International Telecommunication Union

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# Intersection of radio-relay antenna beams with orbits used by space stations in the fixed-satellite service

SF Series

Frequency sharing and coordination between fixed-satellite and fixed service systems

International Telecommunication Union

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*Note*: *This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R SF.765-1*

# Intersection of radio-relay antenna beams with orbits used by space stations in the fixed-satellite service

(1992-2002)

**Scope**

This Recommendation discusses various aspects of the intersection of radio-relay antenna beams with orbits used by space stations in the fixed-satellite service and, in particular, Annex 2 presents an analytical method for calculating separation angles between radio-relay antenna beams and the geostationary-satellite orbit. This revised Recommendation expands the applicability of Annex 2 so that it becomes applicable also to radio-relay antennas with very high elevation angles. Appendix 1 to Annex 2 provides code for a computer program written in C language.

The ITU Radiocommunication Assembly,

*considering*

a)     that the examination of the compliance of fixed wireless stations operating below 15 GHz with the relevant provisions of the Radio Regulations requires the calculation of the angle between the direction of the radio-relay antenna beam and the direction towards the geostationary-satellite orbit;

b)     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 fixed wireless 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. The method given in this Recommendation can also be used for such purpose.

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*     Radiocommunication Study Group 5 made editorial amendments to this Recommendation in December 2009 in accordance with Resolution ITU-R 1.

**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 fixed wireless 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.

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 fixed wireless 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 $\pm 2°$ from its axis, and the effect of refraction. Examination of the compliance of existing radio-relay stations with the relevant provisions of the RR  indicates that the percentage of stations having an antenna-beam direction within $\pm 2°$ 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 fixed wireless systems.

## 2        Some characteristics of the antenna beams of terrestrial fixed wireless systems

Line-of-sight fixed wireless 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

$\varphi$: Earth latitude of the terrestrial station

$\lambda$: difference in longitude between the terrestrial station and the satellite.

Eliminating $\lambda$ 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 $\theta$ 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:

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

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

and where:

$m$: number of satellites in each orbit

$\psi$: 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 the relevant provisions of the RR on the directions of radio-relay antennas to protect reception by geostationary satellites.

Equation (3) can be expressed as:

$$A = \arccos \frac{\tan \varphi}{\tan \left[ \arccos \left( K^{-1} \cos e \right) - e \right]} \tag{8}$$

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

$\varphi$ :    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:

$$e = \varepsilon - \tau \tag{9}$$

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 the relevant provisions of the RR, 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 $\Delta N$ of the index between 0 and 1 000 m are related, the curves showing correction τ

as a function of the angle of elevation $\varepsilon$ can be calculated. Determining the maximum and minimum corrections $\tau_1$ and $\tau_2$ is then equivalent to the assessment of the maximum and minimum of $N$ (or $\Delta N$) 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 $\tau$ 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 $\tau$ 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, $\Delta N$ (as found in worldwide charts). A range for $N_0$ between 250 and 400 ($\Delta N$ 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 $\tau_1$ and $\tau_2$ as a function of angle of elevation of the antenna and station height.

The refraction correction, $\tau$, can be calculated by the following integration:

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

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

$$n(r) \cdot r \cdot \cos \varepsilon = n(r_1) \cdot r_1 \cdot \cos \varepsilon_1 \tag{11}$$

where:

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

$\qquad\quad r_0$ :  Earth radius (6 370 km)

$\qquad\quad r_1 = r_0 + h$ ($h$: station height)

$\qquad\quad \varepsilon_1$ :  elevation angle at the station

$\qquad\quad n_1$ :  refractivity at the station height

$\qquad\quad n_2$ :  refractivity at the orbit

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

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

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

$\qquad\quad N_0 = 250$ 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 2 of Annex 2, § 4, to this Recommendation.

FIGURE 1

**Refraction correction for angle ε**



Angle of elevation of antenna, ε (degrees)



Angle of elevation of antenna, ε (degrees)

