International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R SA.2192

(10/2010)

Compatibility between the space research service (Earth-to-space) and the non-GSO-to-non-GSO systems on the inter-satelllite service in the band 22.55-23.55 GHz

SA Series

Space applications and meteorology

International
Telecommunication
Union

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Annex 1 of Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from http://www.itu.int/ITU-R/go/patents/en where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Reports

(Also available online at http://www.itu.int/publ/R-REP/en)

Series	**Title**
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
M	Mobile, radiodetermination, amateur and related satellite services
P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	**Space applications and meteorology**
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management

***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

Electronic Publication
Geneva, 2011

REPORT ITU-R SA.2192

Compatibility between the space research service (Earth-to-space) and the non-GSO-to-non-GSO systems on the inter-satellite service in the band 22.55-23.55 GHz

(2010)

TABLE OF CONTENTS

Page

1 Introduction

This Report addresses compatibility between space research service mission and inter-satellite service links of HIBLEO-2-type satellite systems. It is envisioned that primarily three types of space missions would be supported by SRS earth station transmissions in the 22.55-23.15 GHz band:

1. low-Earth orbiting scientific satellites;
2. manned and unmanned Lunar exploration missions;
3. scientific missions using satellites located in the vicinity of the Sun-Earth L1 and L2 Lagrangian points.

Data transmissions in the space-to-Earth direction for these types of missions are either currently operational or are planned to be operational in the 25.25-27.5 GHz band – a band allocated for both space-to-Earth and space-to-space transmissions to data relay satellites. Data relay satellites, which are operated by several administrations (Recs ITU-R SA.1018 and ITU-R SA.1414), use the 22.55-23.55 GHz band for forward inter-orbit links and the 25.25-27.5 GHz band for return inter-orbit links to near-earth orbiting user satellites.

The purpose of WRC-12 Agenda item 1.11 is to add an Earth-to-space allocation in the 22.55-23.15 GHz band segment to complement the existing space-to-space and space-to-Earth allocations. The Earth-to-space allocation will add the capability to support near-Earth missions using similar, if not identical technology, onboard the user satellite. The 22.55-23.15 GHz band will be used for both command and control of the user satellite and, in addition, for manned missions voice/video communication with the Earth.

The number of SRS earth stations transmitting in the 22.55-23.15 GHz band will be small. Rather than building new SRS earth stations, upgrading selected existing SRS earth stations will predominate. Selecting which SRS earth stations to upgrade will be based on a number of factors, including the type of mission to be supported. The maximum number of SRS earth stations capable of supporting Lunar and/or L2 missions is not expected to exceed eight or nine on a global basis. A similar number of SRS earth stations may support LEO missions, also on a global basis. These earth stations are typically located in rural, isolated areas at mid-latitudes.

Analyses have been performed to determine the criteria for transmitting earth stations in the space research service (SRS) to share with stations in the inter-satellite (non-GSO-to-non-GSO) service in the 22.55-23.55 GHz band. Analysed is the compatibility of SRS earth stations supporting typical types of space research missions in the Earth-to-space direction in the 23 GHz band. These uplinks are to an SRS satellite in low-Earth orbit; in an orbit around the Moon or on the surface of the Moon; and, in a halo orbit around the L2 Lagrange point. Only the Lunar case is analyzed below because this interference case was shown to be the most severe among the three SRS mission types.

These analyses are presented in the following sections.

2 Characteristics of the SRS earth station emissions

Analysis is performed for interference for both the in-band case and the out-of-band (OoB) case. Both are described below.

2.1 In-band characteristics

The representative characteristics of the SRS earth station emissions in the 23 GHz band and the orbital and receiving characteristics of the mission satellites are summarized in Recommendation ITU-R SA.1882. The characteristics are based on typical 18 m diameter SRS earth stations antennas located at three sites around the world that will support lunar space research missions. The sites chosen are the three NASA deep space ground station locations in Goldstone, (USA), Madrid (Spain) and Canberra (Australia), as well as the three ESA sites in Cebreros (Spain), New Norcia (Australia) and Malargue (Argentina).

The Radio Regulations permit SRS earth station operations down to elevation angles of 5° which is usually the case for single station operations. It may be noted that actual operations involving three earth stations around the globe are conducted such that a spacecraft is handed over from one earth station to another at typical elevation angles between 15° and 25°.

2.2 Out-of-band characteristics

Out-of-band (OoB) emissions for the Lunar case only are also analyzed. Table 1 summarizes the parameters used. For these studies, it was assumed that at least six agencies will operate these links, based on discussions amongst several space agencies in various forums, including SFCG (Space Frequency Coordination Group), and in coordination meetings with these agencies. One 24 MHz carrier and three 12 MHz carriers have been assumed for each of the six space agencies missions as a representative future lunar mission scenario. Instead of three 12 MHz carriers, it may also be possible to consider an additional 24 MHz carrier and one or two channels with lower bandwidths. It was assumed that NASA will operate the same set of channels from each of the three stations in the deep-space network and that the other agencies will use a single station.

The frequency plan needs to take into account 60 MHz DRS channel spacing plans. However, in order to demonstrate the worst-case interference scenario with HIBLEO-2 (i.e. highest possible frequencies used), the analysis does not factor in DRS channel spacing plans. Instead the NASA 24 MHz carrier is placed at the upper edge of the 22.55-23.15 GHz band, and the other carriers are placed on lower frequency adjacent channels, each having a 5 MHz guardband.

Each carrier has the same antenna size and power-spectral density (PSD) as in the single-entry case. The values in the final column (OoB Aggregate PSD) have been calculated by summing the individual OoB PSD values for the four carriers for each agency, since they potentially could all transmit simultaneously from the same earth station.

TABLE 1

Summary of the aggregate SRS earth stations parameters

Agency	Earth Station Location(s)	Lower Freq (MHz)	Upper Freq (MHz)	PSD (dBW/Hz) (1)	Power (dBW)	Delta Freq (MHz)	Normalized Delta Freq	OOB/Atten (dB) (2)(4)	OOB/PSD (dBW/Hz) (3)(4)	OOB/Aggregate PSD (dBW/Hz) (4)
NASA	Goldstone, CA Madrid, Spain Canberra, Aus	23126	23150	-59.7	11.1	45	187.5	34.5	-94.2	-92.3
		23109	23121	-59.7	8.1	68	566.7	42.0	-101.7	
		23092	23104	-59.7	8.1	85	708.3	42.0	-101.7	
		23075	23087	-59.7	8.1	102	850.0	42.0	-101.7	
JAXA	Usuda, Japan	23046	23070	-59.7	11.1	125	520.8	42.0	-101.7	-95.7
		23029	23041	-59.7	8.1	148	1233.3	42.0	-101.7	
		23012	23024	-59.7	8.1	165	1375.0	42.0	-101.7	
		22995	23007	-59.7	8.1	182	1516.7	42.0	-101.7	
RFSA	ECDSA, (Southwest) Russia	22966	22990	-59.7	11.1	205	854.2	42.0	-101.7	-95.7
		22949	22961	-59.7	8.1	228	1900.0	42.0	-101.7	
		22932	22944	-59.7	8.1	245	2041.7	42.0	-101.7	
		22915	22927	-59.7	8.1	262	2183.3	42.0	-101.7	
ISRO	Bangalore, India	22886	22910	-59.7	11.1	285	1187.5	42.0	-101.7	-95.7
		22869	22881	-59.7	8.1	308	2566.7	42.0	-101.7	
		22852	22864	-59.7	8.1	325	2708.3	42.0	-101.7	
		22835	22847	-59.7	8.1	342	2850.0	42.0	-101.7	
CNSA	Weinan, China	22806	22830	-59.7	11.1	365	1520.8	42.0	-101.7	-95.7
		22789	22801	-59.7	8.1	388	3233.3	42.0	-101.7	
		22772	22784	-59.7	8.1	405	3375.0	42.0	-101.7	
		22755	22767	-59.7	8.1	422	3516.7	42.0	-101.7	
DLR	Neustrelitz, Germany	22726	22750	-59.7	11.1	445	1854.2	42.0	-101.7	-95.7
		22709	22721	-59.7	8.1	468	3900.0	42.0	-101.7	
		22692	22704	-59.7	8.1	485	4041.7	42.0	-101.7	
		22675	22687	-59.7	8.1	502	4183.3	42.0	-101.7	

Notes relating to Table 1:

(1) Power-spectral density in-band.

(2) Single carrier OoB attenuation at 23.183 GHz assuming § 5 of Annex 5 of Recommendation ITU-R SM.1541.

(3) Single carrier OoB power-spectral density at 23.183 GHz assuming § 5 of Annex 5 of Recommendation ITU-R SM.1541.

(4) NOTE 1 − Annex 5 of Recommendation ITU-R SM.1541 specifies out-of-band emissions limits, and can be applied to antennas transmitting in both single-carrier mode and multi-carrier mode. Recommendation ITU-R SM.1541 is applicable to the space research service in the range 1-20 GHz. These attenuation figures are derived assuming that a single SRS carrier is transmitted, and that the mask can be applied slightly above 20 GHz. Wider SRS carriers may cause higher OoB emissions at 23.183 GHz due to the higher bandwidth. However, this methodology assumes a flat attenuation of 42 dB beyond 250% of necessary bandwidth, and so may result in an overestimate of the actual OoB attenuation for channels further away from the band edge.

The above scenario results in 32 channels. Another scenario studied assumed 15 earth stations, each of them transmitting with maximum power on three different channels, i.e. 45 channels simultaneously active within the entire allocation.

3 Assumed characteristics for the HIBLEO-2/Ka system

HIBLEO-2 is a non-geostationary-satellite orbit (non-GSO) mobile-satellite service (MSS) system providing ubiquitous fully global coverage to handheld equipment of users in motion. Its constellation consists of 66 satellites arranged in 6 planes of near polar circular orbits at an altitude of 780 km, with 11 satellites per plane. The inclination angle is 86.5º. The links use antennas with maximum gain of 36.7 dBi with 3 dB beamwidths of 2.4º.

3.1 Non-GSO-to-non-GSO ISL characteristics of HIBLEO-2 type system

The technical characteristics of a receiving ISL satellite in a non-GSO orbit are given in Table 2. The orbital parameters are provided in Table 3.

TABLE 2

HIBLEO-2 system ISL specifications

System parameter	Value
Number of satellite planes	6
Number of satellites per plane	11
Nominal altitude	780 (km)
Orbit type	Circular polar (inclination angle of 86.5°)
Necessary bandwidth	8 × 19 MHz channels (total bandwidth 194 MHz)
Peak power	3.5 dBW for the total 8 links
Antenna gain	36.7 dBi
Receiver noise temperature	877 K (29.4 dBK)
Rx: reference radiation pattern	see § 3.2
Rx: antenna pointing	Towards intra-planar satellites: N, S Towards inter-planar satellites: NE or SE, NW or SW

TABLE 3

Relative right ascension of the ascending node (RAAN) and argument of latitude at epoch of HIBLEO-2 constellation

Plane 1 Relative RAAN = 0^{o}		**Plane 2** Relative RAAN = 31.6^{o}		**Plane 3** Relative RAAN = 63.2^{o}	
Satellite	**Arg of Lat.**	**Satellite**	**Arg of Lat.**	**Satellite**	**Arg of Lat.**
1	100.7752	12	83.1116	23	98.1752
2	68.048	13	50.3844	24	65.448
3	35.3207	14	17.6571	25	32.7207
4	2.5934	15	344.9298	26	359.9934
5	329.8661	16	312.2025	27	327.2661
6	297.1389	17	279.4753	28	294.5389
7	264.4116	18	246.748	29	261.8116
8	231.6843	19	214.0207	30	229.0843
9	198.9571	20	181.2935	31	196.3571
10	166.2298	21	148.5662	32	163.6298
11	133.5025	22	115.8389	33	130.9025
Plane 4 Relative RAAN = 94.8^{o}		**Plane 5** Relative RAAN = 126.4^{o}		**Plane 6** Relative RAAN = 157.0^{0}	
Satellite	**Arg of Lat.**	**Satellite**	**Arg of Lat.**	**Satellite**	**Arg of Lat.**
34	80.5116	45	95.5752	56	77.9116
35	47.7844	46	62.848	57	45.1844
36	15.0571	47	30.1207	58	12.4571
37	342.3298	48	357.3934	59	339.7298
38	309.6025	49	324.6661	60	307.0025
39	276.8753	50	291.9389	61	274.2753
40	244.148	51	259.2116	62	241.548
41	211.4207	52	226.4843	63	208.8207
42	178.6935	53	193.7571	64	176.0935
43	145.9662	54	161.0298	65	143.3662
44	113.2389	55	128.3025	66	110.6389

3.2 Antenna characteristics of HIBLEO-2 type system

There are four inter-satellite link antennas on each HIBLEO-2 spacecraft. There are two intra-planer link antennas, one directed in the forward direction and the other directed in the aft direction. The intra-planer antennas are fixed and are directed within the orbital plane at an angle of 16.36° below the local horizontal plane. There are two inter-planer link tracking antennas, one pointing to a HIBLEO-2 spacecraft in the right-adjacent orbital plane and the other pointed at a HIBLEO-2 spacecraft in the left-adjacent orbital plane. Each antenna may independently point either fore or aft at a spacecraft in the adjacent plane.

ITU-R agreed on an oscillating antenna pattern for the HIBLEO-2 inter-satellite link antennas. The pattern is given by the following equations and is shown in Fig. 1.

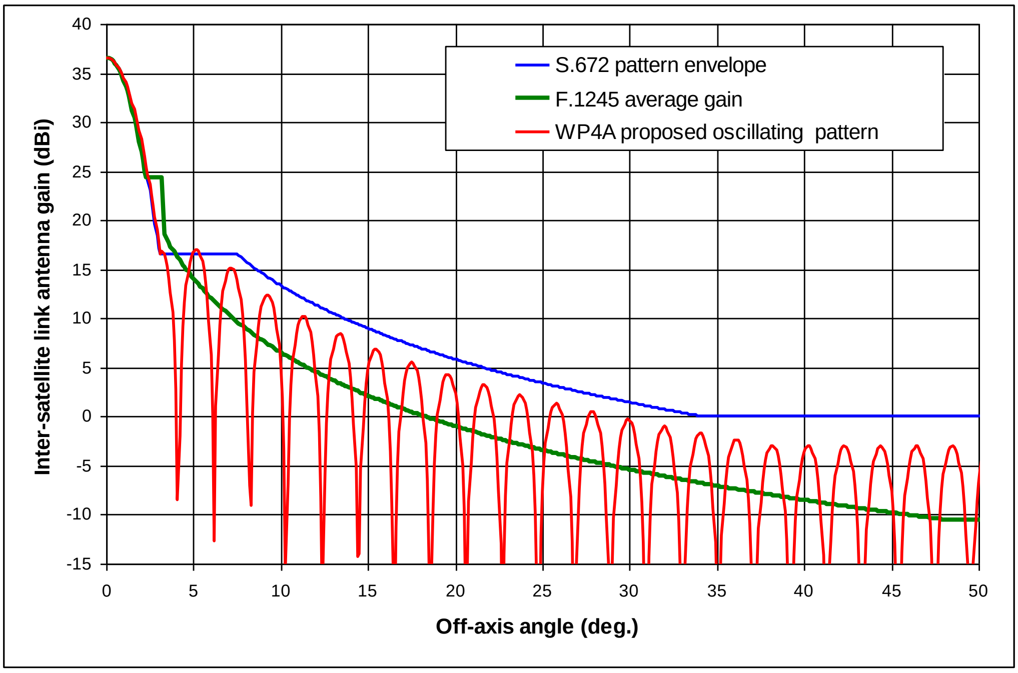
$$G(\gamma) = \begin{cases} 36.7 - 3\left(\dfrac{\gamma}{1.2}\right)^2 & \text{for} \quad 0^\circ < \gamma \le 3.1^\circ \\ 17 + F(\gamma) & \text{for} \quad 3.1^\circ < \gamma \le 6.1^\circ \\ 36.6 - 25 \log \gamma + F(\gamma) & \text{for} \quad 6.1^\circ < \gamma \le 38.4^\circ \\ -3 + F(\gamma) & \text{for} \quad 38.4^\circ < \gamma \le 180^\circ \end{cases}$$

where:

$$F(\gamma) = 10 \log\left(0.999 \sin^2\left(\frac{3\pi\gamma}{6.192}\right) + 0.001\right)$$

FIGURE 1

Antenna pattern for HIBLEO-2/Ka inter-satellite links



3.3 Protection criteria

ITU-R agreed on the following protection criteria for analyses of interference to non-GSO-non-GSO ISS systems:

In-band:

I/N = –10 dB not to be exceeded for more than 0.1% per single link based on the underlying conditions for Recommendation ITU-R SA.1155 which specifies derived Io levels. It should be noted that this criterion was specified for interference from SRS earth stations per single ISS link whereas Recommendation ITU-R SA.1155 applies the protection criteria to the aggregate of all interference sources.

Out-of-band:

$I/N = -16$ dB not to be exceeded for more than 0.01% of time, per HIBLEO-2 inter-satellite link in the 23.183-23.377 GHz band, taking into account the aggregated effect of all SRS earth stations in operation in the 22.55-23.15 GHz band.

4 Summary of analysis methodology and results

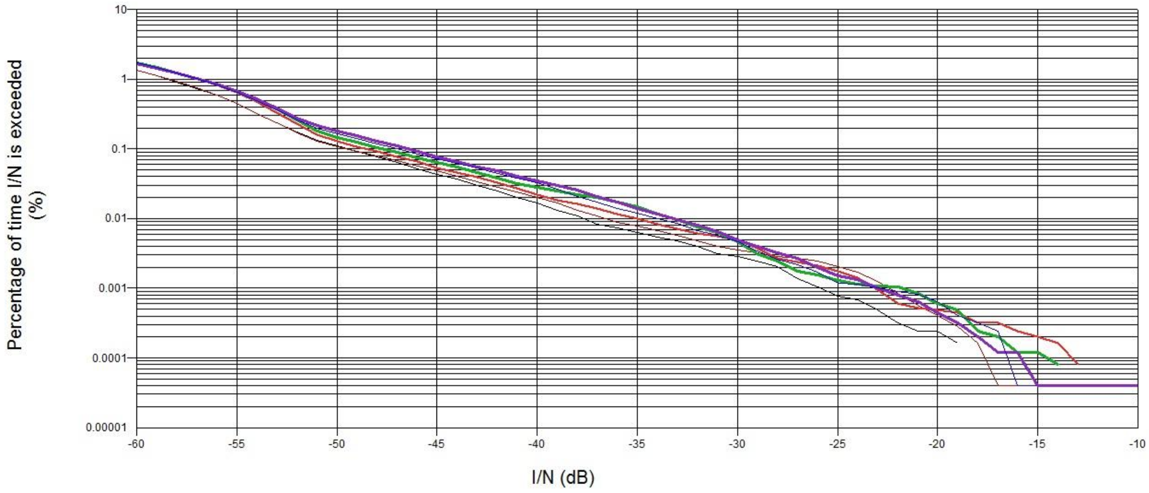
Several independent simulation tools and assessment techniques were used comprising publicly available software tools, proprietary software, ITU-R adopted methodologies, combinations of assessment techniques and deterministic approaches. All contributions were based on the agreed protection requirements for HIBLEO-2 type systems, both in-band and OoB as well as on the characteristics described above.

4.1 Summary for Study 1

Study 1 used the commercially available tool Visualyse 7.0. A summary of this study is contained in Annex 1. Three SRS earth stations were assumed transmitting simultaneously down to elevation angles of 5º. The simulated duration was 28 days with 1s time steps. Figure 2 shows the key results in terms of I_0/N_0. It can be seen that the in-band margin ranges between 37 and 39 dB.

FIGURE 2

Results of interference assessment of Study 1



For OoB emissions, the study concludes that no further analysis of the impact of OoB SRS (E-s) earth station emissions is required in view of the large in-band margins. It is expected that consideration of OoB SRS (E-s) emissions would show increased compatibility with HIBLEO-2 ISS services with a significant additional margin of protection.

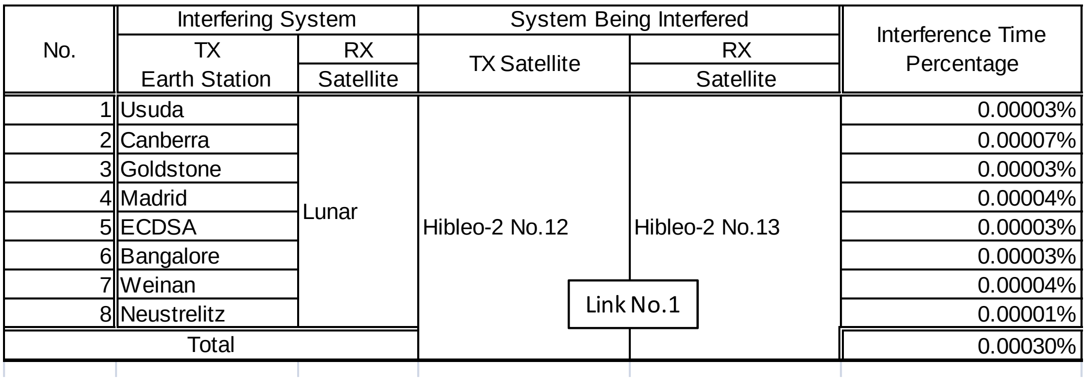
4.2 Summary for Study 2

Study 2 used a computer-based proprietary dynamic simulation method. A summary of this study is contained in Annex 2. Eight individual earth stations were considered transmitting down to elevation angles of 5º. The simulated duration was 365 days. Table 4 shows the key results in terms of I_0/N_0 being exceeded for a percentage of time for link 1 out of 4, which all show similar results. The obtained mean percentage of 0.00030% for exceeding an I_0/N_0 of –10 dB matches with all other results and is equivalent to an in-band margin of around 38 dB.

For OoB emissions, no case could be identified over a period of one year where the I_0/N_0 level of –16 dB would have been exceeded.

TABLE 4

Results of interference assessment of Study 2



No.	Interfering System		System Being Interfered		Interference Time Percentage
	TX Earth Station	RX Satellite	TX Satellite	RX Satellite	
1	Usuda	Lunar	Hibleo-2 No.12	Hibleo-2 No.13	0.00003%
2	Canberra				0.00007%
3	Goldstone				0.00003%
4	Madrid				0.00004%
5	ECDSA				0.00003%
6	Bangalore				0.00003%
7	Weinan				0.00004%
8	Neustrelitz				0.00001%
Total					0.00030%

Link No.1

4.3 Summary for Study 3

Study 3 used the proprietary software tool RFIAT. A summary of this study is contained in Annex 3. Three SRS earth stations were assumed transmitting simultaneously down to elevation angles of 5º. The simulated duration was 365 days with 1s time steps. Figure 3 shows the key results in terms of I_0/N_0. It can be seen that the in-band margin is around 38 dB.

For OoB emissions, the study assumed a worst case of 15 earth stations transmitting simultaneously three channels each, hence 45 channels. In a hypothetical worst situation, it was assumed that all channels would operate at the highest possible Recommendation ITU-R SM.1541 specifications. The obtained margin was at least 47 dB with respect to the OoB criteria. The study also showed that in reality, the OoB emission levels will follow SFCG recommendations, resulting in a margin of at least 69 dB.

This study also listed a number of mitigation techniques typically found in real systems and included interference apportionment for 3 services. Table 5 provides a summary also taking into account interference apportionment. It is then shown that actually available margins are in the range 40-48 dB for the in-band case and 78-91 dB for the OoB case.

FIGURE 3

Results of interference assessment of Study 3

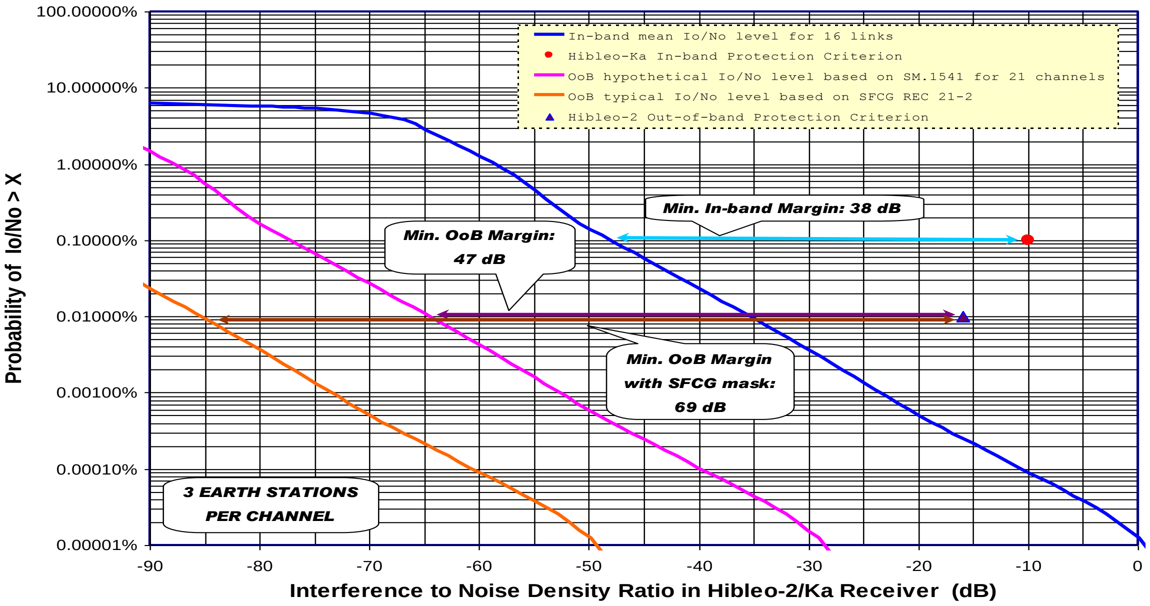


TABLE 5

Additional mitigation factors and their impact on the actual margins

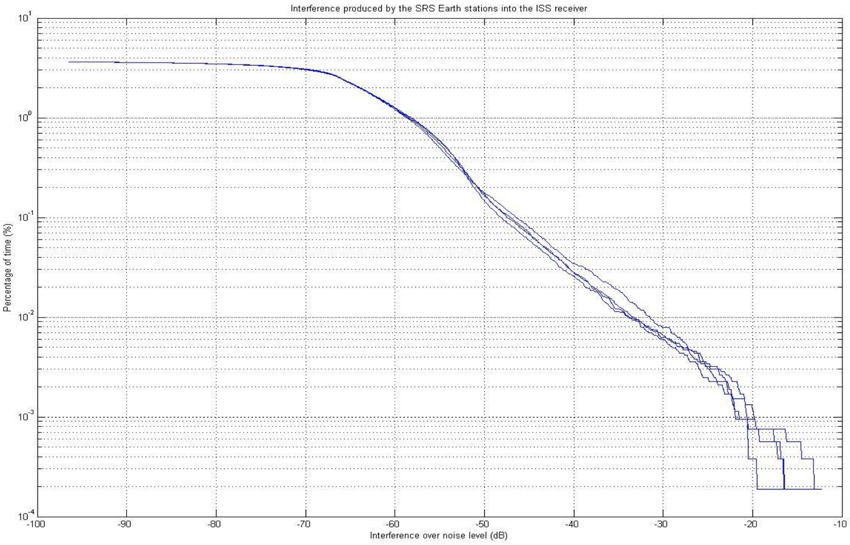
	In-band	Out-of-band
Obtained minimum margins (dB)	38	48
Atmospheric attenuation for more than 99% of time and 5°-90° elevation angles (dB)	2-3	2-3
Average antenna gain reduction (dB)	3-4	3-4
Polarization discrimination in antenna side-lobe regions (dB)	1-3	1-3
Elevation angles of 15°-25° in global network satellite handover (dB)	1-2	1-2
Actual expected duty cycle between 50% and 100% (dB)	0-3	0-3
Interference apportionment between FS, ISS and SRS (dB)	−5	---
SFCG spectral mask compliance (dB)	---	20-23
Spectral density reduction due to additional guardband at 23.15 GHz (dB)	---	3-5
Expected actual margins (dB)	40-48	78-91

4.4 Summary for Study 4

Study 4 used the software tool STK in combination with MATLAB. A summary of this study is contained in Annex 4. Three SRS earth stations were assumed transmitting simultaneously down to elevation angles of 5°. The simulated duration was 31 days with 5s time steps. Figure 4 shows the key results in terms of I_0/N_0 for satellite 6. The obtained in-band margin is around 37-39 dB.

FIGURE 4

Results of interference assessment of Study 4



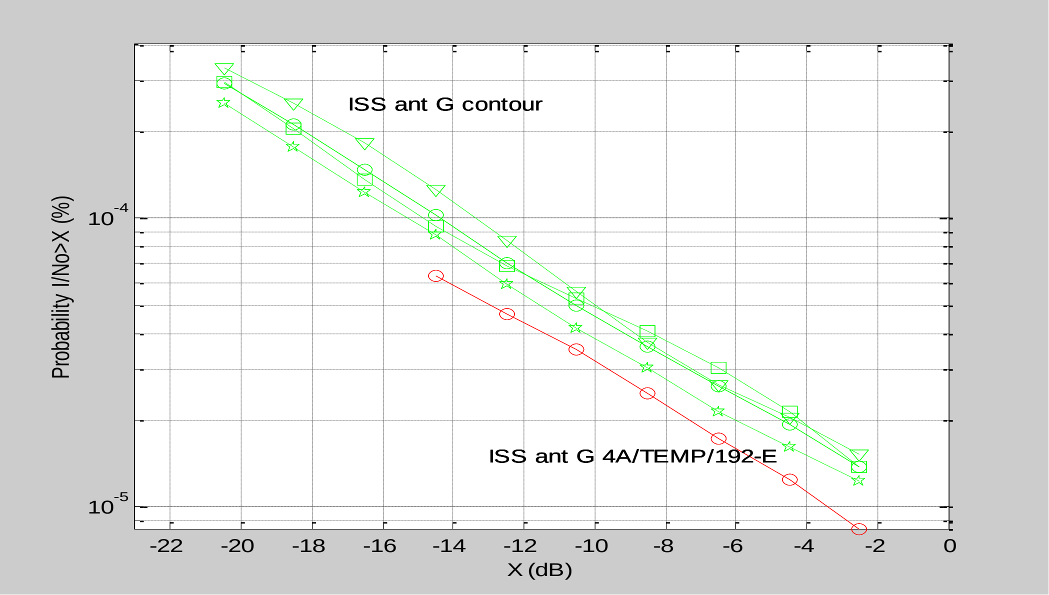
For OoB emissions, the I_0/N_0 level for 0.01% of the time ranges from –37 to –32 dB. This is already 16 to 21 dB below the agreed protection criterion, without even considering any OoB attenuation. The actual interference would be much lower taking into account the OoB attenuation due to the modulation shape only, and any output filter that might be implemented on the SRS earth stations. This study also points out that atmospheric losses were not taken into account in the study which would further reduce interference levels. The study finally concludes that SRS earth stations used for Moon missions are compatible with HIBLEO-2 ISL without any further constraint.

