International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R SA.2067

(11/2005)

Use of the 13.75 to 14.0 GHz band by the space research service and the fixed-satellite service

SA Series

Space applications and meteorology

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Electronic Publication
Geneva, 2010

REPORT ITU-R SA.2067

Use of the 13.75 to 14.0 GHz band by the space research service and the fixed-satellite service

(2005)

CONTENTS

1 Introduction

This Report explains the use of the 13.75-14 GHz band by the space research service (SRS) data relay satellite systems, reviews the permissible levels of interference for SRS data relay satellite systems from Earth-to-space links operating in the fixed satellite service (FSS), and reviews the interference to FSS satellites in geostationary orbit from SRS data relay satellite systems.

2 Use of the 13.75-14.0 GHz band by data relay satellite systems of the space research service

The purpose of this section is to address the use by the space research service of frequencies near 14 GHz and to describe the bandwidth requirements.

2.1 Data relay satellite networks

2.1.1 Use of the 13.75-14 GHz band

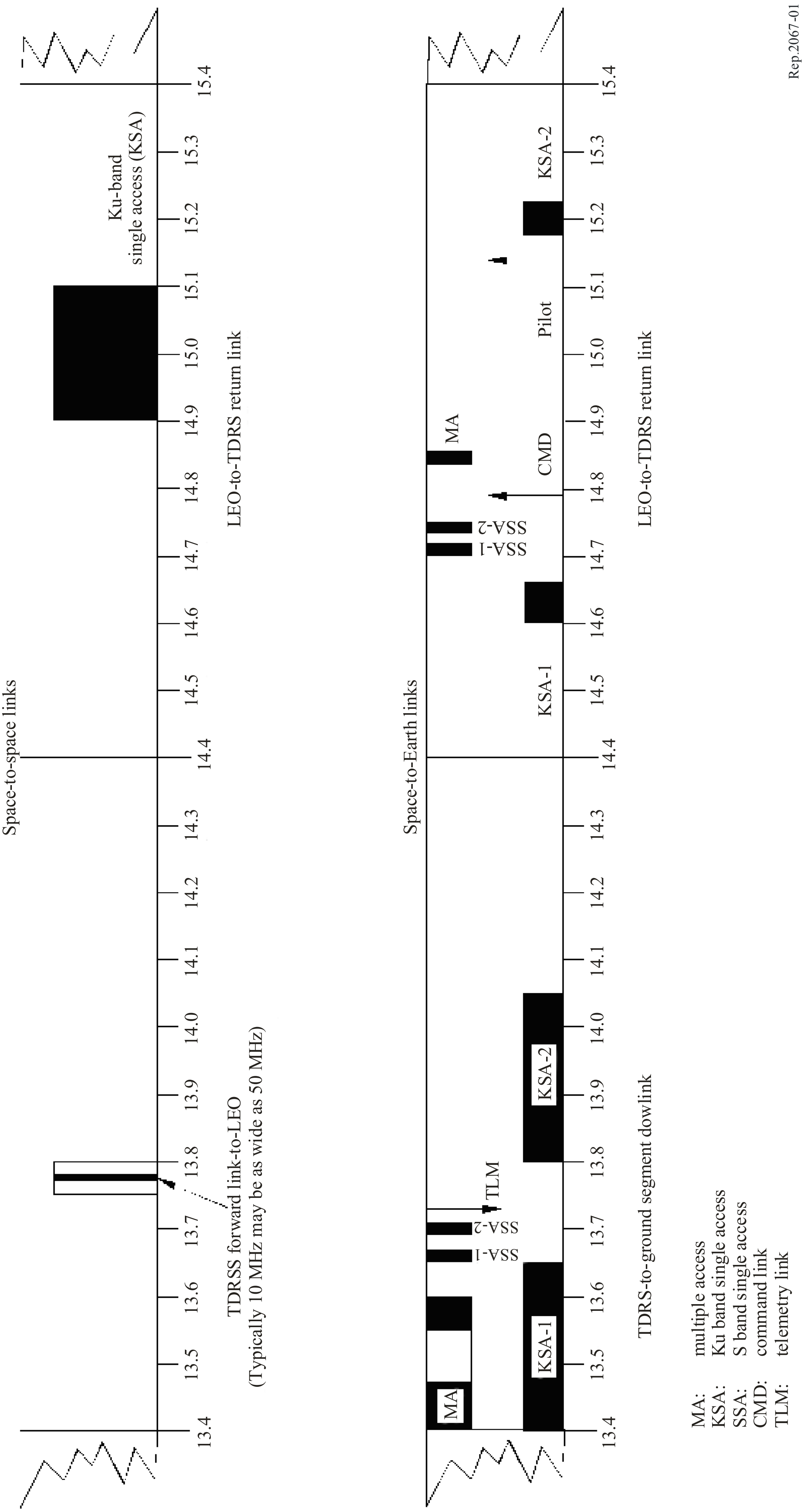
In 1983, the United States of America launched the first satellite in its global tracking and data relay satellite system (TDRSS) data relay satellite network. TDRSS relays commands, scientific data and spacecraft health and safety information for a number of NASA low-Earth orbit (LEO) satellites such as the International Space Station, space shuttle, Landsat as well as a number of non-NASA flight missions, including international or joint venture missions.

The TDRSS network uses frequencies around 2 GHz, 13/15 GHz and 23/26 GHz to operate and to receive data from low-orbiting satellites. The 13/15 GHz bands are also used for feeder links for the geostationary TDRSS network.

Operational tracking and data relay satellites (TDRS) are located at the orbital positions: 41°, 46°, 171° and 174° W longitude on the geostationary orbit. The forward link from the TDRS to a LEO spacecraft, relaying critical command, control and ranging data, is centred at 13.775 GHz in the lower portion of the band 13.75-14 GHz. Furthermore, the 13.75-14 GHz band is one segment of several allocations to the space research service between 13.4 and 15.35 GHz that are extensively used for forward and return links to low-Earth orbiting satellites and for feeder links to connect TDRS satellites to their earth stations. This extensive use is evident in the frequency plan for the TDRSS data relay satellite network shown in Fig. 1, particularly between 13.4-14.05 GHz and 14.6-15.225 GHz. This use is the culmination of substantial investments that have been made in system trade-off studies, the development and qualification of space hardware, and the development and implementation of satellite systems and earth stations comprising the TDRSS data relay network.

FIGURE 1

13.4-15.4 GHz segment of the frequency plan for the United States of America TD RSS data relay satellite network



2.1.2 Bandwidth requirements

The bandwidth requirements are pictured in Fig. 1. The top portion of this figure shows the links between the TDRS and the LEO satellites in the 13.75-14.0 GHz band. The forward service links (two independent links per TDRS spacecraft) from the TDRS to low-Earth orbit satellites are used for command, control and ranging and for transmission of data and video. The forward link design is capable of supporting a 25 MSymbol/s transmission rate at a centre frequency of 13.775 GHz.

