RECOMMENDATION ITU-R SF.1008-1*

POSSIBLE USE BY SPACE STATIONS IN THE FIXED-SATELLITE SERVICE OF ORBITS SLIGHTLY INCLINED WITH RESPECT TO THE GEOSTATIONARY-SATELLITE ORBIT IN BANDS SHARED WITH THE FIXED SERVICE

(1994-1995)

The ITU Radiocommunication Assembly,

considering

a) that, after cessation of North-South station-keeping, nominally geostationary space stations have a "natural" drift to a maximum inclination of approximately ± 15° relative to the equatorial plane at the maximum initial rate of about 0.9° per year;

b) that the use of orbits which are slightly inclined with respect to the geostationary orbit may be attractive for operations in the fixed-satellite service (FSS) for prolonging the useful life of space stations;

c) that inclined orbit usage may be designed at the planning stages of satellite systems;

d) that a satellite may be injected into a pre-inclined orbit in such a way that its inclination first decreases to zero before increasing;

e) that the FSS operations themselves impose constraints which would, in most cases, limit the amount of inclination which would be used by the FSS networks to values considerably less than the natural limit described in § a);

f) that the number of FSS space stations that will utilize slightly inclined orbits will be small in practice;

g) that FSS systems in inclined orbit operating with the power flux-density limits given in Recommendation ITU-R SF.358 could cause interference to terrestrial systems by exposing a larger number of terrestrial stations to direct interference, but that not all such affected fixed-service stations will be associated with a single terrestrial network;

h) that, for maintenance of service area coverage, space station beam-pointing will most probably remain within a reasonable tolerance of the original beam direction but that, under these circumstances, arrival angles at terrestrial stations and satellite antenna off-axis angles will vary from the geostationary case;

j) that, while the end-to-end performance of terrestrial systems might not be affected in all cases by the degree of inclination, the probability of individual hops being affected will increase with the amount of inclination;

k) that the existing fixed service networks in most bands currently shared with the FSS are in a mature state and in most countries the fixed links are designed to avoid the azimuth directions with potential interference on the basis of assuming that space stations are located at their nominal geostationary-satellite orbit (GSO) locations;

l) that the impact on space stations in inclined orbits of terrestrial stations in the fixed service currently observing the limits in Recommendation ITU-R SF.406 with respect to space stations in the GSO depends on inclination;

m) that any increased orbit avoidance requirements on the fixed service would severely restrict the available horizon for future fixed service installations (see Figs. 4a and 4b);

n) that the use of inclined orbit may result in a larger coordination area of an earth station;

o) that earth stations associated with FSS space stations in slightly inclined orbits may employ tracking,

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

recommends

1 that a transmitting space station of a network in the FSS having an assignment on the GSO and intended to operate without North-South station-keeping during part of its in-orbit life be launched with a pre-inclination of:

1.1 at least N – 5° where N is the number of years by which operation without North-South station keeping has been planned, or

1.2 5°, whichever is the smaller (see Note 3);

2 that when it is anticipated that a transmitting space station of a network in the FSS will operate at orbital inclinations in excess of 5°, agreement should be sought from affected administrations. Provisionally an administration is considered affected if:

2.1 as a direct result of a satellite exceeding 5° of orbital inclination, the satellite could illuminate a fixed station within its territory with an elevation angle below 5°. This does not include fixed stations which see the satellite below 5° when the inclination of that satellite is less than or equal to 5°, and

2.2 the power flux-density due to the radiation of the satellite towards the fixed station falling under § 2.1 is expected to reach the values shown in Fig. 1 under clear air propagation conditions;

3 that FSS space stations in orbits which are slightly inclined with respect to the GSO continue to observe Recommendation ITU-R SF.358 from all positions within their orbit;

4 that fixed service systems continue to observe Recommendation ITU-R SF.406 with respect to the GSO;

5 that earth stations be coordinated or, if necessary, re-coordinated, taking into account the degree of tracking required to accommodate the use of inclined orbits;

6 that the following Notes be considered part of this Recommendation.

NOTE 1 – Recommendations ITU-R SF.358 and ITU-R SF.406 have values similar to those in Article S21 of the Radio Regulations (RR) respectively. The values given in the RR have precedence.

NOTE 2 – Station-keeping and beam pointing information submitted in accordance with RR Appendice S4 should include any planned use of a slightly inclined orbit.

NOTE 3 – Launch with pre-inclination refers to a launch which places a spacecraft in an inclined circular geosynchronous orbit having initial parameters which, after injection of the spacecraft into that orbit and without any inclination adjustments, will cause the orbit's inclination to decrease towards zero before increasing.

NOTE 4 – Section 2 does not apply to those space stations which have started the slightly inclined orbit operation or have been notified as such where appropriate before the end of 1993.

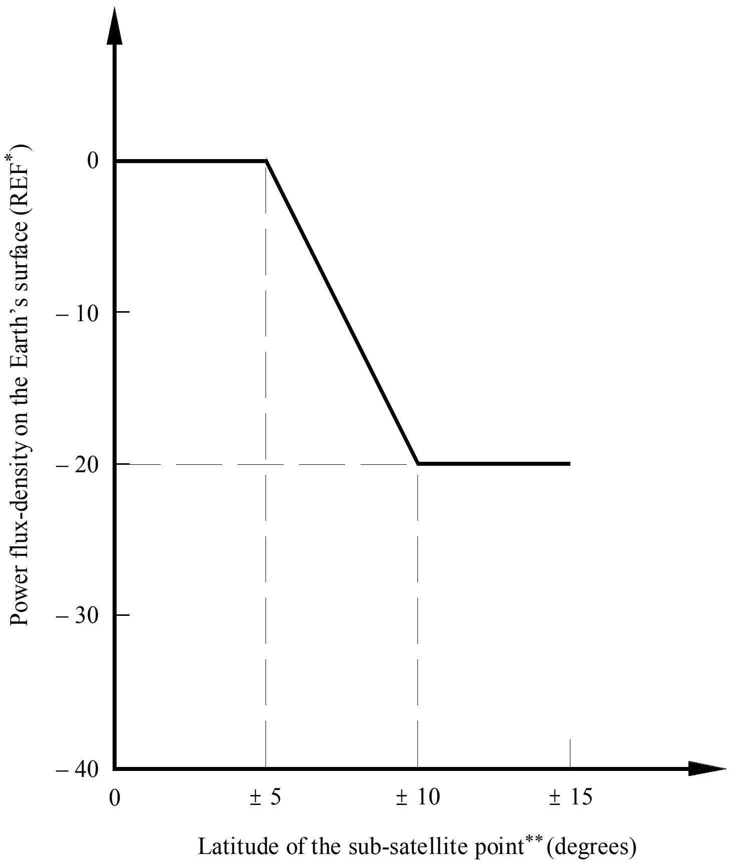
NOTE 5 – Considerations of frequency sharing between the fixed service and the FSS using satellites in orbits slightly inclined with respect to the GSOs are given in Annex 1.

NOTE 6 – Even if the coordination threshold of Fig. 1 is observed, there is still a small but possibly significant risk of high level interference on terrestrial hops with high-gain antennas pointing at the azimuth ranges corresponding to the visibility of inclined orbits with inclinations less than 10°.

NOTE 7 – Recommendation ITU-R S.743 deals with the coordination of satellite networks using slightly inclined GSOs and between such networks and satellite networks using non-inclined GSO satellites.

NOTE 8 – Depending on the number of slightly inclined orbit satellites falling under § 2.1 which interfere into a particular multi-hop radio-relay system, it may be difficult to fulfil the availability and performance objectives of Recommendation ITU-R SF.615. Further studies are required on this matter.

FIGURE 1
Coordination threshold with respect to § 2



* REF level corresponds to the limit in Recommendation ITU-R SF.358.

** The value corresponding to the latitude of the sub-satellite point at the moment when the satellite intersects the boresight of the fixed station antenna should be used.

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ANNEX 1

Frequency sharing between the fixed service and the fixed-satellite service using satellites in orbits slightly inclined with respect to the geostationary-satellite orbit

1 Introduction

There are two strategies for extending the operational life of in-orbit geostationary satellites. These are based on the fact that the useful operational life is largely determined by the North-South station-keeping fuel, which is consumed at a rate about ten times that of East-West station-keeping fuel.

– If a geostationary satellite has nearly exhausted its station-keeping fuel, but is otherwise operating satisfactorily, its useful in-orbit life could be extended significantly if its remaining fuel was used only for longitudinal station-keeping.

– A satellite intended for a geostationary mission is placed in inclined orbit at the start of its operating life but with orbital parameters such that the natural inclination decreases if uncorrected. The orbit will become progressively less inclined and will eventually become equatorial. The inclination will continue to increase unless fuel is spent to counteract the effect of the Sun and the Moon. This strategy permits a satellite to be maintained in a circular geosynchronous orbit of relatively low inclination with a smaller initial fuel load than an initially geostationary orbit would require.

The RR regarding interference between geostationary-satellite systems, and between terrestrial radio-relay systems and geostationary-satellite systems, are not currently framed to cover the case where the orbit deviates significantly from being truly geostationary. However, these modes of interference are clearly affected by any inclination of the orbit.

2 Space station/terrestrial station interaction

2.1 Orbit geometry

2.1.1 Illumination of previously unilluminated parts of the Earth

Figures 2a and 2b show the increase in area of the Earth's surface that will have direct line-of-sight to a satellite that is nominally located at (0,0) if that satellite were to drift into an inclined orbit, for inclinations, for example, of 5° and 15° respectively. The shaded area represents the extra illumination of the Earth. Although the majority of this new coverage falls in the polar regions, the East-West "wedges" cover fairly low latitudes.

Some terrestrial radio-relay receivers which are presently shielded from the GSO (or parts of it) by the curvature of the Earth, will potentially have direct line-of-sight to inclined orbit satellites.

2.2 Orbital zones affecting radio-relay sites

Figure 3 shows the 360° sky-map from a location at 50° N. This diagram shows the GSO as seen from the radio-relay station and how the band in which satellites can be seen at some time during each 24 h period widens for different inclination angles. The shaded arc surrounding the GSO represents the recommended area of de-pointing for radio-relays, i.e. within 2° either side of the GSO for stations transmitting in the band 1-10 GHz (RR No. S21.2.1).

The "figures of eight" show the motions of the satellites, located at every 10° in the GSO, over a 24 h period. The arcs represent the upper and lower limits of the "figures of eight" for the worst case when all satellites in the GSO are in inclined orbits of 5°, 10° and 15° respectively.

Figure 3 clearly illustrates the case where satellites which are not visible to the terrestrial station, now become visible above the horizon.

The figure also illustrates how the zone of direct exposure of radio-relays to satellites and *vice versa*, increases. The size of this zone is directly dependent on the location. Figure 4a illustrates this point and shows the variation with latitude. Note that in the case of bidirectional links with two antennas pointing in opposite directions, the zones of direct exposure of at least one of the two antennas should be considered (see Fig. 4b).

FIGURE 2a

Increase in illumination of Earth's surface (5° inclination)

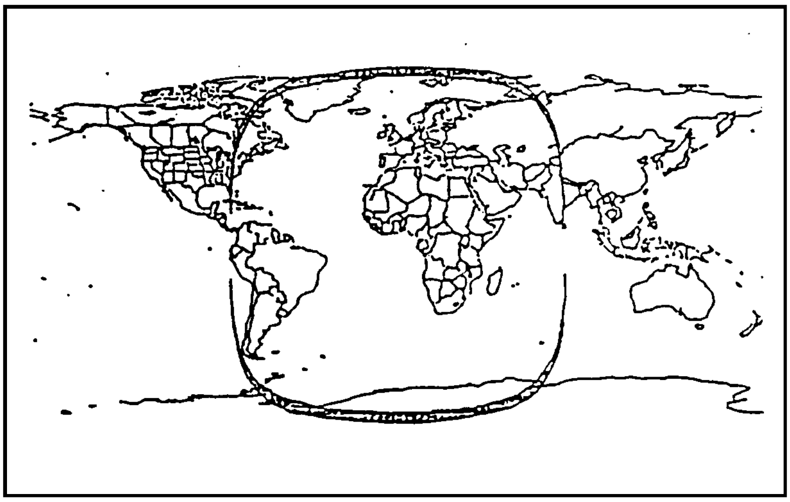

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FIGURE 2b

Increase in illumination of Earth's surface (15° inclination)

