RECOMMENDATION ITU-R S.743-1*

# The coordination between satellite networks using slightly inclined geostationary-satellite orbits (GSOs) and between such networks and satellite networks using non-inclined GSO satellites

(1992-1994)

The ITU Radiocommunication Assembly,

*considering*

a)      that the definition of a geostationary satellite in the Radio Regulations (RR No. S1.189) has no indication for a maximum value of the angle of inclination of the orbit of a geostationary satellite;

b)      that station-keeping fuel on geostationary space stations constitutes an appreciable portion of in-orbit mass and tends to be the limiting factor of a geostationary space station's life;

c)      that North-South station-keeping consumes up to 90% of the total fuel;

d)      that, in the absence of North-South station-keeping, the orbit of a geostationary satellite is subject to no more than about 0.9° of orbit change per year, and the inclination will never exceed the natural limit of 15°;

e)      that, on the other hand, the absence of North-South station-keeping may require additional equipment at the earth stations, such as angular tracking, polarization tracking and for digital transmissions also, larger size elastic buffers and more complex synchronization methods;

f)      that the Second Session of the World Administrative Radio Conference on the Use of the Geostationary-Satellite Orbit and on the Planning of Space Services Utilizing It (Geneva, 1988) (WARC ORB-88) considered the matter of coordinating slightly inclined geostationary-satellite networks, and referred action to the Radiocommunication Bureau and the ITU-R;

g)      that the Radiocommunication Bureau requested the ITU-R to study the related problems:

–      the technical aspects of coordination between geostationary satellites and those in inclined geostationary orbits;

–      the technical aspects of coordination between satellites in inclined geostationary orbits;

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*   Radiocommunication Study Group 4 made editorial amendments to this Recommendation in 2001 in accordance with Resolution ITU-R 44 (RA-2000).

h)       that there appears to be no intrinsic limitation on the coordination of satellite networks using slightly inclined geostationary orbits;

j)       that the data required by RR Appendix S4 (WARC ORB-88) include the effects of using slightly inclined geostationary-satellite orbits,

*noting that*

a)       under co-coverage conditions, the isolation between geostationary-satellite networks with one using a slightly inclined orbit, will be equal to or greater than that between two geostationary-satellite networks (near 0° inclination);

b)       under co-coverage conditions, the isolation between two geostationary-satellite networks using slightly inclined orbits may be either less, or greater, than that between two geostationary-satellite networks near 0° inclination, depending on the relative nodal phase;

c)       under co-coverage conditions, the isolation between two closely spaced geostationary-satellite networks with frequency re-use by dual linear orthogonal polarization, one or both of which use a slightly inclined orbit, may be less than two geostationary-satellite networks, depending on the relative nodal phase;

d)       under non co-coverage conditions, between two geostationary-satellite networks, one or both of which use slightly inclined orbits, the isolation may be less, or greater, than that between two geostationary-satellite networks, depending on a number of factors in addition to the relative nodal phase,

*recommends*

**1**       that the coordination of geostationary-satellite networks using slightly inclined geostationary-satellite orbits be performed in accordance with the RR that apply to geostationary-satellite networks based upon the minimum separation between the satellites concerned;

**2**       that in bands shared with terrestrial services the inclination limit for the application of § 1 may need to be determined by the inter-service sharing considerations (see Note 1); in other bands § 1 may be applied up to the natural inclination limit for satellites launched initially into a geostationary or near-geostationary orbit if N/S station-keeping manoeuvres are not undertaken;

**3**       that for interference considerations involving the coordination of geostationary-satellite networks using slightly inclined geostationary orbits, the information given in Annex 1 should be utilized;

**4**       that the relative nodal phase between the orbits be adjusted if practicable, and/or other measures should be used to minimize any deleterious effects (see § 5 of Annex 1);

**5**       that the following Note should be regarded as part of the Recommendation:

NOTE 1 – Recommendation ITU-R SF.1008 deals with 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.

ANNEX 1

# 1 Introduction

The information contained in this Annex should be used in connection with the coordination of satellite networks using slightly inclined geostationary-satellite orbits (GSO) and between such networks and other satellite networks using non-inclined GSO satellites.

During slightly inclined GSO operation, there are basically three factors which affect the interference between two satellite networks. These are:

– the exocentric angular separation between the coverage areas of the networks as seen from either satellite;

– the exocentric angular width of the coverage areas as seen from either satellite;

– the topocentric angular spacing between the satellites as seen from an earth station of either network.

These factors cause the net antenna discrimination (earth station and satellite antenna) between the two networks to vary in time. In cases where satellite networks have a common service area (co-coverage networks), the earth-station antenna is the basic element providing discrimination between the networks. Where satellite networks have separate service areas (non co-coverage networks), both the earth station and satellite antenna contribute to the discrimination between the networks.

# 2 Geometric considerations

The geocentric angle, $\varphi_g$, between two slightly inclined geostationary satellites with latitudes ($\gamma_1$ and $\gamma_2$) and longitudes ($\varphi_1$ and $\varphi_2$) may be determined by:

$$\cos \varphi_g = \cos \gamma_1 \cos \gamma_2 \cos (\varphi_1 - \varphi_2) + \sin \gamma_1 \sin \gamma_2 \tag{1}$$

The latitude $\gamma$ and longitude excursions $\Delta\varphi$ of a satellite as a function of the orbit inclination angle $i$ and the satellite phase angle position in the orbit $\Delta\gamma$ as measured from the ascending node are:

$$\gamma = \sin^{-1} (\sin i \sin \Delta\gamma) \tag{2}$$

$$\Delta\varphi = \tan^{-1} (\cos i \tan \Delta\gamma) - \Delta\gamma \tag{3}$$

With small angle approximations for sin $i$ and cos $i$, equations (2) and (3) become:

$$\gamma = i \sin \Delta\gamma \qquad \text{radians} \tag{4}$$

$$\Delta\varphi = -0.25 \, i^2 \sin 2 \, \Delta\gamma \qquad \text{radians} \tag{5}$$