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

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

D01-sc
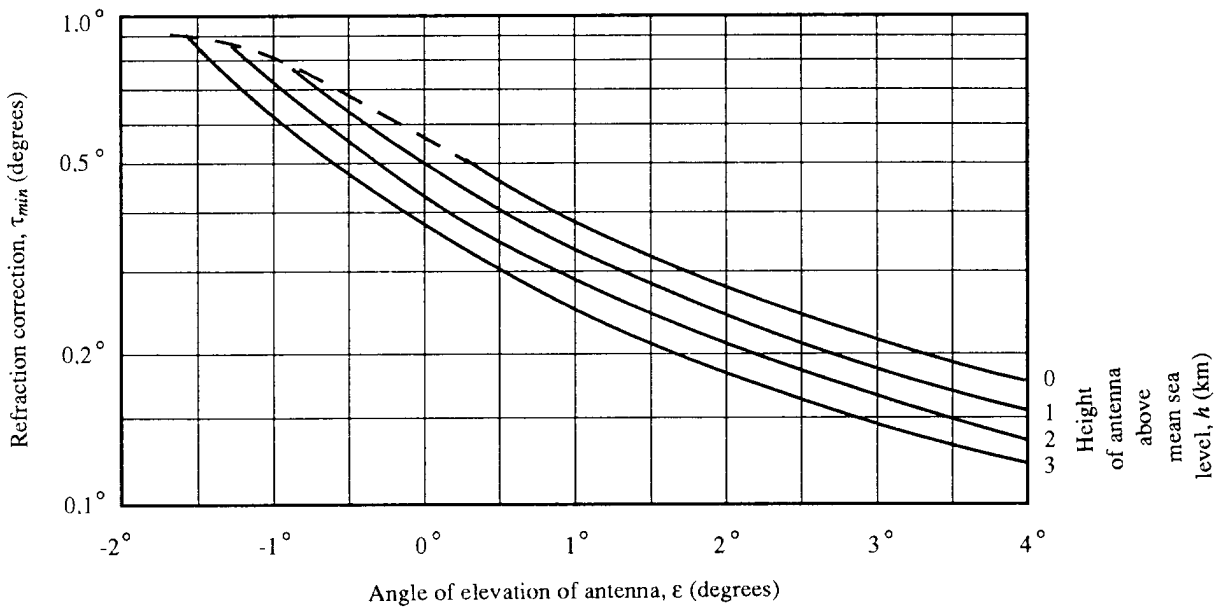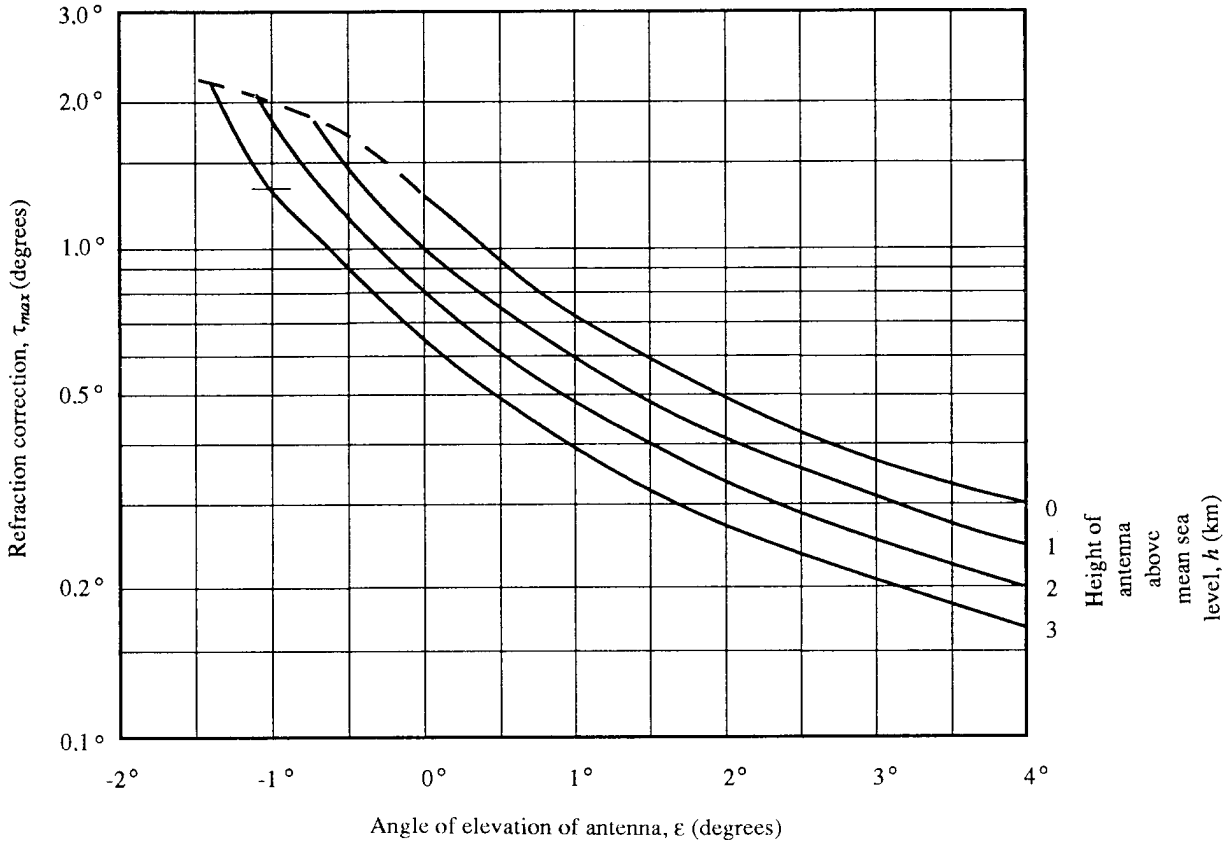
## 5.2 Use of a graphical method for determination of azimuths to be avoided

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.

FIGURE 2

**Sample determination using graphical method**
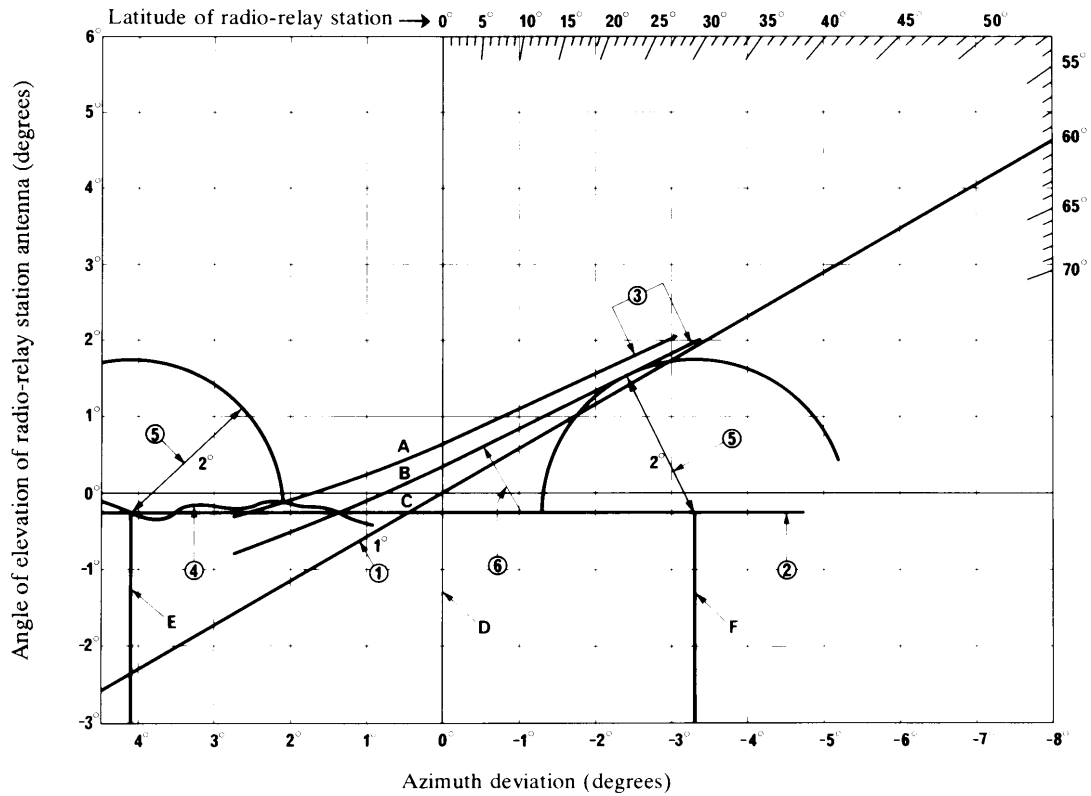


Radio-relay station altitude: 1 km
Latitude: 60°
Angle of elevation $\varepsilon$: $-0.25°$

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

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

This can be done by plotting the point whose elevation is $\varepsilon$ 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 2 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 $\varepsilon$ planned for the antenna.

