RECOMMENDATION ITU-R S.1526-1

Methodology to assess the interference environment in relation to Nos. 9.12, 9.12A and 9.13 of the Radio Regulations when non-geostationary-satellite orbit fixed-satellite service systems are involved*

(Question ITU-R 231/4)

(2001-2002)

The ITU Radiocommunication Assembly,

considering

a) that some non-geostationary-satellite orbit fixed-satellite service (non-GSO FSS) systems are at the early stage of development and as a result some modifications to their design are likely;

b) that changes to one non-GSO FSS system may affect other operational or planned FSS systems;

c) that other operational or planned FSS systems affected by changes to a non-GSO FSS system must retain the flexibility to operate within the limits of their notifications;

d) that Recommendation ITU-R S.1431 describes several mitigation techniques to enhance sharing between non-GSO FSS systems;

e) that it is desirable for the designers of non-GSO FSS systems to have metrics that permit an assessment of the impact of these various mitigation techniques on the system design;

f) that it is common for administrations coordinating their FSS systems to change system parameters of their filed system as a result of their coordination efforts;

g) that provision No. 11.43B of the Radio Regulations (RR) and the associated Rules of Procedure allow for changes in the system characteristics of recorded frequency assignments, including those of non-GSO FSS systems, while retaining the original date of entry in the Master Register, as long as the changes do not increase the probability of harmful interference to assignments already recorded;

h) that *resolves* 2 of Resolution 132 (WRC-97) states that in the bands 18.8-19.3 GHz and 28.6-29.1 GHz for non-GSO FSS systems notified before 18 November 1995 when coordination was not required (before that date) no coordination is required when the characteristics of the modified frequency assignment are within the limits of those of the original notification;

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* Further study is required concerning the applicability of this Recommendation to non-GSO FSS sharing with GSO FSS (RR Nos. 9.12A/9.13) in the bands 19.3-19.7 GHz and 29.1-29.5 GHz.

j) that, in the bands in *considering* h), RR Nos. 9.12, 9.12A and 9.13 apply;

k) that, in some other bands non-GSO FSS, epfd↓ and epfd↑ limits have been adopted in RR Article 22 to limit the interference into GSO FSS and BSS systems, and RR No. 9.12 applies between non-GSO FSS systems;

l) that, in the sharing situations in *considering* j), Recommendation ITU-R S.1323 provides the maximum permissible levels of interference in an FSS satellite network;

m) that it is desirable to have a methodology in the ITU-R to determine whether modifications to the characteristics of a non-GSO FSS system will improve the sharing situation with another FSS system or will worsen this situation,

recommends

1 that the methodology in Annex 1 can be used to assist non-GSO FSS system designers in the evaluation of the impact of various mitigation techniques;

2 that the methodology in Annex 1 may be used (by administrations and system designers) as a way to determine whether a modification introduced to the design of a non-GSO FSS system will improve or worsen the interference environment with respect to another FSS system sharing the same frequency band.

ANNEX 1

Methodology to assess the interference environment generated by a non-GSO FSS system

1 Introduction

A procedure is proposed here for the assessment of how modifications introduced to a non-GSO FSS system (System A) affect the interference environment created by this system with respect to another FSS system (System B). It is recognized that the affected system has a wide degree of operational freedom within the filed parameters of the system, taking into account constraints imposed by previously filed systems. To draw general conclusions about changes to a system, the procedure below would be applied separately using all available transmission parameters for the two systems. In addition, both systems may employ mitigation strategies involving a variety of mitigation techniques in various combinations in order to deal with each of the four interference scenarios. Possible mitigation strategies for consideration include: avoidance leading to loss of service during in-line events, satellite diversity, earth station site diversity, satellite selection strategies, frequency channelization, link balancing, alternate polarization, and improved antenna characteristics. The procedure can be summarized by the following steps:

Step 1: Determine the mitigation strategies (e.g. avoidance angle values) to be used by the given systems to protect all relevant scenarios of interference to System A (with its parameters prior to the modification).

Step 2: Calculate relevant performance statistics (e.g. visibility, satellite handoffs, satellite track time, availability, etc.) throughout the service area of System B, employing the mitigation strategies determined in Step 1.

Step 3: Repeat Steps 1 and 2, substituting the new system parameters for System A.

Step 4: Compare the performance statistics of System B before and after the change to System A.

Step 5: If all statistics have improved, conclude that the design change in System A has made sharing easier for System B.

Step 6: If all statistics have worsened, conclude that the design change in System A has made sharing more difficult for System B.

Step 7: If some statistics have improved and some have worsened, no immediate conclusions about the sharing situation can be made. Consideration may be given to additional factors affecting the distribution of the interference variations for the various earth station locations of System B, such as weighted averaging.

However, it would ultimately be necessary for the parties involved (i.e. the operators of Systems A and B), in any resultant coordination agreement, to agree on the details of the approach to be used, specifically, the calculation/simulation assumptions used in the analysis and the application of any weighted averaging technique.

The four interference scenarios referred to above are described in Fig. 1. The angle θ_T represents the transmit discrimination angle (i.e. the angle off-boresight between the transmitter's signal path and the interference path), and the angle θ_R represents the receive discrimination angle.

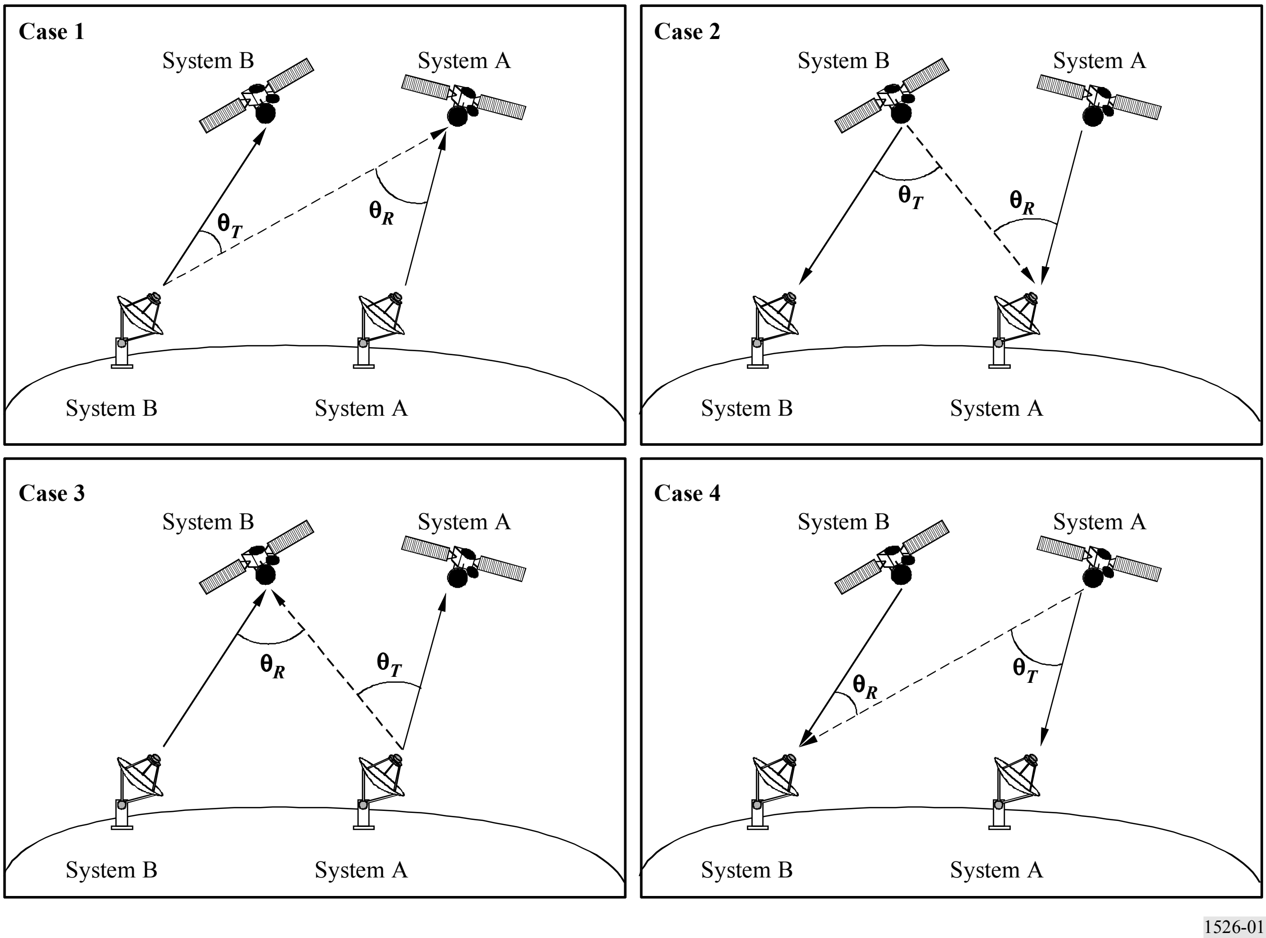
Examples of the application of the methodology, including statistics characterizing visibility, satellite handoffs, satellite track time and availability are described in § 2 and 3.

More details on how visibility statistics can be weighted by population or GDP can also be obtained from these examples.

The impact of modifications introduced to a non-GSO FSS system on the sharing with another non-GSO FSS system assumed to be using satellite diversity is considered in § 2. The impact of these modifications on the sharing with a GSO FSS system is addressed in § 3.

FIGURE 1

Four interference scenarios



NOTE 1 – Dotted lines indicate interference paths. Solid lines indicate wanted signal paths.

2 Example for the sharing between non-GSO FSS systems: Impact of modifications to LEOSAT-1 on USAMEO-1

The following illustrates through a particular example an application of the methodology in a situation where USAMEO-1 is assumed to mitigate using satellite diversity and both systems have chosen to use Recommendation ITU-R S.1323 to determine the avoidance angles. The performance statistics considered here are visibility, satellite handoffs, and satellite track time. Other performance statistics could also be considered.

Other examples may include the case where the mitigating non-GSO FSS system does not employ satellite diversity and suffers loss of service during in-line events. In that case the performance statistics relating to the loss of service can be calculated as illustrated in § 3.3.

2.1 LEOSAT-1 system parameters and assumptions

The basic modelling characteristics for LEOSAT-1 are summarized in Table 1a.

TABLE 1a

LEOSAT-1 system characteristics

Characteristic	LEOSAT-1
Constellation parameters	
Number of satellites	288
Number of planes	12
Number of satellites per plane	24
Plane spacing (degrees)	15.36
Walker phase factor	Not available
Inclination (degrees)	84.7
Orbit altitude (km)	1 375
Inter-plane phasing (degrees)	Random
Elevation mask angle (degrees)	40
Uplink transmission parameters	
Access method	MF/TDMA
Carrier bandwidth (MHz)	3.096
Power control	Yes
Power control value (dB)	13.5
Earth station transmit peak gain (dB)	35.2
Earth station transmit antenna pattern	RR Appendix 8
Earth station transmit antenna diameter (m)	0.3
Satellite receive peak gain (dB)	33.2
Satellite receive antenna pattern	–3 EoC, –25 near side lobe –30 far side lobe
Receive beam adapted for constant cell size?	Yes
Noise temperature (K)	832
Number of receive beams	364/polarization
Downlink transmission parameters	
Access method	ATDMA
Carrier bandwidth (MHz)	500
Power control	No
Earth station receive peak gain (dB)	34.1
Earth station receive antenna pattern	RR Appendix 8

TABLE 1a (*end*)

Characteristic	LEOSAT-1
Downlink transmission parameters (cont.)	
Earth station receive antenna diameter (m)	0.3
Satellite transmit peak gain (dB)	34.7 to 35.7
Satellite transmit antenna pattern	–0.5 EoC, –25 near side lobe –30 far side lobe
Satellite transmit e.i.r.p. at EoC (dB)	53.9
Transmit beam adapted for constant cell size?	Yes
Noise temperature (K)	288
Number of transmit beams	16

ATDMA: adaptive TDMA
e.i.r.p.: equivalent isotropically radiated power
EoC: edge of coverage
TDMA: time division multiple access

Table 1b shows the basic system parameters for two hypothetical variations of the LEOSAT-1 system, designated as LEO-XX and LEO-YY. These modifications each contain less than half the number of satellites of the LEOSAT-1 system. This reduction in the number of satellites is accomplished in LEO-XX by maintaining the minimum elevation angle and near-polar configuration, while raising the altitude to 2 500 km. The decrease in the number of satellites is accomplished in LEO-YY by maintaining the altitude while decreasing the elevation mask angle to 25° and changing to a Walker Delta orbit configuration.

TABLE 1b

LEO-XX and LEO-YY system characteristics

Characteristic	LEO-XX	LEO-YY
Constellation parameters		
Number of satellites	128	120
Number of planes	8	10
Number of satellites per plane	16	12
Plane spacing (degrees)	23	36
Walker phase factor	Not available	1
Inclination (degrees)	84.7	58
Orbit altitude (km)	2 500	1 375
Inter-plane phasing (degrees)	Random	3
Elevation mask angle (degrees)	40	25
Uplink transmission parameters		
Access method	MF/TDMA	FDMA/TDMA
Carrier bandwidth (MHz)	3.1	3.1

TABLE 1b (*end*)

Characteristic	LEO-XX	LEO-YY
Uplink transmission parameters (cont.)		
Power control	Yes	Yes
Power control value (dB)	13.5	13.5
Earth station transmit peak gain (dB)	39.4	39.4
Earth station transmit antenna pattern	RR Appendix 8	RR Appendix 8
Earth station transmit antenna diameter (m)	0.4	0.4
Satellite receive peak gain (dB)	37.1 with adjusts for free space loss and scan loss	36.0 with adjusts for free space loss and scan loss
Satellite receive antenna pattern	Rec. ITU-R S.672, $L_N = -25$ dB, Beamwidth = 2°	Rec. ITU-R S.672, $L_N = -25$ dB, Beamwidth = 2.3°
Receive beam adapted for constant cell size?	No	No
Noise temperature (K)	832	832
Number of receive beams	364/polarization	364/polarization
Downlink transmission parameters		
Access method	ATDMA	ATDMA
Carrier bandwidth (MHz)	500	500
Power control	No	No
Earth station receive peak gain (dB)	36.6	36.6
Earth station receive antenna pattern	RR Appendix 8	RR Appendix 8
Earth station receive antenna diameter (m)	0.4	0.4
Satellite transmit peak gain (dB)	37.2 with adjusts for free space loss and scan loss	36.1 with adjusts for free space loss and scan loss
Satellite transmit antenna pattern	Rec. ITU-R S.672, $L_N = -25$ dB, Beamwidth = 2°	Rec. ITU-R S.672, $L_N = -25$ dB, Beamwidth = 2.3°
Satellite transmit e.i.r.p. at EoC (dB)	57.7	54.6
Transmit beam adapted for constant cell size?	No	No
Noise temperature (K)	288	288
Number of transmit beams	16	16

FDMA: frequency division multiple access

2.2 USAMEO-1 system parameters and assumptions

2.2.1 Basic characteristics

In this example, a particular link from USAMEO-1 has been selected for analysis. Its basic modelling characteristics are summarized in Table 2.