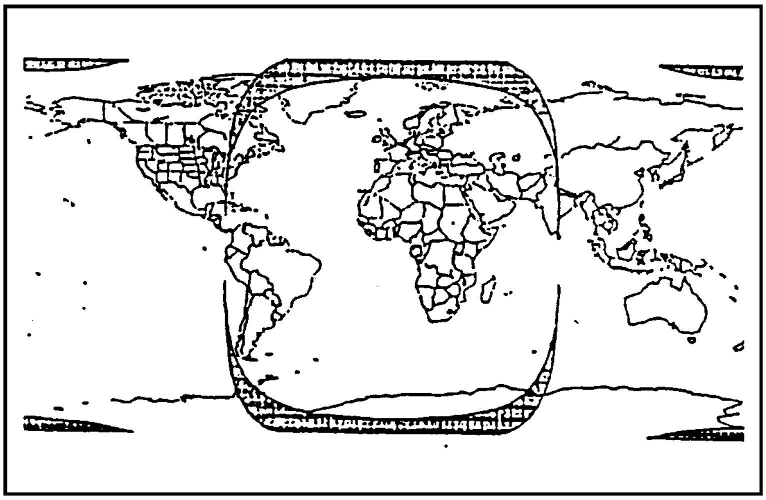

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FIGURE 3

General view of GSO in orbit bands from about 50° N

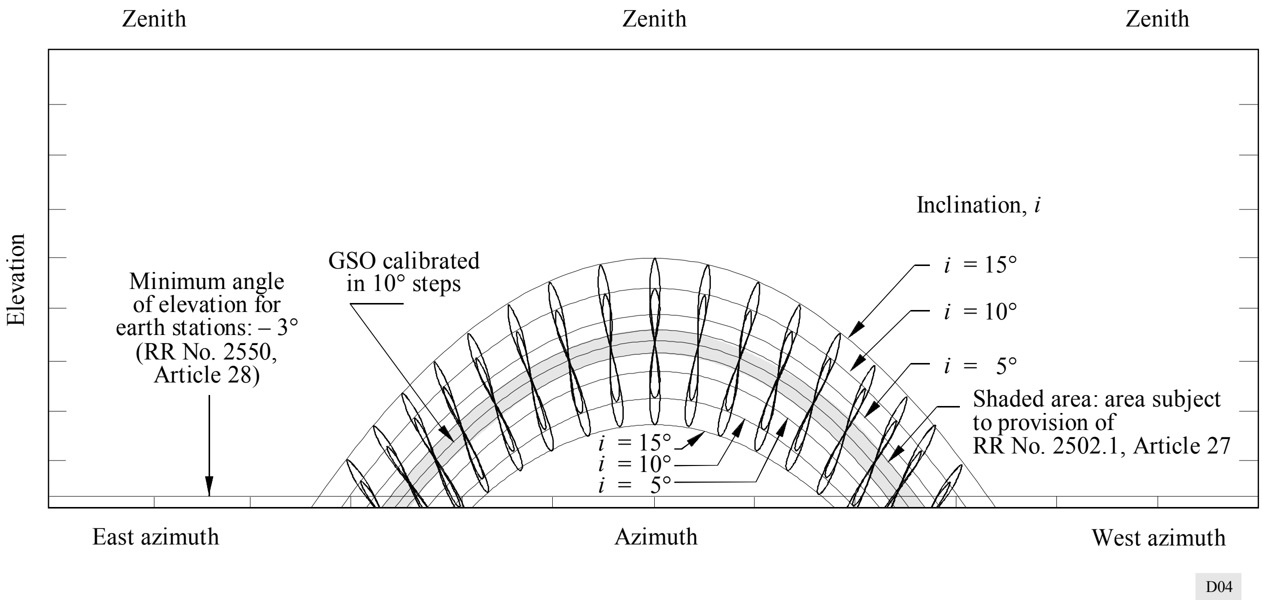


FIGURE 4a

Percentage of the horizon with inclined orbit visible to the terrestrial receiver

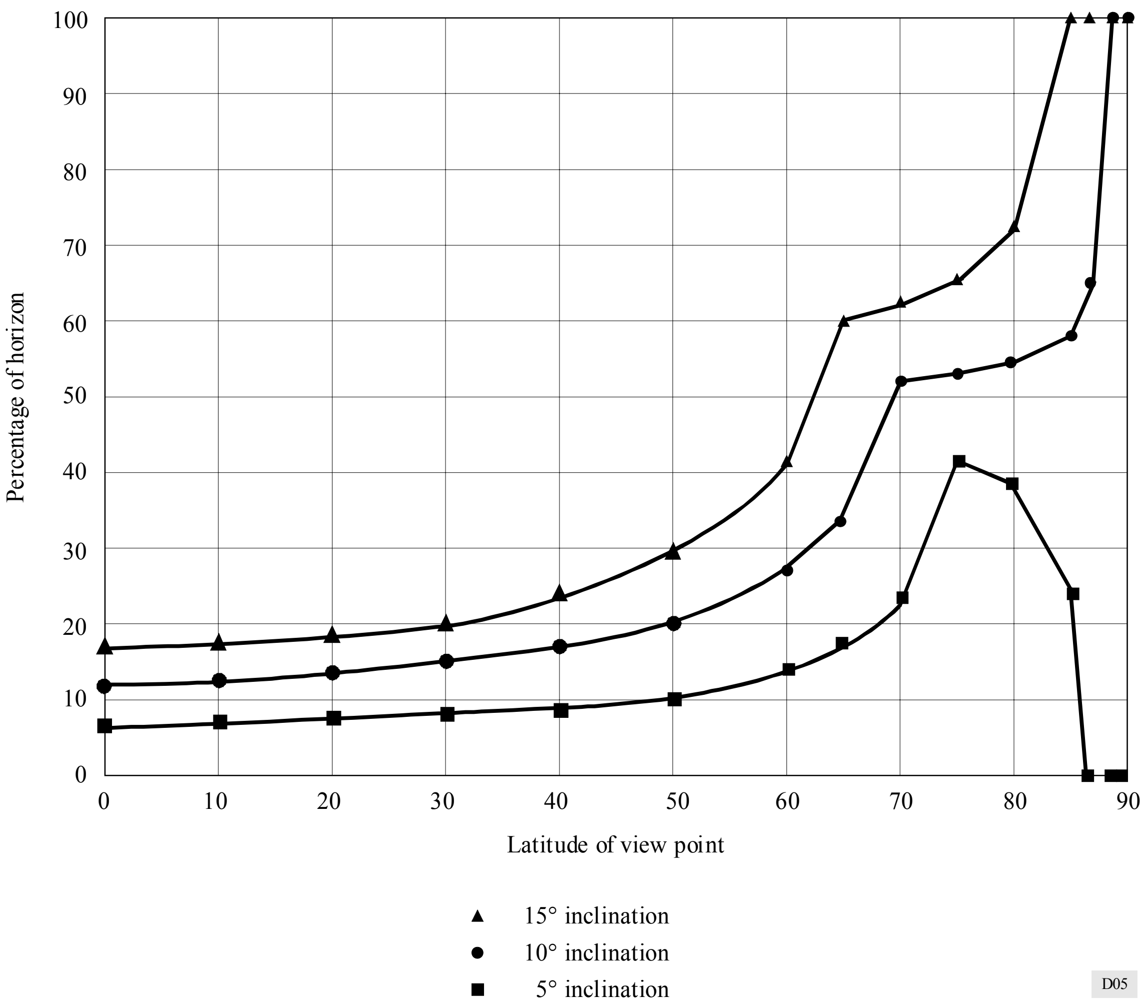
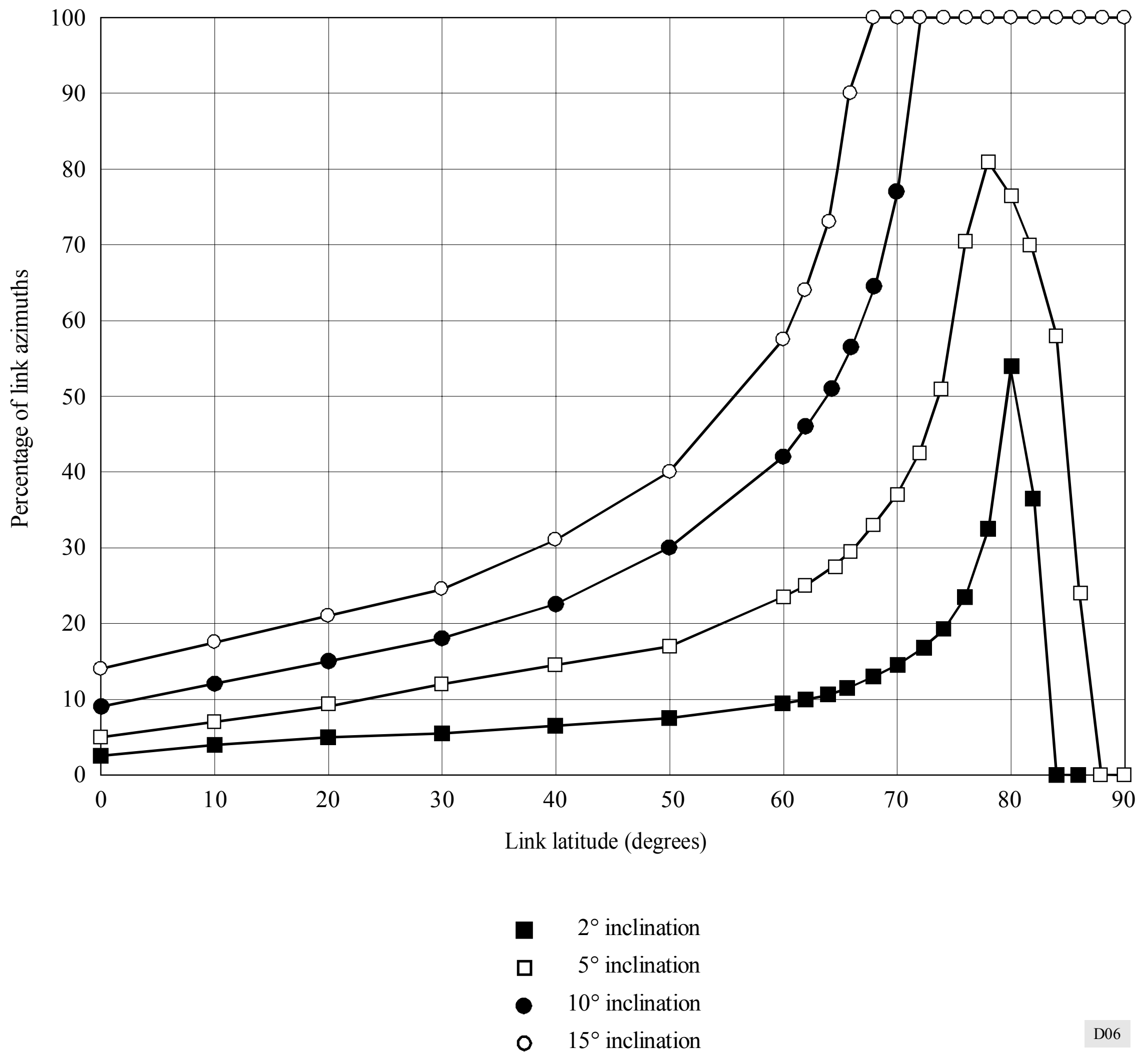


FIGURE 4b

Percentage of the horizon with inclined orbit visible at either end of a bidirectional terrestrial hop



2.3 Space station interference into terrestrial stations

2.3.1 Introduction

The assessment of sharing between FSS and fixed service systems when the former go into slightly inclined orbit is a complex issue. It must take into account the fact that due to orbital inclination some terrestrial stations could become directly exposed to satellites for periods of time dependent upon the amount of inclination and the orientation of the radio-relay beams. It must also take into account that due to the orbital inclination, parts of the terrestrial network which might suffer greater interference will be similarly relieved from interference for some periods of time. However, for digital systems even though the duration of the exposure may be much less than that which occurs when satellites are not inclined, the exposure time could be significant.

This section presents the results of various studies, which analyse the system unavailability, interference exposure and aggregate interference over a hypothetical reference circuit.

2.3.2 System unavailability model

For simplicity only main-lobe interference is considered, and its effects are calculated using a rectangular antenna gain pattern. A satellite interferes with a given terrestrial receiver if the azimuth of its horizon intercept is within $\pm 0.5°$ of the azimuth of the boresight of the receiving antenna. It interferes with that receiver during the time period that it is between the horizon and 1° above the horizon. The ratio δ in Table 1 provides the information to assess this dwell time. For a satellite with a declination which places it on the horizon at a given longitude difference, δ is the elevation angle that results from a 1° increase in declination. For simplicity, the term declination is used in this section to refer to the latitude of the sub-satellite point.