**5.2.3**    Raise the trace of the geometric orbit at each point by the quantity $\tau$ (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).

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 $\varepsilon$, and the nearest orbit trace. The maximum radiated power should be determined by the relevant provisions of the RR.

## 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) (see Note 1)

$L$: 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 $0 \leq A_0 \leq 180°$)

$\varepsilon_0$: elevation of the antenna main beam

$\tau_{max}(\varepsilon)$: maximum atmospheric bending corresponding to elevation angle $\varepsilon$ (see Note 2)

$\tau_{min}(\varepsilon)$: minimum atmospheric bending corresponding to elevation angle $\varepsilon$ (see Note 2)

$\varepsilon_{m1}$: 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 3)

$\varepsilon_{m2}$: 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 3).

In addition, the following formulae are defined:

$$F(E) = \arccos (K^{-1} \cos E) \tag{12}$$

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

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

where $S(A, E)$ is the angle (degrees) between the beam and the orbit (see Note 4)

$$C(E) = \arccos [\tan L/\tan (F(E) - E)] \tag{14}$$

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 arcsin $\alpha$ 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 $L$.

$$SAF(A, E) = \arccos[\cos \varepsilon_0 \cdot \cos E \cdot \cos(A - A_0) + \sin \varepsilon_0 \cdot \sin E] \tag{17}$$

where $SAF(A, E)$ is the separation angle (degrees) between the antenna main beam and the direction of azimuth $A$ and elevation $E$.

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 (see Note 1).

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

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

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

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
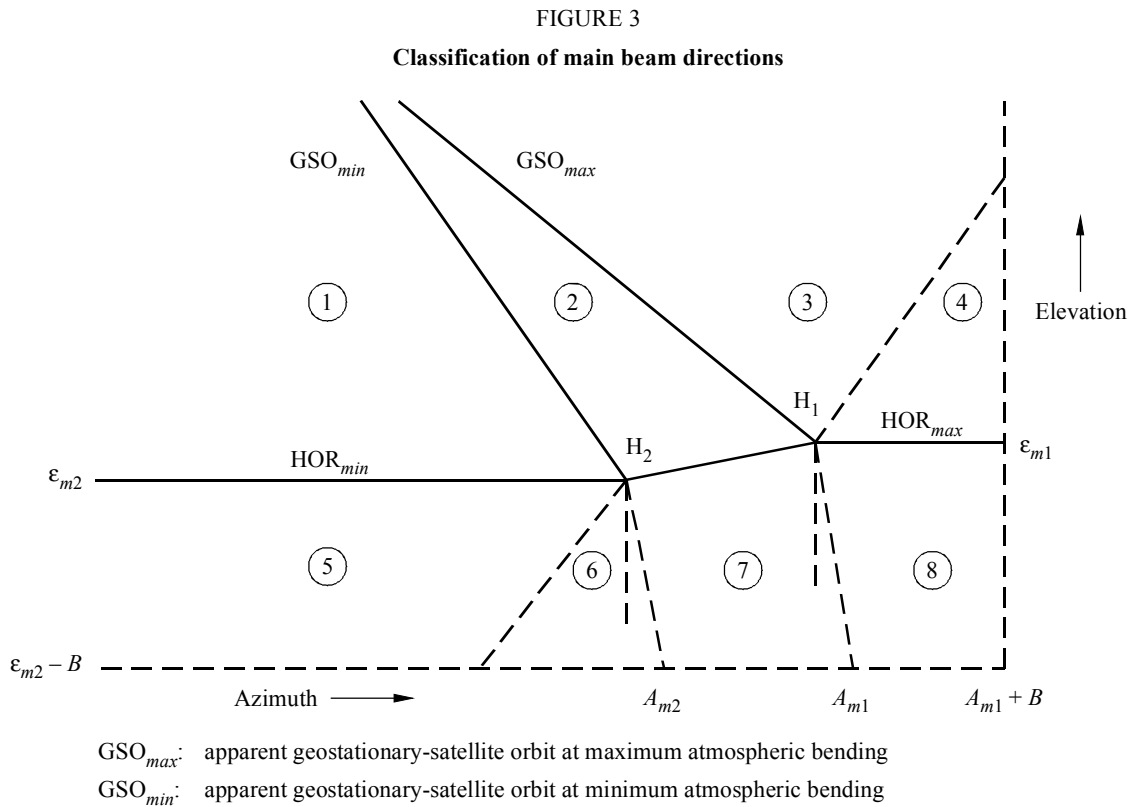
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## 2.2 Classification of main beam directions

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 $\varepsilon_{m2} \le \varepsilon_0$

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: $S_{max} \le 0$ and $S_{min} \ge 0$
>
> Zone 3: $S_{max} > 0$ and $\alpha(A_0 - A_{m1}) < \beta(\varepsilon_0 - \varepsilon_{m1})$
>
> Zone 4: $S_{max} > 0$ and $\alpha(A_0 - A_{m1}) \ge \beta(\varepsilon_0 - \varepsilon_{m1})$

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. If $\varepsilon_0 < 0.3E_T$ (see Note 5 for the calculation of $E_T$), 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:

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

This is appropriate when $|S_{min}|$ is small, but when it is large, this formula may not be accurate. Therefore, when $|S_{min}| > 20°$, the following should be used:

$$SA = |S_{min}| \qquad \text{degrees}$$

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

On the other hand, if $\varepsilon_0 \geq 0.3E_T$, starting from $\varepsilon_s = E_T$, calculate $SA$ for smaller values of $\varepsilon_s$ with 1° step by the following formulae and find out $\varepsilon_s$ which minimizes $SA$:

$$E_s = \varepsilon_s - \tau_{min}(\varepsilon_s), \qquad A_s = C(E_s), \qquad SA = SAF(A_s, \varepsilon_s)$$

Then 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. If $\varepsilon_0 < 0.3E_T$ (see Note 5 for the calculation of $E_T$), 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:

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

An approximate estimate of the separation angle is:

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

This is appropriate when $S_{max}$ is small, but when it is large, this formula may not be accurate. Therefore, when $S_{max} > 20°$, the following should be used:

$$SA = S_{max} \qquad \text{degrees}$$

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 $\text{HOR}_{max}$.

An approximate estimate of the separation angle is:

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

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, $\Delta$ 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.

On the other hand, if $\varepsilon_0 \geq 0.3E_T$, starting from $\varepsilon_s = E_T$, calculate $SA$ for smaller values of $\varepsilon_s$ with 1° step by the following formulae and find out $\varepsilon_s$ which minimizes $SA$:

$$E_s = \varepsilon_s - \tau_{max}(\varepsilon_s), \qquad A_s = C(E_s), \qquad SA = SAF(A_s, \varepsilon_s)$$

Then 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 $\varepsilon_{m1}$ and $A_{m1}$. Therefore, the angle $SA$ between this direction and the main beam is:

$$SA = SAF(A_{m1}, \varepsilon_{m1}) \qquad \text{degrees}$$

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 $\text{HOR}_{min}$ 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 $(A_{51}, \varepsilon_{51})$ is $B$ degrees further away from the direction $(A_5, \varepsilon_{m2})$ 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:

$$SA = SAF(A_{m2}, \varepsilon_{m2}) \qquad \text{degrees}$$

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:

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

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:

$$SA = SAF(A_{m1}, \varepsilon_{m1}) \qquad \text{degrees}$$

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 $SA \geq 2\,B$, it may be safely said that the separation angle is at least $B$ degrees. Therefore, there is no need of further calculations.

If $SA < 2\,B$, further calculations should be carried out in order to arrive at more accurate values. For this purpose, it is appropriate to start from $\varepsilon_s$ 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 $\varepsilon_s$ are given by:

$$E_s = \varepsilon_s - \tau_{min}(\varepsilon_s), \qquad A_s = C(E_s), \qquad SA = SAF(A_s, \varepsilon_s)$$

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

$$E_s = \varepsilon_s - \tau_{max}(\varepsilon_s), \qquad A_s = C(E_s), \qquad SA = SAF(A_s, \varepsilon_s)$$

In any of the above cases, the accurate separation angle can be calculated by means of an iteration method, where $\varepsilon_s$ 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 3. The calculation result should be used for confirming the compliance with the relevant provisions of the RR.

NOTE 1 – In some cases it may be desirable to calculate precise values of separation angles for angles larger than 2°. In such cases a larger value should be chosen for $B$ and then the calculated separation angles will be precise up to $2B$ degrees at the expense of longer computation time. For example, if $B$ is 10°, the calculated separation angles will be generally precise up to 20°. For this purpose, when $B$ is larger than 2°, the preliminary elimination in § 2.1 should be omitted. It is advised that $B$ will not be too large.

NOTE 2 – Atmospheric bending (degrees) can be calculated by using the following formulae:

$$
\begin{aligned}
\tau_{max}(\varepsilon, h) \quad = \quad & 1/[0.7885809 + 0.175963\, h + 0.0251620\, h^2 \\
& + \varepsilon(0.549056 + 0.0744484\, h + 0.0101650\, h^2) \\
& + \varepsilon^2(0.0187029 + 0.0143814\, h)] \\
\tau_{min}(\varepsilon, h) \quad = \quad & 1/[1.755698 + 0.313461\, h \\
& + \varepsilon(0.815022 + 0.109154\, h) \\
& + \varepsilon^2(0.0295668 + 0.0185682\, h)]
\end{aligned}
$$

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 $\varepsilon_m$ is calculated using the equation given in Note 3 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 3 – If the local horizon is formed by a flat terrain or sea, $\varepsilon_m$ is given by:

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

where:

$h$ : antenna height (km) of the station above sea level

$h_1$ : altitude (km) of the local horizon ($h \ge h_1$)

$R$ : Earth radius assumed to be 6 370 km.

$\varepsilon_{m1}$ is an elevation angle corresponding to maximum atmospheric bending ($N_0 = 400$ and $\Delta N = -68$), and $\varepsilon_{m2}$ 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 $\varepsilon_{m1}$ and $\varepsilon_{m2}$ taking into account the complicated skyline of the local horizon. In such a case, it may be simpler to estimate the values of $\varepsilon_{m1}$ and $\varepsilon_{m2}$ 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 (see Note 1), 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 (see Note 1), the calculation should be carried out again using the actual values of $\varepsilon_{m1}$ and $\varepsilon_{m2}$.

NOTE 4 – 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:

$$x = R \cos L + u \, (\sin E \cdot \cos L + \cos E \cdot \sin L \cdot \cos A \,) \tag{18}$$

$$y = -u \cdot \cos E \cdot \sin A \tag{19}$$

$$z = R \sin L + u \, (\sin E \cdot \sin L - \cos E \cdot \cos L \cdot \cos A \,) \tag{20}$$

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:

$$x^2 + y^2 + z^2 = R^2 + u^2 + 2Ru \cdot \sin E \tag{21}$$

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:

$$u / R = \sqrt{K^2 - \cos^2 E} - \sin E \tag{22}$$

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

$$z = K R \sin S \tag{23}$$

Consequently:

$$\sin S = \frac{1}{K} \left[ \sin L + \left( \sqrt{K^2 - \cos^2 E} - \sin E \right) (\sin E \cdot \sin L - \cos E \cdot \cos L \cdot \cos A) \right] \tag{24}$$

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

$$F = \arccos (K^{-1} \cos E \,)$$

$$\sin S = \sin L \cdot \cos (F - E \,) - \cos L \cdot \sin (F - E \,) \cdot \cos A \tag{25}$$

When the radio-relay station is located in the Southern Hemisphere, equations (18) to (20) are expressed in a different way, but the results (equations (24) and (25)) are identical.