The bandwidth is typically 6 MHz in the case of command and control data, where in most cases the low-rate information data is spread with a 3.08 Mchip/s pseudo-random noise (PN) code. However, in the case of the International Space Station, a bandwidth of 10 MHz is the minimum required to provide for the high-speed TCP/IP data protocols needed for payload telescience, payload management and additional Earth-to-space voice transmission capability effected via the TDRSS network. A 50 MHz bandwidth is required for sending higher rate data to a spacecraft or high resolution digital video information to the space shuttle or space station for tele-science and tele-medicine. Reliable transmissions of commands in the 10 MHz around 13.775 MHz are the most critical. The bottom portion of Fig. 1 shows a feeder link used to transmit wideband signals received by the TDRS from LEO satellites to the TDRSS data relay satellite network earth station. The signals consist primarily of scientific data and spacecraft telemetry. The bandwidth of this link may be up to 225 MHz centred around 13.9 GHz.

2.2 Summary and conclusions

This section has addressed the use and bandwidth requirements of the TDRSS network within the 13.75-14 GHz band. Based on studies within ITU-R, the following are concluded for data relay satellite networks:

– a comprehensive frequency plan delineates the use of segments of the spectrum extending from 13.4 GHz to 15.225 GHz for service links to low-orbiting satellites and for feeder links to centrally located earth stations;

– the primary command and control link from the tracking and data relay satellite (TDRS) to the International Space Station is centred at 13.775 GHz with a bandwidth of 10 MHz;

– an important forward link to low-orbiting satellites operates with a centre frequency of 13.775 GHz and a bandwidth that can range from 6 MHz to 50 MHz depending on the application;

3 Permissible levels of interference in data relay satellite systems that use the 13.75-14 GHz band

This section presents criteria for protection of data relay satellite systems operating in the 13.75-14 GHz band from Earth-to-space links operating in the FSS. The criteria consist of a permissible level of interference signal power in a specified reference bandwidth at the output of the receiving antenna that is not to be exceeded for more than a specified percentage of time and locations. The largest possible reference bandwidths are specified in order to enable the greatest possible sharing benefit from averaging interfering signal power over bandwidth.

3.1 Protection criteria for data relay satellite systems

Recommendation ITU-R SA.1155 gives the permissible level of degradation to a data relay satellite link as a 0.4 dB reduction in link power margin, which occurs with an I/N of –10 dB. From this, an aggregate protection criteria of –178 dB(W/kHz) measured at the input to the victim receiver to be exceeded no more than 0.1% of the time is derived. This is equivalent to –138 dB(W/10 MHz). The I/N criterion of –10 dB is applicable over a bandwidth of 10 MHz centred at 13.775 GHz, although operations can extend over a bandwidth of up to 50 MHz centred at the same frequency. In order to achieve the desired link availabilities, the interference threshold should not be exceeded for more than 0.1% of the time as a result of the emissions of FSS earth stations in the Earth-to-space direction. The 0.1% of the time is based on the orbital period of the low-orbiting satellites as given in Recommendation ITU-R SA.1155.

3.2 Characterization of interference to the international space station (ISS) from the emissions of a global deployment of FSS GSO earth stations

This section presents the results of an analysis to determine the probability of interference to the ISS for the worst-case orbit for a range of FSS earth station characteristics.

3.2.1 FSS earth station characteristics

Table 1 is a summary of the characteristics of the FSS earth station populations used in the simulations described within this section. The FSS earth station antenna pattern given in Recommendation ITU-R S.465-5 was used for the analysis presented in this section. A limited set of simulations were performed comparing results derived from the use of Recommendation ITU-R S.465-5 and Recommendation ITU-R S.1428 and it was found that the difference was less than 1 dB.

TABLE 1

Characteristics of FSS earth station populations

Earth station signal info data rate	Earth station transmit data rate	Signal bandwidth occupancy at satellite transponder	Antenna diameter	e.i.r.p. (includes 1 dB transmit loss)	Average e.i.r.p. density (dB(W/Hz))
16 kbit/s	32 kbit/s	33.6 kHz	0.5 m (34.6 dBi)	33.6 dBW	−11.7
64 kbit/s	128 kbit/s	134.4 kHz	1.0 m (41.0 dBi)	40 dBW	−11.3
1 Mbit/s	2 Mbit/s	2.1 MHz	1.8 m (45.7 dBi)	50.7 dBW	−12.5
2 Mbit/s	2 Mbit/s	2.1 MHz	3.0 m (50.2 dBi)	55.2 dBW	−8.0
34 Mbit/s	34 Mbit/s	35.7 MHz	4.5 m (53.7 dBi)	69.7 dBW (in 34 MHz)	−5.8

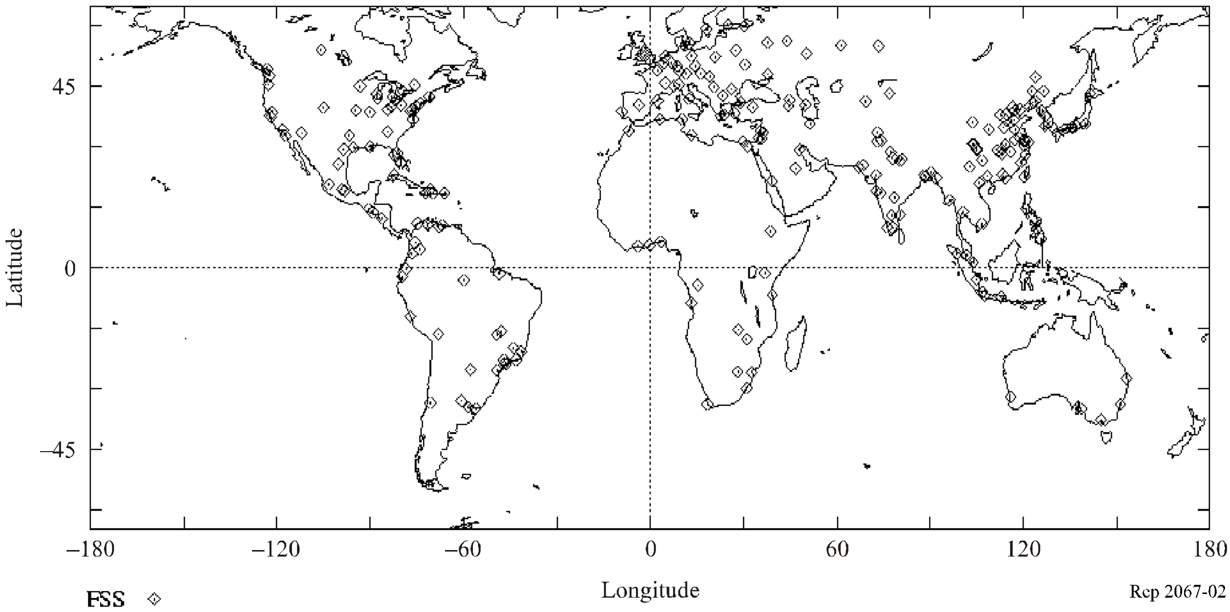
3.2.2 GSO satellite locations and distributions

A 120 FSS GSO satellite constellation, equally placed 3° apart in the geostationary orbit, was used in the analysis.

