03

In the above cases, main beam directions are classified into Zones 1, 2, 3 and 4, according to the following criteria (see Fig. 3):

Zone 1: $S_{min} < 0$

Zone 2: $S_{max} \leq 0$ and $S_{min} \geq 0$

Zone 3: $S_{max} > 0$ and $\alpha(A_0 - A_{m1}) < \beta(\varepsilon_0 - \varepsilon_{m1})$

Zone 4: $S_{max} > 0$ and $\alpha(A_0 - A_{m1}) \geq \beta(\varepsilon_0 - \varepsilon_{m1})$

where S_{max} and S_{min} are given by:

$$E_{max} = \varepsilon_0 - \tau_{max}(\varepsilon_0), \qquad S_{max} = S(A_0, E_{max})$$

$$E_{min} = \varepsilon_0 - \tau_{min}(\varepsilon_0), \qquad S_{min} = S(A_0, E_{min})$$

In other cases where main beam directions are below the horizon, they are further classified into Zones 5, 6, 7 and 8 as follows (see Fig. 3):

Zone 5: $\alpha(A_0 - A_{m2}) < \beta(\varepsilon_0 - \varepsilon_{m2})$

Zone 6: $\alpha(A_0 - A_{m2}) \geq \beta(\varepsilon_0 - \varepsilon_{m2})$ and

$(\varepsilon_{m1} - \varepsilon_{m2})(\varepsilon_0 - \varepsilon_{m2}) + (A_{m1} - A_{m2})(A_0 - A_{m2}) < 0$

Zone 7: $(\varepsilon_{m1} - \varepsilon_{m2})(\varepsilon_0 - \varepsilon_{m2}) + (A_{m1} - A_{m2})(A_0 - A_{m2}) \geq 0$ and

$(\varepsilon_{m1} - \varepsilon_{m2})(\varepsilon_0 - \varepsilon_{m1}) + (A_{m1} - A_{m2})(A_0 - A_{m1}) < 0$

Zone 8: $(\varepsilon_{m1} - \varepsilon_{m2})(\varepsilon_0 - \varepsilon_{m1}) + (A_{m1} - A_{m2})(A_0 - A_{m1}) \geq 0$

3. Preliminary determination of the separation angle

Zone 1

In this case, the main beam direction is below the orbit for both maximum and minimum atmospheric bending. Elevation and azimuth of the direction at the beam circumference with separation angle B from the main beam on the line approximately normal to the orbit are:

$$\varepsilon_1 = \varepsilon_0 + \alpha \cdot B, \qquad A_1 = A_0 + \beta \cdot B$$

Calculate $E_1 = \varepsilon_1 - \tau_{min}(\varepsilon_1)$ and $S_1 = S(A_1, E_1)$

An approximate estimate of the separation angle is:

$$SA = B \cdot S_{min}/(S_{min} - S_1) \quad \text{degrees}$$

Calculate $\varepsilon_s = \varepsilon_0 + \alpha \cdot SA$ and go to § 4 for a more accurate calculation.

Zone 2

In this case, the separation angle is zero.

Zone 3

In this case, the main beam is above the orbit for both maximum and minimum atmospheric bending. Elevation and azimuth of the direction at the beam circumference with separation angle B from the main beam on the line approximately normal to the orbit are:

$$\varepsilon_3 = \varepsilon_0 - \alpha \cdot B, \qquad A_3 = A_0 - \beta \cdot B$$

If $\varepsilon_3 \geq \varepsilon_{m1}$, calculate:

$$E_3 = \varepsilon_3 - \tau_{max}(\varepsilon_3) \quad \text{and} \quad S_3 = S(A_3, E_3)$$

An approximate estimate of the separation angle is:

$$SA = B \cdot S_{max}/(S_{max} - S_3) \quad \text{degrees}$$

Calculate $\varepsilon_s = \varepsilon_0 - \alpha \cdot SA$ (if $\varepsilon_s < \varepsilon_{m1}$, put $\varepsilon_s = \varepsilon_{m1}$), and go to § 4 for a more accurate calculation.

