Electronic Communications Committee (ECC)
within the European Conference of Postal and Telecommunications Administrations (CEPT)

USE OF THE FREQUENCY BAND 8025-8400 MHZ BY EESS

Ljubljana, January 2008

0 EXECUTIVE SUMMARY

The use of the 8 025-8 400 MHz band by Earth exploration-satellite service (EESS) satellites operated by various entities (space agencies, governmental organizations, military, commercial private companies, …) for data downlink operations is increasing and could result in harmful interference between these operators. In addition, the band is shared with the fixed, mobile and fixed-satellite (Earth-to-space) services and the band 8 175-8 215 MHz is also shared with the meteorological satellite (Earth-to-space) service. Furthermore, operating in the adjacent 8 400-8 450 MHz band, are space research (deep space) earth station receivers. These deep space receivers are extremely sensitive and highly susceptible to interference.

This report provides results of analysis, measurements and proposed mitigation techniques to reduce the potential for interference by and to EESS satellites given the growing interest in the use of the 8 025-8 400 MHz band by the EESS. It has to be noted that the measurements performed were limited to EESS satellites transmitting data to Earth stations when in visibility from the Leeheim station.

In order to reduce this interference risk, the following mitigation techniques should be considered :

- EESS satellites operating in a non-broadcasting mode radiate only when transmitting data to one or more Earth stations;
- Phasing of the orbital parameters for sun-synchronous satellites with existing and planned satellites be considered;
- Whenever practicable, low side lobe, high gain satellite antennas be used and if high gain satellite antennas are not practicable, isoflux antennas be considered instead of omnidirectional antennas;
- Broadcast modes be avoided whenever practicable or, if unavoidable, consider the use of a portion of the lower half of the band 8 025-8 400 MHz;
- Bandwidth efficient modulation and coding techniques be used, to reduce the potential for adjacent channel interference by simultaneously limiting power flux-density, out-of-band emissions and occupied bandwidth;
- Careful consideration be given to the use of higher order advanced modulation techniques in view of potential incompatibility with a homogeneous power flux-density environment;
- To reduce the possibility of intersystem interference, due consideration also be given to other interference mitigation techniques such as polarization discrimination, geographical separation of earth stations and large earth station antennas with off-axis gains that do not exceed $32-25 \log \theta$, dBi for $1° \leq \theta \leq 48°$;
- EESS spacecraft using non-directional antennas be designed to limit their spectral pfd on the Earth's surface to less than -123 dB(W/m^2/MHz) - corresponding to -147 dBW/m^2 in 4 kHz - at their sub-satellite points;
- In order to minimize the need for operational coordination, EESS satellites utilize, to the maximum extent possible, appropriate techniques to prevent unwanted emissions exceeding the ITU-R space research service (deep-space) protection criterion in the band 8 400-8 450 MHz, including on-board filtering, large geographical separation between EESS and space research service (deep-space) earth stations, low-sideband modulations, and one or more of the applicable techniques given above;
- EESS satellites use the 25.5-27 GHz band if the techniques given above cannot adequately mitigate both in-band and adjacent-band interference, once suitable ground infrastructures are available.

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LIST OF ABBREVIATIONS

Abbreviation	**Explanation**
ASAR	Advanced Synthetic Aperture Radar
CEPT	European Conference of Postal and Telecommunications Administrations
CNES	Centre National d'Études Spatiales
ECC	Electronic Communications Committee
EESS	Earth Exploration-Satellite Service
EPFD	Equivalent Power Flux Density
ERO	European Radiocommunication Office
ESA	European Space Agency
ITU	International Telecommunications Union
NASA	National Aeronautics and Space Administrations
PFD	Power Flux Density
SFCG	Space Frequency Coordination Group
SRS	Space Research Service
WGSE	Working Group Spectrum Engineering

1 INTRODUCTION

The use of the 8 025-8 400 MHz band by Earth exploration-satellite service (EESS) satellites operated by various entities (space agencies, governmental organizations, military, commercial private companies, …) for data downlink operations is increasing and could result in harmful interference between these operators. In addition, the band is shared with the fixed, mobile and fixed-satellite (Earth-to-space) services and the band 8 175-8 215 MHz is also shared with the meteorological satellite (Earth-to-space) service. Furthermore, operating in the adjacent 8 400-8 450 MHz band, are space research (deep space) earth station receivers. These deep space receivers are extremely sensitive and highly susceptible to interference. This report provides results of analysis, measurements and proposed mitigation techniques to reduce the potential for interference by and to EESS satellites given the growing interest in the use of the 8 025-8 400 MHz band by the EESS.

2 EESS USE OF THE BAND 8025-8400 MHZ

A rapid increase in required frequency spectrum for earth observation satellites has been recorded over the past 2 decades. This is partly due to the growing number of satellites and partly also due to significantly higher data rates in connection with increasing resolution of the images taken of the earth. In addition to traditional space agencies and governmental organisations, commercial companies are now also operating or planning to operate an increasing number of satellites for earth observation purposes. A data base containing key information on all satellites using or planning to use the band 8 025-8 400 MHz has been developed by the Space Frequency Coordination Group (SFCG) and is currently maintained by ESA. The data base contains information from various sources, in particular ITU filings and is intended to provide useful data for simulations and statistical assessments.

Almost all earth observation spacecraft are using the frequency band 8 025-8 400 MHz for transmitting their payload data to ground stations. This may result in a significant increase in the probability of interference unless appropriate measures are taken. Assessments of the probability of interference for current and future earth observation mission scenarios were conducted over the past few years to estimate the increasing interference levels as a function of various system parameters and interference mitigation techniques.

All following data are based on information in the data base as of 2005. Significant deployment of earth observation satellites started about 15 years ago. Figure 1 shows a statistical assessment of the total number of frequency assignments for a time frame between 1995 and 2010, as well as the corresponding deviation in the number of satellites from the respective previous year. The figure also shows the total number of satellites. It shall be noted that one satellite can have several assignments as the total data rate is sometimes transmitted on 2 or more individual channels. Some satellites can also operate at 2 or more data rates. The basis for the date is the announced or effective date of bringing the satellite into operation and its life time. The life time specifications given in the SFCG data base represent rather pessimistic values based on worst case fuel availability, sub-system reliability, budgeted support, etc. In practice, unless a failure occurs, actual EESS satellite life times are significantly longer and can exceed 10 years. Therefore, in cases where no specific information on life time was available, it was assumed that the satellites would be operational for around 8 years. This is a typical value based on ESA's experience with operational satellites.

In addition to these curves, a potential trend is shown based on the assumption that future deployments will follow a similar distribution as in the past. It is interesting to note the negative trend beyond 2007, which just about a year ago occurred around 2006, and 2 years ago around 2005. This indicates that the actual number of satellites is not decreasing in the future. To some extent this is due to the fact that satellite filings are only made once a schedule for bringing it into operation is well known. The decreasing number of data base entries beyond 2007 has been disregarded for the expected trend on future systems.

Some information on systems planned to operate beyond 2010 is also available in the data base but it is probably misleading to show such data as it can be assumed that most satellite systems with a date for bringing it into use beyond 2010 will not be filed at this time.

Figure 2 shows the total bandwidth assigned to all satellites as well as the resulting mean bandwidth per satellite. In addition, some assumptions were made regarding the potential trend. Again, a lifetime of 8 years is assumed for those data base entries where specific information is lacking. In addition, a potential trend is shown for both curves. The basis for the bandwidth assumptions is the notified necessary bandwidth which in most cases equals the data rate. In some cases it was noticed that twice the data rate was considered necessary in the filing.

A somewhat surprising history of the mean bandwidth can be noticed. One would have expected a continuous increase of required spectrum per satellite but since 2004 it appears to remain almost constant and the same trend is noticeable for the coming years. To some extent this could be explained by the use of more bandwidth efficient modulation techniques as well as more efficient data compression techniques. It could also be caused by smaller satellite projects with lower data rate requirements.