TABLE 2

USAMEO-1 system characteristics

Constellation parameters	
Number of satellites	32
Number of planes (for each of 2 subconstellations)	4 (× 2 subconstellations)
Number of satellites per plane	4
Plane spacing (degrees)	90
Walker phase factor	3
Inclination (degrees)	50
Orbit altitude (km)	10 352
Inter-plane phasing (degrees)	67.5
Delta phase between subconstellations (degrees)	30
Delta ascending node between subconstellations (degrees)	0
Elevation mask angle (degrees)	20
Uplink transmission parameters	
Access method	TDMA/FDMA
Carrier bandwidth (MHz)	0.562
Power control	Yes
Power control value (dB)	20.7
Earth station transmit peak gain (dB)	44.16
Earth station transmit antenna pattern	Rec. ITU-R S.465
Earth station transmit antenna diameter (m)	0.65
Satellite receive peak gain (dB)	37.48
Satellite receive antenna pattern	Rec. ITU-R S.672, Beamwidth = 2.3°, $L_N = -25$ dB
Receive beam adapted for constant cell size?	No
Noise temperature (K)	577.98
Number of receive beams	20
Downlink transmission parameters	
Access method	TDM/FDM
Carrier bandwidth (MHz)	96.162
Power control	No
Earth station receive peak gain (dB)	40.78

TABLE 2 (*end*)

Downlink transmission parameters (cont.)	
Earth station receive antenna pattern	Rec. ITU-R S.465
Earth station receive antenna diameter (m)	0.65
Satellite transmit peak gain (dB)	37.5
Satellite transmit antenna pattern	(Same as uplink)
Satellite transmit e.i.r.p. at EoC (dB)	52.3
Transmit beam adapted for constant cell size?	No
Noise temperature (K)	249.41
Number of transmit beams	20

FDM: frequency division multiplex
TDM: time division multiplex

2.2.2 Frequency usage

The USAMEO-1 system proposes to use 1 GHz of spectrum in the bands 28.6-29.1 GHz and 29.5-30.0 GHz for the uplink, and 1 GHz of spectrum in the bands 18.8-19.3 GHz and 19.7-20.2 GHz for the downlink. The frequency bands are divided into 125 MHz channels. It is assumed that multiple channels, to cover the 500 MHz overlapping with LEOSAT-1 (XX, YY) spectrum, can be assigned to the same spot beam for worst-case peaking conditions.

2.2.3 Satellite antenna and earth station model

The satellite uses fixed transmit and receive spot beams. The antennas and beams are maintained in a fixed orientation relative to the spacecraft to allow the beams to move across the surface of the Earth as the satellite moves. Even though the beams are fixed relative to the satellite, the simulation uses tracking beams with each earth station, so that the worst potential interference is caught. The satellite antenna is modelled using Recommendation ITU-R S.672, with a half power beamwidth of 2.3° and side lobe level of –25 dB.

Twenty user stations are modelled in the footprint for uplink interference. The separation distance between earth stations is approximately 728 km.

The downlink interference is computed using a random distribution of earth station locations within each satellite's footprint. These earth station locations are randomly distributed each iteration of the simulation run. The number of stations distributed is the maximum number of simultaneous downlink beams possible for the satellite. In the case that the satellite would be chosen to serve the location of interest for the interference computation (i.e. highest elevation satellite), one earth station location is assigned to this co-located position.

The earth station antenna is modelled using Recommendation ITU-R S.465, which has a side lobe level of $32 - 25 \log_{10}(\varphi)$, where φ = angle off-boresight (degrees).

2.2.4 Link budget and rain degradation assumptions

The link budget shown in Table 3 applies to the USAMEO-1 system model.

TABLE 3

USAMEO-1 link budget

Minimum elevation (degrees) Slant range (km)	20 13 438.27	
	Uplink	*Downlink*
Frequency (GHz)	28.85	19.05
Bandwidth (MHz)	0.56	96.16
Channel spacing (MHz)	0.69	125.00
Power – backoff/losses (dBW)	7.07	14.82
Transmit gain (dB)	44.16	37.50
e.i.r.p. (dBW)	*51.23*	*52.32*
Transmit pointing loss (dB)	0.65	0.50
Free space loss (dB)	204.22	200.61
Atmospheric loss (dB)	1.57	2.10
Total propagation loss (dB)	*206.44*	*203.21*
System temperature (K)	577.98	249.41
Receive gain (dB)	37.48	40.78
Receive loss (dB)	0.98	0.50
Edge of beam loss (dB)	4.10	4.10
G/T (dB/K)	4.78	12.21
Received carrier (C) (dBW)	*–122.81*	*–114.71*
N (dBW)	–143.48	–124.80
C/N (dB)	20.67	10.09
Self interference degradation (dB)	8.21	1.13
$C/(N + I)$ required (dB)	12.05	8.8
Margin (dB)	0.41	0.16

The self interference degradation ($C/N – C/(N + I_s)$) is based on C/I_s = 13.17 dB for the uplink and 15.34 dB for the downlink, where I_s is the self interference. This self interference degradation value is applied to the external interference degradation values ($1 + I_x/N$) computed from the interference values collected during the simulation runs (I_x is the external interference). This is needed because the I/N distribution used in the convolution method of Recommendation ITU-R S.1323 should be based on $I_x/(N + I_s)$ rather than I_x/N ($N = N_{thermal}$).

From the link budgets provided, the external margin for the uplink is 0.41 dB in clear sky and 1.2 dB in rain (rain loss = 7.2 dB), with adaptive coding being used. In addition, the C/I_S under fading is 9.77 dB, which is less than the 13.17 clear sky value. This value of C/I under fading is accounted for by the fact that desired carrier and overall interference are faded differently. The parameter δ, fraction of I not faded, defined in Annex 2 addresses this effect. For this link, δ = 0.28. In effect, the uplink is treated as being able to take 7.2 dB of rain fade before the link starts to degrade, with a margin of 1.2 dB. This rain fade value corresponds to $X = 4.24$ dB, which defines the impulse at 0 in the probability density function (pdf) for X' (X' is the rain degradation accounting for power control, see Annex 2).

For the downlink, the external margin is 0.16 dB in clear sky and 1.1 dB in rain (rain loss = 3.3 dB), again with adaptive coding being used. The downlink is treated as being able to take 3.3 dB of rain fade before the link starts to degrade, with a margin of 1.1 dB. This rain fade value corresponds to $X = 4.46$ and this value is used to determine the impulse value at 0 in the pdf of X' (see Annex 2).

Table 4 summarizes the assumptions used to generate the pdf of the rain degradation. The rain and interference degradation pdf's are convolved to determine whether or not the interference is at an acceptable level. The parameter α represents the percentage of noise increase due to self interference ($I_S/N + I_S$) and is used to relate the rain degradation with the rain fading from the indicated rain model.

TABLE 4

Assumptions for generation of pdf of rain degradation

Link direction	**α**	**Start of link degradation**		**Margin (dB)**	**Link location**
		Rain fade (dB)	**Rain degradation (dB)**		
Uplink	0.85	7.2	4.24	1.2	New York City
Downlink	0.23	3.3	4.46	1.1	New York City

2.3 Simulation results

Separate simulation runs were performed for the USAMEO-1 system operating with each of the following systems:

– LEOSAT-1 (288 satellites, polar constellation, 40° minimum elevation).

– LEO-XX (128 satellites, polar constellation, 40° minimum elevation).

– LEO-YY (120 satellites, Walker Delta constellation, 25° minimum elevation).

Within each set of simulation runs, data was collected for all four interference cases, where each case is defined in Table 5.

TABLE 5

Interference case definition

Case	Link direction	Role of USAMEO-1 system
1	Uplink	Interferer
2	Downlink	Interferer
3	Uplink	Desired system
4	Downlink	Desired system

Except where noted differently, simulation runs were for 2 days at 1 s intervals (172 800 iterations). Multiple satellites were assumed to serve each location, where coverage allowed. For the interference and coverage capability (visibility) simulations, the constellation positions for both systems were randomized each iteration; for the satellite hand-offs and satellite tracking time simulations, the constellations were propagated continuously at the 1 s intervals.

Each plot below shows the $I_x/(N + I_s)$ cumulative distribution functions (cdf's) for various avoidance angles and the corresponding results of the convolution of the rain and interference degradation pdf's. Multiple runs were conducted to determine the avoidance angle necessary to pass the Recommendation ITU-R S.1323 criteria, assuming 10% of the link outage is allowed for external interference.

2.3.1 Results of USAMEO-1 with LEOSAT-1

Because the mitigating system is a MEO and the other system is a LEO, it is appropriate to use a space station based avoidance angle for Cases 2 and 3 and an earth station based avoidance angle for Cases 1 and 4, to provide the necessary protection. The angle values reflected in Figs. 2 and 3 are for space station based or earth station based angles, correspondingly.

In order to protect all four interference cases, the mitigating system would need to employ an earth station based avoidance angle of 16.0° and a space station based avoidance angle of 0.5°.

The impact on the mitigating system is shown in Fig. 4 – the plot for the visibility (i.e. the number of usable satellites satisfying elevation mask and mitigation criteria), and in Fig. 5 – the plots for satellite handoffs (connections) to new satellites, and the average earth station to satellite track time (dwell) of a beam on a satellite.