If $\varepsilon_3 < \varepsilon_{m1}$, calculate:

$$A_{31} = A_0 - (\varepsilon_0 - \varepsilon_{m1}) \cdot \beta/\alpha$$

where A_{31} is the azimuth of the direction at which the line passing through the main beam and normal to the orbit crosses the local horizon HOR_{max}.

An approximate estimate of the separation angle is:

$$SA = [(\varepsilon_0 - \varepsilon_{m1})/\alpha] \cdot S_{max}/(S_{max} - S_{31}) \quad \text{degrees}$$

where $S_{31} = S(A_{31}, E_{m1})$ and E_{m1} has been calculated in § 2.

(Since computers can handle only a limited number of digits, the above formula may not be appropriate in exceptional cases where S_{31} happens to be very close to S_{max}. Therefore, it should be applied when $|S_{max} - S_{31}| > \Delta$ degrees. If not, a reasonable estimate of the separation angle is $SA = S_{max}$ degrees. Here, Δ is an appropriate small number, say, 0.001°.)

Calculate $\varepsilon_s = \varepsilon_0 - \alpha \cdot SA$ and go to § 4 for a more accurate calculation.

Zone 4

In this case, elevation and azimuth of the direction of the orbit nearest from the main beam are ε_{m1} and A_{m1}. Therefore, the angle SA between this direction and the main beam is:

$$SA = \sqrt{(\varepsilon_{m1} - \varepsilon_0)^2 + (A_{m1} - A_0)^2} \quad \text{degrees}$$

This separation angle is accurate and no further calculations are necessary.

Zone 5

In this case, the main beam direction is below the horizon and also below the orbit for both maximum and minimum atmospheric bending.

First, calculate:

$$A_5 = A_0 + (\varepsilon_{m2} - \varepsilon_0) \cdot \beta/\alpha \qquad \text{and} \qquad S_5 = S(A_5, E_{m2})$$

where A_5 is the azimuth of the direction at which the line passing through the main beam and normal to the orbit crosses the local horizon HOR_{min} and E_{m2} has been calculated in § 2.

Next, calculate:

$$\varepsilon_{51} = \varepsilon_{m2} + \alpha \cdot B, \qquad A_{51} = A_5 + \beta \cdot B$$

where the direction (A_{51}, ε_{51}) is B degrees further away from the direction (A_5, ε_{m2}) on the line passing through the main beam and normal to the orbit.

Calculate $E_{51} = \varepsilon_{51} - \tau_{min}(\varepsilon_{51})$ and $S_{51} = S(A_{51}, E_{51})$.

An approximate estimate of the separation angle is:

$$SA = (\varepsilon_{m2} - \varepsilon_0)/\alpha + B \cdot S_5/(S_5 - S_{51}) \qquad \text{degrees}$$

Calculate $\varepsilon_s = \varepsilon_0 + \alpha \cdot SA$ and go to § 4 for a more accurate calculation.

Zone 6

In this case, an approximate estimate of the separation angle is the angle between the main beam and the point H_2, which is given by:

$$SA = \sqrt{(\varepsilon_{m2} - \varepsilon_0)^2 + (A_{m2} - A_0)^2} \qquad \text{degrees}$$

However, because in rare cases the nearest orbit direction may be slightly different, put $\varepsilon_s = \varepsilon_{m2}$ and go to § 4 for a more accurate calculation.

Zone 7

In this case, the nearest orbit direction lies on the horizon connecting H_1 and H_2, and the separation angle is given by:

$$SA = [(\varepsilon_{m1} - \varepsilon_{m2})(A_0 - A_{m1}) - (\varepsilon_0 - \varepsilon_{m1})(A_{m1} - A_{m2})] \, / \sqrt{(\varepsilon_{m1} - \varepsilon_{m2})^2 + (A_{m1} - A_{m2})^2}$$

This separation angle is accurate and no further calculations are necessary.

Zone 8

In this case, the nearest orbit direction is point H_1 and the separation angle is:

$$SA = \sqrt{(\varepsilon_0 - \varepsilon_{m1})^2 + (A_0 - A_{m1})^2} \qquad \text{degrees}$$

This separation angle is accurate and no further calculations are necessary.

