RECOMMENDATION ITU-R S.1595

Interference mitigation techniques to facilitate coordination between non-geostationary fixed-satellite service systems in highly elliptical orbit and non-geostationary fixed-satellite service systems in low and medium Earth orbit

(Question ITU-R 231/4)

(2002)

The ITU Radiocommunication Assembly,

considering

a) that in some frequency bands non-geostationary orbit (non-GSO) satellite systems are required to coordinate with other non-GSO satellite systems if there is frequency overlap;

b) that systems using highly elliptical orbits (HEO) have unique features, such as transmitting and receiving only during a long dwell time (normally around the apogee) of a single satellite over specific range of latitude and longitude, stable and predictable service arcs, and few satellites required to provide coverage over an entire hemisphere;

c) that studies have shown, without the use of interference mitigation techniques, it will be impracticable for non-GSO systems to share the same frequencies and meet performance objectives;

d) that studies have shown there are several different interference mitigation techniques that may allow non-GSO systems to share;

e) that the effectiveness of a mitigation technique to decrease interference may be determined by an improvement in several different performance parameters, i.e. C/I, I/N or $C/(I + N)$;

f) that if the clear sky C/N is large, of the order of 25 to 35 dB, typical ranges for allowable I/N values can have a negligible effect on clear sky-link performance, i.e. $C/(N + I)$ obtained with and without mitigation techniques;

g) that, in the situation described in *considering* f), C/I may be a more useful parameter than I/N in evaluating the effectiveness of interference mitigation techniques;

h) that, in situations other than those described in *considering* f), the use of I/N to evaluate the effectiveness of interference mitigation techniques may be more appropriate;

j) that there are some non-GSO systems in operation in the fixed-satellite service (FSS) that have large clear-sky *C*/*N* values on the order of 25 to 35 dB;

k) that Recommendation ITU-R S.1323 provides methodologies for determining maximum permissible levels of interference between non-GSO FSS systems;

l) that the maximum permissible levels of interference discussed in Recommendation ITU-R S.1323 are based on an increase in the unavailability of the victim system/network,

recommends

1 that the mitigation techniques described in Annex 1 of this Recommendation should be considered for use to facilitate coordination between non-GSO FSS systems in HEO and non-GSO FSS systems in low Earth orbit (LEO) and medium Earth orbit (MEO) when coordination is required by No. 9.12 of the Radio Regulations (RR) (see Notes 1 and 2);

2 that non-GSO FSS systems with large clear-sky *C*/*N* requirements, on the order of 25 dB to 35 dB, may use as a starting point to interference assessment, *C*/*I* as a criterion to determine the effectiveness of interference mitigation techniques (see Note 3);

3 that a more thorough assessment of the effectiveness of mitigation techniques should also take into account the methodologies of Recommendation ITU-R S.1323.

NOTE 1 – Annex 2 shows that the mitigation techniques described in Annex 1 can have adverse operational impacts on the systems implementing them (e.g. coverage, capacity, etc.). The severity of these impacts vary with system characteristics.

NOTE 2 – The mitigation techniques of Annex 1 may also be applicable to sharing between non-homogeneous HEO systems. Further study is required to determine this applicability.

NOTE 3 – Other interference criteria may be more appropriate for non-GSO FSS systems with typical clear-sky *C*/*N* requirements.

ANNEX 1

Mitigation techniques

This Annex provides a summary of mitigation techniques that may be used by non-GSO systems to facilitate sharing between non-GSO systems in HEO and non-GSO systems in LEO and MEO. Four techniques for mitigating interference have been identified and studied. This Annex does not represent an exhaustive list of mitigation techniques, others may be identified in the future. These interference mitigation techniques and combinations thereof are useful to different degrees in facilitating sharing between non-GSO systems in HEO and non-GSO systems in LEO and MEO. Finding the optimum mitigation technique(s) to be applied between any two non-GSO FSS systems, one of which is a HEO, may, in some cases, best be able to be accomplished during inter-system coordination. Annex 2 provides an example of the results of simulations using these mitigation techniques.

1 Satellite diversity

An in-line event occurs when one interfering non-GSO satellite is directly between the wanted non-GSO earth station and the wanted non-GSO satellite. Satellite diversity means that in-line events are avoided by the interfering non-GSO system selecting another visible satellite (with available beams) whenever the current satellite approaches an in-line event with a satellite operating in another non-GSO FSS system. To accomplish this technique, an avoidance angle of $X°$ in reference to the victim earth station is utilized. A cone of $X°$ is placed around the link from the victim earth station and the victim satellite assigned to downlink to that earth station. As a satellite from the interfering system enters that cone, the interfering satellite is not allowed to transmit within the cell radius of the victim earth station.

Satellite diversity implies performing a handover (switching) process due to reselecting the satellite for interference avoidance. Satellite diversity may require a complex process involving cooperation among the systems involved. This mitigation technique requires extensive knowledge of the location of both non-GSO systems satellites and inherently reduces the service capacity of the mitigating satellite system.

To use satellite diversity as an interference mitigation technique, it is necessary for the interfering non-GSO FSS system to be designed to have a sufficient number of satellites with enough beams per satellite capable of serving a given earth station location simultaneously. Not all non-GSO systems meet these criteria.

2 Satellite selection strategies

The algorithm chosen for satellite selection by a given non-GSO FSS system may enhance the ability of that system to share with other non-GSO FSS systems. In general, earth stations will communicate with the satellite that is at the highest elevation. If a system chooses to use a different tracking technique, such as selecting the satellite that has the largest angular discrimination with respect to the satellites of other non-GSO FSS systems, the sharing situation may improve with the expense of added complexity and/or reduced capacity in system operation. This mitigation technique requires extensive knowledge of the location of both satellite systems.

3 Earth station site diversity

In some cases, it may be possible to use earth station site diversity as a mitigation technique. This technique involves separating the earth stations so that when an in-line event occurs the interfering satellite is not pointed toward the victim earth station but is pointed toward another earth station further away. This ensures that there is no main beam-to-main beam interference, rather it is side lobe to main beam interference thus reducing the amount of interference. The fewer earth stations involved the more practical this becomes. This mitigation technique reduces the number of earth stations a non-GSO system could use and restricts the location of those earth stations. Therefore the capacity on the ground and the ability to serve certain areas are reduced but not necessarily the capacity on the satellite.

4 HEO apogee avoidance

HEO apogee avoidance uses a concept similar to the GSO arc avoidance technique proposed by several non-GSO systems which intend to operate in the bands 17.8-18.6 GHz and 19.7-20.2 GHz where protection of the GSO networks by non-GSO systems is required by RR Article 22. This concept uses the fact that an HEO apogee service arc can be defined based on the fact that many HEO systems use an inclination of approximately 63° and an argument of perigee of 270° or 90°. Many HEO systems employ this common inclination because for inclined elliptical orbits the argument of perigee changes due to the non-uniform gravitational pull of the Earth. Lunar and solar gravitation are secondary causes for movement in the argument of perigee. For an HEO type orbit it is necessary to keep the argument of perigee stable so that the operational portion of the orbit (or where the satellite dwells the longest) is consistently in the same place above the Earth. The formula for rate of change of the argument of perigee is:

$$\dot{\omega} = \frac{4.982}{(1-e^2)^2}\left(\frac{R_e}{a}\right)^{3.5}(5\cos^2 i - 1) \qquad \text{degrees/day}$$

where:

$\dot{\omega}$: rate of change of the argument of perigee

e: eccentricity of the orbit

R_e: radius of the Earth

a: semi-major axis of the orbit

i: inclination of the orbit.

When the inclination of the orbit is equal to 63.4° or 116.6° the argument of perigee remains constant since at these angles $\cos^2 i = 1/5$ and $\dot{\omega}$ is zero. Therefore, for any satellite orbit semi-major axis and eccentricity, if the inclination is 63.4°, then the argument of perigee (and therefore the apogee service arc) is constant and well defined. A northern HEO apogee service arc is defined when the argument of perigee for the HEO orbit is 270°. A southern HEO apogee service arc is created when the argument of perigee for the HEO orbits is 90°.

If the HEO system has known earth station locations then the beams on the LEO or MEO satellite could be directed away from those earth stations when the LEO or MEO satellite is within the HEO apogee service arc. If the HEO systems has ubiquitous earth stations then the LEO or MEO satellite would have to direct the beams away from all earth station locations for which there might be an in-line event when the LEO or MEO satellite is in the HEO apogee service arc. This redirection of beams would then avoid in-line conjunction, and thus reduce the interference to acceptable levels between the two non-GSO satellites without having to have extensive knowledge of the location of the HEO satellites. This mitigation technique inherently reduces the service capacity for the mitigating satellite system. Redirecting the beams away from several known earth station locations would have less impact on the interfering systems satellite coverage capability than redirecting the beams away from all of the possible earth station locations with the ubiquitous case.

ANNEX 2

Results from simulations using mitigation techniques

1 System characteristics

The dynamic simulations of this study were performed using data provided in RR Appendix 4 coordination information, Recommendation ITU-R S.1328 and through other contributions to ITU-R. Five systems are characterized by the information found in Table 1: two LEO systems, two MEO systems and one HEO system. For all systems, the satellite selection strategy for nominal operations is assumed to be highest elevation angle, unless otherwise stated for a mitigation technique. The USCSID-P system is modelled such that the satellites do not transmit to any earth station when the subsatellite latitude of the HEO satellite is below 35° in order to protect the GSO arc. This GSO avoidance technique is a typical HEO operational characteristic and is not intended to reflect the actual characteristics of USCSID-P.

The earth station locations of each system were modelled as concentric circles around a co-located earth station with the victim non-GSO system. The distance between earth stations was based on the beamwidth of the satellite downlink such that the non-GSO system would not cause self interference. For the HEO system only one earth station was modelled because the earth stations for this system are very far apart and multiple earth stations would not have any cumulative effect on the results of the simulations.

TABLE 1

System characteristics

Characteristic	USCSID-P	LEOSAT-1	LEOSAT-2	USAMEO-2	USAMEO-3
Number of satellites	8	288	63	15	20
Number of planes	8	12	7	3	4
Number of satellites per plane	1	24	9	5	5
Plane spacing (degrees)	45	15.36	51.43	120	90
Inclination (degrees)	63	84.7	48	50	55
Orbit altitude (km)	Apogee = 39 400 Perigee = 1 000	1 375	1 400	10 355	10 352
Inter-plane phasing (degrees)	$45^*(j-1)$ $j = 1, 3, 5, 7$ $45^*(j+1)$ $j = 2, 4, 6, 8$	Random	28,57	24	0
Minimum earth station elevation angle (degrees)	3	40	16	25	30
Downlink transmission parameters					
Carrier bandwidth (MHz)	3 200	500	35	222	133.47
Power control	No	No	Yes	No	No
Earth station receive peak gain (dB)	70 and 59.5	34.1	34.2	51.7	35.9
Earth station receive antenna pattern	Rec. ITU-R S.1428	Rec. ITU-R S.1428	Rec. ITU-R S.1428	Rec. ITU-R S.1428	Rec. ITU-R S.1428
Earth station receive antenna diameter (m)	20 and 6	0.3	0.35	2.2	0.36
Earth station receive noise temperature (K)	255	288	678.4	259.6	192
Satellite transmit peak gain (dB)	51	34.7 to 35.7	34.3	41.28	44.6
Satellite transmit antenna pattern	Rec. ITU-R S.672	–0.5 edge of coverage, –25 near side lobe, –30 far side lobe	Rec. ITU-R S.672 $L_N = -25$ dB	Rec. ITU-R S.672 $L_N = -25$ dB	Rec. ITU-R S.672 $L_N = -25$ dB
Satellite transmit e.i.r.p. (dBW)	70	53.9	37.22	42.5	60.34
Number of co-frequency co-polarized transmit beams	1	8	260	24	20
Number of earth stations modelled	1	91	91	91	91

2 Analysis

Simulations were run to determine the effectiveness of the different mitigation techniques and to understand the impact of these mitigation techniques on the individual systems analysed. Interference, in the form of *C*/*I*, is compared to a given threshold. For these simulations the threshold was set arbitrarily at *C*/*I* = 20 dB. For a large clear sky *C*/*N* such as 35 dB, rain could lower the *C*/*N* to approximately 20 dB. The effect of rain includes signal attenuation, an increase in the earth station receiver noise temperature, and (if dual polarization) an increase in cross-polarization interference. A *C*/*N* of 20 dB combined with *C*/*I* of 20 dB gives a *C*/(*N* + *I*) of 17 dB, which is considered sufficient for link performance in this study. The *C*/*I* threshold chosen does not reflect the actual *C*/*I* threshold of any of the systems modelled and could be refined using the criterion specified in Recommendation ITU-R S.1323 (10% aggregate reduction in unavailability). Additionally, the joint probability of fading and interference should be considered. However, for this analysis, interference is considered acceptable if the resulting *C*/*I* value equals or exceeds 20 dB.