TABLE 1

Terrestrial interference from geostationary satellites in orbits with a satellite orbital separation of 3°

a) *Satellite inclination 5°*

	λ_S	Z_S	δ	100 P_I	100 P_u	100 P_{nu}
Latitude of interfered receiver (degrees N)	Longitude span of visibility (degrees)	Azimuth span of visibility (degrees)	Degrees of elevation per degree of declination	Per cent of hops with receivers exposed to interference	Per cent of time that interfered hop is unavailable	Per cent of time that a 50 hop circuit is unavailable
20	3.70	10.78	0.35	1.4	0.1429	0.098
30	5.88	11.73	0.51	2.2	0.0980	0.107
40	8.59	13.33	0.65	3.2	0.0769	0.122
50	12.32	16.04	0.78	4.6	0.0641	0.146
60	18.33	21.10	0.88	6.8	0.0568	0.193

b) *Satellite inclination 10°*

	λ_S	Z_S	δ	100 P_I	100 P_u	100 P_{nu}
Latitude of interfered receiver (degrees N)	Longitude span of visibility (degrees)	Azimuth span of visibility (degrees)	Degrees of elevation per degree of declination	Per cent of hops with receivers exposed to interference	Per cent of time that interfered hop is unavailable	Per cent of time that a 50 hop circuit is unavailable
20	7.5	22	0.35	2.8	0.071	0.10
30	12	23.5	0.51	4.4	0.049	0.11
40	17.5	27	0.65	6.5	0.038	0.12
50	25	32.5	0.78	9.3	0.032	0.15
60	37.5	43	0.88	13.9	0.028	0.20

To facilitate calculations it is assumed that the declinations of a satellite in an inclined orbit are uniformly distributed. This is equivalent to assuming a triangular rather than sinusoidal shape for the variation of the declination of a satellite with time. This assumption decreases the exposure time of those affected receivers whose antennas are pointed furthest from the point where the geostationary orbit crosses the horizon, but it significantly simplifies the statistics for the calculation of network availability.

2.3.2.1 Unavailability calculation

Consider a terrestrial radio station operating at a particular latitude under the condition that all satellites are in inclined orbits with inclinations α_m of 10°. One can determine λ_S, the span of longitudes from which interference is potentially observable for a given latitude and inclination. This span increases almost linearly with inclination angle. Similarly, one can determine Z_S, the span of azimuths over which the interference will be observed. Since Z_S is greater than λ_S, the satellites will appear more widely spaced in azimuth than their orbital separation. Consequently, each satellite on the arc λ_S will form a distinct interference source.

For a satellite separation of S degrees on the geostationary orbit, the number of potential interferers, N_S, is given by:

$$N_S = \frac{\lambda_S}{S} \tag{1}$$

Since terrestrial paths are bidirectional and there are interferers both East and West of South, the probability that a hop is subject to interference, P_I, neglecting the beamwidth of the receiving antennas and assuming that the path directions in the terrestrial network are uniformly distributed in angle, is given by:

$$P_I = \frac{N_S}{90} = \frac{\lambda_S}{90\,S} \tag{2}$$

For a path with a receiving antenna aimed at an azimuth within 0.5° of the azimuth at which a satellite crosses the horizon, one can determine the fraction of time that the path will be subject to interference. Because a satellite passes through each declination twice a day, the satellite spends $12/\alpha_m$ hours per day in each 1° interval of declination. The elevation increase per degree of declination, δ, is typically less than unity, and more strongly dependent on latitude than on the difference in longitude to the satellite. Hence, one may use an average representative value of δ for the latitude of the path. Then the time that the satellite spends between the horizon and an elevation 1° above the horizon is given by $12/\delta\,\alpha_m$, and the fraction of time that the path is exposed to interference, f_I, is given by:

$$f_I = \frac{1}{2\delta\,\alpha_m} \tag{3}$$

To assess the effect of the interference arriving at low elevation angles, assume that the satellites are illuminating the terrestrial receivers with the maximum allowed power flux-density of −152 dB(W(m^2/4 kHz)). For a terrestrial digital radio with a noise bandwidth of 15 MHz and a receiving aperture with an area of 10 m^2 and an efficiency of 80%, the received interference power could be −77 dBm (−152 + 30 + 36 + 9).

At present most unwanted satellite signals operate at lower power levels. As a current example, a single dispersed video signal with a 3 MHz bandwidth is taken and this produces a received interference power of −84 dBm. The system noise power at the receiver input, due to thermal noise and receiver noise commensurate with a 3 dB noise figure, would be −99 dBm. Hence, the interference will degrade the thermal noise fade margin of the receiver by 15 dB.

A typical digital radio in the 4 GHz band has a thermal noise fade margin of 40 to 44 dB. Taking a middle value of 42 dB, the interference would reduce this margin to 27 dB. If the digital radio employed automatic transmit power control (ATPC), and operated at a nominal power level 12 dB below its maximum, the effective fade margin of the receiver would be 15 dB. Fading of this magnitude on a terrestrial path tends to be slowly varying and non-dispersive. A path can be expected to experience fades of this depth for 0.2 to 2.0% of the time. For the purposes of this calculation 0.5% will be taken as a representative percentage of the time that the path is unavailable when interference is present. Hence, the probability that an interfered hop is unavailable, P_u, may be obtained from equation (3) as:

$$P_u = \frac{5 \times 10^{-3}}{2\delta\,\alpha_m} \tag{4}$$

Unavailability objectives are specified in Recommendation ITU-R F.557 for the hypothetical digital reference path (HRDP), which is typically comprised of 50 individual paths. Since the interference sources for the different hops comprising a circuit are different and independent as are also the additional fading occurrences necessary to cause unavailability. Thus, the network, or circuit unavailability due to interference, P_{nu}, is given by:

$$P_{nu} = 50\,P_I P_u \tag{5}$$

or from equations (2), (4) and (5)

$$P_{nu} = \frac{\lambda_S \times 10^{-2}}{7.2\,S\delta\,\alpha_m} \tag{6}$$

Table 1 gives values of the relevant parameters and probabilities for the case where all satellites have inclinations of 10°. Note that the network unavailabilities exceed the objectives described in Recommendation ITU-R SF.615 for all sources of interference by more than an order of magnitude. In addition, no temporal correlation between the occurrence of fading and the presence of interference is assumed. As a result, the calculations are annual averages, and it may be even more difficult to satisfy the any-month performance objectives of Recommendation ITU-R SF.615.

While the large value of circuit unavailability may appear to be a consequence of the large assumed value of orbital inclination, it is in practice almost independent of the value of orbital inclination. The span of longitudes is linearly related to the range of declinations. Thus, the network unavailability is independent of the value of α_m. Decreasing the maximum orbital inclination α_m reduces the fraction of hops that experience interference, P_I while increasing the fraction of unavailable time for any hop that does experience interference, P_u. Also reducing the orbital separations of the satellites increases both P_I and P_u. Since the beamwidth of the receiving antenna was neglected in calculating P_I the calculated circuit unavailability represents the additional contribution from allowing orbits to acquire significant inclination angles. Not all satellites in the orbit necessarily radiate at the −152 dB(W(m²/4 kHz)) power flux-density limit. Also, they do not uniformly occupy the whole frequency band.

However, the performance requirements of a high grade digital HRDP may not permit the direct exposure of any terrestrial receivers. Tables 1a) and 1b), column 5, show that increasing the orbital inclination will increase the number of exposed receivers that might need to be fixed in order to satisfy the system performance. Moreover, there might be a need to satisfy the interference related performance requirements of a digital section. This performance might be influenced by the maximum orbital inclination.

2.3.2.2 Effects of small orbital inclinations

A more detailed analysis is required to assess the effects of inclination angles so small that the span of visibility in azimuth, Z_S, is comparable to the antenna beamwidth. In the absence of orbital inclinations, the fraction of terrestrial receivers that would be exposed to mainbeam interference depends on the apparent angle, ε, with which the geostationary orbit crosses the geometric horizon of a terrestrial observer. For satellites with 3° spacings, the fraction n_0 of receiving antennas with 1° square lobes that is exposed to interference in latitudes of interest, assuming that the antennas are uniformly distributed in angle and in location along a latitude, is given by:

$$n_0 = \frac{1}{180\, S \sin \varepsilon} \tag{7}$$

Table 2 gives representative values of n_0, which represents the fraction of terrestrial receivers that require special attention to facilitate band sharing. The additional fraction of receivers that would be affected per degree of maximum orbital inclination may be obtained as half of the per-hop probability of exposure divided by the maximum orbital inclination, $0.5\, P_I / \alpha_m$, or:

$$n_{\alpha_m} = \frac{\lambda_S}{180\, S \alpha_m} \tag{8}$$

Table 2 shows that the sharing burden is approximately doubled in latitudes above 20° for orbital inclinations of less than 1°. Note that the entries in both columns are inversely proportional to the satellite orbital spacings.

The results in Table 2 show that the number of terrestrial receivers that would be exposed to interference increases with orbital inclination. This indicates a need to limit the inclinations of satellite orbits. Further studies using more comprehensive models of the terrestrial receiving antennas would be required to determine whether restrictions in inclination would be necessary to limit the number and level of exposure of terrestrial receivers to acceptable levels.

2.3.3 Aggregate interference over a hypothetical reference circuit

Geostationary satellites generally appear to fixed service (FS) receivers as point sources of interference operating from fixed orbit assignments. Previous studies, using computerized Monte Carlo models have calculated the levels of interference that the FS might experience from fixed location FSS space stations under different parametric assumptions.

In order to study the aggregate effect of this different time varying geometry on the FS, a model was implemented using practical radio-relay system parameters and full satellite orbit occupancy with 3° spacing, each producing the allowable power flux-density levels at all angles of arrival. In addition, the model was modified to incorporate the ability to simulate each satellite being placed in a separate randomly selected inclined geosynchronous orbit with angles of inclination of 0° to 15°.

TABLE 2

Percentage of terrestrial receivers subjected to main lobe interference from space stations with orbital separations of 3°

	100 n_0	100 n_{α_m}
Latitude of interfered receiver (degrees N)	Percentage of receivers exposed to main lobe interference with no orbital inclination	Additional percentage of exposed receivers per degree of orbital inclination
20	0.20	0.14
30	0.21	0.22
40	0.24	0.32
50	0.29	0.46
60	0.37	0.69

Using the above model as a study tool, runs were made to determine the average levels of interference that the FS would experience at various latitudes and route directions when the FSS space stations occupied a range of orbit inclinations. The study demonstrated that at any latitude the aggregate interference into the FS caused by an FSS geometry of randomly inclined geosynchronous orbits is only marginally different from the interference caused when all satellites are in the geosynchronous orbit. Figures 5a and 5b summarize the results of one run made during the study. They both compare the probability distributions of interference into the FS from 0° and 15° inclined. FSS orbits for radio-relay routes centred at 40° latitude. In one case (Fig. 5a) the route direction was chosen for maximum received interference (about 77°). It is observed that for this specific case the average interference into the FS is less for 15° inclination.

Other runs (see Fig. 5b) indicate the opposite effect for different choices of route direction. The study concludes that, at any latitude, the average interference into the FS for all route directions is independent of the orbit inclination; but, that specific routes may periodically experience measurable variations in the level of interference as satellites move in relation to the FS antenna patterns. It should be cautioned, however, that these studies only address the relative amount of interference, from the FSS, due to inclined orbits and that they do not comment on the total number of FS stations that may be affected as a consequence of the inclination.

2.3.4 Aggregate interference over a practical FS network

Studies have been undertaken to examine the effect of permitting geosynchronous orbits with various inclinations on major FS networks.

2.3.4.1 Study A

The FS model used was the 4 GHz trans-Canada network from Vancouver to Halifax (129 hops). The satellites identified were those in the ex-IFRB List A of December 1988, with appropriate advance publication information (API) parameters. The total number of satellites was 167. The assumed e.i.r.p. was derived from the peak power density over a 20 MHz band and up to a maximum power of 10 W per 20 MHz.

The outage of each hop was calculated by aggregating the interference from all satellites in various inclined orbits. The total end-to-end outage was calculated as the sum of the outages in each hop. In this way the relative outage due to various levels of inclined orbit could be obtained.

It was found that most of the 129 hops did not experience significant outage increases when the satellites were in orbital inclinations of up to ± 7°. However, several hops did experience significant changes, some increasing, others decreasing. The end-to-end outage, however, masked these changes and varied by less than 5% increase in one direction and about 10% increase in the other direction.

Based on this study, which covers a wide range of circumstances, it could be concluded that from a strictly satellite interference viewpoint, up to ± 7° of orbital inclination would be acceptable. However, other considerations such as the earth station/fixed station coordination area may place further restrictions which would define what the maximum allowable inclination would be.