4. Detailed calculations of the separation angle

In case of Zones 1, 3, 5 and 6, the separation angle calculated in the preceding section is an approximate one. However, if $SA \geq 1.5\ B$, it may be safely said that the separation angle is at least B degrees. Therefore, there is no need of further calculations.

If $SA < 1.5\ B$, further calculations should be carried out in order to arrive at more accurate values. For this purpose, it is appropriate to start from ε_s which has already been calculated, corresponding to the approximate separation angle.

In case of Zones 1, 5 and 6, the nearest orbit direction lies on GSO_{min}. The azimuth A_s and the separation angle SA corresponding to ε_s are given by:

$$E_s = \varepsilon_s - \tau_{min}(\varepsilon_s), \qquad A_s = C(E_s), \qquad SA = \sqrt{(\varepsilon_0 - \varepsilon_s)^2 + (A_0 - A_s)^2}$$

In case of Zone 3, the nearest orbit direction lies on GSO_{max}. The azimuth and the separation angle corresponding to ε_s are given by:

$$E_s = \varepsilon_s - \tau_{max}(\varepsilon_s), \qquad A_s = C(E_s), \qquad SA = \sqrt{(\varepsilon_0 - \varepsilon_s)^2 + (A_0 - A_s)^2}$$

In any of the above cases, the accurate separation angle can be calculated by means of an iteration method, where ε_s is gradually changed upward or downward to find a minimum value of SA.

If the calculation is made on an assumption of $h_1 = 0$, see Note 2. The calculation result should be used for confirming the compliance with Recommendation ITU-R SF.406.

Note 1 – Atmospheric bending (degrees) can be calculated by using the following formulae:

$$\begin{aligned}\tau_{max}(\varepsilon, h) = 1/[&0.7885809 + 0.175963\, h + 0.0251620\, h^2 \\ &+ \varepsilon(0.549056 + 0.0744484\, h + 0.0101650\, h^2) \\ &+ \varepsilon^2(0.0187029 + 0.0143814\, h)]\end{aligned}$$

$$\begin{aligned}\tau_{min}(\varepsilon, h) = 1/[&1.755698 + 0.313461\, h \\ &+ \varepsilon(0.815022 + 0.109154\, h) \\ &+ \varepsilon^2(0.0295668 + 0.0185682\, h)]\end{aligned}$$

where h is the antenna height (km) of the station above sea level.

The above formulae have been derived as an approximation for the range of $\varepsilon_m \le \varepsilon \le 8°$ and $0 \le h \le 4$ km, where ε_m is calculated using the equation given in Note 2 with the condition $h_1 = 0$. The algorithm in this Annex guarantees that the above formulae are applied only when $\varepsilon \ge \varepsilon_m$.

Note 2 – If the local horizon is formed by a flat terrain or sea, ε_m is given by:

$$\varepsilon_m = -\text{arc cos}\left[\frac{R + h_1}{R + h} \cdot \frac{1 + N_0 \cdot 10^{-6}\,(1 + \Delta N / N_0)^{h_1}}{1 + N_0 \cdot 10^{-6}\,(1 + \Delta N / N_0)^{h}}\right]$$

where:

- h : antenna height (km) of the station above sea level
- h_1 : altitude (km) of the local horizon ($h \ge h_1$)
- R : is the Earth radius assumed to be 6 370 km.

ε_{m1} is an elevation angle corresponding to maximum atmospheric bending ($N_0 = 400$ and $\Delta N = -68$), and ε_{m2} is an elevation angle corresponding to minimum atmospheric bending ($N_0 = 250$ and $\Delta N = -30$). It should be noted that $\varepsilon_{m1} \ge \varepsilon_{m2}$.

In practice it may be cumbersome to estimate the precise values of ε_{m1} and ε_{m2} taking into account the complicated skyline of the local horizon. In such a case, it may be simpler to estimate the values of ε_{m1} and ε_{m2} using the above formula under an assumption of $h_1 = 0$. If the calculation based on this assumption shows that the separation angle is at least B degrees, this conclusion is correct even when a complicated skyline of the local horizon is taken into account. If the calculation shows that the separation angle is less than B degrees, the calculation should be carried out again using the actual values of ε_{m1} and ε_{m2}.