The 4.5 m FSS Gateway earth station distribution is based on the locations of Urban Population Center (UPC) around the world. The UPCs are obtained from the "*Urban Agglomerations, 1950-2015, United Nation Population Division, NY, USA*". All the selected UPCs are projected to have a population of one million or more by the year 2015. A total of 326 UPCs were identified. Each satellite will be capable of supporting two links in the same channel using orthogonal polarizations. A total of 240 cities were selected from the urban agglomerations. The cities were selected based on the satellite capacity and that the elevation angle to the satellite was greater than 20°. The resultant distribution of earth stations is shown in Fig. 2.

FIGURE 2

Worldwide distribution of 4.5 m ground stations



The FSS earth stations were randomly distributed worldwide based on the population in each continent. The FSS earth stations were randomly allocated to satellites in the geosynchronous arc for which the elevation angle exceeded 20°. For each FSS earth station, a satellite with free channels was randomly selected from this group of satellites. The azimuth and elevation angle for the FSS earth station antenna was computed for the selected satellite. In densely populated areas such as Europe the total number of ground stations exceeds the total number of satellites in the visible arc. Some of the ground stations were not assigned a satellite and were removed from the analysis. Similarly, satellites above the oceans did not have sufficient ground stations to fill them to capacity. Consequently, those satellites were not fully utilized. Table 2 shows the maximum channel capacity and utilizations of the GSO satellites supporting the different types of FSS earth stations.

TABLE 2

FSS earth station allocations for the simulation

Antenna diameter (m)	Signal BW occupancy at satellite transponder	FSS earth station carriers in 10 MHz bandwidth	FSS earth station carriers in 10 MHz per satellite	Maximum carriers (FSS earth station) for constellation	FSS earth station assignments	Utilization (%)
0.5	33.6 kHz	300	600	72 000	60 251	83.6
1.0	134.4 kHz	75	150	18 000	15 100	83.8
1.8	2.1 MHz	5	10	1 200	1 000	83.3
3.0	2.1 MHz	5	10	1 200	1 000	83.3
4.5	35.7 MHz	1	2	240	240	100.0

3.2.3 Statistics of the interference to the ISS

Simulations, using the orbital geometry of the ISS, were set up to quantify the interference from the FSS earth station emissions. The ISS has an orbit inclination of 51.6° and an altitude of 390 km. In order to make sure that the results are representative, the ground tracks of the ISS must cover the Earth evenly so that the signal from each earth station will be included in the calculations. In all, four separate simulations with 45 orbits each, were performed and the results were combined to generate the final earth station interference characteristics. The ascending node of the ISS trajectory in each simulation was shifted 2° from the previous one to ensure that it covered different parts of the Earth. The method is equivalent to a single simulation of about 20 days.

The ISS uses a tracking antenna with a 1.8 m diameter and a peak gain of 45.2 dBi. The antenna pattern, shown in Fig. 3, is based on actual test data. There is a circuit loss of 2.0 dB between the antenna and the receiver. This 1.8 m antenna is used to track and communicate with the data relay satellites (DRS) in geosynchronous orbit (GSO).

The level of interference is determined as a function of time. Depending on the ground track of the ISS, the level of interference during any orbit will vary and the one with the greatest interference is marked as the worst case. Figure 4 shows the probability of exceedance vs. the interference level for the worst-case orbit from the simulations. Figure 5 shows the probability of interference vs. earth station e.i.r.p. density at the equivalent Recommendation ITU-R SA.1155 protection threshold of –141 dBW/10 MHz.