FIGURE 5a
Interference distribution

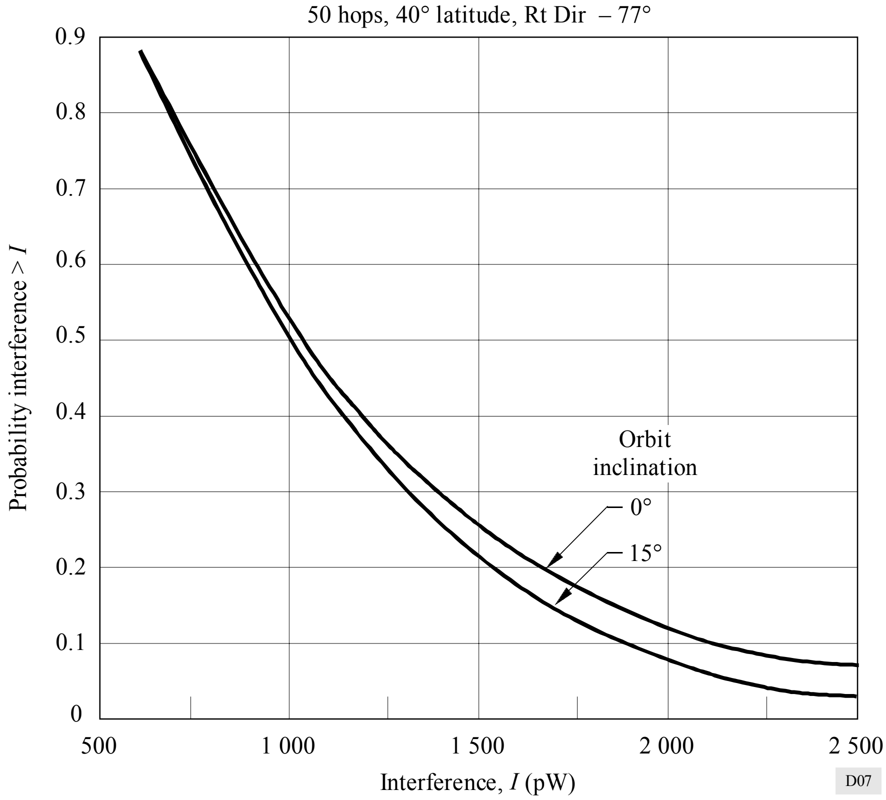
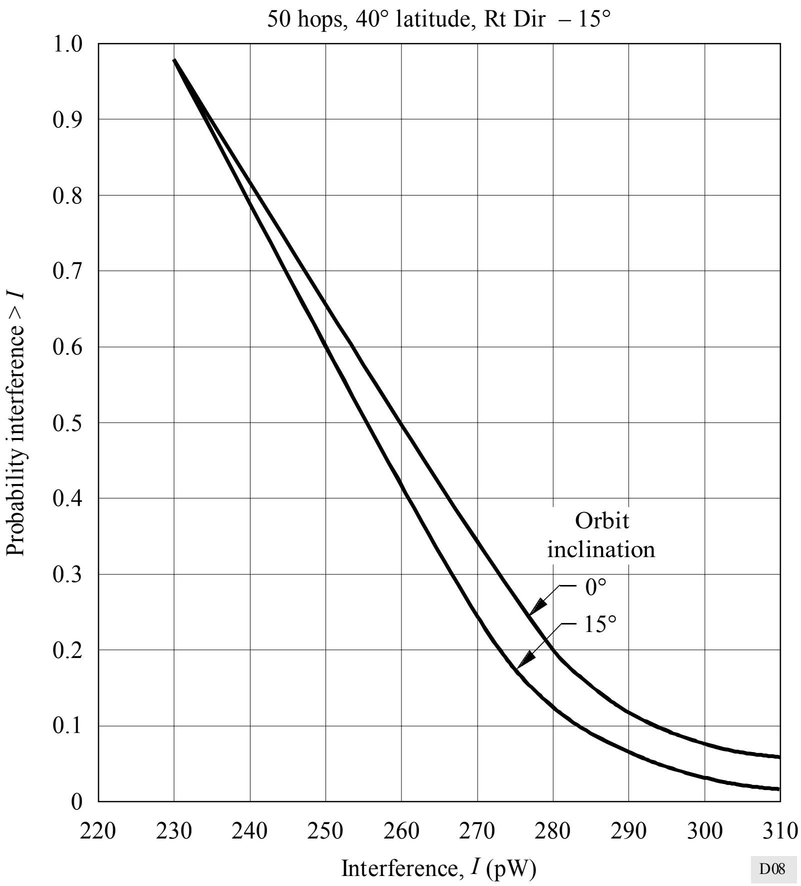


FIGURE 5b
Interference distribution



2.3.4.2 Study B

The FS model used was the route connecting Tokyo and Osaka operating in the 4 GHz band (61 hops and 122 antennas). The antenna radiation pattern was assumed to use the characteristics described in Recommendation ITU-R F.699 with $D/\lambda = 50$. Feeder loss was assumed to be 3 dB and receiver noise figure was assumed to be 4 dB. Each satellite was assumed to produce the maximum power flux-density as specified in Recommendation ITU-R SF.358. No atmospheric loss was taken into account.

Satellites were assumed to be operating with an inclination angle of $i°$. In such a case, the probability density $p(x)$ of a satellite having separation angle of $x°$ with the GSO can be approximated by:

$$p(x) = \frac{1}{\pi\sqrt{i^2 - x^2}} \tag{9}$$

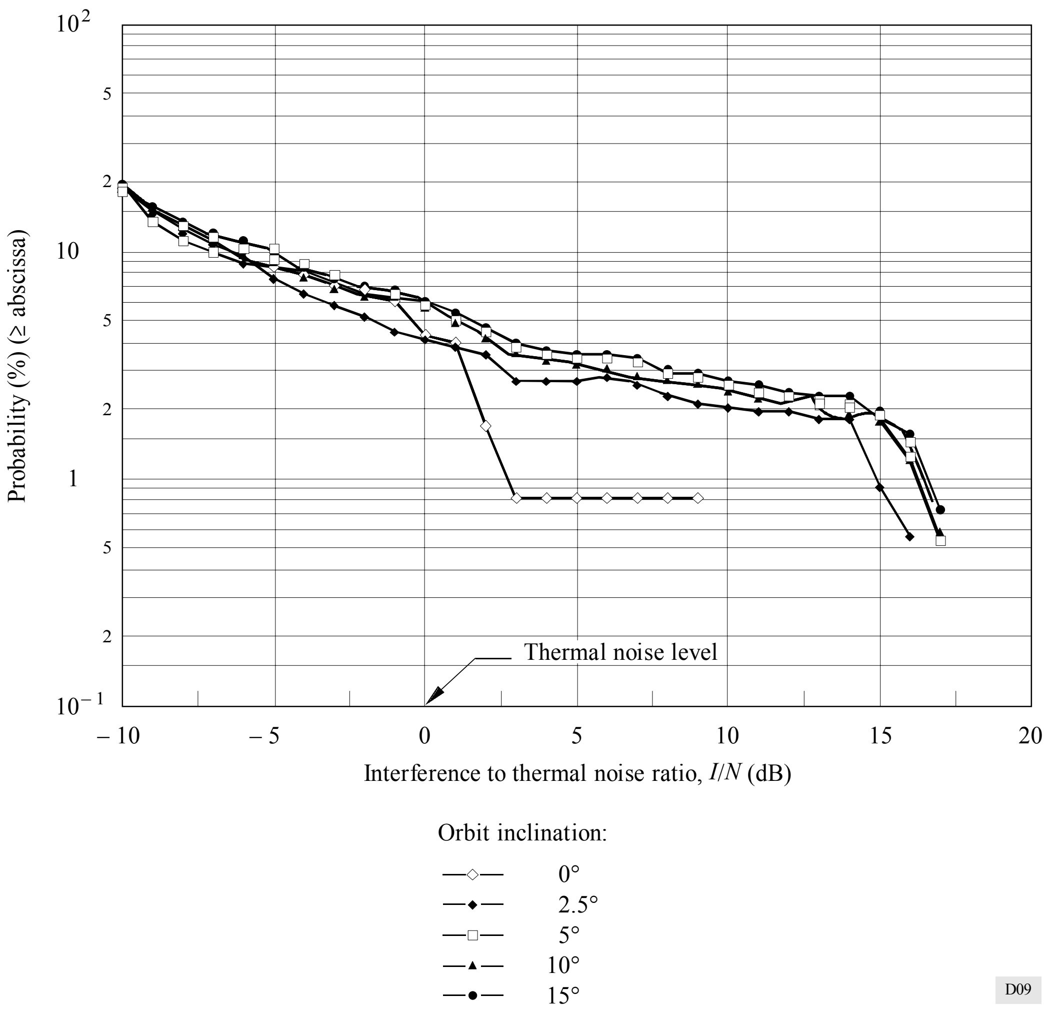
The separation angle between a radio-relay antenna and the inclined orbit was calculated for each x taking into account the atmospheric refraction of the antenna beam and considering the probability density function *p(x)*. Effects of the horizon were also taken into account.

The interfering power to each radio-relay receiver was calculated from the nearest satellite.

The results are shown in Fig. 6. The abscissa is the interference-to-thermal noise, *I/N,* ratio. It is noted that, when inclined orbit operation is not allowed, the probability of *I/N* exceeding 10 dB is zero and when the inclination angle becomes 2.5°, the probability of *I/N* exceeding 10 dB becomes approximately 3%. When the inclination angle becomes larger than 2.5°, there is a tendency for the probability of *I/N* exceeding 10 dB to become larger, but the increase is not significant.

FIGURE 6

Satellite interference power statistics



The above results show that when the inclined orbit (IO) operation is introduced, it will increase the percentage of high I/N, even when the inclination angle is small. This is because radio-relay routes have been planned so that the directions of receiving antennas will avoid exposure to the GSO. However, it should be noted that the above calculations are somewhat conservative in a sense that the calculations assume that the satellites are located in the worst longitudinal positions nearest to the directions of receiving antennas. Therefore, in actual situations, the increase of the percentage of high I/N will be smaller.

Taking into account various factors including that only a few satellites will employ inclined orbit operation, it is concluded that inclined orbit operation within a certain limit should be accepted from the standpoint of interference from satellites to radio-relay systems.

2.3.5 A study for statistical assessment of interference

2.3.5.1 Introduction

This study is an attempt to make a statistical assessment of interference to radio-relay systems from satellites in the FSS employing slightly inclined orbits. The values used in this study may not be worst case values but were chosen as typical values for radio-relay networks in many countries. The effects of certain factors such as space diversity and antenna gain are discussed in § 2.3.5.4.

2.3.5.2 Interference model

2.3.5.2.1 Radio-relay system model

Operating frequency:	4 GHz and 11 GHz
Antenna diameter:	3 m (gain = 39.7 dB at 4 GHz, 48.5 dB at 11 GHz)
Receiver noise temperature:	750 K
Feeder loss:	3 dB
Antenna elevation angle:	0°
Antenna azimuth angle:	uniform within 360° except for the directions within 2° or 1.5° towards the GSO
Antenna radiation pattern:	see Recommendation ITU-R F.699

The interference from a satellite was evaluated in terms of interference-to-thermal noise ratio, I/N. Under the above conditions, the maximum I/N when a radio-relay station has a direct exposure to the satellite is 15.1 dB at 4 GHz and 17.1 dB at 11 GHz under free space propagation conditions without atmospheric absorption loss.

2.3.5.2.2 Satellite model

It is assumed that only one satellite exists in the slightly inclined orbit. Because of sharp directivity of radio-relay antennas, it is considered that this assumption is sufficient for the interference assessment discussed here.

The latitude and the longitude of a satellite employing inclined orbit operation are determined in accordance with the formulae given in Recommendation ITU-R S.743.

The satellite is assumed to produce the maximum power flux-density at the surface of the Earth in accordance with Recommendation ITU-R SF.358 at all angles (§ 1.2 for 4 GHz and § 1.3 for 11 GHz).

The power flux-density is assumed to be constant over the bandwidth of the radio-relay receiver.

2.3.5.2.3 Propagation

Atmospheric refraction was not taken into account in order to simplify calculations.

However, atmospheric absorption loss due to oxygen and water vapour (7.5 g/m^3 as typical) was taken into account as a function of elevation.

The loss was calculated in accordance with the method described in Recommendation ITU-R P.676. The actual values are shown in Fig. 8.

2.3.5.3 Interference assessment

2.3.5.3.1 Calculations

I/*N* ratios experienced by a radio-relay station have been calculated and some results are shown in Figs. 7a to 7d as follows:

Figure 7a: 4 GHz system station at 40° latitude

Figure 7b: 11 GHz system station at 40° latitude

Figure 7c: 4 GHz system station at 60° latitude

Figure 7d: 11 GHz system station at 60° latitude

Effects of interference are generally larger at higher latitudes. Therefore, calculations at 40° and 60° latitudes are considered to be representative.

Calculations have been made for inclination angles of 2.5°, 5° and 10°. The abscissa of each figure is the satellite longitude relative to the longitude of the horizon/orbit intercept (78.6° for 40° latitude and 72.4° for 60° latitude).

The calculations have been made as follows. For each satellite longitude, the azimuth angle of the radio-relay station antenna direction is chosen uniformly within 360° except for the directions within 2° (in case of 4 GHz system) or 1.5° (in case of 11 GHz system) towards the GSO.

For each of the above cases, the interference is evaluated in terms of *I*/*N* ratio for all possible locations of the satellite in the inclined orbit. The following two values are determined. One is the worst case *I*/*N* ratio and the other is the 10% *I*/*N* ratio which is exceeded for no more than 10% of the time. These two values are both functions of the radio-relay antenna azimuth. The plotted "10% values" were determined from the 10% *I*/*N* ratios which were exceeded for no more than 1% of the possible azimuth angles.

The dashed curves and the solid curves in the figures correspond to the worst values and the 10% values as defined above, respectively.