The impact of a given mitigation technique is measured by the decrease in the number of satellites in the mitigating system available to service a given area. Another type of impact, which is not included in this study, is the increase in the amount and complexity of switching required in implementing the mitigation techniques. However, it should be noted that the HEO system modelled is not designed for complex switching. The satellites of USCSID-P have only a single beam and although the mitigation technique of satellite diversity is modelled in these simulations, USCSID-P is not capable of performing the switching required to implement this mitigation technique.

The simulations were run for 100 days at 0.5 s intervals. The scenarios modelled examined interference into USCSID-P small and large earth station antennas from LEOSAT-1, LEOSAT-2, USAMEO-2, and USAMEO-3. Interference from USCSID-P into the LEO and MEO systems was also examined. The following are some additional assumptions used in the simulations:

– A satellite selection strategy of highest elevation angle criteria was used at each non-GSO earth station to select a non-GSO satellite for nominal operations.

– If the satellite at the highest elevation angle was not available due to mitigation techniques or all the beams were servicing other earth stations then the next highest satellite was chosen.

– If no satellites were available for the interfering system due to mitigation techniques or all beams were servicing other earth stations (i.e. there was no interference event), the *C*/*I* was set to a large number so that the statistics were not skewed.

– The sample LEO and MEO systems plan to have ubiquitously deployed earth stations. This was modelled by placing a grid of earth stations around the central LEO/MEO earth station, which was co-located with a single HEO earth station.

– The LEO and MEO earth stations were spaced in a grid around the HEO earth station. The cell size and the distance required for frequency reuse are what determined the distance between the LEO and MEO earth stations. The earth stations were aligned in concentric circles centred at the HEO earth station.

– Only one non-GSO satellite beam was able to transmit to one non-GSO cell.

Four mitigation techniques were modelled in this study: satellite diversity, earth station site diversity, satellite selection criteria and HEO apogee avoidance. All of the mitigation techniques were examined with the LEO and MEO protecting the HEO and the HEO protecting the LEO and MEO, except for HEO apogee avoidance. HEO apogee avoidance technique, with respect to the HEO protecting the LEO and MEO, was examined in the sense that if the LEO or MEO system uses HEO apogee avoidance what are the benefits to them regarding interference from the HEO.

2.1 Satellite diversity

Satellite diversity is a mitigation technique that is not generally available for use by satellite systems that utilize HEOs, as most such systems are not designed to have multiple satellites with multiple beams per satellite capable of simultaneously serving a given earth station location. Even so, there is nothing inherent in the definition of a HEO or any orbit that precludes the use of satellite diversity.

Table 2 lists the characteristics of several HEO systems. Upon examining this Table, note that the operating portion of most of these orbits is quite small. The systems are designed such that as one satellite is leaving the operational portion of the orbit, another satellite is entering. Generally these systems operate on the assumption that only one satellite is in the defined operational window for the major portion of time.

Dual satellite coverage for an HEO orbit is generally not required in order to provide continuous coverage. A constellation, implementing HEO orbits, designed to have many satellites visible or accessible to an earth station for more than a short period of time would depart from the natural characteristics of the HEO orbit. Therefore, satellite diversity does not seem to be the optimum mitigation technique for HEO systems because this would require HEO systems to be designed to work with a larger operational window, decreased minimum elevation angle, more complex earth stations and to add additional satellites to the constellations. The use of a larger operational window could increase interference to GSO satellites. A decrease in minimum elevation angle would increase the complexity of the earth station tracking. Adding satellites to the constellation would increase cost and complexity. It should be noted that, these impacts are generally applicable to any non-GSO system. However, these measures could increase the possibility to coordinate with other non-GSO systems.

To develop the proper avoidance angle as illustrated in Fig. 1, several simulations were run to determine the most appropriate avoidance angle to just allow the *C*/*I* threshold to be met. Satellite diversity takes advantage of the antenna gain discrimination that an earth station antenna can provide.

TABLE 2

Orbital parameters of HEO systems

System	1	2	3	4	5	6
Apogee altitude (km)	35 970	44 640.5	Approximately 39 000	35 800	52 700	40 000
Perigee altitude (km)	4 500	26 931.5	500	35 800	18 900	31 600
Eccentricity	0.59	0.21	0.74	0 (circular)	0.4	0.1
Orbital period	Approximately 12 h	23 h 56 min	11.97 h	23 h 56 min	23 h 56 min	23 h 56 min
Orbital inclination (degrees)	50	42.5	63.43	63.4	60	40
Operating portion of orbit	4 h before apogee to 4 h after apogee	4.5 h before apogee to 3.5 h after apogee	3.5 h around apogee	(See Note 1)	4 h	6 h
Number of satellites in constellation	3 or 4	3 or 4	7	(See Note 1)	6	4

TABLE 2 (*continued*)

System	7	8	9	10	11	12
Apogee altitude (km)	50 400	52 400	20 180	34 800	39 300	27 470
Perigee altitude (km)	21 200	19 200	20 180	20 600	1 075	310
Eccentricity	0.347	0.393	0	0.55	0.72	0.67
Orbital period	23 h 56 min	23 h 56 min	Approximately 12 h	Approximately 12 h	Approximately 12 h	Approximately 8 h
Orbital inclination (degrees)	63.4	63.4	63.4	45	63.4	45
Operating portion of orbit	6 h	4 h	2 h	8 h	6 h	4 h
Number of satellites in constellation	4	6	12	3	4	6

TABLE 2 (*end*)

System	Quasi-GSO 31 (Rec. ITU-R S.1328-2, Table 1, p. 8)	USAKU-H1 (Rec. ITU-R S.1328-2, Table 24, p. 36)	Tanya (Rec. ITU-R S.1328-2, Table 25, p. 37)	USAKU-H2 (Rec. ITU-R S.1328-2, Annex 13, § 3, p. 59)	LEO E[(1)] (Rec. ITU-R S.1328-2, Table 1, p. 2)
Apogee altitude (km)	40 000	41 449	41 449	27 288.3	7 846
Perigee altitude (km)	1 000	4 100	4 100	517.4	520
Eccentricity	0.73	0.64	0.64	0.66	0.35
Orbital period	12 h	14 h	14 h	8 h	3 h
Orbital inclination (degrees)	63	63.4	63.4	63.435	116.6
Operating portion of orbit	NA[(2)]	NA[(2)]	NA[(2)]	Satellite latitude above 45°	NA[(2)]
Number of satellites in constellation	8	12	4	15	10

(1) The LEO E system is a mobile-satellite service system that operates feeder links.

(2) "NA" denotes that the information is not presently available.

NOTE 1 – For the orbit described for systems 4, 5, 6, 7 and 8, the following table gives the operating portion of the orbit and corresponding number of satellites in the constellation:

Operating portion of orbit	4 h	8 h	6 h	4 h 48 min	3 h 26 min	3 h
Number of satellites in constellation	6	3	4	5	7	8

FIGURE 1

Description of avoidance angle mitigation technique

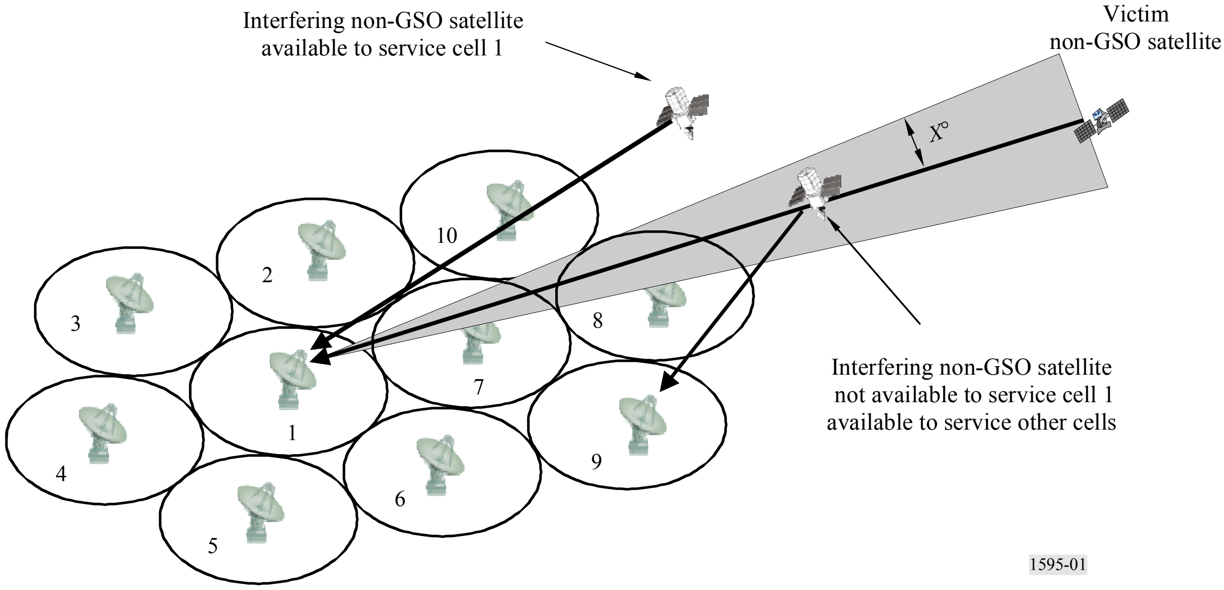


Table 3 lists the angles used for these simulations. Listed in the first half of Table 3 are the angles that are required to reduce interference into USCSID-P. Analyses were run for investigating the interference into the large and the small earth station antennas of USCSID-P. The avoidance angle in this Table represents the larger of the two angles or the avoidance angle required to sufficiently reduce the interference to meet the 20 dB threshold for both the large and small earth station receive antennas. The second half of Table 3 indicates the avoidance angles required for USCSID-P to just allow the *C*/*I* threshold to be met for the LEO and MEO systems. It should be noted that USCSID-P has only one beam per satellite and was not designed to perform complicated switching algorithms. The simulations indicate that this mitigation technique can work if the HEO system is designed to perform this type of switching, however, USCSID-P is not designed in this manner.

TABLE 3

Avoidance angles

Mitigating about USCSID-P

Mitigating system	Avoidance angle (degrees)
LEOSAT-1	18.0
LEOSAT-2	12.0
USAMEO-2	0.1
USAMEO-3	2.8

USCSID-P as mitigating system

System mitigated about	Avoidance angle (degrees)
LEOSAT-1	2.7
LEOSAT-2	3.3
USAMEO-2	1.7
USAMEO-3	2.6

As seen in Table 3, the avoidance angles for the LEO systems avoiding the HEO system are much larger than the same angles for the MEO system.

This technique will inherently reduce the capacity of the mitigating non-GSO system and requires knowledge of the orbital location of both non-GSO systems' satellites. For this analysis the amount of reduced capacity is characterized by the reduction in the number of satellites available to service a given location on the Earth.

2.2 Earth station site diversity

The second mitigation technique examined was earth station site diversity. This technique involves separating the earth stations so that when the satellites are in an in-line geometry the interfering satellite is not pointed toward the victim earth station but is pointed toward another earth station further away. This ensures that there is no main beam-to-main beam interference, rather it is side lobe to main beam interference thus reducing the amount of interference. Earth station site diversity takes advantage of the antenna gain discrimination that a satellite antenna can provide. The fewer earth stations involved the more practical this becomes. This mitigation technique reduces the number of earth stations a non-GSO system could use and restricts the location of those earth stations. This technique was modelled in the simulation by removing earth stations from the grid of earth stations for the LEO and MEO constellations, an example can be seen in Fig. 2. The number of earth stations to remove, or the distance between the interfering and victim earth stations, was determined by running several test simulations until the appropriate distance was determined to just allow the *C*/*I* threshold to be met. Table 4 indicates the number of earth stations removed for each case and the results of those removals.