FIGURE 1

Total number of satellites and difference with respect to previous year including a potential trend based on development history for an average lifetime of 8 years

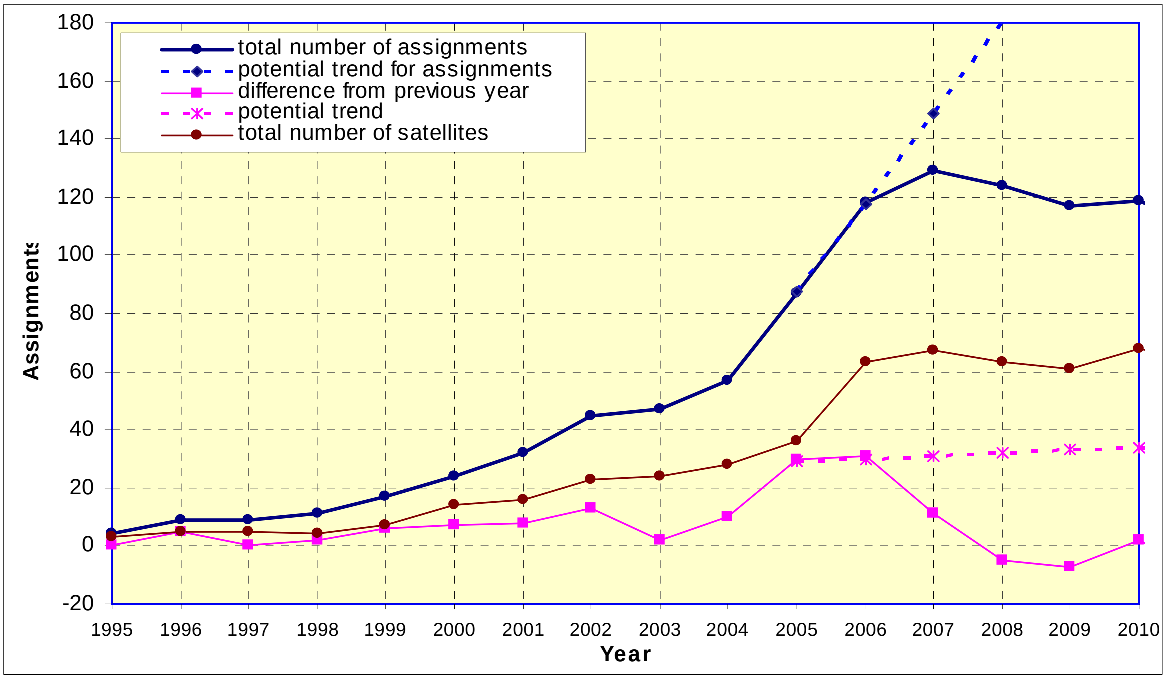
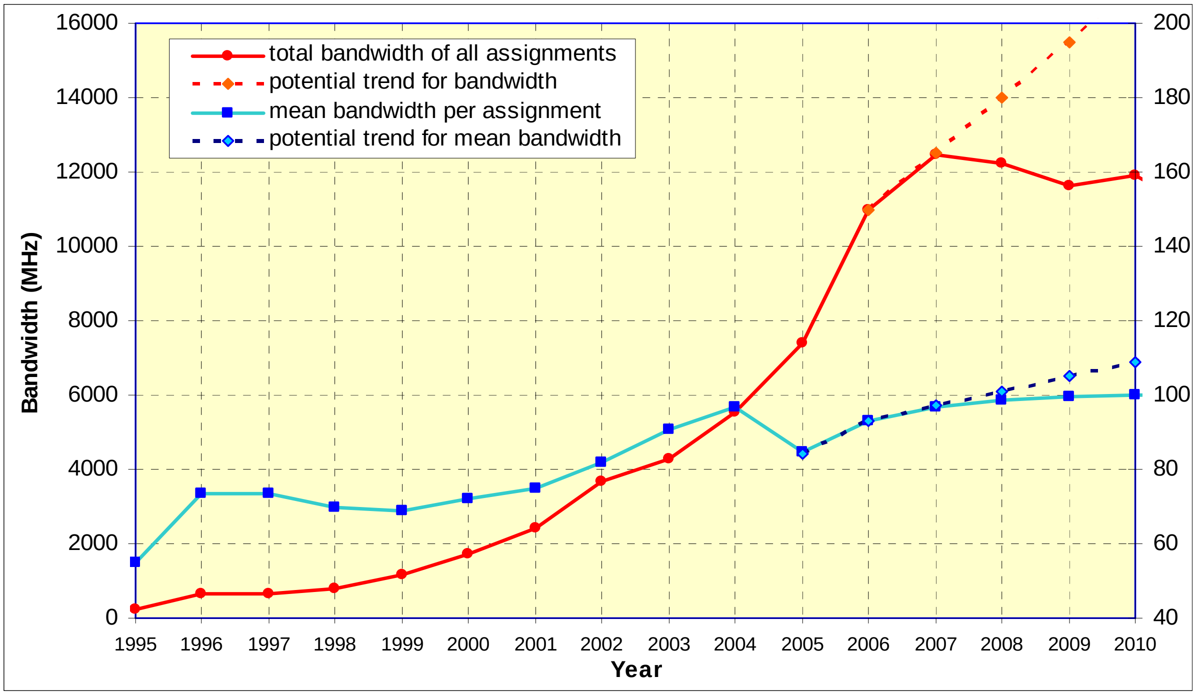


FIGURE 2

Total bandwidth used by all satellites and mean bandwidth per satellite including a potential trend based on development history for an average lifetime of 8 years

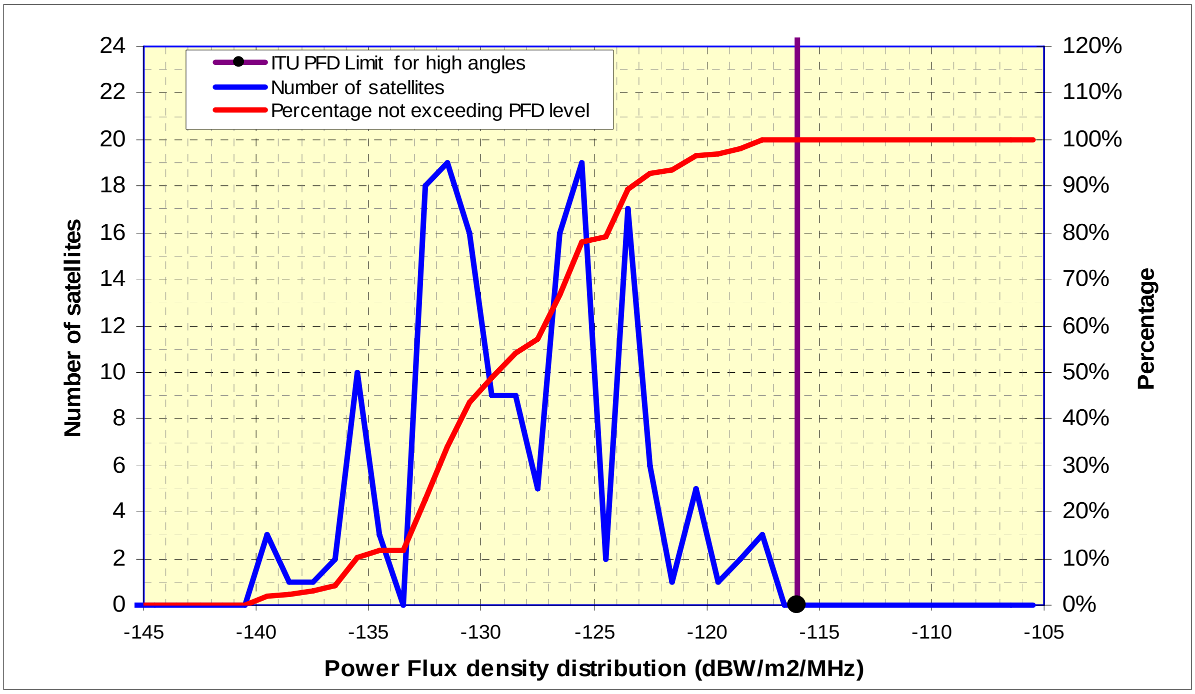


The following Power Flux Density (PFD) statistics have been derived from the data base considering information on 168 assignments. The PFD limits in the Radio Regulations have been scaled to 1 MHz. A 3 dB compensation factor has been taken into account as the maximum PFD level for PSK modulation techniques is 2 times higher than the average PFD over the specified bandwidth. Two cases have been considered, one for PFDs at high angles of arrival and one for low angles of arrival.

Figure 3 shows PFD levels at high angles of arrival based on the minimum specified perigee. The antenna gain towards the sub-satellite point for isoflux antennas (maximum gain between 4 and 10 dBi) has been assumed with 4 dB less than the maximum gain. For quasi omni-directional antennas with gains of less than 4 degrees and parabolic antennas, the maximum gain has been assumed. The average PFD value is –128.4 dBW/m^2/MHz, ranging between –139.3 and –106.8 dBW/m^2/MHz. Around 90% of all links have PFD levels below –123 dBW/m^2/MHz.