4.5 Summary for Study 5

Study 5 is a deterministic analysis using software tools based on MATLAB which are publicly available. A summary of this study is contained in Annex 5. Interference results are based on one SRS earth station transmitting down to elevation angles of 5°. The simulated durations were 84 days (three lunar months) and three consecutive periods of 28 days (one lunar month each). Time steps varied between 18s to identify time periods of interest for more detailed investigations and 0.06s for very detailed assessments. This study comprises several parts by assessing in-band as well as OoB interference to lunar missions and Lagrangian missions. The study considers also interference to single links as well as to the entire system. In addition, this study addresses performance limitations due to noise radiated by the Sun. For the lunar case based on a single ISS link, Fig. 5 shows the key results in terms of percentage for exceeding a specific I_0/N_0. It can be seen that an $I_0/N_0 = -10$ dB would only be exceeded for around 4×10^{-5}% of time which is roughly equivalent with an in-band margin of around 38 dB.

FIGURE 5

Results of interference assessment of Study 5



For OoB emissions, it is concluded that large margins are available per link as well as per full HIBLEO-2 constellation and that no undue interference would be caused to non-GSO ISS links.

4.6 Summary for Study 6

Study 6 used an analytic methodology contained in Recommendation ITU-R S.1529 which allows for assessment of low probability areas on the CDF curve at shorter computer times as compared to most other methods. A summary of this study is contained in Annex 6. Three SRS earth stations were assumed transmitting simultaneously down to elevation angles of 0º. This study examined co-frequency sharing. Figure 6 shows the key results in terms of I/N with the reference asterisk being the in-band criterion of $I/N = -10$ dB for 0.1% of time, indicating a protection margin around 38 dB. It can also be seen in this figure that the margin with respect to the OoB criterion of $I/N = -16$ dB for 0.01% of time is around 20 dB, to which signal attenuation due to spectral roll-off and filtering, of at least 35 dB, would be added if Recommendation ITU-R SM.1541 would be applied to a single carrier of 24 MHz operating at the upper edge of the band 22.55-23.15 GHz as assumed in several studies. If SFCG Recommendation 21-2 is applied, this attenuation would increase under the same conditions to 40 dB.

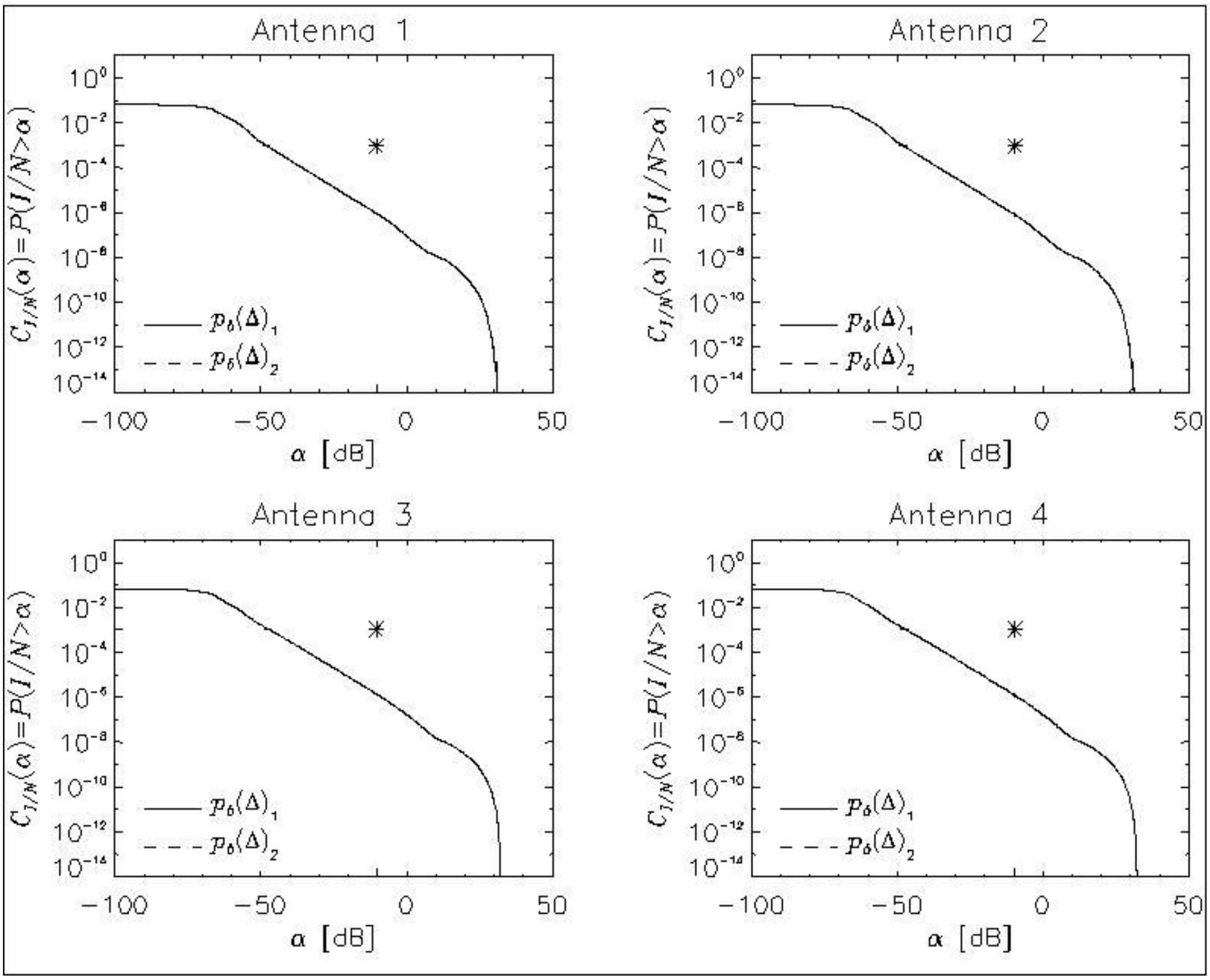
This study also carried out a sensitivity analysis on the interference impact by varying operation angles of the earth stations, latitude of the SRS earth stations, earth station antenna size and the number of SRS earth stations.

Regarding operational angles, the study considered a scenario where SRS earth stations would transmit to a spacecraft at the highest elevation angle in a 3 earth station global network consistent with practical operations which showed an increase in the protection margins up to 3 dB.

The study on effect of latitude of the SRS earth station location on the statistical behaviour of the I/N protection margin for the victim ISS link showed a 5 dB increase in the I/N protection margin as the SRS earth station latitude was moved from around 35° to 0° and a 7 dB decrease in protection margin when the ES was moved from 35° to 70°. However, there are operational disadvantages to locating an ES transmitting to the moon or Lagrange points at high latitudes, so that this scenario is unlikely to occur.

FIGURE 6

Results of interference assessment of Study 6



The same study examined the effect of decreasing the SRS antenna size from 18 m to 10 m. This reduction in antenna size reduced the protection margin by 5.1 dB as the power is increased to compensate for the difference in antenna gain.

A further hypothetical case was considered in which 15 SRS stations were modelled, located at 70° latitude and spread evenly in longitude, and operating co-frequency. Although such a case would not be possible for lunar missions, it indicated the sensitivity to increasing numbers of SRS stations operated on the same frequency channel. The result showed that the protection margin was reduced by approximately 7 dB.

The study also examined the "Conditional" *I*/*N* cdf, which describes the *I*/*N* distribution under the condition that the ISS link is receiving non-zero interference. Although there were no applicable protection criteria against which to measure the absolute impact, the results were found to be useful by describing the impact on the overall system. Results have indicated that there would be a difference of around 16 dB on the overall multi-link ISS system, compared to a single ISS link.

4.7 Summary for Study 7

Study 7 used a NASA proprietary software tool and Visualyse 7 to verify the obtained results. A summary of this study is contained in Annex 7. Three SRS earth stations were assumed transmitting simultaneously down to elevation angles of 5º. The simulated duration was 365 days with 1s time steps. This study considered all potential 242 ISS links. Figure 7 shows the key results in terms of I_0/N_0. It can be seen that the in-band margin is around 38 dB.

FIGURE 7

Results of in-band interference assessment of Study 7

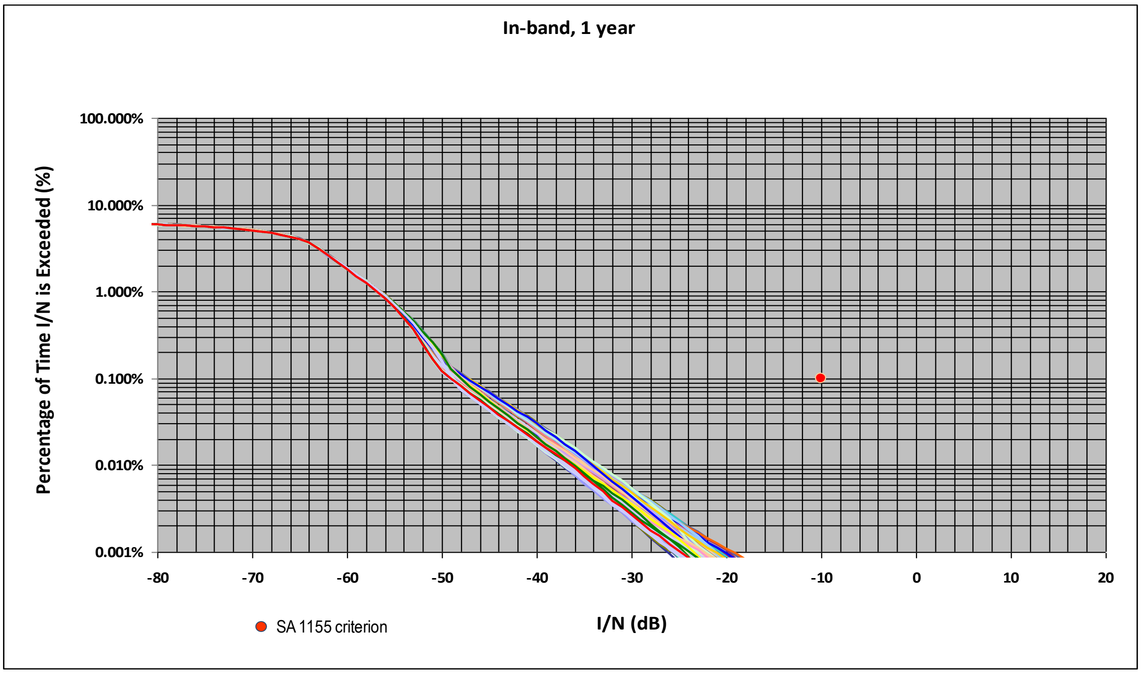
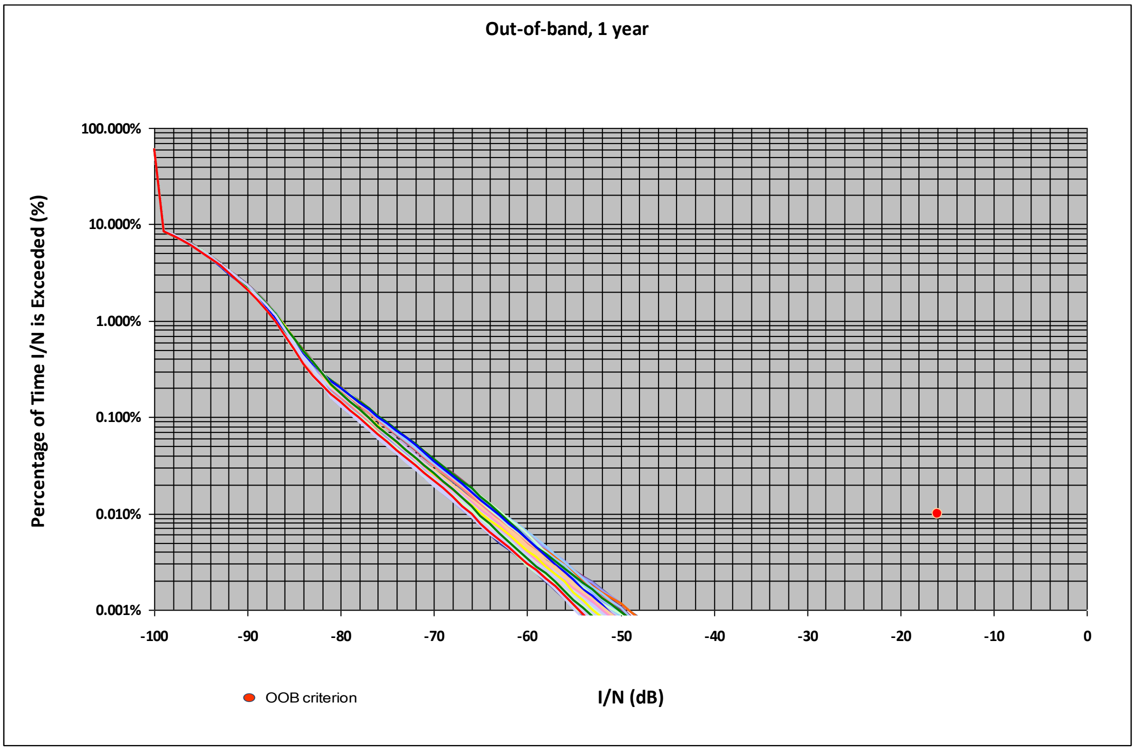


Figure 8 shows the results for the OoB assessment. In this case the obtained margin is around 49 dB.

FIGURE 8

Results of out-of-band interference assessment of Study 7



5 Comparison of study results

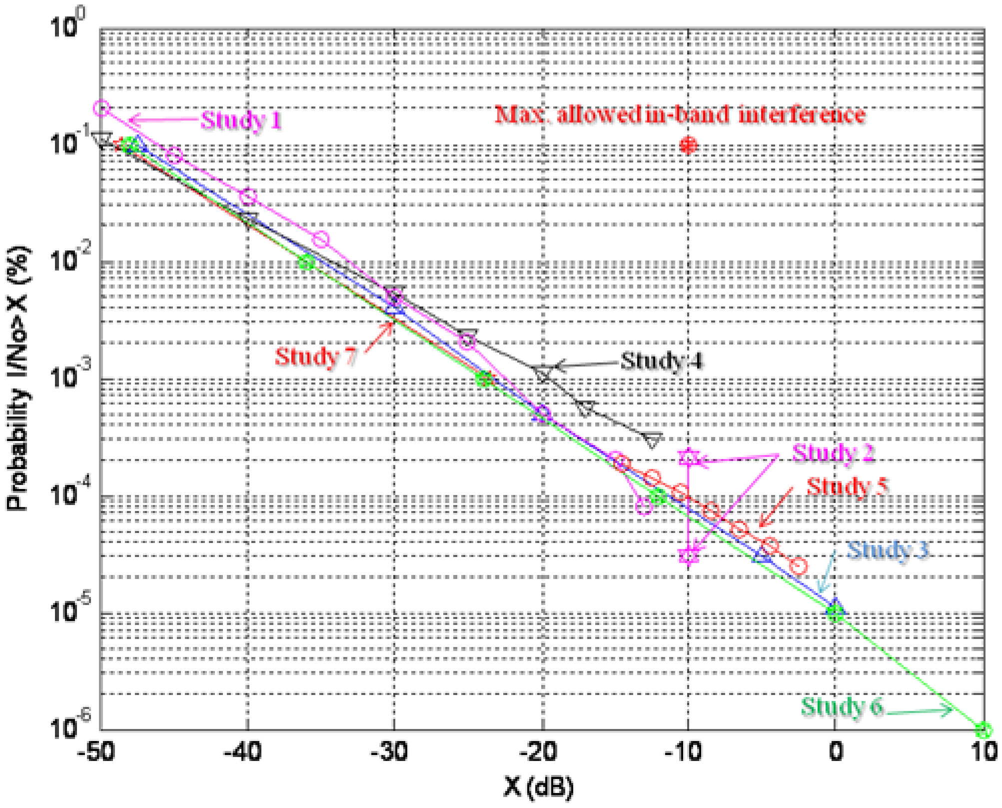
Based on equal assumptions, all seven contributions resulted in obtaining very consistent margins differing by only around ±1 dB. Figure 9 shows an overview of the obtained results for the agreed in-band protection criterion of $I_0/N_0 = -10$ dB not to be exceed for more than 0.1% of time.

Figure 9 shows the results of the 7 compatibility studies. Since most of the studies have been referred to the cumulative interference effects into a single ISS-link of 3 SRS ES transmitting to the Moon, all the results have been normalized to these conditions where required.

The dot at –10 dB and 0.1% identifies the required in-band protection criteria for the ISS link. The curves have been obtained from Figs 2 through 7 of the corresponding studies.

FIGURE 9

Comparison of summary of results for in-band margins



Annex 1

Summary of Study 1

1 System descriptions

The characteristics of the systems under consideration in this interference assessment, including their operational and technical parameters are as follows.

1.1 SRS (Earth-to-space) system characteristics

The characteristics of earth stations supporting SRS lunar exploration-type services are given in Table A1-1 which shows that a small number of earth stations deployed in different parts of the world could be considered as being part of a global network supporting a lunar mission. Equally, they may represent three different lunar missions conducted simultaneously by three different administrations. A large antenna with a very high antenna gain is assumed, characteristics necessary given that a reliable link is assumed to be maintained over a distance of nearly 400 000 km. It is also noted that a conservative (meaning with the potential to overestimate interference) antenna pattern is used for the SRS (E-s) earth stations. In reality, suppression of off-axis emissions of such large antennas may be well in excess of that specified in Recommendation ITU R F.1245.

TABLE A1-1

Characteristics of SRS earth stations under consideration in this report

Parameter			Value
SRS earth station locations	Canberra	Latitude	–35.4041°
		Longitude	148.9802°
	Madrid, Spain	Latitude	~40.5°
		Longitude	~–3.75°
	California, USA	Latitude	~35.4°
		Longitude	~–116.9°
Transmitting antenna diameter (m)			18
Frequency (GHz)			23
Antenna gain G_t max/min (dBi)			70.4/–10
Antenna pattern			Recommendation ITU-R F.1245
Transmit power P_{SRS} (dBW)			11.1
Transmit power density (dBW/Hz)			–59.7
e.i.r.p. density (maximum) (dBW/Hz)			10.7

Although the SRS receiving system under consideration in this Report is not identified as requiring protection (it is the interference from the SRS which is the primary consideration), its characteristics are included for completeness and given in Table A1-2.

TABLE A1-2

SRS space segment characteristics

Parameter	Value
Mission type	Lunar
Orbital altitude (km)	384,400
Inclination(1) (degrees)	22
Orbit type	Circular
Orbital inclination (degrees)	Non-specific
Antenna gain (dBi)	44.7
Noise temperature (K)	410

(1) The average inclination of the Moon is used for simplicity. The actual inclination of the Moon varies between about 18°-28° over an 18.6 year period.

This shows that the SRS earth stations considered in this report are communicating with an object which is either located on the surface of the Moon, or in a low-orbit around the Moon. Given that the receiving characteristics are assumed to be the same for both scenarios, and that there is only a slight difference in angular distance between these two operational scenarios, Table A1-2 is considered, for the purposes of this report, to take account of both lunar-roving and lunar-orbiting missions.

1.2 HIBLEO-2 ISS (s-s) characteristics

The characteristics of the non-GSO–non-GSO HIBLEO-2 type ISS links considered in this study are the same as in the introductory section of this Report.

2 Interference assessment

To assess the interference potential from SRS earth stations into ISS links of the HIBLEO-2 constellation, the level of interference is compared with the system noise temperature of the HIBLEO-2 constellation according to the following equation:

$$I / N = P_{SRS} + G_{tx}(\theta) - L + G_{rx}(\varphi) - kT \tag{1}$$

where:

I/N: interference-to-noise ratio in the receiver of an HIBLEO-2 inter-satellite link (dB)

P_{SRS}: SRS earth station transmit power density (dBW/Hz)

$G_{tx}(\theta)$ is the gain of an SRS earth station antenna in the direction of an HIBLEO-2 satellite, where θ is the angle between the main axis of the SRS beam and the direction of the HIBLEO-2 satellite (dBi)

L: propagation loss between an SRS earth station and an HIBLEO-2 satellite, which varies with time primarily due to the varying distance between SRS earth station and ISS satellite (dB)

$G_{rx}(\varphi)$: gain of the receiving antenna of an HIBLEO-2 satellite in the direction of an SRS earth station, where φ is the angle between the main axis of the HIBLEO-2 ISS beam and the direction of the SRS earth station (dBi)

kT: represents the system noise floor density of the receiving system of the HIBLEO-2 inter-satellite link, k is Boltzmann's constant and T is the system noise temperature of the receiving system of the HIBLEO-2 inter-satellite link (dBW/Hz).

3 Interference protection criteria

For studies of OoB interference from proposed SRS uplinks operating in 22.55-23.15 GHz into HIBLEO-2 inter-satellite links operating in 23.183-23.377 GHz, ITU-R adopted a protection criteria in the 23.183-23.377 GHz band of $I/N = -16$ dB not to be exceeded more than 0.01% per HIBLEO-2 inter-satellite link be applied, taking into account the aggregated effect of all SRS earth stations in operation in the 22.55-23.15 GHz band.

Recognizing that HIBLEO-2 shares its spectrum with other services, the above criterion does not apply now or in the future to the existing service sharing arrangements for systems operating in the part of the allocation in which the inter-satellite links of HIBLEO-2 operate. The protection criterion in Recommendation ITU-R SA.1155 applies to the existing systems with which HIBLEO-2 shares spectrum.

ITU-R agreed that sharing studies between SRS uplinks and non-GSO-non-GSO ISS links operating co-frequency in the band 22.55-23.15 GHz should apply the value of $I/N = -10$ dB not to be exceeded more than 0.1% per link as set forth in Recommendation ITU-R SA.1155.

For adjacent band considerations, this assessment will initially assume that there is no frequency discrimination between the SRS and ISS. Subsequently, in the event that there is an excess of interference from the SRS into the ISS, further analysis will be performed into the effect of frequency separation of the two services.

4 Interference analysis

4.1 Step-by-step simulation

The characteristics of Tables A1-1 and A1-2 are used to model the dynamics of the interfering SRS earth stations and victim ISS satellite links. An appropriate interval between calculations and simulation length are chosen, allowing a step-by-step calculation of the I/N as per § 3. In this way, the cumulative distribution of the I/N can be calculated and compared to the protection criteria in § 4.

4.2 Simulation assessment of interference

A simulation has been performed to determine the time statistics of interference. An analysis of the results will be used to determine the compatibility of the proposed SRS (E-s) earth station emissions with co-frequency ISS receivers of the HIBLEO-2 constellation of satellites. Visualyse Professional Version 7 (Release 7.0.7.1) has been used to conduct this analysis, under the following conditions:

– simulation length of 28 days, 16 h, 40 min, this length of time falling between the orbital period and synodic period of the Moon;

_ constant visibility of at least two HIBLEO-2 satellites exists at latitudes around 35° from at least one of the locations of Table A1-1 at any given point of time;

– time-step of 1 s between calculations, this interval being sufficient to capture interference events;

– SRS and ISS with orbital and radiocommunications characteristics given in the relevant Tables;

– free space propagation loss, with atmospheric absorption loss included, and calculated according to Recommendation ITU-R P.676 Attenuation by atmospheric gases;

– temperature and water vapour density values calculated according to Recommendations ITU-R P.1510 and ITU-R P.836, and standard atmospheric pressure (1 013 hPa);

– time percentage of harmful interference calculated by the percentage of steps for which an ISS link exceeds the protection criteria;

– no frequency separation, bandwidth advantage, or polarization discrimination has been assumed.

5 Simulation results

Figure A1-1 shows the results of the interference assessment with an antenna pattern following the agreed HIBLEO-2 pattern. Six cumulative distribution functions, representing SRS (E-s) emissions into one ISS link selected randomly from each orbital plane, are displayed. Of note in Fig. A1-1 is that the in-band protection criterion (e.g. Recommendation ITU-R SA.1155) is met with a minimum margin of 37 dB.

Furthermore, the OoB interference protection criterion of –16 dB, not to be exceeded for more than 0.01% of time, is achieved with a margin of at least 18 dB if applied to a co-frequency scenario.

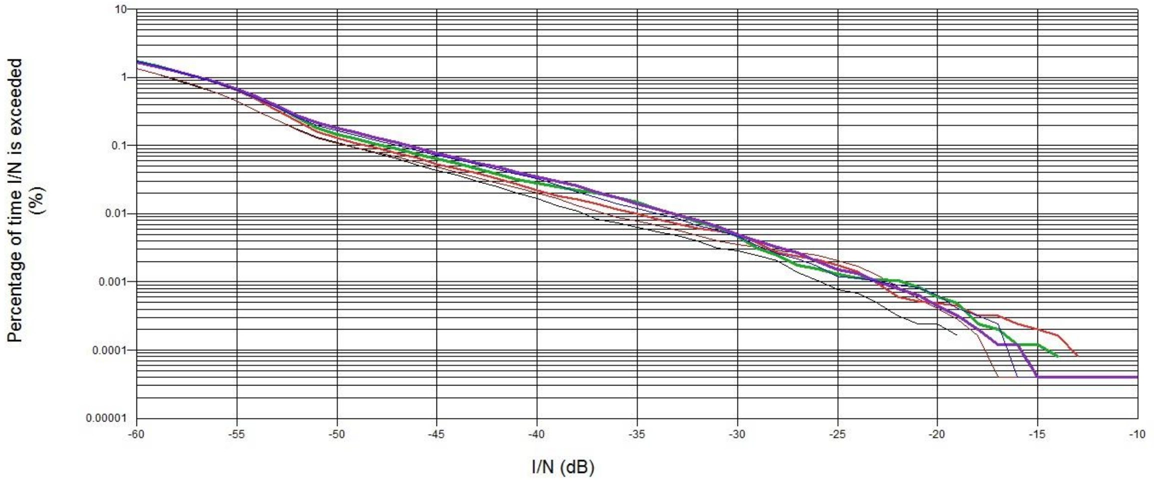
It should be stressed that this margin with respect to the OoB criterion assumes no suppression of OoB emissions. Several orders of magnitude of additional margin over the OoB protection criterion can therefore be assumed.

Actual SRS earth station antenna patterns, which employ large antennas, will likely have a side-lobe performance exceeding that used to produce the above results. Further consideration of such increases in antenna performance is likely to show an even greater level of compatibility with HIBLEO-2 ISS links.

Finally, with respect to OoB compatibility, consideration of all SRS earth stations in operation in the 22.55-23.15 GHz band is taken into account by considering emissions of three earth stations which transmit whenever in view of the Moon over a period of one month. Although the maximum number of SRS earth stations in the band may be greater than this, their aggregate effect will only slightly reduce the very high margin over the agreed OoB criterion for the HIBLEO-2 ISS, and will be offset by the considerations of SRS antenna pattern mentioned in the previous paragraph.

FIGURE A1-1

Results of interference assessment



6 Conclusion

An analysis of the interference impact from the proposed SRS (E-s) into existing HIBLEO-2 ISS in a hypothetical co-frequency sharing scenario in the band 22.55-23.15 GHz has been performed in the form of a step-by-step simulation. The analysis utilized the agreed HIBLEO-2 ISS OoB protection criteria. This protection criteria is more stringent than the in-band criteria agreed by WP 4A. The results of the analysis indicate that there is no harmful interference to HIBLEO-2 ISS.

Given that this in-band study shows compatibility with a large margin of protection for HIBLEO-2 even when the OoB protection criteria is applied in an in-band/co-frequency scenario, no further analysis of the impact of OoB SRS (E-s) earth station emissions is required. It is expected that consideration of OoB SRS (E-s) emissions would show increased compatibility with HIBLEO-2 ISS services with a significant additional margin of protection.

With respect to the HIBLEO-2 ISS, in-band and OoB compatibility exists with the proposed SRS (E-s) in 22.55-23.15 GHz, without undue constraint to HIBLEO-2 ISS.

Annex 2

Summary of Study 2

1 System characteristics

1.1 SRS earth station and mission satellite characteristics

The introductory section of this Report provides the SRS earth station and mission satellite characteristics for use in developing sharing studies within the 22.55-23.15 GHz band. These characteristics are representative of the technical and operating characteristics of earth stations and mission satellites supporting near-Earth, lunar, and Sun-Earth Lagrangian space research service (SRS) missions.

The characteristics of the SRS earth station emissions in the 23 GHz band are summarized in Table A2-1a). The SRS missions supported by these earth stations will be non-deep space SRS missions. The SRS earth station characteristics are based on supporting three types of space research missions: low-Earth orbiting (LEO) missions; Lunar missions; and Sun-Earth Lagrangian (L1/L2) missions. Table A2-1b) lists the orbital and receiving characteristics of these mission satellites.