FIGURE 2

cdf of *I*/*N*, USAMEO-1 into LEOSAT-1 uplink and downlink

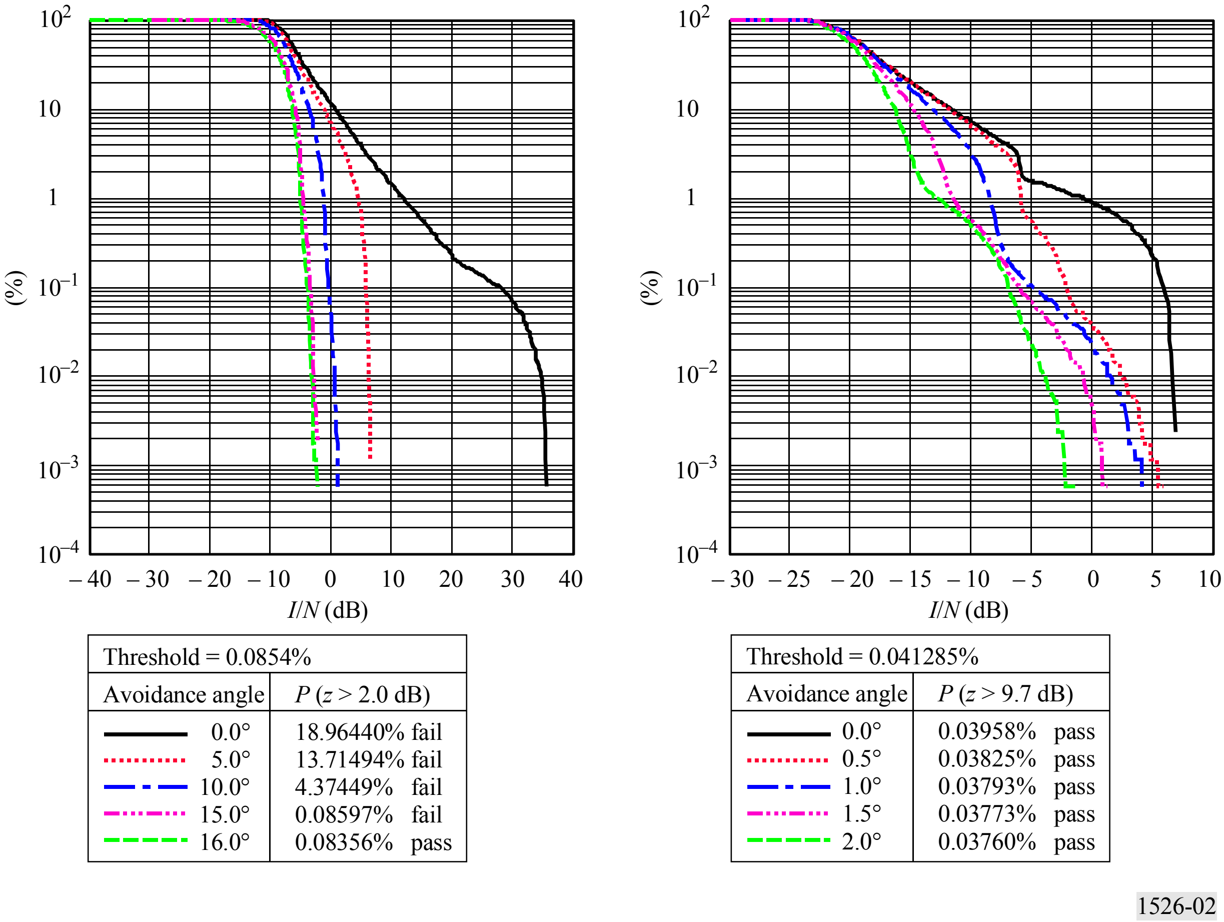


FIGURE 3

cdf of *I*/*N*, LEOSAT-1 into USAMEO-1 uplink and downlink

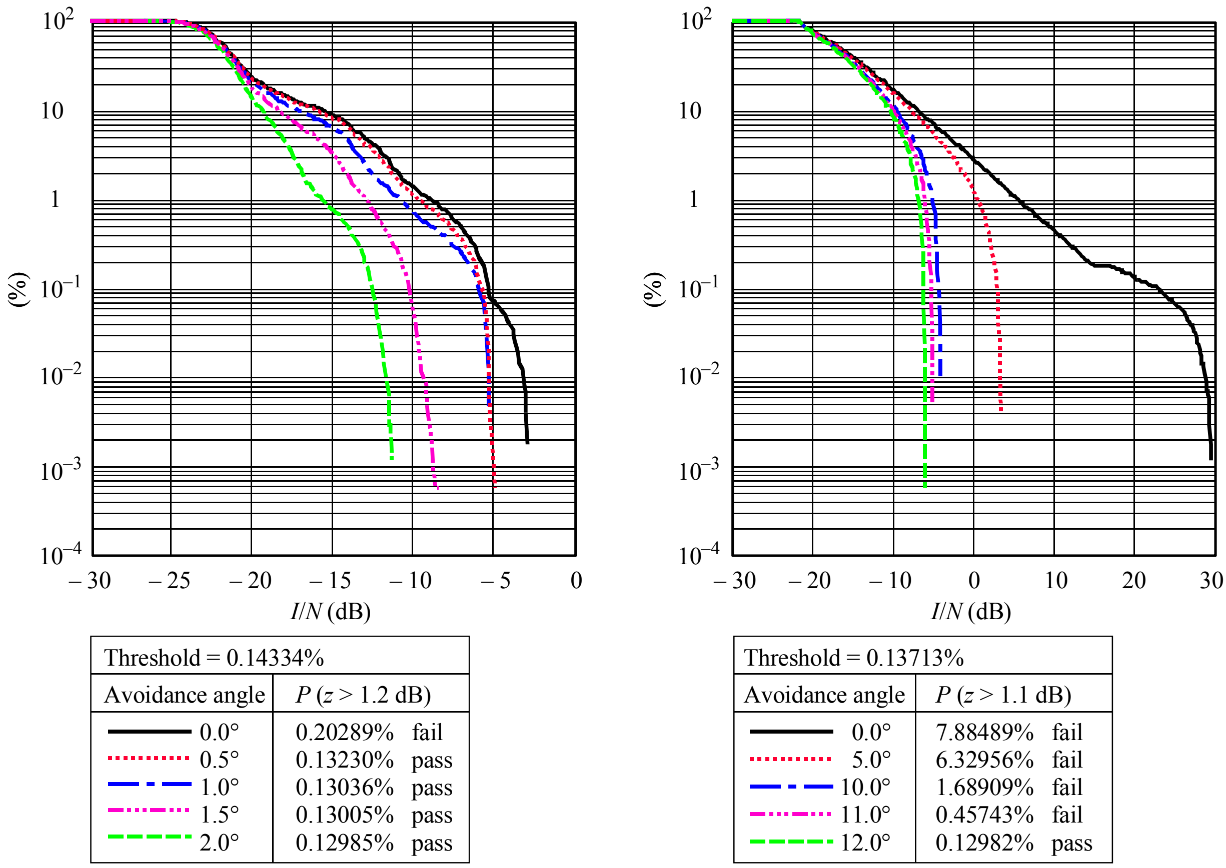


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FIGURE 4

Impact of mitigation about LEOSAT-1 on USAMEO-1 visibility

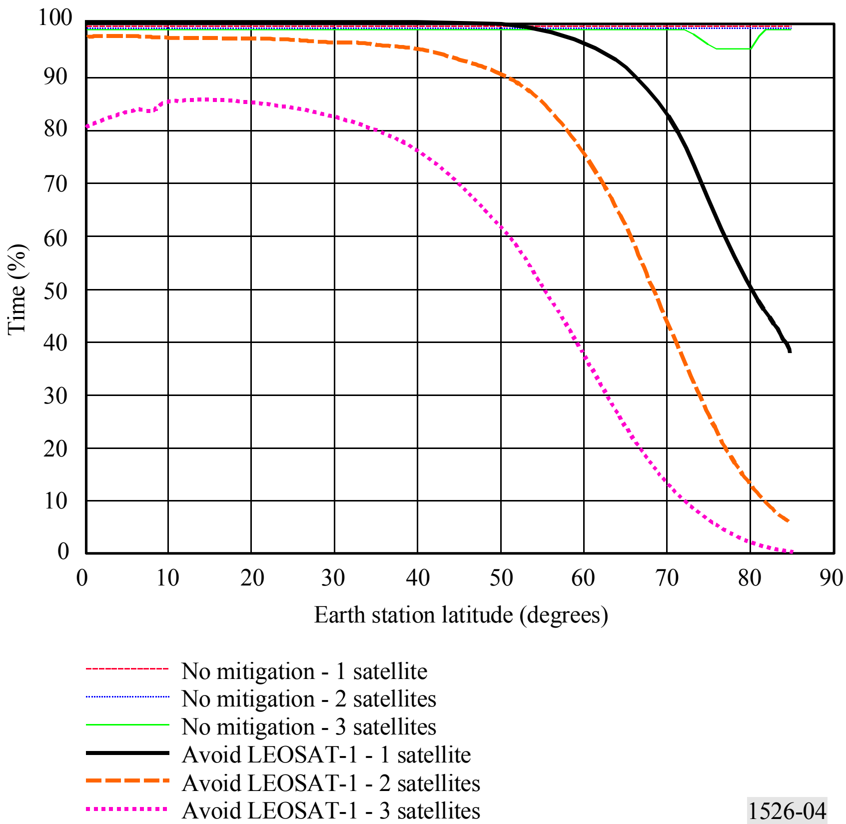
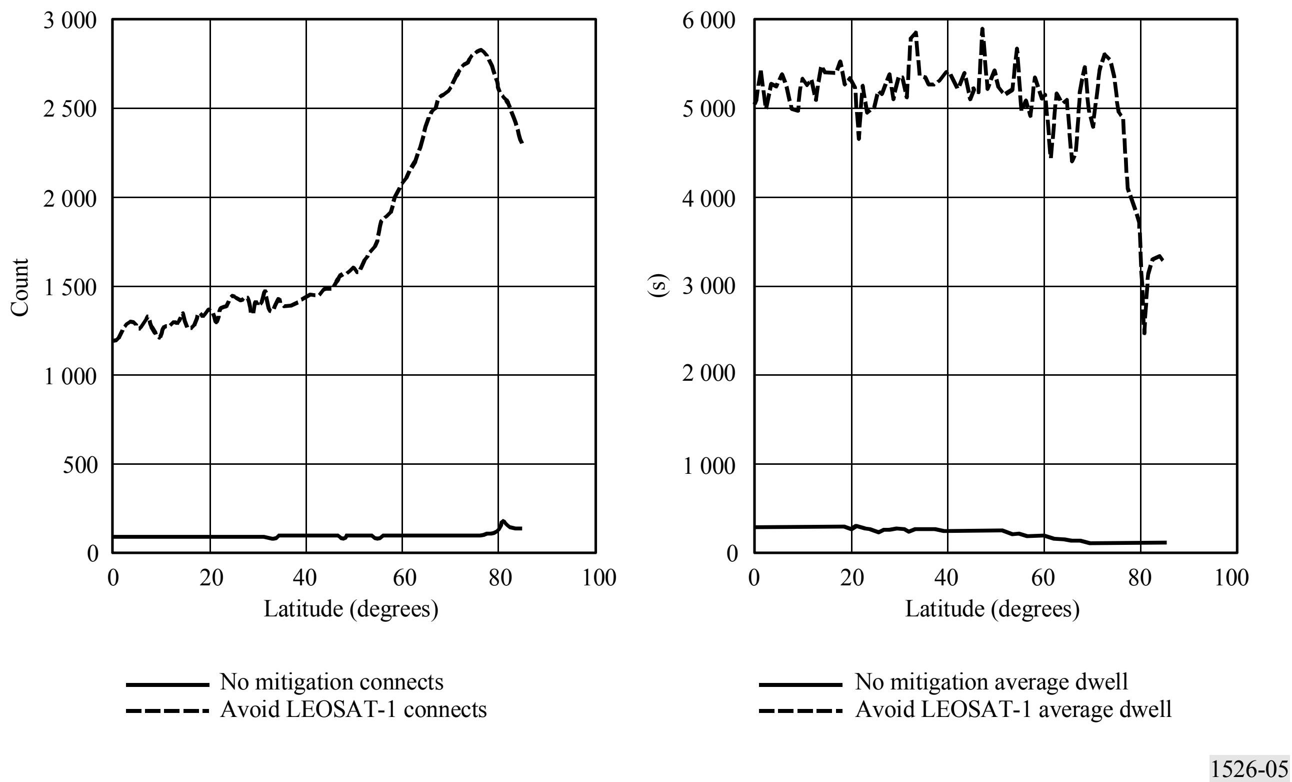


FIGURE 5

Impact of mitigation about LEOSAT-1 on USAMEO-1 satellite handoffs and satellite average track time



The effect of weighting the visibility statistics by the population distribution and the GDP distribution (1999 estimates) is shown in Tables 6 and 7. However, it would ultimately be necessary for the parties involved (i.e., the operators of Systems A and B), in any resultant coordination agreement, to agree on the application of any weighted averaging technique.

TABLE 6

Per cent of world population receiving coverage level at indicated percentile with LEOSAT-1 avoidance

Percentile	Coverage with no mitigation			Coverage with mitigation		
	1X	2X	3X	1X	2X	3X
100	100.00	100.00	100.00	0.00	0.00	0.00
99	100.00	100.00	100.00	94.99	0.00	0.00
95	100.00	100.00	100.00	99.71	79.95	0.00
90	100.00	100.00	100.00	99.89	93.81	0.00
80	100.00	100.00	100.00	99.99	99.01	67.57
50	100.00	100.00	100.00	100.00	99.94	98.22

TABLE 7

Per cent of world GDP receiving coverage level at indicated percentile with LEOSAT-1 avoidance

Percentile	Coverage with no mitigation			Coverage with mitigation		
	1X	2X	3X	1X	2X	3X
100	100.00	100.00	100.00	0.00	0.00	0.00
99	100.00	100.00	100.00	88.06	0.00	0.00
95	100.00	100.00	100.00	99.37	52.44	0.00
90	100.00	100.00	100.00	99.83	84.36	0.00
80	100.00	100.00	100.00	99.99	97.89	28.96
50	100.00	100.00	100.00	100.00	99.91	96.73

2.3.2 Results of USAMEO-1 with LEO-XX

As with LEOSAT-1, because the mitigating system is a MEO and the other system is a LEO, it is appropriate to use a space station based avoidance angle for Cases 2 and 3 and an earth station based avoidance angle for Cases 1 and 4, to provide the necessary protection. The angle values reflected in Figs. 6 and 7 are for space station based or earth station based angles, correspondingly.

In order to protect all four interference cases, the mitigating system would need to employ an earth station based avoidance angle of 13° and a space station based avoidance angle of 0.5°.

FIGURE 6

cdf of *I*/*N*, USAMEO-1 into LEO-XX uplink and downlink

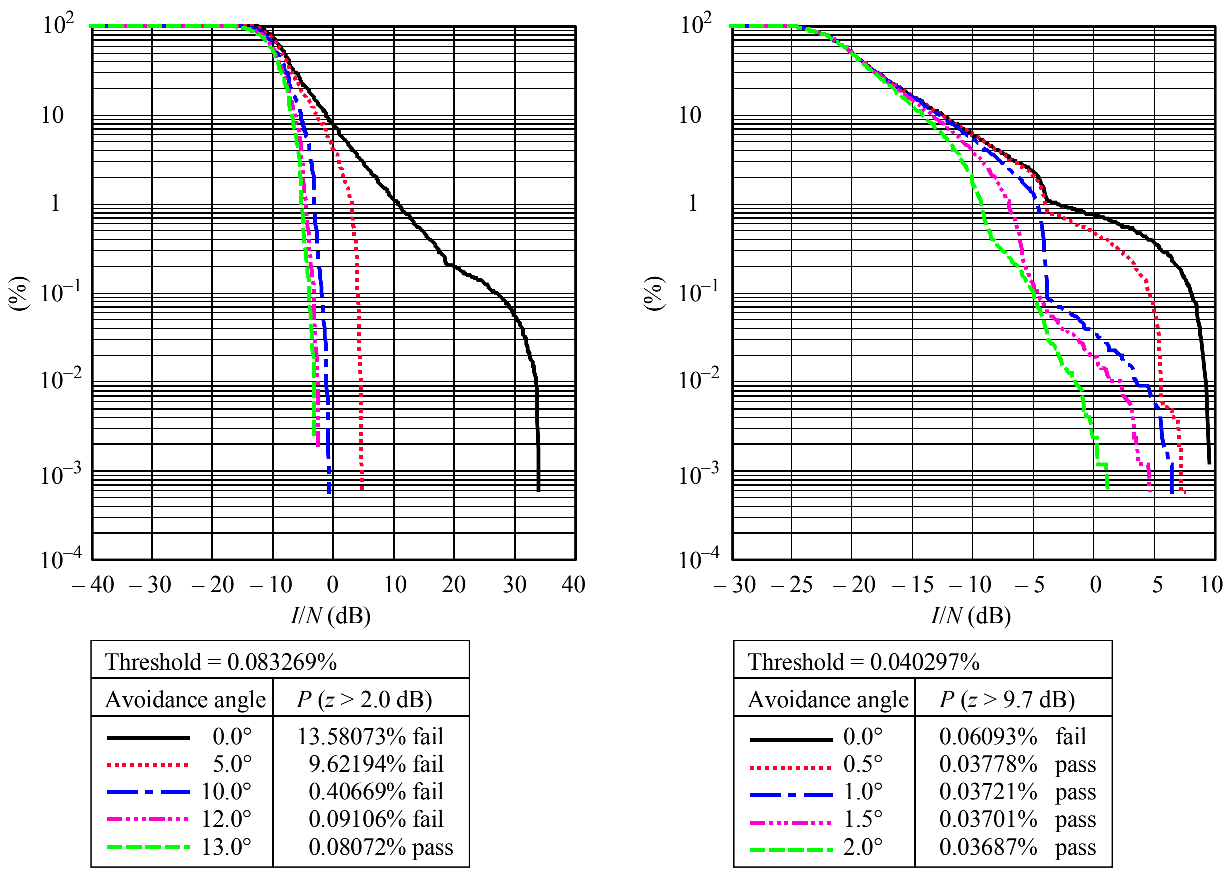


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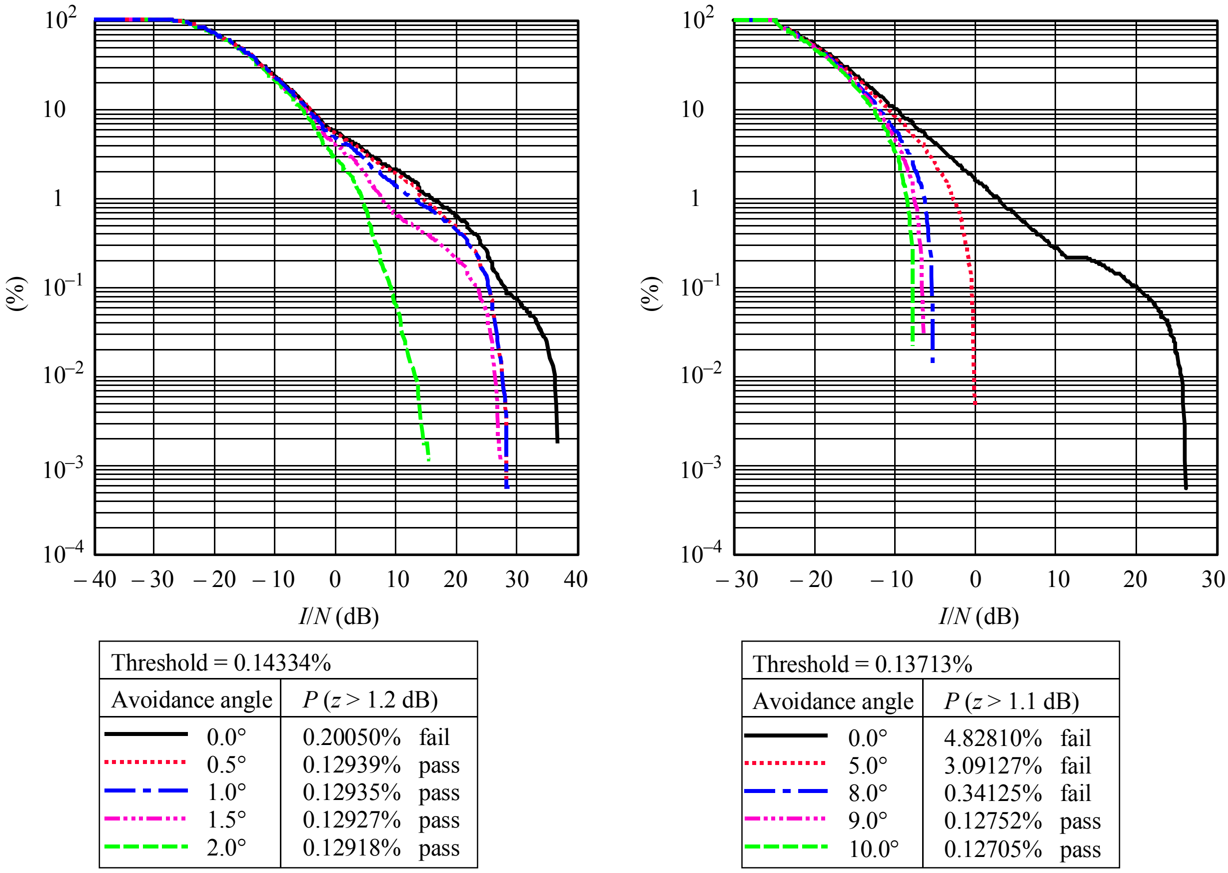
FIGURE 7

cdf of *I*/*N*, LEO-XX into USAMEO-1 uplink and downlink



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The impact on the mitigating system is shown in Fig. 8 – the plot for the visibility (i.e. the number of usable satellites satisfying elevation mask and mitigation criteria), and in Fig. 9 – the plots for satellite handoffs (connections) to new satellites, and the average earth station to satellite track time (dwell) of a beam on a satellite.