The longitudinal excursions of a satellite in a circular geostationary orbit can be determined from the above equations. Figure 1 shows a plot of the maximum excursions as a function of inclination.
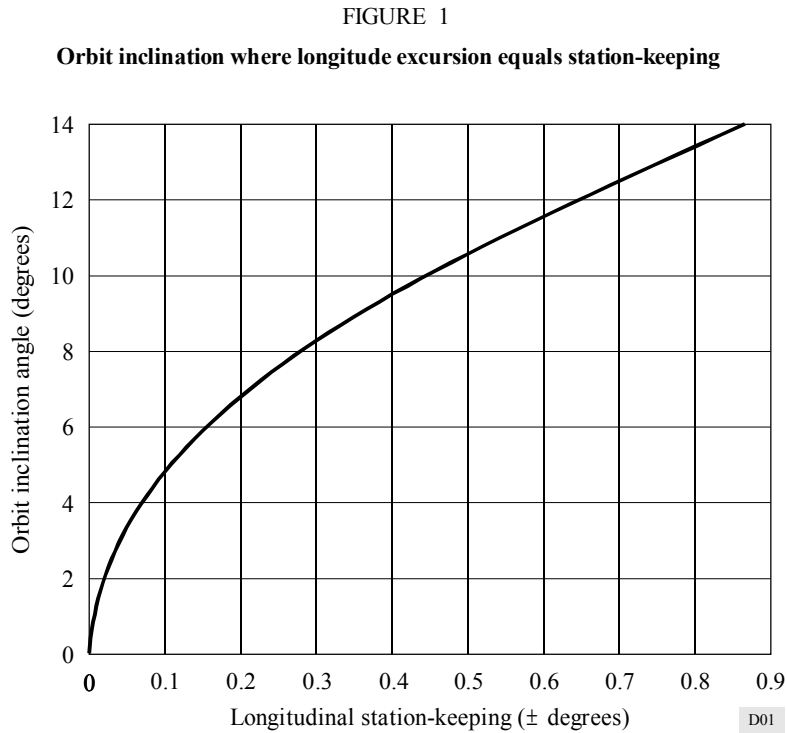
For two satellites having inclinations $i_1$ and $i_2$, designating $\Delta\gamma_0$ as the phase angle difference between the satellite orbit positions ($0 \leq \Delta\gamma_0 \leq 2\pi$) and $\varphi_s$ as the angle between the ascending nodes, the minimum value of the geocentric angular separation $\varphi_g$ may be derived from the preceding equations and is closely approximated by:

$$(\varphi_g)_{min} = 0.5\, i_1\, i_2\, \sin \Delta\gamma_0 + \varphi_s \qquad\qquad \text{radians} \qquad\qquad (6)$$

Equation (6) may be expressed as the ratio of the minimum geocentric angle to the geocentric angle of the nodes:

$$(\varphi_g)_{min}/\varphi_s = 1 + (i_1\, i_2\, \sin \Delta\gamma_0)/2\, \varphi_s \qquad\qquad\qquad (7)$$

where $i_1$, $i_2$ and $\varphi_s$ are small compared to 1 rad.

FIGURE 1

**Orbit inclination where longitude excursion equals station-keeping**



Depending on the phase angle difference between the satellite orbit positions $(\varphi_g)_{min}$ can be less than or greater than $\varphi_s$; i.e. when $\pi \leq \Delta\gamma_0 \leq 2\pi$ or $0 \leq \Delta\gamma_0 \leq \pi$ respectively (see Fig. 2). If either $i_1$ or $i_2$ is zero, then $(\varphi_g)_{min} = \varphi_s$. The worst phase angle difference is $3\pi/2$ and equation (7) for that value is:

$$(\varphi_g)_{min}/\varphi_s = 1 - i_1\, i_2/2\, \varphi_s \qquad\qquad\qquad (8)$$

FIGURE 2

**Inclined circular geostationary orbit geometry**
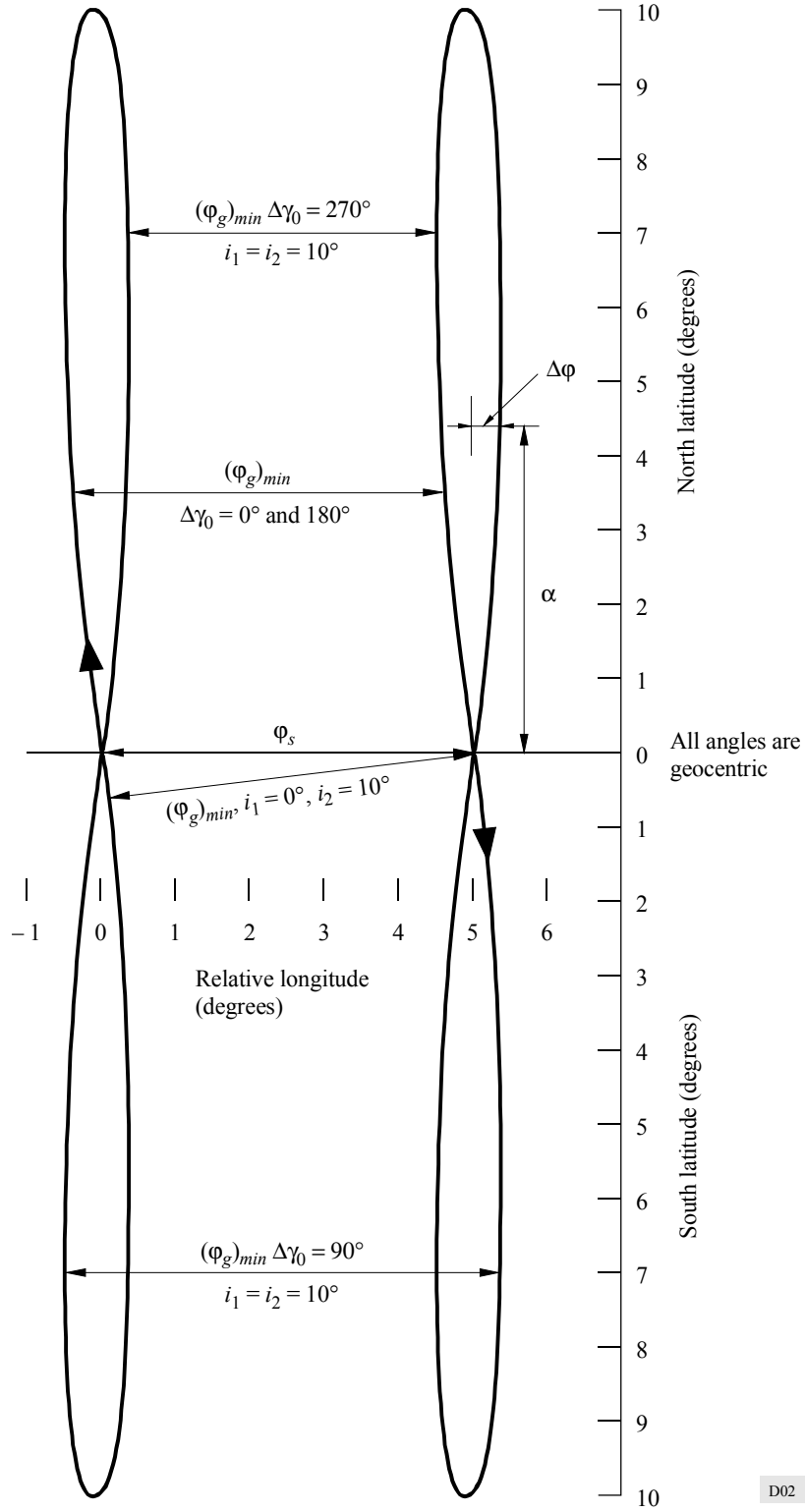
When there is some inclination in the orbit of either of a pair of satellites, the time averaged value of angular spacing is always greater than the nodal spacing $\varphi_s$. The portion of time $T_1$ in which $\varphi_g$ is less than $\varphi_s$ under worst-case phase angle conditions is approximately:

$$T_1 = 0.64\left[(i_1\,i_2\,\varphi_s)/(i_1^2 + i_2^2)\right]^{0.5} \tag{9}$$

When $i_1 = i_2$, $T_1$ varies from 1 h twice daily for a $\varphi_s$ of 2° to about 2.25 h twice daily for a $\varphi_s$ of 10° for equal inclinations and worst-case phase angle. A plot of equation (9) is shown in Fig. 3 for a $\varphi_s$ of 3°.