Note 3 – This formula can be derived as follows:

Assuming that the parameters of a terrestrial radio-relay station are as follows:

– latitude, L (absolute magnitude);

– azimuth of the antenna main beam, A (measured clockwise from the South in the Northern Hemisphere and from the North in the Southern Hemisphere);

– elevation angle of the antenna main beam, E (after taking into account the effects of refraction).

For a radio-relay station in the Northern Hemisphere, the calculation is as follows:

The trajectory of the radio-relay main beam can be expressed in three dimensional space as:

$$x = R \cos L + u (\sin E \cdot \cos L + \cos E \cdot \sin L \cdot \cos A) \tag{17}$$

$$y = -u \cdot \cos E \cdot \sin A \tag{18}$$

$$z = R \sin L + u (\sin E \cdot \sin L - \cos E \cdot \cos L \cdot \cos A) \tag{19}$$

where R is the Earth radius and the longitude of the radio-relay station is assumed to be zero (on the x-z plane). The following formula is derived:

$$x^2 + y^2 + z^2 = R^2 + u^2 + 2Ru \cdot \sin E \tag{20}$$

The radio-relay main beam arrives at the surface of a sphere with orbit radius when $x^2 + y^2 + z^2 = K^2 R^2$ (where K is orbit radius/Earth radius, assumed to be 6.63), that is:

$$u/R = \sqrt{K^2 - \cos^2 E} - \sin E \tag{21}$$

The separation angle S can be calculated by the following formula:

$$z = K R \sin S \tag{22}$$

Consequently:

$$\sin S = \frac{1}{K}\left[\sin L + \left(\sqrt{K^2 - \cos^2 E} - \sin E\right) \left(\sin E \cdot \sin L - \cos E \cdot \cos L \cdot \cos A\right)\right] \tag{23}$$

where S is positive if the antenna beam axis is above the orbit. This formula can be also expressed as:

$$F = \text{arc cos } (K^{-1} \cos E)$$

$$\sin S = \sin L \cdot \cos (F - E) - \cos L \cdot \sin (F - E) \cdot \cos A \tag{24}$$

When the radio-relay station is located in the Southern Hemisphere, equations (17) to (19) are expressed in a different way, but the results (equations (23) and (24)) are identical.

It should be noted that when S is zero, equation (24) above is equivalent to equation (8) in Annex 1.

Note 4 – In many cases of the above calculations, the separation angle SA between the main beam and the direction of elevation ε and azimuth A is calculated as follows:

$$SA = \sqrt{(\varepsilon - \varepsilon_0)^2 + (A - A_0)^2}$$

In fact, this formula is an approximate one. The accurate formula is given by:

$$SA = 2 \cdot \text{arc sin} \sqrt{\sin^2 \Delta\varepsilon + \cos \varepsilon \cdot \cos \varepsilon_0 \cdot \sin^2 \Delta A}$$

where:

$$\Delta\varepsilon = (\varepsilon - \varepsilon_0)/2 \qquad \text{and} \qquad \Delta A = (A - A_0)/2.$$

However, provided that $|\varepsilon|$, $|\varepsilon_0|$, $|\Delta\varepsilon|$ and $|\Delta A|$ are relatively small, the approximate formula gives sufficiently precise values.

Note 5 – A computer program for calculating separation angles on the basis of this Annex is given in Appendix 1.