FIGURE 3

Power flux density distribution for high angles of arrival



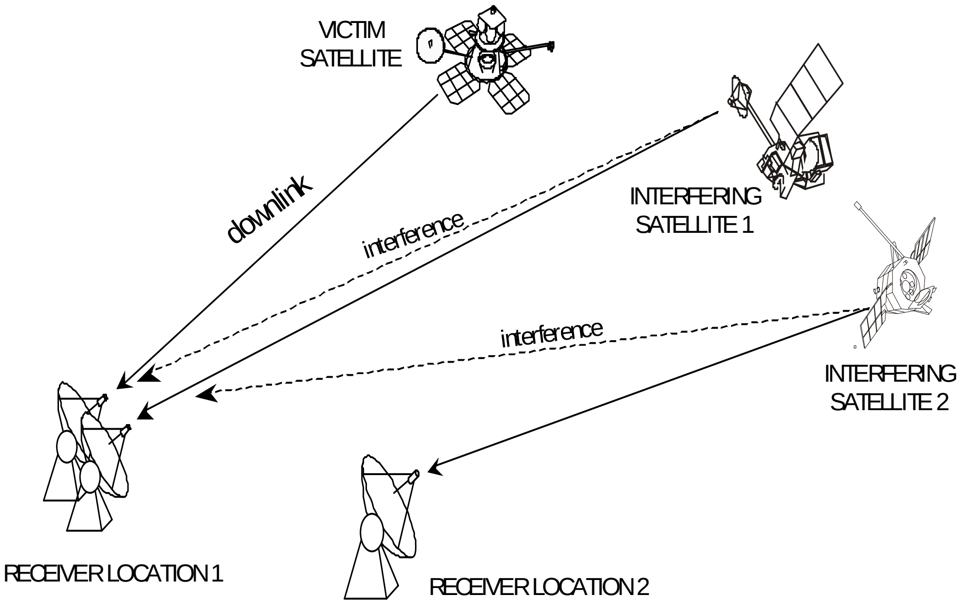
3 INTERFERENCE ANALYSIS

3.1 Interference analyses and suitable mitigation techniques

Figure 4 shows a typical constellation for an interference environment. A victim satellite transmits on a downlink to an earth station and one or several other satellites transmit to either a different antenna at the same location as the victim or to a separate location but with a line-of-sight connection to the victim earth station. For simplicity, only 2 interfering satellites are shown but the analysis below assumed up to 9 different interfering satellites. In addition, some satellites operate in a broadcast mode serving several earth stations. In this case it was assumed that their signals would be transmitted continuously.

FIGURE 4

Typical interference scenario



The actual interference received is a function of a several parameters. Of key importance are transmitter power levels, antenna gain, antenna type, spectrum, orbital separation, earth station diameter, earth station separation, signal polarisation and the number of satellites involved.

Table 1 shows the key parameters for 10 satellites used in ESA’s interference study. This was done around 2003 and its satellite parameters are therefore based on the data base at that time. Moreover some parameters were selected in a way to study their specific impact, such as antenna type, transmission mode, etc. In particular 4 satellites with parabolic antennas were choosen in order to study the mitigation effect of pointing higher gain antennas. In reality, most EESS satellites use still a cardioid antenna and the average gain is consequently lower. Also the number of broadcasting satellites is above the average in the data base, but that was required to study the impact of continuous transmissions. Similar considerations apply to the assumed bandwidths which are above average. The parameters used for the interference assessment study should therefore not be considered as representative parameters from the data base. The prime objective was the investigation of interference mitigation techniques.

The interference assessment was carried out by means of a software simulations tool. The simulations started with an assessment of the individual interference probability for every single satellite selected. Then the number of satellites was increased one by one until the maximum of 9 interfering satellites. Satellite 1 was selected as the victim satellite and satellites 2 to 10 as the interferers.

Regarding an appropriate protection criterion for the receiving earth station, recommendation ITU-R SA.1026-3 was selected as the only official source available. It specifies -197 dBW/Hz for 0.025% of time and -207 dBW/Hz for 20% of time. It has been argued by the EESS community (ESA, NASA, CNES, etc.), though, that these criteria may be 10-20 dB too relaxed compared to similar ITU-R recommendations of other satellite services. ITU-R WP 7B drafted a revision of its recommendation SA.1026 with the objective to tighten the protection criteria. It can be assumed that a protection value around -217 dBW/Hz (-187 dBW(kHz) may be closer to reality and technical possibilities. This criterion has been used in the simulations but for comparison, both criteria are shown in all interference charts shown below.

TABLE 1

Satellite parameters used for the interference assessment

	SAT-1	SAT-2	SAT-3	SAT-4	SAT-5	SAT-6	SAT-7	SAT-8	SAT-9	SAT-10
Apogee (km)	781	817	705	690	705	450	789	600	822	680
Perigee (km)	769	817	705	673	705	450	789	600	822	680
Inclination (degrees)	98.5	98.7	98.2	98.4	98.2	97.2	98.6	97.7	98.7	82
Right ascension (degrees)	330	220	204.5	337.5	330	157.5	300	345	337.5	270
Transmitter power (dBW)	12	14.5	12.5	1.2	13	3.8	0	7.5	13	3.4
Antenna gain (dBi)	7	7	8	29.6	8.2	24.7	26	6.5	6	29.6
Antenna type	card.	Card.	card.	dish	card.	dish	dish	card.	card.	dish
Broadcast mode	no	Yes	yes/no	yes	no	no	no	No	no	no
Bandwidth (MHz)	100	85	15/150	320	75	320	100	115	50	320
Ground station	Kiruna	Bangalore	Kiruna	Fairbanks	Svalbard	Kiruna	Kiruna	Kiruna	Svalbard	Kiruna

Figure 5 shows the resulting interference probability for every individual satellite. It is interesting to note that basically all interferers meet the ITU-R protection criterion and that about half of the interferers meet the alternative criterion.

Figure 6 shows the cumulative interference probability for an increasing number of satellites up to a total of nine. The interfering satellites have been selected in such a way that any new satellites added have either a similar or higher single interference probability. Otherwise no impact in the aggregate interference level can be noticed

FIGURE 5

Interference probabilities of individual satellites

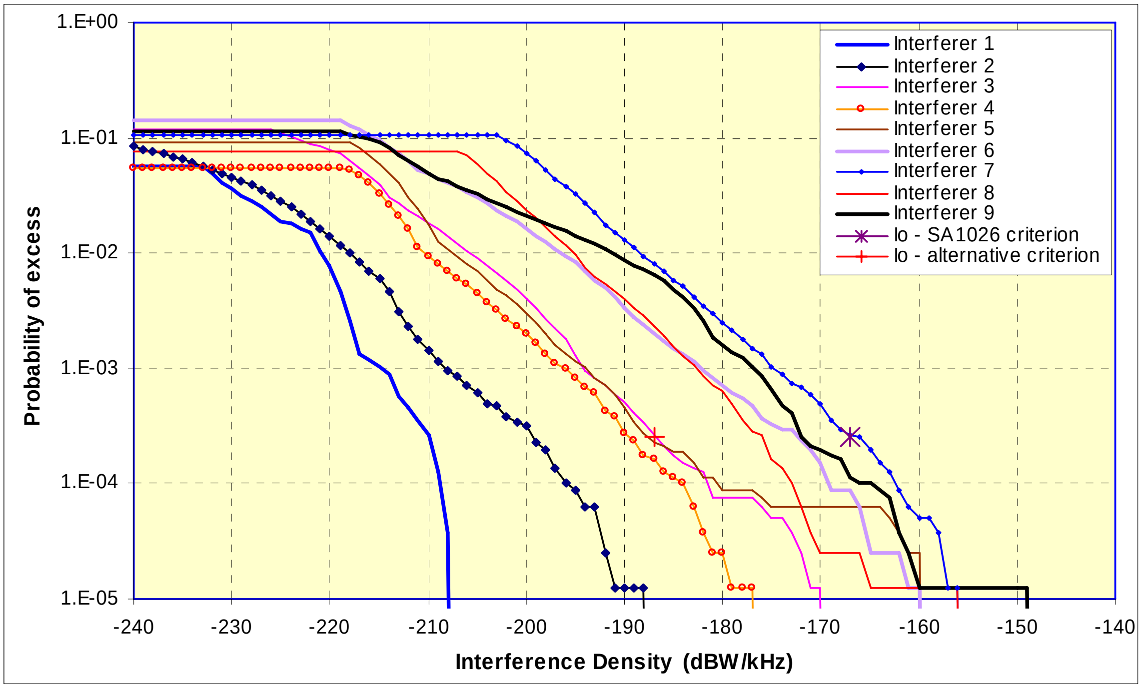
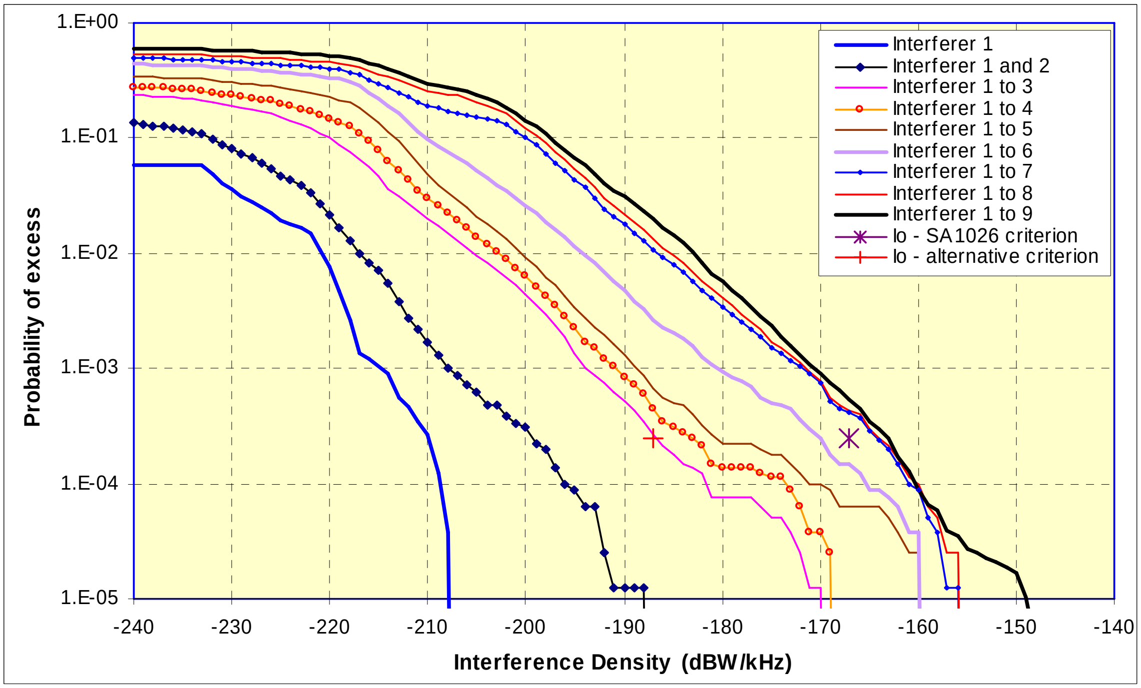