FIGURE 2

Description of earth station diversity mitigation technique

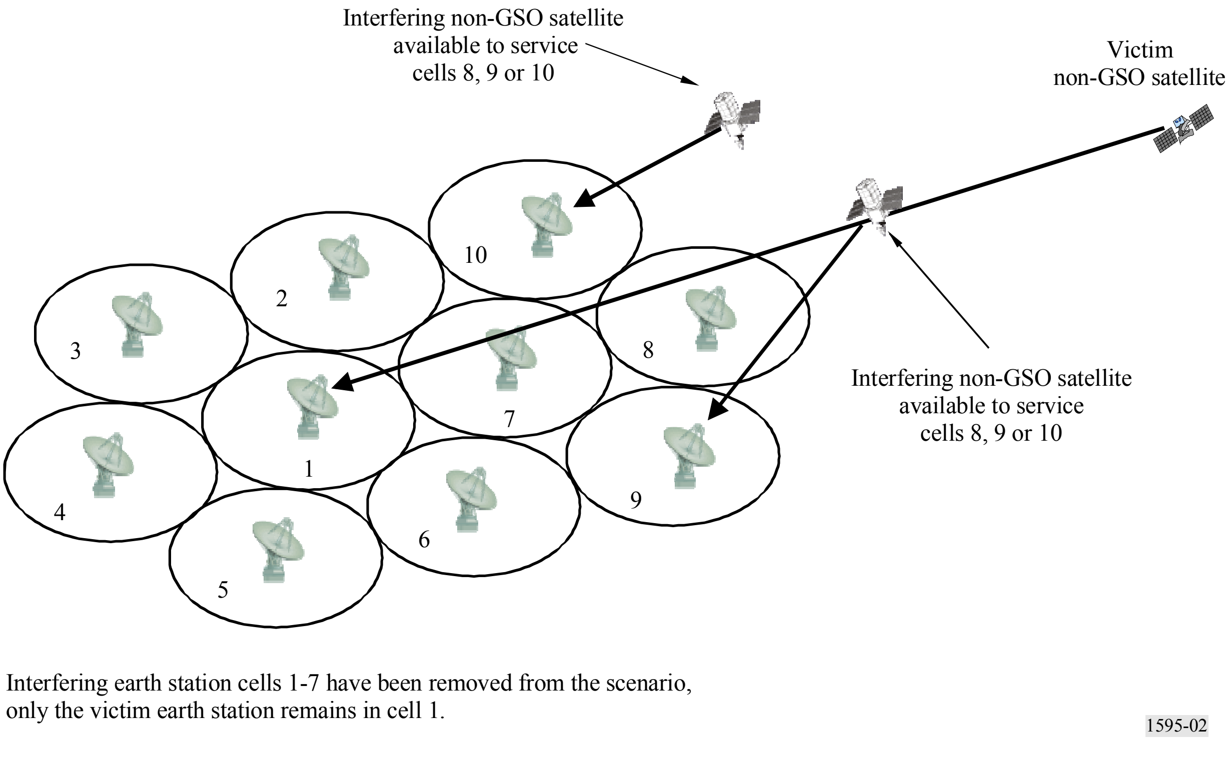


TABLE 4

Earth station separation

Mitigating about USCSID-P

Mitigating system	Number of earth stations	Results
LEOSAT-1	Co-located plus 4 rings	Improvement, did not meet 20 dB
LEOSAT-2	Co-located plus 3 rings	Met 20 dB
USAMEO-2	Co-located	Met 20 dB
USAMEO-3	Co-located plus 4 rings	Improvement, did not meet 20 dB

USCSID-P as mitigating system

System mitigated about	Number of earth stations	Results
LEOSAT-1	Co-located plus 1 ring	Met 20 dB
LEOSAT-2	Co-located plus 1 ring	Met 20 dB
USAMEO-2	Co-located plus 3 rings	Met 20 dB
USAMEO-3	Co-located plus 1 ring	Met 20 dB

The impact of this mitigation technique is not necessarily on the usable capacity of the satellites. Rather this technique limits the number of earth stations that a given non-GSO may serve in a given area and also restricts the locations of those earth stations. This technique also requires knowledge of all possible locations of the victim earth stations.

2.3 Satellite selection strategy

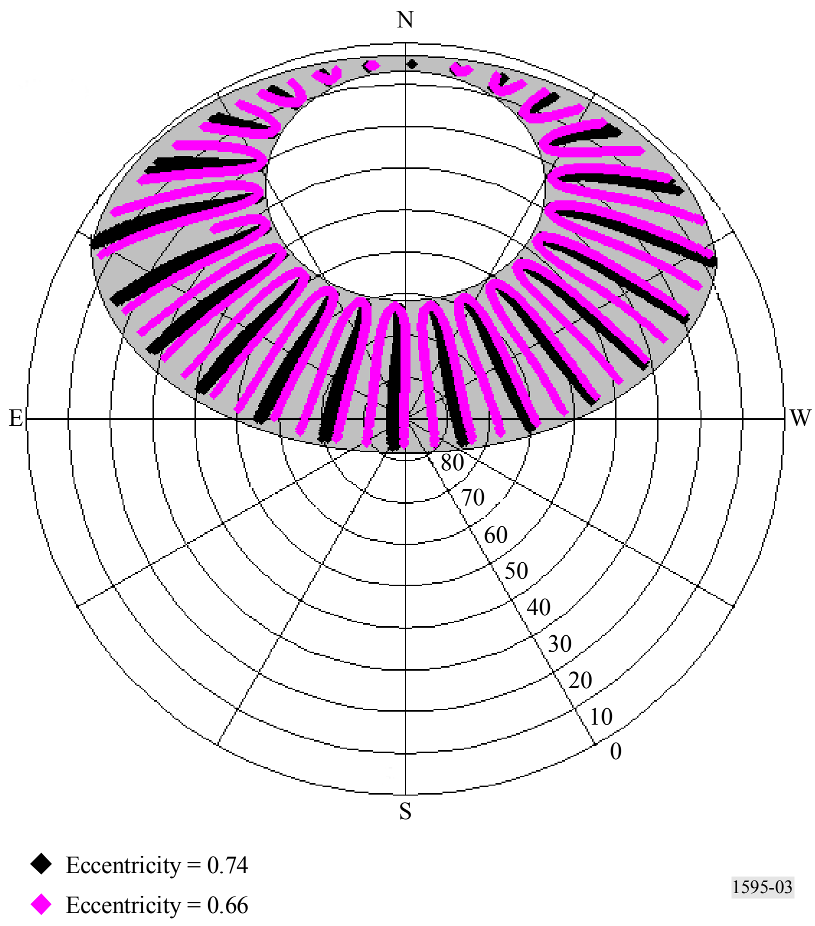
The third mitigation technique modelled for this analysis was an alternate satellite selection. In general earth stations will select a satellite based on the highest elevation angle. This mitigation technique hopes to improve interference based on a strategy in which the earth stations will select the satellite that has the largest angular discrimination with respect to the satellites of the other non-GSO system. This technique also requires knowledge of the orbital location of both the non-GSO systems satellites. Although this technique does not reduce the number of satellites visible, the amount of switching required could increase and the quality of service may be degraded due to utilizing links at a lower elevation angle more often. Utilizing links at a lower elevation angle might also reduce the separation angle to the GSO arc but not below the minimum separation as defined for each system.

2.4 HEO apogee avoidance

Simulations were run using an argument of perigee at 270°, an earth station at 40° latitude and two different HEO arc service scenarios. The first scenario, shown in Fig. 3, shows an HEO operating when the sub-satellite latitude is above 35°. The percentage of the sky that is occupied by the HEO satellites is approximately 32%. The second scenario reduces the HEO service arc to ±3 h from apogee, therefore reducing the service arc significantly. The percentage of the sky that is occupied by the HEO in this scenario is 16%. These service scenarios represent typical operations of some, but not all, HEO satellite systems.

FIGURE 3

Azimuth and elevation to the HEO apogee service arc from 40° latitude (12 h orbit)
(HEO satellite transmits only when sub-satellite latitude is greater than 35°)



For all cases, interference into the HEO system was reduced below the target threshold when the LEO and MEO systems avoid the HEO apogee service arc was defined as the grey portion of the sky trace as depicted in Fig. 3. When the LEO and MEO systems use this technique there is also benefit to them with decreased interference from the HEO system. Although in most cases the interference from the HEO system into the LEO and MEO systems did not reach the target threshold, it was significantly decreased.

This technique inherently reduces the capacity of the interfering non-GSO system but does not require knowledge of the orbital location of the victim HEO systems' satellites. For this analysis the amount of reduced capacity is characterized by the reduction in the number of satellites available to service a given location on the Earth.

3 Results

The *C*/*I* cumulative distribution function (CDF) plots for the simulation of each of the LEO and MEO systems into the HEO system with and without mitigation techniques are presented in Figs. 4 to 11. Figures 12 to 15 present the CDF plots for the simulation of the HEO system into each of the LEO and MEO systems with and without mitigation techniques. Figures 16 to 20 present statistics on the number of satellites available to an earth station at 40° latitude when the interfering system operates in a nominal mode with no mitigation, when the interfering system operates using satellite diversity (angular discrimination) mitigation about the wanted non-GSO system, and when the interfering system is using both of the HEO avoidance scenarios. No statistics on the number of satellites available are necessary for earth station separation mitigation technique or the alternate satellite selection mitigation technique since these options do not affect the number of satellites that are available for use.