2.3.5.3.2 Interference experienced by a station at 40° latitude

Figure 7a shows the *I*/*N* ratio experienced by a 4 GHz radio-relay station at 40° latitude. The dashed curves show the worst values. They are functions of the satellite longitude and the highest *I*/*N* value is 13.2 dB. When the satellite is located very close to the horizon/orbit intercept, the worst value becomes low, because the radio-relay station is directed at least 2° away from the GSO. When the relative satellite longitude exceeds a certain limit, the satellite disappears below the horizon and hence there is no interference.

The 10% value is somewhat lower than the worst value and this phenomenon becomes more prominent when the inclination angle becomes large. If the inclination angle is 10°, the worst value is very large in a wide range from −10° to +8°, but the 10% value is below 0 dB except for certain longitudes near −9° and +7°.

Figure 7b shows the similar data for 11 GHz. The highest *I*/*N* value is 13.6 dB. Because of the narrower beamwidth of the 11 GHz antenna, the 10% value is much lower than that at 4 GHz. This indicates that the interference effect is smaller at 11 GHz than at 4 GHz.

2.3.5.3.3 Interference experienced by a station at 60° latitude

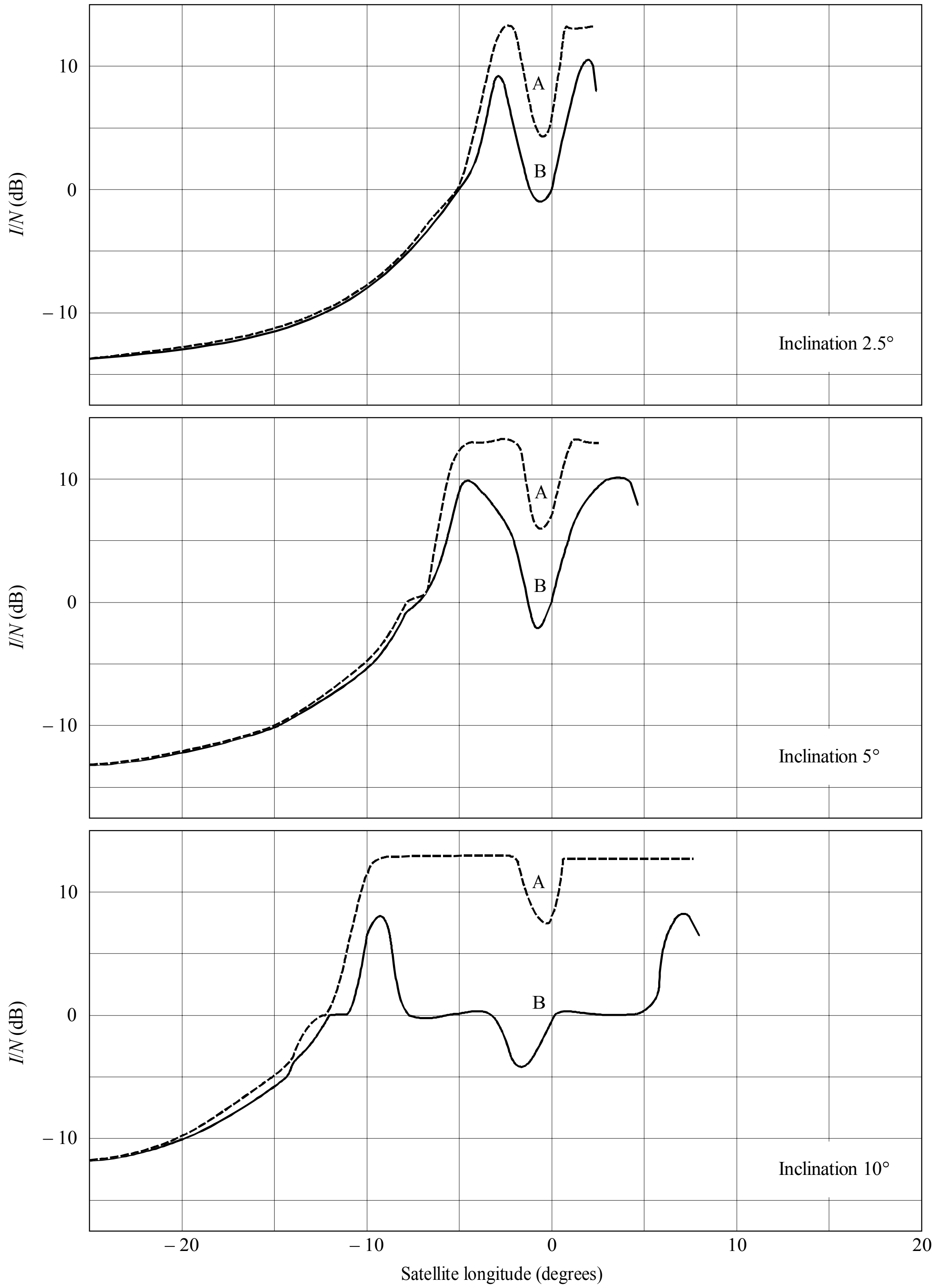
Figures 7c and 7d show the interference into a radio-relay station at 60° latitude for 4 GHz and 11 GHz, respectively.

The worst value curves are at the highest value in a range of the satellite longitude broader than that at a station of 40° latitude, but the general tendency is similar to that in Figs. 7a and 7b. That is, the 10% value is lower than the worst value and, if the attention is limited to the 10% value, the interference effect is not so significant.

FIGURE 7a

***I/N* ratio experienced by a radio-relay station at a latitude of 40° (4 GHz)**

Satellite longitude relative to the horizon/orbit intercept (78.6°)

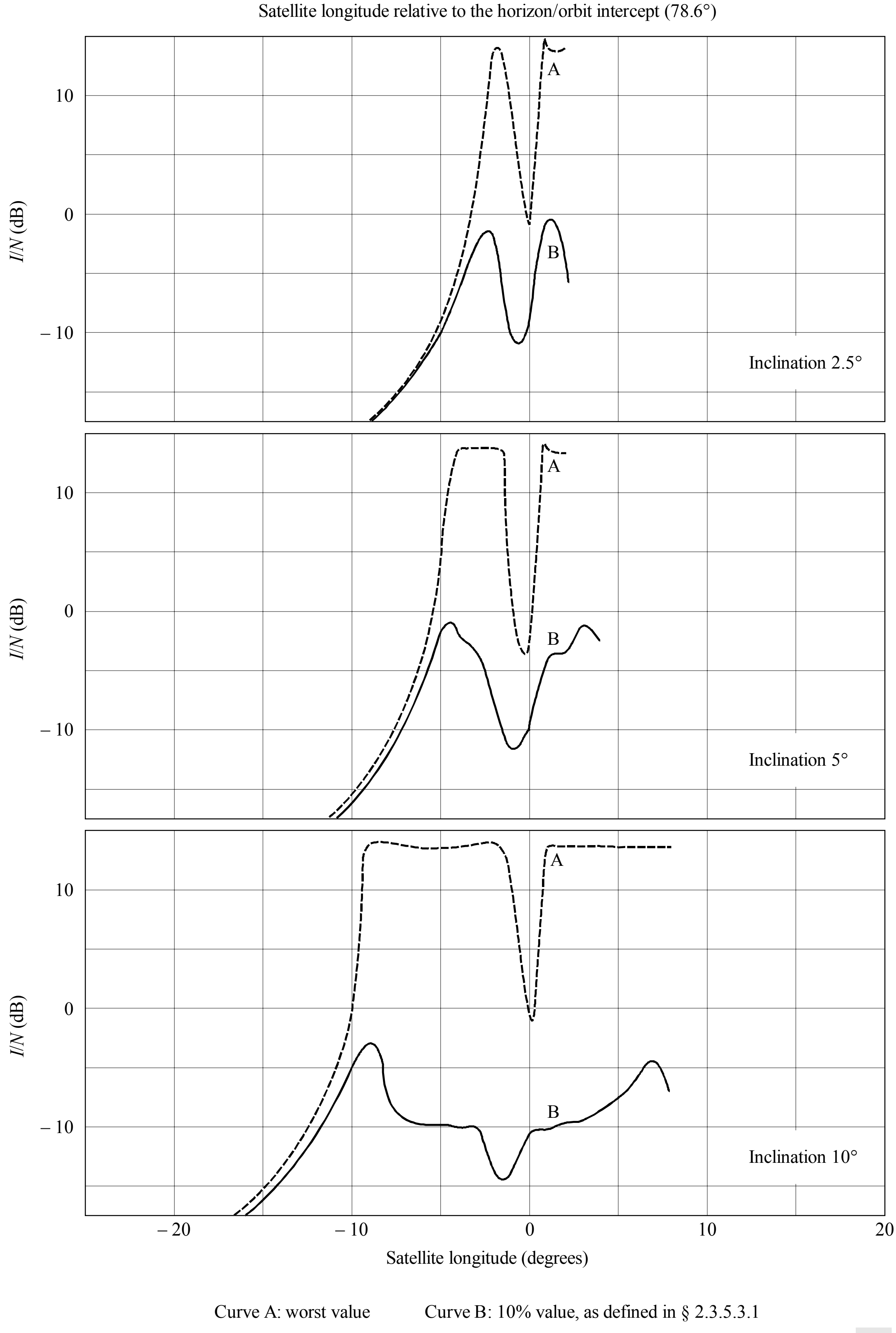


Curve A: worst value Curve B: 10% value, as defined in § 2.3.5.3.1

D10

FIGURE 7b

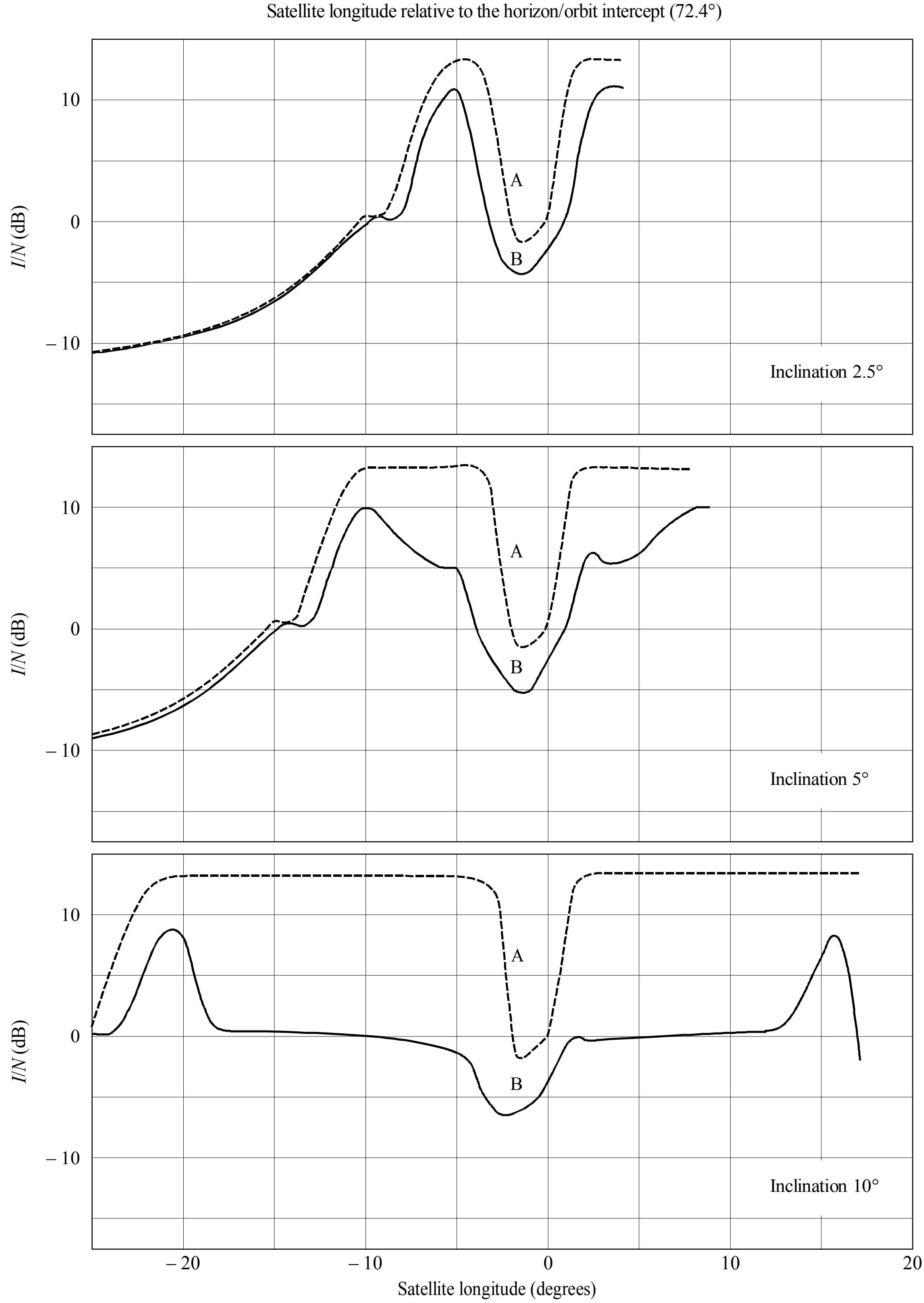
***I*/*N* ratio experienced by a radio-relay station at a latitude of 40° (11 GHz)**