TABLE A2-1a

Technical and operating characteristics of SRS earth stations supporting example missions

Parameter	Value		
Supported mission	LEO	Lunar	L1/L2
SRS earth station latitude (degrees)	32.5 N	32.5 N	35.4 N
SRS earth station longitude (degrees)	106.6 W	106.6 W	116.9 W
Transmitting antenna diameter (m)	10	18	34
Antenna gain (dBi)	65.3	70.4	75.9
Off-axis antenna gain envelope	ITU RR Appendix 7, Annex 4⁽¹⁾		
Bandwidth (MHz)	24	24	3
Power at the antenna input (dBW)	0.0	11.1	0.0
Power-spectral density at antenna input (dBW/Hz)	–70.8	–59.7	–61.4
e.i.r.p. (dBW)	65.3	81.5	75.9
e.i.r.p. density (dBW/Hz)	–5.5	10.7	14.5

(1) In this study, ITU RR Appendix 7, Annex 4 is used instead of Annex III to RR Appendix 8/ Recommendation ITU-R F.1245 as the former better represents the actual antennas in use today.

TABLE A2-1b

Science mission satellite characteristics

Parameter	Values		
Mission type	LEO	Lunar	L1/L2
Orbital altitude (km)	700	384 400	1 500 000
Orbit type	Circular	Circular	Halo
Orbital inclination (degrees)	98.2	Non-specific(1)	≈ 0° wrt ecliptic
Antenna gain (dBi)	40.3	44.7	44.7
Noise temperature (K)	410	410	410

(1) 23.45° is used in this study.

1.2 HIBLEO-2 system characteristics

System characteristics, protection criteria and antenna patterns used in this study are given in the introductory section of this Report.

2 Analysis method and results

2.1 Configuration for computer simulation

This computer-based dynamic simulation simulated the followings, for a period of one-year, to identify the interference events caused for one HIBLEO-2 satellite which is receiving four ISL signals from the nearest four HIBLEO-2 satellites.

- orbits of HIBLEO-2 satellites;
- pointing direction of HIBLEO-2 satellite antennas together with their antenna patterns;
- pointing direction of SRS earth station antennas together with their antenna patterns when SRS earth stations are transmitting uplink signals to lunar satellites.

Figure A2-1 shows this configuration.

In this simulation, HIBLEO satellite No. 13 is selected as a representative case, which is receiving ISL signals from the nearest four HIBLEO satellites of No. 12, No. 2, No. 25 and No. 14, as shown in Fig. A2-2.

2.2 In-band sharing study

While the HIBLEO-2 ISL frequencies do not overlap with the proposed SRS band in the 22.55-23.15 GHz, this analysis assumes two situations for both the in-band and out-of-band cases.

For the in-band studies, the PSD value for the lunar mission in Table A2-1a is used for computer simulation.

The simulation results are summarized in Table A2-2. The HIBLEO-2 protection criterion for the in-band, $I/N = -10$ dB not to be exceeded for more than 0.1% of time per link, is satisfied for all HIBLEO-2 ISLs.

The largest total interference time percentage caused by SRS aggregate uplinks is 0.00032%, which is far below the 0.1%.

FIGURE A2-1

HIBLEO-2 satellites interfered with by SRS uplink stations

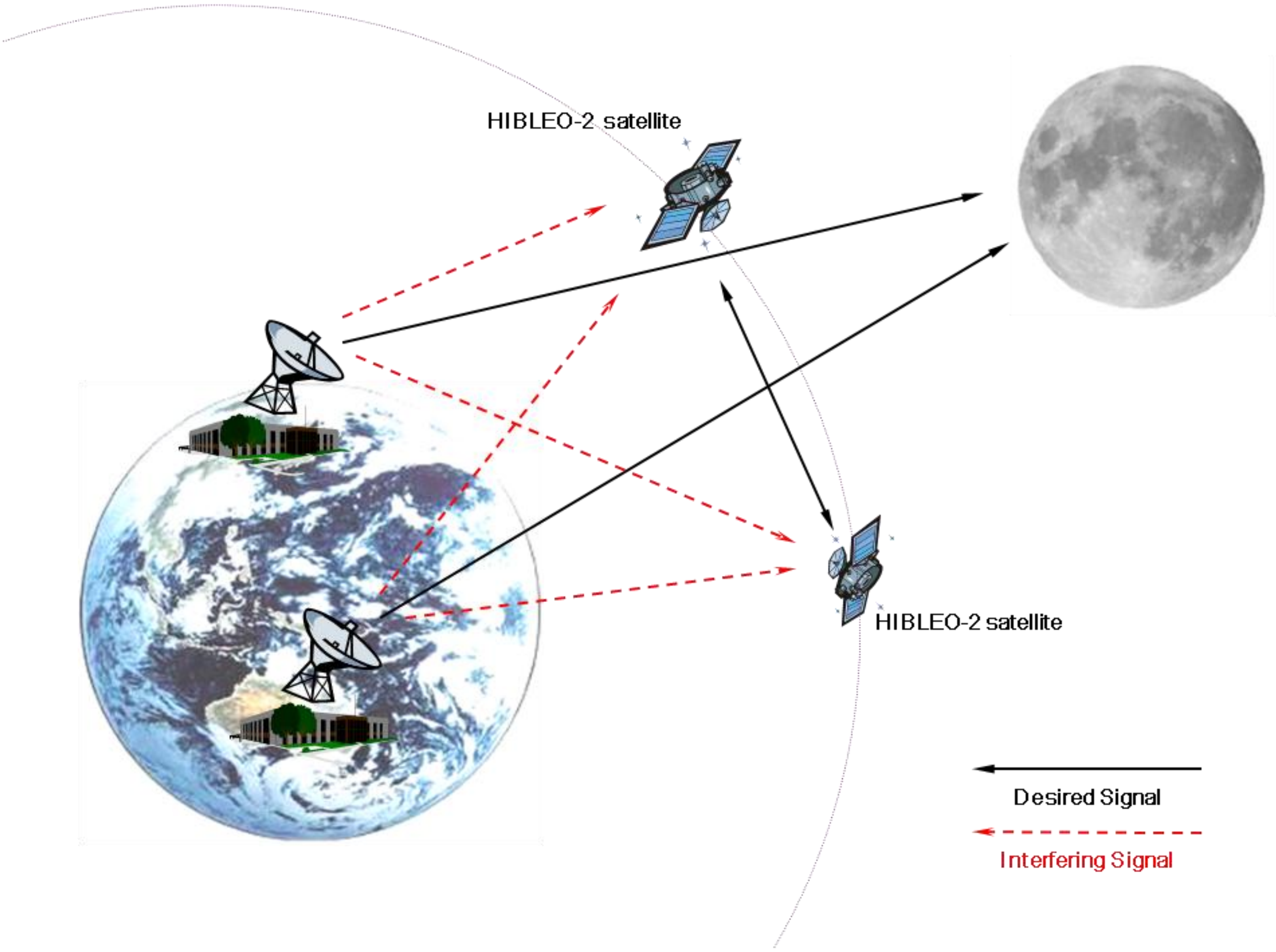


FIGURE A2-2

ISL for HIBLEO-2 satellite No. 13

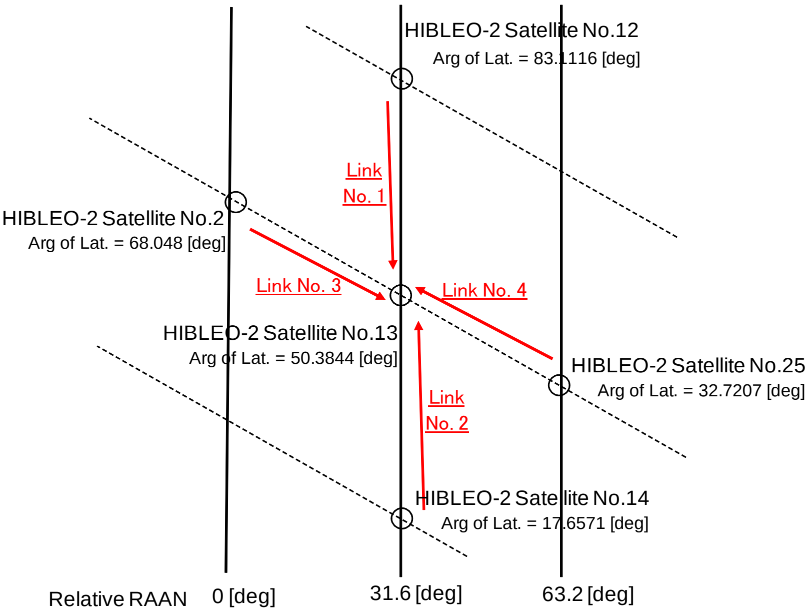


TABLE A2-2

Results for in-band case

No.	Interfering System		System Being Interfered		Interference Time Percentage
	TX Earth Station	RX Satellite	TX Satellite	RX Satellite	
1	Usuda	Lunar	Hibleo-2 No.12	Hibleo-2 No.13	0.00003%
2	Canberra				0.00007%
3	Goldstone				0.00003%
4	Madrid				0.00004%
5	ECDSA				0.00003%
6	Bangalore				0.00003%
7	Weinan				0.00004%
8	Neustrelitz				0.00001%
Total					0.00030%

Link No.1

No.	Interfering System		System Being Interfered		Interference Time Percentage
	TX Earth Station	RX Satellite	TX Satellite	RX Satellite	
9	Usuda	Lunar	Hibleo-2 No.14	Hibleo-2 No.13	0.00003%
10	Canberra				0.00007%
11	Goldstone				0.00004%
12	Madrid				0.00003%
13	ECDSA				0.00003%
14	Bangalore				0.00003%
15	Weinan				0.00003%
16	Neustrelitz				0.00001%
Total					0.00028%

Link No.2

No.	Interfering System		System Being Interfered		Interference Time Percentage
	TX Earth Station	RX Satellite	TX Satellite	RX Satellite	
17	Usuda	Lunar	Hibleo-2 No.2	Hibleo-2 No.13	0.00003%
18	Canberra				0.00009%
19	Goldstone				0.00004%
20	Madrid				0.00005%
21	ECDSA				0.00003%
22	Bangalore				0.00004%
23	Weinan				0.00003%
24	Neustrelitz				0.00001%
Total					0.00032%

Link No.3

No.	Interfering System		System Being Interfered		Interference Time Percentage
	TX Earth Station	RX Satellite	TX Satellite	RX Satellite	
25	Usuda	Lunar	Hibleo-2 No.25	Hibleo-2 No.13	0.00003%
26	Canberra				0.00007%
27	Goldstone				0.00003%
28	Madrid				0.00003%
29	ECDSA				0.00003%
30	Bangalore				0.00003%
31	Weinan				0.00003%
32	Neustrelitz				0.00001%
Total					0.00028%

Link No.4

2.3 Out-of-band sharing study

For the OoB case, the following conditions are assumed in order to calculate the largest OoB aggregate PSD value under a conceivable future scenario where many lunar missions are being supported by all 8 SRS stations:

a) All SRS stations are simultaneously transmitting four uplink channels with one 24 MHz carrier and three 12 MHz carriers as explained in the introductory section of this Report.

b) All SRS stations have the same antenna size and power-spectral density for each uplink channel.

c) The out-of-band aggregate PSD for each SRS station is calculated by totalling the individual out-of-band PSD values to represent the total of four carriers.

The largest out-of-band aggregate PSD values are –92.3 to –95.7dBW/Hz, which are about 35 dB less than the in-band PSD values.

The simulation results show that there are no interference events occurring over a period of 1 year for every HIBLEO-2 ISL link. For all links shown in Fig. A2-2, the HIBLEO-2 criteria, $I/N = -16$ dB not to be exceeded for more than 0.01% of time per HIBLEO-2 ISL in the 23.183-23.377 GHz, is not exceeded.

3 Conclusions

As demonstrated in this study, the sharing between the SRS (Earth-to-space) and the inter-satellite link of the HIBLEO-2 system in the 23.183–23.377 GHz band, as well as future HIBLEO-type system in the 22.55-23.55 GHz band, are feasible with no constraints on the SRS.

Annex 3

Summary of Study 3

1 Characteristics of potential SRS systems

Table A3-1 contains expected characteristics of the SRS earth station emissions in the 23 GHz band. The use of SRS earth stations in this band will focus on support of lunar missions with antenna diameters of around 18 m. In addition, also Lagrangian point missions are planned to be supported by earth stations with antenna diameters between 26 and 35 m. Cebreros has been used as a typical earth station to be used by ESA. Low-Earth orbiting missions are generally supported by antennas with around 10 m diameter.

TABLE A3-1

Technical and operating characteristics of SRS earth stations to support example missions

Parameter	**Value**		
Supported mission	LEO	Lunar	L1/L2
SRS earth station latitude (degrees)	40.45 N	40.45 N	40.45 N
SRS earth station longitude (degrees)	4.37 W	4.37 W	4.37 W
Transmitting antenna diameter (m)	10	18	35
Antenna gain (dBi)	65.3	70.4	75.9
Off-axis antenna gain pattern	Recommendation ITU-R F.1245 for dynamic interference situations		
Bandwidth(MHz)	24	24	3
Power at the antenna input (dBW)	0.0	11.1	0.0
Power-spectral density at antenna input (dBW/Hz)	–70.8	–59.7	–61.4
e.i.r.p. (dBW)	65.3	81.5	75.9
e.i.r.p. density (dBW/Hz)	–5.5	10.7	14.5

It is expected that worldwide a very limited number of SRS earth stations will be operated. Over the next few decades, some 10-15 earth stations may use this band mainly for support of lunar missions. They are almost exclusively deployed around mid-latitudes for mission specific reasons.

2 Assumed characteristics for the HIBLEO-2/Ka system

The characteristics provided in the main body of this Report have been used.

3 Assessment of interference to the HIBLEO-2/Ka satellite system

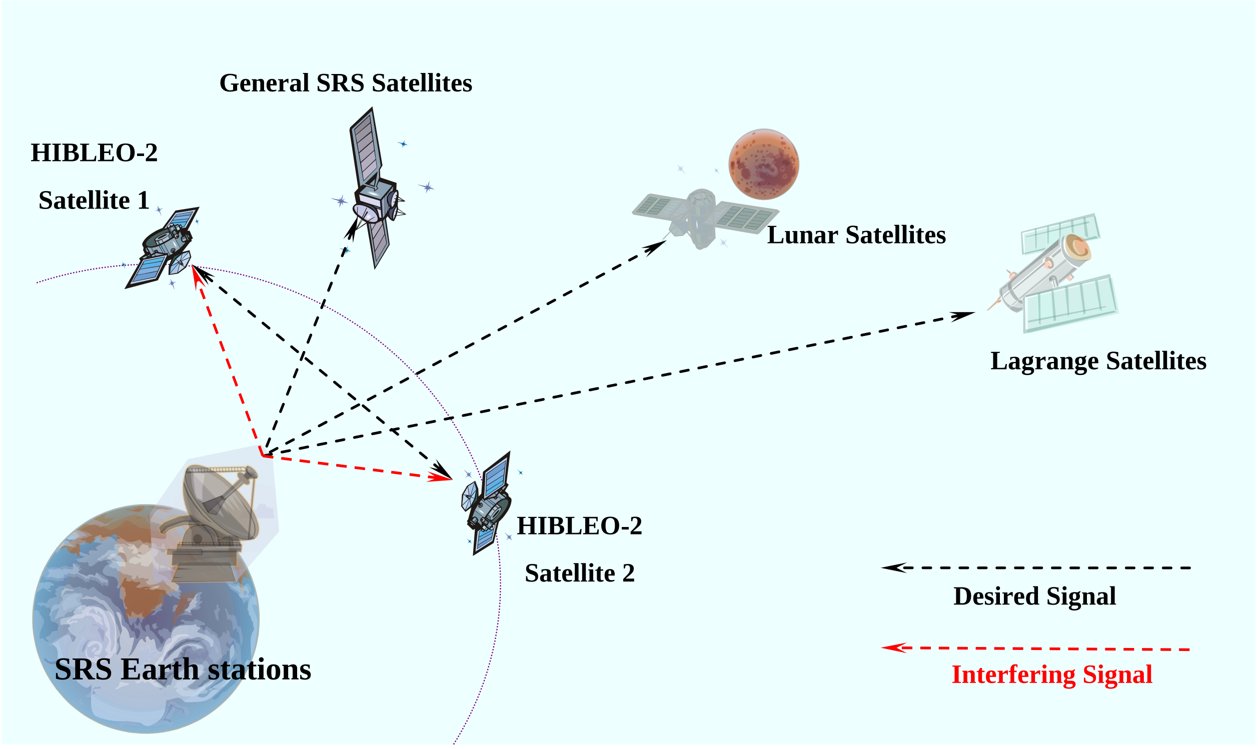
Figure A3-1 illustrates the potential interference configurations. The HIBLEO-2/Ka satellites may receive part of the SRS uplink signal through its side-lobes on both in-plane links as well as cross-plane links.

For ESA SRS missions, Cebreros in the centre of Spain ($\varphi = 40.45°$, $\lambda = -4.37°$), New Norcia in Australia ($\varphi = -31.05°$, $\lambda = 116.19°$) and Malargue in Argentina ($\varphi = -35.77°$, $\lambda = -69.37°$) would be typical locations to support missions to Lagrangian points or, potentially, to the Moon. In view of the long distances to L1 and L2, the power flux density of the received signals is rather low, requiring large earth stations up to 35 m. Lunar missions can be supported by smaller antennas around 18 m. Typical operations would be based on 3 earth stations supporting one satellite with the satellite being handed over between earth stations at elevation angles between 15° and 25°.

Simulations have been conducted with ESA’s radio frequency interference assessment tool (RFIAT). Minimum durations of 1 month were agreed for the simulations. In order to obtain smoother curves, simulated durations were increased to 1 year at time steps of 1 s. For the simulations, a hypothetical worst case minimum elevation angle of 5° has been assumed for all three earth stations.

FIGURE A3-1

Potential interference cases between SRS missions and HIBLEO-2/Ka links



The number of inter-satellite links affected by potential interference from one worst case SRS channel, either co-channel in case of an in-band situation or the nearest channel in case of an out-of-band situation, can be estimated to be on the order of 16. This number can be derived taking into account that the HIBLEO-2 system operates on 8 channels, does not transmit across seam-lines, does not operate inter-planer links above mid-latitudes and does not operate on all intra-planer links in the polar regions. Other factors such as unavailability of satellites or reduced traffic per channel may also apply. It is difficult to estimate the actual activity factor as no detailed information has been provided but it appears safe to assume that the total links fully operational at any time do not exceed 50%. This leaves around 16 links per channel operational at any time. Consequently, 8 different inter-planer links and 8 intra-planer links were randomly selected as shown in Table A3-2. Earlier studies concluded already that there is little difference between the various inter-satellite links as long as the simulated duration is sufficiently long.

TABLE A3-2

Inter-satellite links considered in assessment

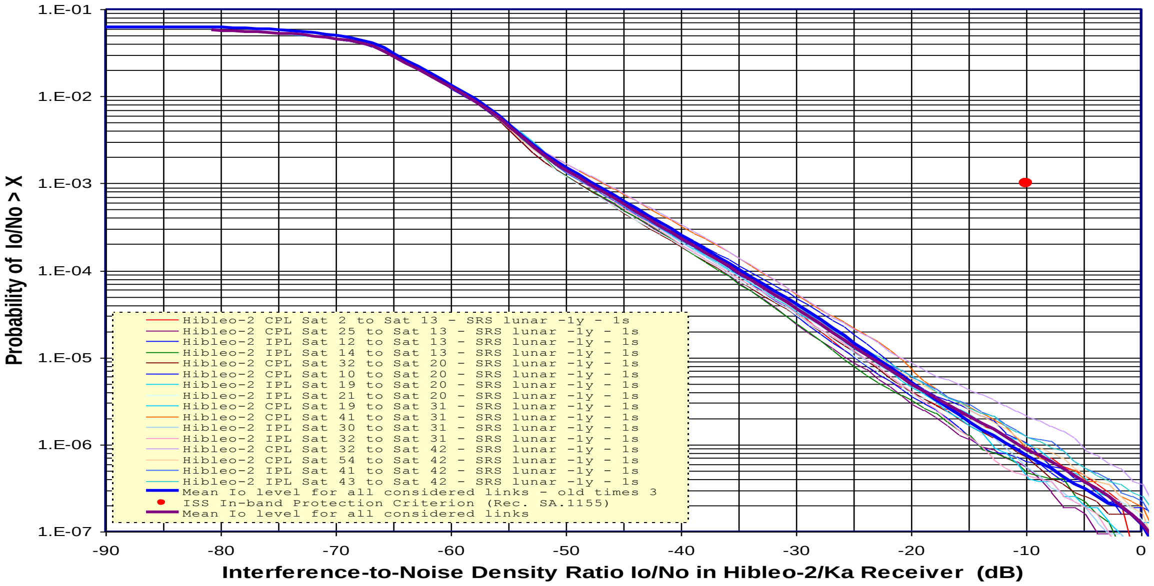
Transmitting satellites	2, 12, 14, 25	10, 19, 21, 32	19, 30, 32, 41	32, 41, 43, 54
Receiving satellite	13	20	31	42

3.1 In-band assessment of interference to HIBLEO-Ka satellite system

Figure A3-2 shows the interference-to-noise density ratios for the 16 links and the average of all curves. It can be seen that 1 s simulations steps result in smooth and reliable cumulative distribution functions down to at least 10^{-6}, i.e. 0.0001%. The simulations last around 1 hour per link and the results are based on 31.5 million samples each. The reference protection requirement of $I_0/N_0 = -10$ dB is shown as a red circle. A margin of around 38 dB is available for co-channel operations of three SRS earth stations down to hypothetical elevation angles of 5°.

FIGURE A3-2

I_0/N_0 ratios for selected set of 16 inter-satellite links



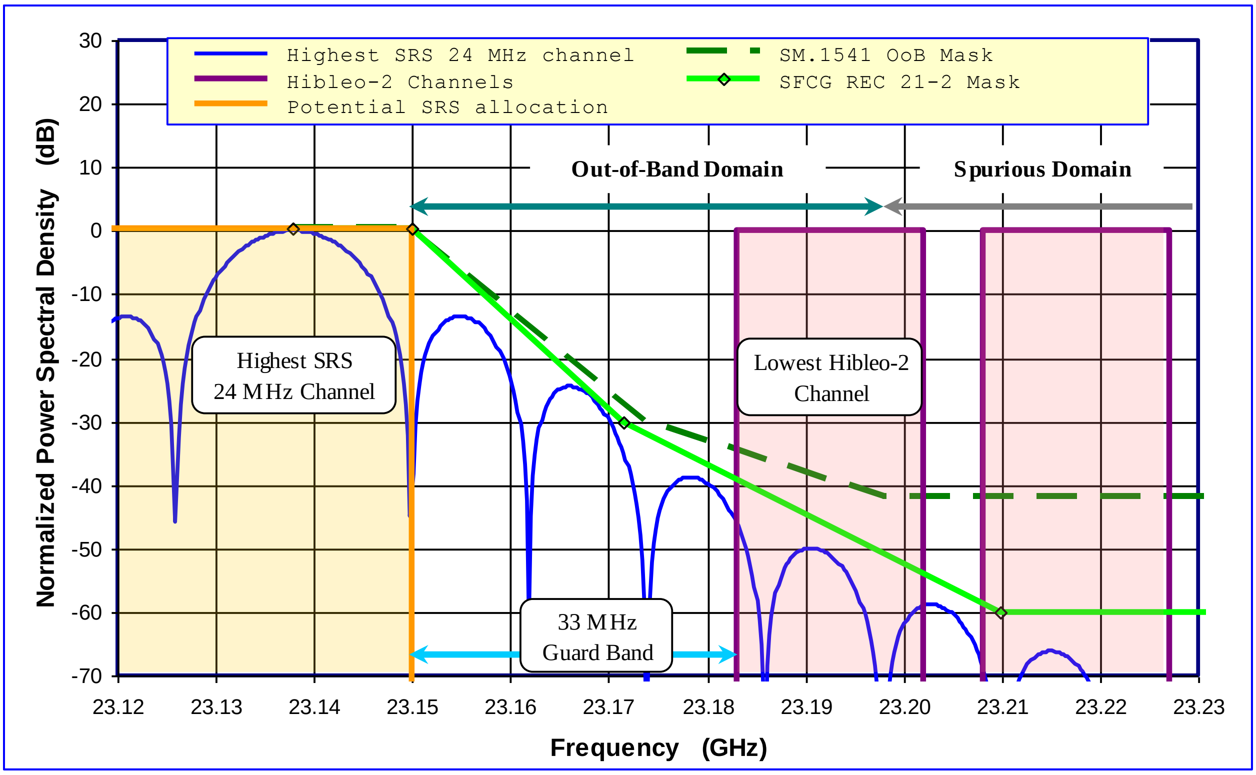
3.2 Out-of-band assessment of interference to HIBLEO-2 satellite system

Regarding out-of-band interference, the agreed protection criterion is $I_0/N_0 = -16$ dB not to be exceeded for more than 0.01% of time per inter-satellite link. The above derived Io levels will be reduced by typical spectral roll-off functions. Minimum specifications to be met are contained in Recommendation ITU-R SM.1541. At 1.5 times of the necessary bandwidth, the level has to be reduced to −30 dB. At 2.5 times the necessary bandwidth, the level would be lower than −42 dB.

Actually applicable specifications are more stringent. Spectral masks internationally agreed by the Space Frequency Coordination Group (SFCG REC 21-2) specify levels of −60 dB at 3 times the data rate from the carrier frequency. Figure A3-3 shows the relevant OoB masks and typically associated spectral power density levels.

FIGURE A3-3

Out-of-band spectral power density levels and relevant masks



All SRS earth stations have been taken into account for out-of-band interference. Assuming 15 earth stations and each of them transmitting with maximum power on 3 different channels, a very pessimistic number of 45 channels may be active within the entire SRS allocation.

Considering an available guardband of 33 MHz between 23.15 GHz and 23.183 GHz, the lower boundary of the first HIBLEO-2 channel at 23.183 GHz, and a maximum 24 MHz SRS channel just below 23.15 GHz without any guardband, it can be safely assumed that mean out-of-band emissions over the entire channel bandwidth will be at least 35 dB below the maximum power-spectral density for the highest channel used by 3 earth stations. In a hypothetical worst case, it may be assumed that the other 14 channels would operate at the highest possible Recommendation ITU-R SM.1541 specifications of −42 dB. The cumulative impact of all 15 channels would then be −29 dB below the maximum in-band level. In reality, any SRS channels below the highest channel will show spectral densities orders of magnitude lower than −35 dB within the HIBLEO-2 channels.

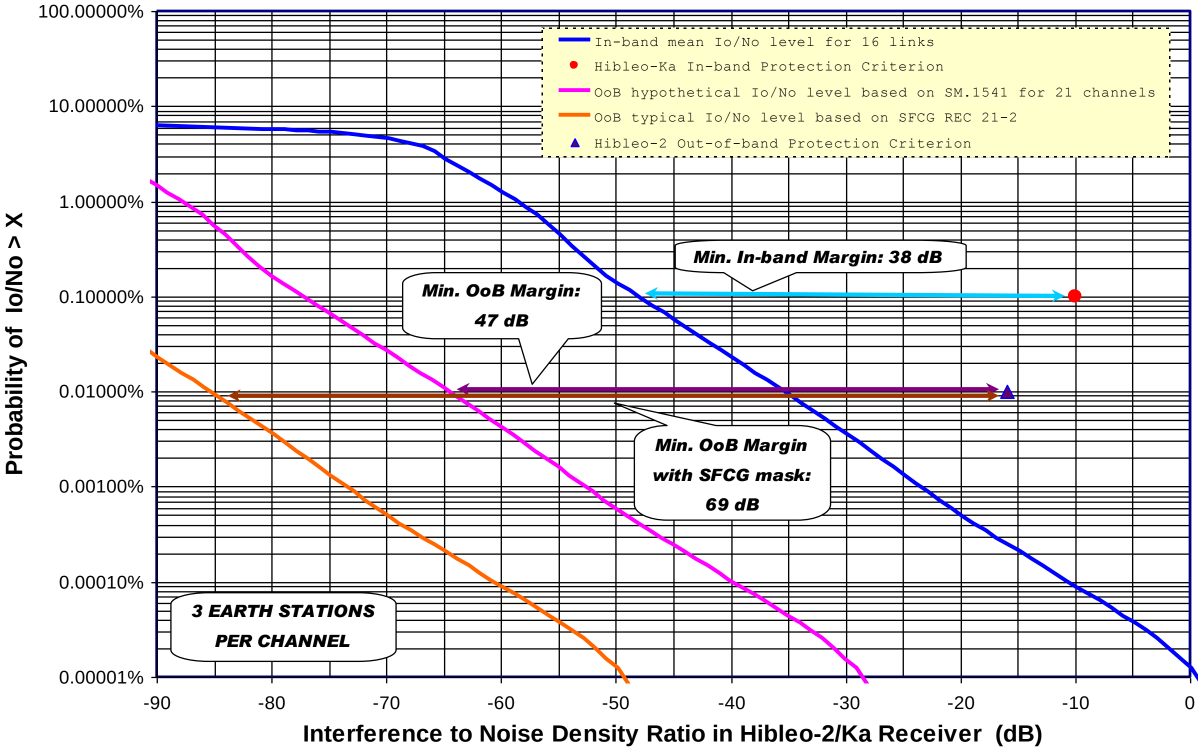
Assuming 15 earth stations transmitting on 3 SRS channels, each would result in a margin of at least 48 dB with respect to the proposed out-of-band criteria. In reality, the out-of-band emission levels will follow the SFCG recommendation, leading to an average spectrum level well below −50 dB and hence a margin of at least 69 dB.

4 Summary and technical discussions

Figure A3-4 shows the average interference–to-noise density obtained from the 16 arbitrarily selected HIBLEO-2/Ka inter-satellite links which is approximately the number of active links per channel. Regarding in-band interference, it can be seen that a margin of around 38 dB is available with respect to an $I_0/N_0 = -10$ dB criterion agreed by ITU-R.

FIGURE A3-4

I_0/N_0 levels originating from SRS earth stations supporting a Lunar Mission



Although ITU-R proposed to consider the I_0/N_0 criterion exclusively for SRS links, it may be noted that Recommendation ITU-R SA.1155 addresses aggregate interference per link. In an in-band situation, it is therefore not uncommon to apportion the allowed interference on an equal basis to all services using the band. Considering that the band would be used by the FS, ISS and SRS, a 5 dB margin reduction could be taken into consideration for the in-band sharing situation. An allocation is also available to the mobile service but no MS systems are known to use the band.