APPENDIX I

TO ANNEX 2

```
1000 '    SANGLE-A.BAS
1010 '*****************************************************************
1020 '*        Separation Angles between                              *
1030 '*        radio-relay antenna beams and                          *
1040 '*        the geostationary-satellite orbit                      *
1050 '*****************************************************************
1060 SCREEN 0: WIDTH 80: CLS
1070 '---------- Function definition ----------------------------------
1080 DEF FNTMAX (E) = DR / (.7885809 + .175963 * H0 + .025162 * H0 ^ 2 +
     E * RD * (.549056 + .0744484 * H0 + .010165 * H0 ^ 2) +
     (E * RD) ^ 2 * (.0187029 + .0143814 * H0))
1090 DEF FNTMIN (E) = DR / (1.755698 + .313461 * H0 +
     E * RD * (.815022 + .109154 * H0) +
     (E * RD) ^ 2 * (.0295668 + .0185682 * H0))
1100 DEF FNASIN (X) = ATN (X / SQR (-X * X + 1))
1110 DEF FNACOS (X) = -ATN (X / SQR (-X * X + 1)) + PI / 2
1120 DEF FNF (E) = FNACOS (1 / K * COS (E))
1130 DEF FNS (A, E) = FNASIN (SINL * COS (FNF (E) - E) -
     COSL * SIN(FNF(E) - E) * COS (A))
1140 DEF FNC (E) = FNACOS (TANL / TAN (FNF (E) - E))
1150 '-----------------------------------------------------------------
1160 '    PI    : circular constant
1170 '    RD    : radian to degree
1180 '    DR    : degree to radian
1190 '    F     : transmitter frequency
1200 '    BD     : separation angle to be avoided in degree
1210 ' LD,LM,LS : latitude of the station in degrees,minutes,seconds
1220 '    PT     : allowable e.i.r.p value
1230 '----------- Parameter input -------------------------------------
1240 PI = 4 * ATN(1): RD = 180 / PI: DR = PI / 180
1250 PRINT "Do you want print output on printer ?(YIN)"
1260 A$ = INKEY$: IF A$ = "" THEN 1260
1270 IF A$ = "Y" OR A$ "y" THEN IPRT = 1 ELSE IPRT = 0: GOTO 1320
1280 OPEN "LPTI:" FOR OUTPUT AS #l
1290 PRINT #1, STRING$(70, "-")
1300 PRINT #1, "F(GHz) Latitude A0(°) E0(°) H0(m) Hl(m) ZONE "
     SA(°) EIRP(dBW)"
1310 PRINT #1, STRING$ (70, "-")
1320 CLS : INPUT "F : frequency     (GHz) "; F
1330 IF F < 1 OR F > 15 THEN PRINT "1<=F<=15": GOTO 1320
1340 IF F <= 10 THEN BD = 2 ELSE BD = 1.5
1350 B = BD * DR
1360 INPUT "L : latitude (°, ', ") ";  LD, LM, LS
1370 L = ABS((LD + LM / 60 + LS / 3600) * DR)
1380 SINL = SIN(L): COSL = COS(L): TANL = SINL / COSL
1390 INPUT "A0: antenna azimuth  (°) "; A0D: A0 = A0D * DR
1400 INPUT "E0: antenna elevation          (°) "; E0D: E0 = E0D * DR
1410 INPUT "H0: station height   (m) "; H0: H0 = H0 / 1000
1420 INPUT "H1: horizon height   (m) "; Hl: Hl = Hl / 1000
1430 IF Hl > HO THEN PRINT "H1<=H0": GOTO 1420
1440 '--------   Call subroutine --------------------------------------
1450 GOSUB 2000
1460 '---------- Print result -----------------------------------------
1470 CLS : PRINT STRING$ (70, "-")
```

```