Curve A: worst value Curve B: 10% value, as defined in § 2.3.5.3.1

FIGURE 7c

***I/N* ratio experienced by a radio-relay station at a latitude of 60° (4 GHz)**

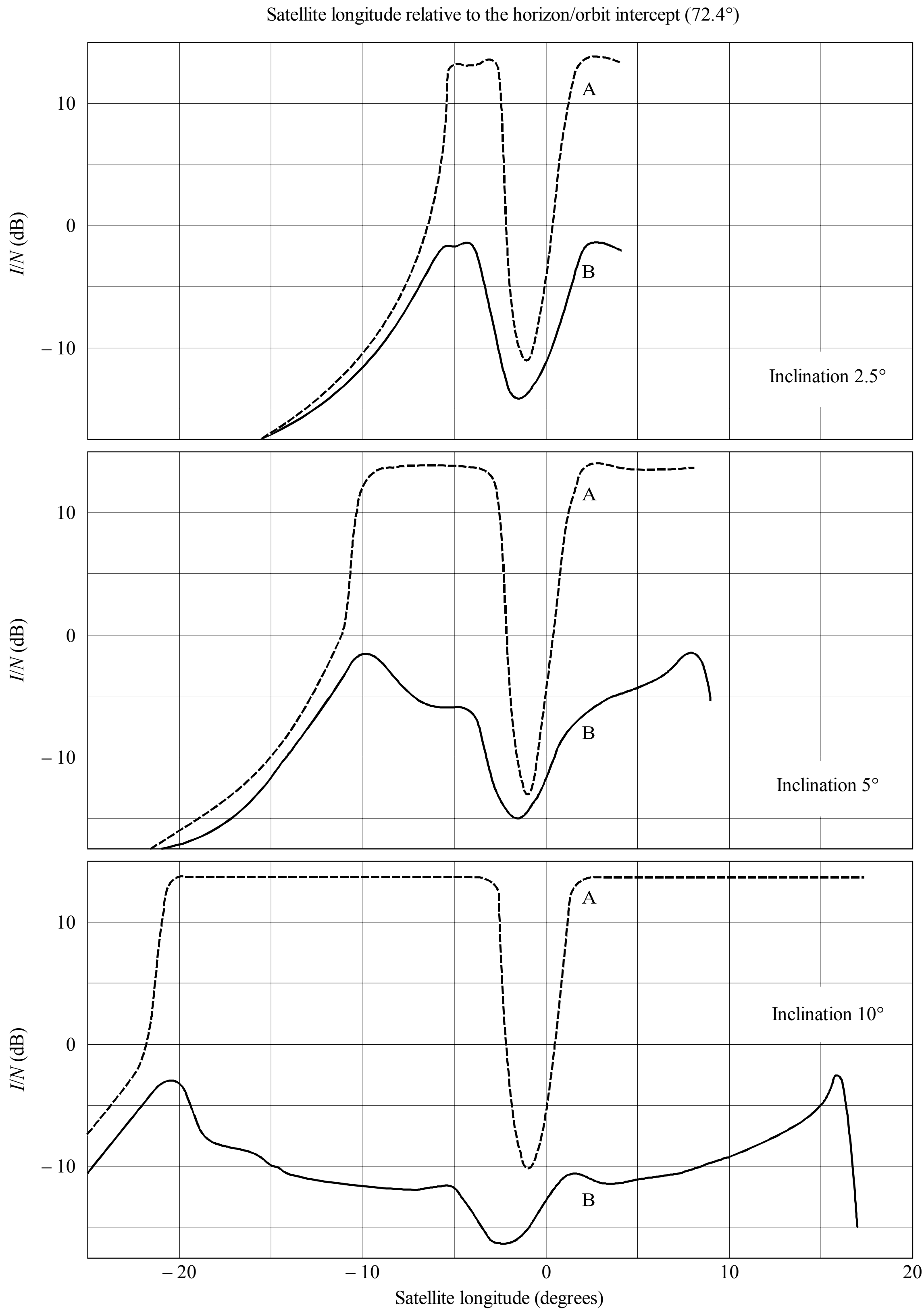


Curve A: worst value Curve B: 10% value, as defined in § 2.3.5.3.1

D12

FIGURE 7d

***I/N* ratio experienced by a radio-relay station at a latitude of 60° (11 GHz)**

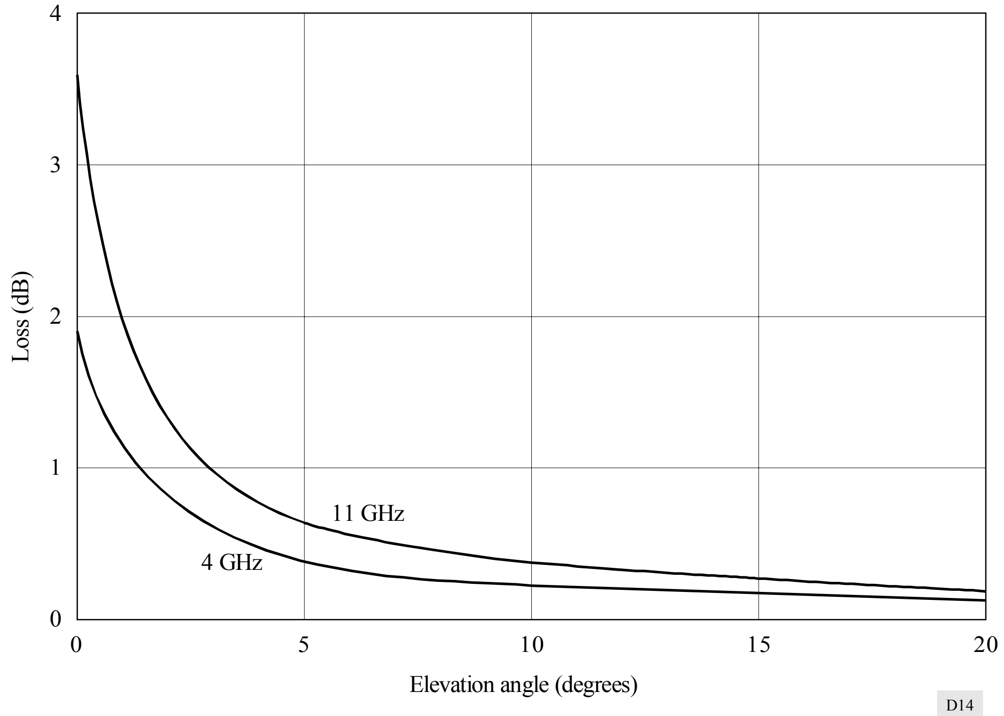


Curve A: worst value Curve B: 10% value, as defined in § 2.3.5.3.1

D13

FIGURE 8

Atmospheric absorption loss



2.3.5.4 Effects of certain factors

2.3.5.4.1 Space diversity

If space diversity reception is applied to the radio-relay station, the worst *I*/*N* values will increase by about 3 dB. However, because of sharp directivity in the vertical plane introduced by space diversity, there is no significant increase in terms of the 10% *I*/*N* values.

2.3.5.4.2 Antenna gain

If a larger diameter antenna is employed in the radio-relay station, the worst *I*/*N* values will increase. For example, in the case of a 4 m diameter antenna at 4 GHz, the worst *I*/*N* values will increase by about 2.5 dB as compared with a 3 m diameter antenna. However, the width of the main beam of an antenna with a larger diameter is narrower. In fact, the gain (in the main beam) of the 4 m diameter antenna is lower than that of the 3 m diameter antenna at angles above 0.9°. This will to some extent offset the effect of the increase of the maximum antenna gain. Therefore, the increase of the 10% values is as an average less than 1 dB.

2.3.5.4.3 Feeder loss

In some cases the feeder loss of the radio-relay station may be as low as 0.5 dB. This would increase all *I*/*N* values in § 2.3.5.3 by 2.5 dB.

2.4 Interference from terrestrial stations into space stations

2.4.1 Introduction

The analysis of the risk of interference into space stations assumes a probability basis, since specific data on locations, etc. of radio-relay stations are not available. The analysis is based on estimating the probability for the GSO case and then using the same model to assess the relative risk for the IO case. For the IO case, 5° inclination has been chosen as representing a reasonable value for the analysis. Lower inclination values yield a proportionally lower estimate of potential interference, while higher values will yield a higher estimate.

2.4.2 The model

Radio-relay stations which can have mainbeams which intersect the GSO are limited to those with a particular radiation azimuth at a specific latitude. There are four such points for each satellite location on the GSO accounting for both North and South latitudes as well as locations East and West of the GSO location.

Making an allowance for the beamwidth of the radio-relay antenna, its elevation angle and accounting for refractive effects, a small strip similar to that of Fig. 2a is established, which contains all the stations which could have an intersection with the GSO or the IO at some point in time. The width of this strip is a function of the values assumed for the model parameters.

The model parameters assumed here are: elevation angles from −1° to 4° for the radio-relay antenna and a range for the radio refractivity from 250 to 400. This latter factor adds 2° to the effective range of visibility at the outer edge of the strip. It is also assumed that the beam centre is separated from the orbit under study by 1.5° to account for the beamwidth with some margin.

2.4.3 GSO case

For the assumed parameters, the width of the strip for the GSO case is approximately 7°. The number of stations located within this strip is a function of the area of the strip and an assumed density for the terrestrial stations. The area need only be calculated for one quadrant from the equator to 70° latitude and, by symmetry, it applies to all quadrants. Intersection with a specific point on the GSO can take place from all four quadrants.

For the 7° (775 km) strip of one quadrant, the area of the strip is 7 875 000 km^2.

2.4.4 Inclined orbit case

The width of the strip is not changed by the inclination at low latitudes, but it increases with latitude depending upon the inclination. For the case of 5° inclination, the area of the strip in one quadrant is 13 230 000 km^2 and the number of stations would be expected to be 1.68 times that of the GSO case.

This result will vary directly with inclination and it can be taken as representative of the effects of IO.

2.4.5 Quantitative assessment

Estimates of the number of potential intersections can be made by assuming a maximum density of radio-relay stations for all of the land area contained in the strip which has sufficient population to justify the assumption. The maximum density of one station per 2 500 km^2 allows for a station every 50 km in all directions. This corresponds to the normal single hop distance used by radio-relay designers.

It is further assumed that with considerations of population density and the effects of ocean areas, the area of concern would be of the order of 20% of the total. Random pointing of the radio-relay antenna with a 2° beamwidth is assumed and applying these considerations to the GSO case, the total number of stations with possible intersections would be about 14 while those for the inclined orbit case would be about 24.

2.4.6 Practical considerations

This model contains several assumptions which are very conservative, such as:

– radio-relay elevation angles from −1° to 4°,

– the use of a uniform density of radio-relay stations,

– uniform 2° range of elevation angle, considered to be representative,

– a standard nominal refractivity value of 300.

Adjustments can be made to this model, the net effect of which is to reduce the area of concern to 42% of the original model for the GSO case and to 64% for the inclined orbit case. The number of potential exposures is reduced to about 6 for the GSO case and 15 for the inclined orbit case.

2.4.7 Actual experience

A review of INTELSAT satellites in the GSO experiencing interference from terrestrial radio-relay sites has shown that the effects have been minor. In fact only one such case has been recorded over the last ten years.

3 Earth station/terrestrial station interference

3.1 Introduction

The absence or cessation of North-South station keeping of a geostationary satellite will cause it to change its orbital inclination continually. An earth station operating with such a satellite may have to track it with its antenna mainbeam through an apparent diurnal trajectory (a narrow figure-of-eight). When such an earth station has been coordinated with stations of terrestrial services for "strictly" geostationary operation (satellite movement within prescribed or stated small positional tolerances), the need to follow a satellite having or acquiring significant orbital inclination will cause the earth station antenna mainbeam to assume elevation angles and, associated with these, azimuth angles that are different from (both less and greater than) those for which coordination had been effected. Of particular concern is the case when elevation angles are less than required for geostationary operation because in this case the resulting higher earth station horizon antenna gain can cause potential interference from and to a terrestrial station.

3.2 Geometric considerations

3.2.1 Analytic expressions

The elevation angle (ε_s) and azimuth (α_s) of the mainbeam of an earth station towards a space station in geostationary inclined orbit at the point of maximum excursion are given by the following expressions:

$$\varepsilon_s = \arcsin\left((K A - 1.0)/B\right) \tag{10}$$

$$\alpha_s = 90.0 + \arccos\left(K \cos i \cdot \sin \delta / B \cdot \cos \varepsilon_s\right) \tag{11}$$

$$A = \cos i \cos \zeta \cos \delta + \sin i \sin \zeta \tag{12}$$

$$B = (1.0 + K^2 - 2K A)^{0.5} \tag{13}$$

Note that $\arccos(-x) = 180.0 - \arccos(x)$

where:

- K: geostationary orbit radius/Earth radius, assumed to be 6.62
- i: orbit inclination (+ve ascending node East of Greenwich)
- ζ: earth station latitude (+ve North)
- δ: difference in longitude between the space station and the earth station.