Regarding out-of-band interference, minimum margins based on the criterion agreed by ITU-R and specifications contained in Recommendation ITU-R SM.1541 are at least 48 dB in a hypothetical worst case. Typical margins based on actually applicable spectral mask in accordance with SFCG Recommendation 21-2 are around 70 dB. It may be noted that even the originally claimed 0.001% of time with reference to the entire HIBLEO-2 system could be met with large margins.

Interference resulting from spurious emissions is insignificant as compared to out-of-band emissions in view of the low levels of −54 dBW permitted by RR Appendix 3.

All above derived minimum margins are based on worst case assumptions. In a realistic situation, additional mitigation factors will be available. Actual average antenna gains will be around 3 dB lower due to laws of physics and atmospheric attenuation of 2-3 dB will reduce SRS signals in particular at lower elevation angles, where the more critical interference events would occur. Reception of interference via far antenna sidelobes is often subject to 1-3 dB polarization discrimination. In addition, Lunar and Lagrangian satellites are often handed over to the next earth station in a global network long before the minimum elevation angle of 5° is reached. Furthermore, the SRS earth stations are unlikely to transmit continuously. A duty cycle of 50% may be representative for many missions. Table A3-3 shows a summary of additional mitigation factors and their estimated interference reduction.

TABLE A3-3

Additional mitigation factors and their impact on the actual margins

	In-band	**Out-of-band**
Obtained minimum margins (dB)	38	48
Atmospheric attenuation for more than 99% of time and 5°-90° elevation angles (dB)	2-3	2-3
Average antenna gain reduction (dB)	3-4	3-4
Polarization discrimination in antenna side-lobe regions (dB)	1-3	1-3
Elevation angles of 15°-25° in global network satellite handover (dB)	1-2	1-2
Actual expected duty cycle between 50% and 100% (dB)	0-3	0-3
Interference apportionment between FS, ISS and SRS (dB)	−5	---
SFCG spectral mask compliance (dB)	---	20-23
Spectral density reduction due to additional guardband at 23.15 GHz (dB)	---	3-5
Expected actual margins (dB)	40-48	78-91

5 Conclusions

– In-band sharing with a potential future HIBLEO-Ka system is feasible. Protection criteria based on Recommendation ITU-R SA.1155 can be met with a minimum worst case margin of 38 dB. Actual margins are expected to lie in the range 40-48 dB The large margins are basically due to the facts that SRS earth station antenna beam widths are extremely narrow and that main beam coupling with inter-satellite link antennas can never occur.

– Out-of-band compatibility with the existing HIBLEO-2 system based on criteria recommended by Working Party 4A can be achieved with a hypothetical minimum margin of around 48 dB if all SRS channels would emit at the highest possible levels contained in Recommendation ITU-R SM.1541. In reality, all SFCG member agencies apply SFCG Recommendation 21-2 and only the highest SRS channel will generate dominant interference. This alone would result in a minimum OoB margin of around 69 dB. Taking into account several additional mitigation factors results in expected actual margins between 78-91 dB.

Annex 4

Summary of Study 4

1 HIBLEO-2 ISL characteristics

The system characteristics as contained in the introductory section of this Report have been used.

2 SRS earth station characteristics

The characteristics of the SRS earth station emissions in the 23 GHz band are summarized in Table A4-1.

TABLE A4-1

Technical and operating characteristics of SRS earth stations to support example missions

Parameter	Value		
Supported mission	LEO	Lunar	L1/L2
Transmitting antenna diameter (m)	10	18	34
Antenna gain (dBi)	65.3	70.4	75.9
Off-axis antenna gain envelope(1)	Annex III to RR Appendix 8/ Recommendation ITU-R F.1245		
Bandwidth (MHz)	24	24	3
Power at the antenna input (dBW)	0.0	11.1	0.0
Power-spectral density at antenna input (dBW/Hz)	–70.8	–59.7	–61.4
e.i.r.p. (dBW)	65.3	81.5	75.9
e.i.r.p. density (dBW/Hz)	–5.5	10.7	14.5

(1) Annex III should be used for static interference analyses and Recommendation ITU-R F.1245 should be used for dynamic interference analyses.

Recommendation ITU-R F.1245 was used to model an average antenna pattern.

3 Simulation and results

A simulation was performed over 1 month with a time step of 5 s taking into account 3 SRS earth stations following the Moon based in Canberra, Goldstone and Madrid, and one HIBLEO-2 satellite connected to the other 4 adjacent satellites.

No atmospheric attenuation was taken into account in the SRS to ISS path, noting that the frequency band used by ISL links corresponds to an absorption line with attenuations from 0.5 dB (at zenith) to more than 10 dB for low-elevation paths. This would drastically reduce the interference level determined here.

The simulation was performed assuming that the SRS earth station is transmitting within the same band as the ISL. No out-of-band attenuation factor was therefore considered.

Figures A4-2 and A4-3 give the simulation results for HIBLEO-2 satellite 6, randomly chosen. Figure A4-2 gives an overview of the interference events vs. time, with a zoom on a particular pike, whereas Fig. A4-3 gives the cumulative distribution function obtained for all 4 crosslinks of the satellite.

FIGURE A4-1

Simulation scenario

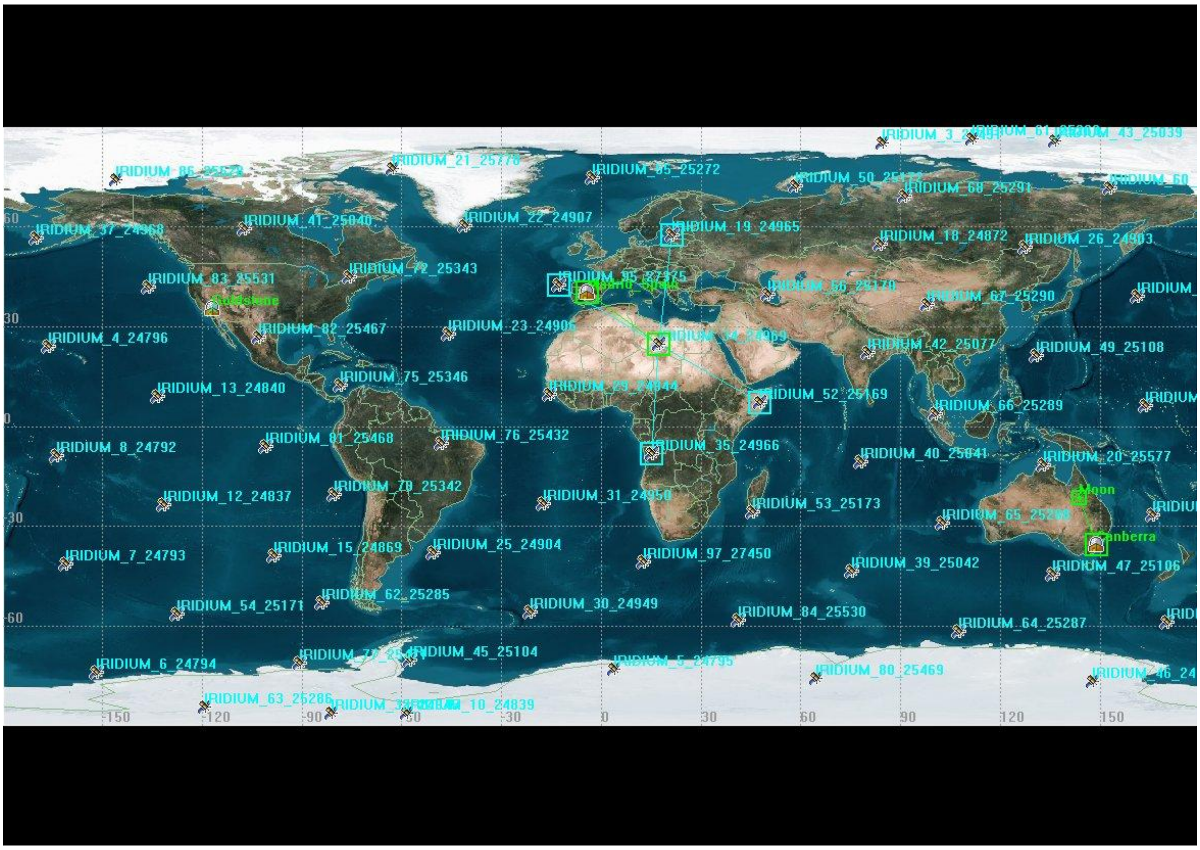
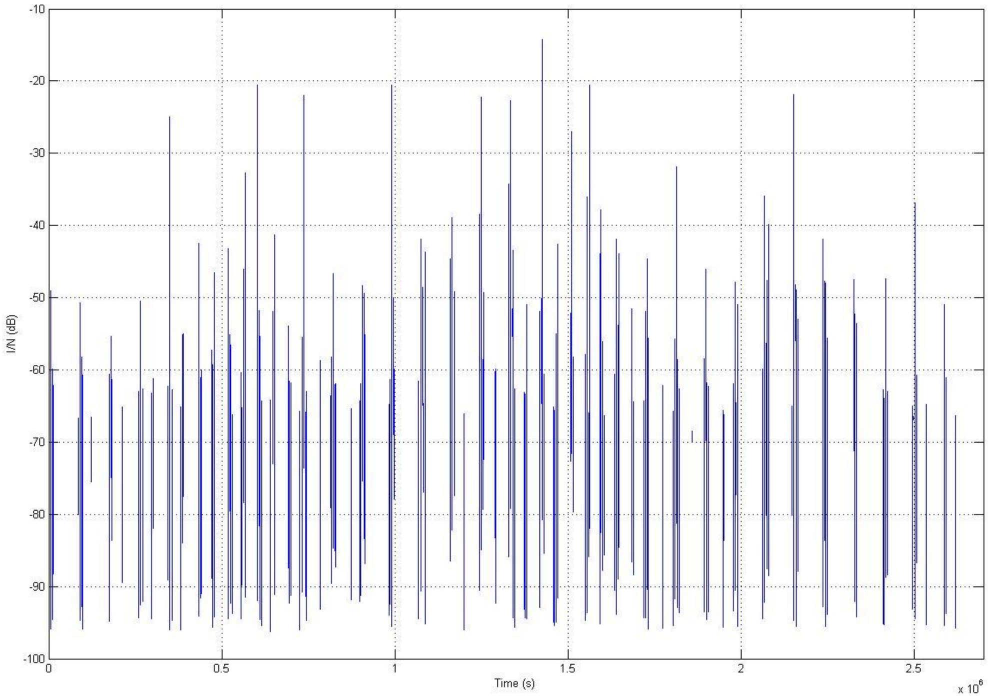


FIGURE A4-2



Interference over noise vs. time for HIBLEO-2 satellite 6

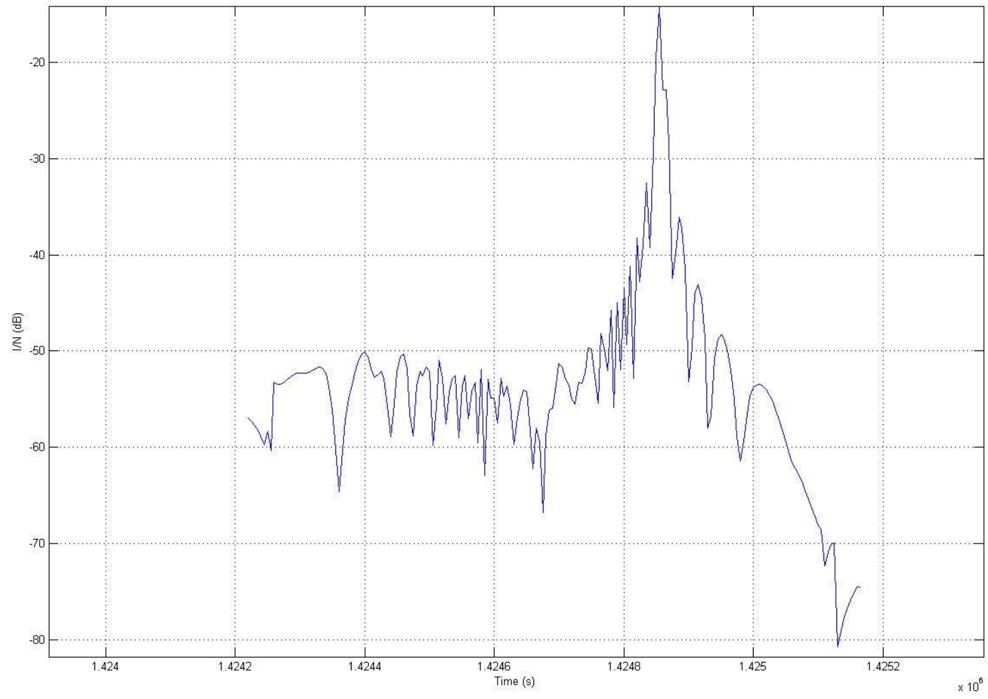
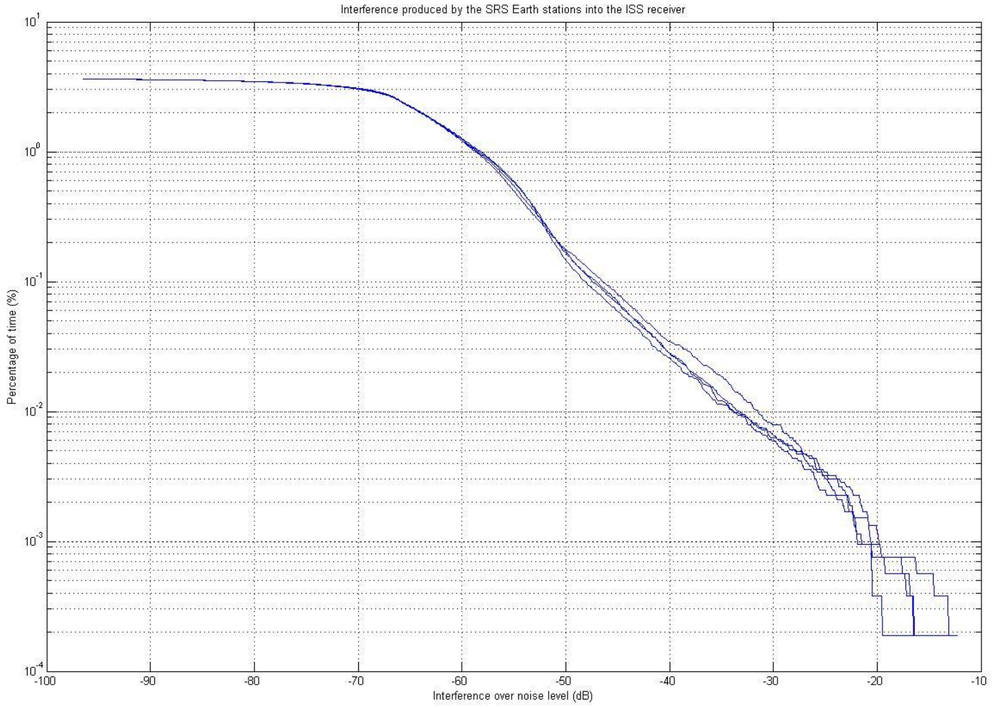


FIGURE A4-3

Interference over noise cumulative distribution function for HIBLEO-2 satellite 6



Figures A4-4 and A4-5 give the simulation results for HIBLEO-2 satellite 13, determined to be the one with the highest occurrence of SRS stations main beam interception. Figure A4-4 gives an overview of the interference events vs. time, with a zoom on a particular pike, whereas Fig. A4-5 gives the cumulative distribution function obtained for all 4 crosslinks of the satellite.

FIGURE A4-4

Interference over noise vs. time for HIBLEO-2 satellite 13

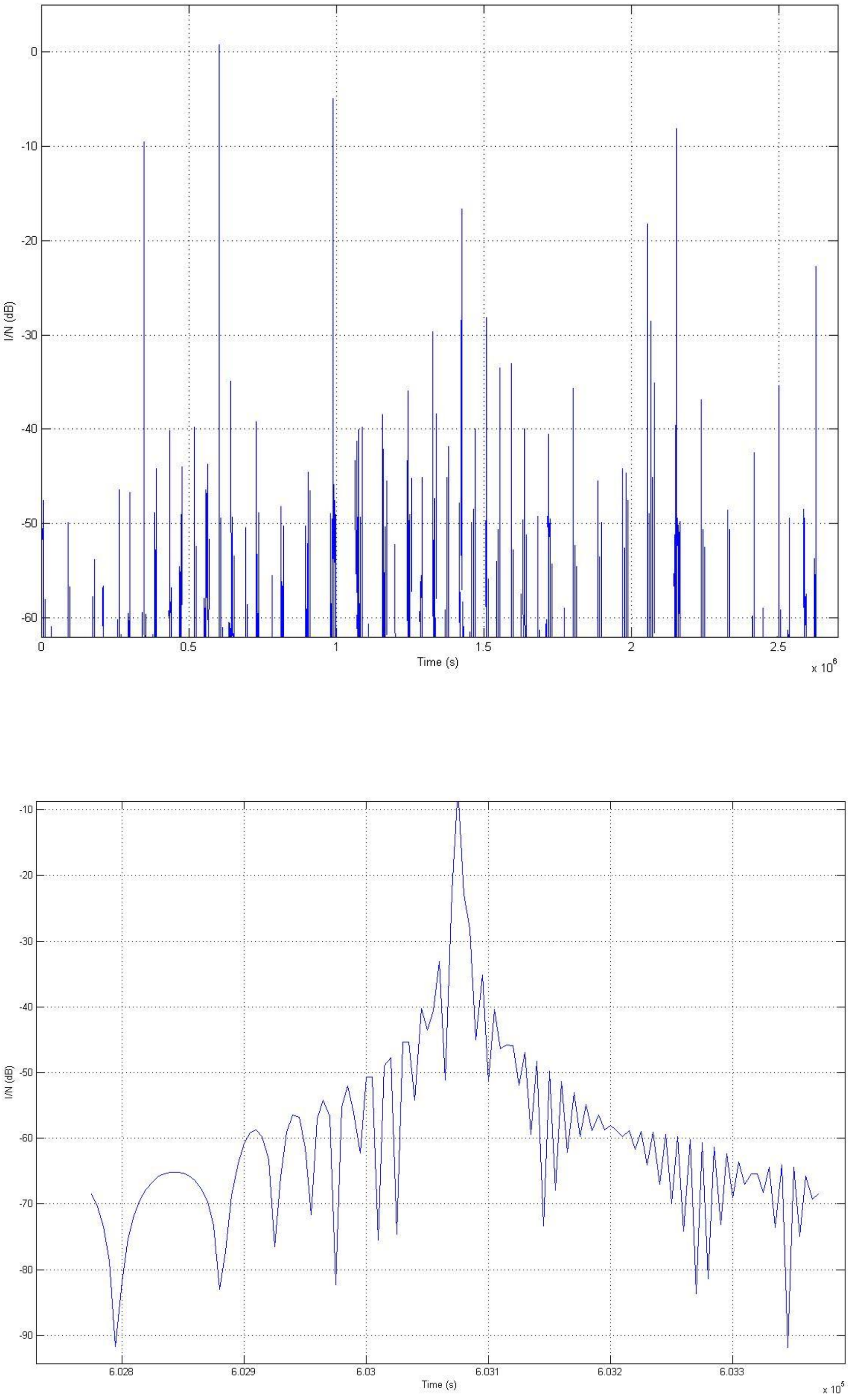
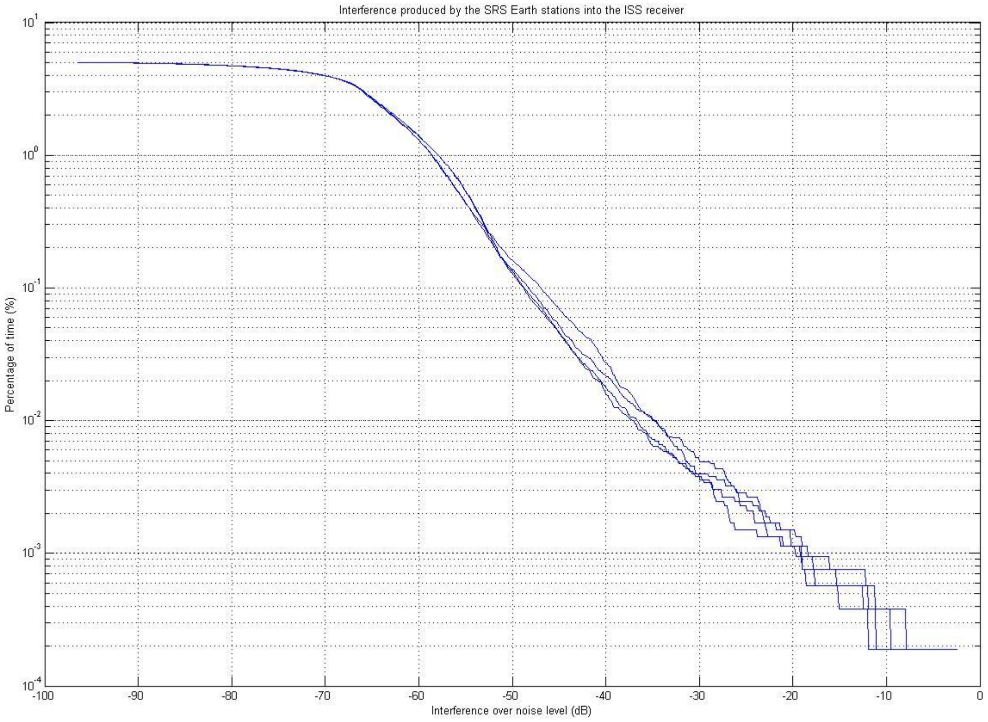


FIGURE A4-5

Interference over noise cumulative distribution function for HIBLEO-2 satellite 13



The level of interference over noise for 0.1% of the time is from –49 to −47 dB. There is therefore a 37 to 39 dB margin with regard to the agreed in-band protection criterion within ITU-R (*I*/*N* of –10 dB, 0.1% of the time).

The level of interference over noise for 0.01% of the time is from –37 to –32 dB. This is already 16 to 21 dB below the protection criterion agreed by WP 4A (–16 dB, 0.01% of the time), without even considering any OoB attenuation. The actual interference would be much lower taking into account the OoB attenuation due to the modulation shape only, and any output filter that might be implemented on the SRS earth stations.

Additional atmospheric losses were not taken into account in the study and would further reduce the level of interference.

4 Conclusion

The results of the simulation above, the important atmospheric attenuations for this frequency band, as well as the out-of-band signal attenuation due to the SRS earth station transmitter modulation shape, show that SRS earth stations used for Moon missions are compatible with HIBLEO-2 ISL without any further constraint.

Annex 5

Summary of Study 5

1 Introduction

This Report presents a methodology based on the numerical simulation of the analytical formulas involved in the calculations of RF interference when complex scenarios of satellite constellations of many satellites and very directive Earth antennas tracking the Moon or the Sun are involved[1].

Part I presents the methodology to be used using a simplified example of the ISS antenna pattern in the Moon scenario. Simulations have been modelled with a time series approach implementing the appropriate analytical equations representing the radiocommunication links performance as well as the geometrical orbits of the Earth, the Moon, the L2 point and the entire HIBLEO-2 satellite constellation. It should be emphasized the insight that this method provides to the experimenter in the course of designing the appropriate MATLAB programs for the scenario being studied.

Results for a worst-case interference scenario caused by one SRS ES transmitting to the Moon into the inter-satellite links of the HIBLEO-2 constellation have been simulated for an SRS ES antenna diameter of 18 m and PSD input to the antenna of –59.7 dB(W/Hz). Long-term availabilities have been found to vary from 99.9989% (I/N_0 = –2.5 dB) to 99.92% (I/N_0 = –14.5 dB). Short-term interference events have also been quantified. Since the percentage of interference is a "per-link" basis, semi-log plots relating the I/N_0 of the ISS forward link receiver to the in-band interference are provided for this scenario in Fig. A5-7 showing a margin much greater than 12 dB for in-band sharing.

Results for an interference scenario with a PSD of –61.4 dB(W/Hz) input to a 34 m SRS ES antenna transmitting to the Lagrangian L2 point showed that the worst-case long-term availability (30 days, "Winter") may vary from 99.9988% (I/N_0 = –2.5 dB) to 99.9942% (I/N_0 = –14.5 dB). Margins for this scenario are even larger than those of the Moon scenario.

Based on the agreed protection criteria, these results confirm the feasibility of sharing. Furthermore, the results yielded by this deterministic approach have an excellent agreement with the statistical method results, thus providing an appropriate verification tool.

---

[1] BENITO O. GUTIERREZ LUACES [2008] Basic MATLAB programs used in all simulations may be found in the book "Principles of radio frequency interference analysis with emphasis on computer simulations of satellite constellations". BUBOCK PUBLISHING S.L. (www.bubok.com).

PART I

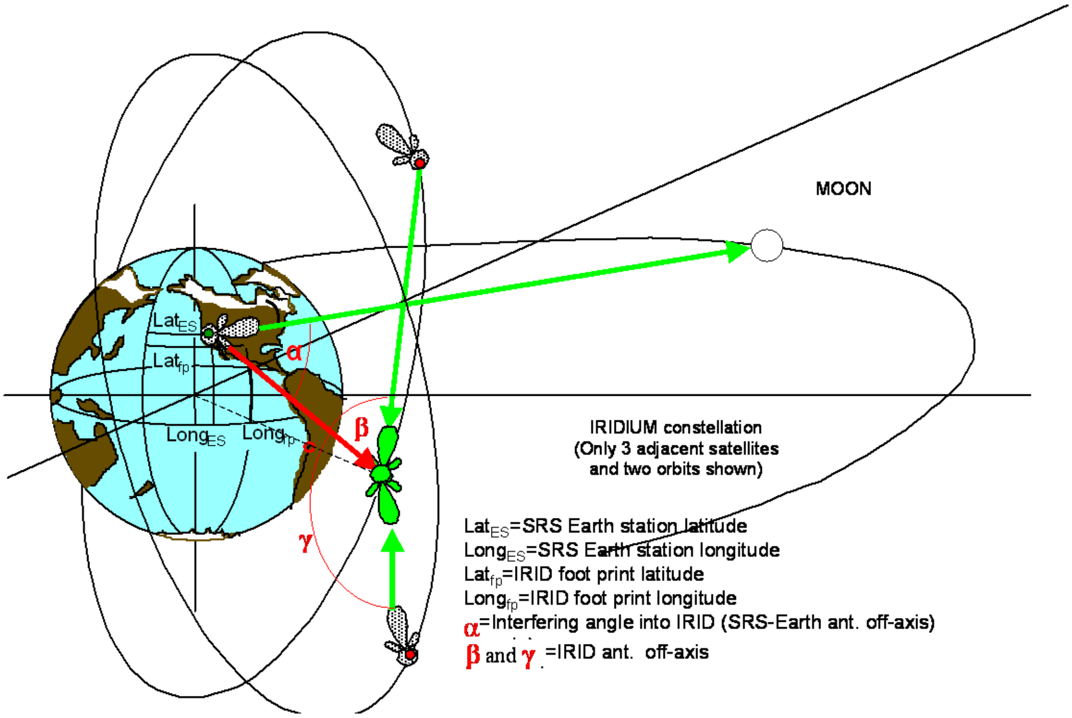
Scenarios and simulations description

2 Interference scenario of the space research service transmissions to the Moon into space-to-space links of the inter-satellite service

Figure A5-1 shows a simplified version of the scenario to be analysed. Only 2 satellites comprising a single forward-link out of the 11 per plane are shown. A third satellite of an adjacent orbit completes the only cross-link shown out of the 11 operational between the two adjacent orbits. A more complete description of the satellite constellation will be given later.

FIGURE A5-1

The interference scenario



The space research service earth station (SRS ES) will be transmitting through a very directive antenna towards the Moon. Therefore these emissions will reach the victim satellite with a different spectral power flux density (SPFD, dB (W/(Hz m^2)) as a function of the SRS ES antenna off-axis angle (α). As shown in Fig. A5-1 two totally different interference scenarios will be analysed depending on the inter-satellite link considered. The interference into the 11 forward-links that will depend on the inter-satellite antenna off-axis angle (β) will be first analysed to finalize with the analysis of the interference into the 11 cross-links with off-axis angle (γ).

Further details to complete these scenarios will be provided in next paragraphs.

2.1 The Earth

The Earth is considered to be a perfect sphere of 6 378 km of radius that is rotating with a period of 1 440 min around the North-South polar axis. The three-dimensional scenario described in paragraph above will be referred to the centre of the Earth.

Table A5-1 summarizes the space research service earth station (SRS ES) parameters used in this simulation.

TABLE A5-1

Summary of SRS ES parameters

Operating frequency (GHz)	23.1
SRS ES latitude (degrees)	32.5 N
SRS ES longitude (degrees)	106.6 W
Antenna diameter (m)	18
Maximum antenna gain (dBi)	70.4
Power-spectral density at antenna input (dB(W/Hz))	–47.9

The SRS ES antenna pattern used corresponds with the one in the RR Appendix 8, Annex III.

2.2 The near-Earth satellite constellation

The near-Earth satellite constellation to be modelled is the HIBLEO-2 constellation with technical characteristics similar to the IRIDIUM constellation as published by the FCC in the Motorola application dated December 3, 1990.

The asymmetric HIBLEO-2 constellation at an altitude of 780 km, inclination angle of 86.5° and orbital period of 100.45 min will be composed of 6 planes spaced 31.6° in the Right Ascension of the Ascending Node (RAAN). The 11 satellites per plane will be symmetrically spaced 32.7° with the appropriate phasing factor between the circular orbits of each plane to maximize the separation between satellites at the orbits crossing points.