FIGURE 6

Cumulative interference probabilities for an increasing number of satellites



3.2 Interference mitigation techniques and their impact

A number of mitigation techniques are available in order to reduce the interference levels and the associated probabilities. Key techniques are:

- Orbital phasing results in a separation time between satellites. This technique works only for satellites with similar orbits and requires coordination between all operators involved.
- Earth station diversity is very effective when the interferers do not operate in a continuous (broadcast) mode. The drawback is additional infrastructure and operational cost as compared to one complex serving several users. In addition, only a limited number of locations is available in the high latitude regions.
- Pointable parabolic antennas (dish) offer very attractive advantages over cardioid antennas if operation in a broadcast mode is not required or if the number of multiple stations to be served is small. Pointing control needs to be implemented on-board the satellite.
- Earth station antenna size. The higher the antenna gain of the earth station, the narrower the beamwidth and hence the better the de-coupling. The drawback is increased cost for the antenna and the motion control.
- Similar power flux density (isoflux) on the surface of the earth. Operating close to the power flux density limits avoids a strong imbalance in received signal levels at the earth stations.
- Transmission shut-down when not in view of the receiving earth station significantly reduces interference and works very well if there is no requirement for a broadcast mode.
- Band segmentation (bandwidth limitations) allows for several users to transmit signals within the total bandwidth available. Difficult to control for all potential users without legally binding restrictions adopted by ITU.
- Polarisation discrimination allows for transmission of 2 channels on the same frequency.

Last but not least, it is worth mentioning that the adopted protection criteria have a big influence on determining whether interference is considered unacceptable or not. Some applications may not require a data availability of 99.975% or more, in particular, when data can be re-transmitted or when the same or similar measurements can be conducted during one of the following orbital passes.

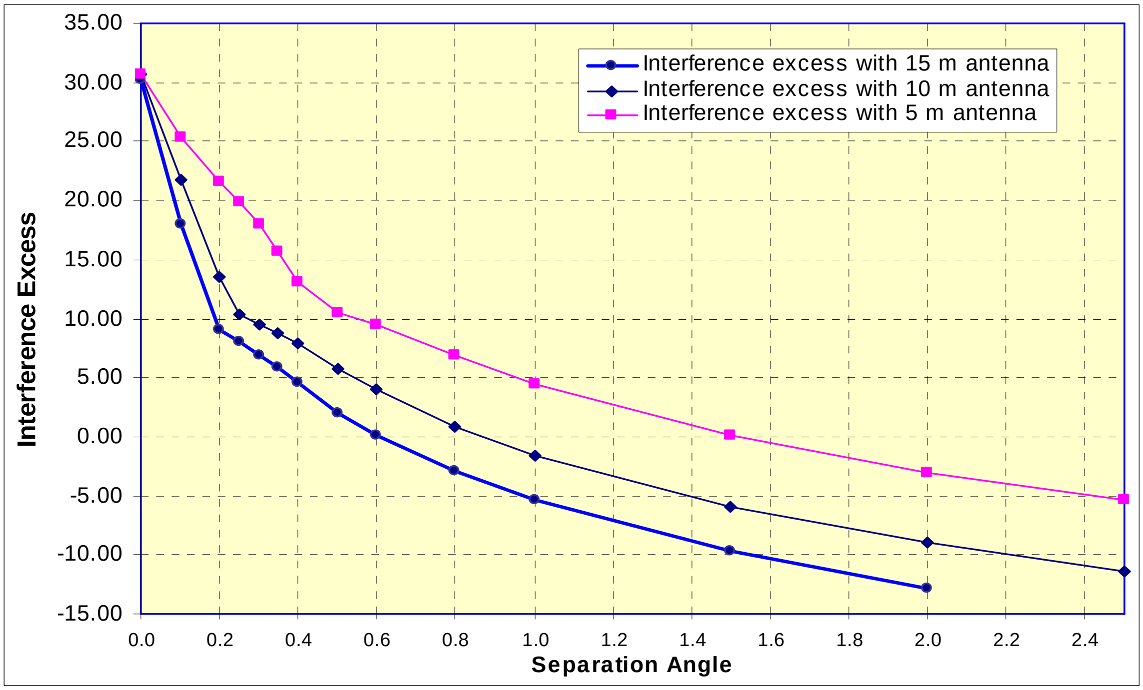
For some of the above mitigation techniques, it is obvious to what extent they can reduce the aggregate interference levels and simulations are not required in such cases. This applies particularly to polarisation discrimination and band segmentation. Regarding the impact of an isoflux concept, NASA has already conducted interesting simulations available for review. This study therefore concentrates on the impact of orbital phasing, earth station antenna size and diversity, pointable antennas in place of cardioid antennas and transmission control.

3.2.1 Impact of orbital phasing

Figure 7 shows the simulation results for a range of orbital separations and several earth station antenna diameters. Two satellites were assumed with the same orbital data, so that the distance between the 2 satellites is constant. As expected, the earth station antenna diameter has a major influence. The results are in general very encouraging as already small orbital separations result in an enormous interference reduction. For a 15 meter earth station diameter, a separation of 0.6 degrees is already sufficient to attenuate the interfering signal by 30 dB. For a 5 meter earth station diameter, an orbital separation of 1.5 degrees would be sufficient. 1 degree of separation corresponds to approximately 30 seconds of separation in time.

FIGURE 7

Interference excess as a function of orbital separation and varying antenna diameter



3.2.2 Impact of Earth Station Diversity

In order to allow for a quantitative assessment of some of the above mitigation techniques, a simulation set-up of 3 interferers with variable but identical RF parameters was selected. The orbital data are similar but selected in a way that basically all orbital configurations are possible over a simulation duration of 100 days where samples were taken every 10 seconds. Table 2 shows the parameters for the victim and the 3 interfering satellites.

Figure 8 shows the interference probability for a victim satellite transmitting to 4 different earth station locations, Kiruna, Svalbard, Fairbanks and Villafranca, respectively. Three interfering satellites transmit via cardioid antennas to Kiruna when the elevation angle exceeds 5 degrees.

Figure 9 shows the interference probability for a victim satellite transmitting to 4 different earth station locations. Three interfering satellites transmit via cardioid antennas in a continuous (broadcasting) mode.

Figure 10 shows the interference probability for a victim satellite transmitting to 4 different earth station locations. Three interfering satellites transmit via parabolic (dish) antennas to Kiruna when the elevation angle exceeds 5 degrees.

It can be seen that a wider geographical separation results in a significant reduction of interference. The difference between Svalbard and Kiruna is rather small as the distance between these 2 locations is relatively small.

It can also be seen that, as expected, a continuous transmission mode is the worst case. An enormous improvement can be achieved by using parabolic antennas. The resulting interference levels are orders of magnitude lower. Even for the relatively close Svalbard location, around 15 dB less interference is received. Using parabolic antennas onboard the satellite is therefore one of the most attractive mitigation techniques. The antenna characteristics assumed for this assessment are based on an 18cm dish with an efficiency of 42% and a gain of around 20 dBi. It is therefore a very small, low cost antenna.