1480 PRINT USING "F : frequency              ##.# (GHz) "; F
1490 PRINT USING "L : latitude          ####°##'##''"; LD; LM; LS
1500 PRINT USING "A0: antenna azimuth       ####.# (°) "; A0D
1510 PRINT USING "E0: antenna elevation      ###.# (°) "; E0D
1520 PRINT USING "H0: station height          #### (m) "; H0 * 1000
1530 PRINT USING "H1: horizon height          #### (m) "; Hl * 1000
1540 PRINT "Separation angle should be at least"; BD; "degrees."
1550 PRINT STRING$ (70, "-")
1560 PRINT " The main beam is in "; C$; "."
1570 IF KF < > 3 THEN PRINT "The separation angle is";
1580 IF KF = 2 THEN PRINT USING "at least##.## degrees."; SA * RD
1590 IF KF = 1 THEN PRINT "at least"; BD; "degrees."
1600 IF KF = 0 THEN PRINT "zero."
1610 IF KF < 0 THEN PRINT "less than"; BD; "degrees."
1620 IF KF = -2 THEN PRINT "If the local horizon is not flat,"
     PRINT "further investigation should be carried out."
1630 IF KF = 3 THEN PRINT "You can't see orbit from your latitude."
1640 IF SA > 90 * DR OR KF = 3 OR KF = 2 THEN GOTO 1660
1650 PRINT USING "Actual separation angle can be estimated
     as ##.### degrees."; SA * RD
1660 '---------- DETERMINATION OF EIRP ---------------------------------
1670 IF 10 < F THEN PT = 55: GOTO 1710
1680 IF SA <= .5 * DR THEN PT = 47: GOTO 1710
1690 IF SA >= 1.5 * DR THEN PT = 55: GOTO 1710
1700 PT = 47 + 8 * (SA * RD - .5)
1710 PRINT USING "Maximum e.i.r.p shall not exceed ##.### dBW."; PT
1720 PRINT STRING$(70, "-")
1730 IF IPRT = 0 THEN 1750
1740 PRINT #1, USING "##.# ####°##'##" ####.# ###.# #### ##, #
     \     \###.## ##.##"; F; LD; LM; LS; A0D; E0D; H0 * 1000;
     Hl * 1000; C$; SA * RD; PT
1750 '------------end ----------------------------------------------------
1760 PRINT "Do you continue? (Y/N)"
1770 A$ = INKEY$: IF A$ = "" THEN 1770
1780 IF A$ = "N" OR A$ = "n" THEN CLOSE #1: STOP ELSE GOTO 1320
2000 '= = = = = =subroutine = = = = = == = = = = = = = = = = = = = = = = =
2010 ' IN  B  : separation angle to be avoided in radian
2020 '      L  : latitude of station in radian
2030 '      A0 : azimuth of antenna main beam in radian
2040 '      E0 : elevation of antenna main beam in radian
2050 '      H0 : height of station in km
2060 '      H1 : height of horizon in km
2080 '      N0 : refractivity at sea level in N unit
2090 '      DN : refractivity difference at 1 km above sea level in N unit
2100 '      EM1: the local horizon at maximum atmospheric bending
2110 '      EM2: the local horizon at minimum atmospheric bending
2120 '      R  : Earth radius
2130 '      K  : orbit radius / Earth radius
2140 '      AL : equation (12)
2150 '
2160 ' OUT SA : estimated separation angle
2170 '      C$ : judged zone
2180 '      KF : decision flag
2190 '            3 .. extreme northern or southern latitude
2200 '            2 .. SA is at least SA