FIGURE 8

Impact of mitigation about LEO-XX on USAMEO-1 visibility

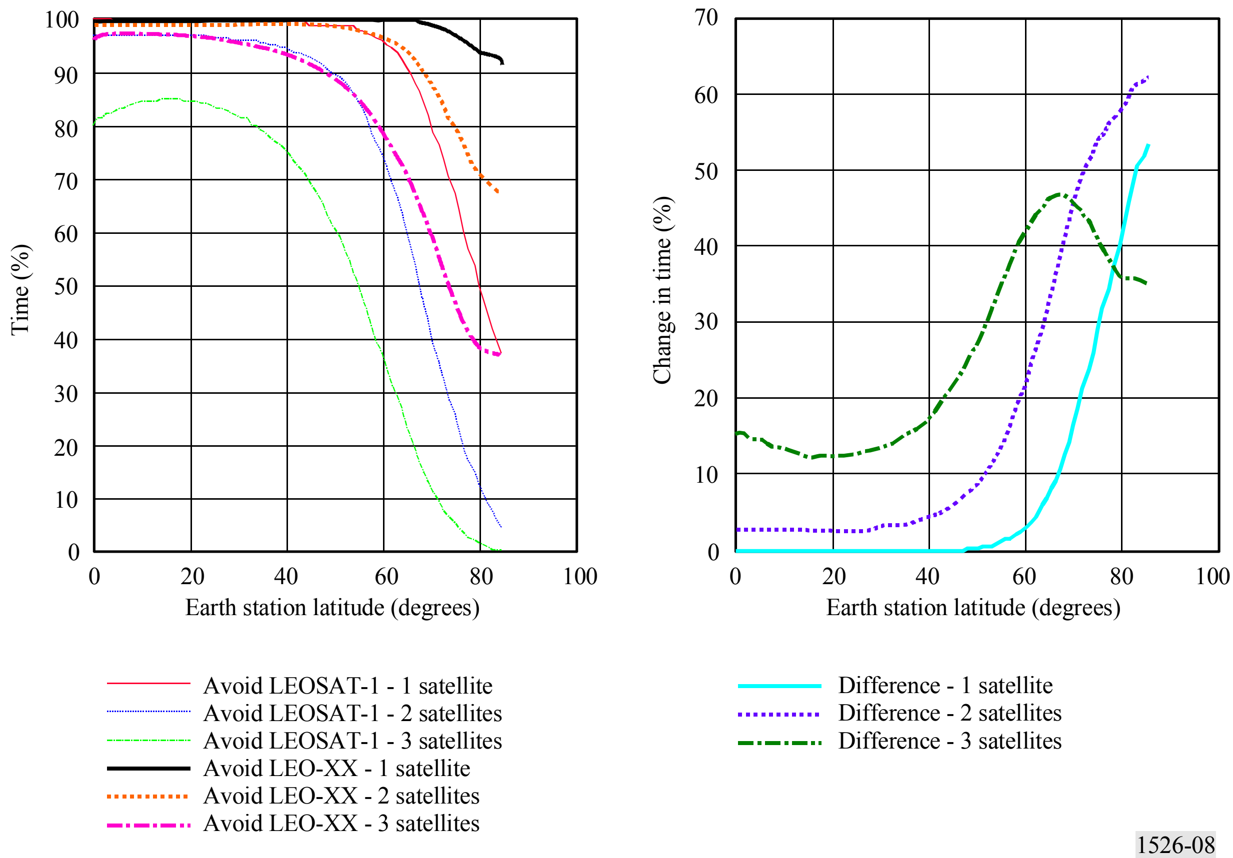
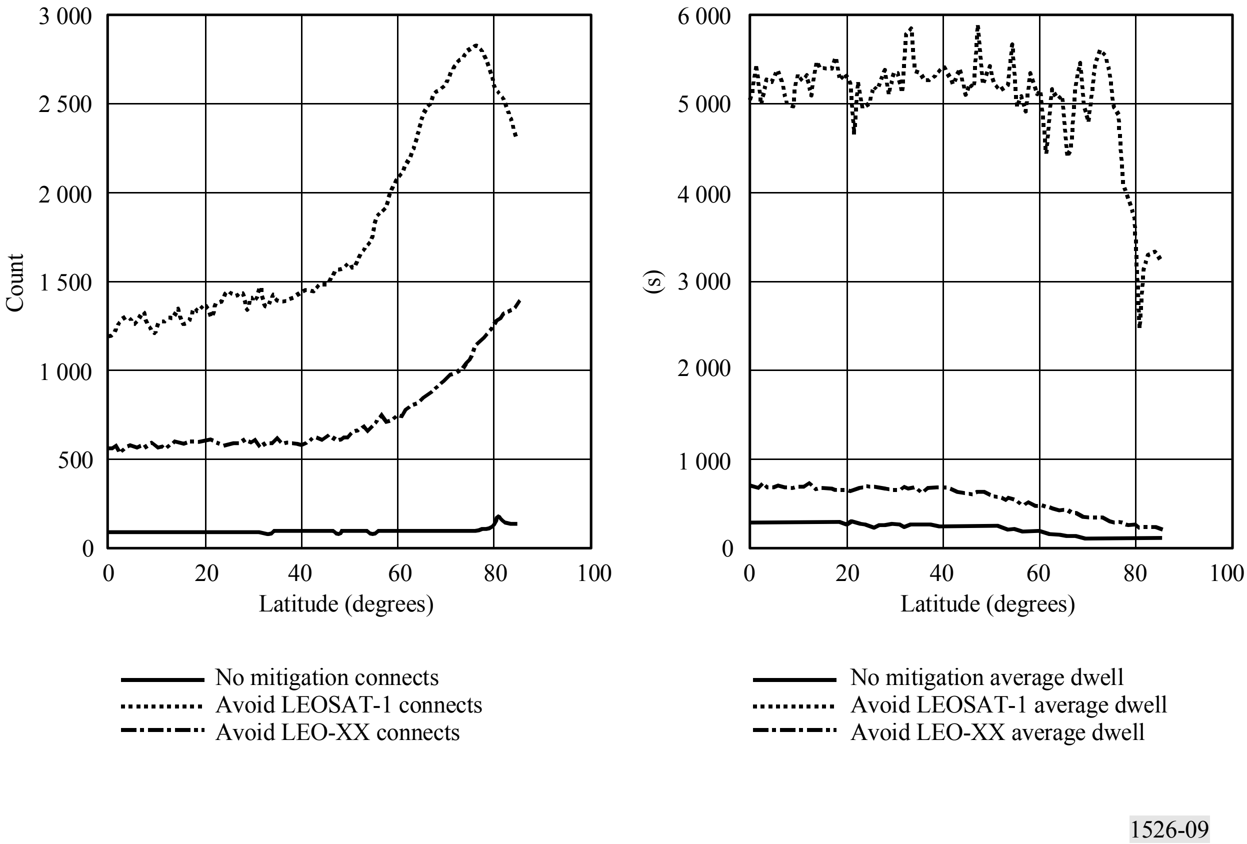


FIGURE 9

Impact of mitigation about LEO-XX on USAMEO-1 satellite handoffs and satellite average track time



The effect of weighting the visibility statistics by the population distribution and the GDP distribution (1999 estimates) is shown in Tables 8 and 9.

TABLE 8

Per cent of world population receiving coverage level at indicated percentile with LEO-XX avoidance

Percentile	Coverage			Change from LEOSAT-1 coverage		
	1X	2X	3X	1X	2X	3X
100	0.00	0.00	0.00	0.00	0.00	0.00
99	99.98	85.47	0.00	4.99	85.47	0.00
95	100.00	99.82	61.87	0.29	19.87	61.87
90	100.00	99.96	90.79	0.11	6.15	90.79
80	100.00	100.00	99.39	0.01	0.99	31.83
50	100.00	100.00	100.00	0.00	0.06	1.78

TABLE 9

Per cent of world GDP receiving coverage level at indicated percentile with LEO-XX avoidance

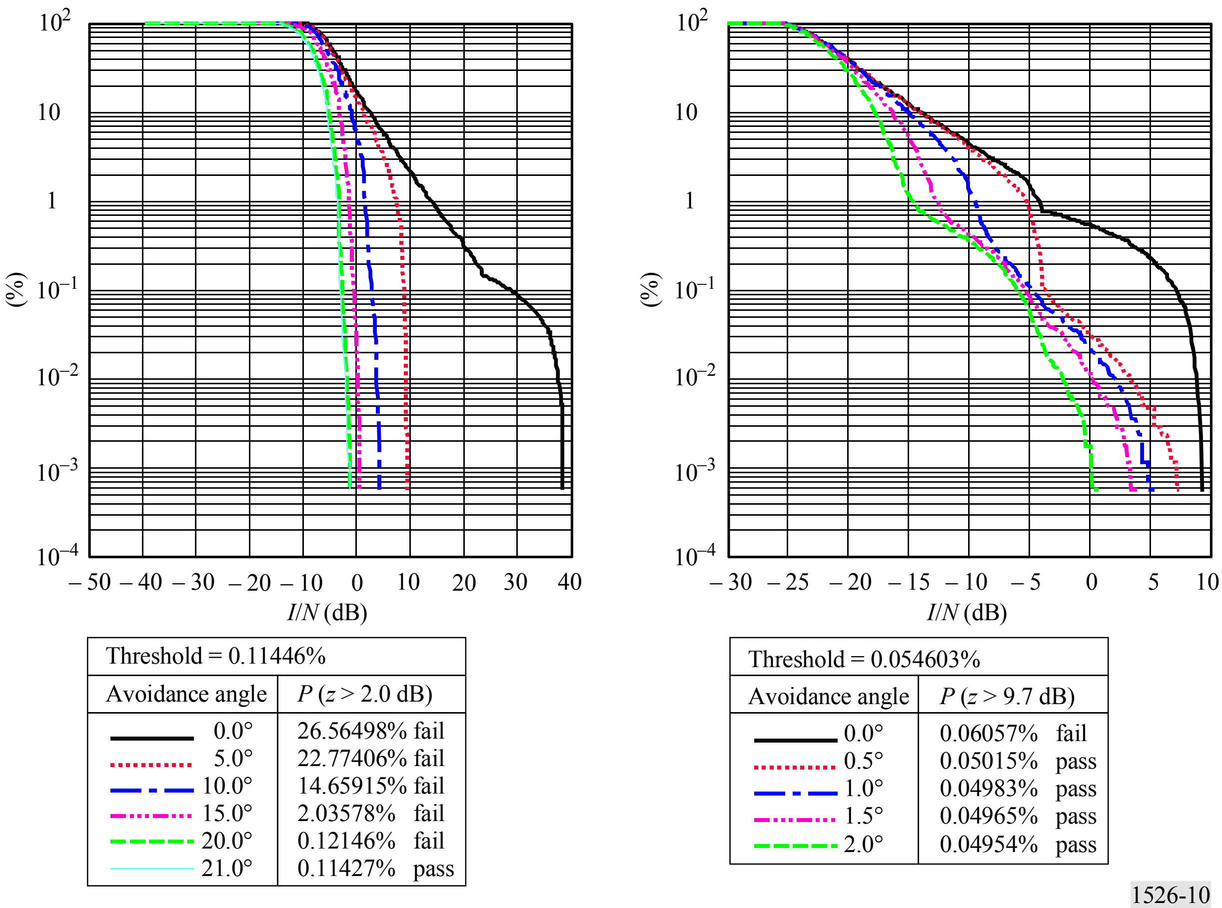
Percentile	Coverage			Change from LEOSAT-1 coverage		
	1X	2X	3X	1X	2X	3X
100	0.00	0.00	0.00	0.00	0.00	0.00
99	99.97	64.36	0.00	11.92	64.36	0.00
95	100.00	99.67	20.39	0.63	47.23	20.39
90	100.00	99.94	76.54	0.17	15.58	76.54
80	100.00	100.00	98.58	0.01	2.11	69.62
50	100.00	100.00	100.00	0.00	0.09	3.27

2.3.3 Results of USAMEO-1 with LEO-YY

Again, because the mitigating system is a MEO and the other system is a LEO, it is appropriate to use a space station based avoidance angle for Cases 2 and 3 and an earth station based avoidance angle for Cases 1 and 4, to provide the necessary protection. The angle values reflected in Figs. 10 and 11 are for space station based or earth station based angles, correspondingly.