FIGURE 4

CDF of LEOSAT-1 *C*/*I* into USCSID-P large antenna

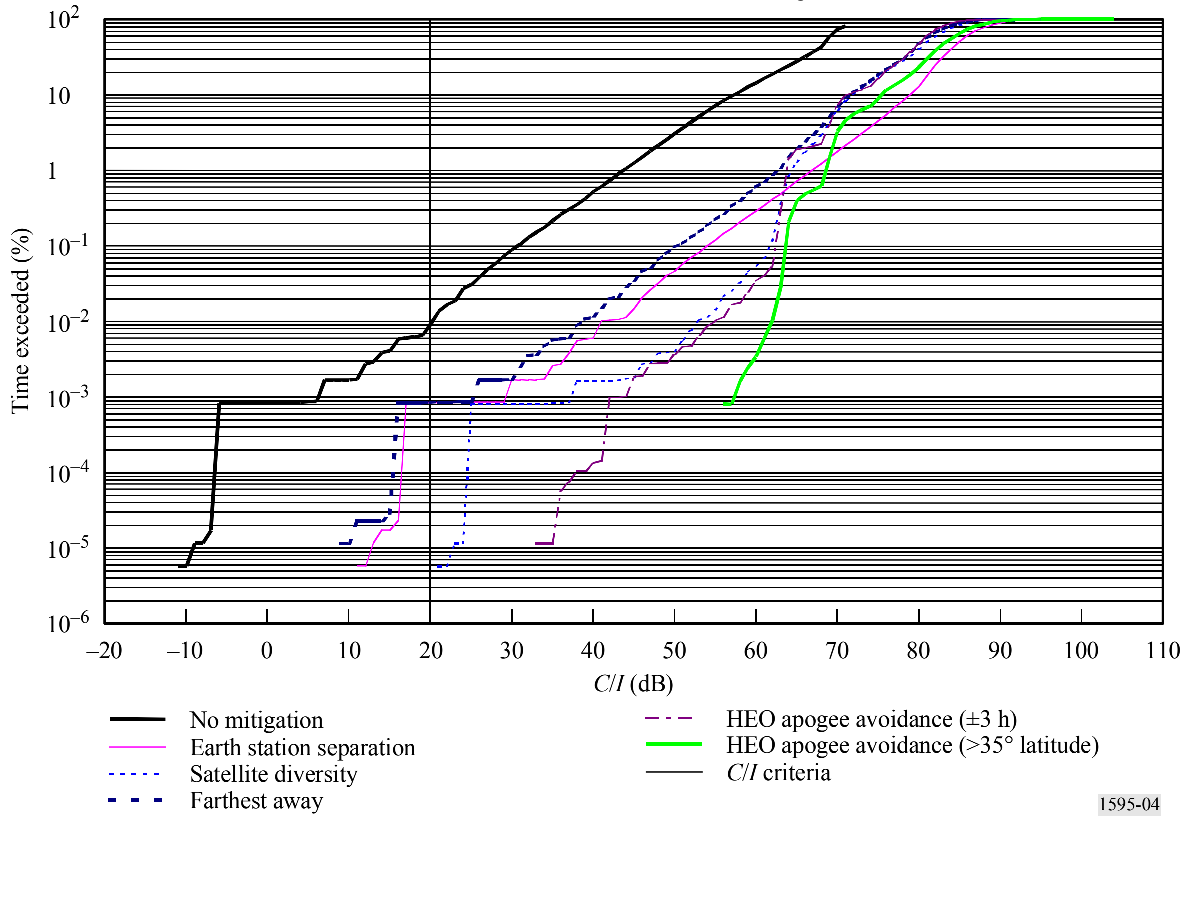


FIGURE 5

CDF of LEOSAT-1 *C/I* into USCSID-P small antenna

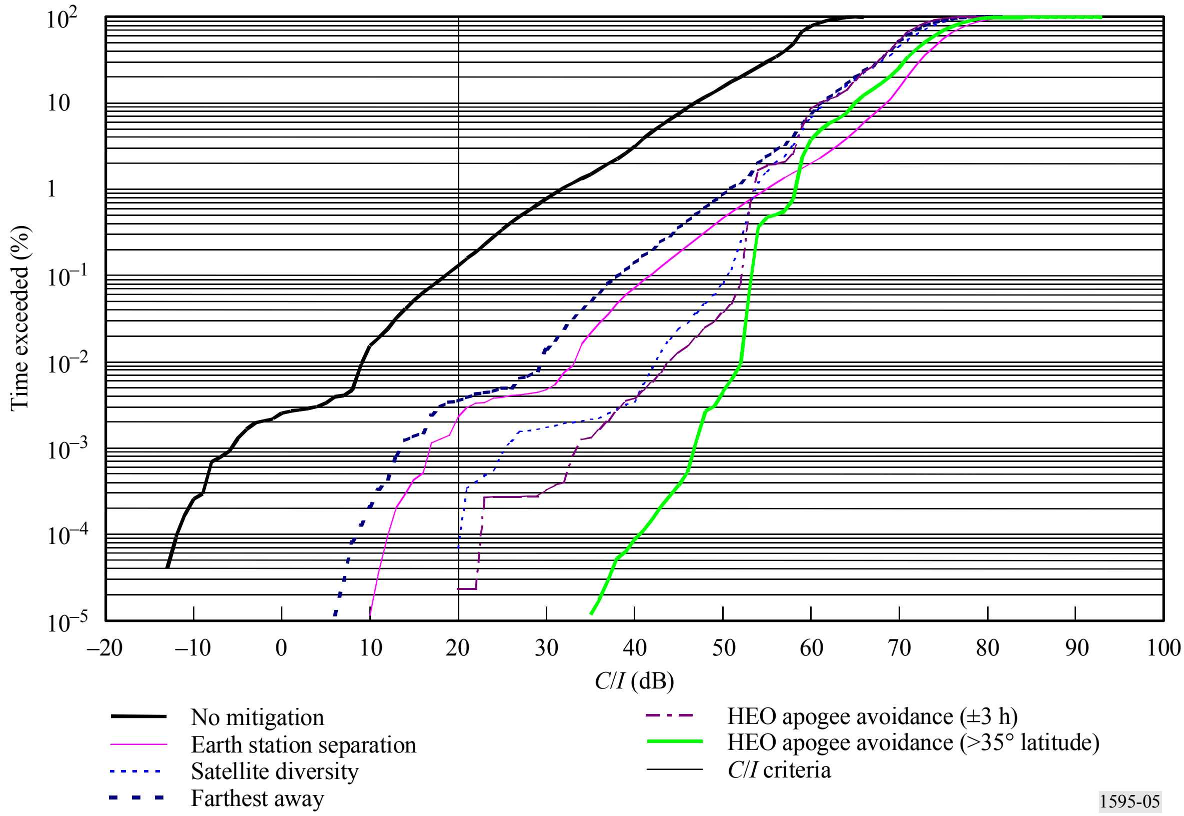


FIGURE 6

CDF of LEOSAT-2 *C/I* into USCSID-P large antenna

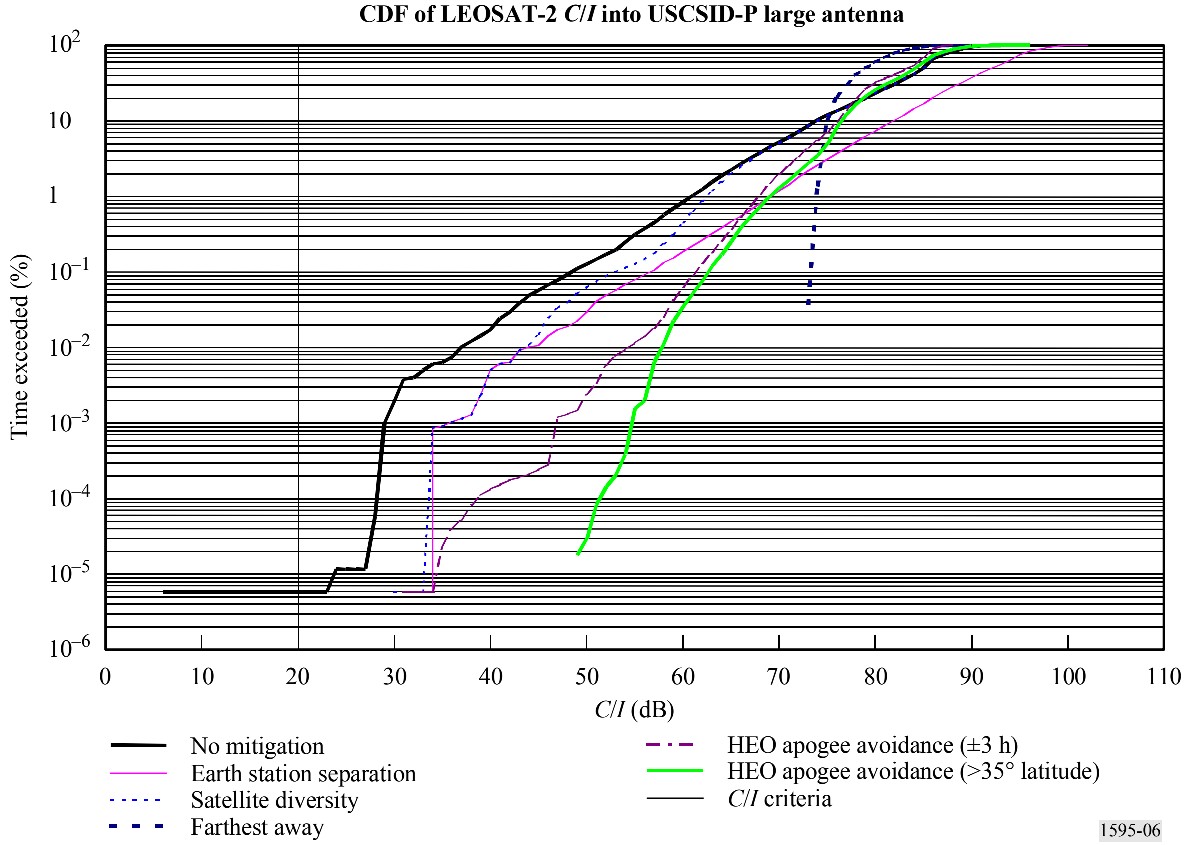


FIGURE 7

CDF of LEOSAT-2 *C/I* into USCSID-P small antenna

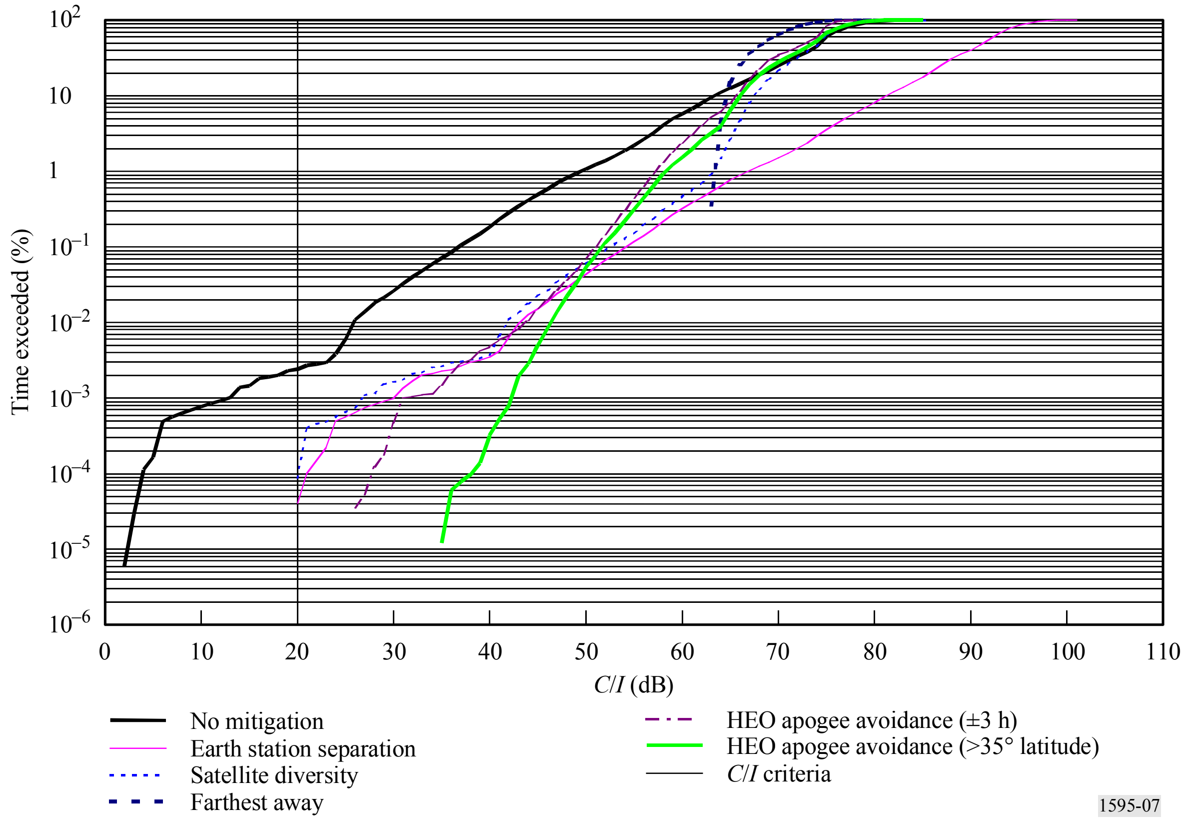


FIGURE 8

CDF of USAMEO-2 *C/I* into USCSID-P large antenna

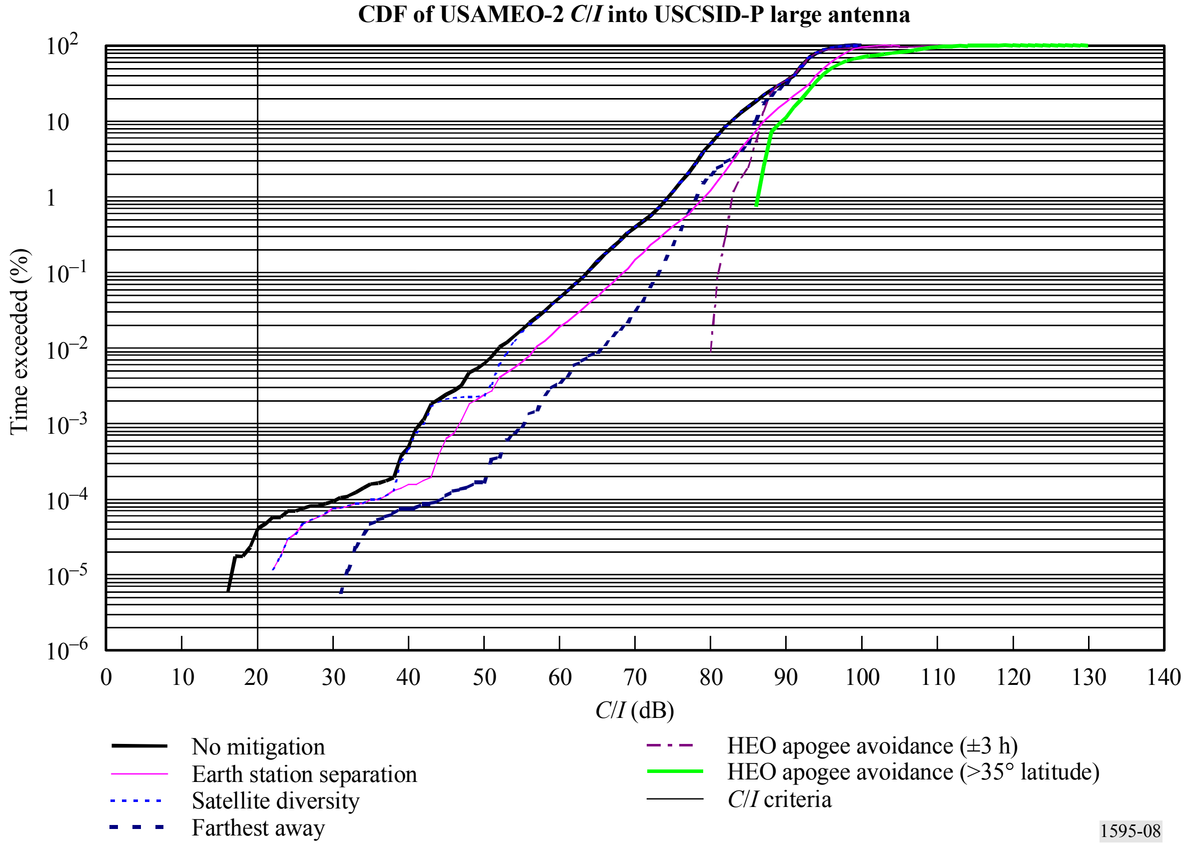


FIGURE 9

CDF of USAMEO-2 *C*/*I* into USCSID-P small antenna

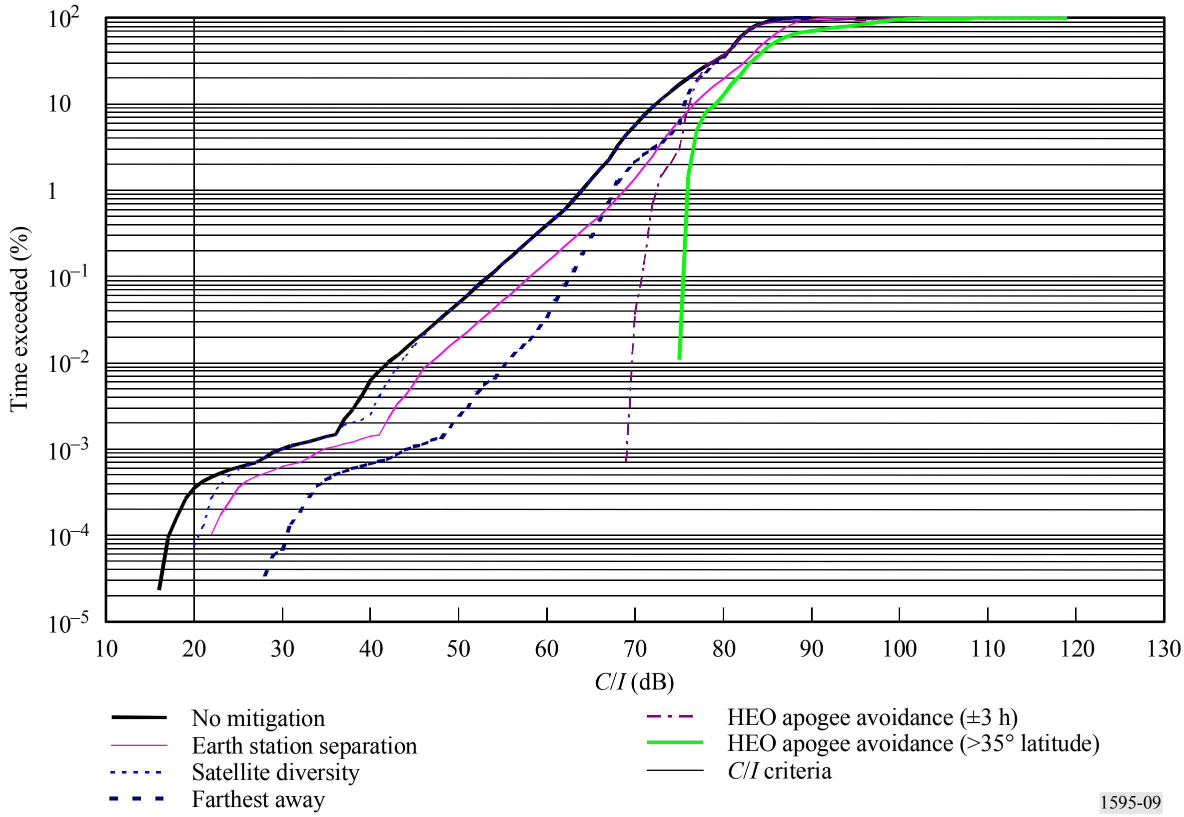


FIGURE 10