FIGURE 3

**Percentage of time that satellite spacing is less than nodal spacing**
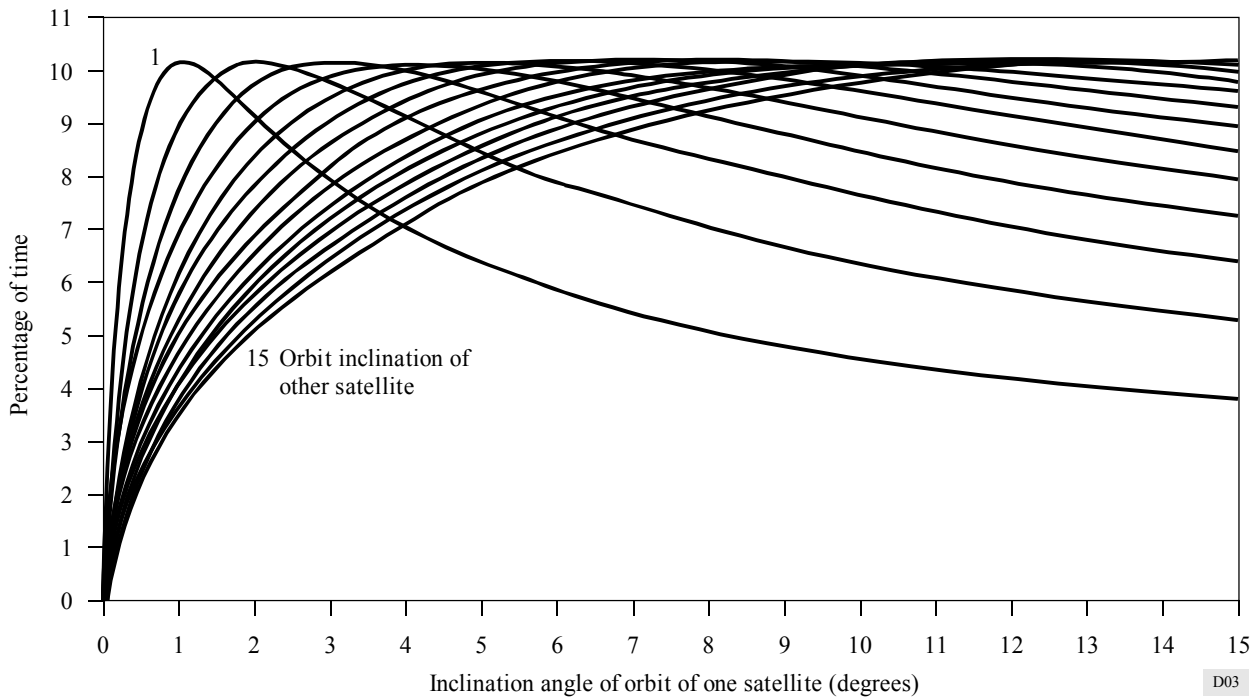
## 3      Co-coverage networks

Under co-coverage conditions, little if any satellite antenna discrimination exists so that only the earth-station antennas provide spatial discrimination. For tracking earth stations, the discrimination is a function of the angular spacing between the satellites. Assuming a $-25 \log(\varphi)$ side-lobe envelope slope, equation (7) may be expressed as:

$$\Delta d \leq 25 \log_{10}\left[1 + \frac{i_1\,i_2\,\sin\Delta\gamma_0}{2\,\varphi_s}\right] \qquad \text{dB} \tag{10}$$

where $\Delta d$ is the change in discrimination (dB) with respect to the earth-station antenna discrimination at a nominal spacing of $\varphi_s$.

Figure 4 shows the antenna discrimination for $i_1 = 7°$ and $i_2 = 9°$ and a nominal satellite spacing $\varphi_s = 1°$.

As shown in Fig. 4, the nodal phase difference appears to be a critical factor determining the relative earth-station antenna discrimination. Depending on the nodal phase difference, relative earth-station discrimination can be larger or smaller than nominal, reaching a minimum at 270° of nodal phase difference. It is important to note that for either $i_1$ or $i_2$ equals zero, the minimum

relative discrimination also becomes zero. Practically, this means that the discrimination between a geostationary-satellite network and a slightly inclined geostationary orbit network will always be larger than or equal to the nominal discrimination which would have been achieved if the two networks were geostationary.