TABLE 2

Parameters of a representative set of satellites used for the mitigation technique assessment

	Victim	Interferer-1	Interferer-2	Interferer-3
Apogee (km)	781	600	700	800
Perigee (km)	769	600	700	800
Inclination (degrees)	98.5	97.7	98.2	98.6
Right ascension (degrees)	330	345	270	300
Transmitter power (dBW)	13/0	13/0	13/0	13/0
Antenna gain (dBi)	0/20	0/20	0/20	0/20
Antenna type	card./dish	card./dish	card./dish	card./dish
Broadcast mode	no	yes/no	yes/no	yes/no
Bandwidth (MHz)	100	100	100	100
Earth station diameter (m)	5/10/15	5/10/15	5/10/15	5/10/15
Earth station locations	Kiruna, Svalbard, Fairbanks, Villafranca	Kiruna	Kiruna	Kiruna

FIGURE 8

Interference probability for victim transmitting to various earth station locations – 3 Interferer with cardioid antennas transmitting to Kiruna when elevation in excess of 5°

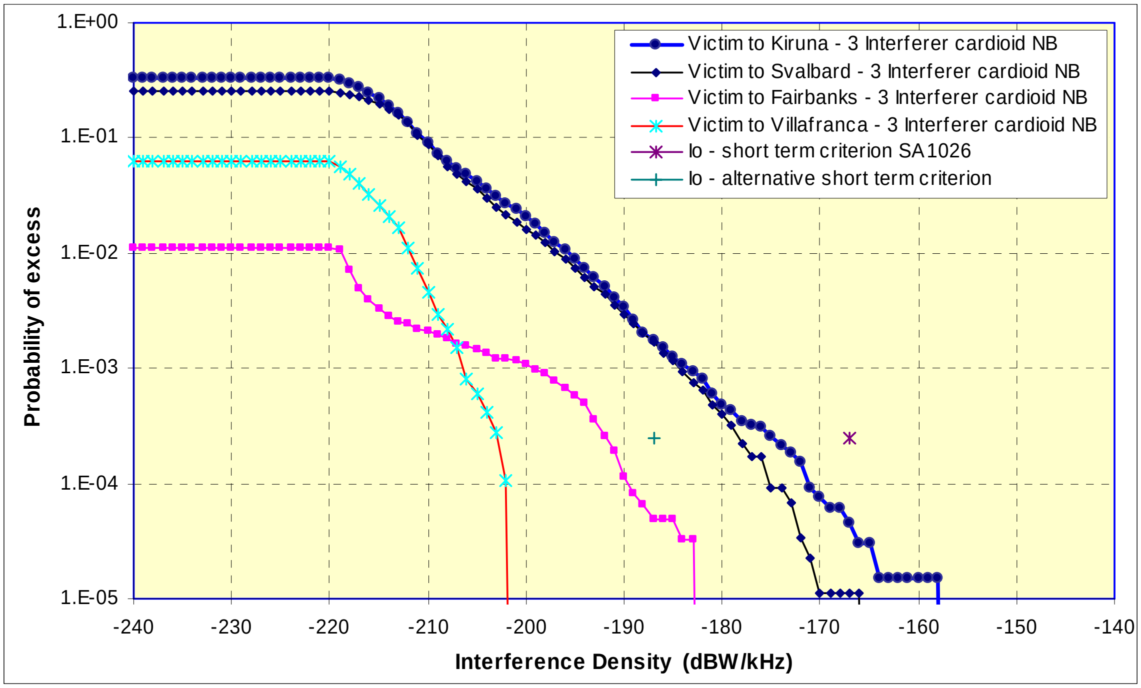


FIGURE 9

Interference probability for victim transmitting to various earth station locations – 3 Interferer with cardioid antennas continuously transmitting in broadcast mode

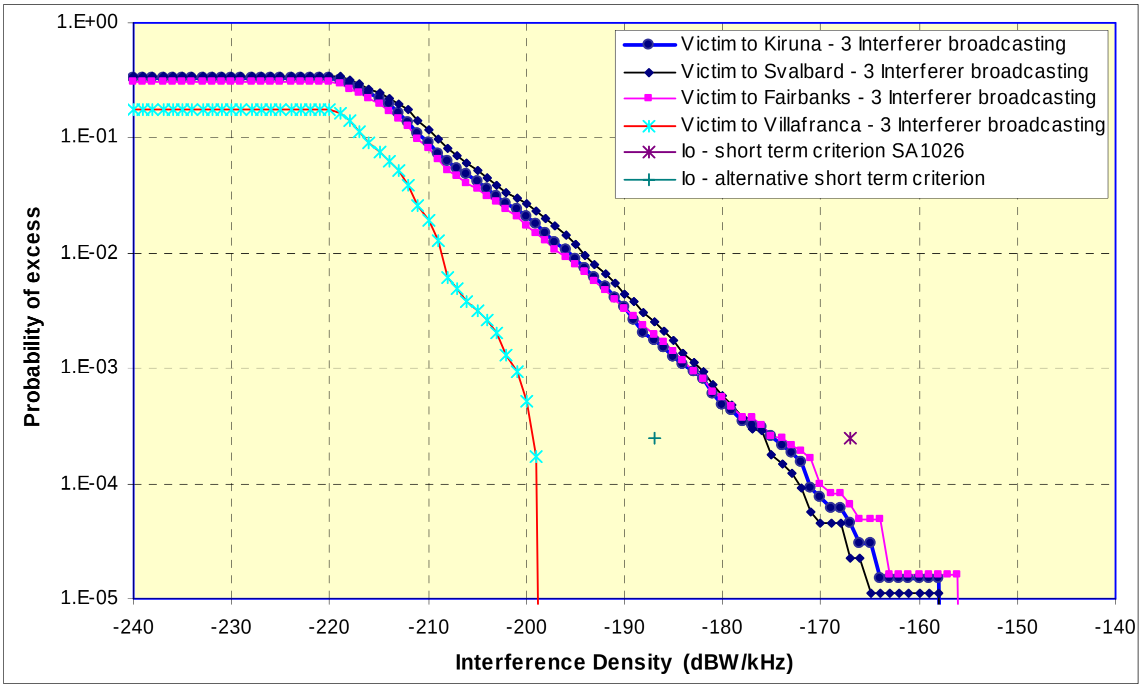


FIGURE 10

Interference probability for victim transmitting to various earth station locations – 3 Interferer with dish antennas transmitting to Kiruna when elevation in excess of 5º

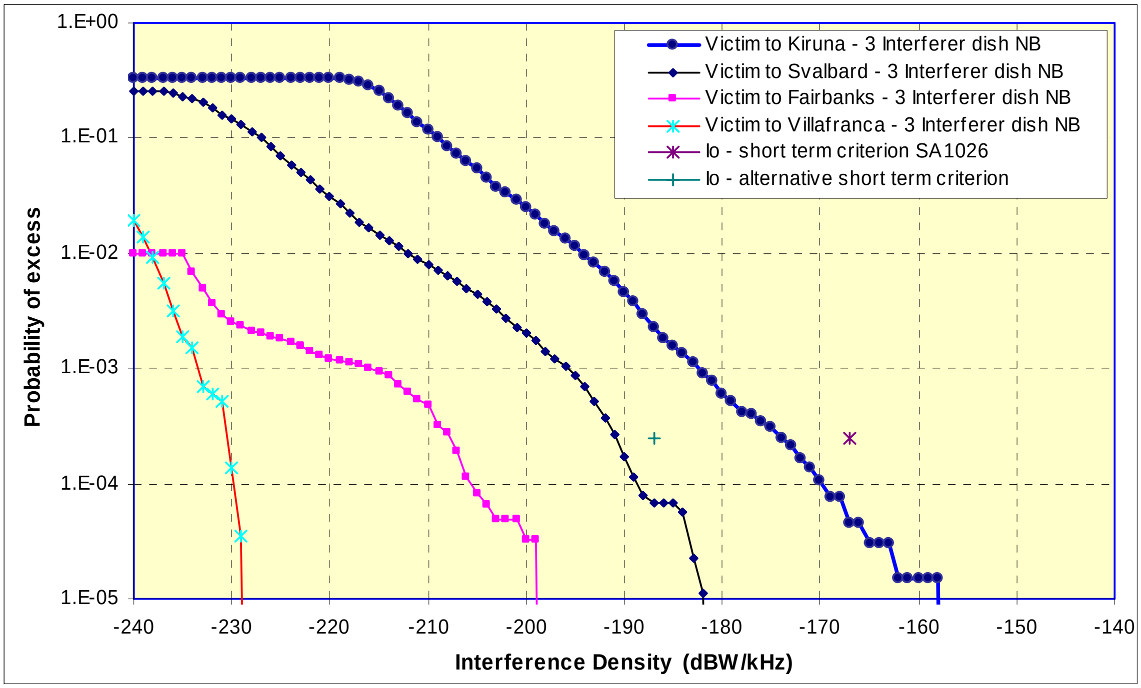


FIGURE 11

Interference probability for victim transmitting to Fairbanks earth station – 3 Interferer with cardioid antennas and dish antennas transmitting to Kiruna when elevation in excess of 5 degrees and broadcast mode, respectively