FIGURE 3

ISS antenna pattern

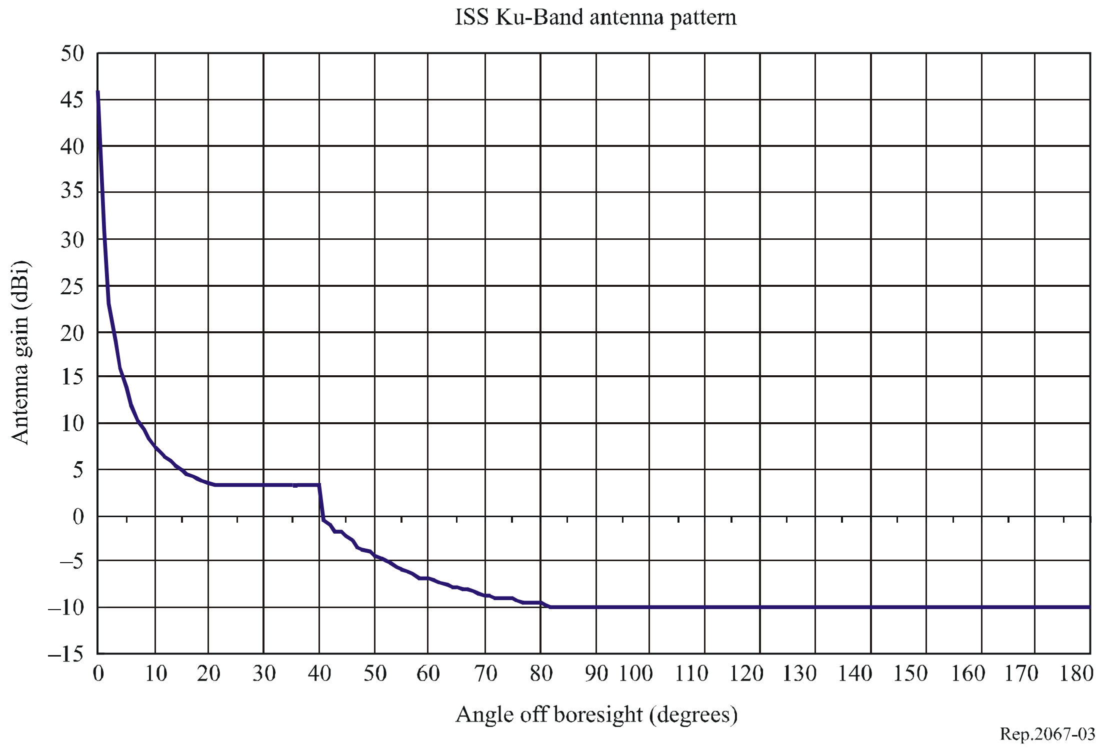


FIGURE 4

Worst-case single orbit interference from the FSS earth stations

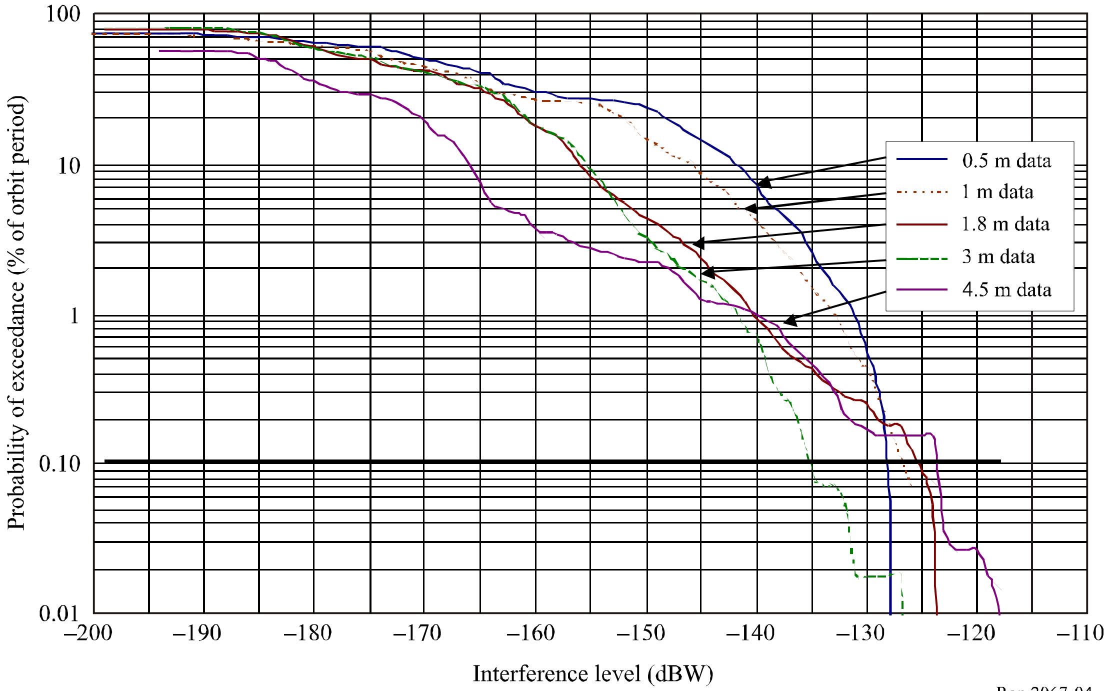


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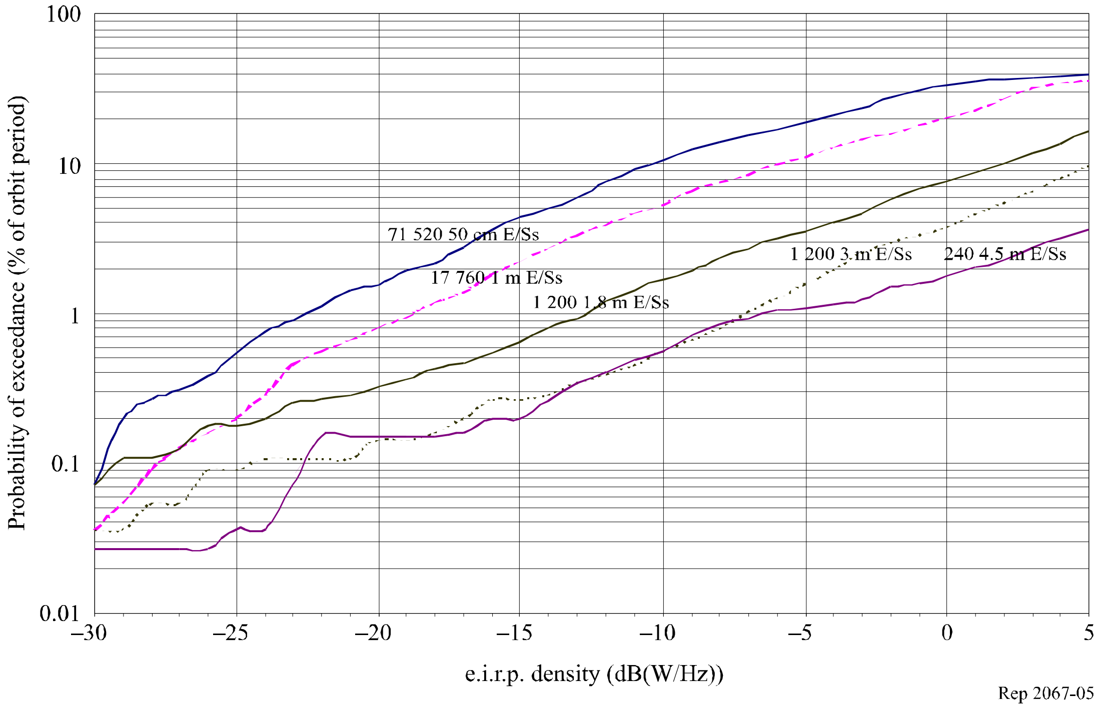
FIGURE 5

Probability that the interference exceeds FS –141 dB(W/10 MHz) vs. e.i.r.p. density of FSS earth stations (worst-case orbit)



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3.2.4 Discussion of results

Table 3 summarizes the probability of exceedance for the various FSS GSO earth station antenna sizes, as derived from the Recommendation ITU-R SA.1155 protection criteria of –178 dB(W/kHz) at the receiver input. The corresponding interference density at the ISS antenna with the 2.0 dB circuit loss is –176 dB(W/kHz), which is equivalent to an interference power of −138 dBW within the 10 MHz bandwidth. Allocating equal interference to GSO and to non-GSO FSS, the acceptable interference contribution from the GSO FSS is 3 dB lower than the aggregate interference at the antenna input. The maximum acceptable interference from the GSO FSS per Recommendation ITU-R SA.1155 is –141 dBW in 10 MHz for no more than 0.1% of the time. As the Table shows, the criteria of Recommendation ITU-R SA.1155 are not satisfied, even when using a 4.5 m diameter FSS earth station transmitting antenna. Accommodation of FSS earth stations using smaller diameter antennas will require some adjustment to the sharing criteria and to the emission characteristics of FSS earth stations.