FIGURE 10

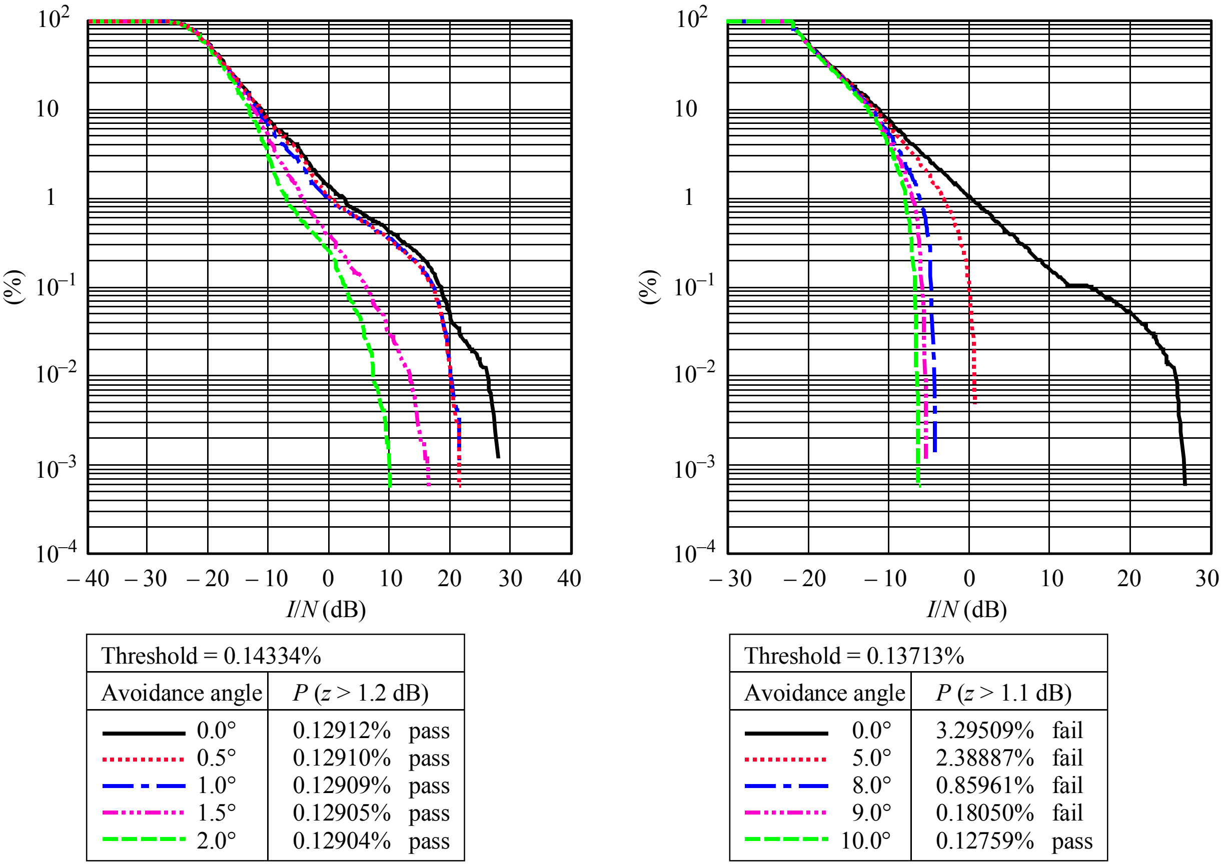
cdf of *I*/*N*, USAMEO-1 into LEO-YY uplink and downlink



1526-10

FIGURE 11

cdf of *I*/*N*, LEO-YY into USAMEO-1 uplink and downlink



1526-11

In order to protect all four interference cases, the mitigating system would need to employ an earth station based avoidance angle of 21.0° and a space station based avoidance angle of 0.5°.

The impact on the mitigating system is shown in Fig. 12 – the plot for the visibility (i.e. the number of usable satellites satisfying elevation mask and mitigation criteria), and in Fig. 13 – the plots for satellite handoffs (connections) to new satellites, and the average earth station to satellite track time (dwell) of a beam on a satellite.

FIGURE 12

Impact of mitigation about LEO-YY on USAMEO-1 visibility

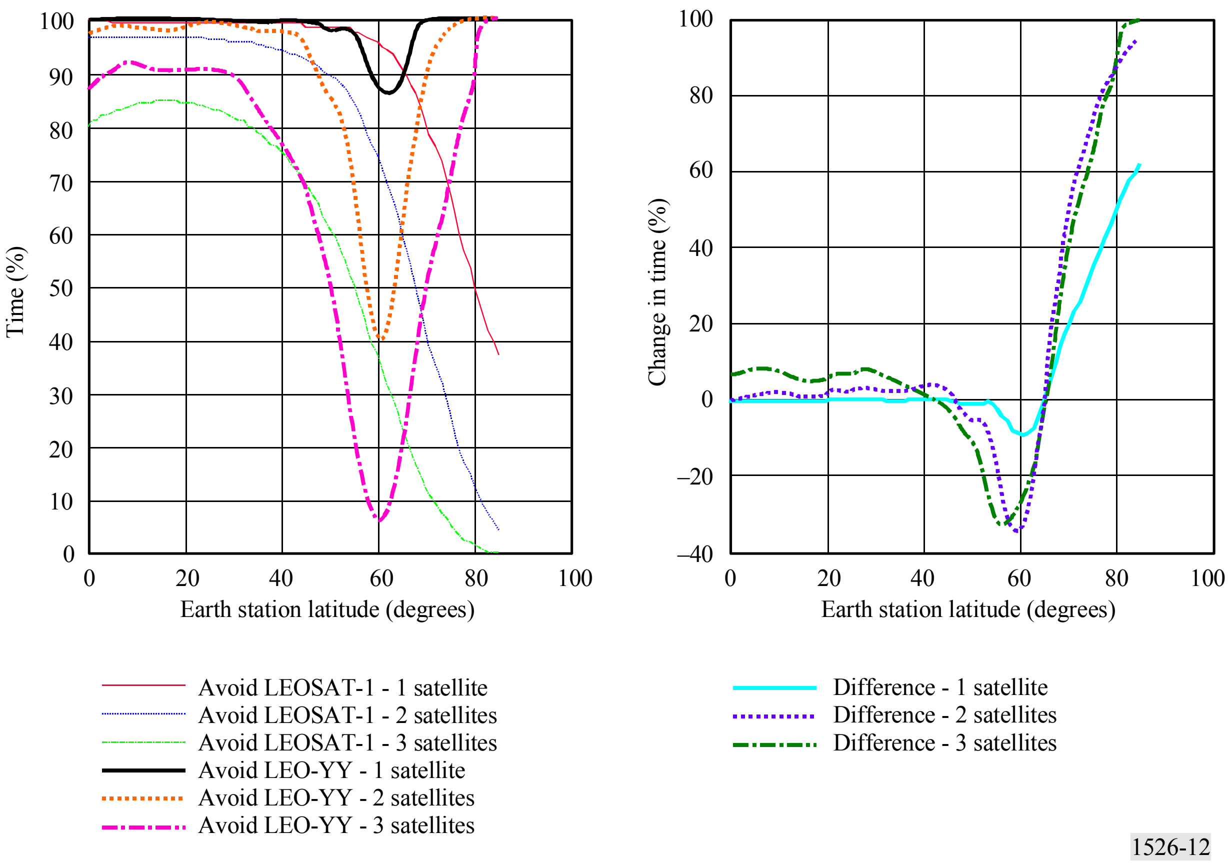
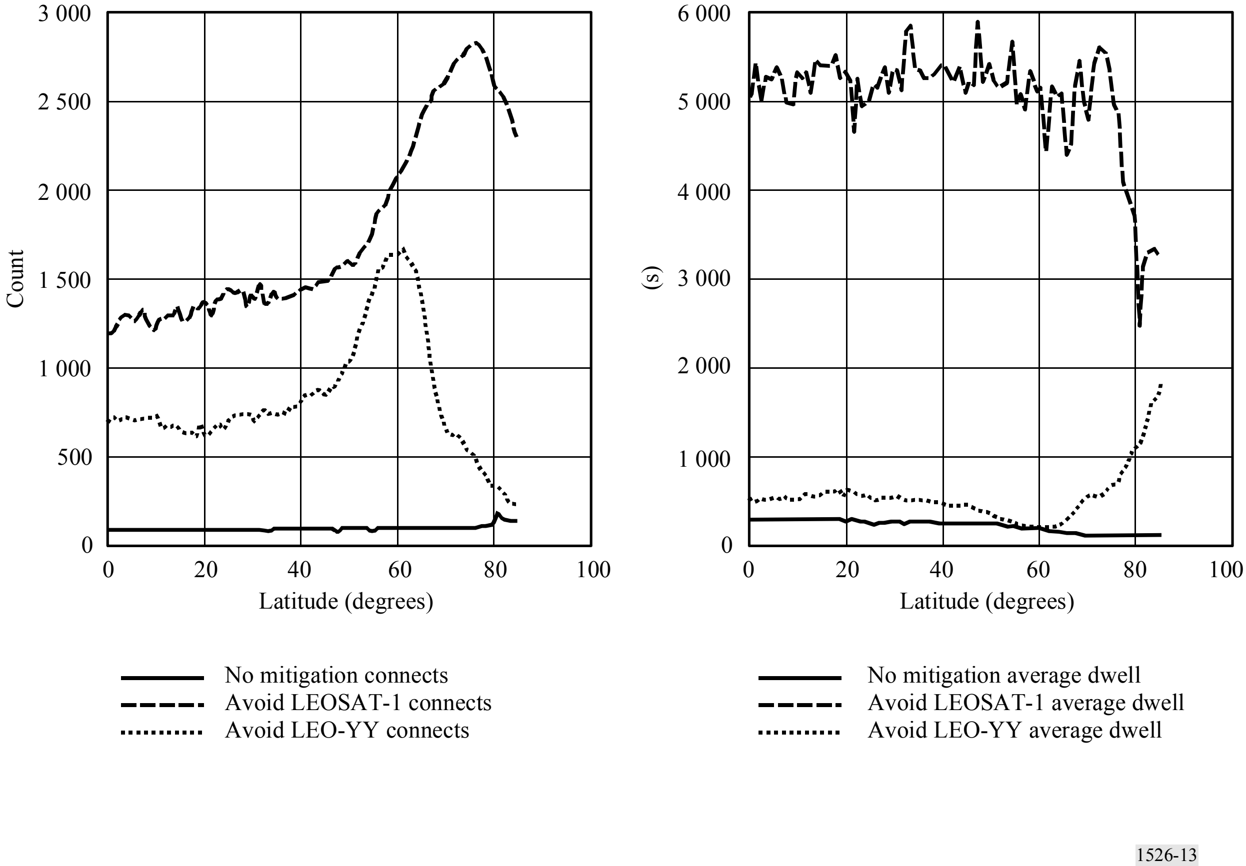


FIGURE 13

Impact of mitigation about LEO-YY on USAMEO-1 satellite handoffs and satellite average track time



The effect of weighting the visibility statistics by the population distribution and the GDP distribution (1999 estimates) is shown in Tables 10 and 11.

TABLE 10

Per cent of world population receiving coverage level at indicated percentile with LEO-YY avoidance

Percentile	Coverage			Change from LEOSAT-1 coverage		
	1X	2X	3X	1X	2X	3X
100	8.53	0.00	0.00	8.53	0.00	0.00
99	91.86	41.22	0.00	–3.13	41.22	0.00
95	98.79	88.86	0.00	–0.92	8.91	0.00
90	99.34	90.80	50.32	–0.54	–3.01	50.32
80	100.00	97.04	78.26	0.01	–1.97	10.69
50	100.00	99.19	93.82	0.00	–0.75	–4.40

TABLE 11

Per cent of world GDP receiving coverage level at indicated percentile with LEO-YY avoidance

Percentile	Coverage			Change from LEOSAT-1 coverage		
	1X	2X	3X	1X	2X	3X
100	6.64	0.00	0.00	6.64	0.00	0.00
99	79.28	13.49	0.00	–8.78	13.49	0.00
95	97.58	72.33	0.00	–1.79	19.89	0.00
90	98.42	76.55	14.81	–1.41	–7.81	14.81
80	100.00	94.36	49.37	0.01	–3.53	20.42
50	100.00	98.22	84.37	0.00	–1.69	–12.36

3 Example for the sharing with a GSO FSS system: Impact of modifications to LEOSAT-1 on GSO FSS System P

The following illustrates through a particular example an application of the methodology in a situation where co-frequency transmissions to and from the satellite of GSO FSS System P cease near in-line events in order to limit mutual interference between the two systems to the 10% of time interference allowances prescribed in Recommendation ITU-R S.1323. If deemed appropriate other interference allowances might be used. No assumption is made here about how the mitigating FSS system would maintain service during the cessation of co-frequency transmissions. Determining the statistics for the interference level corresponding to a 10% increase in unavailability is useful because this level can be considered to define the point at which interference is permissible according to Recommendation ITU-R S.1323. If, in both cases, interference is below a level corresponding to a permissible single-entry allowance, there is no need to assess changes to a non-GSO FSS system. In this example, the 10% increase in unavailability is used to determine this single-entry interference level. However, further work is needed to determine an appropriate value for such a level. Results for these assumptions are shown in § 3.2.

However, it may be that in some cases the affected system (System B) may find it preferable to accept more interference into its own links while continuing to protect the modified system (System A) to the levels indicated in Recommendation ITU-R S.1323. Results of these modified assumptions are shown in § 3.3. Note that assumptions in this example are also applicable to the case of two non-GSO FSS systems if the mitigating system does not have diversity capability. It should also be noted that this is one particular example. Other examples may include the case where a non-GSO FSS and GSO FSS system have reached a coordination agreement and both systems plan to employ mitigation techniques to enable co-frequency sharing. In this case the mitigation strategies of both systems would be used when computing the performance statistics before and after the proposed modifications.

The characteristics of System P are contained in Table 5 of Recommendation ITU-R S.1328 – Satellite system characteristics to be considered in frequency sharing analyses between geostationary-satellite orbit (GSO) and non-GSO satellite systems in the fixed-satellite service (FSS) including feeder links for the mobile-satellite service (MSS). Accordingly, four earth station-based avoidance angles are determined, each one corresponding to one of the four interference scenarios shown in Fig. 1.

In order to determine performance statistics, a certain number of earth stations are considered in the satellite service area. For each of them, the percentage of time during which communications between this earth station and the satellite can be maintained is calculated. Performance statistics are: the percentage of time the two-way link between an earth station and the GSO satellite can operate without an increase in unavailability of 10% being caused to or received from the non-GSO FSS system, and this quantity averaged over the set of considered earth stations; this same average percentage of time weighted by population distribution; and again the same average percentage of time weighted by GDP. Also useful would be the duration and frequency statistics of loss of service.

In general, FSS systems have a wide range of frequencies available to them and it would be unwise to assume that simultaneous overlap in both the uplink and the downlink will necessary occur. If a given system has enough flexibility in the use of frequencies so that there might be overlap only in the uplink, only in the downlink, or in both directions, all these three cases would have to be examined.

The parameters of LEOSAT-1 and its variations LEO-XX and LEO-YY are the same as described in § 2.1.

3.1 System P parameters and assumptions

3.1.1 Basic characteristics

The GSO system used in the simulations was based on satellite System P with the regenerative link parameters (Ka-3 and Ka-4). A GSO longitude of 80° W was chosen as an orbital location from where service can be provided to the Americas. The basic simulation modelling parameters are listed in Table 12.