FIGURE 4

**Minimum relative earth-station antenna discrimination**
**versus nodal phase difference for 9° and 7°**
**inclined geostationary orbit satellites**
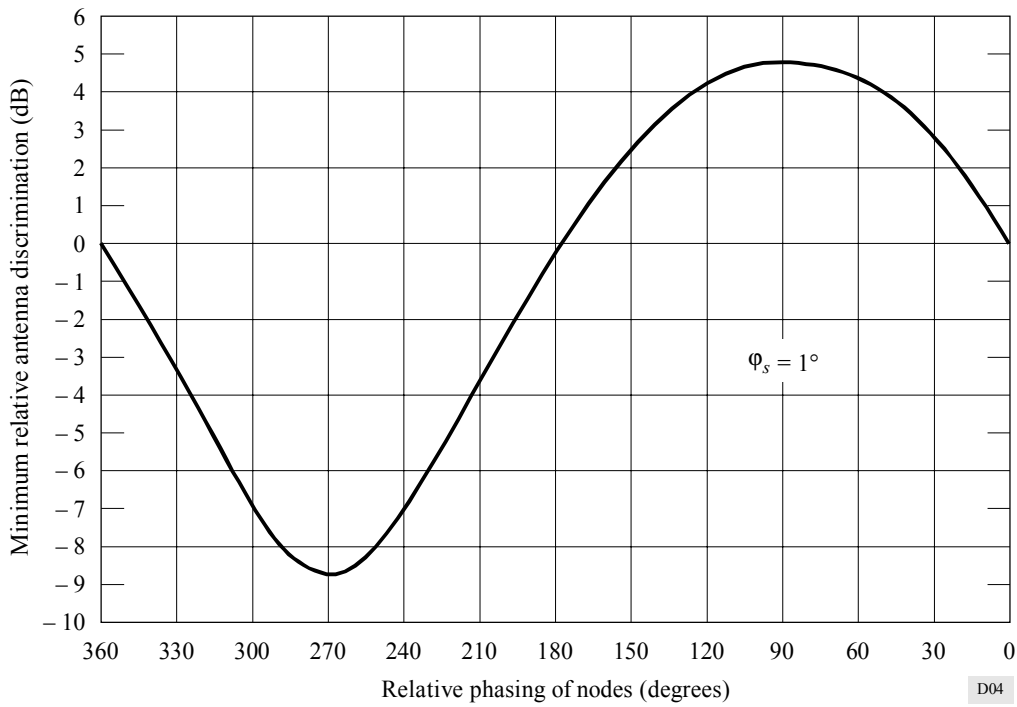
The worst-case discrimination loss (corresponds to the minimum discrimination at 270° nodal phase difference) as a function of inclinations of two satellites spaced 2°, is shown in Fig. 5.
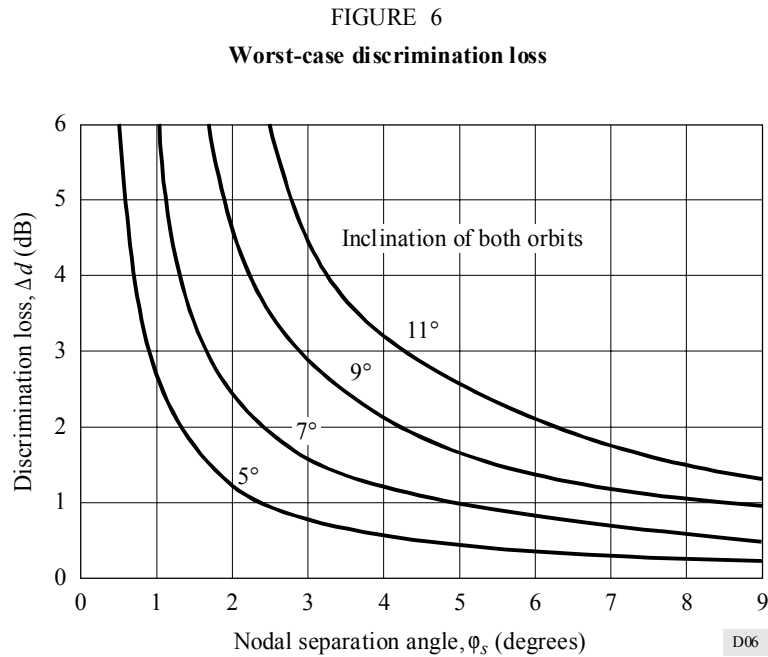
FIGURE 5

**Earth-station discrimination loss (worst case) for two**
**inclined geostationary orbit satellites**
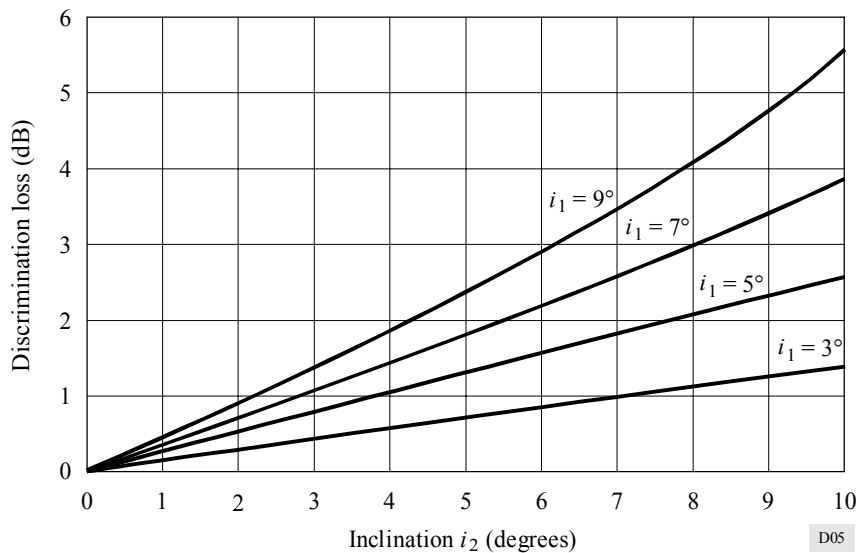
For the very worst case, $i_1 = i_2 = i$ and $\Delta\gamma_0 = 270°$, equation (10) becomes:

$$\Delta d \;\leq\; 25 \log_{10}\left[(1 \;-\; i^2/2\varphi_s)\right] \qquad\qquad \text{dB} \qquad\qquad (11)$$

Plots of this function are shown in Fig. 6 which demonstrates the effects of the satellite nodal spacing $\varphi_s$.

FIGURE  6

**Worst-case discrimination loss**



The probability that the two orbits would have equal inclinations and also the most adverse phase angle should be quite small. It is also to be noted that the value of $\Delta d$ in equation (10) is a peak value and is approached for short periods of time. The portion of time in which the change in discrimination is between 0 dB and $\Delta d$ is determined by equation (9).

For the worst-case discrimination loss to happen it would be necessary that:

–        both (adjacent) satellites be in significantly inclined orbits; and that

–        a nodal phase difference of about 270° exists.

The combination of the two events does not seem likely to occur under normal circumstances when station-kept satellites are left without North-South station-keeping in order to extend their operational life.

If two satellites initiate inclined geostationary orbit operation approximately at the same time (say, in the same year), the phase shift between their orbit's lines of nodes will be negligible because the conical motion of the orbit normals, produced by identical force fields, will be identical. Only if one of the satellites initiates inclined geostationary orbit operation a few years after the other will a

nodal phase difference be appreciable. But in such a case, the satellite which initiated inclined orbit operation later will not have any significant orbit inclination, until additional years of combined operation accumulate. The phase angle difference does not significantly change with time and the change in inclination of two adjacent satellites will be nearly the same. Thus when unfavourable conditions exist, they remain unfavourable until a satellite manoeuvre is made to change the conditions. However, when two adjacent satellites are initially placed in inclined geostationary orbits, the inclinations and phase angle difference can have any value. Therefore, it is of interest to estimate the probabilities associated with $\Delta d$. It is assumed that the inclinations and phase angle difference are statistically independent, that the inclinations have a constant probability density function between 0 and $i_0$, and that the phase angle difference probability density function is constant between 0 and $2\pi$. With these assumptions equation (10) may be expressed as:

$$\overline{\Delta d} \leq 25 \log_{10}\left[(1 + Ki_0^2)/2\varphi_s\right] \qquad \text{dB} \qquad (12)$$

where $\overline{\Delta d}$ is the value of $\Delta d$ which will not be exceeded with a probability $P$, and $K$ is the normalized value obtained from the above assumed probability functions for a given value of $P$. For $P = 90\%$, the value of $K$ is about $-0.3$. For $P$ values of 95% and 99%, the values of $K$ are about $-0.44$ and $-0.78$. For $P = 50\%$, the value of $K$ is zero.