3.2.2 Loss of discrimination

As the satellite goes into an inclined orbit, the elevation angle and azimuth vary with time. This may result in variations in gain toward the horizon, as discussed in the following sections.

Both the elevation angle reduction and the associated azimuth shift are not only functions of the orbital inclination of the satellite being tracked, but also of the latitude and relative longitude (longitude difference to the subsatellite nodal point) of the earth station in question, as shown in Figs. 9a, 9b, 9c and 9d for the two orbital inclinations 5° and 10°, respectively.

In Figs. 9a, 9b, 9c and 9d, the outer circumference describes those locations on the surface of the Earth (in terms of latitude and longitude relative to the subsatellite nodal point) at which the earth station antenna mainbeam elevation angle to the inclined-orbit satellite is never less than 3°. The inner, almond-like area contains that part of the Earth's surface at which the elevation angle is never less than 48° and, thus, not subject to variations of horizon antenna gain (assuming that beyond an off-beam axis angle of 48° there is no appreciable change in antenna gain).

FIGURE 9a

Earth station antenna horizon gain increase and mainbeam azimuth shift (5° inclination)

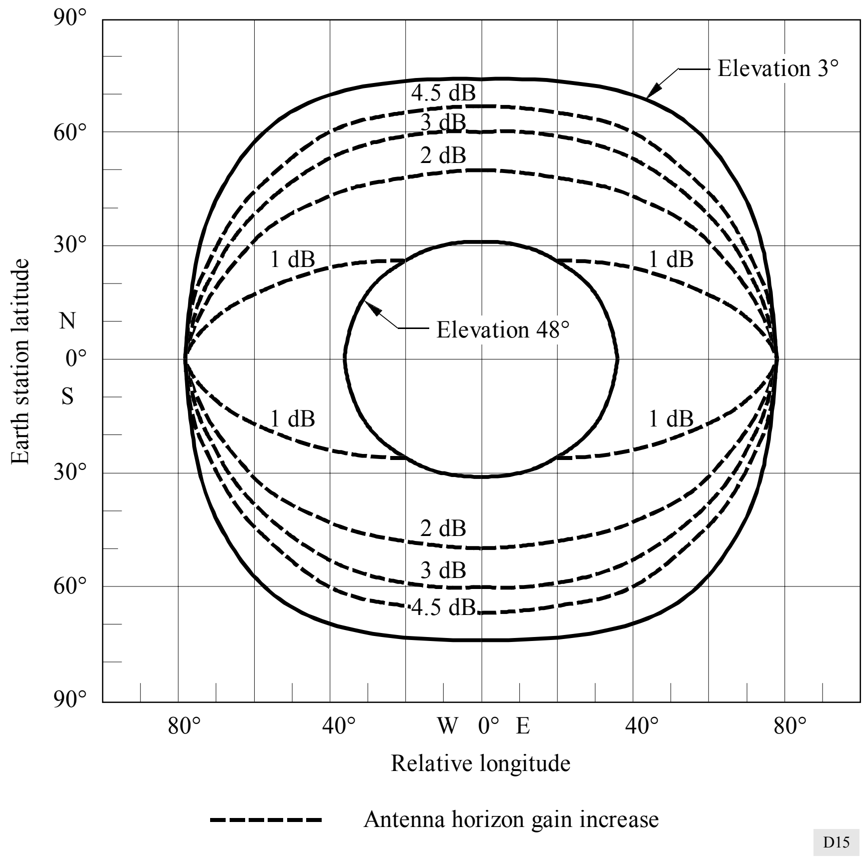


FIGURE 9b

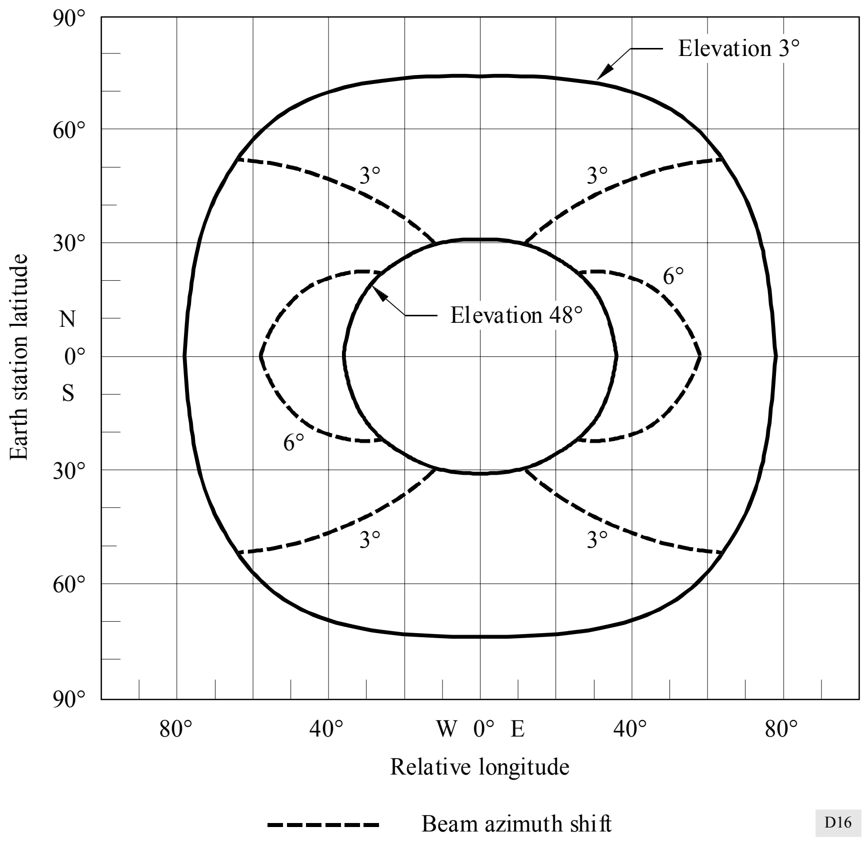
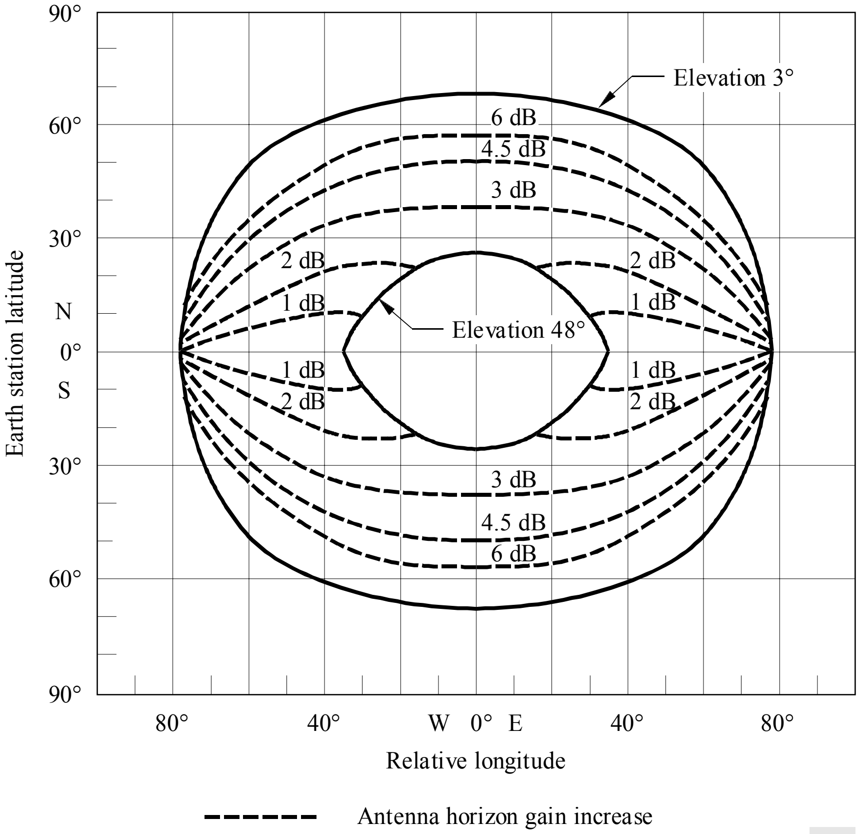


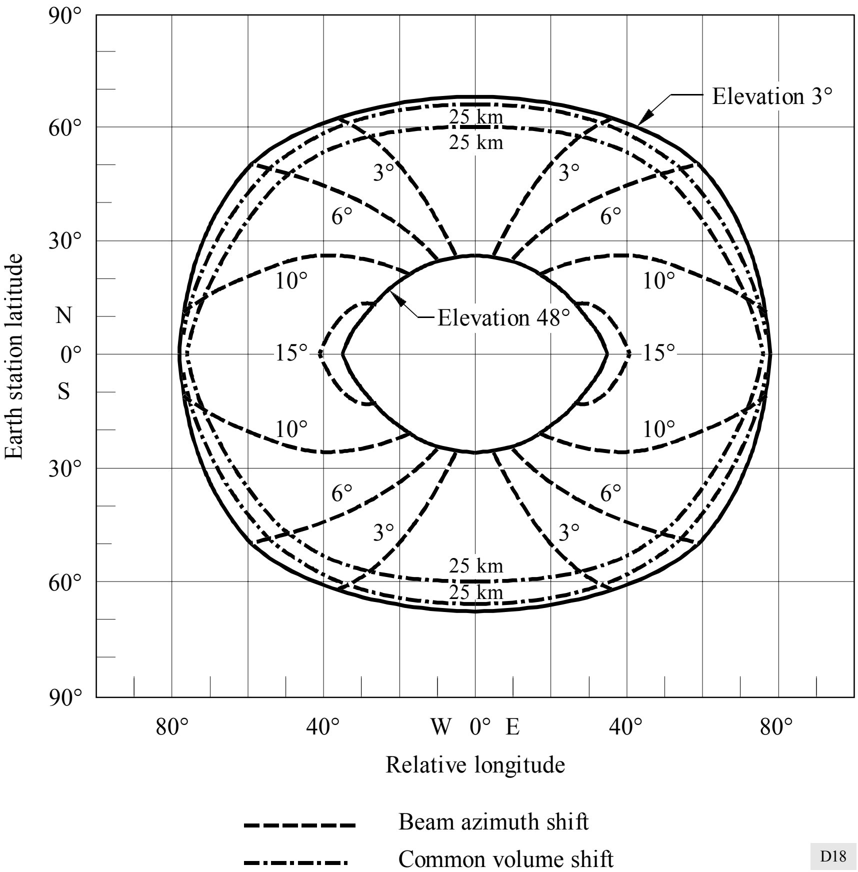
FIGURE 9c

Earth station antenna horizon beam gain increase and mainbeam azimuth shift (10° inclination)



D17

FIGURE 9d



D18

In the upper diagram of each figure, the broken lines show the magnitude of the earth station horizon antenna gain increase (dB), based on an antenna pattern of the form A – 25 log θ dB. In the lower diagram the broken lines show, for the corresponding earth station locations, the shift in earth station antenna mainbeam azimuth from that associated with strictly geostationary operation to that at which the satellite is seen under the lowest elevation angle in its inclined orbit. The azimuth shift is always towards the equator. Earth stations on the satellite node's longitude have the greatest horizon antenna gain increase, and the smallest azimuth shift; earth stations near the equator have the smallest horizon antenna gain increase and the largest azimuth shift. The greater the inclination, the greater are both the horizon antenna gain increase and the azimuth shift.

Figure 9d shows, as an additional set of curves, the lateral shift of a "common volume" at 4 km altitude. This is the highest altitude from which rain scatter interference can be expected.

3.3 Effect on earth station coordination area

Due to the variation in azimuth and elevation angle, earth stations which were previously coordinated with terrestrial systems on the basis that they would operate with a satellite on the GSO may be affected by the use of inclined orbits. Additional terrestrial stations may also be affected. The new coordination contours would then be a function of the GSO location(s) and the arc for which they were calculated. There will be a wide variety of situations which will affect many earth stations in the world.

A set of boundary conditions has been examined which may help in assessing the potential problem of re-coordinating earth stations where it proves to be necessary.

3.3.1 Effect of earth station location

Earth stations which can operate with inclined orbit satellites with 5° inclination are limited to those with elevation angles of 5° to 10° at the nominal GSO location depending on the earth station latitude. The largest dimension of the coordination contour is in this case based on an antenna gain in the horizontal plane of 7 to 14.5 dB. At a receiving station this gain sets the interference sensitivity, while at a transmitting station, it sets the e.i.r.p. density in the horizontal plane.

For an earth station at the equator which has a low elevation angle, the antenna movement in azimuth is approximately twice the inclination angle. However, in this case the elevation angle changes very little.

For an earth station operating at 5° nominal elevation angle, the increase for the range-influenced azimuthal directions of ± 50° for the case of 5° inclination is from 0 to 4.9 dB. The impact on the coordination area for an earth station that had been coordinated at 5° at 6 GHz using the maximum allowable e.i.r.p. density of 40 dB(W/4 kHz) is a broadening of the contour around the main-beam region with no change on the nominal azimuth.