The antenna pattern to be used at this time will be composed of two main parts: the "back-lobe" antenna gain of –10 dBi for off-axis angles between 36° to 180° and gains above 0 dBi for off-axis angles smaller than 36° A more detailed antenna pattern will be used and described again in Parts II, III and IV. The equations implemented in the simulations used in this Part I are:

$G(\theta) = 36.7$ dBi $\theta < 1.2°$

$G(\theta) = 36.7\text{-}3 \times (\theta/1.2)^2$ dBi $1.2° < \theta < 3.1°$

$G(\theta) = 17$ dBi $3.1° < \theta < 7.6°$

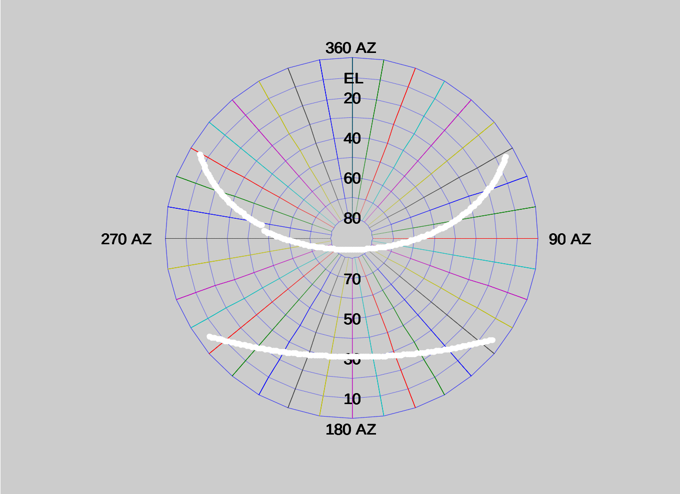
$G(\theta) = 39\text{-}25 \log(\theta)$ dBi $7.6° < \theta < 36°$

$G(\theta) = -10$ dBi $36° < \theta < 180°$

The system noise temperature of all inter-satellite receiver links will be considered to be 720.3 K equivalent to a PSD of –200 dB(W/Hz).

FIGURE A5-2

Stereographic representation (azimuth, elevation) of the Moon's limits



2.3 Maximum PSD, dB(W/Hz), interference allowed by HIBLEO-2 inter-satellite links

Maximum I/N_0 allowed by the inter-satellite receivers of these near-Earth constellations were at the time subjected to discussions and since this Part I will serve the purpose of describing some particularities of the scenario to be simulated, a maximum of $I/N_0 = –2$ dB at the inter-satellite links will be allowed. The main reason for choosing this I/N_0 is the Sun effects on the main beam of the HIBLEO-2 receiver presented in ITU-R documentation and summarized in next paragraph. Results for I/N_0 as large as –22.5 dB will be presented in Part II for an update of the systems characteristics on this Moon scenario analyzed here.

2.3.1 Sun effects conclusions

Sun radiation into space-to-space forward-links and cross-links of a typical satellite constellation such as HIBLEO-2 with 6 planes and 11 satellites per plane operating around 23 GHz show that interference of about $I/N_0 = –2$ dB will be encountered in both ISS link types with long term interference of about 0.1% per plane for the forward-links and 0.06% for cross-links. These interference events will last from 36 s to 30 s approximately and will not be present in the Earth's central zone with latitudes smaller than 50°.

Since the space-to-space link budgets will have to be designed for this $I/N_0 = –2$ dB (see the FCC document), there will be an excess margin of approximately 2 dB when the Sun radiation is not in the receiving antenna main lobe. Therefore to facilitate sharing of this space-to-space links with the space research service (SRS) transmissions to the Moon and to the L2 Lagrange point, this excess margin may be made available to improve the possibility of sharing with these systems whenever their emissions are not coincident with those of the Sun into the bore-sight of the victim HIBLEO-2 antenna.

2.4 The Moon

Since the scenario considered will be referred to the centre of the Earth, the Moon will be in a theoretical circular orbit rotating around the Earth with an inclination with respect to the Earth's polar axis of 28.6° and a period of 28 days with a RAAN = 92.5° and an argument of latitude of –69.3° at the epoch considered in previous paragraph for the HIBLEO-2 constellation to be simulated in this scenario.

Figure A5-2 shows the local horizon limits (azimuth and elevation) when the Moon is tracked from an SRS ES located at 32.5 N and 106.6 W.

3 SRS ES interference into HIBLEO-2 forward-links – The simulation

Above described scenario has been modelled with the appropriate analytical equations[1] in a time series referred to the same epoch for the Earth, the Moon and the HIBLEO-2 satellite constellation. The minimum SRS ES elevation angle is set to 5°, which will be the elevation limit for the SRS ES when tracking the Moon. On the contrary the minimum elevation angle for the HIBLEO-2 constellation when viewed from the SRS ES location will be –22°. Note that this minimum elevation angle is necessary not to miss any of the 11 forward-links receivers when the corresponding transmitting HIBLEO-2 satellite is below the SRS ES horizon.

Time increment (Δt) used in this time series simulations is of concern since very small (Δt) will provide very detailed results but the simulation will take a long time, unpractical to obtaining the first results to properly characterize the scenario analyzed. In this direction the following paragraphs will determine some parameters of interest to help determine an optimum time increment.

3.1 Omnidirectional transmissions; SRS ES antenna gain limits in the forward-links scenario

As it will be shown later, it will be of interest to determine the limits on the SRS ES antenna gain that will produce interference events on the scenario being considered.

Thus a simulation was run assuming that the PSD input to the SRS ES antenna is –47.9 dB(W/Hz) (maximum expected power for SRS ES transmissions at the time. Note that the actual maximum is –57.9 dB(W/Hz) to be used in Part II) and that the radiation diagram of the SRS ES antenna corresponds to an omnidirectional antenna (with variable gain) instead of the actual very directive antenna. The omnidirectional antenna gain value was varied to find that a gain of 20 dBi would not produce any interference larger than –202 dB(W/Hz) at the HIBLEO-2 forward-link receiver at any pointing direction above the SRS ES horizon (5° elevation) as is shown in Fig. A5-3. From that figure that relates the PSD at the HIBLEO-2 receiver with the SRS ES antenna elevation, it is found that the worst-case interference will be concentrated for SRS ES elevations below approximately 45°. Note that the cluster of points above the continuous curve is a consequence of the HIBLEO-2 antenna gains above 0 dBi.

For elevation angles above 45° the SRS ES antenna gain needed to reach the –202 dB(W/Hz) at the HIBLEO-2 receiver would be decreasing from approximately 36 dBi at 45° elevation to 33.5 dBi at 70° elevation.

3.2 HIBLEO-2 antenna gain limits in the forward-links scenario

It was noted above that the largest interference events always happen at the most southern and northern latitudes of the SRS ES when the SRS ES bore-sight is at an angle of approximately 13° with respect to the HIBLEO-2 antenna bore-sight forward-link (β, see Fig. A5-1) which is the minimum coupling angle (maximum HIBLEO-2 antenna gain of approximately 12 dBi) to be encountered in this scenario.

Figure A5-4 shows the HIBLEO-2 antenna forward-link gain as a function of azimuth and elevation when viewed from the SRS ES site (32.5 N; 106.6 W, minimum elevation angle of 5°). It is noticeable that the maximum HIBLEO-2 antenna gain happens in the ascending and descending direction (nodes) of the HIBLEO-2 spacecrafts in the orbits shown.

FIGURE A5-3

PSD produced by an omnidirectional transmission of 20 dBi

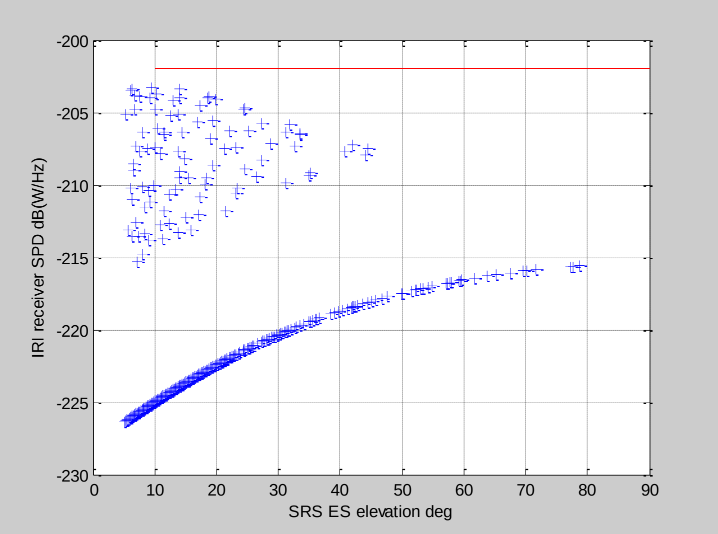
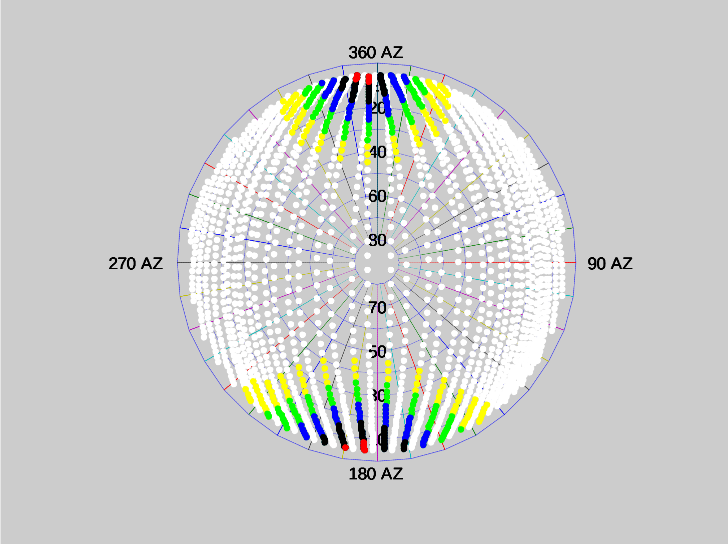


FIGURE A5-4

HIBLEO-2 antenna gains as a function of azimuth and elevation (ES at)
13 dBi>Red>12 dBi; black>9di; blue> 6 dBi; green>3 dBi;
yellow>0 dBi; white = –10 dBi



3.3 Optimum time increment (Δ*t*) for simulations of the forward-links scenario

Simplifying the antenna symmetric radiation patterns to the back-lobe region (36° to 180° off-axis) where in general the antenna gains are around –10 dBi and the main-lobe (from 0° to 36° off-axis) with larger antenna gains, the potential couplings of the SRS ES to the HIBLEO-2 antenna gains to be considered would be:

1. main-beam to main-beam;
2. main-beam to back-lobe;
3. back-lobe to main beam;
4. back-lobe to back-lobe.

Comparing Fig. A5-2 (Moon's coordinates limits) and Fig. A5-4 (HIBLEO-2 antenna gains) it is deduced that the northern area where the HIBLEO-2 antenna gain is larger than –10 dBi back-lobe gain, the only possible coupling will be No. 4 since this area is totally out of the SRS ES Moon's visibility coordinates. As for the small southern area where the HIBLEO-2 antenna gain is larger than the –10 dBi back-lobe gain all of the above antenna gain couplings may be present. This situation will be analyzed in a later paragraph.

In spite of what has been said above the simulations to be run will automatically consider all four coupling modes.

The SRS ES antenna gain of 45 dBi corresponds approximately to an off-axis SRS ES antenna angle of 0.3° as deduced from the antenna pattern used. Note that this off-axis bore-sight angle translates into a geocentric angle of approximately 0.15° (Bore-sight to central angle ratio of 2). The 34 dBi translates to an off-axis angle of 0.8° and with a Bore-sight to central angle ratio of 8 to a geocentric angle of 0.1°. Therefore the SRS ES antenna beam-width when seen from the centre of the Earth will be twice these values, or approximately 0.3°.

Since all the interference events are referred to the HIBLEO-2 constellation with circular orbits of an approximate period of 100 min, this geocentric angle of 0.3° translates in a time interval (Δt) of approximately of 100 min/360° * 0.3° = 0.08 min.

Time increment (Δt) used in these time series simulations is of concern since very small (Δt) will provide very detailed results but the simulation will take a long time, unpractical to obtaining the first results and properly characterize the scenario. On the contrary, if the (Δt) used is large, the simulation completion will be short and useful at the cost of loosing important events only made visible for very small (Δt). Therefore a combination of both approaches will be taken; that is to start with the longest (Δt) necessary for detecting all the events of interest to concentrate subsequently in smaller time spans with very small (Δt) to properly characterize them.

Using this time increment (Δt) = 0.08 min = 5 s would find all the interference events of interest in a single simulation but it makes the simulation to last an unpractical long time. A longer (Δt) = 0.3 min makes the simulation to last a reasonable time. This (Δt) corresponds approximately to a geocentric angle of:

$$360°/\ 100 \text{ min} * 0.3 \text{ min} = 1°$$

which in turn translates into a minimum SRS ES antenna bore-sight angle of approximately 2° at 5° elevation and 9° at 70° elevation corresponding to SRS ES antenna off-axis of 1° (30 dBi) and 4.5° (15 dBi) respectively.

3.4 Long-term interference of SRS ES transmissions into HIBLEO-2 constellation

The interfering events found with a (Δt) = 0.3 min will surely be missing some of those corresponding to larger SRS ES antenna gains, therefore a second simulation with a (Δt) much smaller will have to be performed. In order to shorten this second simulation it is convenient to remove those events with SRS ES antenna gains smaller than the 15 dBi antenna gain just found above.

All the 6 x 11 orbital planes were simulated each one at a time but keeping their corresponding epoch. It must be emphasized that the common epoch used as well as the one assigned to the Earth and Moon was carefully chosen so that at least one interfering event produced by the SZRS ES main beam antenna was assured (at 24 603 min of plane 1 satellite 9). The simulation was run for 28 days (the approximate period of the Moon) and the epoch of each one of the interference events noted.

There exists the possibility of a larger antenna gain being missed on the middle of the time span used (Δt) = 0.3 min. Since the epoch of each one of these interference is now known, inspection of a time span of i.e. ±0.6 min at a time interval (Δt) = 0.001 min may be done in a reasonable time. Note that this small time interval is approximately equivalent to an angle of 0.004°, at the HIBLEO-2 orbit, which in turn translates into a SRS ES bore-sight angle between 0.008° and 0.04° which may resolve the SRS ES main-beam antenna (0.066°). This small time interval will also define precisely the short-term interference event structure.

A detailed example of the process just described above follows. A reduced set of important parameters obtained in the simulation for all orbital planes was noted. Table A5- 2 is included as an example showing results only for orbital planes 1, 2 and 3. Each column represents:

1. time in minutes (epoch);
2. day number;
3. PSD dB(W/Hz) at the HIBLEO-2 receiver;
4. HIBLEO-2 plane number;
5. HIBLEO-2 satellite number;
6. HIBLEO-2 antenna gain (dBi);
7. SRS ES antenna gain (dBi);
8. longitude of HIBLEO-2 s/c foot print on Earth (degrees);
9. latitude of HIBLEO-2 s/c foot print on Earth (degrees);
10. HIBLEO-2 s/c azimuth as seen from SRS ES (degrees);
11. HIBLEO-2 s/c elevation as seen from SRS ES (degrees);
12. Number of events larger than –202 dB(W/Hz);
13. Interfering time (s).

TABLE A5-2

Interference events for planes 1 through 3 (Δt = 0.06 s)

3765.7	9474.6	16618	24603	6782.8	34771	9800	11206	21215	30664	37779
2.6151	6.5796	11.54	17.085	4.7103	24.147	6.8056	7.7822	14.733	21.295	26.235
–193.77	–196.45	–193.25	–169.04	–193.78	–193.3	–185.33	–190.15	–192.43	–195.14	–197.3
1	1	1	1	2	2	3	3	3	3	3
10	1	11	9	9	6	8	8	1	4	6
–10	–10	–10	-10	–10	–10	–10	–10	–10	-10	-10
49.126	39.821	49.126	68.464	49.126	47.347	57.988	49.126	46.541	49.126	44.028
–119.36	–106.16	–91.303	–112.27	–121.78	–102.2	–124.18	–115.75	–97.825	–123.95	–102.36
23.891	29.524	36.159	30.753	27.224	23.218	31.072	31.278	33.081	24.75	21.934
235.73	172.59	69.608	251.62	252.08	156.2	269.24	263.5	83.126	247.42	159.33
17.85	64.061	20.021	49.546	17.802	28.179	16.151	36.055	38.016	12.491	24.797
72	**47**	**61**	**57**	**65**	**79**	**65**	**58**	**53**	**66**	**74**
4.32	2.82	3.66	3.42	3.9	4.74	3.9	3.48	3.18	3.96	4.44

3.5 Availability of forward-links

The purpose of this paragraph is to get some approximate availability results for the forward-links scenario to be compared in a later paragraph to the availability of the cross-links scenario. It should also be noted at this time that the availability results to be found refer to the 66 forward-link receivers of the HIBLEO-2 constellation. Since the total number of events considered in the final simulation with a $(\Delta t) = 0.001$ min will be:

$$\text{Total number of events}=28\ \text{day}*24\ \text{hour/day}*3600\ \text{s/hour}/0.06\text{s}= 4.032\ 10^{7}$$

and the cumulative number of interfering events from Table A5-2 for orbital planes 1, 2 and 3 as well as results found for planes 4,5 and 6 (and not shown in Table A5-2) are:

$$\text{Cumulative number of interfering events} =134+172+282+316+144+237 = 1\ 285$$

the long-term interference will be:

$$\text{Long-term interference}=1285/4.032\ 10^{7} =3.187\ 10^{-5}$$

and the long-term availability will be:

$$\text{Long-term availability}= 1-3.187\ 10^{-5} = 0.999968 = 99.9968\%$$

4 SRS ES interference into HIBLEO-2 cross-links – The simulation

In § 2 "Interference scenario of the space research service transmissions to the Moon into space-to-space links of the inter-satellite service" a general description of the scenario to be analysed in this case may be found. Also Fig. A5-1 synthesizes this scenario that has been modeled[1] with the appropriate analytical equations in a time series referred to the same epoch for the Earth, Moon and the HIBLEO-2 satellite constellation. The same parameters used in the simulations for the forward-links in § 3 will be used now for the cross-links. For convenience they will be repeated here.

Thus, the minimum SRS ES elevation angle is set to 5°, which will be the elevation limit for the SRS ES when tracking the Moon. On the contrary the minimum elevation angle for the HIBLEO-2 constellation when viewed from the SRS ES location will be –22°. Note that this minimum elevation angle is necessary not to miss any of the 11 cross-links receivers of one orbital plane when the transmitting HIBLEO-2 receiver from the contiguous orbital plane is below the SRS ES horizon. An important difference with respect to the forward-links simulations is the modelling of two HIBLEO-2 orbital planes simultaneously otherwise necessary in order to complete the 11 cross-links between the same satellite numbers of each contiguous HIBLEO-2 orbital planes.

4.1 Omnidirectional transmissions; SRS ES antenna gain limits in the cross-links scenario

As in the case of the HIBLEO-2 forward-links scenario it will be of interest to determine the limits on the SRS ES antenna gain that will produce interference events on the scenario being considered. On this direction, the same scenario in which the SRS ES is radiating through an omnidirectional antenna instead of the actual very directive SRS ES antenna has been simulated. A PSD input of –47.9 dB(W/Hz) will again be considered instead of the actual maximum PSD of −59.7 dB(W/Hz) that will be used in Part II.

The omnidirectional antenna gain value was varied to find that a gain of 34 dBi would not produce any interference larger than –202 dB(W/Hz) at the HIBLEO-2 cross-link receivers at any pointing direction above the SRS ES horizon (5° elevation) as is shown in Fig. A5-5. Note that in this case there is no cluster of points due to the HIBLEO-2 antenna gain. This confirms the fact that the HIBLEO-2 antenna off-axis angle will never be smaller than the angle corresponding to the HIBLEO-2 antenna back lobe of 36° (–10 dBi of gain).

The actual minimum SRS ES to HIBLEO-2 antenna off-axis angle was confirmed to be around 40° as is shown in Fig. A5-11 where all the off-axis angles for the 11 cross-link antennas have been represented in a stereographic graph (SRS ES azimuth and elevation) for the ascending and descending nodes of the two orbital planes (Plane 2 × 11 transmitting to receiving Plane 1 × 11).

4.2 Long-term interference of SRS ES transmissions into the cross-links of the HIBLEO-2 constellation

The HIBLEO-2 antenna off-axis gain with respect to the SRS ES bore-sight will always be –10 dBi (back-lobe gain) as it is the case for the HIBLEO-2 forward-links in § 3. Therefore the interference events into the cross-links will be those already found in § 3 for the HIBLEO-2 forward-links.

Note that these findings enormously simplify the problem, since no need of further simulations will be necessary for the HIBLEO-2 cross-links case. Thus, using previous results for the forward-links the availability of HIBLEO-2 cross-links transmissions may already be estimated.

4.2.1 Availability of cross-links

It should be noted at this time that the availability results to be found refer to the 55 cross-link receivers of the HIBLEO-2 constellation, that is 11 cross-links for planes 2 to 1, 3 to 2, 4 to 3, 5 to 4 and 6 to 5, since there will not be any cross-link between planes 1 and 6.

Since the total number of events to be considered is the same as in the forward-links simulation with a (Δt) = 0.001:

$$\text{Total number of events}=28\ \text{day}*24\ \text{hour/day}*3\,600\ \text{s/hour}/0.06\text{s}= 4.032\ 10^{7}$$

and the cumulative number of interfering events from Table A5-2 will be for the HIBLEO-2 cross-link receivers in planes 1, 2, 3, 4 and 5:

$$\text{Cumulative number of interfering events} =134+172+282+316+144= 1\,048$$

the long-term interference will be:

$$\text{Long-term interference}=1048/4.032\ 10^{7} =2.5992\ 10^{-5}$$

and the long-term availability will be:

$$\text{Long-term availability}= 1\text{-}2.5992\ 10^{-5} = 0.999974 = 99.9974\%$$

FIGURE A5-5

PSD produced by an omni-directional transmission of 34 dBi

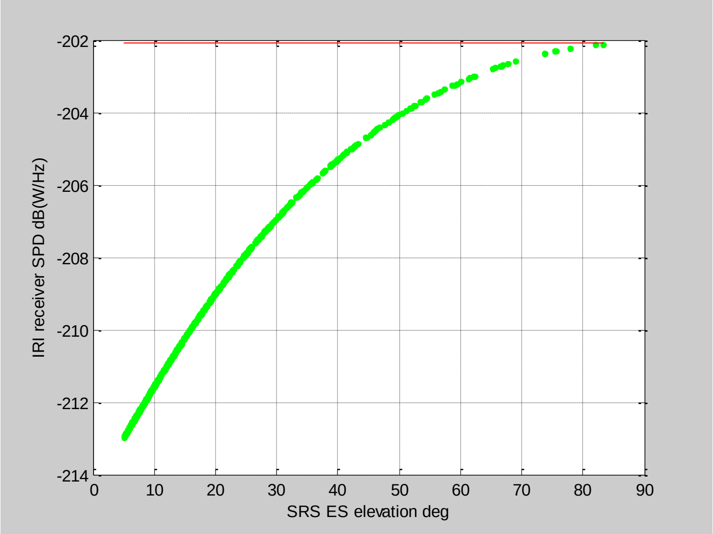
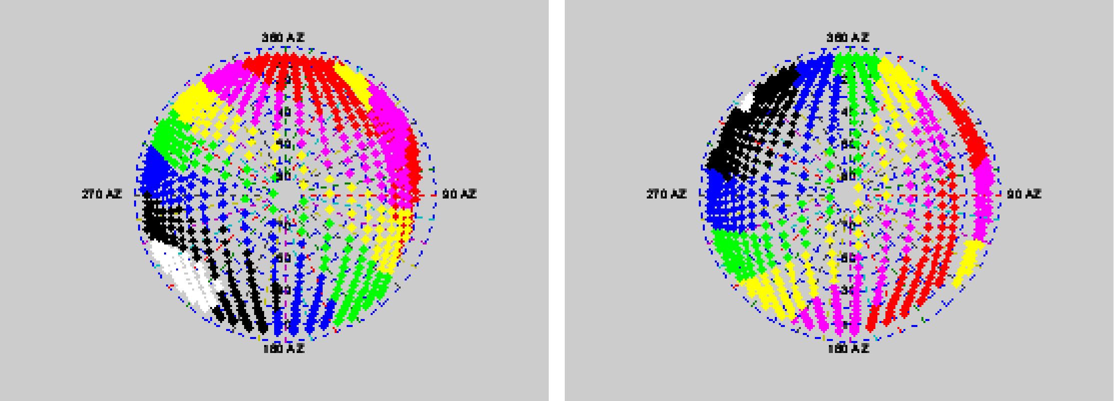


FIGURE A5-6

HIBLEO-2 antenna off-axis angles, degrees (ascending and descending nodes)
40>red<60>magenta<80>yellow<100>green<120>blue<140>black<160>white



4.3 Part I conclusions

Part I has shown a general methodology for deterministic simulations of interference between SRS ES transmitting to the Moon into the ISS links of a representative non-GSO system that will be applied in Part II for the Moon and Part III for the L2 scenarios. Since the interfering events on the cross-links are a smaller subset of the interfering events on the forward-links, the scenario previously described for the forward-links will be the only one to be analyzed.

PART II

In-band sharing simulation results for the Moon scenario

5 Introduction

In this Part II results for the simulations described in Part I when applied to the Moon scenario will be given. Table 1a and Table 1b of main body of the report, contain the SRS and the ISS systems characteristics which have been used

WORST-CASE SCENARIO OF SRS ES INTERFERENCE TRANSMITTING TO THE MOON INTO HIBLEO-2 FORWARD-LINKS

MOON CASE 1

(–59.7 dB(W/Hz) input to a 18 m SRS ES)

The same simulations approaches taken previously in § 3 "SRS ES interference into HIBLEO-2 forward-links" will be exercised now with a few parameters changes. Thus the previous PSD of –47.9 dB(W/Hz) into the SRS ES antenna will now be changed to –59.7 dB(W/Hz). Also, as indicated above, the Moon's orbital parameters used previously (see § 2.3 "The Moon") were changed to a RAAN = 196.5° and to an argument of latitude of 27.7° Also the HIBLEO-2 constellation parameters described in § 2.2 were slightly modified to a RAAN = 101.512° and to an argument of latitude of –87.5°. These modifications assured a worst-case scenario of interference in which some of the interfering events were due to the SRS ES main-beam-to-HIBLEO-2 main-beam coupling as it is apparent on Table A5-3 that summarize the results for 3 full Moon periods of 84 days (i.e. see Table A5-3, column under 26 759 m).

6 Interference events on the Moon scenario as a function of I/N_0

Analysis and results previously presented have been referred to the maximum interference PSD of –202.5 dB(W/Hz) which is equivalent to an Interference-to-Noise power of I/N_0 = –2.5 dB in the receivers of the inter-satellite links analyzed.

More stringent requirements on this I/N_0 are being or have been proposed; therefore the question as what would be the availability results for these new I/N_0 values have to be answered. Since these proposed values have not yet been confirmed, values from I/N_0 = –2.5 dB (equivalent PSD of –202.5 dB(W/Hz)) to a I/N_0 = –14.5 dB (equivalent PSD of –214.5 dB(W/Hz)) will be checked.

Since the interfering events on the cross-links are a subset of the interfering events on the forward-links as concluded in Part I, the scenario previously described for the forward-links will only be analyzed.

Before giving a summary of the results obtained it should be noted that due to the smaller interference PSD of –214.5 dB(W/Hz), I/N_0 = –14.5 dB, the minimum SRS ES gain (PSD of –59.7 dB(W/Hz) at antenna input) that will produce this level of interference will approximately be of 8 dBi instead of the 20 dBi found in § 3.1. This in turn will tend to increase the simulation time required as well as the number of days with interference larger than –214.5 dB(W/Hz).

Table A5-3 is a very reduced set of interference results of the simulation for this scenario. Each row represents:

1. time in minutes (epoch);
2. day number;
3. PSD dB(W/Hz) at the HIBLEO-2 receiver;

4. HIBLEO-2 plane number;
5. HIBLEO-2 satellite number;
6. HIBLEO-2 antenna gain (dBi);
7. SRS ES antenna gain (dBi);
8. longitude of HIBLEO-2 s/c foot print on Earth (degrees);
9. latitude of HIBLEO-2 s/c foot print on Earth (degrees);
10. HIBLEO-2 s/c azimuth as seen from SRS ES (degrees);
11. HIBLEO-2 s/c elevation as seen from SRS ES (degrees);
12 to 18. Number of events larger than –202.5 dB(W/Hz) through –214.5 dB(W/Hz).

TABLE A5-3

Short sample of interference results for days 1 through 84 for transmissions to the Moon (–59.7 dB(W/Hz); 18 m SRS ES antenna; Δ*t* = 0.06 s)

1	19504	22495	23910	26759	28342	29608	29767	31349	34050
2	13.544	15.621	16.604	18.583	19.682	20.561	20.671	21.77	23.646
3	–206.42	-212.54	–199.12	-170.44	-204.34	–209.32	–208.26	–207.2	–204.75
4	6	1	1	1	2	1	2	3	2
5	3	5	4	11	2	7	11	2	4
6	–5.4461	–7.8506	–1.6109	2.2334	1.2894	–14.452	1.9713	–2.839	–4.2604
7	42.615	41.078	46.283	69.786	37.462	48.984	31.782	37.818	42.222
8	–118.21	–120.75	–114.61	–106.88	–110.9	–99.162	–107.04	–111.06	–97.731
9	25.972	21.952	22.31	22.43	22.028	21.875	23.174	23.723	25.42
10	240.14	233.47	216.83	181.5	201.09	146.31	182.49	205.21	130.14
11	22.642	13.614	21.71	28.142	24.994	21.484	30.549	29.613	26.854
I/N_0 (dB)									
–2.5	0	0	33	76	0	0	0	0	0
–4.5	0	0	45	89	14	0	0	0	0
–6.5	5	0	59	104	54	0	0	0	24
–8.5	27	0	72	119	79	0	22	35	37
–10.5	42	0	86	135	102	8	69	60	51
–12.5	55	0	101	153	123	26	97	81	63
–14.5	68	46	116	169	143	49	119	100	75

6.1 Worst-case full constellation availability of HIBLEO-2 forward-links under SRS ES transmissions to the Moon

Same approach as previously used in § 3.5 “Availability of forward-links” will now be used to find the long-term interference as a function of I/N_0 from the cumulative interference events found for days 1 through 84. Thus the interference events shown in Table A5-4 (“Intf. events”) correspond to the 66 forward-link receivers of the HIBLEO-2 constellation.