Assuming a satellite nodal spacing of 2° and that both satellites have inclinations of 5°, the worst-case discrimination loss is 1.25 dB as shown in Fig. 5. From equation (12) the maximum value of discrimination loss $\overline{\Delta d}$ is 0.36 dB with a 90% probability. For a 9° inclination, the corresponding discrimination loss is 4.73 dB and the discrimination loss which will not be exceeded with 90% probability is 1.25 dB.

From the preceding equations, values of $\overline{\Delta d}$ can be equated to changes in satellite spacing so that the interference could be equal to, or less, than that with 0° inclinations (1 dB is equivalent to about 0.1 $\varphi_s$) i.e. the spacing could be adjusted. It is also noted that $\overline{\Delta d}$ can also be positive, i.e. that discrimination is increased. If it is assumed that the phase angle $\Delta\gamma$ is a random value among an ensemble of satellites (plus and minus values of $\overline{\Delta d}$ are equally probable) and that nodal spacing changes are made to equate minimum spacings, the net effect would be that an ensemble of satellites would occupy the same orbital arc as would be occupied if all inclinations were 0°.

Thus, it is not evident that the number of orbit node positions in a given orbital arc will be adversely affected by orbit inclinations.

## 4 Non co-coverage networks

The analysis in this case is considerably more complex than in the co-coverage case and thus, a parametric approach used in the co-coverage case is difficult to apply. Therefore, the total discrimination between two satellite systems achieved through the earth station and satellite antenna discriminations was analysed using the following model.

A satellite in the inclined geostationary orbit was assumed to have a circular beam of a certain diameter. The beam was directed towards different points on the Earth and the motion of a point at the edge of the beam, as a consequence of the motion of the satellite in the inclined orbit, was plotted in the satellite coordinates. The impact of the motion of the satellite beam was computed as a change of the satellite antenna gain at a point close to the coverage area. This point was chosen to correspond to point A at the satellite antenna reference pattern in Fig. 7. Nominally, if there was no motion of the satellite antenna, due to the inclination of the satellite orbit, the discrimination achieved at this point, through the satellite antenna, would be 22 dB, referred to the edge of coverage. The point was so chosen to analyse the worst-case situation. The gain variation was expressed relative to this nominal gain. The discrimination between this satellite system and a neighbouring geostationary satellite system achieved through the earth-station antenna operating in the inclined orbit satellite system, was also computed and expressed relative to the discrimination achieved if both systems were geostationary. The total relative net discrimination achieved through the satellite and earth-station antennas was computed as a function of time, for satellite beamwidths of 1.5° and 3°, and for inclinations of 3° and 9°. The satellite beam was directed towards three different areas on the Earth, as shown in Fig. 8.

FIGURE  7

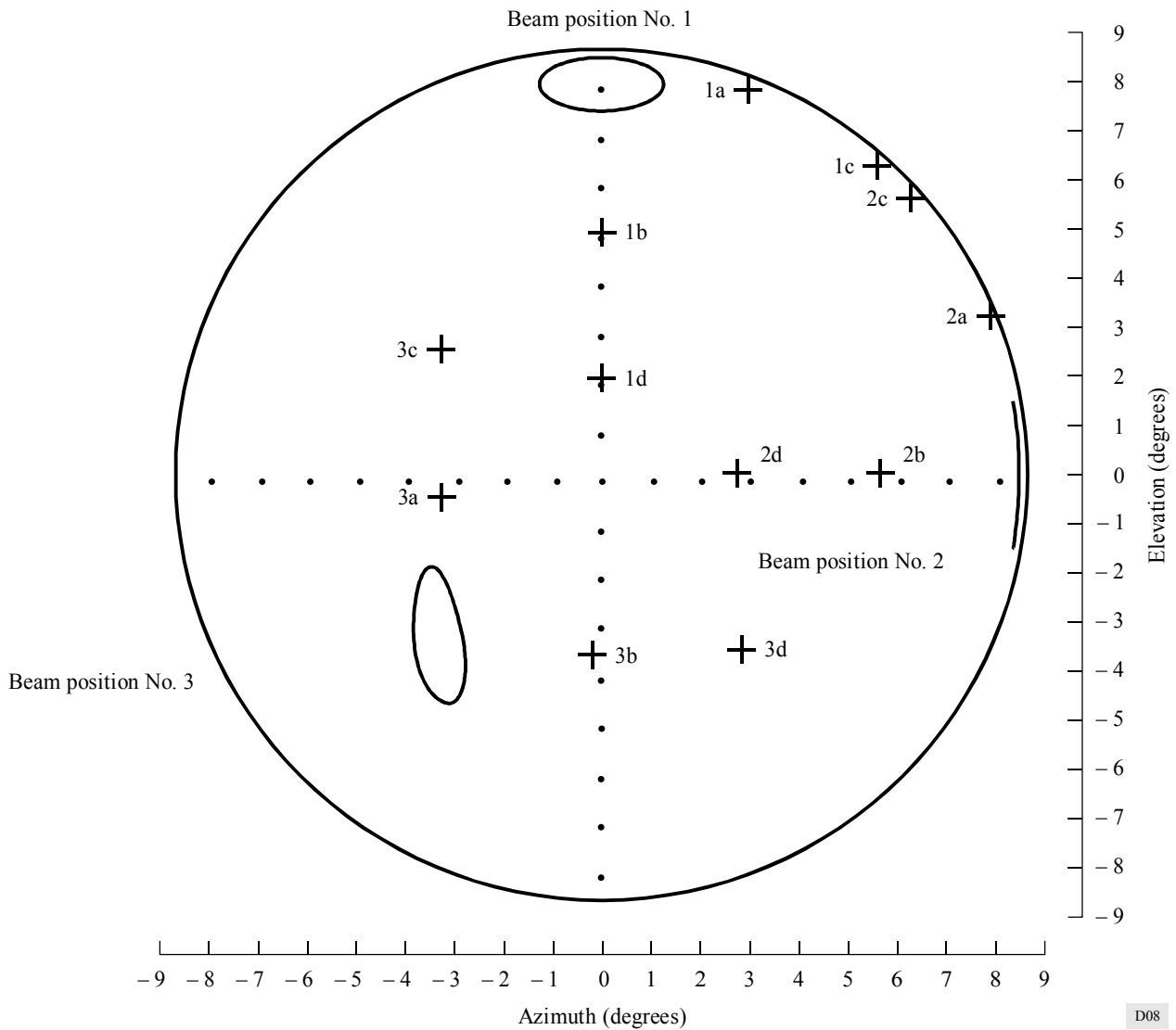**Satellite antenna reference pattern**
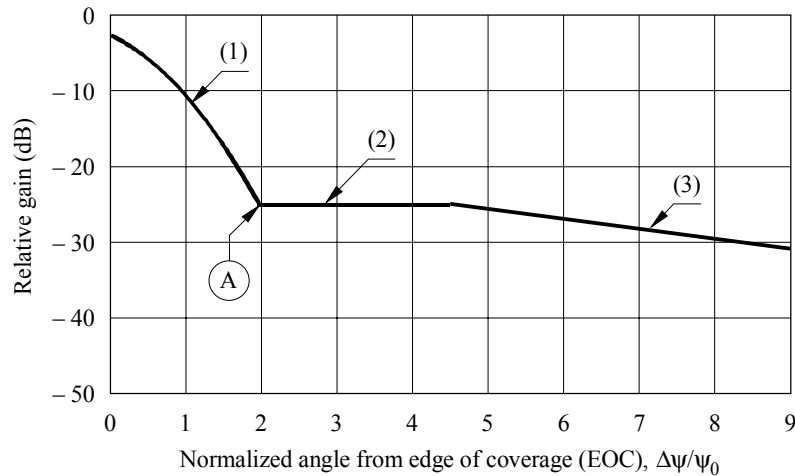