For earth stations at high latitude, the azimuth changes very little while the elevation range will be approximately equal to twice the inclination. Inclined orbit operation would therefore be limited to earth stations with a nominal GSO elevation of 10°. This could mean going as low as 5° during part of the tracking time and would yield a gain increase of 7.5 dB on that azimuth resulting in an increase mainly along the mainbeam azimuth.

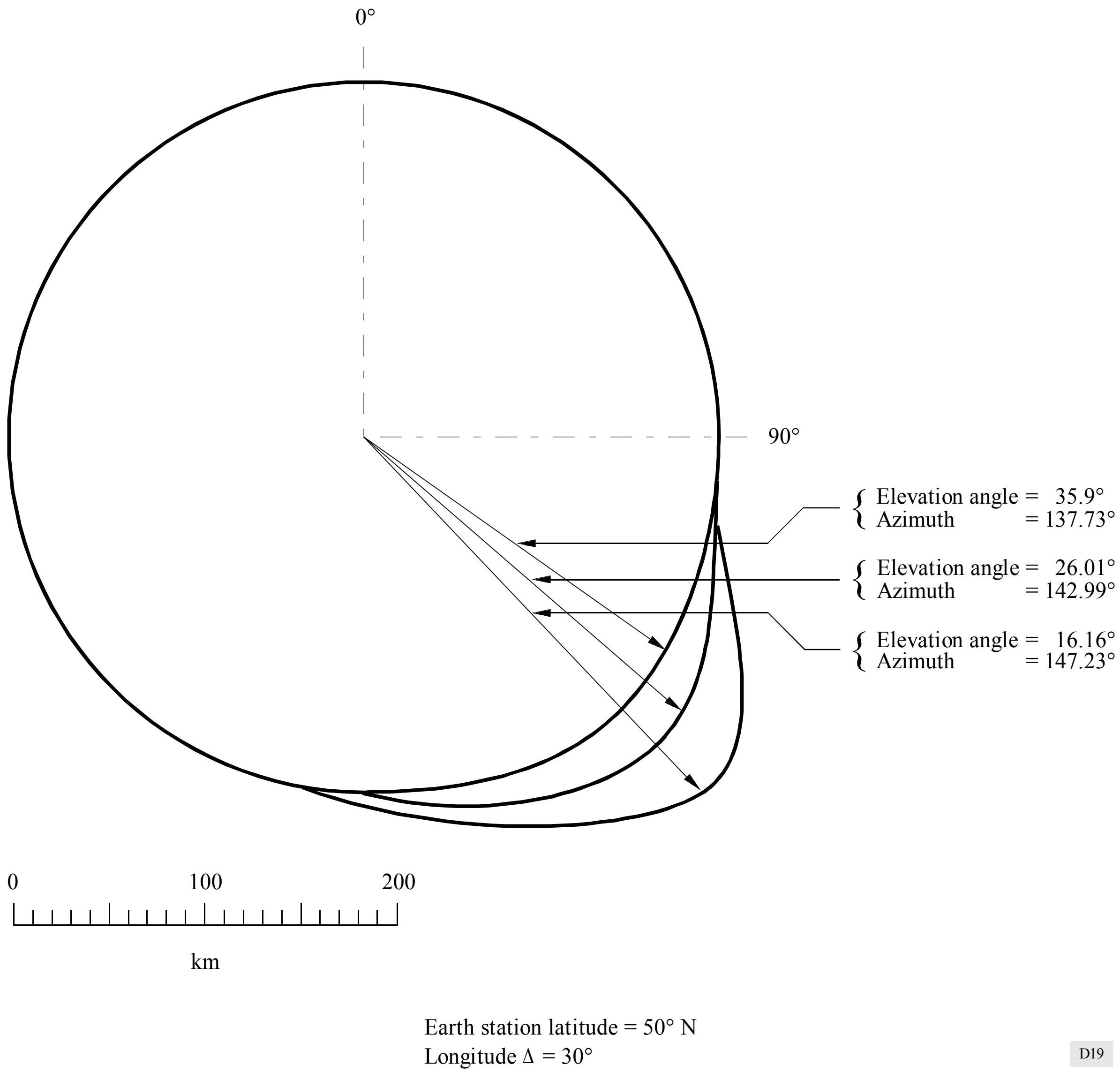
There are locations where both the azimuth and elevation angles change by about the same amount, but this change is less than either of the above cases. Here the gain changes will be less than the extreme cases and the coordination area in all cases changes most in the region of the mainbeam of the earth station. Figure 10 provides an overview of such a case.

3.3.2 Change in coordination distances

The effects on the coordination distances are due to elevation angle changes. For nominal elevation angles in the range of 15° to 20°, the gain change would have a maximum value of about 4.4 dB. For elevation angles greater than 20°, a 5° elevation angle change from nominal will result in a maximum increase in the gain in the horizontal plane of 3 dB. For nominal elevation angles larger than about 53°, there will be no gain change.

FIGURE 10

Mode 1, Zone A coordination area of transmitting 6 GHz earth station under 10° inclined orbit operation



Results of a study on change in maximum coordination distance Mode 1 (great circle propagation) as a function of earth station latitude and longitudinal differences, when compared with a typical 6 GHz earth station coordination contour are presented in Fig. 11. A transmitter power of 20 dBW and 2 MHz energy dispersal have been assumed. The increase of the maximum coordination distance is of the order of 10-20% for nominal antenna elevation angles between 10° and 20°, and a few per cent for the higher elevation angles. The change in per cent is independent of the propagation zone considered (Zones A, B and C).

The changes for propagation Mode 2 (scattering due to hydrometeors) are small and in most of the cases, less than 6%.

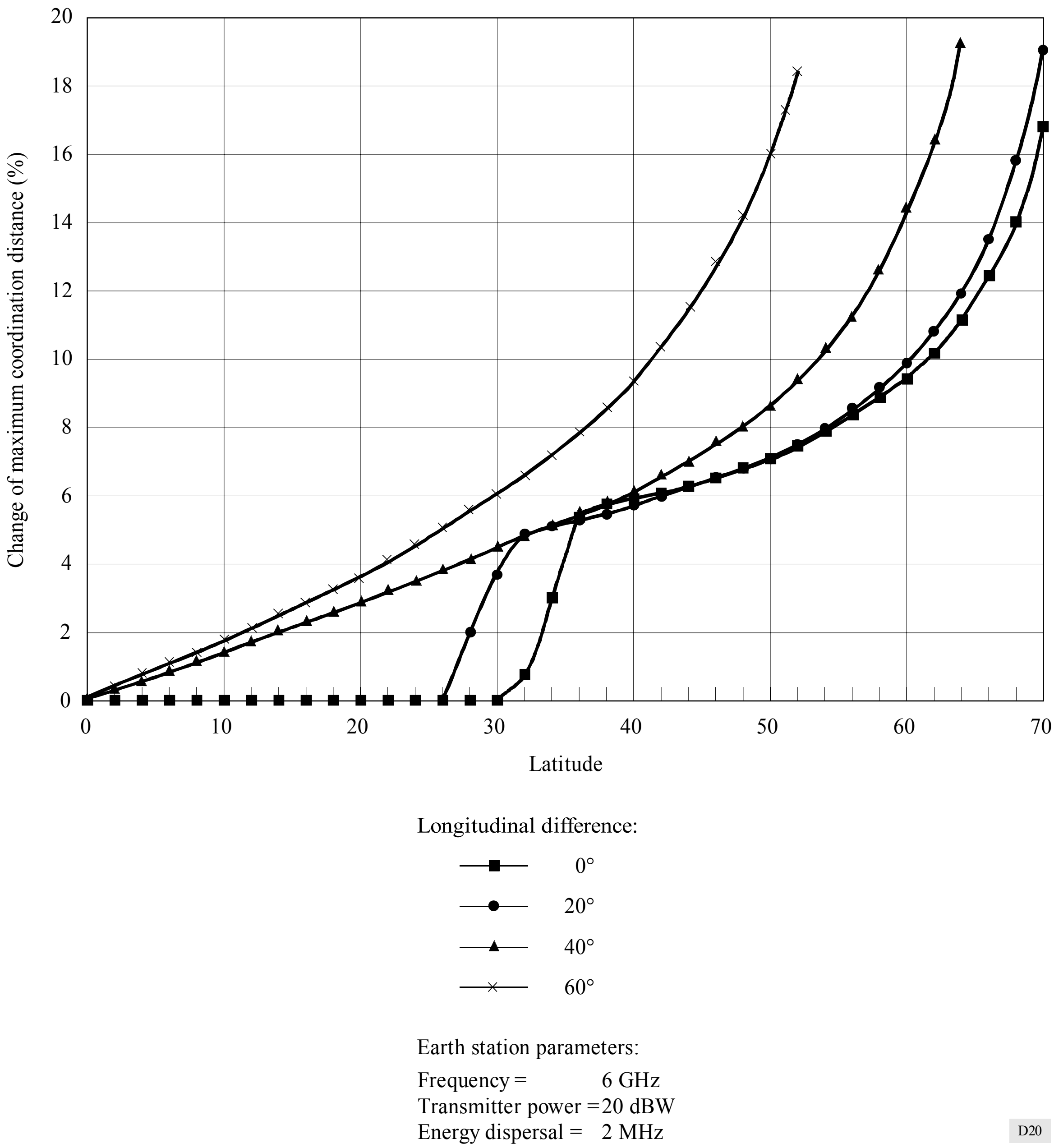
3.4 Interference into FS receivers from earth stations

A stochastic study assessing the input of inclined orbit operations into terrestrial stations has been carried out in which earth stations at latitudes 41° N were used and constrained so that their elevation angles were the local maximum towards the inclined orbit. The results for 15° orbit inclination were a 4.5 dB increase for 23% of the terrestrial receivers for at least 10% of the time (2.4 hours daily) while for 5° inclination 38% of the receivers would receive 1.5 dB increase in interference for 10% of the time. The expected interference increase will be less for higher elevation angles or for azimuths of the terrestrial receiver that tend to point away from the geostationary-satellite orbit rather than the uniform distribution that was assumed. However, for higher latitudes with smaller elevation angles, the expected interference will be greater.

FIGURE 11

Change of maximum coordination distance (%) when compared to coordination distance of a typical earth station

5° inclination, Zone A, frequency = 6 GHz



3.5 Summary

Countries close to the Equator will generally not require re-coordination of their earth stations when these operate with an inclined-orbit satellite. Even when their relative longitudes do not fall within the almond-shaped zone above 48° elevation angle, there will be only little earth station antenna horizon gain increase which can usually be neglected.

Countries at higher latitudes are increasingly more affected and may, in some cases, have difficulties coordinating and especially re-coordinating their earth stations to operate with larger orbit inclinations of their satellite(s). However, in all cases a trade-off is possible between accepting increased difficulties in earth station coordination and more extensive inclined-orbit operation.

4 Conclusions

This Annex has examined the sharing situation between the fixed and the FSS when satellites go into inclined orbit. The impact caused to terrestrial networks results from both the space and earth stations. Similarly, satellite networks will also be affected by interference caused to space and earth stations.

The sharing situation when satellites go into slightly inclined orbits is complex. For a short period, it involves greater exposure of fixed service receivers to direct satellite interference and *vice versa*. The number of terrestrial stations exposed to interference increases with the amount of inclination.

The effect of such exposure upon the system unavailability as well as total interference received has been studied in this Annex. A model has been developed which indicates that under the assumptions of that model an order of magnitude increase in unavailability could be expected. These assumptions include: a system with adaptive power control, all satellites in 10° inclined orbit using −124 dB(W/m^2) power flux-density and satellites spaced 3° apart. However, it is noted that with the trend toward the use of small earth station antennas, it is doubtful that large inclination angles will be used by satellite operators. Other models, based on an assessment of the distribution of beams from an actual radio-relay network, indicate that the total end-to-end interference may in some cases be reduced, depending upon the interference exposure factor.

In a further model, calculation of the aggregate interference over a hypothetical reference circuit shows that the interference does not increase but is re-distributed over the length of the network.

Further studies are needed on the models to be used for interference calculations. Additional information is required on the distribution of terrestrial beams around the orbit.

Studies are also necessary which would aid in the development of techniques for both services to ameliorate the interference situation, particularly for low inclination angles. These include such techniques as the methods of using automatic power control, interference cancellers, using wide-band pfd limits, satellite antenna pointing restrictions, limits to inclination, coordination procedures, site shielding and others.

With regard to the effect upon the coordination area between earth stations and space stations, the impact varies with elevation angle, azimuth and longitude of the earth station. The resulting increases in coordination distances vary with the degree of inclination. When the satellite inclination is 5° and the nominal elevation angle of the earth station is between 10° and 20°, the increase of the maximum coordination distance, compared with the case where no inclined orbit operation is performed, is of the order of 10-20% and for higher elevation angles the increase is a few per cent.