The HIBLEO-2 constellation also has another 66 forward-links looking north at the beginning of the simulation that should also be accounted for to find the availability of the full constellation. Noting that every orbit starts as an ascending node orbit and after half orbital period becomes a descending one the symmetry of the forward links looking north or south will be assumed.

Therefore the contribution of the forward-links to the HIBLEO-2 constellation interference will be twice the one shown in Table A5-4 with corresponding availability shown. In short:

Long-term availability = (1- 2*int. events/total events)*100

Duration of the worst-day short-term interference has also been included in Table A5-4.

TABLE A5-4

Summary of 84 days for Moon transmissions of a 18 m SRS ES (–59.7 dB(W/Hz), $\Delta t = 0.06$ s). Full HIBLEO-2 constellation (6 × 11 × 2 links)

I/N_0	**Intf. events**	**Worst day Intf. events**	**Worst day Intf. time (s)**	**Interference (%)**	**Availability (%)**
–2.5	673	76	4.5	0.00111	99.9989
–4.5	993	89	5.3	0.00164	99.9984
–6.5	1373	104	6.2	0.00227	99.9977
–8.5	1986	119	7.1	0.00328	99.9967
–10.5	2808	135	8.1	0.00464	99.9954
–12.5	3734	153	9.2	0.00617	99.9938
–14.5	5017	169	10.1	0.00829	99.9917

6.1.1 “Per-link” interference for forward-links

As agreed within ITU-R, the “per-link interference” has to be assessed.

Since Table A5-4 summarizes results for 84 days (3 Moon periods) of the cumulative interference events for I/N_0 of 2.5, 4.5, 6.5, 8.5, 10.5, 12.5 and 14.5 dB the following approach to find the “per-link” interference will be follow:

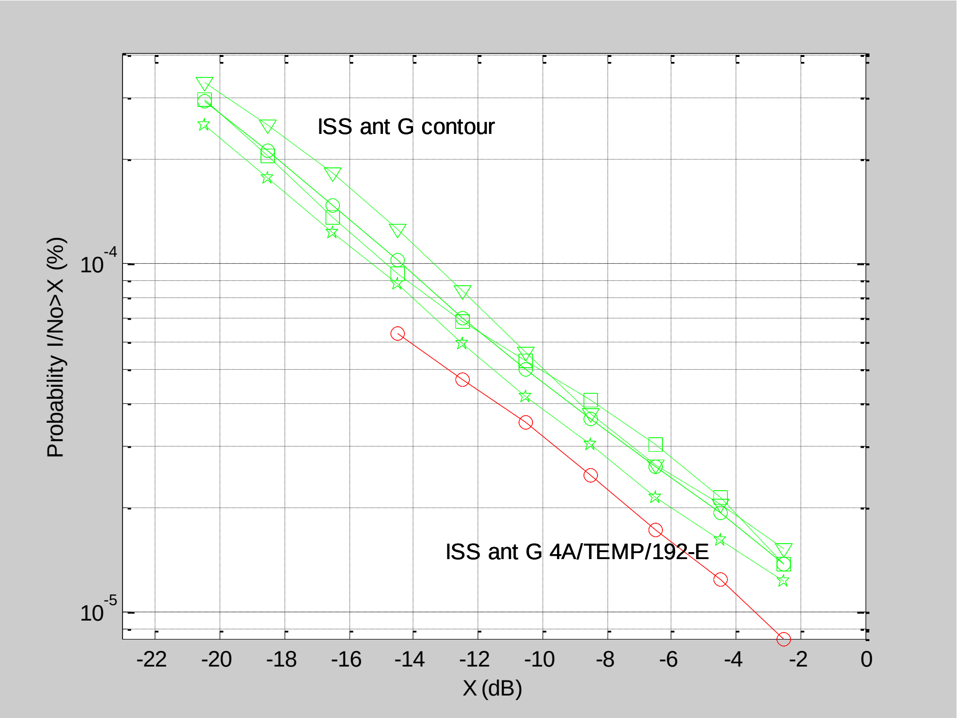
1. Number of seconds in 84 days; TimeTot=84*24*3 600=7 257 600 s.
2. Total forward-links considered; LinksTot = 11*6 = 66 links.
3. Cumulative interference time; IntfTime2to14dB = Column 2 of Table A5-4*0.06s/event.
4. Mean per cent interference per-link = IntfTime2to14dB/ LinksTot/ TimeTot*100.

In order to facilitate comparison with other simulation approaches published elsewhere, Fig. A5-7 has been included showing interference results percentage, {4) Mean per cent interference per-link)} by the red (o) continuous line for the 84 days (3 Moon periods) for the ISS antenna pattern shown in Fig. 1 of main body of the Report .

The green graphics in Fig. A5-7 will be next explained.

FIGURE A5-7

Per-link interference to forward-links of a full HIBLEO-2 constellation (space-to-space) from emissions of a SRS ES (Earth-to-space) to the Moon



6.1.2 Contour antenna pattern and the length of simulations

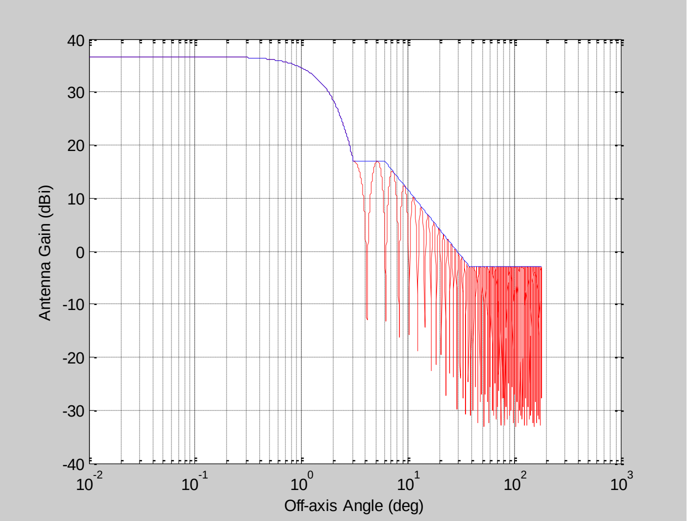
Row 6 in Table A5-3 represents the HIBLEO-2 antenna gain at the time shown in Row 1. The antenna gain variations are clearly the consequence of the oscillating antenna pattern shown in Fig. A5-8 making more difficult the interpretation of the results of the simulation. The use of the contour of this antenna pattern shown also in Fig. A5- 8 no doubt will remove most of these variations improving therefore the interpretation of the overall results.

In order to give a quick assessment of this simpler antenna pattern, the same simulation originating results of Table A5-3 have been repeated using the HIBLEO-2 antenna contour pattern of Fig. A5-8. Results for this simulation representing I/N_0 from 2.5 to 22.5 dB have been represented in Fig. A5-7 by the continuous green line that represents the results for 84 days (3 Moon periods). Green dotted lines in Fig. A5-7 are the results for each one of the three Moon periods (28 days) taken independently. These results confirm that simulation times covering a Moon period of 28 days may be considered satisfactory.

On these simulations, simplicity on the mathematical representation of the different technical parameters used such as the antenna gain patterns is of substance when dealing with long-term results. It would also be recognized that other more elaborate approaches would sometimes benefit the outcome of the results by representing more closely the actual phenomena. With these considerations in mind it is suggested that in future studies antenna gain patterns contour approach be used for the long-term simulations while the more elaborate patterns such as the typical oscillating gain approach be used for the short-term analysis.

FIGURE A5-8

Contour HIBLEO-2 Inter-satellite-link antenna pattern (blue)



6.2 Part II, Moon scenario, conclusions

Since the agreed protection criteria provides a very large margin when compared with per-link interference as it is inferred from Fig. A5-7, or even when the full constellation interference results shown in Table A5-4 are considered, it is concluded that SRS ES transmissions to the Moon may share a common spectrum with ISS non-GSO links.

Note that the limit of 0.1% interference at $I/N_0 = -10$ dB has not been represented keeping the maximum achievable definition in Fig. A5-7.

Annex 6

Summary of Study 6

1 Introduction

This study analyses the compatibility between non-GSO ISS systems and SRS systems (only Lunar missions were considered for the SRS system). More specifically, the study evaluates the statistical behaviour (Cumulative Distribution Function – CDF) of the interference produced by SRS transmitting earth stations on the receivers of non-GSO inter-satellite links, in several interfering scenarios. The main differences in the examined scenarios concern the number and location of the SRS transmitting earth stations and the strategy under which they are active (transmitting). Besides the usual I/N cumulative distribution functions, the unconditional CDF and the conditional CDF given that the victim satellite is receiving interference was also determined. Although there were no applicable protection criteria against which to measure the absolute impact, the results were found to be useful by describing the impact on the overall system. They have indicated that there would be a difference of around 16 dB on the overall multi-link ISS system, compared to a single ISS link.

The analytical method in Recommendation ITU-R S.1529 [3] was used to determine the various cumulative distribution functions involved in the study. It is a precise tool that produces reliable estimates of the interference cumulative distribution functions. As stated in [2, 3, 4], the theory behind it indicates that it produces results that correspond to those obtained via dynamic simulation when the simulation time tends to infinity. Even those events having a very low probability are adequately considered by the method.

2 Interference calculations

Consider the geometry illustrated in Fig. A6-1 and let i denote the interference power-spectral density (W/Hz) produced at the output of an ISS receiver antenna by the transmission of an SRS earth station. This interference power-spectral density is given by:

$$i = \frac{p_t \, g_t(\beta) \, g_r(\gamma_j)}{l_u \, f_d} \tag{1}$$

where:

p_t: denotes the power-spectral density at the SRS antenna input (W/Hz)

$g_t(\beta)$: the SRS earth station transmission antenna gain in the direction of the victim ISS satellite

$g_r(\gamma_j)$: the gain of the j^{th} ISS satellite receiving antenna in the direction of the interfering SRS earth station

f_d : the frequency discrimination factor between the desired and the interfering signals

l_u: the free space loss, given by:

$$l_u = \left(\frac{4\pi \, d}{\lambda} \right)^2 \tag{2}$$

with λ denoting the wavelength corresponding to the transmission frequency and d being the distance between the SRS interfering earth station and the ISS victim satellite.

The Total Probability Theorem allows us to write

$$P(i > \alpha) = P(i > \alpha \,|\, i = 0) \, P(i = 0) + P(i > \alpha \,|\, i \neq 0) \, P(i \neq 0) \tag{3}$$

Noting that

$$P(i > \alpha \,|\, i = 0) = \begin{cases} 1 & ; \quad \alpha < 0 \\ 0 & ; \quad \alpha \geq 0 \end{cases} \tag{4}$$

and defining

$$h(\alpha) = P(i > \alpha \,|\, i \neq 0) \, P(i \neq 0) \tag{5}$$

it is possible to write (3) as:

$$P(i > \alpha \,|\, i = 0) = [1 - u(\alpha)] \, P(i = 0) + h(\alpha) \tag{6}$$

with u( ) denoting the unit step function defined by:

$$u(x) = \begin{cases} 1 & ; \quad x \geq 0 \\ 0 & ; \quad x < 0 \end{cases} \tag{7}$$

and $h(\alpha)$ given by (5).

Considering that the interference-to-noise ratio I/N is given by:

$$\frac{\mathsf{I}}{\mathsf{N}} = \frac{iB}{kTB} = \frac{i}{kT} \tag{7}$$

with k denoting the Boltzmann constant and T the ISS receiver noise temperature, it is possible to write the Cumulative Distribution Function of the ratio I/N as:

$$C_{\mathsf{I/N}}(\alpha) = P\left(\frac{\mathsf{I}}{\mathsf{N}} > \alpha\right) = P\left(\frac{i}{kT} > \alpha\right) = P(i > \alpha kT) \tag{8}$$

or, considering (6),

$$C_{\mathsf{I/N}}(\alpha) = u(-\alpha\, kT)\, P(i = 0) + h(\alpha\, kT) \tag{9}$$

with $h(\ )$given by (5). Another important characterization of the statistical behaviour of the interference to noise ratio is the Conditional Cumulative Distribution Function given that the victim satellite is receiving non-zero interference, that is:

$$C_{\mathsf{I/N}|i\neq 0}(\alpha) = P\left(\frac{\mathsf{I}}{\mathsf{N}} > \alpha \middle| i \neq 0\right) = P(i > \alpha kT | i \neq 0) = \frac{h(\alpha\, kT)}{P(i \neq 0)} \tag{10}$$

When expressed in dB, the interference to noise ratio in (1) is written as:

$$\frac{I}{N} = 10\log\left(\frac{\mathsf{I}}{\mathsf{N}}\right) = P_t + G_t(\beta) + G_r(\gamma_j) - 20\log\left(\frac{4\pi d}{\lambda}\right) - 10\log f_d - 10\log(kT) \tag{11}$$

where:

P_t: denotes the power-spectral density at the SRS antenna input (dB(W/Hz))

$G_t(\beta)$: the SRS earth station transmission antenna gain in the direction of the victim ISS satellite (dBi)

$G_r(\gamma_j)$: the gain of the jth ISS satellite receiving antenna in the direction of the interfering SRS earth station (dBi).

In this case, the unconditional and the conditional cumulative distribution functions of I/N are written as:

$$C_{I/N}(\alpha) = C_{\mathsf{I/N}}(10^{\alpha/10}) \tag{12}$$

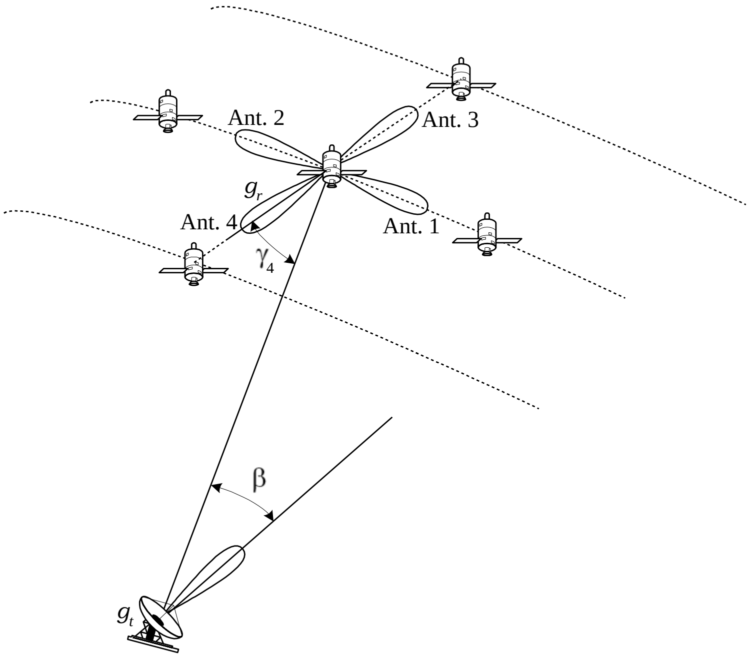
and

$$C_{I/N|i\neq 0}(\alpha) = C_{\mathrm{I/N}|i\neq 0}(10^{\alpha/10}) \tag{13}$$

with $C_{I/N}(\,)$ and $C_{I/N|i\neq 0}(\,)$ given by (9) and (10), respectively.

FIGURE A6-1

SRS to ISS interference geometry



Now, let δ denote the Moon orbital plane inclination with respect to the Earth's equator. Suppose that the cumulative distribution functions in (12) and (13) are calculated for a given value of δ, say δ = Δ.

This means that:

$$C_{I/N|\delta=\Delta}(\alpha) = P\left(\frac{I}{N} > \alpha \middle| \delta = \Delta\right) \tag{14}$$

and

$$C_{I/N|i\neq 0,\delta=\Delta}(\alpha) = P\left(\frac{I}{N} > \alpha \middle| i \neq 0, \delta = \Delta\right) \tag{15}$$

are determined. The cumulative distribution functions in (12) and (13) can then be calculated, respectively, from (14) and (15) by using the Total Probability Theorem, that is,

$$C_{I/N}(\alpha) = \int_{-\infty}^{+\infty} C_{I/N|\delta=\Delta}(\alpha)\, p_\delta(\Delta)\, d\Delta \tag{16}$$

and

$$C_{I/N|i\neq 0}(\alpha) = \int_{-\infty}^{+\infty} C_{I/N|i\neq 0,\delta=\Delta}(\alpha)\, p_{\delta}(\Delta) d\Delta \tag{17}$$

with $p_{\delta}(\Delta)$ denoting the probability density function of the Moon orbital plane inclination δ.

3 Numerical results

In this section, different scenarios are examined. In all of them the SRS system parameter values presented in Table A6-1 were considered. The antenna radiation pattern in Recommendation ITU-R F.1245 was assumed for the SRS transmitting earth station.

TABLE A6-1

SRS system parameters

System parameter	**Value**
Orbital parameters	
Mission type	Lunar
Orbital altitude (km)	384,400
Orbit type	Circular
Orbital plane inclination (degrees)	Non-specific
SRS earth station parameters	
Transmitting antenna diameter (m)	18.0
Transmitting antenna gain (dBi)	70.4
Power-spectral density at antenna input (dBW/Hz)	−59.7

Concerning the ISS system, in all cases, the parameter values presented in Table A6-2, taken from [2], were considered. The antenna radiation pattern in Fig. 1 of main body of the report was assumed for the ISS receiving antennas.

TABLE A6-2

ISS system parameters

System parameter	**Value**
Orbital parameters	
Number of satellite planes	6
Number of satellites per plane	11
Orbital altitude (km)	780
Orbit type	Circular
Orbital plane inclination (degrees)	86.5
ISL earth station parameters	
Antenna gain (dBi)	36.7
Noise Temperature (K)	877

Also, in all examined scenarios the frequency discrimination factor f_d in (1) was made equal to 1, meaning that co-channel interference was assumed. As illustrated in Fig. A6-1, it was considered that each satellite employs four inter-satellite links: two of them interconnect the satellite intra-plane (forward and aft) and the other two interconnect the satellite with the closest satellites in the adjacent orbital planes. These examined scenarios are described and analysed in the following sections.

3.1 Scenario 1

In this scenario, three SRS transmitting earth stations are considered: one in US (32.5°N, 106.6°W), one in Spain (40.5°N, 3.75°W) and one in Australia (35.4041°S, 148.9802°E). The condition for an SRS earth station to be considered *active* (transmitting) is that it sees the Moon with an elevation angle greater than or equal to zero. Simultaneously active earth stations are assumed to transmit co-channel and the *I*/*N* ratio is calculated considering the aggregate interference from simultaneously active SRS earth stations.

In applying (16), two different probability density functions were considered for the random variable δ. They are illustrated in Fig. A6- 2 and their analytical expressions are given by:

$$p_\delta(\Delta)_1 = \begin{cases} \dfrac{1}{10.26} & ; \quad \Delta \in [18.32, 28.58] \\ 0 & ; \quad \Delta \notin 18.32, 28.58] \end{cases} \tag{24}$$

and

$$p_\delta(\Delta)_2 = \begin{cases} \dfrac{1}{\pi\sqrt{(5.13)^2 - (\Delta - 23.45)^2}} & ; \quad \Delta \in [18.32, 28.58] \\ 0 & ; \quad \Delta \notin 18.32, 28.58] \end{cases} \tag{25}$$

The resulting cumulative distribution functions are shown in Fig. A6- 3 for the four ISS receiving antennas.

FIGURE A6-2

Example of probability density functions that may be used to model the statistical behaviour of the Moon orbital plane inclination

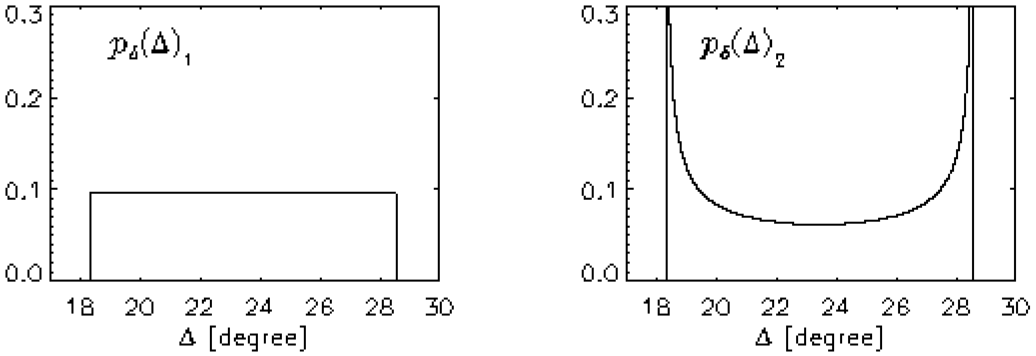
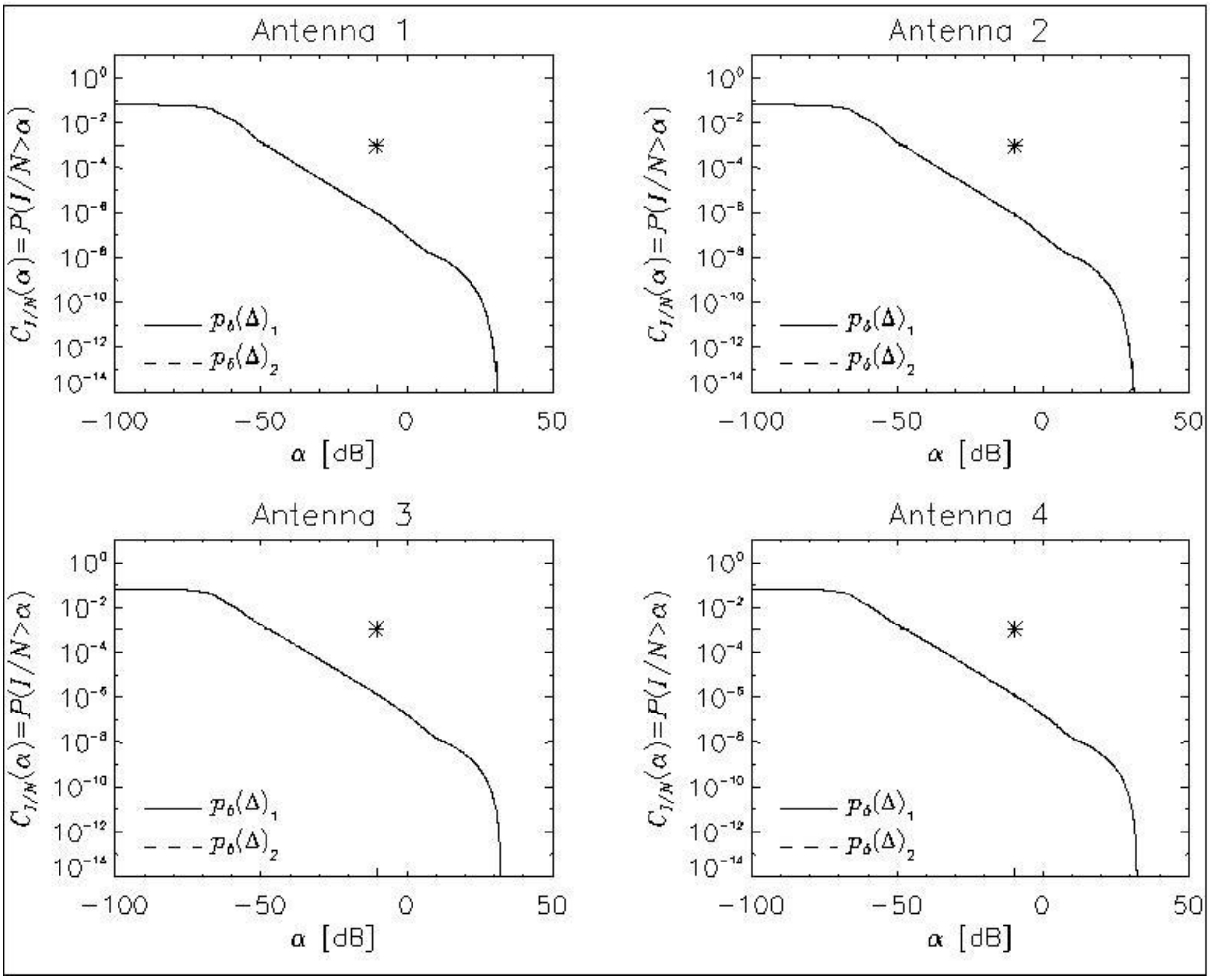


FIGURE A6-3

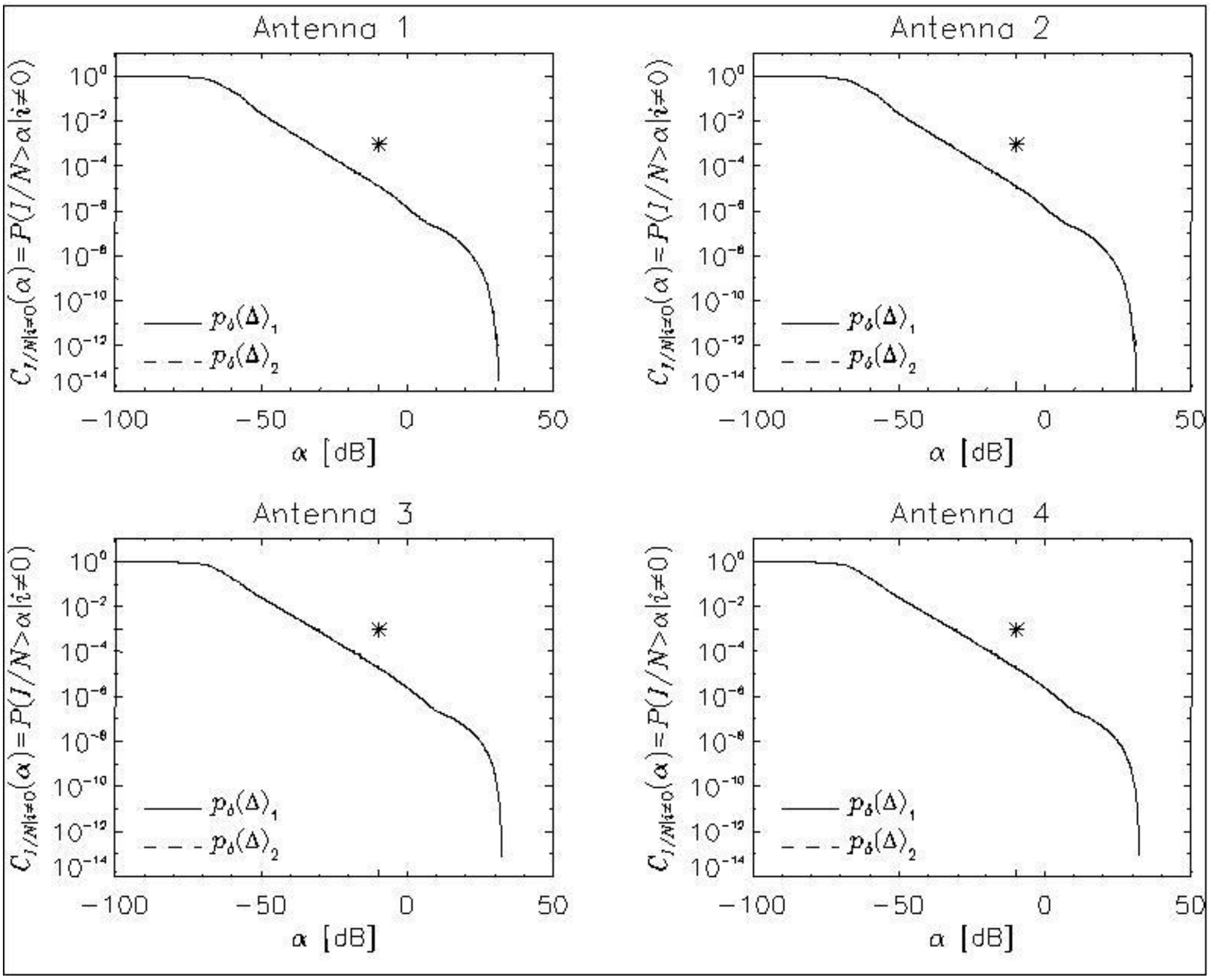
Cumulative distribution functions of the ratio *I*/*N* (Scenario 1)



As mentioned before, another important characterization of the statistical behaviour of the ration *I*/*N* is the conditional cumulative distribution function under the assumption that the victim satellite is receiving interference which is given by (17). In applying (17), the two probability density functions in (24) and (25) were used. The resulting Conditional CDFs are shown in Fig. A6-4 for the four ISS receiving antennas.