(1)   $G(\Delta\psi) = G_{EOC} - 2.79\ [(1 + \Delta\psi/\psi_0)^2 - 1];$ or
      $G(\Delta\psi) = G_{EOC} - 3.266\ [(0.9(\Delta\psi/\psi_0) + 1)^2 - 1]$    $\Big\}\ 0 \leq (\Delta\psi/\psi_0) \leq 1.98$

(2)   $G(\Delta\psi) = G_{EOC} - 22$ dB; $1.98 < (\Delta\psi/\psi_0) < 4.5$

(3)   $G(\Delta\psi) = G_{EOC} - 22 - K\left(\Delta\psi/\psi_0 - 4.5\right);\ K = 1.2$
      ... until $G(\Delta\psi) = 0$ dBi; equivalent to –6 dB/octave                    D07

FIGURE 8

**The motion of satellite beams at the Earth
(inclination 9°) and check points**



The results in Figs. 9-12 show that the net discrimination between a slightly inclined geostationary orbit satellite network and a geostationary-satellite network is greatly impacted by the relative positions of the coverage areas of the two networks. In some cases (see Fig. 12), the net discrimination is practically always greater than nominally achieved if the two networks were geostationary. These are the cases where the impact of the satellite antenna discrimination is negligible. In some other cases, where the impact of the satellite antenna is significant, there is a loss of the net discrimination (compared to nominal) for a certain period of time during the day. The magnitude of the loss and its duration are functions of the inclination, satellite spacing and the width of the coverage area. However, it should be emphasized that, due to the choice of point A on the satellite antenna pattern (see Fig. 7) the above results represent the "worst case". In many cases, the relative positions of satellite network coverage areas will be such that the motion of the coverage area due to the slightly inclined orbit operation will have a negligible effect on the net discrimination between the two networks. In these cases, the variation of the overall discrimination will be determined by the discrimination of the earth-station antenna, which for this case (one slightly inclined geostationary and one geostationary network) is always equal to or greater than nominal.
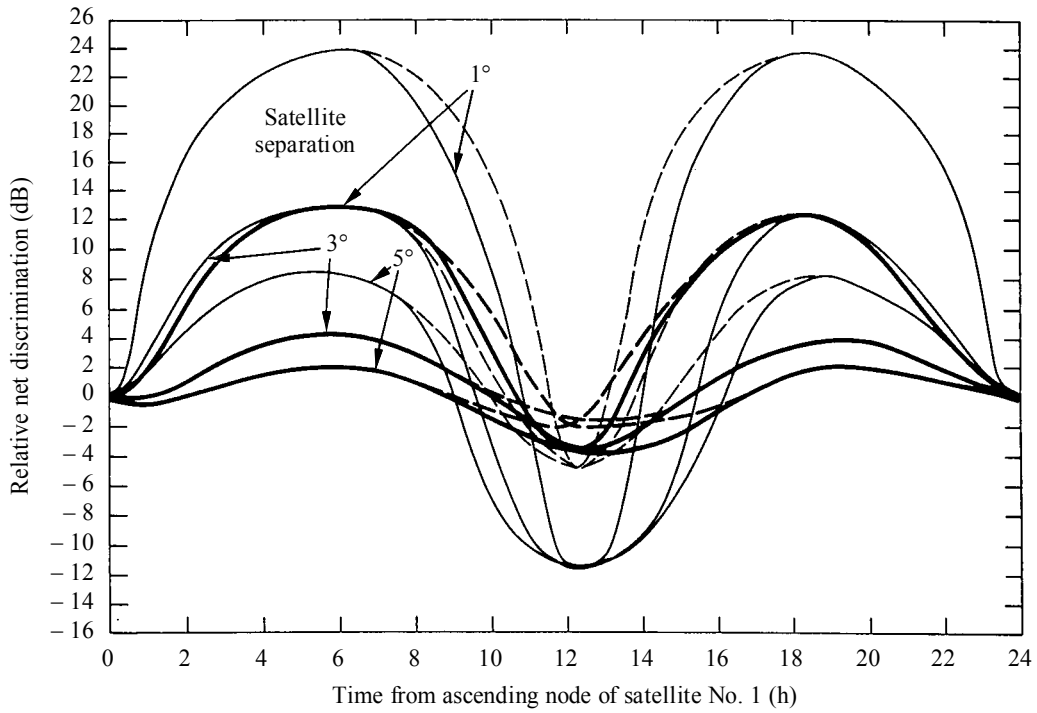
Further studies are needed for the cases involving two slightly inclined geostationary orbit satellite networks.