It should be noted that when $S$ is zero, equation (25) above is equivalent to equation (8) in Annex 1.

NOTE 5 – $E_T$ is the highest elevation angle of the geostationary-satellite orbit as seen from latitude $L$ and is given by:

$$E_T = \arctan [(K \cos L - 1) / (K \sin L \,)] \tag{26}$$

NOTE 6 – A computer program for calculating separation angles on the basis of this Annex is given in Appendix 1.

# Appendix 1
# to Annex 2

# A computer program for calculating separation angles

```c
/**************************************************************************/
/* sangle-a.c                                                         */
/* Separation angles between radio-relay antenna beams and            */
/* the geostationary-satellite orbit                                  */
/**************************************************************************/

/*-- include files --*/
#include <stdio.h>
#include <math.h>
#include <error.h>
#include <string.h>   /* for strcmp */

/* static */
#define PI  3.1415926       /* circular constant */
#define DR   PI /180.0                  /* degree to radian */
#define RD   180.0 / PI              /* radian to degree */
#define K   6.63              /* orbit radius / earth radius */
static double SINL,COSL,TANL;
static double H0;               /* height of station in km */
static double H1;               /* height of horizon in km */
FILE* fp;                  /* Result File */

/* function */
/**************************************************************************/
/* module:fn_TMAX,fn_TMIN                                             */
/* function: calculate maximum/minimum atmospheric bending in radian   */
double fn_TMAX(double e)
{
        return  (double)(DR / (.7885809 + .175963 * H0 + .025162 * H0 * H0
            + e * RD * (.549056 + .0744484 * H0 + .010165 * H0 * H0
            + e * RD * (.0187029 + .0143814 * H0))));
}
double fn_TMIN(double e)
{
        return (DR / (1.755698 + .313461 * H0 + e * RD * (.815022
```

```
                + .109154 * H0 + e * RD * (.0295668 + .0185682 * H0))));
}
/**********************************************************************/
/* module:fn_F                                                      */
/* function: calculate auxiliary elevation angle                    */
double fn_F(double e)
{
        return ( acos( cos(e) / K ) );
}
/**********************************************************************/
/* module:fn_S                                                      */
/* function: calculation angle between the beam and the orbit       */
double fn_S(double a, double e)
{
        return (asin(SINL * cos(fn_F(e) - e)
            - COSL * sin( fn_F(e) -e ) * cos(a)));
}
/**********************************************************************/
/* module:fn_C                                                      */
/* function: calculate azimuth of the orbit                         */
double fn_C(double e)
{
        return (double)(acos(TANL / tan( fn_F(e) - e )));
}
/**********************************************************************/
/* module:fn_Em                                                     */
/* function: calculation elevation angle toward the local horizon   */
double fn_Em(double r, double t6, double dn, double n0)
{
        double emh;
        emh = (r + H1) / (r + H0) * (1 + n0 * t6 * pow((1 + dn / n0),H1))
            / (1 + n0 * t6 * pow((1 + dn / n0),H0));
        if(emh == 1) return 0.0;
        else return (-1 * acos(emh));
}
/**********************************************************************/
/* module: fn_ET                                                    */
/* function: calculate highest elevation angle of                   */
/*       the geostationary-satellite orbit                          */
```

```
double fn_ET(double l)

{

        double et;

        if (l == 0)

            et = PI / 2.0 ;

        else

            et = atan(( K * cos(l) - 1) / (K * sin(l)));

        return et;

}
/************************************************************************/
/* module: fn_SAF                                                       */
/* function: calculate separation angle                                 */
double fn_SAF(double a, double e, double a0, double e0)

{

        return ( acos (cos(e0) * cos(e) * cos(a - a0) + sin(e0) * sin(e)) );

}
/************************************************************************/
/* module: CalculationSub                                               */
/* function: separation angle calculation                               */
/* in:     l :latitude of the station                                   */
/*         b :separation angle to avoided                               */
/*         a0:azimuth of the antenna main beam                          */
/*         e0:elevation of the antenna main beam                        */
/*         nFlg: if this flg = 0, skip "preliminary elimination"        */
/* out:    psa :separation angle                                        */
/*         pstr:judged zone                                             */
/*         pkf :decision flag                                           */