FIGURE A6-4

Conditional cumulative distribution functions of the ratio *I*/*N* given that the victim satellite is receiving interference (Scenario 1)



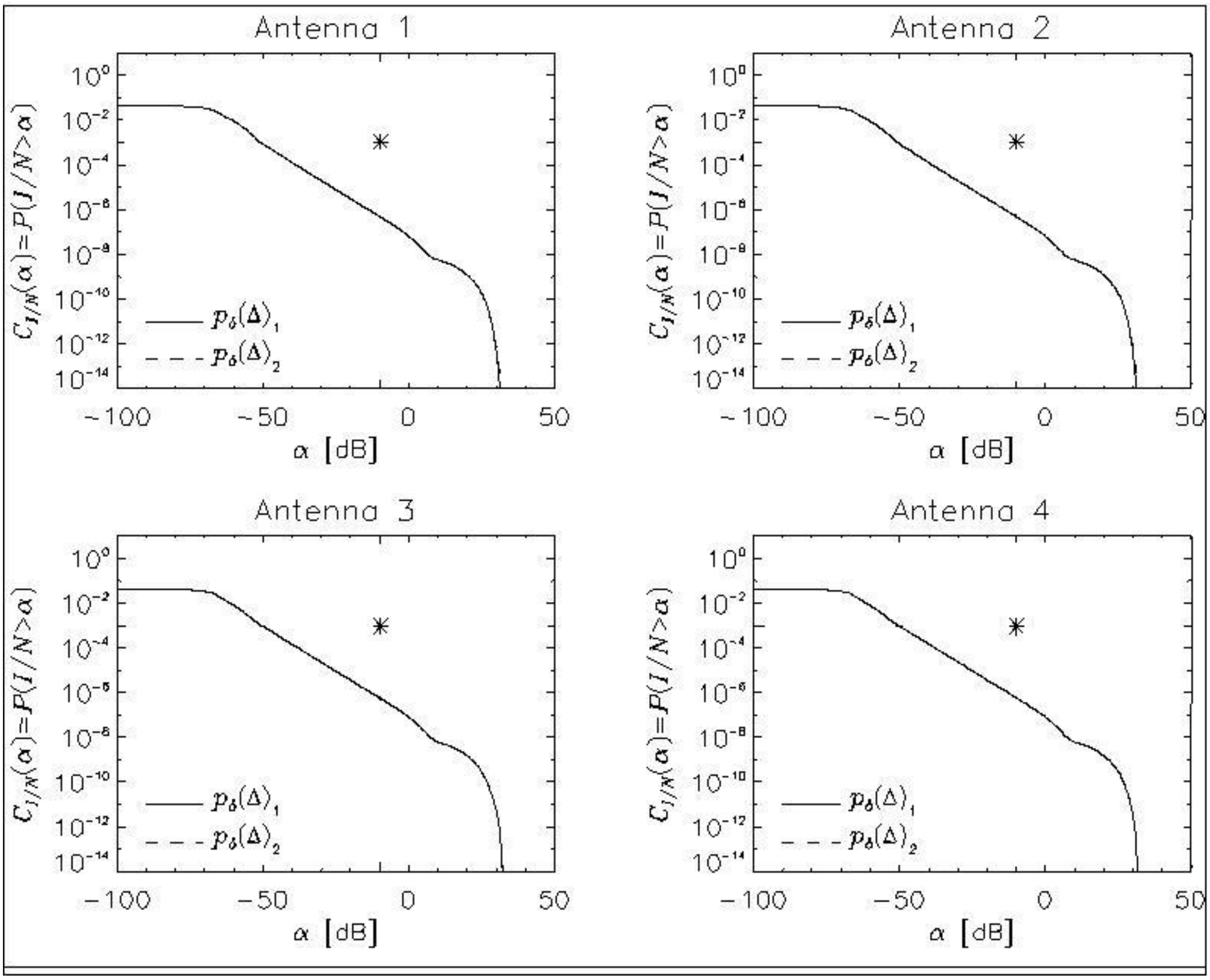
3.2 Scenario 2

Here, the same three SRS transmitting earth stations as those in Scenario 1 are considered: one in US (32.5°N, 106.6°W), one in Spain (40.5°N, 3.75°W) and one in Australia (35.4041°S, 148.9802°E). In this second scenario, it is assumed that when multiple SRS earth stations see the Moon with an elevation angle greater than or equal to zero, only one of them is considered active (transmitting): the one having the largest elevation angle. We believe that this is assumption is closer to the real system implementation than that in the first scenario.

The resulting cumulative distribution functions are shown in Fig. A6-5 for the four ISS receiving antennas. Note that, as expected, in the region corresponding to long term interference the cumulative distribution functions in Fig. A6-5 are a little bit below those in Fig. A6-3. Indeed, in this second scenario the probability of having no interference (i = 0) is a little higher than in Scenario 1.

FIGURE A6-5

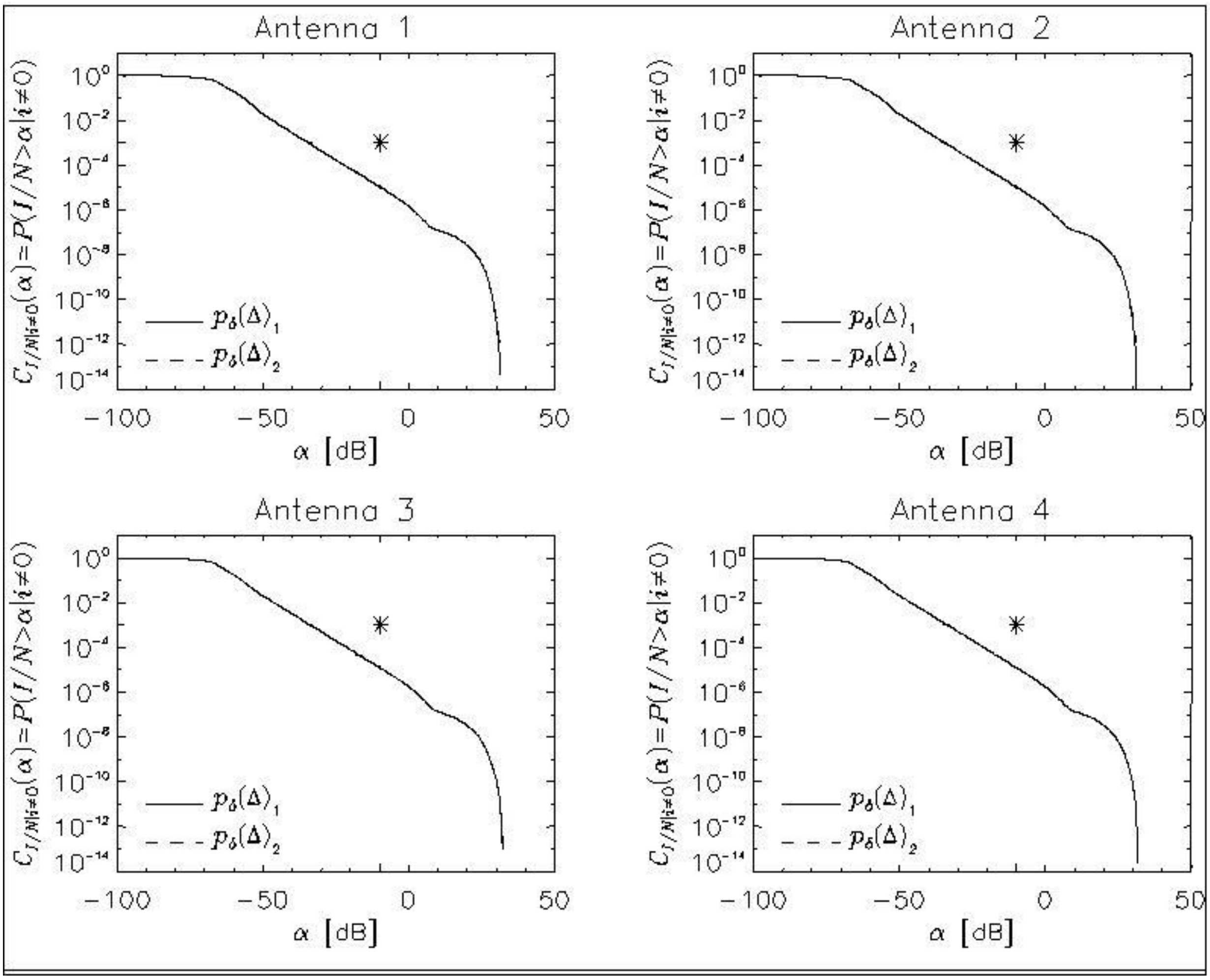
Cumulative distribution functions of the ratio *I*/*N* (Scenario 2)



In this second scenario, the conditional cumulative distribution functions under the assumption that the victim satellite is receiving interference are also calculated for the four ISS receiving antennas and are shown in Fig. A6-6.

FIGURE A6-6

Conditional cumulative distribution functions of the ratio *I*/*N* given that the victim satellite is receiving interference (Scenario 2)

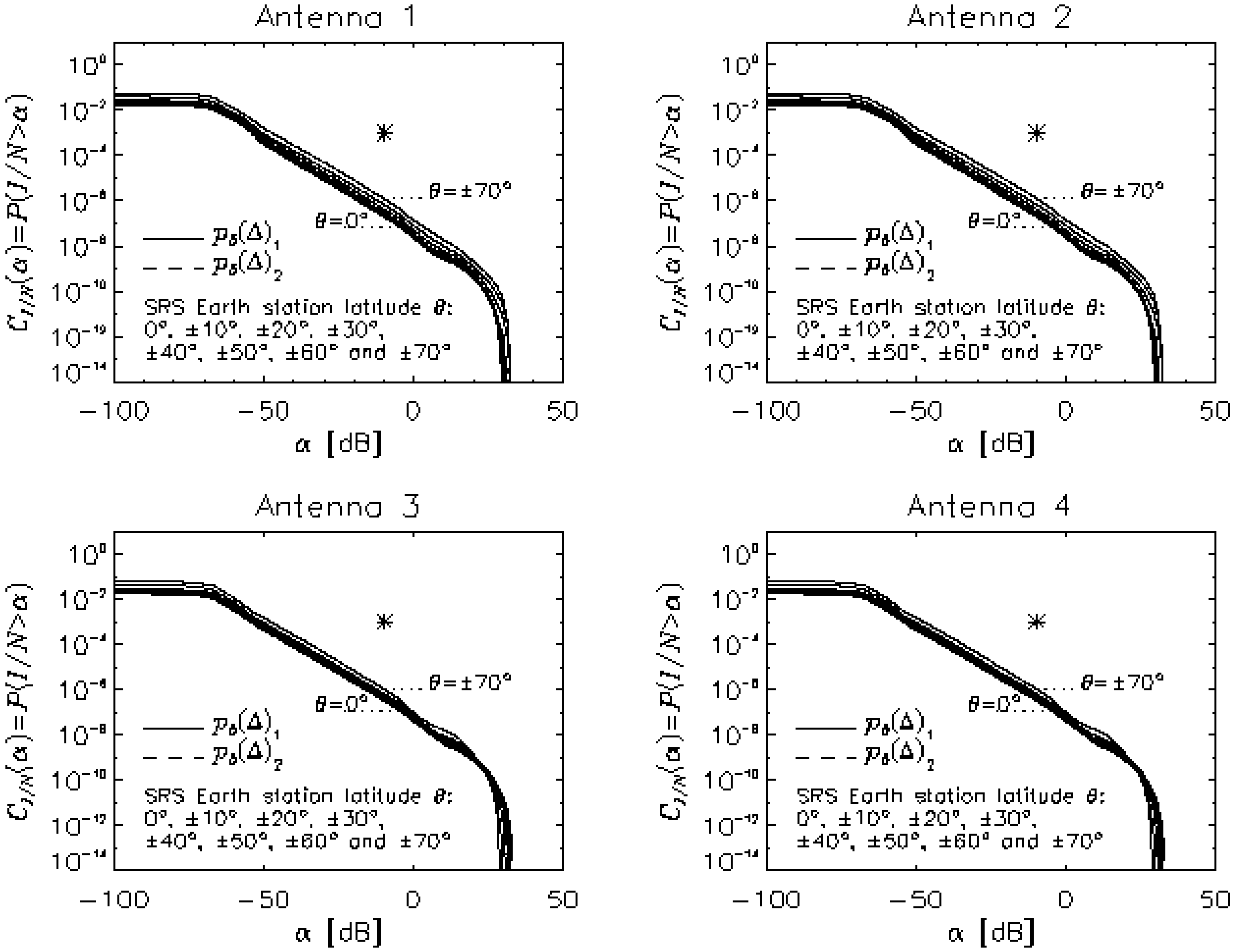


3.3 Scenario 3

The motivation for examining this third scenario is the fact that, due to the problem symmetry, the *I*/*N* CDFs do not dependent on the SRS location longitude. The purpose here is then to analyse the effect of the latitude of the SRS transmitting earth station in the statistical behaviour of the *I*/*N* ratio. In this scenario, only one SRS earth station is considered. The *I*/*N* cumulative distribution functions are then determined for locations of the SRS earth station that vary, in latitude, from 0° to 70°. Note that, also due to the problem symmetry, the resulting curves are identical for positive and negative latitudes having the same absolute value. In this scenario, the condition for the SRS earth station to be considered *active* (transmitting) is that it sees the Moon with an elevation angle greater than or equal to zero. Again, (17) was used to determine the *I*/*N* CDFs corresponding to SRS earth stations at different latitudes. They are presented in Fig. A6-7.

FIGURE A6-7

Cumulative distribution functions of the ratio *I*/*N*, for different values of the SRS earth station latitude (Scenario 3)



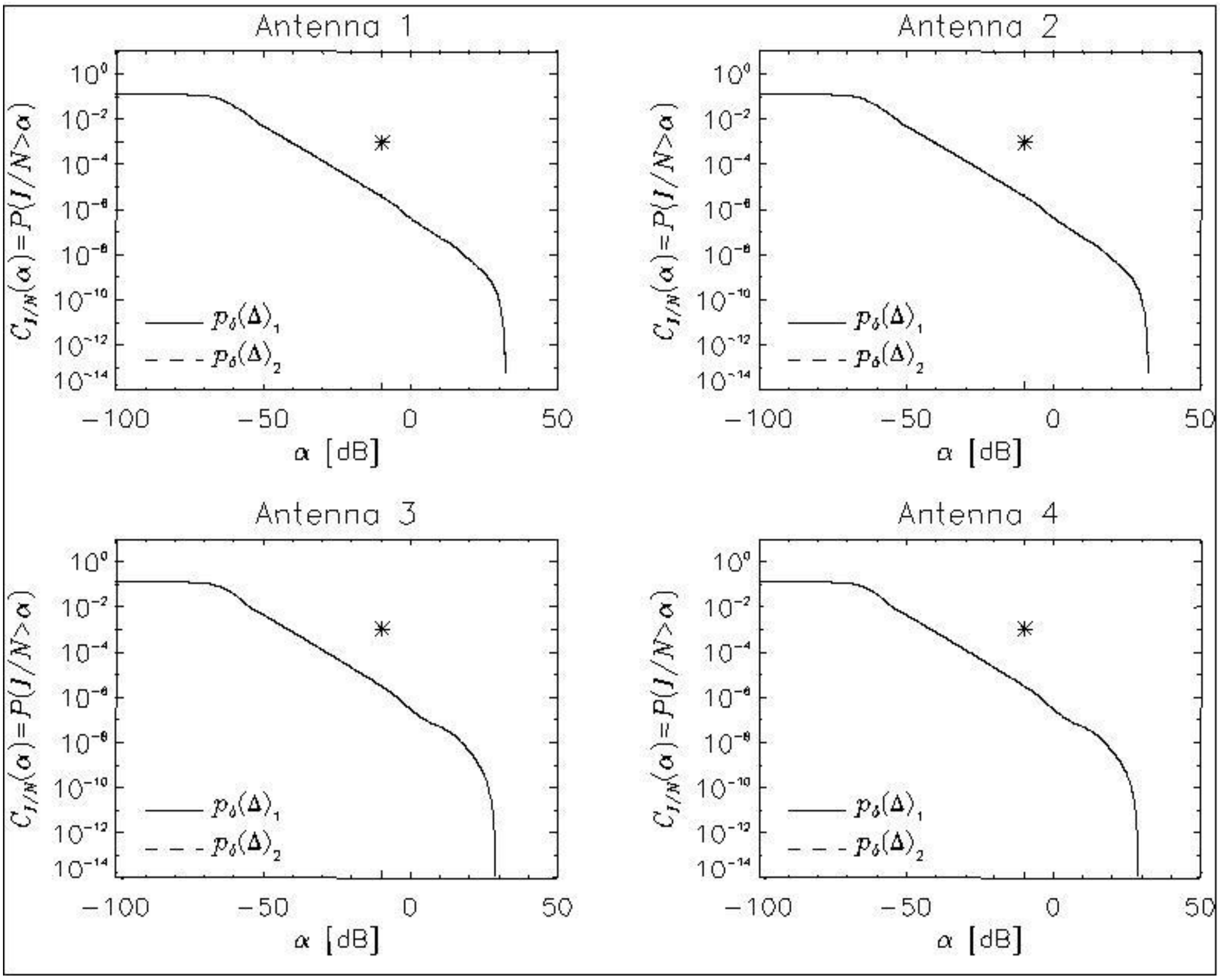
The results in the Scenario 3 have indicated that, in the neighbourhood of the interference criterion, the *I*/*N* cumulative distribution function increases with the latitude of the SRS earth station location. This fact has motivated the examination of two additional scenarios (Scenarios 4 and 5) under assumptions that, except for the location of the three SRS transmitting earth stations, are respectively identical to those assumptions in Scenarios 1 and 2. In both of them the three SRS earth stations are placed at a 70 °N

3.4 Scenario 4

In this scenario, the three SRS Earth transmitting stations are placed at a 70 °N latitude, with longitude separations equal to 120°. As in Scenario 1, it considers that the condition for an SRS earth station to be *active* (transmitting) is that it sees the Moon with an elevation angle greater than or equal to zero and that simultaneously active earth stations transmit co-channel. The *I*/*N* ratio is then calculated considering the aggregate interference from simultaneously active SRS earth stations. The resulting cumulative distribution functions are shown in Fig. A6-8 for the four ISS receiving antennas.

FIGURE A6-8

Cumulative distribution functions of the ratio *I*/*N* (Scenario 4)

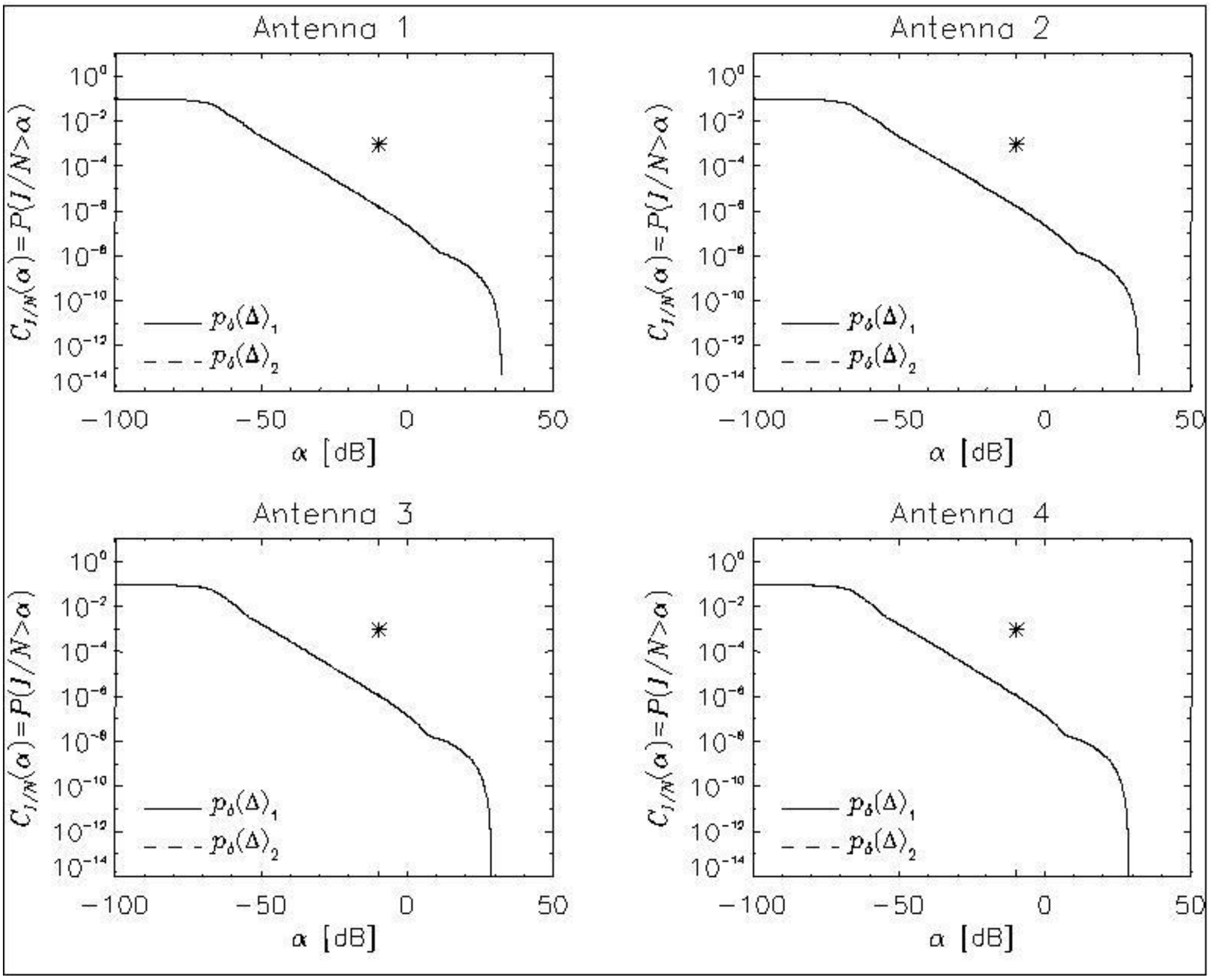


3.5 Scenario 5

Here again, the three SRS Earth transmitting stations are placed at a 70°N latitude, with longitude separations equal to 120°. As in Scenario 2, it is assumed that when multiple SRS earth stations see the Moon with an elevation angle greater than or equal to zero, only one of them is considered active (transmitting): the one having the largest elevation angle. The resulting cumulative distribution functions are shown in Fig. A6-9 for the four ISS receiving antennas.

FIGURE A6-9

Cumulative distribution functions of the ratio *I*/*N* (Scenario 5)



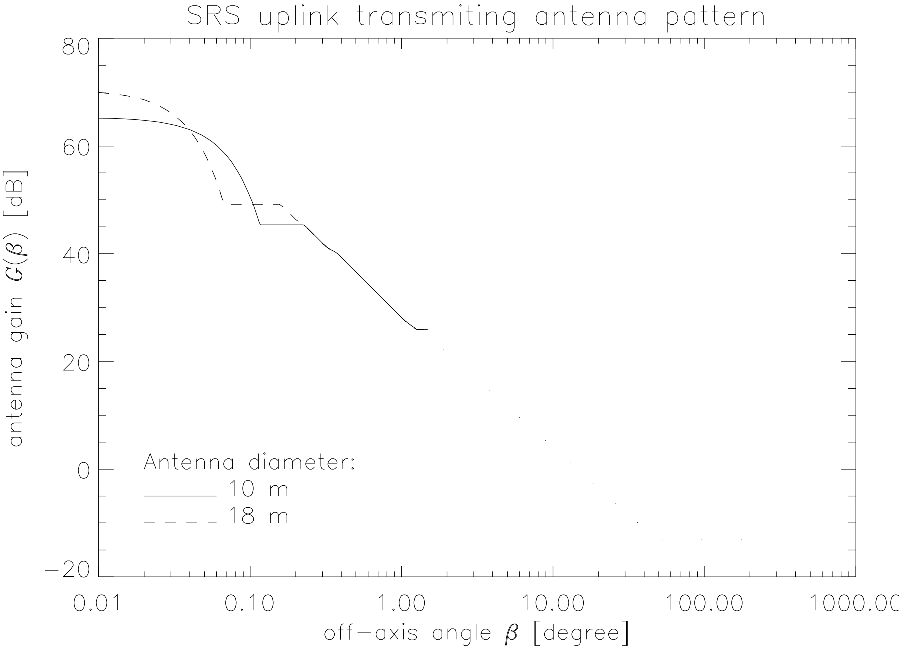
Taking into account that some of the assumptions in the study favours interference (for example, that the SRS earth stations transmit even when its elevation angle to the Moon is equal to zero, and that interference was assumed to be co-channel, meaning that for out-of-band interference a frequency discrimination must be added), study results tend to indicate that SRS systems and non-GSO ISS systems are compatible. This conclusion, however, is constrained to situations involving SRS systems with the characteristics presented in Table A6-1 and Fig. A6-2, and to the number of SRS earth stations considered in the examined scenarios. This fact has motivated the examination of two additional points: the effect, on the statistical behaviour of the *I*/*N* ratio, of the SRS antenna size and of the number of SRS earth stations. Example cases considering these two points are presented in the following sections.

3.6 Effect of the SRS earth station antenna size

To examine the effect of the SRS earth station antenna size on the statistical behaviour of the *I*/*N* ratio, Scenarios 1 and 2 were re-evaluated. Except for the SRS antenna size, here equal to 10 m, all other assumptions are the same as those in Scenarios 1 and 2. The antenna radiation pattern is given by Recommendation ITU-R F.1245 and, in this case, the transmitting antenna gain is 65.3 dBi (see Fig. A6-10). To compensate for the loss in antenna gain, the power-spectral density at the antenna input was increased to −54.6 dBW/Hz.

FIGURE A6-10

SRS uplink transmitting antenna radiation pattern: Recommendation ITU-R F.1245

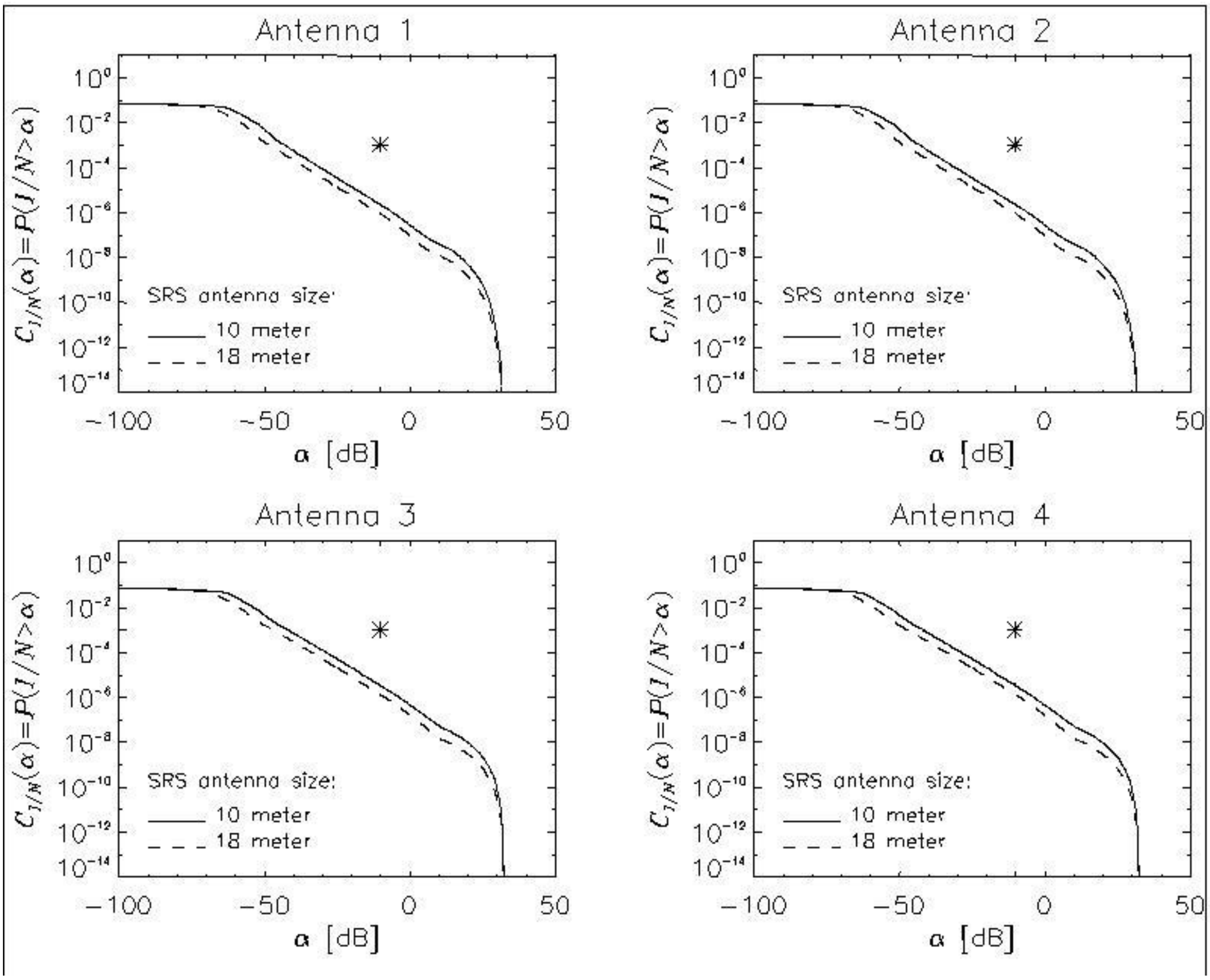


3.6.1 Scenario 1 – 10 m SRS antenna size

The resulting cumulative distribution functions are shown in Fig. A6- 11 for the four ISS receiving antennas. To better visualize the effect of the SRS antenna size, this figure also presents the CDFs resulting from the use of 18 m antennas.

