

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)

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.

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 $\pm 2^\circ$ 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 $\pm 2^\circ$ 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:

$$A = \arctan (\pm \tan \lambda / \sin \varphi) \quad (1)$$

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

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:

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

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:

$$P = m \theta / (2\pi) \quad (4)$$

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:

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

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:

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

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:

$$P = m n \theta^2 / (8\pi \cos \psi) \quad (7)$$

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 ITU-R SF.406 on the directions of radio-relay antennas to protect reception by geostationary satellites.

Equation (3) can be expressed as:

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

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:

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

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 ΔN 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 ΔN) 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, ΔN (as found in worldwide charts). A range for N_0 between 250 and 400 (ΔN 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:

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

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

$$n(r) \cdot r \cdot \cos \epsilon = n(r_1) \cdot r_1 \cdot \cos \epsilon_1 \quad (11)$$

where:

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

r_0 : Earth radius (6 370 km)

$$r_1 = r_0 + h \text{ (} h \text{: station height)}$$

ϵ_1 : elevation angle at the station

n_1 : refractivity at the station height

n_2 : refractivity at the orbit

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

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

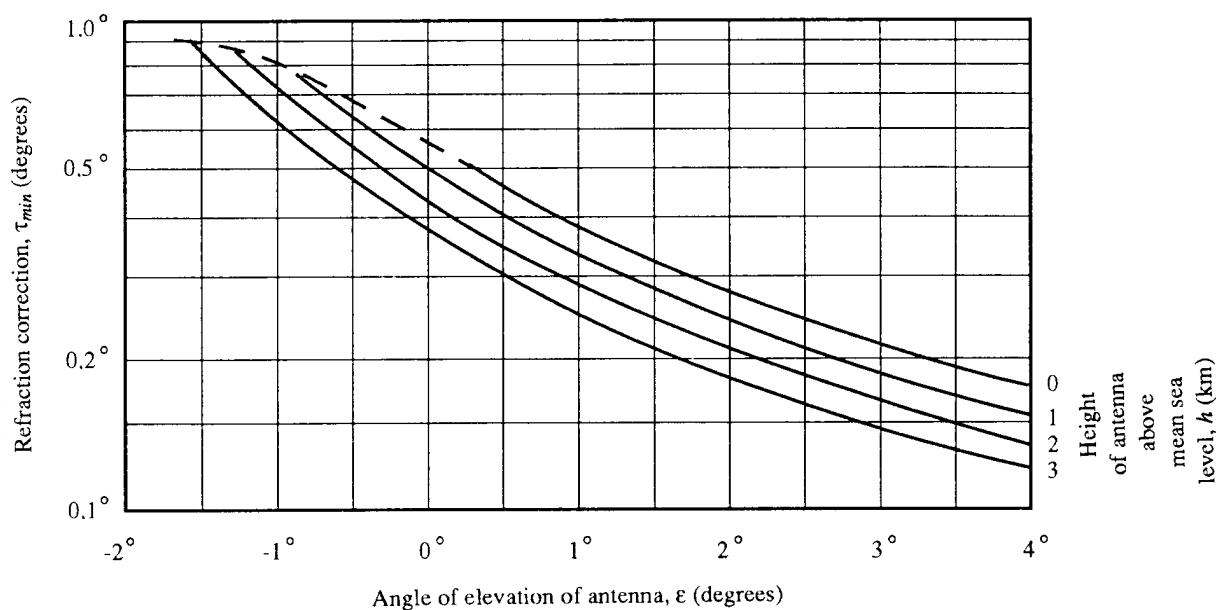
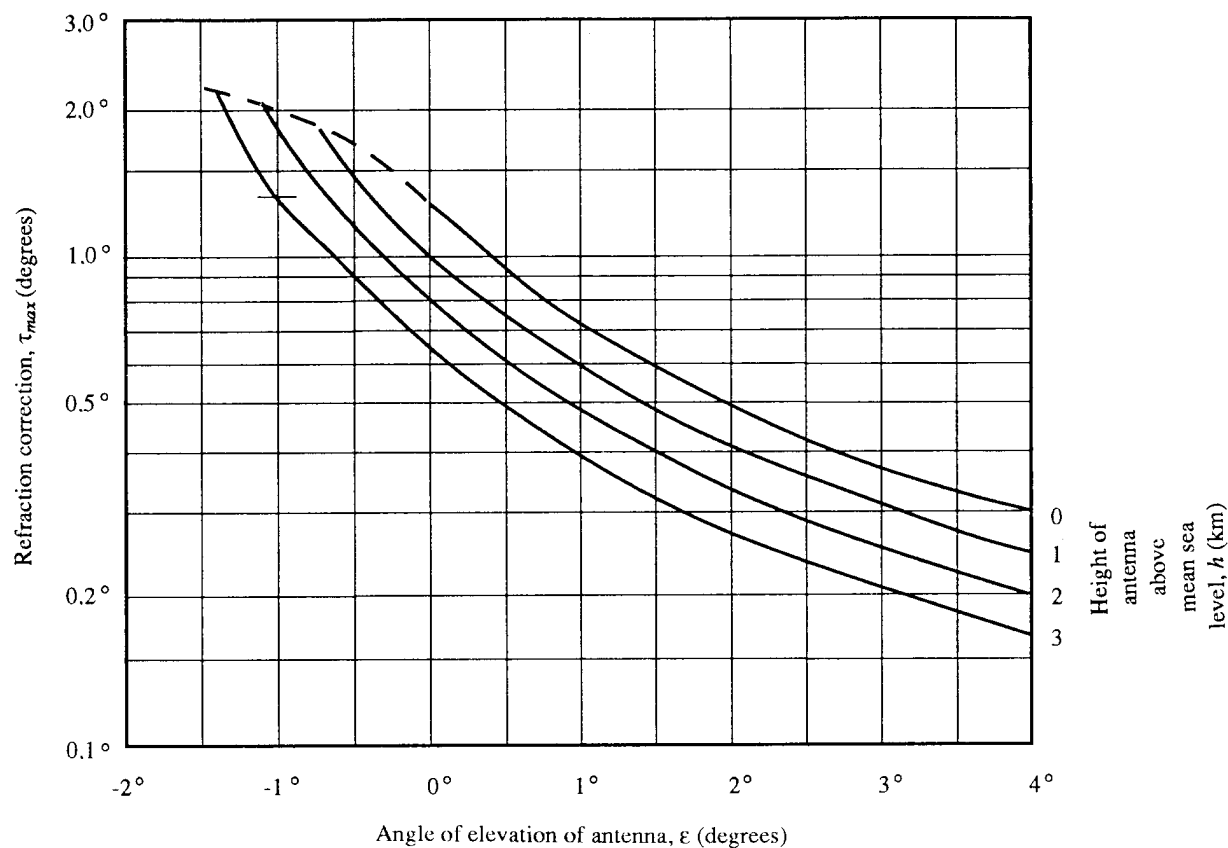
$N_0 = 400$ and $\Delta N = -68$ for maximum bending