FIGURE 9

**Relative net discrimination as a function of time**
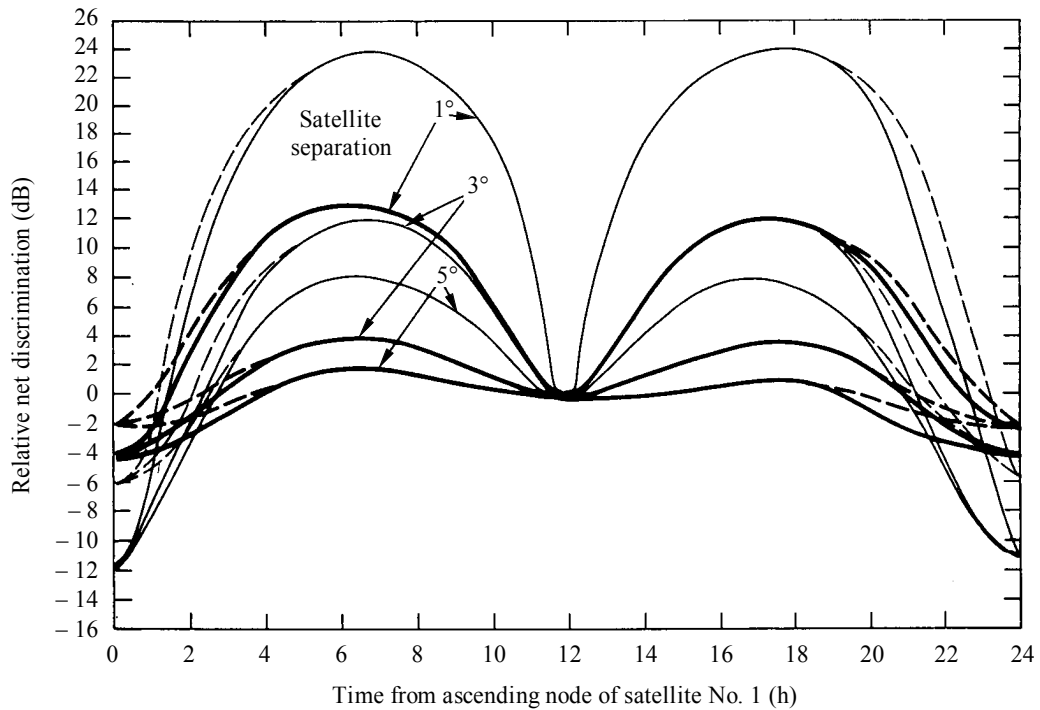


Inclination:                          3° ( ━━━━ ) ;        9° ( ──────── )

Beam position:                     1

Check point:                        1a ⎱ ( ━━━━ ) ;      1c ⎱ ( ▬ ▬ ▬ ▬ ▬ )

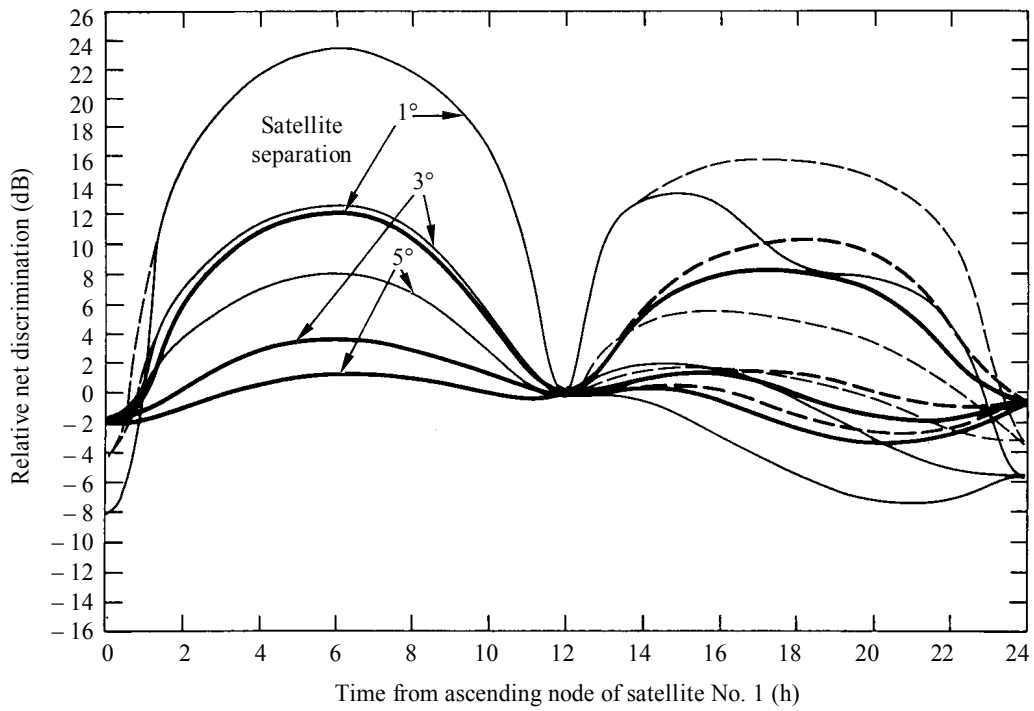Satellite beam diameter: 1.5° ⎰ ( ──────── ) ;  3.0° ⎰ ( ─ ─ ─ ─ ─ )

D09

FIGURE 10

**Relative net discrimination as a function of time**



Inclination:      3° ( ▬▬▬▬ ) ;      9° ( ———— )

Beam position:      2

Check point:      2a } ( ▬▬▬▬ ) ;      2c } ( ▬ ▬ ▬ ▬ )

Satellite beam diameter: 1.5° } ( ———— ) ;      3.0° } ( – – – – – )

D10

FIGURE 11

**Relative net discrimination as a function of time**



Inclination:                    3° ( ——————— ) ;        9° ( ——————— )

Beam position:          3

Check point:          3a ⎫ ( ——————— ) ;   3c ⎫ ( — — — — — )

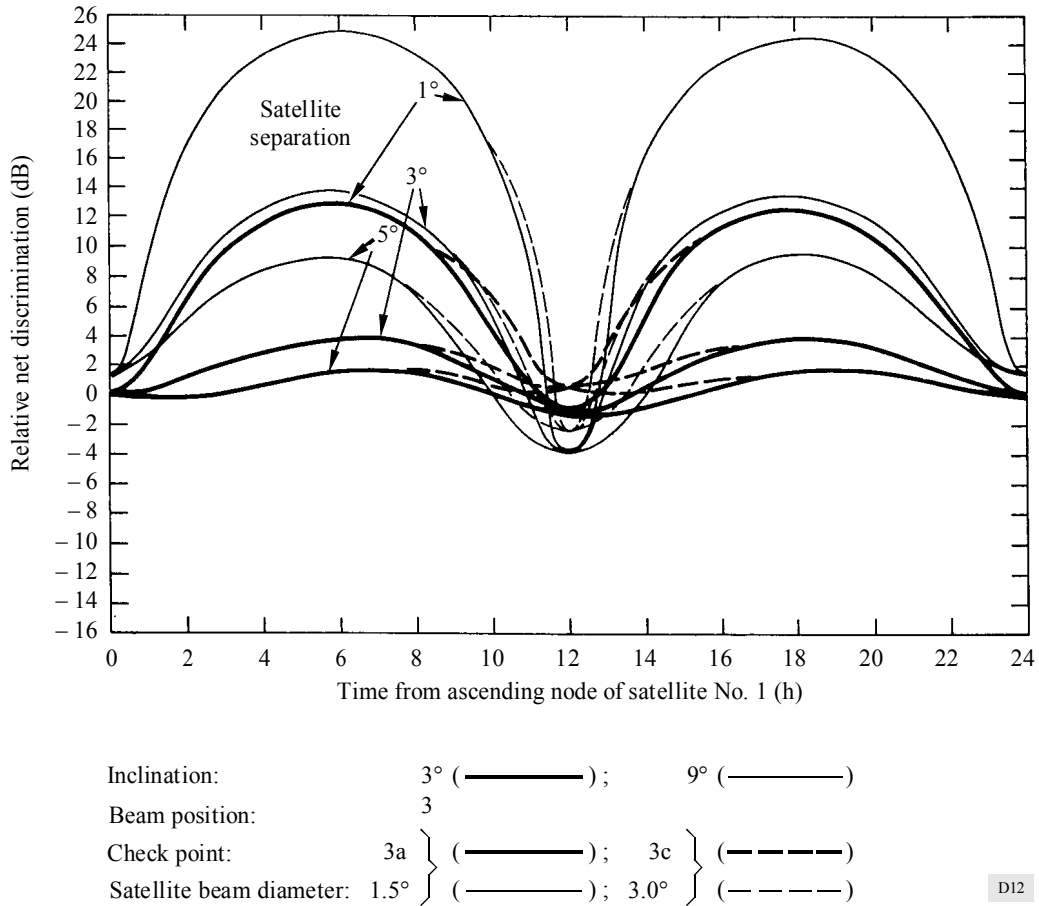Satellite beam diameter: 1.5° ⎭ ( ——————— ) ;   3.0° ⎭ ( – – – – – )