/*             3:extreme northern or southern latitude                  */
/*             2:SA is at least SA                                      */
/*             1:SA is at least B                                       */
/*             0:SA is 0                                                */
/*            -1:SA is less than B                                      */
/*            -2:If horizon is flat then SA is less than B              */
/************************************************************************/
int CalculationSub(double l, double b, double a0, double e0, double *psa, char* pstrC, int* pkf, int nFlg)

{

        double r;        /* earth radius */

        double t6; /*  */

        double n0;/* refractivity at sea level in N unit */
```

```
double dn; /* refractivity difference at 1km above sea level in N unit */
double em1;      /* the local horizon at maximum atmospheric bending */
double em2;      /* the local horizon at minimum atmospheric bending */
double al;  /* equation */
double am1,am2, dem, dam;
double be,emax,smax,emin,smin, e1,a1,ee1,s1,es,
     e3,a3,a31,s31,ee3,s3, a5,s5,e51,ee51,a51,s51,
     de,ees,as,sa0,es1,sa1;
double eem1, eem2;
double wkes, wkEs_0, wkAs_0, wkSA_0, wkEs_1, wkAs_1, wkSA_1;          /* for SAF */
/* constants init*/
r = 6370.0; t6 = .000001;
n0 = 400.0; dn = -68; em1 = fn_Em(r,t6,dn,n0);
n0 = 250.0; dn = -30; em2 = fn_Em(r,t6,dn,n0);
SINL = sin(l); COSL = cos(l); TANL = tan(l);
al = SINL / sqrt(pow((1 - 1 / (K * K)),2) + pow((SINL / K),2));
/* preliminary calculation */
eem1 = em1 - fn_TMAX(em1);
eem2 = em2 - fn_TMIN(em2);
if( al > 1.0 ){    sprintf(pstrC,"PRELIM"); *pkf = 3; return 1;}
else{be = sqrt(1 - al * al);}
am1 = fn_C(eem1); am2 = fn_C(eem2);
dem = em1 - em2; dam = am1- am2;
/* preliminary elimination */
if(nFlg == 1){
   if( a0 >= am1 + b ) {*psa = a0 - am1; sprintf(pstrC,"PRELIM"); *pkf = 2; return 1;}
   if( e0 <= em2 - b ) {*psa = em2 - e0; sprintf(pstrC,"PRELIM"); *pkf = 2; return 1;}
}
/* classification of main beam direction  */
if( (am1 <= a0 && em1 <= e0) ||
   (am2 <= a0 && a0 < am1 && dem * (a0 - am1) <= (e0 - em1) * dam ) ||
   (a0 < am2 && em2 <= e0)
      ){
      /* main beam is on or above the horizon */
      emax = e0 - fn_TMAX(e0); smax = fn_S(a0, emax);
      emin = e0 - fn_TMIN(e0); smin = fn_S(a0, emin);
      if( smin < 0 ) goto PROC_ZONE_1 ;
      if( smax <= 0 )          goto PROC_ZONE_2 ;
      if( al * (a0 - am1) < be * (e0 -em1) ) goto PROC_ZONE_3 ;
```

```
              else goto PROC_ZONE_4 ;
        }else{
              /* main beam is below the horizon */
              if( al * (a0 - am2) < be * (e0 - em2)) goto PROC_ZONE_5 ;
              if( dem * (e0 - em2) + dam * (a0 - am2) < 0 ) goto PROC_ZONE_6 ;
              if( dem * (e0 - em1) + dam * (a0 - am1) < 0 ) goto PROC_ZONE_7 ;
              else goto PROC_ZONE_8 ;
        }
        /* preliminary determination */
PROC_ZONE_1:
        if( e0 < .3 * fn_ET(l) ){
              e1 = e0 + al * b; a1 = a0 + be * b;
              ee1 = e1 - fn_TMIN(e1); s1 = fn_S(a1, ee1);
              *psa = b * smin / (smin - s1);
              if( fabs(smin) > 20.0 * DR){ *psa = fabs(smin); }
              es = e0 + al * (*psa);
        }else{
              wkes = fn_ET(l); wkEs_0 = wkes - fn_TMIN(wkes); es = wkes;
              wkAs_0 = fn_C(wkEs_0); wkSA_0 = fn_SAF(wkAs_0, wkes, a0, e0);
              do{
                    wkes = wkes - 1.0 * DR; wkEs_1 = wkes - fn_TMIN(wkes);
                    wkAs_1 = fn_C(wkEs_1); wkSA_1 = fn_SAF(wkAs_1,wkes, a0, e0);
                    if(wkSA_1 < wkSA_0){ wkSA_0 = wkSA_1; es = wkes;}
              }while (wkSA_1 <= wkSA_0);*psa = wkSA_0;
        }
        sprintf(pstrC, "ZONE 1");
        goto DETAIL_CALC_ZONE156 ;
PROC_ZONE_2:
        *psa = 0; sprintf(pstrC,"ZONE 2"); *pkf = 0; return 1;
PROC_ZONE_3:
        if( e0 < .3 * fn_ET(l) ){
              e3 = e0 - al * b; a3 = a0 - be * b; sprintf(pstrC, "ZONE 3");
              if (e3 < em1){
                    a31 = a0 -(e0 - em1) * be / al;        s31 = fn_S(a31, eem1);
                    if( fabs(smax - s31) <= .001 * DR ) *psa = smax;
                    else *psa = (e0 -em1) / al * smax / (smax - s31);
                    es = e0 - al * (*psa);
              }else{
                    ee3 = e3 - fn_TMAX(e3);   s3 = fn_S(a3, ee3);
```

```
            *psa = b * smax / (smax - s3); es = e0 - al * (*psa);

            if( es < em1 ) es = em1;

        }

        if (smax > 20.0 * DR) *psa = smax;

    }else{

        sprintf(pstrC, "ZONE 3");

        wkes = fn_ET(l); wkEs_0 = wkes - fn_TMAX(wkes); es = wkes;

        wkAs_0 = fn_C(wkEs_0); wkSA_0 = fn_SAF(wkAs_0, wkes, a0, e0);

        /* search */

        do{

            wkes = wkes - 1.0 * DR; wkEs_1 = wkes - fn_TMAX(wkes);

            wkAs_1 = fn_C(wkEs_1); wkSA_1 = fn_SAF(wkAs_1,wkes, a0, e0);

            if(wkSA_1 < wkSA_0){ wkSA_0 = wkSA_1; es = wkes;}

        }while (wkSA_1 <= wkSA_0);*psa = wkSA_0;

    }

    goto DETAIL_CALC_ZONE3;

PROC_ZONE_4:

    *psa = fn_SAF(am1,em1,a0,e0); sprintf(pstrC,"ZONE 4"); goto JUDGEMENT ;

PROC_ZONE_5:

    a5 = a0 + (em2 - e0) * be / al;         s5 = fn_S(a5, eem2);

    e51 = em2 + al * b; a51 = a5 + be * b;

    ee51 = e51 - fn_TMIN(e51); s51 = fn_S(a51, ee51);

    *psa = (em2 - e0) / al + b * s5 / (s5 -s51);

    if( *psa > 1 ) *psa = (em2 - e0) / al -s5;

    es = e0 + al * (*psa);          sprintf(pstrC, "ZONE 5"); goto DETAIL_CALC_ZONE156 ;

PROC_ZONE_6:

    *psa = fn_SAF(am2,em2,a0,e0); es = em2;

    sprintf(pstrC, "ZONE 6"); goto DETAIL_CALC_ZONE156 ;

PROC_ZONE_7:

    *psa = (dem * (a0 -am1) - (e0 - em1) * dam) / sqrt( dem * dem + dam * dam );

    sprintf(pstrC, "ZONE 7"); goto JUDGEMENT ;

PROC_ZONE_8:

    *psa = fn_SAF(am1,em1,a0,e0);

    sprintf(pstrC, "ZONE 8"); goto JUDGEMENT ;

/* detailed calculation for zone 1,5,6 */

DETAIL_CALC_ZONE156:

    /* step 1 */

    if( *psa >= 2.0 * b) goto JUDGEMENT ;

    else de = be * b / 200.0;
```

```
ZONE156_STEP1_LOOP:
        ees = es - fn_TMIN(es);
        if( fn_F(ees) - ees <1 ){ es = es- de; goto ZONE156_STEP1_LOOP ;}
        as = fn_C(ees);  sa0 = fn_SAF(as,es,a0,e0); es1 = es + de;
        ees = es1 - fn_TMIN(es1);
        if( fn_F(ees) - ees  <1 ){ es1 = es; *psa = sa0; goto ZONE156_STEP3 ;}
        as = fn_C(ees);  *psa = fn_SAF(as, es1, a0, e0);
        if( *psa > sa0 ){ es1 = es; *psa = sa0; goto ZONE156_STEP3 ;}
        /* step 2 */
ZONE156_STEP2:
        es1 = es1 + de;  ees = es1 - fn_TMIN(es1);
        if( fn_F(ees) - ees <1 ) goto JUDGEMENT ;
        as = fn_C(ees);  sa1 = fn_SAF(as, es1, a0, e0);
        if( sa1 < *psa ){ *psa = sa1; goto ZONE156_STEP2 ;}else{ goto JUDGEMENT ;}
        /* step 3 */
ZONE156_STEP3:
        if( es1 <= em2 ) goto JUDGEMENT ;
        es1 = es1 - de;
        if( es1 < em2 ) es1 = em2;
        ees = es1 - fn_TMIN(es1); as = fn_C(ees); sa1 = fn_SAF(as, es1, a0, e0);
        if( sa1 < *psa ){ *psa = sa1; goto ZONE156_STEP3 ;}else{ goto JUDGEMENT ;}
/* detailed calculation for zone 3 */
DETAIL_CALC_ZONE3:
        /* step 1 */
        if( *psa >= 2.0 * b ) goto JUDGEMENT ; else de = be * b / 200.0;
ZONE3_STEP1:
        ees = es - fn_TMAX(es);
        if ( fn_F(ees) - ees <1 ){ es = es - de; goto ZONE3_STEP1 ;}
        as = fn_C(ees);  sa0 = fn_SAF(as,es,a0,e0);
        es1 = es + de; ees = es1 - fn_TMAX(es1);
        if( fn_F(ees) - ees <1 ){es1 = es; *psa = sa0; goto ZONE3_STEP3 ;}
        as = fn_C(ees);  *psa = fn_SAF(as,es1,a0,e0);
        if(*psa > sa0){  es1 = es; *psa = sa0; goto ZONE3_STEP3;          }
        /* step 2 */
ZONE3_STEP2:
        es1 = es1 + de; ees = es1 -fn_TMAX(es1);
        if( fn_F(ees) - ees <1 ) goto JUDGEMENT ;
        as = fn_C(ees);  sa1 = fn_SAF(as, es1, a0, e0);
        if( sa1 < *psa){ *psa = sa1; goto ZONE3_STEP2 ;          }else{ goto JUDGEMENT; }
        /* step 3 */
```

```
ZONE3_STEP3:

        if( es1 <= em1 ) goto JUDGEMENT ;

        es1 = es1 - de;
        if( es1 < em1 ) es1 = em1;

        ees = es1 - fn_TMAX(es1); as = fn_C(ees);

        sa1 = fn_SAF( as, es1, a0, e0);

        if( sa1 < *psa ){ *psa = sa1; goto ZONE3_STEP3 ;}

JUDGEMENT:

        if( *psa >= b ) *pkf = 1; else *pkf = -2;

        return 1;

}
/**********************************************************************/
/* main routine                                                     */
/**********************************************************************/

void main()

{

/* parameters */

        double f;     /* frequency */

        double bd;   /* separation angle to be avoided in degree */

        double b;     /* separation angle to be avoided in radian */

        double ld,lm,ls;  /* latitude of the station in degrees, minutes, sec */

        double l;      /* latitude of the station in radian */

        double a0;    /* azimuth of antenna main beam in radian */

        double a0d;         /* azimuth of antenna main beam in degree */

        double e0;    /* elevation of antenna main beam in radian */

        double e0d;         /* elevation of antenna main beam in degree */

        double sa;    /* estimated separation angle */

        int    kf;      /* decision flag */

        char   strC[32];   /* judge zone */

        double pt;    /* allowable e.i.r.p value */

        double recbd;       /* recommended bd*/

        char   strRedo[4],strLog[4]; /*keyin buffer for redo control */

        int    nDefaultBDFlg,nLogFlg;

        ld = lm = ls = a0d = e0d = 0.0;


        /*  file out flg */

        printf(" Do you want to make output file? (sf765.txt)?[y/n] ");

        do{
```

```
                gets(strLog);
        }while(!strcmp (strLog,""));
        if(strcmp(strLog,"y") == 0  || strcmp(strLog,"Y") == 0){
                nLogFlg = 1; fp = fopen("sf765.txt","wt");
                if(fp == NULL){
                        printf(" Cannot create result file (sf765.txt)\n "); nLogFlg = 0;
                }
        }else{ nLogFlg = 0;}
        /* parameters input */
PARAMETERS_INPUT_START:
INPUT_F:
        printf(" input F : frequency (GHz) ");
        scanf("%le", &f);
        if (f < 0 || f > 15){ printf("  1 <= F <= 15 "); goto INPUT_F ; }
        if(f <= 10) bd = 2; else bd = 1.5;recbd = bd;
INPUT_B:
        printf(" input B : separation angle to be avoided (deg) ");