FIGURE A6-11

Cumulative distribution functions of the ratio *I*/*N* given that the victim satellite is receiving interference (Scenario 1, 10 and 18 m SRS antennas, $p_\delta(\Delta)_2$)

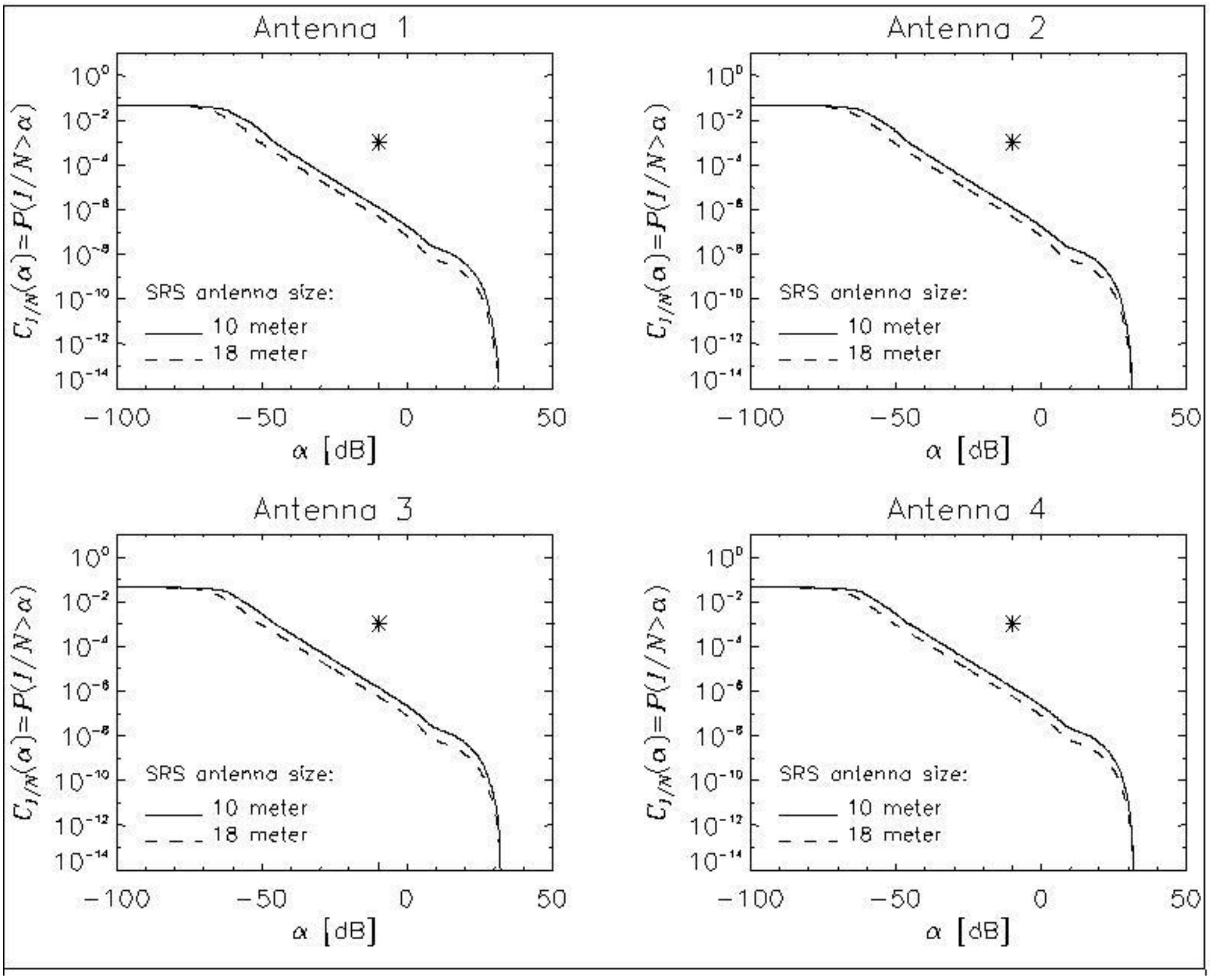


3.6.2 Scenario 2 – 10 m SRS antenna size

The resulting cumulative distribution functions are shown in Fig. A6-12 for the four ISS receiving antennas. To better visualize the effect of the SRS antenna size, this figure also presents the CDFs resulting from the use of 18 m antennas.

FIGURE A6-12

Cumulative distribution functions of the ratio *I*/*N* given that the victim satellite is receiving interference (Scenario 2, 10 and 18 m SRS antennas)



Results in this section have indicated that if 10 m antennas are considered for the SRS transmitting earth stations and the difference in antenna gain (approximately 5.1 dB) is compensated by increasing the power, the *I*/*N* cumulative distribution functions (unconditional and conditional) will be shifted by approximately 5.1 dB to the right, in the neighbourhood of the interference criterion. This is indeed expected since the interference reaching the ISS satellite comes mainly from the side-lobe of the SRS transmitting antenna, which does not change when the antenna size is decreased to 10 m.

3.7 Effect of the number of SRS earth stations

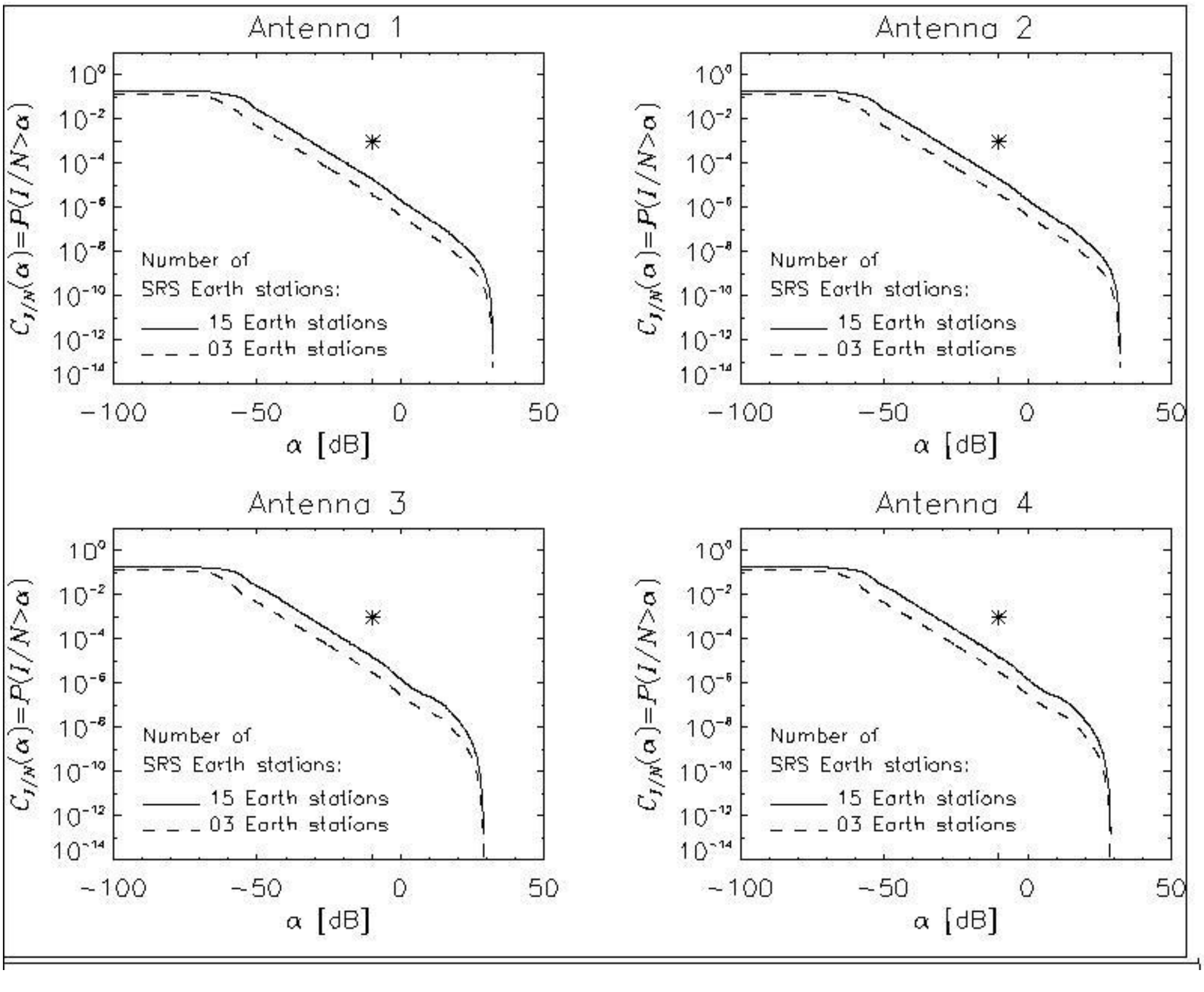
To examine the effect of the number of SRS earth stations the statistical behaviour of the *I*/*N* ratio, Scenario 4 was re-evaluated. Except for the number of SRS earth stations, here equal to 15, all other assumptions are the same as those in Scenario 4. All SRS earth stations were assumed to be located at 70° latitude and with longitudes uniformly distributed in (0°,360°). Although such a case would not be realistic for lunar missions, the results indicate the sensitivity in case of increasing numbers of SRS stations operated on the same frequency channel. As in Scenario 4, the condition for an SRS earth station to be *active* (transmitting) is that it sees the Moon with an elevation angle greater than or equal to zero and it is assumed that simultaneously active earth stations transmit co-channel. The *I*/*N* ratio is then calculated considering the aggregate interference from simultaneously active SRS earth stations. The obtained results are presented in the following section.

3.7.1 Scenario 4 – 15 SRS earth stations

The resulting cumulative distribution functions are shown in Fig. A6-13 for the four ISS receiving antennas. To better visualize the effect of increasing the number of SRS earth stations, this figure also presents the CDFs resulting from the use of 3 and 15 SRS earth stations. The results indicate that if the number of SRS interfering earth stations is increased from 3 to 15 the *I*/*N* cumulative distribution functions (unconditional and conditional) will be shifted by approximately 7.0 dB to the right, in the neighbourhood of the interference criterion (a 7.0 dB reduction in the protection margin with respect to the results in Scenario 4).

FIGURE A6-13

Cumulative distribution functions of the ratio *I*/*N* given that the victim satellite is receiving interference (Scenario 4, 3 and 15 SRS earth stations, $p_\delta(\Delta)_2$)



4 Conclusion

Results in scenarios 1 and 2 have indicated a 38 dB margin with respect to the in-band protection criterion and, assuming a 30 dB frequency discrimination factor, a 50 dB margin with respect to the out-of-band protection criterion. The study also examined the "Conditional" *I*/*N* cdf, which describes the *I*/*N* distribution under the condition that the ISS link is receiving non-zero interference. Although there were no applicable protection criteria against which to measure the absolute impact, the results were found to be useful by describing the impact on the overall system. Results have indicated that there would be a difference of around 16 dB on the overall multi-link ISS system, compared to a single ISS link.

The sensitivity analysis in Scenario 3 indicated a 12 dB increase in the *I*/*N* cumulative distribution function as the SRS earth station latitude was varied from 0° to 70°. Considering an SRS station located at 35° latitude as a reference, an increase in latitude to 70° would result in a reduction of 7 dB in the protection margin and a decrease in latitude to 0° would result in an increase of 5 dB in the protection margin. This result motivated the examination of scenarios 4 and 5. The results in these scenarios have indicated a 32 dB margin with respect to the in-band protection criterion and, assuming a 30 dB frequency discrimination factor, a 42 dB margin with respect to the out-of-band protection criterion.

The effect of decreasing the SRS antenna size from 18 to 10 m was also analysed. This decrease in antenna size has reduced the protection margin by 5.1 dB as the power is increased to compensate for the difference in antenna gain.

A further hypothetical case was considered in which 15 SRS earth stations were modelled, located at 70° latitude and spread evenly in longitude, and operating co-frequency. Although such a case would not be possible for lunar missions, it indicated the sensitivity in case increasing numbers of SRS stations operated on the same frequency channel. The result showed that the protection margin was reduced by approximately 7 dB.

References

[1] Recommendation ITU-R F.1245-1 (2000) – Mathematical Model of Average and Related Radiation Patterns for Line-of-sight Point-to-point Radio-relay System Antennas for Use in Certain Coordination Studies and Interference Assessment in the Frequency Range from 1 GHz to about 70 GHz.

[2] FORTES, J. M. and SAMPAIO-NETO, R. [1999] An Analytical Method for assessing interference in interference environments involving non-GSO satellite networks. International Journal of Satellite Communications, Vol. 17, **6**, p 399-419 and Corrigendum in Vol. 18, **3**, p 219, 2000.

[3] Recommendation ITU-R S.1529 (2001) – Analytic Method for determining the statistics of interference between non-GSO FSS systems and other non-GSO FSS systems or GSO FSS networks.

[4] FORTES, J. M., SAMPAIO-NETO R. and GOICOCHEA, J. M. [February, 2004] Fast computation of interference statistics in multiple non-GSO satellite systems environments using the Analytical Method. IEE Proceedings on Communications Vol. 151, **1**.

Annex 7

Summary of Study 7

1 Analysis methodology

1.1 In-band

Simulations were performed using a NASA internal simulation program and verified using Visualyse. The interference simulations assume that all interfering uplink carriers are transmitting 100% of the time when in view of the Moon. Simulations were run for a total time span of one year more precisely 365 days. At each time point, I/N is calculated separately per link, into 242 inter-satellite links in the HIBLEO-2 system as there are no interplanar links between planes 6 and 1 (i.e. the counter-rotating seam where satellites in plane 6 are moving in the opposite direction of satellites in Plane 1).

Additionally, the following assumptions were made:

- Lunar orbiting satellite systems are modelled as if the satellite is at the centre of the Moon.
- SRS earth stations only transmit when in view of the Moon.
- Each HIBLEO-2 like satellite is modelled with 4 ISL antennas, pointing to the following satellites: intra-planar fore, intra-planar aft, inter-planar West-adjacent, intra-planar East-adjacent. At each time point and for each satellite, the corresponding antenna gain into each of these 4 ISL antennas is calculated.
- Interferer power density is calculated over the worst-case (i.e. maximum PSD) 1 MHz bandwidth.
- Simulation propagation: Free space only – Recommendation ITU-R P.525 basic transmission loss in free space.
- In order to ensure that the analysis accurately reflects the aggregate in-band interference that could be received by a 19 MHz HIBLEO-2 like carrier, it is assumed that a network consisting of the 3 NASA earth stations could be sequentially operating co-frequency in this band. A single 24 MHz carrier is used for each of the 3 earth stations, and this carrier is represented by the first row of Table 2 of the main body of the report.

1.2 Out-of-band

As for the in-band case, at each time point, I/N is calculated separately per link, into 242 inter-satellite links in the HIBLEO-2 system.

Since this analysis is concerned with OoB attenuation from the SRS carriers operating in the 22.55-23.15 GHz band into HIBLEO-2 carriers, which operate in the 23.183-23.377 GHz band, interference is mitigated by an OoB factor. Interferer power density is calculated in a 1 MHz bandwidth and then reduced by the out-of-band attenuation factor.

In order to calculate this factor, the worse-case assumptions are made that:

- the upper edge of the first null of the SRS signal falls at 23.15 GHz;
- the Iridium carrier operates at its lowest frequency channel, which placed the lower edge of the first null of the Iridium signal at 23.183 GHz;
- the lowest frequency channel is being simultaneously received on each of the four ISL links on all 66 HIBLEO-2 satellites.

In order to ensure that the analysis accurately reflects the aggregate out-of-band interference that could be received by a 19 MHz HIBLEO-2 like carrier, it is assumed that six networks consisting of the earth stations from six agencies could be sequentially operating in this band. A single 24 MHz carrier and three 12 MHz carriers are used for each network, and these carriers are represented by the entirety of Table 1 of the main body of the Report.

The OoB attenuation factor is calculated using the methodology of Recommendation ITU-R SM.1541, and is applied to antennas transmitting in both single-carrier mode and multi-carrier mode. This methodology results in very conservative estimates of the actual OoB attenuation that would be realized in practice. A summary of the single-entry calculations is presented in Table A7-1. This Table A7-1 is only a representative sample of the OoB attenuation factors, and the carriers that are shown are taken from Table 1 of the main body of the report. The values for other carriers may be calculated in a similar manner.

TABLE A7-1

OoB Attenuation factor

Parameter	NASA Frequency 1	NASA Frequency 2	JAXA Frequency 1
HIBLEO-2 lower frequency (MHz)	23 183	23 183	23 183
SRS lower frequency (MHz)	23 126	23 109	23 046
SRS upper frequency (MHz)	23 150	23 121	23 070
Power (dBW)	11.1	8.1	11.1
BW (MHz)	24	12	24
Max in-band PSD (dB(W/Hz))	–59.7	–59.7	–59.7
Delta frequency (MHz)	45.0	68.0	125.0
Normalized delta frequency (%)	187.5	566.7	520.8
OoB attenuation (dB)	34.5	42.0	42.0
OoB PSD (dB(W/Hz))	–94.2	–101.7	–101.7

2 Results for sharing with space stations in the inter-satellite service

A number of simulations have been run using the technical and operating characteristics listed in the previous sections.

2.1 Statistical interference to a non-GSO-to-non-GSO inter-satellite links – HIBLEO-2 type system

For each simulation, the *I*/*N* statistics discussed below are presented and contain:

- CDF curves;
- The *I*/*N* value that is exceeded for a specified percentage of time.

2.2 In-band case

The in-band case was run using sequential 1-second time intervals over a 1 year period, for a total of 31.536×10^6 time points. Table A7-2 summarizes the results for the simulation scenario's *I*/*N* statistics for the in-band cases. Figure A7-1 shows the *I*/*N* values for all 242 inter-satellite links for this case. The protection criterion is met by a wide margin.

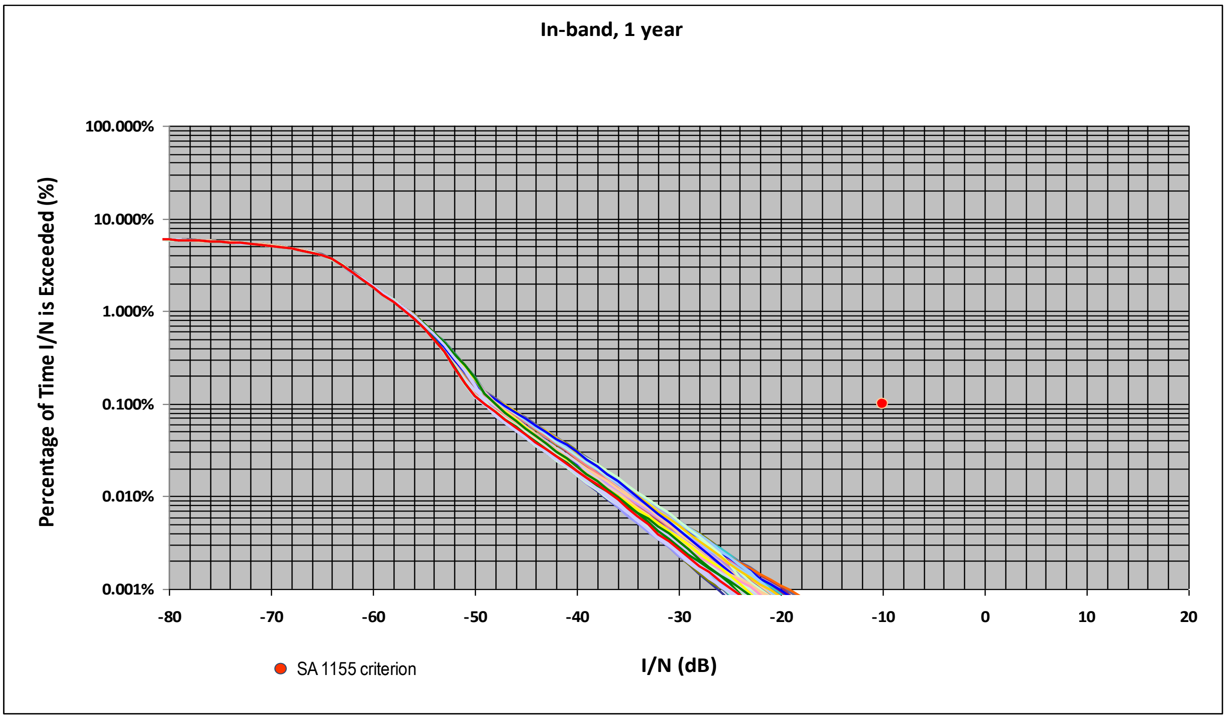
TABLE A7-2

In-band case summary for *I*/*N* statistics

		In-band case – per year Per link
I/*N* (dB) at 0.1%	mean	–48.3
	min.	–49.2
	max.	–47.2

FIGURE A7-1

In-band, one year



2.3 Out-of-band case

The OoB case was run using sequential 1-second time intervals over a 1 year periods, for a total of 31.536×10^6 time points. Table A7-3 summarizes the results for the simulation scenarios's *I*/*N* statistics for the out-of-band cases. Figure A7-2 shows the *I*/*N* values for all 242 inter-satellite links for this case. The protection criterion is met by a wide margin.

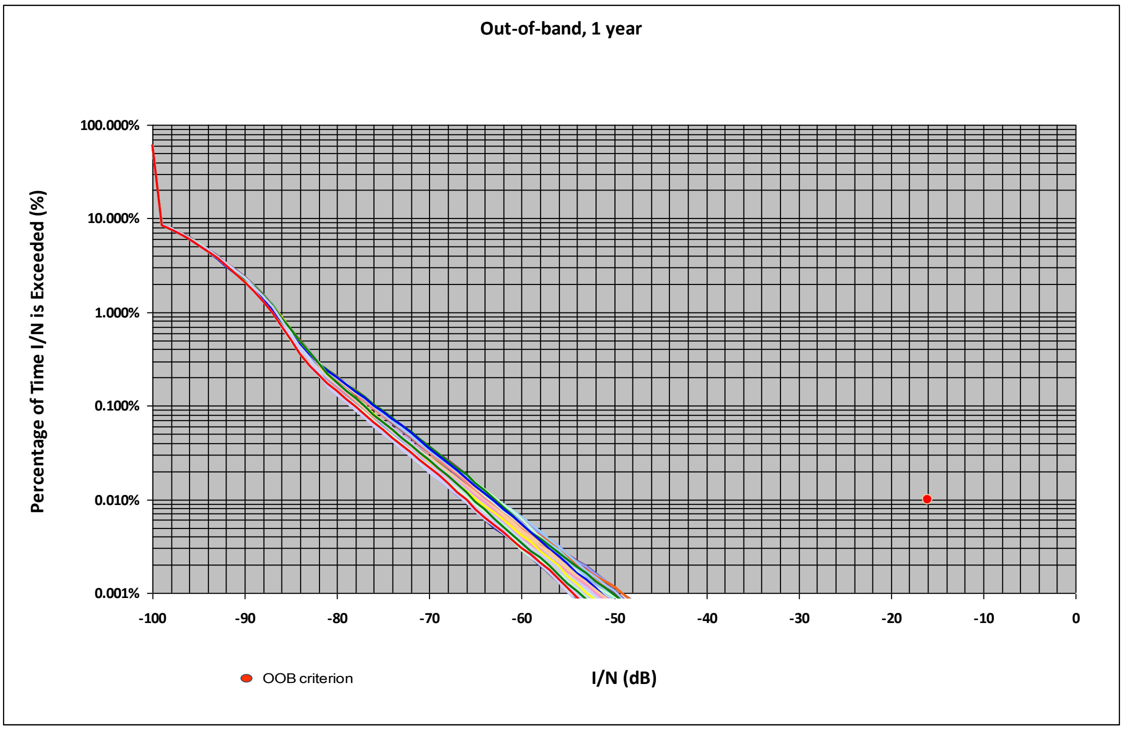
TABLE A7-3

Out-of-band case summary for *I*/*N* statistics

		Out-of-band case – per year Per link
I/*N* (dB) at 0.01%	mean	–65.0
	min.	–66.4
	max.	–62.7

FIGURE A7-2

Out-of-band, 1 year



The event statistics in Table A7-4 are presented based on the individual satellite links. The simulation was run using sequential 0.05-second time intervals over a representative 30 day period, for a total of 51.85 × 10^6 time points. Table A7-4 contains an I/N level above which an interference "event" is defined to occur (e.g. $I/N > = -16$ dB). The Table A7-4 also contains the number of events, the mean, minimum and maximum time of events, and the total time of all events. Note that 0.01% of one month's time is 259.2 s.

TABLE A7-4

Out-of-band case summary for event statistics

Start month 1		**Out-of-band Per link**
Num Events at $I/N = -16$ dB	mean	0.14
	min.	0.00
	max.	3.00
Event time (s) at $I/N = -16$ dB	mean	0.15
	min.	0.05
	max.	0.60
Cumulative time (s) at $I/N = -16$ dB	mean	0.02
	min.	0.00
	max.	0.60

3 Verification results

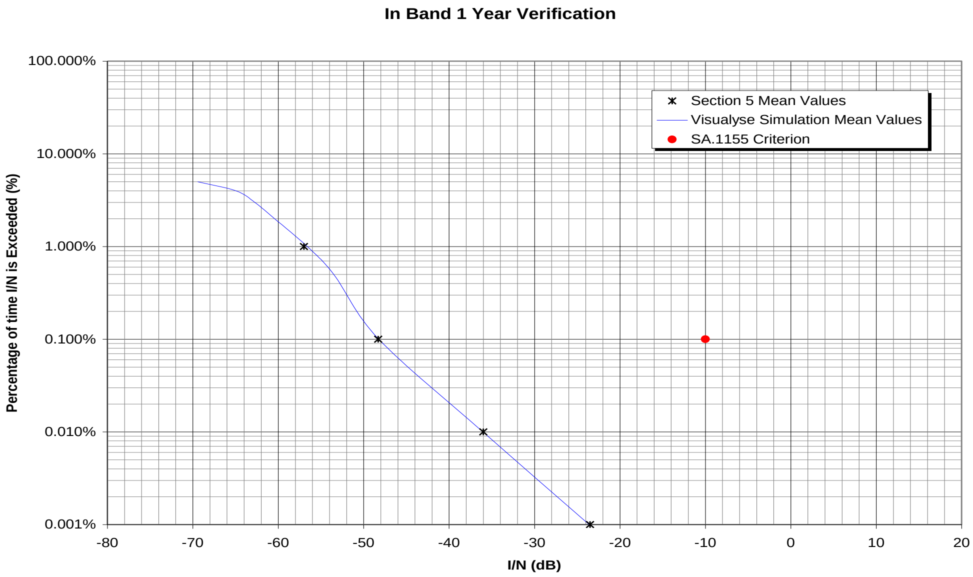
Since there may be differences in how simulation software tools may implement mathematical models of orbits and radio frequency propagation, the simulation scenario used above was repeated using a commercially available simulation and analysis tool, Visualyse[2]. The simulation methodology and system configurations are identical to that used in the NASA simulation tool for the results given in § 2.

3.1 In-band case

The in-band case was run using 1-second time steps over a one year time period. For comparison purposes, mean *I*/*N* values from § 2.2 are plotted against the mean of the Visualyse simulation results and are shown in Fig. A7-3. The results from § 2.2's simulation and the Visualyse simulation are very close, results are within 0.5 dB.

FIGURE A7-3

In-band verification comparison of mean values



3.2 Out-of-band cases

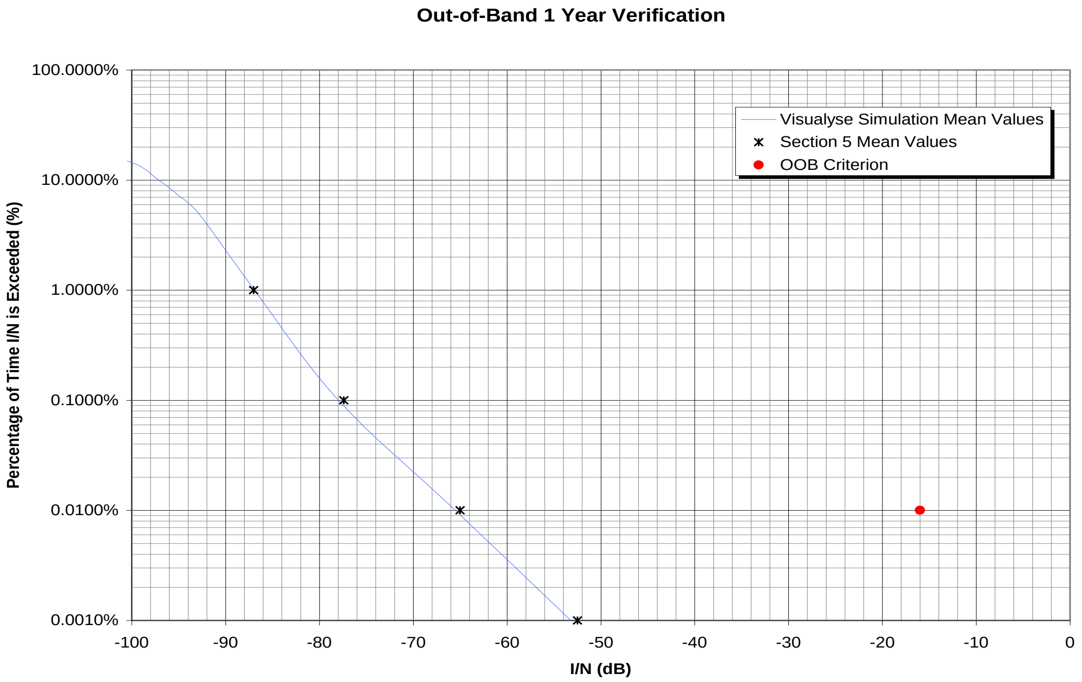
The OoB case was run using a 1-second time step over a one year period. For comparison purposes, mean *I*/*N* values from § 2.3 are plotted against the mean of the Visualyse simulation results and are shown in Fig. A7-4. The OoB case is also shows very close agreement between the two simulation models.

---

[2] Visualyse Professional Version 7.05 (Transfinite Systems Ltd).

FIGURE A7-4

Out-of-band verification comparison of mean values



3.3 Verification summary

The commercially available Visualyse simulation and analysis tool is a validated and verified program for radio frequency and satellite modelling (www.transfinite.com/content/itu3.html). Using the same set of assumptions and inputs, the results for the two simulation models are very closely aligned for both the in band and OoB cases.

4 Conclusions

This study has considered the determination of the compatibility between transmitting SRS earth stations and non-GSO-to-non-GSO space stations in the inter-satellite service of type HIBLEO-2 in the 22.55-23.55 GHz band for the criteria presented in § 3.3 of the main body of the Report, as specified by WP 4A, the results of the simulations were verified by using Visualyse, a commercially available simulation software tool.

Table A7-5 is a summary of the results presented in § 2 above. Also shown in the Table are reference levels of aggregate interference protection criteria for the in-band and out-of-band cases. For the in-band case, the agreed reference level is $I_0/N_0 = –10$ dB not to be exceeded for more than 0.1% per single link. For the out-of-band case, the reference level is $I_0/N_0 = –16$ dB not to be exceeded for more than 0.01% per single link. It is important to note that the aggregate interference. levels produced by the proposed SRS range from about 38 dB (for the in-band case) to 49 dB (for the OoB case) below the aggregate interference levels provided in the protection criteria. The relative contribution of the SRS interference is negligible when compared to the overall aggregate level allowed for all sources of interference. Hence, it is concluded from these studies that sharing between the SRS (Earth-to-space) and the inter-satellite service of type HIBLEO-2 in the 22.55-23.15 GHz band is feasible with no constraints on the SRS.

TABLE A7-5

Summary of the worst-case level of interference

	Protection criterion	**SRS interference margin, relative to aggregate interference criterion (dB)**
In-band case	Aggregate $I/N = -10.0$ dB, from all services, not to be exceeded for 0.1% of time	38.3
OoB case	Aggregate $I/N = -16.0$ dB, from all SRS earth stations, not to be exceeded for 0.01% of time	49.0