TABLE 3

Interference results from the worst-case orbits

Aggregate interference power density at receiver input (dB(W/kHz))	Equivalent maximum GSO FSS interference power at ISS antenna (dBW/10 MHz)	Probability of exceedance for FSS ground stations (%)				
		0.5 m	1.0 m	1.8 m	3.0 m	4.5 m
−178 (SA.1155)	−141	9.49	4.38	0.67	1.27	0.16
−176	−140	8.82	3.64	0.59	1.05	0.15
−175	−139	8.41	2.90	0.53	0.91	0.14
−170	−138	8.13	2.22	0.47	0.80	0.13
−169	−136	5.74	1.50	0.34	0.25	0.10
−168	−135	4.26	1.30	0.34	0.56	0.09
−167	−130	1.03	0.47	0.10	0.29	*
−166	−129	0.61	0.30	0.08	0.26	*
−165	−128	0.27	0.14	0.06	0.22	*
−164	−127	0.18	0.03	0.05	0.14	*
−163	−126	0.08	*	*	0.12	*
−162	−125	*	*	*	0.09	*

* Negligible percentage.

3.3 Derivation of FSS earth station e.i.r.p. density limits for the protection of international space station operations

This section differs from § 3.2 in that § 3.2 is based on Recommendation ITU-R SA.1155 protection criteria whereas this section provides an analysis based on a relaxation of the Recommendation ITU-R SA.1155 protection criteria arriving at potential sharing conditions. The analysis presented in this section uses the average of many orbits as opposed to the single orbit criteria used in Recommendation ITU-R SA.1155.

This section also provides an analysis of the ISS forward link system parameters and derives the interference threshold level that could be tolerated using the ISS *I*/*N* criterion of –6 dB. This interference threshold level is then used in the earth station deployments scenarios to analyse the impact to ISS operations in this band. The 99.90% availability criterion (average) of the ISS link is used to determine the e.i.r.p. transmit levels that could be tolerated from each antenna diameter included in this analysis. FSS earth stations with antenna sizes ranging from 75 cm to 4.5 m were examined in homogeneous deployments. Earth station parameters used in the simulations are shown in Table 5. Recommendation ITU-R S.1428 was used for the antenna radiation pattern. The allowable e.i.r.p. transmit levels for each antenna diameter form an e.i.r.p. mask for permissible earth station operations in this band which do not cause unacceptable degradation of the performance of the forward link.

The FSS earth station e.i.r.p. spectral densities are derived from scenarios where all earth stations were transmitting. The spectral density of the emissions are assumed to be uniform over the bandwidth associated with each type of FSS earth station and are specified in dB(W/Hz). As a result, these e.i.r.p. spectral densities are assumed to apply over a bandwidth of 10 MHz as well as other bandwidths.

3.3.1 International space station forward link system parameters

The ISS relies on the DRS forward and return links for transmissions of critical ISS data and telemetry to and from the ground control center. The forward link, centred at 13.775 GHz, enables transmission of critical real time command and control data from the Ground Mission Control Center to manage the required communications functions in support of mission and science objectives of the ISS. The forward link data includes station video conferencing, control centre-to-ISS voice communications, and high-speed TCP/IP data protocols for payload tele-science and payload management. In accordance with the DRS specified signal design options, a minimum RF bandwidth of 10 MHz is necessary to accommodate the data rate of 9 Mbit/s with uncoded QPSK modulation and necessary guard bandwidth. The use of coding with the QPSK modulation would require more bandwidth than the 10 MHz considered in this analysis. Table 4 shows the link budget with a data threshold, in terms of the received power to noise power spectral density ratio (C/N_0) and total received power (C), of 80.5 dB-Hz and –121.7 dBW respectively.

TABLE 4

Link budget for the forward link

	Parameter	Value	Source
1	TDRS e.i.r.p. (dBW)	46.5	TDRSS KSAF normal power mode
2	Space loss (dB)	−208.0	d = 43 657.0 km f = 13.775 GHz
3	Polarization loss (dB)	−0.1	TDRS antenna axial ratio: 1.0 dB (LHCP) ISS antenna axial ratio: 2.0 dB (LHCP)
4	Total pointing loss (dB)	−0.5	Estimate
5	Antenna gain (dB)	45.2	Estimate
6	Receive circuit loss (dB)	−2.0	Estimate
7	Total received power (C) (dBW)	−118.9	1 + 2 + 3 + 4 + 5 + 6
8	System noise temperature (dBK)	26.4	Antenna temperature = 160.0 K Receiver noise figure = 2.5 dB

TABLE 4 (*end*)

	Parameter	Value	Source
9	Boltzmann's constant (dBW/K/Hz)	−228.6	1.38 × 10^{-23} W/K/Hz
10	Noise spectral density (N_0) (dBW/Hz)	–202.2	8 + 9
11	G/T (dB/K)	16.8	5 + 6 − 8
12	Total received power/noise spectral density (C_c/N_0) (dBHz)	83.3	7 − 10 or 1 + 2 + 3 + 11 − 9
13	Bit rate bandwidth (dBHz)	69.5	9 Mbit/s
14	SNR in bit rate bandwidth (E_b/N_0) (dB)	13.8	12-13
15	Theoretical required E_b/N_0 (dB)	9.6	Uncoded QPSK, BER × 10^{-5}
16	Implementation loss (dB)	−1.4	Estimate
17	Required E_b/N_0 (dB)	11.0	15-16
18	Required C/N_0 (dBHz)	80.5	17 + 13
19	Required C at the receiver input (dBW)	−121.7	18 + 10
20	Circuit margin (dB)	2.8	14-17 or 12-18

The interference from the FSS earth station uplink emissions is considered as an in-band broadband noise to the receiver. As a result, the ISS receiver thermal noise floor will be increased which then degrades the link performance. The degradation of the ISS receiver link margin is 1.8 dB when using an I/N of –6 dB is 1 dB.

Based on the expected performance of the ISS forward link and the required margin to maintain a viable link in its operating environment, the maximum allowable aggregate FSS (GSO + non-GSO) interference power at the ISS antenna output is determined. The value is −136.2 dBW/10 MHz. Assuming equal interference contribution from GSO and non-GSO earth stations then the GSO portion of the interference threshold is −139.2 dB/10 MHz. The ISS forward link must maintain a margin of at least 1.8 dB to mitigate possible degradations (other than the interference contribution from the FSS) from the environment. Environmental degradations include uncertainties in the ephemeris resulting in additional pointing loss of the ISS receiving antenna and multipath effects due to the complex structures of the ISS. The allowance of total interference power up to –136.2 dBW/10 MHz translates to an equivalent I/N of –6 dB (1 dB link degradation) and a relaxation of the Recommendation ITU-R SA.1155 protection criterion of $I/N = -10$ dB by 4 dB.

3.3.2 Earth station deployment methodology

In the interference simulations, the following methodology was used to distribute earth stations over the Earth's surface. In an attempt to model a realistic scenario, earth stations are randomly distributed among cities taken from the U.N. city database with a normally distributed weighting factor based on city population. Within a given city, earth stations are randomly distributed within the city's equivalent circular area based on population.