CDF of USAMEO-3 *C*/*I* into USCSID-P large antenna

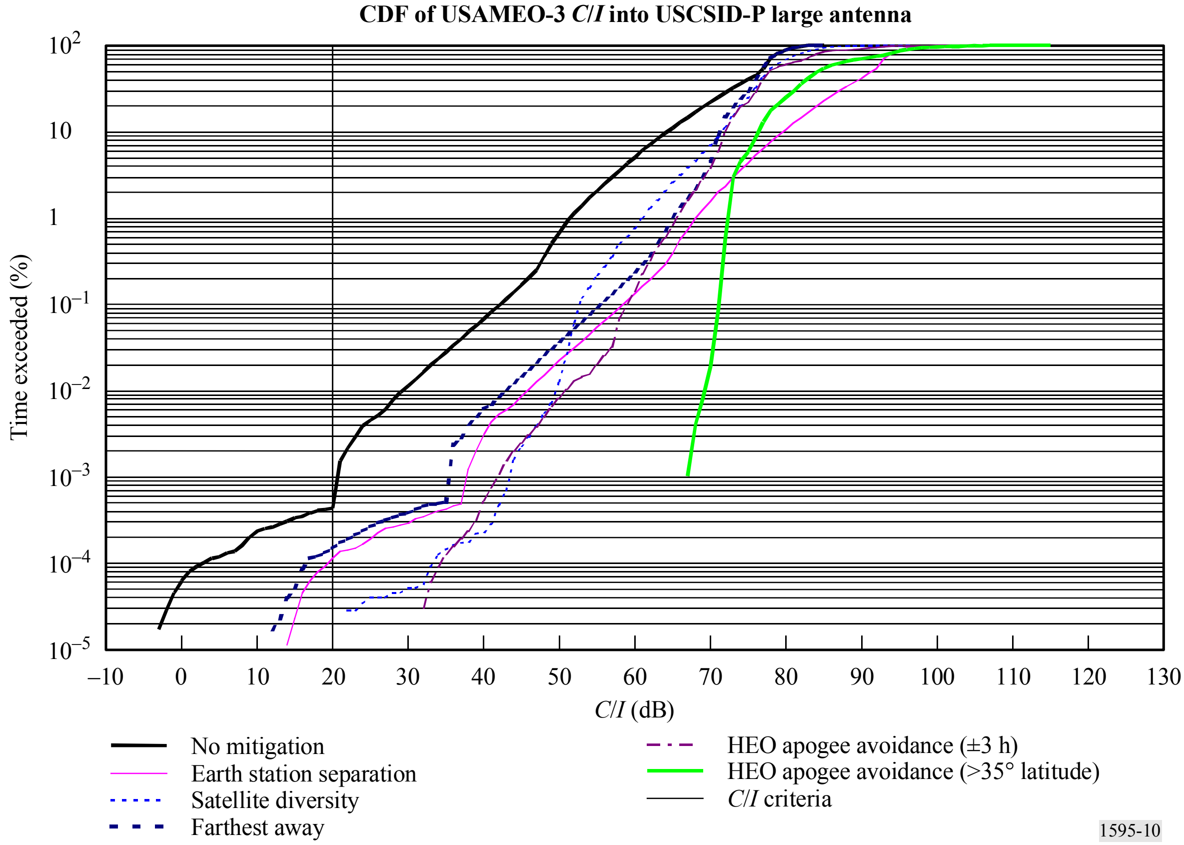


FIGURE 11

CDF of USAMEO-3 *C/I* into USCSID-P small antenna

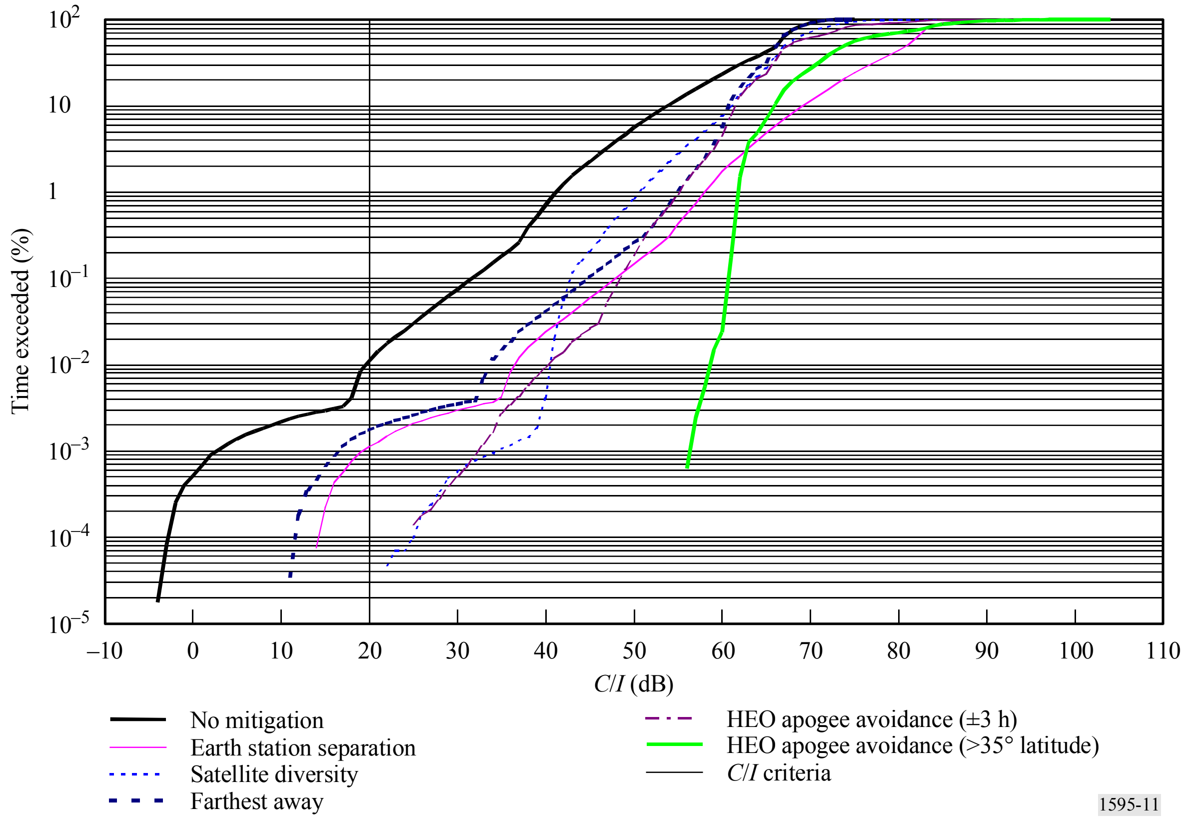


FIGURE 12

CDF of USCSID-P *C/I* into LEOSAT-1

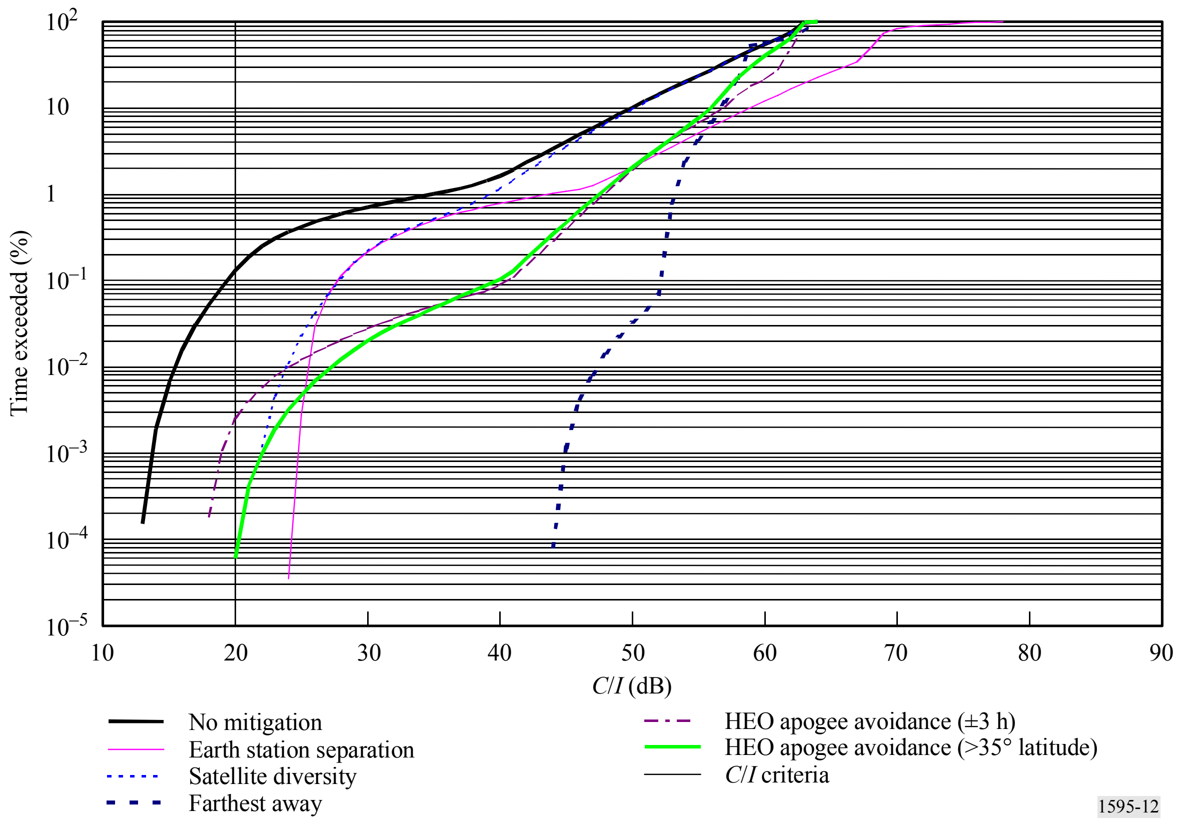


FIGURE 13

CDF of USCSID-P *C/I* into LEOSAT-2

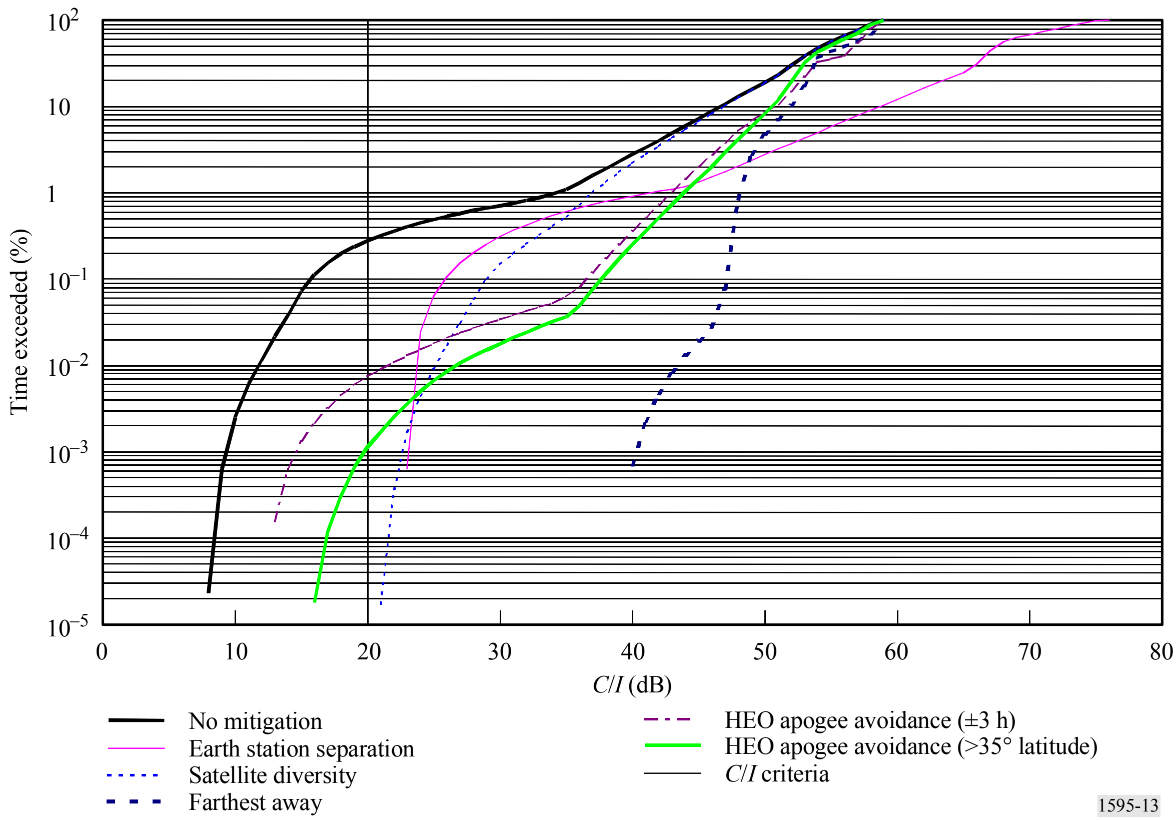


FIGURE 14

CDF of USCSID-P *C/I* into USAMEO-2

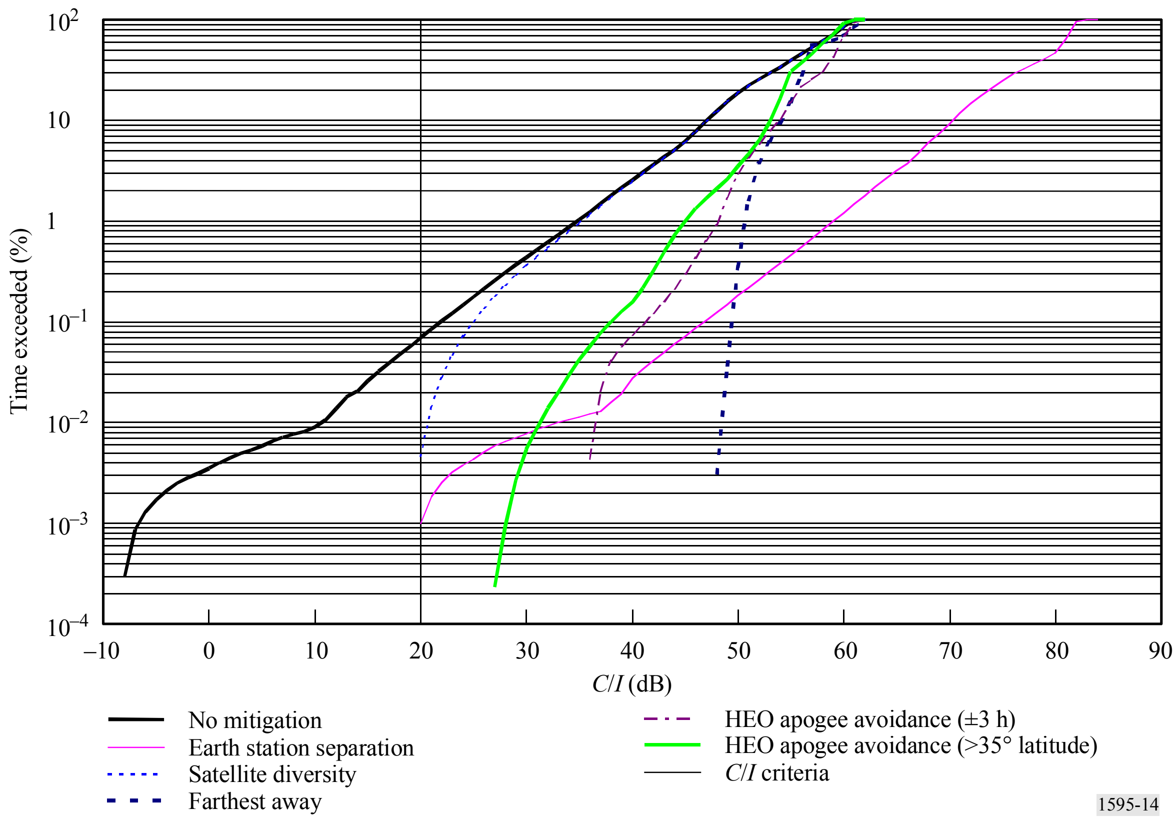
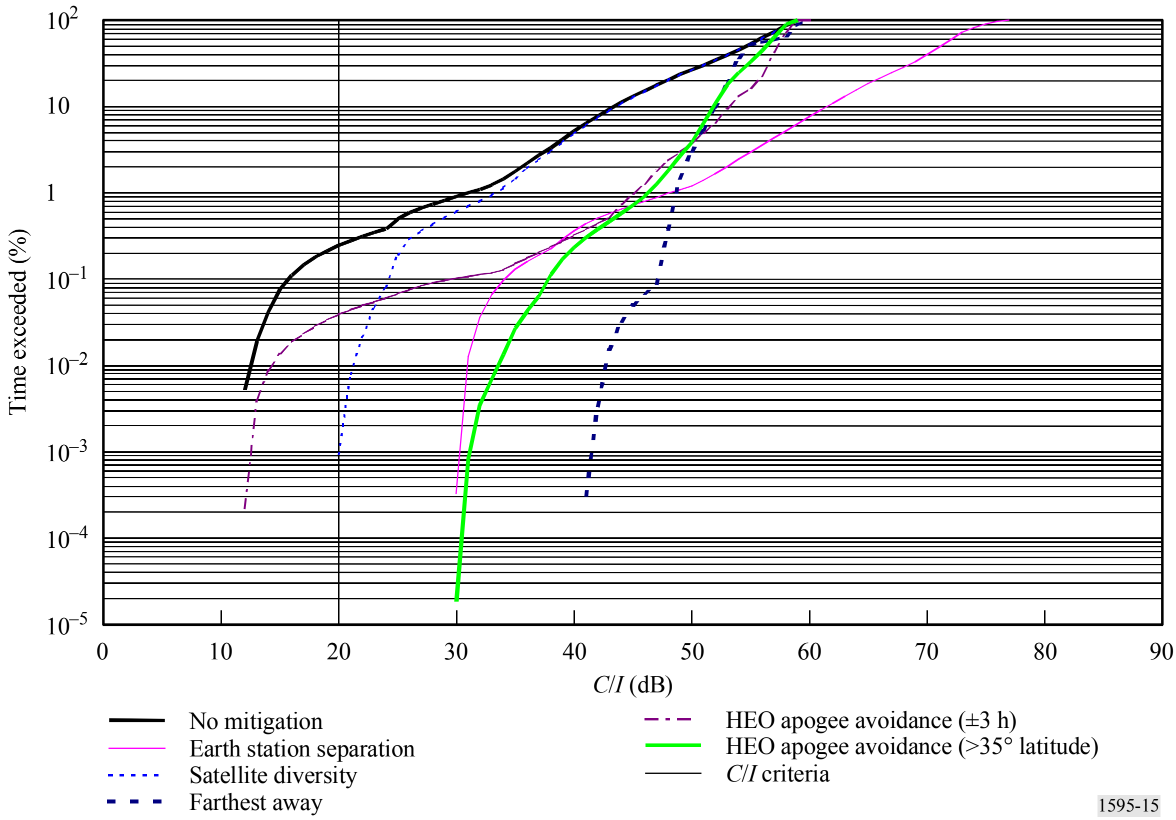


FIGURE 15

CDF of USCSID-P *C/I* into USAMEO-3



3.1 LEO and MEO mitigating around HEO

As seen in Figs. 4 to 15, all of the mitigation techniques have some effect on decreasing the interference into and from USCSID-P. The most effective of these techniques for mitigating interference into the HEO systems were satellite diversity (angular discrimination) and the HEO apogee avoidance. For mitigating interference from the HEO system, earth station separation, satellite diversity and the alternate satellite selection techniques were the most effective. The next few paragraphs will examine the results of mitigating the interference from each of the LEO and MEO systems into the HEO system and then the results of mitigating the interference from the HEO system into each of the LEO and MEO systems.