        printf("        (if the Recommendation is followed, B = %.1f) ", recbd);
        scanf("%le", &bd);
        if (bd <= 0){ printf("  B should be positive. "); goto INPUT_B ; }
        if(bd == recbd)  nDefaultBDFlg = 1; else nDefaultBDFlg = 0;
        b = bd * DR;
        printf(" input l : latitude( deg, min, sec ) ");
        scanf("%le,%le,%le",&ld, &lm, &ls);
        l = fabs(ld + lm / 60.0 + ls / 3600.0) * DR;
        printf(" input A0 : antenna azimuth ( deg ) ");
        scanf("%le",&a0d); a0 = a0d * DR;
        printf(" input E0 : antenna elevation ( deg ) ");
        scanf("%le",&e0d); e0 = e0d * DR;
        printf(" input H0 : station height ( m ) ");
        scanf("%le",&H0); H0 = H0 / 1000.0;
INPUT_H1:
        printf(" input H1 : horizon height ( m ) ");
        scanf("%le",&H1); H1 = H1 / 1000.0;
        if (H1 > H0){ printf("  H1<=H0 "); goto INPUT_H1 ; }
        /* call calculation function */
        CalculationSub(l, b, a0, e0, &sa, strC, &kf, nDefaultBDFlg);
        /* output result */
        printf(" F : frequency = %4.1f(GHz) ",f);
```

```
        printf(" L : latitude = %.0f˚ %.0f'%.0f" ", ld, lm, ls);

        printf(" A0 : antenna azimuth = %.1f( deg ) ",a0d);

        printf(" E0 : antenna elevation = %.1f( deg ) ",e0d);

        printf(" H0 : station height = %.0f( m ) ", H0 * 1000);

        printf(" H1 : horizon height = %.0f( m ) ",H1 * 1000);

        if(nDefaultBDFlg == 1) printf(" Separation angle should be at least %.2f degrees. ",bd);

        printf(" --------------------------------------------------------------------- ");

        printf(" The main beam is in %s. ",strC);

        if(kf != 3 && nDefaultBDFlg == 1) printf(" The separation angle is");

        if(kf == 2 && nDefaultBDFlg == 1) printf(" at least %.2f degrees. ", sa * RD);

        if(kf == 1 && nDefaultBDFlg == 1) printf(" at least %.2f degrees. ",bd);

        if(kf == 0 && nDefaultBDFlg == 1) printf(" zero. ");

        if(kf <  0 && nDefaultBDFlg == 1) printf(" less than %.2f degrees. ",bd);

        if(kf == -2 && nDefaultBDFlg == 1){

                printf(" If the local horizon is not flat,");

                printf(" further investigation should be carried out. ");

        }

        if(kf == 3) printf(" You can't see the orbit from your latitude. ");

        if(sa > 90 * DR || kf == 3 || kf == 2) goto DETERMINATION_EIRP ;

        printf(" Actual separation angle can be estimated as %.3f degrees. ", sa * RD);


        if(nDefaultBDFlg == 1 ){

DETERMINATION_EIRP:

                /* determination of eirp */

                if ( 10 < f )           { pt = 55.0; goto PRINT_PT ;}

                if ( sa < .5 * DR )     { pt = 47.0; goto PRINT_PT ;}

                if ( sa >= 1.5 * DR )   { pt = 55.0; goto PRINT_PT ;}

                pt = 47.0 + 8.0 * (sa * RD -.5);

PRINT_PT:

                printf(" Maximum e.i.r.p shall not exceed %.3f dBW ",pt);

        }

        printf(" ----------------------------------------------------------------- ");

        /* file out */

        if(nLogFlg == 1){

                fprintf(fp," F : frequency = %4.1f(GHz) ",f);

                fprintf(fp," L : latitude = %.0f˚ %.0f'%.0f" ", ld, lm, ls);

                fprintf(fp," A0 : antenna azimuth = %.1f( deg ) ",a0d);

                fprintf(fp," E0 : antenna elevation = %.1f( deg ) ",e0d);

                fprintf(fp," H0 : station height = %.0f( m )  ", H0 * 1000);
```

```
        fprintf(fp," H1 : horizon height = %.0f( m )  ",H1 * 1000);

        if(nDefaultBDFlg == 1) fprintf(fp," Separation angle should be at least %.2f degrees. ",bd);

        fprintf(fp," ------------------------------------------------------------------ ");

        fprintf(fp," The main beam is in %s. ",strC);

        if(kf != 3 && nDefaultBDFlg == 1) fprintf(fp," The separation angle is");

        if(kf == 2 && nDefaultBDFlg == 1) fprintf(fp," at least %.2f degrees. ", sa * RD);

        if(kf == 1 && nDefaultBDFlg == 1) fprintf(fp," at least %.2f degrees. ",bd);

        if(kf == 0 && nDefaultBDFlg == 1) fprintf(fp," zero. ");

        if(kf <  0 && nDefaultBDFlg == 1) fprintf(fp," less than %.2f degrees. ",bd);

        if(kf == -2 && nDefaultBDFlg == 1){

                fprintf(fp," If the local horizon is not flat,");

                fprintf(fp," further investigation should be carried out. ");

        }

        if(kf == 3) fprintf(fp," You can't see the orbit from your latitude. ");

        if(sa > 90 * DR || kf == 3 || kf == 2){

                if(nDefaultBDFlg == 1 ) fprintf(fp," Maximum e.i.r.p shall not exceed %.3f dBW ",pt);

        }else{

                fprintf(fp," Actual separation angle can be estimated as %.3f degrees. ", sa * RD);

        }

        fprintf(fp," ------------------------------------------------------------------ ");

    }

    /* redo calculation */

    printf(" Do you continue? (y/n) ");

REDO:

    gets(strRedo); if (strcmp(strRedo,"") == 0) goto REDO;

    if(strcmp(strRedo,"n") == 0 || strcmp(strRedo,"N") == 0) {

        fclose(fp);

        return;

    }

    else goto PARAMETERS_INPUT_START ;

}
```