The following is an outline of the steps used in this simulation:

Step 1: Determine the maximum e.i.r.p. spectral density in the transmission bandwidth (B) of the FSS earth station based on specified data rate, modulation, and coding scheme (e.g. 1 m earth station transmitting 384 kbit/s with QPSK and rate ½ convolutional coding has a bandwidth of 768 kHz.)

Step 2: Assuming each FSS satellite has two co-frequency cross-polarized transponders that encompass the ISS (victim) receiver bandwidth, determine the number of interfering earth stations per FSS satellite (e.g. for 1 m earth station with transmission bandwidth of 768 kHz and ISS bandwidth of 10 MHz, number of interfering earth stations per transponder is 10 MHz/768 kHz ≅ 13 earth stations × 2 transponders per satellite = 26 interfering earth stations per FSS satellite).

Step 3: Load worldwide city database consisting of 2 763 cities with population and latitude/longitude data.

Step 4: Specify a population threshold and extract those cities from the database whose population exceed this threshold (e.g. 545 cities have population ≥ 500 000 people).

Step 5: Compute the equivalent area urban radii of the cities in Step 4 using the empirical relationship $R_p = \alpha P^{\beta}$ (km) where P is the city population and α and β are constants (see Recommendation ITU-R F.1509). For the United States of America, $\alpha = 0.035$ and $\beta = 0.44$ were used. For other areas of the world, $\alpha = 0.0155$ and $\beta = 0.44$ were used.

Step 6: Specify number of FSS GSO satellites and their orbital spacing and set their orbital locations (e.g. in this analysis 120 FSS satellites were assumed at 3° spacing).

Step 7: For *each* FSS GSO satellite perform the following steps:

7a: Determine which cities in Step 4 are visible from the GSO orbital location based on a specified minimum elevation angle (e.g. 20° used in this analysis).

7b: Take this subset of visible cities and sort them in descending order of population.

7c: Let m be the number of earth stations computed in Step 2 and let N be the number of cities (sorted in descending order of population) in Step 7b. Randomly distribute the m earth stations among the N cities according to a normal distribution as follows:

i) Generate a large number K (e.g. K = 10 000) of normally distributed random samples with mean = 1 and standard deviation $\sigma = (N - 1)/3$. This will cause about 99.75% of the samples to be between $1 - 3\sigma = 2 - N$ and $1 + 3\sigma = N$.

ii) Extract those samples (~ $K/2$) that are ≥ 1 and select m samples out of this subset.

iii) Round the m samples from Step 7c-ii) downward to the nearest integer to get m integers with values between 1 and N.

iv) Assign the m earth stations to the N cities according to the integer values in Step 7c-iii) where the integer values correspond to the city indices of the N visible cities. This results in the more populated cities having on average more earth stations than less populated cities.

Step 8: After performing Step 7 for each FSS GSO satellite, determine the number of earth stations in each of the cities found in Step 4.

Step 9: For each city in Step 8, randomly distribute the earth stations located in that city within a circular area according to its equivalent radius as found in Step 5.

As a result of the assignment methodology, the earth stations are randomly assigned to the satellites that are visible. Figures 6 and 7 are illustrations of the earth station distribution resulting from this method for the case of the 75 cm earth stations. In this case, earth stations are clustered around cities whose population exceeds 100 000.

For a given earth station population, the methodology described above yields essentially the same results for multiple simulation runs (i.e. repeating Steps 1 to 9). This was verified by performing multiple simulations for the 1 m earth station scenario. The same interference results were obtained in each of these runs primarily because earth stations are always clustered about population centers and thus the interference geometry as viewed from the ISS orbit stays essentially constant.

3.3.3 Analysis results

Based on the –139 dBW/10 MHz ISS interference threshold, Fig. 9 shows the cumulative interference statistics as a function of earth station e.i.r.p. density resulting from interference simulations of the various FSS scenarios. Probabilities shown here are based on the total simulation period of 200 ISS orbits or approximately 13 days. (The 1 m, 1.8 m and 3 m cases were also run for 1 000 orbits or 64 days.) Note that e.i.r.p. density is the independent variable in this plot. For example, if the desired ISS availability is 99.90% (i.e. the aggregate interference should not exceed −139 dBW/10 MHz more than 0.1% of the time), the e.i.r.p. density of the 1 m earth stations should not exceed about –19 dB(W/Hz). Likewise, the e.i.r.p. density of 2.4 m earth stations should not exceed –9 dB(W/Hz). Changing the interference threshold shifts the curves either left or right in a linear fashion. For example, if the interference threshold were –143 dBW/10 MHz instead of –139 dBW/10 MHz, the 1 m curve would cross the 0.1% probability level at −19 − 4 = −23 dB(W/Hz).

Figure 8 shows the plot of the average probability (over many orbits) of exceedance vs. the interference to the international space station forward link. The earth station e.i.r.p. densities used in Fig. 8 correspond to those shown in Table 5. The e.i.r.p. densities of each earth station were selected so that the probability of interference threshold exceedance is 0.1% (−139 dBW/10 MHz). Also shown is the result of 240 4.5 m antennas deployed with an e.i.r.p. density of 3.2 dB(W/Hz) (limit set by No. 5.503 of the Radio Regulations prior to WRC-03).

Figure 10 is also based on a –139 dBW/10 MHz interference threshold, but shows the percentage in terms of the ISS orbit period (T_P = 92.7 min) for the worst case orbit instead of the average time over many orbits. Note that this represents a much more stringent basis for establishing FSS e.i.r.p. density limits. Referring to the earlier example, an e.i.r.p. density limit of −19 dB(W/Hz) on the 1 m earth stations yields an average probability of exceedance of 0.1%, but represents a 1% exceedance in terms of the worst case ISS orbit. The 2.4 m earth stations with an e.i.r.p. density of −9 dB(W/Hz) will exceed the −139 dBW/10 MHz interference threshold about 0.3% of the time for the worst orbit.

The simulations performed for this study considered six different FSS antenna sizes. In order to estimate appropriate e.i.r.p. density limits for other antenna sizes, an e.i.r.p. density mask based on a linear approximation of the above data was developed. Referring again to Table 5 or Fig. 10, the e.i.r.p. density values for the −139 dBW/10 MHz threshold and the 0.1% probability level for the selected earth station sizes are −21.0 (75 cm), −19.2 (1 m), −12.9 (1.8 m), −9.2 (2.4 m), −4.6 (3 m) and −1.4 (4.5 m) dB(W/Hz). A plot of these e.i.r.p. densities vs. antenna size is shown in Fig. 11. Using this plot, a linearized e.i.r.p. density mask may be determined.