TABLE 12

GSO FSS System P characteristics

Constellation parameters	
Number of satellites	1
GSO longitude (degrees)	–80
Minimum elevation mask angle (degrees)	10
Uplink transmission parameters	
Access method	TDMA/FDMA
Carrier bandwidth (MHz)	0.333
Power control	No
Earth station transmit peak gain (dB)	45.1
Earth station transmit antenna pattern	Rec. ITU-R S.465
Earth station transmit antenna diameter (m)	0.66
Satellite receive peak gain (dB)	47.7
Satellite receive antenna pattern	Rec. ITU-R S.672, Beamwidth = 0.6°, L_N = –25 dB
Receive beam adapted for constant cell size?	No
Noise temperature (K)	577.85
Number of receive beams	1
Downlink transmission parameters	
Access method	TDM/FDM
Carrier bandwidth (MHz)	115
Power control	No
Earth station receive peak gain (dB)	41.6
Earth station antenna pattern	Rec. ITU-R S.465
Earth station antenna diameter (m)	0.66
Satellite transmit peak gain (dB)	46.2
Satellite transmit antenna pattern	(same as uplink)
Satellite Transmit e.i.r.p. at EOC (dB)	62.5
Transmit beam adapted for constant cell size?	No
Noise temperature (K)	187.45
Number of transmit beams	1

3.1.2 Link budget and rain degradation assumptions

The link budget shown in Table 13 applies to the GSO system model.

TABLE 13

GSO FSS System P link budgets

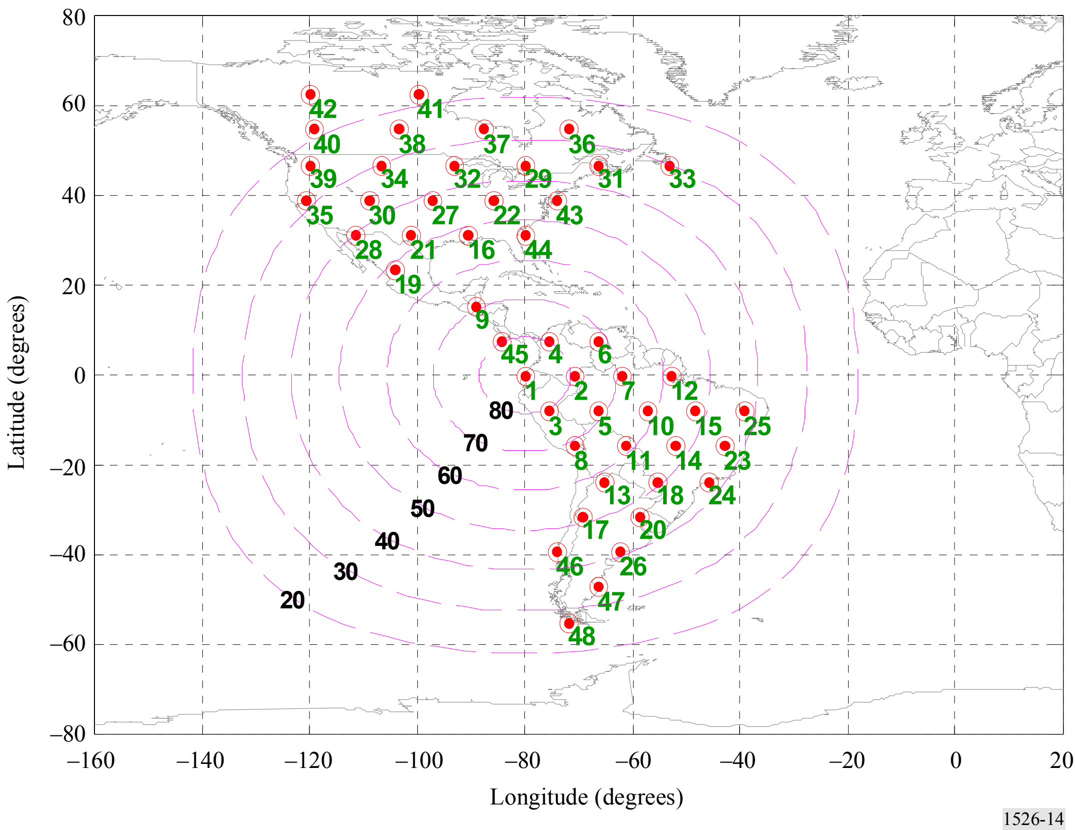
Minimum elevation (degrees) Slant range (km)	10 40 586	
	Uplink	*Downlink*
Frequency (GHz)	30	20
Bandwidth (MHz)	0.33	115
Data rate (Mbit/s)	0.38	120
Channel spacing (MHz)	0.42	140
Power – backoff/losses (dBW)	–3.39	16.30
Transmit gain (dB)	45.10	46.20
e.i.r.p. (dBW)	*41.71*	*62.50*
Transmit pointing loss (dB)	1.00	3.00
Free space loss (dB)	214.16	210.64
Atmospheric loss (dB)	0.23	0.25
Total propagation loss (dB)	*215.39*	*213.89*
System temperature (K)	577.85	187.45
Receive gain (dB)	47.70	41.60
Receive loss (dB)	0.00	1.00
Receive edge of beam loss (dB)	3.00	0.00
G/T (dB)	17.08	17.87
Received carrier (C) (dBW)	*–128.98*	*–110.79*
N (dBW)	–145.76	–125.26
C/N (dB)	16.78	14.47
C/N required (dB)	5.80	4.80
Required margin (dB)	2.50	2.50
Margin for rain external interference (dB)	8.48	7.17

The entry in Table 13 labelled "Required margin" is assumed to refer to self-interference and other degradations not related to rain or external interference. Based on the small variation in e.i.r.p. between the minimum and maximum values listed in Table 5 of Recommendation ITU-R S.1328, no power control is assumed for either uplink or downlink. These variations are assumed to allow for pointing errors and edge-of-beam losses. With both uplink and downlink using constant transmit powers, any rain fading will start to degrade the link.

The ground segment of the GSO system was modelled with evenly spaced earth stations covering the land masses over the Americas above 10° elevation. A spacing of 1 000 km was used, resulting in 48 earth station locations. These earth station locations are shown in Fig. 14, along with elevation angle contours with respect to the GSO satellite.

FIGURE 14

Distribution of system P earth stations used in the simulations



Because the elevation angle and rain characteristics are different for each of these 48 earth station locations, a different rain degradation model was assumed for each position. (The rain and interference degradation pdfs from each simulation run are convolved to determine whether or not the interference is at an acceptable level.) For each location, the corresponding elevation angle, rain loss, atmospheric loss, and antenna temperature were adjusted to determine the resulting link margin.

Table 14 summarizes the assumptions used to generate the pdf of the rain degradation for each of the 48 earth station locations. The α parameter, which represents the percentage of noise increase due to self interference $I_S/(N + I_S)$ and is used in relating the rain degradation with the rain fading from the indicated rain model, is zero in all cases. The rain model of Recommendation ITU-R P.618 was used for this analysis.

TABLE 14

Link margins and downlink rain fade

Earth station ID	Uplink rain fade and margin (dB)	Downlink margin (dB)	Downlink rain fade (dB)
1	9.57	11.59	8.24
2	9.54	11.55	8.20
3	9.54	11.55	8.20
4	9.54	11.55	8.20
5	9.49	11.47	8.14
6	9.49	11.47	8.14
7	9.46	11.43	8.11
8	9.46	11.42	8.10
9	9.46	11.42	8.10
10	9.39	11.30	8.01
11	9.38	11.29	8.00
12	9.33	11.21	7.94
13	9.33	11.20	7.93
14	9.25	11.07	7.83
15	9.23	11.04	7.81
16	9.22	11.02	7.80
17	9.22	11.02	7.80
18	9.22	11.01	7.78
19	9.22	11.01	7.78
20	9.13	10.85	7.67
21	9.13	10.85	7.67
22	9.07	10.75	7.59
23	9.07	10.74	7.58
24	9.05	10.70	7.55
25	9.03	10.67	7.53
26	9.00	10.61	7.49
27	9.00	10.61	7.49

TABLE 14 (*end*)

Earth station ID	Uplink rain fade and margin (dB)	Downlink margin (dB)	Downlink rain fade (dB)
28	8.97	10.55	7.44
29	8.87	10.34	7.29
30	8.86	10.32	7.28
31	8.82	10.25	7.23
32	8.82	10.25	7.23
33	8.69	9.95	7.01
34	8.69	9.95	7.01
35	8.63	9.82	6.92
36	8.58	9.71	6.85
37	8.58	9.71	6.85
38	8.46	9.41	6.64
39	8.44	9.36	6.61
40	8.18	8.67	6.14
41	8.12	8.50	6.03
42	7.69	7.32	5.24
43	9.07	10.75	7.59
44	9.26	11.08	7.84
45	9.54	11.55	8.20
46	9.07	10.75	7.59
47	8.82	10.25	7.23
48	8.58	9.71	6.85

3.2 Simulation results based on limiting interference in all four cases to the Recommendation ITU-R S.1323 levels

Separate simulation runs were performed for the GSO System P operating with each of the following systems:

– LEOSAT-1 (288 satellites, polar constellation, 40° minimum elevation).

– LEO-XX (128 satellites, polar constellation, 40° minimum elevation).

– LEO-YY (120 satellites, Walker Delta constellation, 25° minimum elevation).

Within each set of simulation runs, data was collected for all four interference cases, where each case is defined in Table 15.

TABLE 15

Interference case definition

Case	Link direction	Role of GSO System P
1	Uplink	Interferer
2	Downlink	Interferer
3	Uplink	Desired system
4	Downlink	Desired system

Similarly to what has been described in § 2.3.1, 2.3.2 and 2.3.3, runs were initially conducted to determine the avoidance angle necessary to pass the Recommendation ITU-R S.1323 criteria, assuming 10% of the link outage allowed for external interference is allocated for a single interference entry. To clarify, in this section, availability for the mitigating system is defined with respect to service occurring at angles greater than the calculated avoidance angle. However, if System P does not have any other alternative of providing service during in-line events, the total outage time of System P would also include periods of time corresponding to angles smaller than the calculated avoidance angle. These runs were for 2 days at 1 s intervals (172 800 iterations). All avoidance angles in § 3 are earth station-based angles.

These simulations have shown that the controlling avoidance angle is either associated with Case 1 (interference from GSO earth station into non-GSO satellite) or with Case 4 (interference from non-GSO satellites into GSO earth station). Table 16 presents the avoidance angles for Cases 1 and 4 corresponding to each of the 48 earth stations of the GSO system and each of the three non-GSO systems under consideration. For any given earth station and non-GSO FSS system, the controlling avoidance angle is in bold.

TABLE 16

Earth station based avoidance angles

	Case 1	*Case 4*	*Case 1*	*Case 4*	*Case 1*	*Case 4*
Earth station ID	T288	T288	T120	T120	T128	T128
1	**6.6**	5.1	**5.2**	4.2	4.6	**5.5**
2	**6.6**	5.2	**5.2**	4.2	4.6	**5.6**
3	**6.6**	5.6	**5.2**	4.2	4.6	**5.9**
4	**6.6**	6.3	**5.2**	4.3	4.6	**6.6**
5	**6.6**	5.7	**5.2**	4.3	4.6	**5.9**
6	**6.6**	5.7	**5.2**	4.3	4.6	**6.0**
7	**6.6**	5.5	**5.2**	4.2	4.6	**5.7**
8	6.7	**10.5**	5.4	**5.7**	4.7	**10.9**
9	**6.6**	6.3	**5.3**	4.2	4.6	**6.5**

TABLE 16 (*end*)

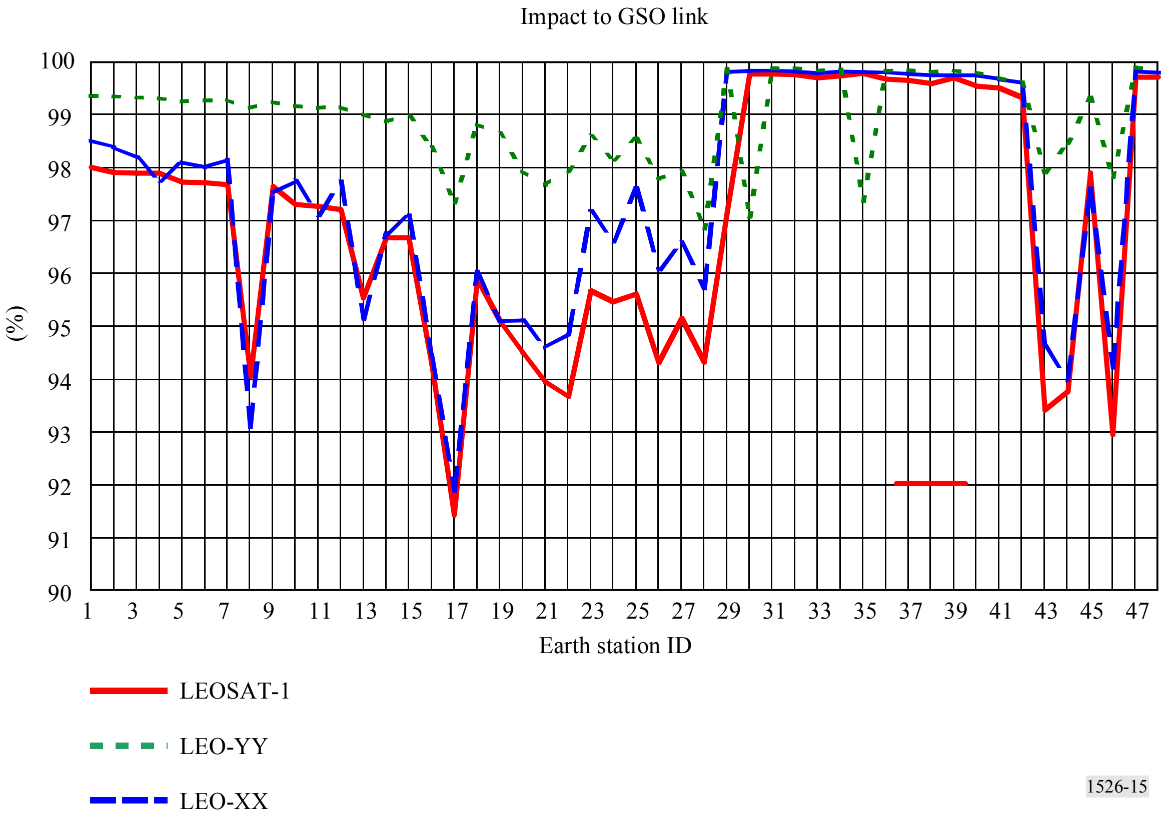
	Case 1	*Case 4*	*Case 1*	*Case 4*	*Case 1*	*Case 4*
Earth station ID	T288	T288	T120	T120	T128	T128
10	**6.6**	5.9	**5.1**	4.2	4.6	**6.0**
11	**6.6**	6.6	**5.3**	4.3	4.7	**6.7**
12	**6.6**	5.7	**5.2**	4.2	4.6	**5.8**
13	6.7	**8.1**	**5.4**	5.3	4.7	**8.3**
14	**6.6**	6.6	**5.3**	4.6	4.7	**6.6**
15	**6.6**	6.1	**5.0**	4.2	4.5	**6.1**
16	6.6	**8.3**	5.3	**6.2**	4.6	**8.2**
17	6.7	**10.1**	5.4	**7.8**	4.7	**9.9**
18	6.6	**7.1**	**5.4**	5.4	4.6	**7.0**
19	6.6	**7.8**	5.4	**5.8**	4.7	**7.8**
20	6.6	**7.6**	5.4	**6.5**	4.6	**7.3**
21	6.6	**7.9**	5.4	**6.9**	4.7	**7.6**
22	0.0	**7.5**	5.4	**6.0**	0.0	**7.1**
23	**6.4**	5.6	**5.3**	5.2	3.4	**5.5**
24	**6.5**	6.0	5.3	**6.0**	3.5	**5.9**
25	**6.1**	5.0	**5.3**	5.0	0.0	**4.9**
26	0.0	**6.8**	5.4	**5.9**	0.0	**6.0**
27	0.0	**6.3**	5.4	**5.7**	0.0	**5.5**
28	6.5	**6.8**	5.4	**7.2**	0.0	**6.2**
29	0.0	**4.2**	0.0	**1.2**	0.0	**1.3**
30	0.0	**1.3**	0.0	**6.1**	0.0	**1.2**
31	0.0	**1.2**	0.0	**1.2**	0.0	**1.1**
32	0.0	**1.2**	0.0	**1.2**	0.0	**1.1**
33	0.0	**1.2**	0.0	**1.2**	0.0	**1.1**
34	0.0	**1.2**	0.0	**1.2**	0.0	**1.1**
35	0.0	**1.1**	0.0	**5.0**	0.0	**1.1**
36	0.0	**1.2**	0.0	**1.1**	0.0	**1.1**
37	0.0	**1.2**	0.0	**1.1**	0.0	**1.1**
38	0.0	**1.2**	0.0	**1.1**	0.0	**1.1**
39	0.0	**1.1**	0.0	**1.1**	0.0	**1.1**
40	0.0	**1.1**	0.0	**1.0**	0.0	**1.0**
41	0.0	**1.1**	0.0	**1.1**	0.0	**1.1**
42	0.0	**1.1**	0.0	**1.1**	0.0	**1.1**
43	0.0	**7.7**	5.4	**6.1**	0.0	**7.3**
44	6.6	**8.8**	5.3	**6.1**	4.6	**8.7**
45	**6.6**	6.5	**5.1**	4.3	4.6	**6.9**
46	0.0	**7.9**	5.4	**6.2**	0.0	**7.5**
47	0.0	**1.3**	0.0	**1.2**	0.0	**1.2**
48	0.0	**1.1**	0.0	**1.1**	0.0	**1.1**