The use of the mitigation techniques of satellite diversity and HEO apogee avoidance decreased the interference from LEOSAT-1 to the target threshold, see Figs. 4 and 5. The angular discrimination that is required for LEOSAT-1 to meet the *C/I* criteria of 20 dB is 18°. As seen in Fig. 16, this large angle decreases the single satellite availability from 100% to 93% and severely decreases the dual satellite availability from 83% to 59%. However, the HEO apogee avoidance technique, when HEO operations are limited to ±3 h around apogee, only reduces single satellite availability to 94% and dual satellite availability to 68%. When the HEO apogee is restricted to above 35° latitude the single satellite availability is severely decreased to 69%. The HEO apogee avoidance technique when the HEO service arc is so large would most likely not be an option for the LEOSAT-1 system. Figures 4 and 5 also show that the earth station separation and alternate satellite selection techniques do not reduce the interference to the target threshold. However interference is reduced significantly, approximately 20 dB, by both of these techniques.

Figures 6 and 7 show that all of the modelled mitigation techniques reduce the interference from LEOSAT-2 into USCSID-P to below the target threshold and have minimal effects on satellite availability. The angular discrimination required is 12°. Figure 17, show that this relatively large angle reduces single satellite availability from 100% to 99.9% and reduces dual satellite availability from 100% to 96%. However, the HEO apogee avoidance technique, when HEO operations are limited to ±3 h around apogee, does not reduce single satellite availability and reduces dual satellite availability to only 97%. When the HEO apogee is restricted to above 35° latitude the single and dual satellite availability decrease to 96% and 69% respectively. The HEO apogee avoidance mitigation technique when the HEO service arc is quite large would most likely not be an option for the LEOSAT-2 to reduce interference. The earth station separation technique also worked well for LEOSAT-2. In the simulation when the co-located plus 3 rings of earth stations were removed the *C*/*I* reduced to the target of 20 dB. This technique does not affect the availability of satellite systems but does limit the placement and number of LEOSAT-2 earth stations. The last technique, alternate satellite selection strategy, also worked quite well for the LEOSAT-2 system. The *C*/*I* was reduced well below the target threshold and satellite availability is not effected with this mitigation technique. However, the LEOSAT-2 satellite system could experience some decrease in quality of service due to increased use of links at lower elevation angles.

Figures 8 and 9 demonstrate that the *C*/*I* from USAMEO-2 when operating with no mitigation techniques is very close to the target threshold and that all of the mitigation techniques work very well. The angular discrimination required to reduce the interference to the target threshold is only 0.1°. Figure 18 shows that this small discrimination angle does not reduce the single or double satellite availability and only reduces the triple satellite availability by 6%. This technique would be very effective. The HEO apogee avoidance technique was also very effective for reducing interference from USAMEO-2. When the HEO apogee is confined to ±3 h the single satellite availability is reduced from 100% to 95% and the double satellite availability is reduced from 87% to 75%. When the service area of the HEO apogee is increased to above 35° latitude the single and double satellite availability decrease dramatically to 69% and 51% respectively. The HEO apogee avoidance technique would probably only be possible with the smaller window of operation at ±3 h. The earth station separation technique also reduced the interference to the target threshold. Only the co-located earth station was eliminated therefore, there is not much impact to the USAMEO-2 system. The alternate satellite selection mitigation technique was quite successful in reducing the interference to the target threshold. However, USAMEO-2 could experience a decrease in quality of service due to the increased use of links at low elevation angles. There is potential for use for all of the mitigation techniques studied by USAMEO-2 to reduce interference into USCSID-P.

The simulations with USAMEO-3, seen in Figs. 10 and 11, indicate that only satellite diversity and HEO apogee avoidance mitigation techniques reduced the *C*/*I* to the target threshold. Although the earth station separation and alternate satellite selection mitigation techniques did not reduce the *C*/*I* to the target threshold, they did significantly reduce the *C*/*I* by approximately 15 dB. The angular discrimination required for USAMEO-3 to meet the *C*/*I* criteria of 20 dB is actually quite small, 2.8°. As seen from Fig. 19, there are at least two satellites available for 99% instead of 100% of the time when no mitigation techniques are used. The HEO apogee avoidance technique (both scenarios) is also very effective for USAMEO-3 to reduce the *C*/*I* to the target threshold. Figure 19 shows that there would be 8% of simulation time when there are no satellites available when the HEO service area is restricted to ±3 h around apogee. However when the service area is increased the single satellite availability is significantly reduced to 63%. This large percentage of unavailability would most likely not be acceptable for the USAMEO-3 system.

3.2 HEO mitigating around LEO and MEO

Figures 12 and 13 present the results of the simulations where USCSID-P is mitigating around the various LEO and MEO satellite systems. The exception to this is the HEO apogee avoidance technique. This technique is aimed at the LEO and MEO type systems to protect an HEO system. However, when the LEO and MEO systems do utilize this technique there is also a benefit for the LEO and MEO in the reduction of the *C*/*I* from the HEO. It should also be noted that the simulations included USCSID-P utilizing the satellite diversity mitigation technique. This system and many HEO systems are not designed to perform this technique and do not have sufficient number of beams nor the complicated switching algorithm required. This type of simulation was performed only to demonstrate that an HEO type system could effectively use satellite diversity if it is designed to do so. Figure 20 shows that the satellite diversity mitigation technique would have little effect on the USCSID-P satellite availability, if USCSID-P were able to operate in this manner.

Figure 12 shows that all but the ±3 h HEO apogee avoidance techniques are effective in reducing the *C*/*I* from USCSID-P into LEOSAT-1. A discrimination angle of 2.7° will reduce the *C*/*I* to the target threshold with little effect on USCSID-P satellite availability. The HEO apogee avoidance scenarios also significantly reduce the *C*/*I* from USCSID-P into LEOSAT-1. The alternate satellite selection technique is the most effective mitigation technique. To reduce the *C*/*I* to the target threshold with earth station separation, the co-located and one ring of LEOSAT-1 earth stations were removed. Although this would restrict the location of the LEOSAT-1 and USCSID-P earth stations, USCSID-P earth stations are not intended to be ubiquitously deployed so this technique may not be overly constraining.

Figure 13 presents the results of USCSID-P mitigating around LEOSAT-2. This Figure shows that the alternate satellite selection mitigation technique significantly reduces the *C*/*I* into LEOSAT-2 by approximately 30 dB. The angular discrimination angle required to reduce the *C*/*I* to the target threshold is 3.3° and Fig. 20 shows that there is little effect on USCSID-P satellite availability. Although the HEO apogee avoidance scenarios do not reduce the *C*/*I* to the target threshold they do reduce the *C*/*I* significantly. To achieve the target threshold with earth station separation the co-located plus one ring of LEOSAT-2 earth stations were removed. As stated in the previous paragraph this technique may not be overly constraining because USCSID-P earth stations are not intended to be ubiquitously deployed.

Figure 14 shows that all of the mitigation techniques simulated reduce the *C*/*I* from USCSID-P into USAMEO-2 to the target threshold. The angular discrimination required for satellite diversity is 1.7° and the technique has little adverse affect on the satellite availability of USCSID-P. Earth station separation is effective when the co-located plus 3 rings of USAMEO-2 earth stations are removed. This result indicates that this mitigation technique could be very constraining to the USAMEO-2 system because of the large separation distance.

Figure 15 shows that all but the HEO apogee avoidance scenario where the HEO apogee service is limited to ±3 h around apogee are effective in reducing the *C*/*I* into USAMEO-3 to the target threshold. Once again the alternate satellite selection strategy technique significantly reduces the *C*/*I*, approximately 30 dB. The angular discrimination required to reduce the *C*/*I* to 20 dB is 2.6° and this small angle does not adversely affect the satellite availability of USCSID-P. The target threshold is achieved with earth station separation by removing the co-located plus one ring of USAMEO-3 earth stations. This technique may not be overly constraining because USCSID-P earth stations are not intended to be ubiquitously deployed.

Table 5 presents a summary of the results presented. The scenario of interferer and victim are along the left-hand column with the different mitigation techniques across the top. For each mitigation technique the number represents the percentage of time there is at least one satellite available, the yes or no represents whether or not the implementation of the mitigation technique reduced the *C*/*I* to below the required threshold and the NA means the mitigation technique did not effect availability.

TABLE 5

Summary of results

	No mitigation	**Earth separation**	**Satellite diversity**	**Farthest away**	**HEO apogee (±3 h)**	**HEO apogee (>35° latitude)**
Interferer/Victim	**Yes or No (%)**	**Yes or No (%)**	**Yes or No (%)**	**Yes or No (%)**	**Yes or No (%)**	**Yes or No (%)**
LEOSAT-1/USCSID-P	100/No	NA/No	93/Yes	NA/No	94/Yes	69/Yes
LEOSAT-2/USCSID-P	100/No	NA/Yes	99.9/Yes	NA/Yes	100/Yes	96/Yes
USAMEO-2/USCSID-P	100/No	NA/Yes	100/Yes	NA/Yes	95/Yes	69/Yes
USAMEO-3/USCSID-P	100/No	NA/No	100/Yes	NA/No	92/Yes	63/Yes
USCSID-P/LEOSAT-1	100/No	NA/Yes	100/Yes	NA/Yes	100/No	100/Yes
USCSID-P/LEOSAT-2	100/No	NA/Yes	100/Yes	NA/Yes	100/No	100/No
USCSID-P/USAMEO-2	100/No	NA/Yes	100/Yes	NA/Yes	100/Yes	100/Yes
USCSID-P/USAMEO-3	100/No	NA/Yes	100/Yes	NA/Yes	100/No	100/Yes

NA: not available

4 Conclusions

All the mitigation techniques presented in this Recommendation are effective in decreasing the interference between the example LEO and MEO systems and the example HEO system. The analysis indicates that the satellite diversity mitigation technique is more constraining for the LEO systems than for the HEO and MEO systems. The angle required to meet the target *C*/*I* threshold is larger than 10° for the LEO systems and below 3° for the HEO and MEO systems. Although the required discrimination angles for the HEO system to protect the LEO and MEO systems are small, it is not possible for USCSID-P to use satellite diversity. Satellite diversity is only a possible technique if the HEO system has been designed to have multiple satellites in view to an earth station for long periods of time. This technique also requires close communications between the satellite systems and extensive knowledge of the location of the satellites.

The HEO apogee avoidance mitigation technique is effective in reducing the interference to acceptable levels. When the HEO apogee service area is reduced to ±3 h around apogee the impact to the LEO systems was less severe than the impact of satellite diversity. The single coverage is reduced to 94% for HEO apogee avoidance versus 93% for satellite diversity with LEOSAT-1 and no reduction versus 99% for LEOSAT-2. For the MEO systems the impact was more severe, single coverage reduced to 95% versus 100% for USAMEO-2 and 92% versus no reduction for USAMEO-3. This is mainly due to the fact that the MEO systems required much smaller avoidance angles than the LEO systems to reduce the *C*/*I* to the target threshold. This does not hold true when the HEO service area is increased to greater than 35° latitude. The impact to all the systems is quite severe, reduction of single satellite coverage to as much as 63%. This type of HEO operational scenario would not be a candidate for the HEO apogee avoidance technique. The benefit of the HEO apogee avoidance technique is that if the entire HEO service zone is avoided then interference is reduced to acceptable levels into the HEO system and the interference is simultaneously reduced into the mitigating system without the need for knowledge of the specific locations of the satellites within a HEO system. However, the impact, in some cases, to the mitigating non-GSO FSS system is severe and would undoubtedly require additional resources.

The earth station separation successfully reduced the interference to the required threshold for several of the scenarios. This technique could be overly constraining if both non-GSO systems were to deploy ubiquitous earth stations. However, in the examples shown, the technique effectively reduces interference if the one of the systems does not plan to deploy ubiquitous earth stations and the separation distance between the earth stations of the non-GSO systems is not too large.

The alternate satellite selection mitigation technique was very effective in reducing interference from the HEO system into the LEO and MEO systems. However, the reverse had mixed results. The mitigation technique sufficiently reduced the interference from LEOSAT-2 and USAMEO-2 but not from LEOSAT-1 or USAMEO-3. The consequence of this mitigation technique may be a decrease in the quality of service provided by the satellite system. This would be due to the increased use of links at low elevation angles.

A single mitigation technique may not be the solution to satisfactorily reduce interference in all situations. It is possible that a combination of two different mitigation techniques may sufficiently reduce interference in a more efficient and less demanding manner than a single mitigation technique. The results of these example simulations have shown that every sharing situation will be unique depending on the operational and system characteristics of the systems involved. Finding the optimum mitigation technique(s) to be applied between any two non-GSO FSS systems, one of which is an HEO, may, in some cases, best be able to be accomplished during inter-system coordination.