TABLE 5

13.75-14 GHz earth station simulation parameters

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Antenna diameter (m)	0.75	1.0	1.8	2.4	3.0	4.5
Antenna gain (dBi) (13.775 GHz)	38.5	41	46.1	48.6	50.5	54
Source data rate	64 kbit/s	384 kbit/s	1.544 Mbit/s (T1)	2.048 Mbit/s (E1)	8.448 Mbit/s (E2)	34.368 Mbit/s (E3)
Coding	Convolutional rate 1/2	Convolutional rate 1/2	Convolutional rate 1/2	None	None	None
Coded data rate	128 kbit/s	768 kbit/s	3.088 Mbit/s	2.048 Mbit/s	8.448 Mbit/s	34.368 Mbit/s
Modulation	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK
Symbol rate	64 kSymbol/s	384 kSymbol/s	1.544 MSymbol/s	1.024 MSymbol/s	4.224 MSymbol/s	17.18 MSymbol/s
Mainlobe bandwidth	128 kHz	768 kHz	3.088 MHz	2.048 MHz	8.448 MHz	34.368 MHz
Transmit power	0.15 W (−8.4 dBW)	0.7 W (−1.3 dBW)	3.9 W (5.9 dBW)	3.4 W (5.3 dBW)	26.3 W (14.2 dBW)	97.7 W (19.9 dBW)
On-axis e.i.r.p. (dBW)	30.1	39.7	52.0	53.9	64.7	73.9
Peak e.i.r.p. density (on antenna axis at center frequency) (dB(W/Hz))	−18.0	−16.2	−9.9	−6.2	−1.6	1.6
Average e.i.r.p. density (on antenna axis over mainlobe BW)	−21.0 dBW/Hz 49.0 dBW/ 10 MHz	−19.2 dBW/Hz 50.8 dBW/ 10 MHz	−12.9 dBW/Hz 57.1 dBW/ 10 MHz	−9.2 dBW/Hz 60.8 dBW/ 10 MHz	−4.6 dBW/Hz 65.4 dBW/ 10 MHz	−1.4 dBW/Hz 68.6 dBW/ 10 MHz
Number of interfering earth stations in 10 MHz ISS receive BW per FSS satellite transponder	78	13	3	5	1	1
Number of interfering earth stations in ISS/LEO BW per FSS satellite (assume 2 co-frequency, cross-polar transponders per FSS satellite)	156	26	6	10	2	2
Total number (interfering) Earth stations in scenario (assume 120 FSS satellites at 3° orbit spacing)	18 720	3 120	720	1200	240	240
Number of cities modelled in simulation	2 693 (pop > 100 000)	545 (pop > 500 000)	545	545	545	545

NOTE 1 – e.i.r.p. densities listed are those that satisfy the ISS interference threshold level (i.e. aggregate interference power into the ISS receiver not to exceed −139 dBW/10 MHz for more than 0.1% of the time on average).

FIGURE 6

Illustration of Case 1 earth station distribution: 18 720 75 cm earth stations

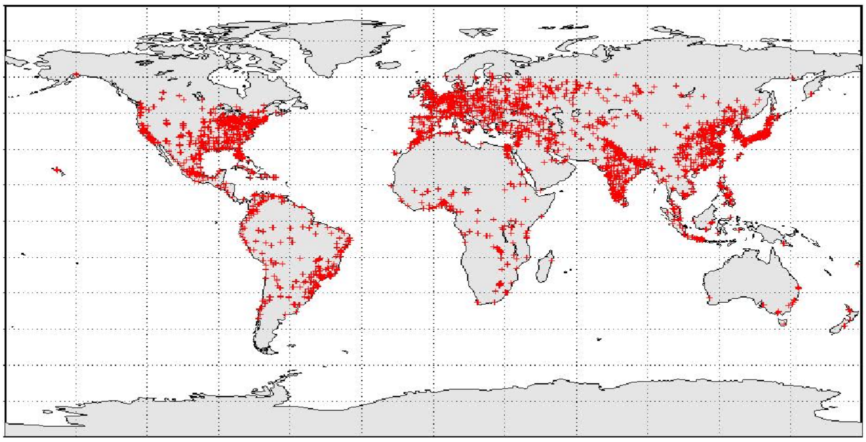

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FIGURE 7

Close-up view of 75 cm earth station distribution over northeast United States of America

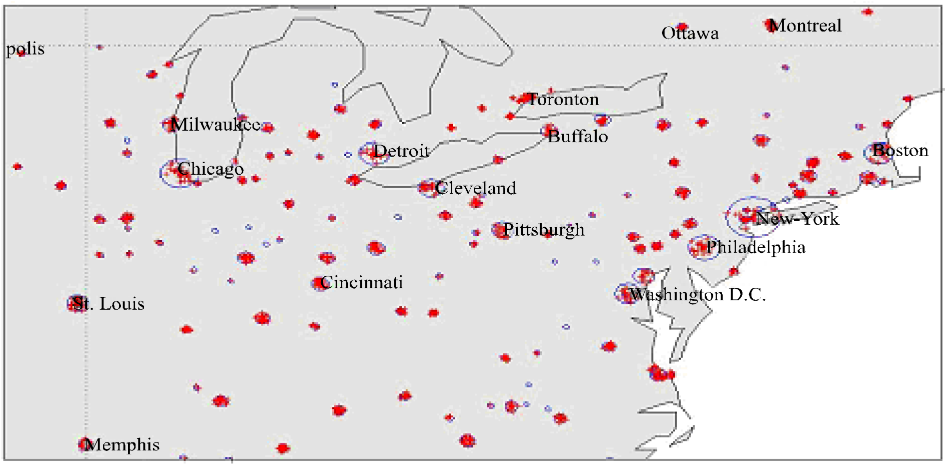

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FIGURE 8

Average probability of exceedance vs. interference level (dBW/10 MHz)