2210 '            1 .. SA is at least B
2220 '            0 .. SA is 0
2230             –1 .. SA is less than B
```

```
2240            -2 .. If horizon is flat then SA is less than B
2250 -----------------------------------------------------------------------
2260 R = 6370: K = 6.63: T6 = .000001
2270 N0 = 400: DN = -68: GOSUB 2290: EM1 = EM
2280 N0 = 250: DN = -30: GOSUB 2290: EM2 = EM: GOTO 2310
2290 EMH = (R + H1) / (R + H0) * (1 + N0 * T6 * (1 + DN / N0) ^ H1) /
     (1 + N0 * T6 * (1 + DN / N0) ^ H0)
2300 IF EMH = 1 THEN EM = 0: RETURN ELSE EM = -FNACOS(EMH): RETURN
2310 AL = SINL / SQR ((1 - 1 / K ^ 2) ^ 2 + (SINL / K) ^ 2)
2330 '----------- PRELIMINARY CALCULATION ------------------------------
2340 EEMI = EM1 - FNTMAX(EMI): EEM2 = EM2 - FNTMIN(EM2)
2350 IF AL > 1 THEN C$ = "PRELIM": KF = 3: RETURN ELSE BE = SQR(1 - AL ^ 2)
2360 AM1 = FNC(EEM1) : AM2 = FNC(EEM2) DEM = EM1 - EM2: DAM = AMl - AM2
2380 '----------- PRELIMINARY ELIMINATION -------------------------------
2390 IF A0 >= AM1 + B THEN SA = A0 - AM1: C$ = "PRELIM": KF = 2: RETURN
2400 IF E0 <= EM2 - B THEN SA = EM2 - E0: C$ = "PRELIM": KF = 2: RETURN
2420 '----------- CLASSIFICATION OF MAIN BEAM DIRECTIONS ----------------
2430 IF AM1 <= A0 AND EM1 <= E0 OR AM2 <= A0 AND A0 < AM1 AND DEM *
     (A0 -AM1) <= (E0 - EM1) * DAM OR A0 < AM2 AND EM2 <= E0
     GOTO 2450 ELSE 2520
2450 ' ----------- main beam is on or above the horizon -----------------
2460 EMAX = E0 - FNTMAX(E0): SMAX = FNS(A0, EMAX)
2470 EMIN = EO - FNTMIN(E0): SMIN = FNS(A0, EMIN)
2480 IF SMIN < 0 GOTO 2590
2490 IF SMAX <= 0 GOTO 2630
2500 IF AL * (A0 - AM1) < BE * (E0 - EM1) GOTO 2660 ELSE 2750
2520 ' ----------- main beam is below the horizon -----------------------
2530 IF AL * (A0 - AM2) < BE * (E0 - EM2) GOTO 2780
2540 IF DEM * (E0 - EM2) + DAM * (A0 - AM2) < 0 GOTO 2850
2550 IF DEM * (E0 - EM1) + DAM * (A0 - AM1) < 0 GOTO 2880 ELSE 2920
2570 '----------- PRELIMINARY DETERMINATION -----------------------------
2590 ' ----------- ZONE 1 ----------
2600 El = E0 + AL * B: A1 = A0 + BE * B: EE1 = E1 - FNTMIN(E1)
     S1 = FNS(A1, EE1)
2610 SA = B * SMIN / (SMIN - Sl): IF SA > 1 THEN SA = - SMIN
2615 C$ = "ZONE 1": ES = E0 + AL * SA: GOTO 2950
2630 ' ----------- ZONE 2 ----------
2640 SA = 0: C$ = "ZONE 2": KF = 0: RETURN
2660 ----------- ZONE 3 ----------
2670 E3 = E0 - AL * B: A3 = A0 - BE * B: C$ = "ZONE 3"
     IF E3 < EM1 GOTO 2710
2680 EE3 = E3 - FNTMAX(E3): S3 = FNS(A3, EE3)
2690 SA = B * SMAX / (SMAX - S3): ES = E0 - AL * SA
     IF ES < EM1 THEN ES = EM1
2700 GOTO 3200
2710 A31 = A0 - (E0 - EM1) * BE / AL: S31 = FNS(A31, EEM1)
2720 IF ABS (SMAX - S31) <= .001 * DR THEN SA = SMAX
     ELSE SA (E0 – EM1) / AL * SMAX / (SMAX – S31)
2730 ES = E0 - AL * SA: GOTO 3200
2750 ----------- ZONE 4 ---------