D11

FIGURE 12

**Relative net discrimination as a function of time**



Inclination: 3° ( ———— ) ; 9° ( ———— )

Beam position: 3

Check point: 3a } ( ———— ) ; 3c } ( — — — — )

Satellite beam diameter: 1.5° } ( ———— ) ; 3.0° } ( — — — — )     D12

## 5      Control of nodal phasing

In the previous sections, it was shown that the loss of the earth-station antenna discrimination becomes significant when nodal phase difference between two neighbouring satellites approaches 270°. However, it is possible at moderate cost in station-keeping fuel to prevent the occurrence of worst orbital phasing of two neighbouring satellites through controlling the orbital nodes, a form of second order station-keeping.

Figure 13 shows, in the lower pair of curves, the yearly requirements in terms of orbital velocity changes $\Delta V$ for a satellite subject to tight North-South station-keeping (curve A) and for one subject to maintenance of its orbital node at 90° right ascension (curve B). The velocity changes, which are proportional to the amount of station-keeping fuel needed to produce them, become equal after about 9 years. When considering total cumulative fuel requirements for the two modes of operation, node phasing would require the same amount of fuel as North-South station-keeping only after 16 years (upper curve pair). For a 7 year satellite operation with no North-South station-keeping, the maintenance of a node at 90° right ascension would use only half as much fuel as full North-South station-keeping.

In practice, it will not be necessary to maintain a node at 90° right ascension – what is needed is a node correction which prevents the occurrence of the worst case interference geometry. How much fuel will be required depends, *inter alia*, on the difference in the inclination of the satellites; in favourable situations no node control may be needed even though the satellites of two potentially interfering networks may both be in slightly inclined geostationary orbits.

FIGURE  13

**Yearly (lower curve pair) and cumulative ΔV requirements**
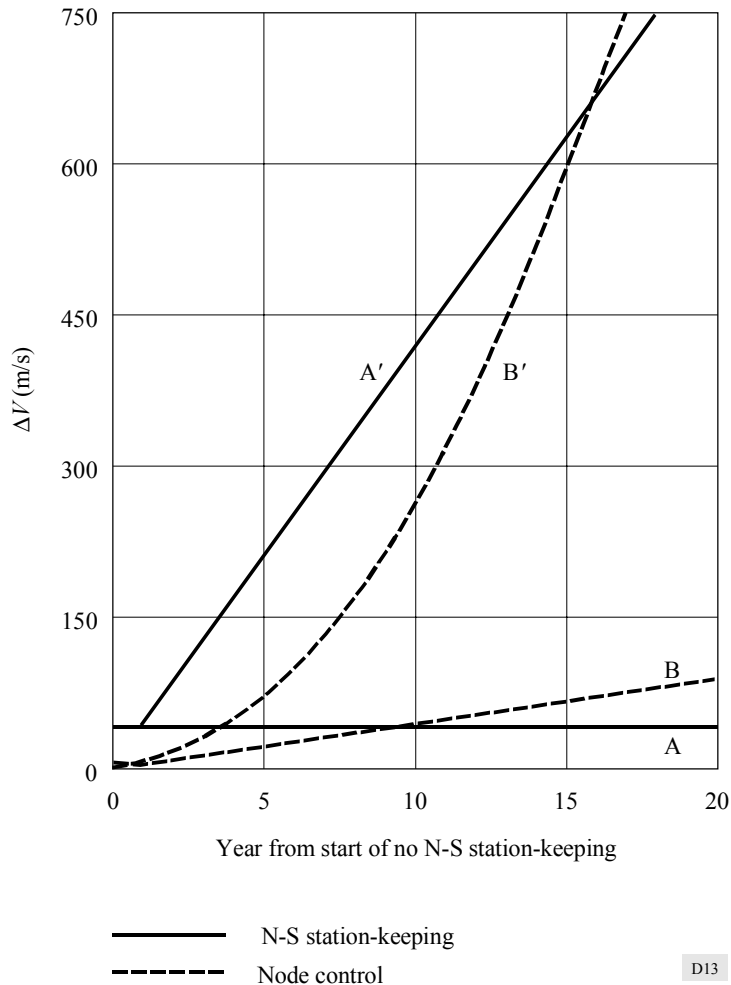


# 6      Coordination considerations

From the previous analyses there appears to be no intrinsic limitation on the coordination of networks using circular slightly inclined geostationary orbits.

In the case of a geostationary network and a network using a slightly inclined geostationary orbit, the isolation between the networks will be equal to or greater than it would be in the case of the two geostationary-satellite networks under co-coverage conditions. Thus, coordination will be the same as if both networks were geostationary.

If both satellite networks use slightly inclined geostationary orbits, some decrease in isolation as compared to the isolation between geostationary-satellite networks might occur under the most unfavourable nodal phasing of the satellites and under co-coverage conditions. However, this can be determined and accounted for in coordination.

Under non co-coverage conditions, satellite antenna discrimination is involved and this adds complexity in terms of estimation of interference effects. These effects can also be determined and accounted for in the coordination process.

However, there is the case where coordination was achieved on the basis of essentially 0° inclination but at some later date the inclination is allowed to increase. It would appear that in most practical cases, the increase in interference would not be significant, i.e. the probability that all conditions are simultaneously present for worst-case interference is considered to be quite small. Hence, in most such cases, there will be no need to re-coordinate a network previously coordinated as geostationary and planning to suspend North-South station-keeping with other geostationary networks.

While, generally, the inclined orbit operation of a network's satellite is supportable on the basis of inter-network coordination agreements that assume the network's satellite to be geostationary, there may be some circumstances where geostationary inter-network coordination agreements provide insufficient protection for inclined geostationary orbit operation. Thus, there is a need to determine the conditions for which geostationary inter-network coordination agreements would not suffice to prevent unacceptable inter-network interference from occurring when one or more networks commence inclined geostationary orbit operation.