Having determined the earth station avoidance angles applicable in each case, simulation runs for five days at 1 s intervals (432 000 iterations) were conducted to compute the percentages of time during which the angle θ_T (Fig. 1, Case 1) or the angle θ_R (Fig. 1, Case 4), as applicable, is larger than the required avoidance angle. In Fig. 1, System A is the non-GSO FSS system and System B is the GSO system.

These percentages of time are shown in Fig. 15 as a function of the earth station identification number (1 through 48) and in Fig. 16 as a function of the elevation angle at the considered GSO earth station with respect to the GSO satellite.

FIGURE 15

Percentage of time that GSO link to and from a given earth station can operate without a specified level of interference being caused to or received from the non-GSO FSS system (as a function of GSO earth station ID)



The percentages of time shown in Fig. 15 (or Fig. 16) were averaged over the 48 earth stations and subsequently were averaged over the same earth stations weighted by population and then by GDP. These three different average percentages of time are given in Table 17 for each of the three non-GSO FSS systems under consideration. It is noted that in this example there is a large variation in the resulting unavailability for GSO FSS System P, ranging from 0.2% to 8.6%, depending on the specific earth station locations; averaging such large differences in unavailability percentages across all of the earth stations would not highlight such differences. It might also be appropriate, in addition to averaging, to compute the variance of these unavailability values. However, it would ultimately be necessary for the parties involved (i.e., Systems A and B), in any resultant coordination agreement, to agree on the details of the approach to be used, specifically, the calculation/simulation assumptions used in the analysis and the application of any weighted averaging technique.

FIGURE 16

Percentage of time that GSO link to and from a given earth station can operate without a specified level of interference being caused to or received from the non-GSO FSS system (as a function of GSO earth station elevation angle)

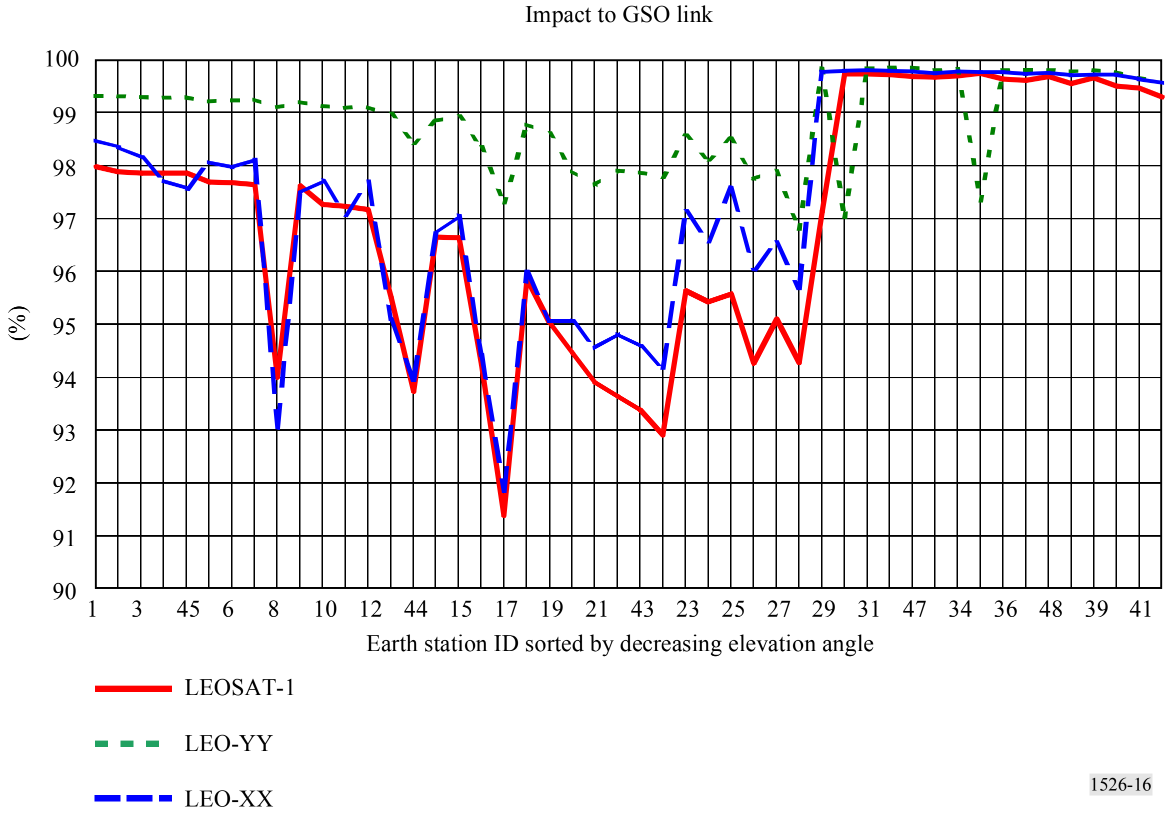


TABLE 17

Average percentages of time that GSO links to and from earth stations distributed over GSO service area can operate without a specified level of interference being caused to or received from the non-GSO FSS system

	LEOSAT-1	LEO-XX	LEO-YY
Average (%)	97.1	98.9	97.5
Average (weighted by population) (%)	95.8	98.5	96.4
Average (weighted by GDP) (%)	95.4	98.2	96.2

3.3 Simulation results based on only limiting interference in Cases 1 and 2 to Recommendation ITU-R S.1323 levels

In § 3.2, it was assumed that the GSO FSS System P would protect all four interference cases to a specified interference level. If, however, the GSO FSS System P (or a mitigating non-GSO FSS system) did not have some alternative means of continuing service during the cessation of co-frequency transmissions, link availability would be higher by accepting more interference into its own links rather than shutting off. In the limiting case, the GSO FSS System P might choose to operate its downlinks throughout all in-line events, effectively employing an avoidance angle of zero for interference Case 4. In this situation, the interference and the rain degradation have a combined effect on the availability of the GSO FSS System P downlink. To assess the impact to System P from the hypothetical modifications made to LEOSAT-1 in this situation, the relevant performance statistic is the resulting link availability before and after the modifications. Of course, protection for interference Cases 1 and 2 would still be required as determined in § 3.2.

In the example addressed in § 3.2, no avoidance angles were required for protection of Case 2 or Case 3 because the interference was less than a 10% increase in unavailability for each of the systems considered. In the general case, there could be avoidance angles for all four cases. Using the earth station avoidance angles derived for protecting Case 1 on the uplink, simulation runs for 5 days at 1 s intervals (432 000 iterations) were conducted to compute the percentages of time during which the angle θ_T (Fig. 1, Case 1) is larger than the required avoidance angle.

These percentages of time are shown in Fig. 17 as a function of the earth station identification number (1 through 48) and in Fig. 18 as a function of the elevation angle at the considered GSO earth station with respect to the GSO satellite.

FIGURE 17

Percentage of time that GSO links from a given earth station can operate without causing a specified level of interference to the non-GSO FSS system (as a function of GSO earth station ID)

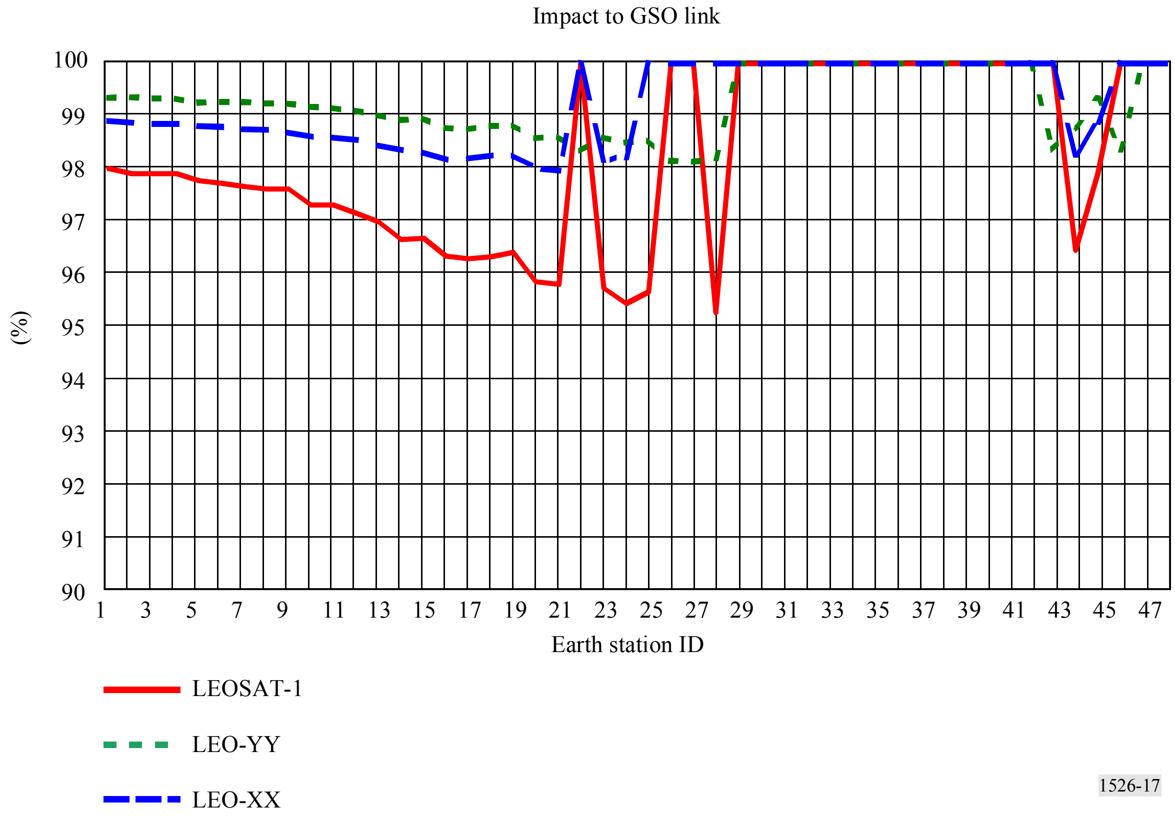
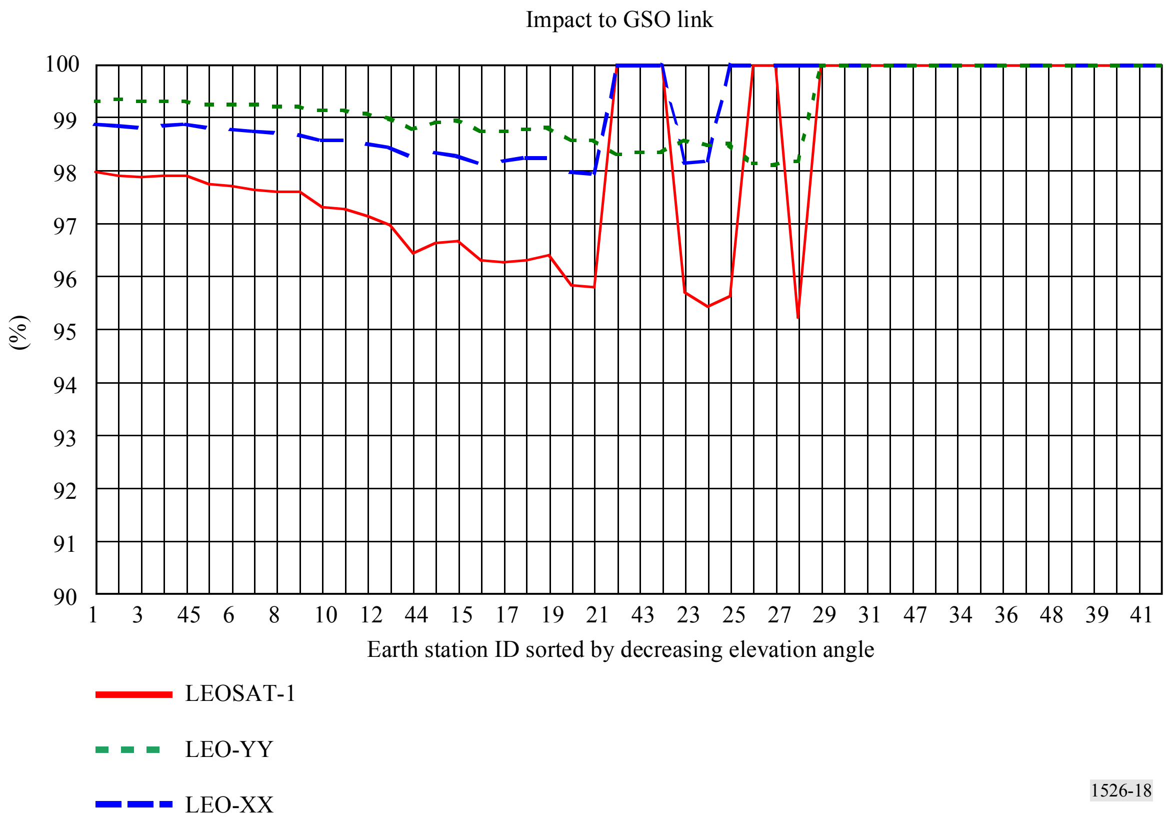


FIGURE 18

Percentage of time that GSO links from a given earth station can operate without causing a specified level of interference to the non-GSO FSS system (as a function of GSO earth station elevation angle)



The percentages of time shown in Fig. 17 (or Fig. 18) were averaged over the 48 earth stations and subsequently were averaged over the same earth stations weighted by population and then by GDP. These three different average percentages of time are given in Table 18 for each of the three non-GSO FSS systems under consideration.