2760 SA = SQR((EM1 - E0) ^ 2 + (AM1 - A0) ^ 2): C$ = "ZONE 4": GOTO 3450
2780 ' -------- ZONE 5 ----------
2790 A5 = A0 + (EM2 - E0) * BE / AL: S5 = FNS(A5, EEM2)
2800 E51 = EM2 + AL * B: A51 = A5 + BE * B
2810 EE51 = E51 - FNTMIN(E51): S51 = FNS(A51, EE51)
2820 SA = (EM2 - E0) / AL + B * S5 / (S5 - S51)
     IF SA > 1 THEN SA = (EM2 - E0) / AL - S5
2830 ES = E0 + AL * SA: C$ = "ZONE 5": GOTO 2950
```

```
2850 ' -----------  ZONE 6  ----------
2860 SA = SQR ((E0 - EM2) ^ 2 + (A0 - AM2) ^ 2): ES = EM2
     C$ = "ZONE 6": GOTO 2950
2880 -----------  ZONE 7  ----------
2890 SA = (DEM * (A0 - AM1) - (E0 - EM1) * DAM) / SQR(DEM ^ 2 + DAM ^ 2)
2900 C$ = "ZONE 7": GOTO 3450
2920 ' -----------  ZONE 8  ----------
2930 SA = SQR((E0 - EM1) ^ 2 + (A0 - AM1) ^ 2): C$ = "ZONE 8": GOTO 3450
2950 ' -----------  DETAILED CALCULATIONS FOR ZONES 1, 5 AND 6-----------
2970 ' -----------  STEP 1  ----------
2980 IF SA >= 1.5 * B GOTO 3450 ELSE DE = BE * B / 60
2990 EES = ES - FNTMIN(ES)
3000 IF FNF(EES) - EES < L THEN ES = ES - DE: GOTO 2990
3010 AS=FNC(EES):SAO=SQR((ES-E0)^2+(AS-A0)^2)
3020 ES1 = ES + DE: EES = ES1 - FNTMIN(ES1)
3030 IF FNF(EES) - EES < L THEN ES1 = ES: SA = SA0: GOTO 3130
3040 AS=FNC(EES):SA=SQR((ES1-E0)^2+(AS-A0)^2)
3050 IF SA > SA0 THEN ES1 = ES: SA = SA0: GOTO 3130
3070 ' ----------- STEP 2  ----------
3080 ES1 = ES1 + DE: EES = ES1 - FNTMIN(ES1)
3090 IF FNF(EES) - EES < L GOTO 3450
3100 AS=FNC(EES):SA1=SQR((ES1-E0)^2+(AS-A0)^2)
3110 IF SA1 < SA THEN SA = SA1: GOTO 3080 ELSE 3450
3130 '-----------  STEP 3  ----------
3140 IF ES1 <= EM2 GOTO 3450
3150 ES1 = ES1 - DE: IF ES1 < EM2 THEN ES1 = EM2
3160 EES=ES1-FNTMIN(ES1):AS=FNC(EES)
3170 SA1=SQR((ES1-E0)^2+(AS-A0)^2)
3180 IF SA1 < SA THEN SA = SA1: GOTO 3140 ELSE 3450
3200 ' ----------- DETAILED CALCULATION FOR ZONE 3 ---------------------
3220 ' ----------- STEP 1 ----------
3230 IF SA >= 1.5 * B GOTO 3450 ELSE DE = BE * B / 60
3240 EES = ES - FNTMAX(ES)
3250 IF FNF(EES) - EES < L THEN ES = ES - DE: GOTO 3240
3260 AS=FNC(EES):SA0=SQR((ES-E0)^2+(AS-A0)^2)
3270 ES1 = ES + DE: EES = ES1 - FNTMAX(ES1)
3280 IF FNF(EES) - EES < L THEN ES1 = ES: SA = SA0: GOTO 3380
3290 AS=FNC(EES):SA=SQR((ES1-E0)^2+(AS-A0)^2)
3300 IF SA > SA0 THEN ES1 = ES: SA = SA0: GOTO 3380
3320 '----------- STEP 2 ----------
3330 ES1 = ES1 + DE: EES = ES1 - FNTMAX(ES1)
3340 IF FNF(EES) - EES < L GOTO 3450
3350 AS=FNC(EES):SA1=SQR((ES1-E0)^2+(AS-A0)^2)
3360 IF SA1 < SA THEN SA = SA1: GOTO 3330 ELSE 3450
3380 '----------- STEP 3 ----------
3390 IF ES1 <= EM1 GOTO 3450
3400 ES1 = ES1 - DE: IF ES1 < EM1 THEN ES1 = EM1
3410 EES=ES1-FNTMAX(ES1):AS=FNC(EES)
3420 SA1=SQR((ES1-E0)^2+(AS-A0)^2)
3430 IF SA1 < SA THEN SA = SA1: GOTO 3390
3450 '----------- JUDGMENT ----------------------------------------
3460 IF SA >= B THEN KF = 1: RETURN ELSE KF = -2: RETURN
```