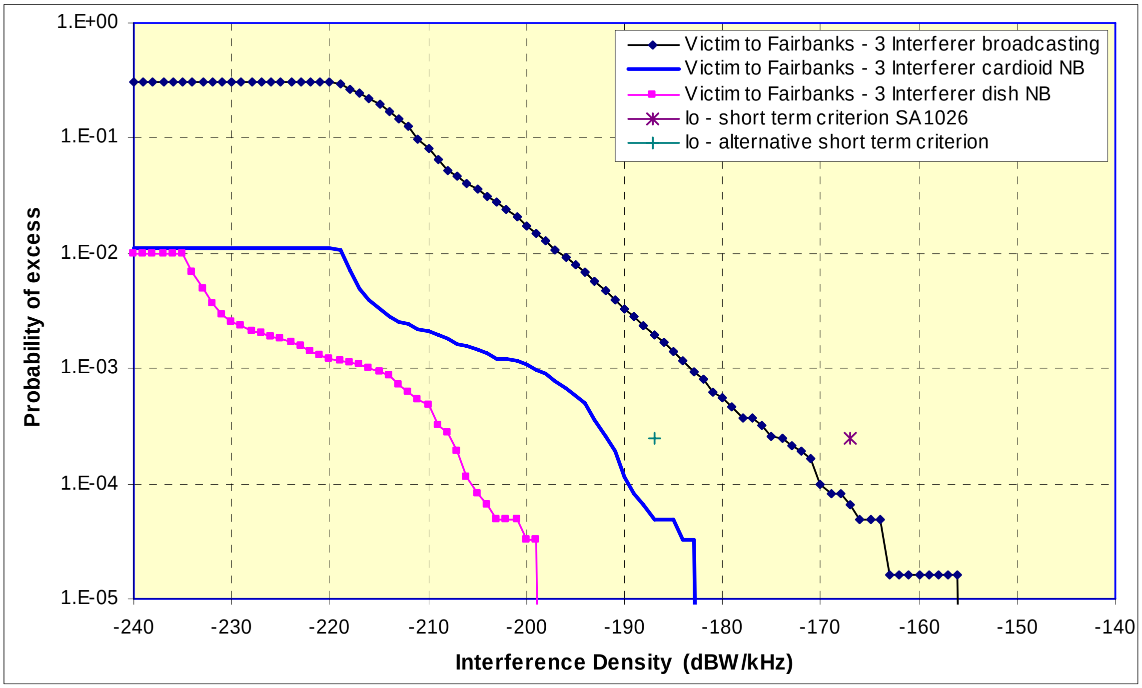
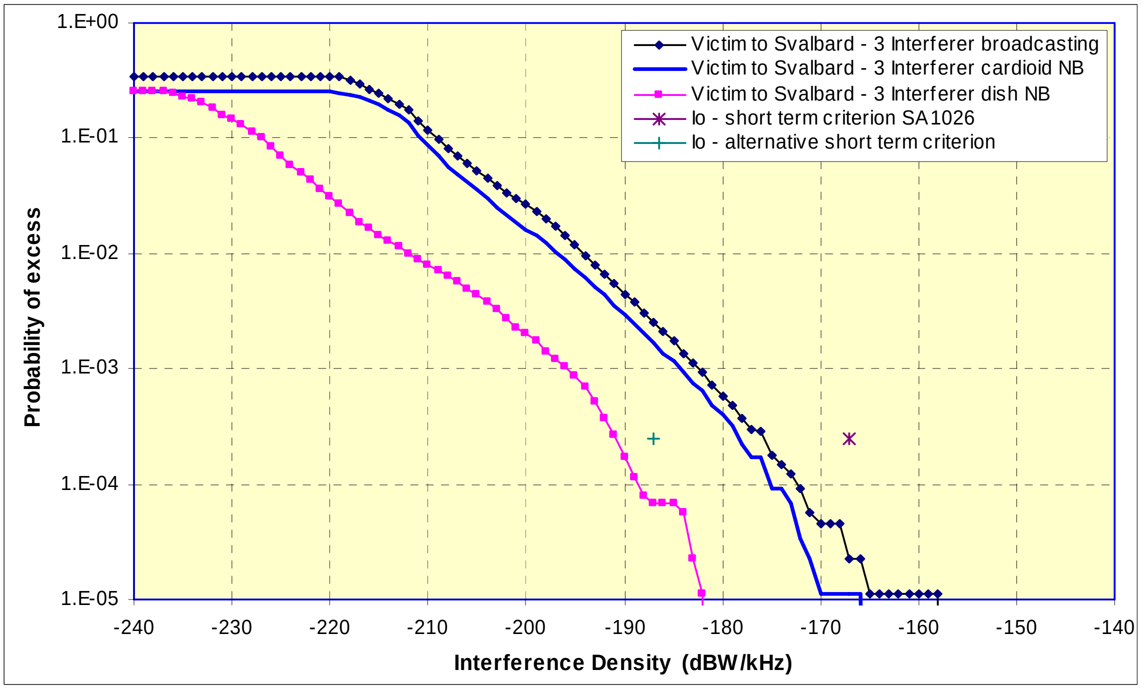


FIGURE 12

Interference probability for victim transmitting to Svalbard earth station – 3 Interferer with cardioid antennas and dish antennas transmitting to Kiruna when elevation in excess of 5 degrees and broadcast mode, respectively



3.2.3 Impact of Antennas and Transmission Mode

In order to assess the impact of antenna types and transmission modes, specific locations have been picked for the victim earth station location.

Figure 11 shows the interference probability for a victim satellite transmitting to Fairbanks. The first and worst combination is three interfering satellites transmitting via cardioid antennas in a continuous mode. The second combination is three interfering satellites transmitting via cardioid antennas to Kiruna when the elevation angle exceeds 5 degrees. The third and by far best combination is three interfering satellites transmitting via parabolic antennas to Kiruna when the elevation angle exceeds 5 degrees.

Figure 12 shows the interference probability for a victim satellite transmitting to Svalbard. Again, the first and worst combination is three interfering satellites transmitting via cardioid antennas in a continuous mode. The second combination is three interfering satellites transmitting via cardioid antennas to Kiruna when the elevation angle exceeds 5 degrees. This time the second combination is hardly better than the worst because of the relative close proximity between Kiruna and Svalbard. The third and by far best combination is again three interfering satellites transmitting via parabolic antennas to Kiruna when the elevation angle exceeds 5 degrees.

The simulations were also done for the earth station locations Kiruna and Villafranca. For Kiruna, and in general for any identical victim amd interferer earth station location, the antenna type and transmission mode are irrelevant. Villafranca showed similar results as Fairbanks.

In general, the wider the separation between the receiving earth stations, the better the impact of antenna types and transmission modes.

4 MEASUREMENTS OF EMISSIONS CHARACTERISTICS OF EESS SATELLITES

In the framework of the Memorandum of Understanding on Satellite Monitoring within CEPT (June 2002) the Monitoring Earth Station Leeheim has measured:

- Spectra and spectrograms of emissions of EESS satellites in the band 8025-8400 MHz,
- the power flux density and EIRP for different elevation angles,
- the power flux density in the band 8400-8450 MHz used for deep space exploration,

for the following satellites: AQUA (NASA), ENVISAT (ESA), SPOT-5 (CNES), TERRA (NASA), DEMETER (CNES), and AURA (NASA). The measurements performed were limited to EESS satellites transmitting data to Earth stations when in visibility from the Leeheim station. The list of satellites was also limited for budget reasons.

These measurements were conducted during 2 different campaigns conducted in 2004 and 2006 and the results are contained in 2 reports from Leeheim which are available from the ERO website.

4.1 POWER FLUX DENSITY

The maximum pfd values recorded during the relevant fly over of satellites are given in Table 3 in a reference bandwidth of 4 KHz.

TABLE 3

Maximum measured RMS pfd levels of EESS satellites

Satellite	Frequency (MHz)	Elevation angle (°)	Maximum RMS pfd (dBW/m² in 4 kHz)	Emission	Campaign
DEMETER	8253	20	-156.0		2006
SPOT-5	8253	20	-154.7		2006
SPOT-5	8253	17	-152.0		2004
SPOT-5	8365	31	-154.6		2006
SPOT-5	8365	17	-152.5		2004
ENVISAT	8100	7	-137.6	Anomaly	2006
ENVISAT	8100	15	-139.0[1]	Anomaly	2004
ENVISAT	8100	54	-152.5	Wide band	2004
ENVISAT	8200	19	-152.9	Wide band	2006
ENVISAT	8200	15	-156.0	Wide band	2004
AQUA	8160	11	-165.0	Wide band	2004
AQUA	8160	12	-153.5	Narrow band	2004
AURA	8160	48	-154.9		2006
TERRA	8215	11	-150.5	Narrow band	2004
TERRA	8215	9	-155.5	Wide band	2004

The following tables show comparisons between the RMS values measured by Leeheim and the RMS values provided by space agencies before launch.