FIGURE 16

Number of LEOSAT-1 satellites available

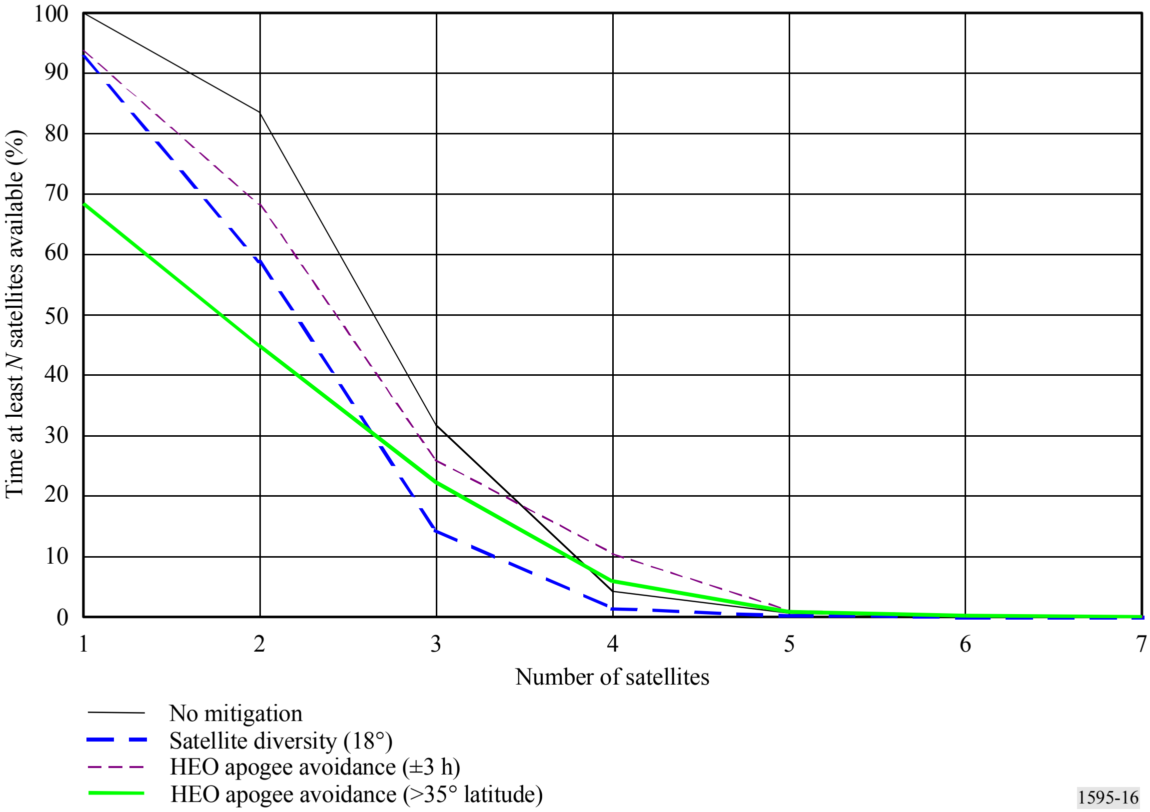


FIGURE 17

Number of LEOSAT-2 satellites available

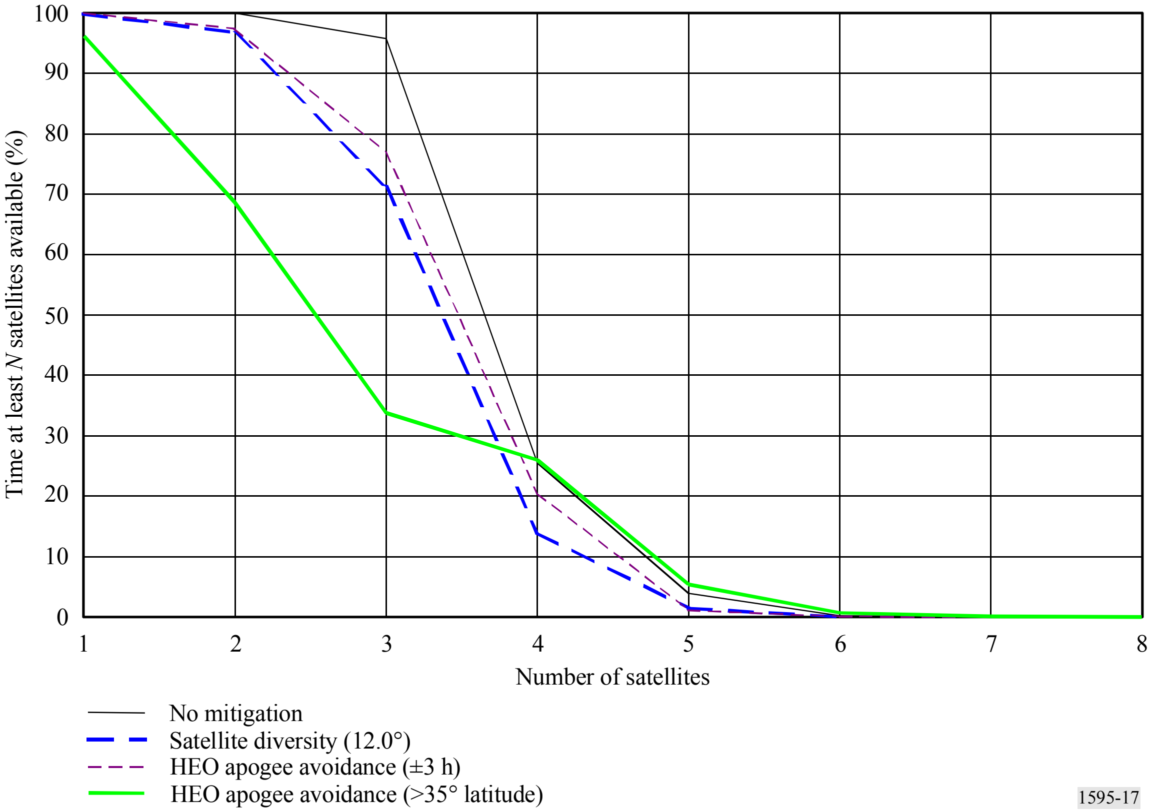


FIGURE 18

Number of USAMEO-2 satellites available

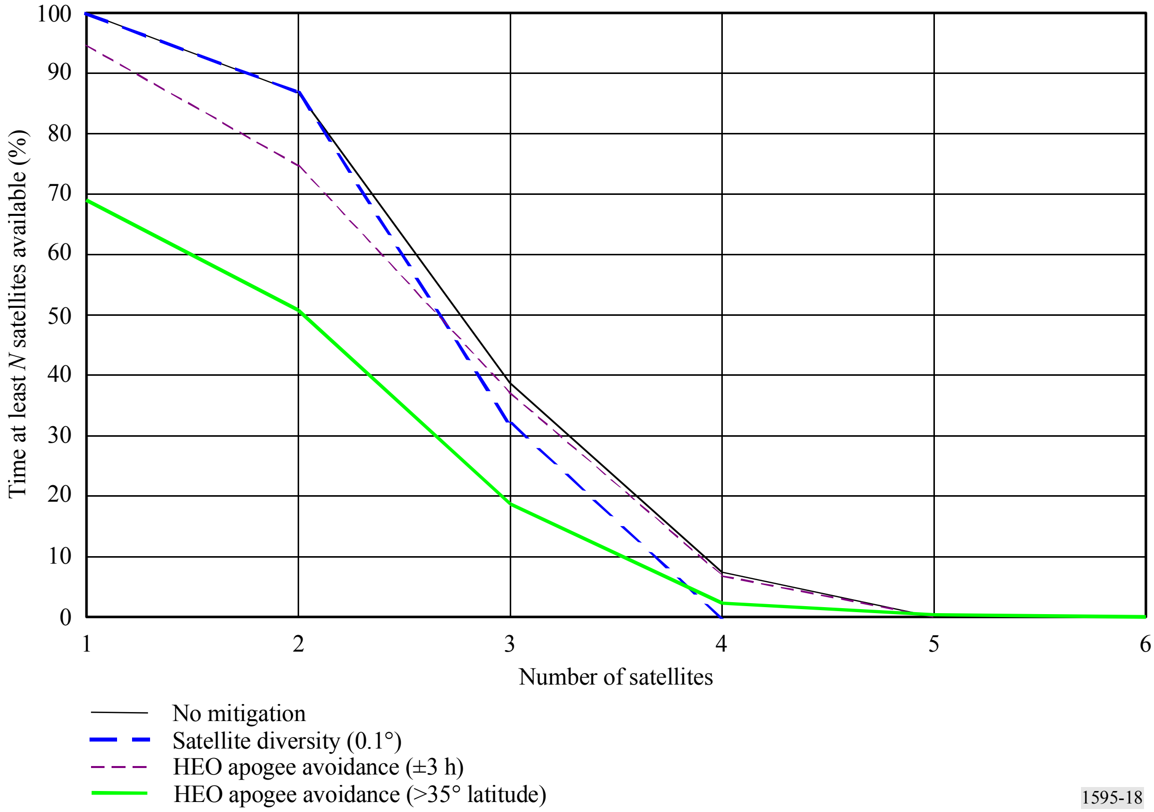


FIGURE 19

Number of USAMEO-3 satellites available

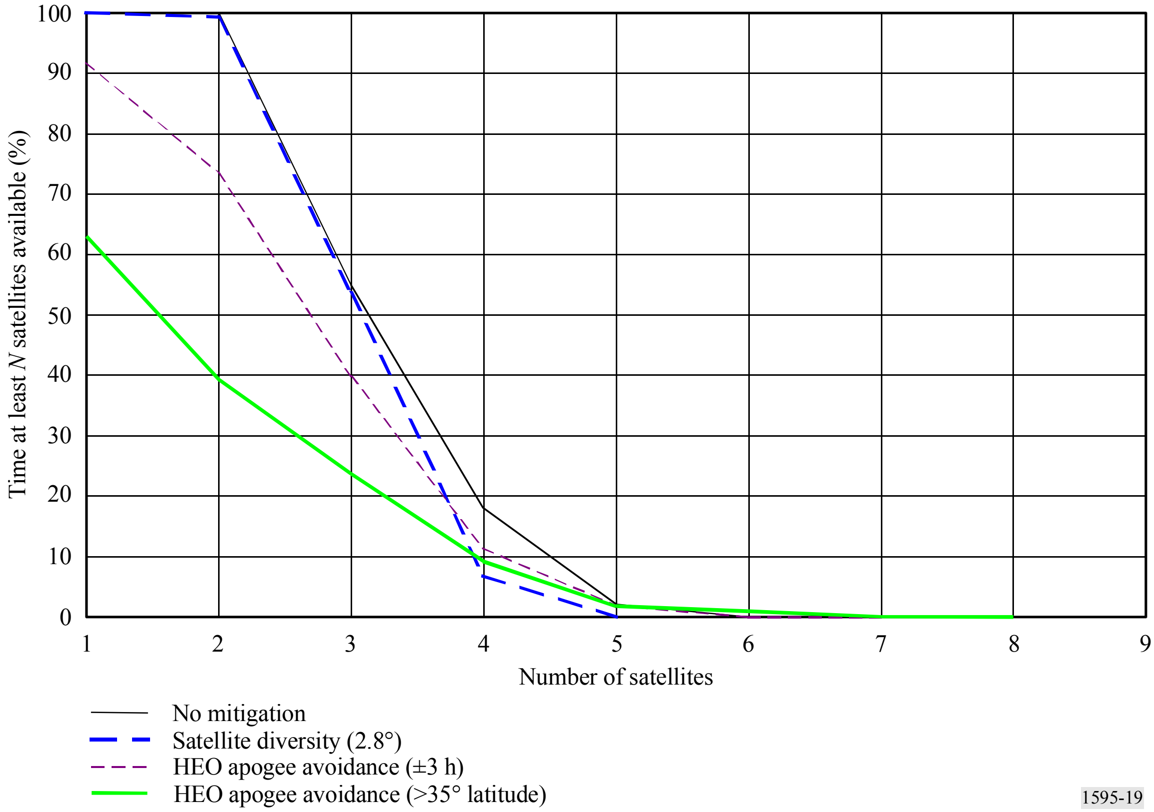


FIGURE 20

Number of USCSID-P satellites available