TABLE 18

Average percentages of time that GSO links from earth stations distributed over GSO service area can operate without a specified level of interference being caused to the non-GSO FSS system

	LEOSAT-1	LEO-XX	LEO-YY
Average (%)	98.3	99.3	99.3
Average (weighted by population) (%)	97.7	98.9	99.1
Average (weighted by GDP) (%)	98.5	98.9	99.4

Similar runs were also made assuming that no avoidance angles were used to protect the GSO FSS downlink. The resulting availability of the GSO downlink in the presence of both interference and rain is then shown as a percentage of time for each of the GSO earth stations, as a function of earth station ID in Fig. 19, and as a function of the elevation angle at the considered GSO earth station with respect to the GSO satellite in Fig. 20.

FIGURE 19

Percentage of time for the GSO downlink availability in the presence of rain and interference from the non-GSO FSS system (as a function of GSO earth station ID)

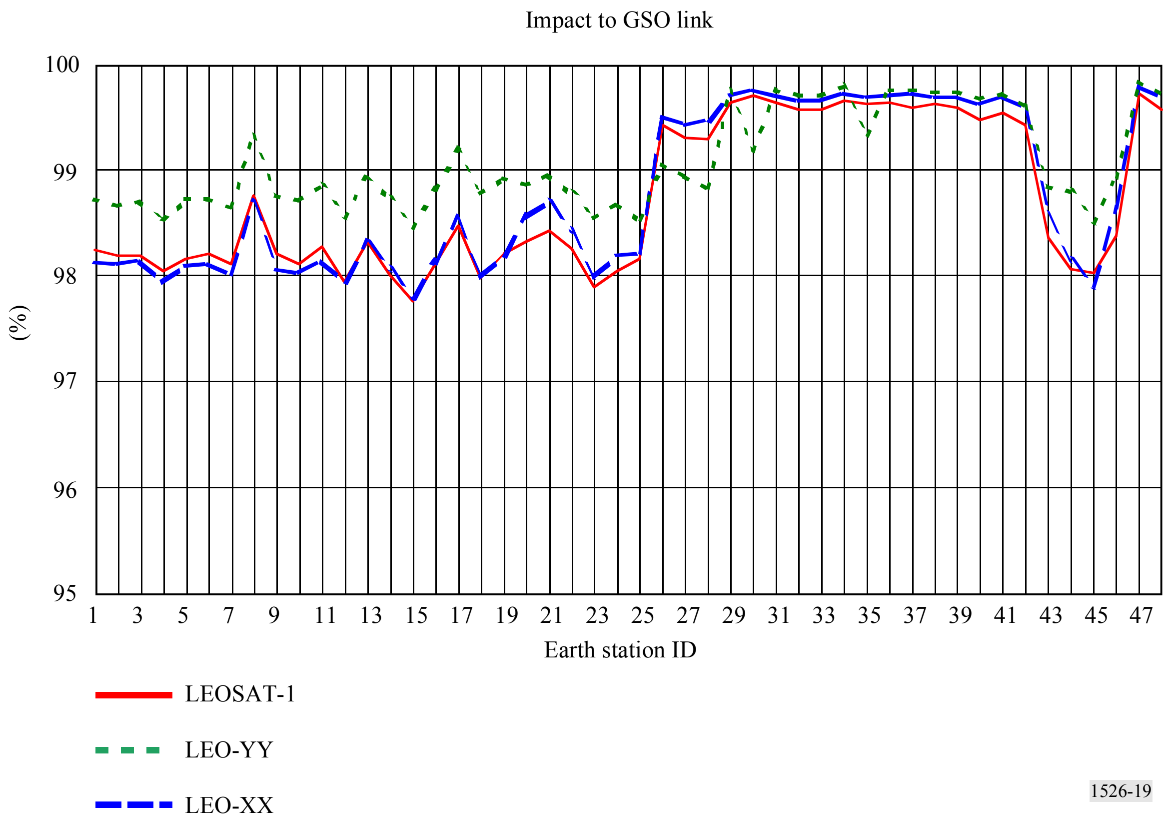
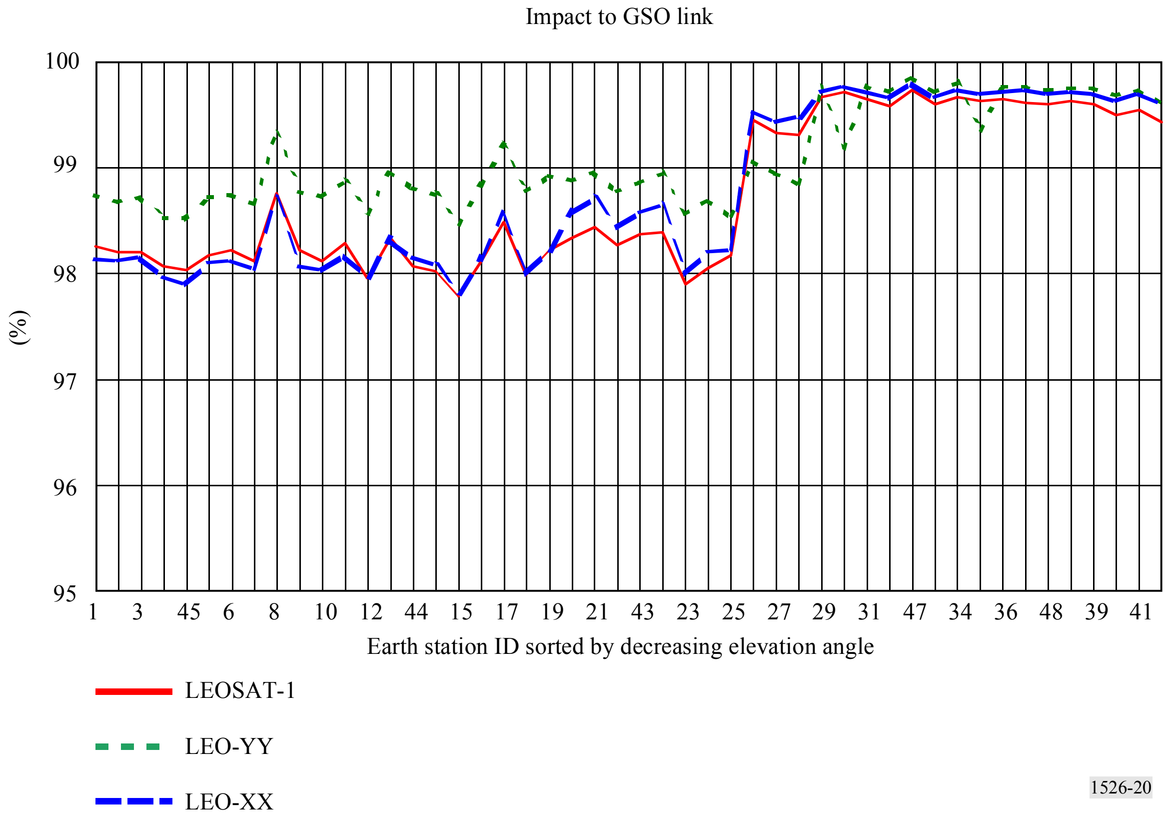


FIGURE 20

Percentage of time for the GSO downlink availability in the presence of rain and interference from the non-GSO FSS system (as a function of GSO earth station elevation angle)



The percentages of time shown in Fig. 19 (or Fig. 20) were averaged over the 48 earth stations and subsequently were averaged over the same earth stations weighted by population and then by GDP. These three different average percentages of time are given in Table 19 for each of the three non-GSO FSS systems under consideration.

TABLE 19

Average percentages of time for GSO downlink availability for earth stations distributed over GSO service area operating through all in-line interference events with the non-GSO FSS system

	LEOSAT-1	**LEO-XX**	**LEO-YY**
Average (%)	98.7	99.1	98.8
Average (weighted by population) (%)	98.4	98.9	98.5
Average (weighted by GDP) (%)	98.6	99.0	98.8

ANNEX 2

Rain degradation modelling for convolutions

1 Introduction

NOTE 1 – All symbols in this Annex represent numerical rather than decibel values.

Recommendation ITU-R S.1323 (methodology A) has been used in the example presented in Annex 1 to evaluate whether or not the external interference generated by a given system is acceptable to another system. This requires the convolution of the pdf of the rain degradation, X, with that of the interference degradation, Y, to produce a total degradation, Z, pdf. Assuming at most 10% of the total degradation is allowed for external interference (i.e. all of external interference is allocated to one system), and that a link outage occurs with a specified degradation threshold value, D_{th}, then 90% of the probability of the total degradation exceeding D_{th} must be less than or equal to the probability of the rain degradation exceeding D_{th}:

$$P(Z \geq D_{th}) \leq P(X \geq D_{th}) / 0.9$$

In order to generate a rain degradation pdf, one of the standard rain models is used, such as Recommendation ITU-R P.618, to determine the probability of the rain fade, L_R, attenuation being in any given range. The relationship between the rain attenuation, L_R, and the rain degradation, X, is specific to the link being evaluated. Other methodologies, such as methodology D′ of Recommendation ITU-R S.1323, can also be used to evaluate the interference generated by a non-GSO FSS system into another system.

2 Rain fade and rain degradation relationship in downlink

Recommendation ITU-R S.1323 provides the following relationship between X and L_R for a generic downlink, which assumes that the interference is faded along with the carrier under rain:

$$X = \frac{(1-\alpha)\left(L_R + \frac{(T_0 - T_B)}{T_{SYS}} \cdot \frac{(L_R - 1)}{L_A}\right) + \frac{\alpha}{L_A}}{(1-\alpha) + \frac{\alpha}{L_A}} \qquad (1)$$

where:

- α: fraction of the total downlink noise in clear-sky which is due to interference (i.e. $\alpha = I/(N + I)$)
- L_R: attenuation due to rain (numerical ratio)
- T_0: mean absorption temperature (typical value = 274.8 K)
- T_B: background temperature (2.76 K for the sky)
- T_{SYS}: downlink thermal noise temperature
- L_A: attenuation due to atmospheric absorption (numerical ratio).

3 Rain fade and rain degradation relationship in uplink

In the case of an uplink, where the interference may or may not be faded with the rain, a more general expression is needed relating the L_R and X values. The following derives general expressions for $(C/(N+I))_{faded}$ and for the rain degradation X.

Let $\beta = \left(\frac{I}{N}\right)_{clear-sky}$ $\qquad\qquad$ δ = fraction of I not faded

$$\left(\frac{C}{N+I}\right)_{unfaded} = \frac{C}{N+\beta N} = \frac{C}{N(1+\beta)} \qquad (2)$$

$$\left(\frac{C}{N+I}\right)_{faded} = \frac{C/L_R}{N+\delta I+(1-\delta)\, I/L_R} = \frac{C}{L_R \cdot N(1+\delta\, I/N+(1-\delta)\,(I/N)/L_R)} \cdot \frac{1+\beta}{1+\beta} \qquad (3)$$

$$= \frac{1+\beta}{L_R(1+\delta\beta+(1-\delta)\,\beta/L_R)} \cdot \frac{C}{N(1+\beta)}$$

$$X = \frac{(C/N+1)_{unfaded}}{(C/N+1)_{faded}} = \frac{L_R(1+\delta\beta+(1-\delta)\,\beta/L_R)}{1+\beta} = \frac{L_R(1+\delta\beta)+(1-\delta)\,\beta}{1+\beta} \qquad (4)$$

Since

$$\beta = \frac{I}{N} = \frac{I/(I+N)}{(N+I-I)/(I+N)} = \frac{\alpha}{1-\alpha} \qquad (5)$$

the expression for X can still be rewritten as:

$$X = L_R((1-\alpha)+\delta\alpha) + (1-\delta)\,\alpha \qquad (6)$$

The following derives an expression to determine δ, the fraction of I not faded, in terms of given C/I values in faded and unfaded conditions:

$$\left(\frac{C}{I}\right)_{faded} = \frac{C/L_R}{\delta I+(1-\delta)\, I/L_R} = \frac{1}{L_R \cdot \delta+(1-\delta)} \cdot \left(\frac{C}{I}\right)_{unfaded} \qquad (7)$$

and therefore

$$\delta = \frac{1}{L_R-1} \cdot \left(\frac{(C/I)_{unfaded}}{(C/I)_{faded}} - 1\right) \qquad (8)$$

In the case where C/I is the same in faded and unfaded conditions (i.e. I is equally faded with the carrier and therefore $\delta = 0$), the above expression for X simplifies to:

$$X = L_R(1 - \alpha) + \alpha \qquad (9)$$

In the case where I is not faded at all (i.e. $\delta = 1$), the expression for X becomes simply:

$$X = L_R \qquad (10)$$

4 Power control modelling

In the case where there is no power control employed on a given link, the degradation of the link starts with any rain fade, so the pdf for X derived from the appropriate equation above as a function of L_R can be used directly.

When power control is used to compensate for rain fading, there is no degradation of the link until the dynamic range of the power control function is reached. In this case, a modified pdf applicable to the rain degradation X' (with power control) has to be obtained, based on the pdf for the rain degradation X (without power control). The pdf for X' should have an impulse at 0 dB degradation which indicates the probability of a rain fade less than or equal to the maximum rain fade compensated by the power control function. If F is the maximum rain fade without degradation, and M is the value of X at this rain fade value,

$$P(X' = 0) = P(L_R \leq F) = P(X \leq M) \tag{11}$$

$$P(X' \leq i) = P(X \leq i + M) \qquad \text{for } X > M\,(i > 0) \tag{12}$$