TABLE 4

Comparison of RMS pfd levels for the DEMETER satellite

Elevation (°)	**Leeheim RMS pfd (dBW/m² in 30 kHz)**	**CNES RMS pfd (dBW/m² in 30 kHz)**	**Difference CNES/Leeheim (dB) RMS**
9.3	-161	**-160.3**	0.7
15.3	-159.4	**-158.1**	1.3
20.1	-156	**-156.5**	-0.5
24.5	-156.6	**-156**	0.6

The comparison of results for the DEMETER satellite shows a good correspondence between the CNES pre-launch and the Leeheim measurements.

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[1] The value of -139 dBW/m² is the maximum value measured in the first campaign, while the value reproduced in figure 13 for the same elevation angle (-137 dBW/m²) comes from the 2006 measurements campaign.

TABLE 5

Comparison of RMS pfd for the SPOT5 satellite at 8253 MHz

Elevation (°)	Leeheim RMS pfd (dBW/m² in 30 kHz)	CNES RMS pfd (dBW/m² in 30 kHz)	Difference CNES/Leeheim (dB)
6.1	-158.1	-159.5	-1.4
6.2	-157.5	-159.4	-1.9
19.6	-154.7	-156.7	-2.0
22.9	-155.5	-156.1	-0.6
48.6	-155.3	-157.5	-2.2
55,3	-157,3	-156	1,3

The comparison of results for the SPOT5 satellite at 8253 MHz shows a difference of up to 2.2 dB between the CNES pre-launch tests and the Leeheim measurements. The correspondence between the CNES pre-launch and the Leeheim measurements is not as good as it is for the DEMETER satellite since the values used to compute the RMS pfd value for the CNES pre-launch campaign are those obtained at the beginning of life of the satellite with little atmospheric attenuation. All the values obtained at Leeheim (except at 55.3° elevation angle) are all higher than the CNES pre-launch measurements by about 2 dB.

TABLE 6

Comparison of pfd levels (max and RMS) for the SPOT5 satellite at 8353 MHz

Elevation (°)	Leeheim RMS pfd (dBW/m² in 30 kHz)	CNES RMS pfd (dBW/m² in 30 kHz)	Difference CNES/Leeheim (dB)
12	-156.5	-157.7	-1.2
14	-156.2	-157.8	-1.6
31.1	-154.6	-155.3	-0.7
35.5	-157.7	-155	2.7
68.3	-161.3	-157.4	3.9

The comparison of results for the SPOT5 satellite at 8353 MHz shows a difference of -1.6 dB to 3.9 dB (in that specific case, the values obtained at Leeheim are lower of 3.9 dB than the CNES pre-launch measurements) between the CNES pre-launch tests and the Leeheim measurements. The values used to compute the RMS pfd for the CNES pre-launch are those obtained at the beginning of life of the satellite with little atmospheric attenuation.

According to RR Article 21, the pfd limits for angles of arrival (δ) above the horizontal plane in dBW/m^2/4 kHz are the following ones.

If $0° < \delta < 5°$, pfd_limit = - 150 dBW/m^2/4 kHz

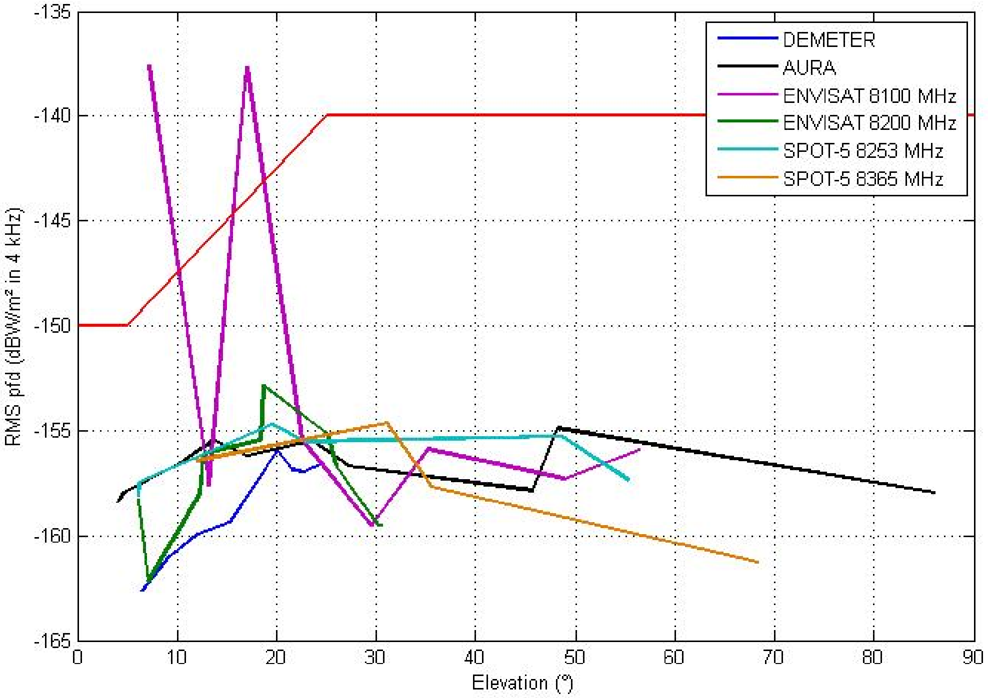
If $5° < \delta < 25°$, pfd_limit = - 150 + 0.5(δ-5) dBW/m^2/4 kHz

If $25° < \delta < 90°$, pfd_limit = - 140 dBW/m^2/4 kHz

This pfd mask is reproduced in red in Figure 13. Only the pfd level of EESS satellites measured during the 2006 campaign are reproduced in this figure.

FIGURE 13

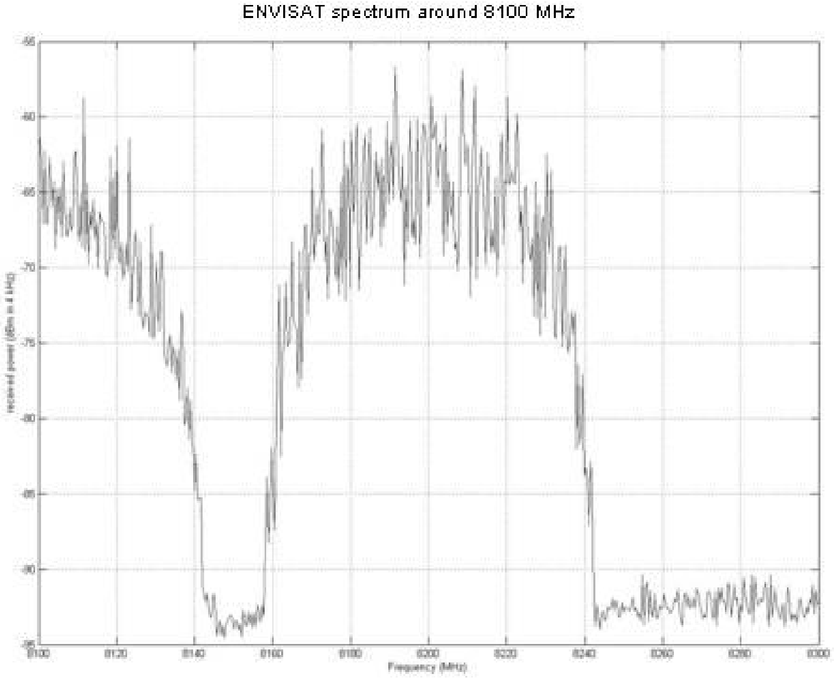
RMS pfd vs elevation of EESS satellites measured in 2006 in the band 8025-8400 MHz



It appears that according to Figure 13, all the satellites respect these pfd limits, with the exception of ENVISAT when considering the frequency 8100 MHz, where high level spikes are detected from time to time. These spikes correspond to the transmission of Advanced Synthetic Aperture Radar (ASAR) data in low resolution mode on the 8.1 GHz channel. Normally, the ASAR high resolution data are transmitted on such channel by using a standard scrambling code as shown in Figure 14.