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

FIGURE 1
Refraction correction for angle ε



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

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

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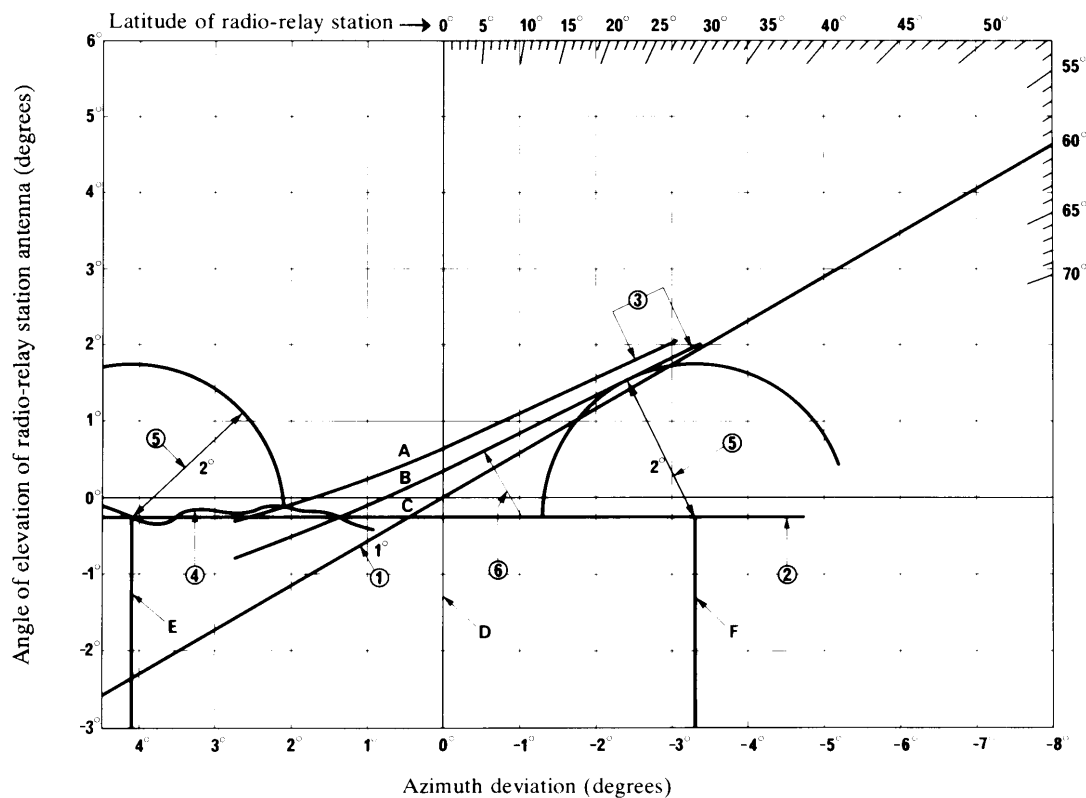
5.2 Use of a graphical method for determination of azimuths to be avoided

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 ϵ : -0.25°

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

D: reference azimuth: 74.68° (from equation (8))
 E: upper limit $74.68^\circ + 4.1^\circ = 78.78^\circ$
 F: lower limit $74.68^\circ - 3.3^\circ = 71.38^\circ$

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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 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 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).

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) (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 $0 \leq A_0 \leq 180^\circ$)
- ϵ_0 : elevation of the antenna main beam
- $\tau_{max}(\epsilon)$: maximum atmospheric bending corresponding to elevation angle ϵ (see Note 2)
- $\tau_{min}(\epsilon)$: minimum atmospheric bending corresponding to elevation angle ϵ (see Note 2)
- ϵ_{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)
- ϵ_{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:

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

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

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

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

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

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)