FIGURE 14

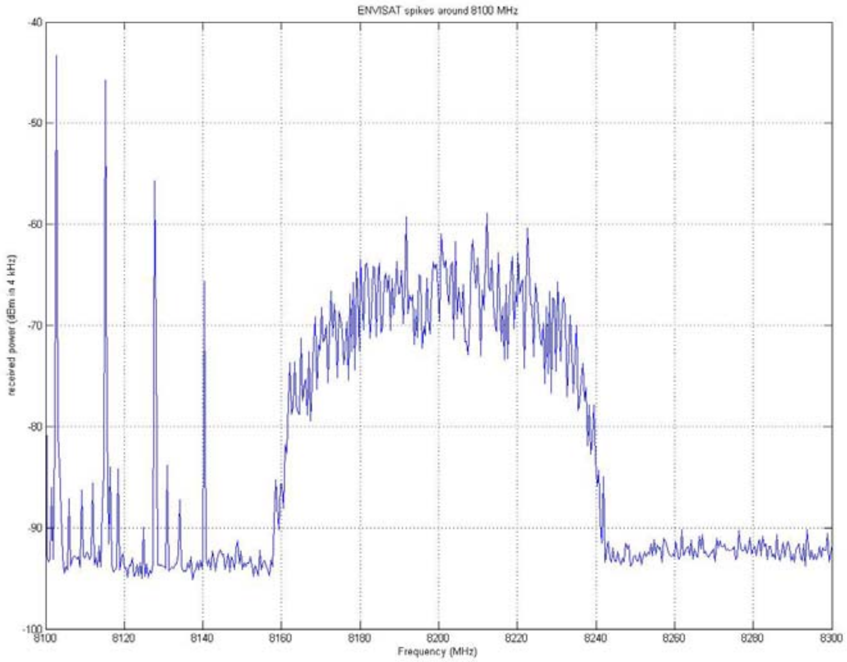
ENVISAT transmission in the band 8025-8400 MHz



When the high resolution data are not available (in low resolution mode), the 8.1 GHz channel modulator is fed with an 8-bit PN code while the low resolution data after being scrambled are transmitted on the 8.2 GHz channel. When the PN code used is short, the generated spectrum is not a continuous QPSK/BPSK spectrum but a series of discrete lines with an envelope modelling the QPSK/BPSK shape. The resulting signal contains therefore lines spaced at 12.5 MHz as shown in Figure 15.

FIGURE 15

Spikes on ENVISAT around 8100 MHz



The spectral lines levels are higher than the theoretical QPSK spectrum resulting in higher than expected pfd levels.

A possible workaround has been proposed to reduce the high pfd levels observed. It consists on inhibiting the transmission of the ASAR data on the channel centred on 8100 MHz when in low resolution mode. In this mode, the ASAR data will be sent only to the channel centred on 8200 MHz via the standard randomizer. This workaround has been verified and is being implemented as the nominal operations procedure.

A further reduction of the pfd limits down to a value of -147 dBW/m² in 4 kHz corresponding to -123 dBW/m²/MHz would not impose further constraints on the satellites measured.

4.2 UNWANTED EMISSIONS IN THE DEEP SPACE BAND

The limit of sensitivity of the monitoring set-up for a recorded bandwidth of 100 MHz is in the order of –178 dBW/m²/4 kHz which is well above the interference criteria of deep space of -219 dBW/m²/4 kHz (derived from the value of -255 dBW/m²/Hz given in Table 5 of recommendation ITU-R SA. 1157-1). When applying the monitoring method “measurements below the noise floor” (see recommendation ITU-R SM.1681) the noise level may be decreased by about 12 to 15 dB. Therefore, the best reachable sensitivity is -193 dBW/m²/4 kHz.

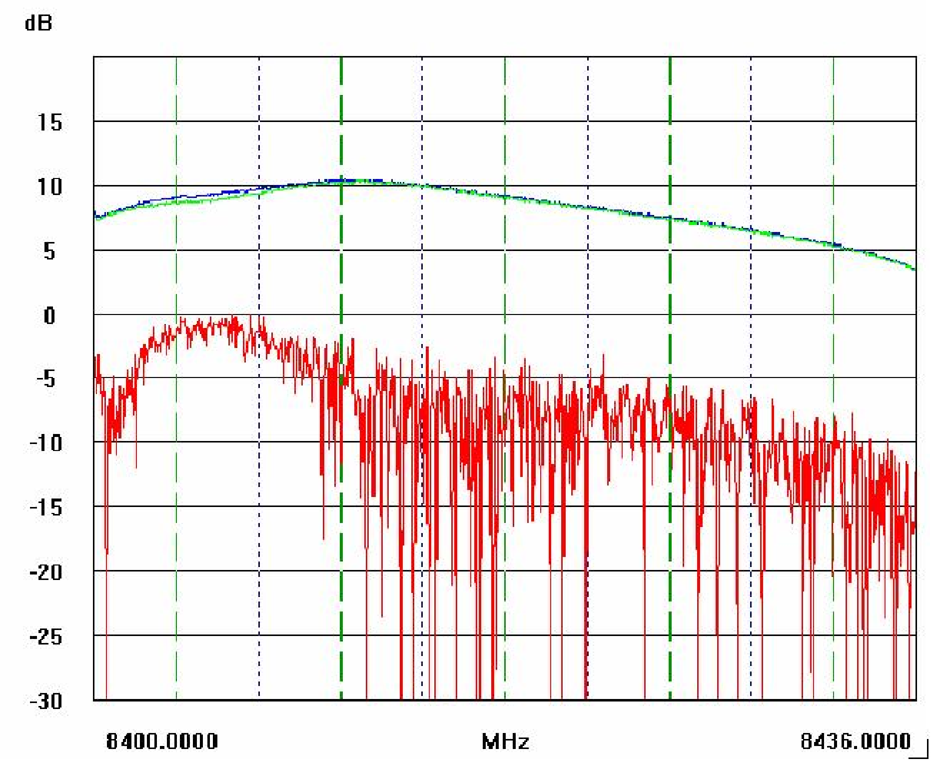
Using this technique, unwanted emissions have been detected only for SPOT-5, at the edge of the SRS band. Figure 16 shows:

- in green, the signal measured when the antenna points at clear sky,
- in blue, the signal measured when the antenna points towards the satellite,
- in red, the difference between both, integrated over several thousand samples.

The lobe appearing on the left side of the figure comes from unwanted emissions from SPOT-5. The level is estimated to be around -188 dBW/m² in 4 kHz, 30 dB above the protection criteria of the deep-space stations.

FIGURE 16

Unwanted emissions of SPOT-5



As stated in Recommendation ITU-R SA.1157-1, this protection criteria is the maximum allowable interference at the receiver input of a deep-space earth-station receiver. In Europe, there are very few deep space earth stations. Therefore, taking into account the geographic distribution of deep space earth sations and X band EESS earth stations, it is unlikely that the SPOT5 unwanted emissions will cause interference to the closest deep space earth station.

5 CONCLUSIONS

This report has shown that, due to the increase use of the band 8025-8400 MHz by EESS satellites to download data obtained by their sensors to ground stations, there is a risk for interference in the future between those satellites within the EESS band. In order to reduce this risk, the following mitigation techniques should be considered :

- EESS satellites operating in a non-broadcasting mode radiate only when transmitting data to one or more Earth stations;
- Phasing of the orbital parameters for sun-synchronous satellites with existing and planned satellites be considered;
- Whenever practicable, low side lobe, high gain satellite antennas be used and if high gain satellite antennas are not practicable, isoflux antennas be considered instead of omnidirectional antennas;
- Broadcast modes be avoided whenever practicable or, if unavoidable, consider the use of a portion of the lower half of the band 8 025-8 400 MHz;
- Bandwidth efficient modulation and coding techniques be used, to reduce the potential for adjacent channel interference by simultaneously limiting power flux-density, out-of-band emissions and occupied bandwidth;
- Careful consideration be given to the use of higher order advanced modulation techniques in view of potential incompatibility with a homogeneous power flux-density environment;
- To reduce the possibility of intersystem interference, due consideration also be given to other interference mitigation techniques such as polarization discrimination, geographical separation of earth stations and large earth station antennas with off-axis gains that do not exceed 32-25 log θ, dBi for $1° \leq \theta \leq 48°$;
- EESS spacecraft using non-directional antennas be designed to limit their spectral pfd on the Earth’s surface to less than -123 dB(W/m^2/MHz) - corresponding to -147 dBW/m^2 in 4 kHz - at their sub-satellite points;
- In order to minimize the need for operational coordination, EESS satellites utilize, to the maximum extent possible, appropriate techniques to prevent unwanted emissions exceeding the ITU-R space research service (deep-space) protection criterion in the band 8 400-8 450 MHz, including on-board filtering, large geographical separation between EESS and space research service (deep-space) earth stations, low-sideband modulations, and one or more of the applicable techniques given above;
- EESS satellites use the 25.5-27 GHz band if the techniques given above cannot adequately mitigate both in-band and adjacent-band interference, once suitable ground infrastructures are available.