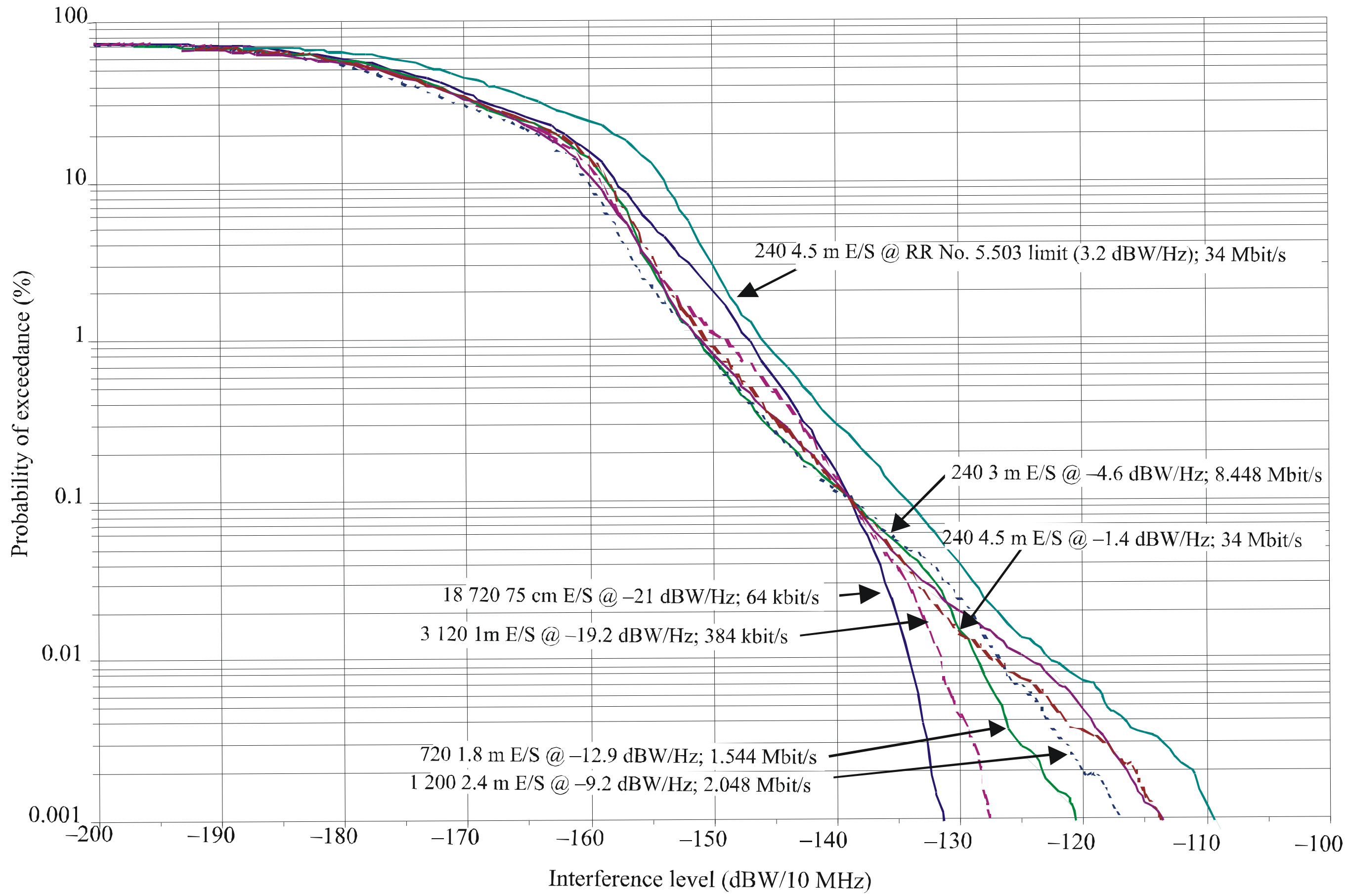

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FIGURE 9

Average probability of exceedance vs. earth station e.i.r.p. density for –139 dBW/10 MHz ISS interference threshold

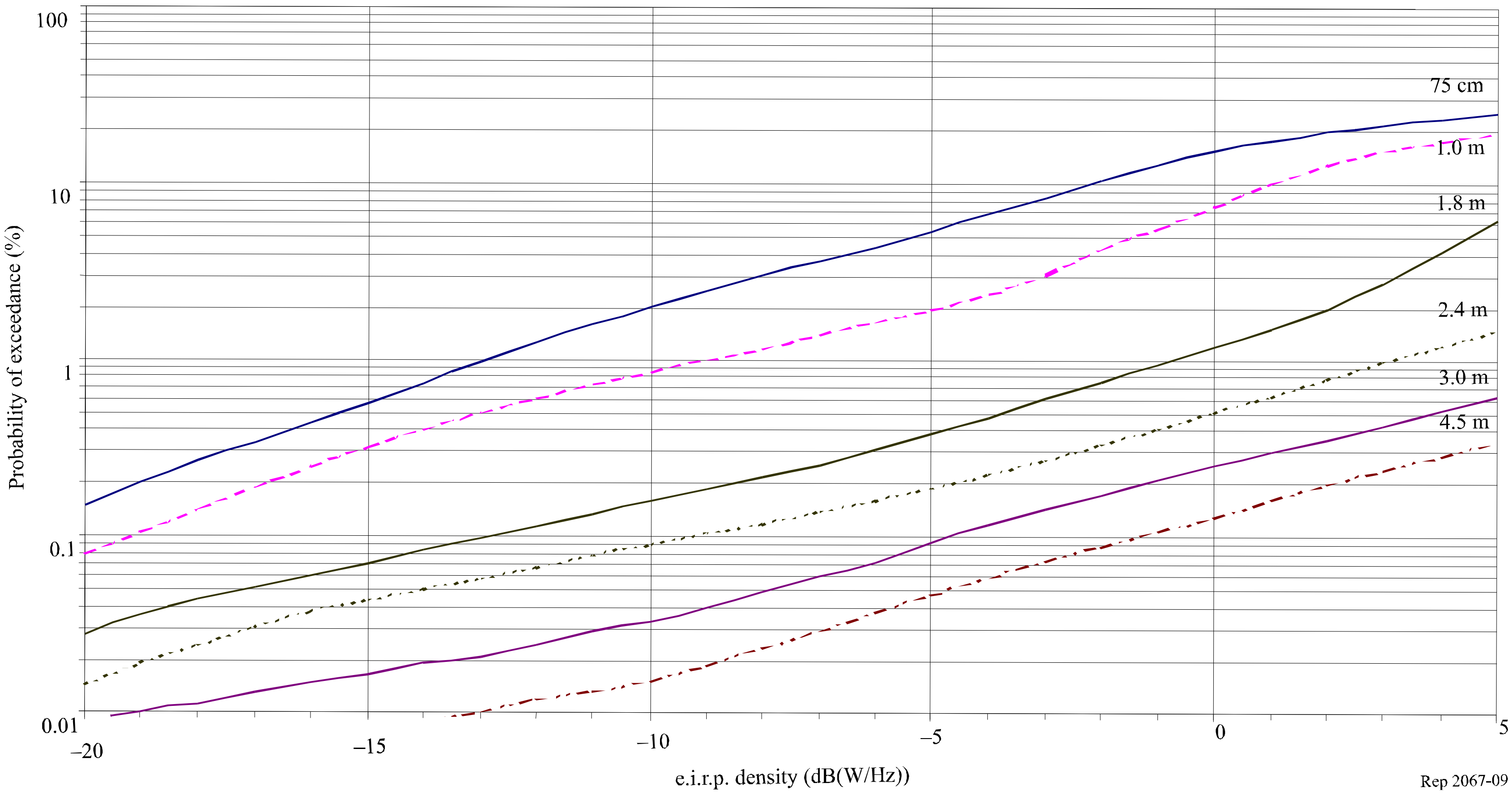

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FIGURE 10

Worst case percent of ISS orbit period that interference exceeds –139 dBW/10 MHz
(Note: ISS orbit period = 92.7 min)

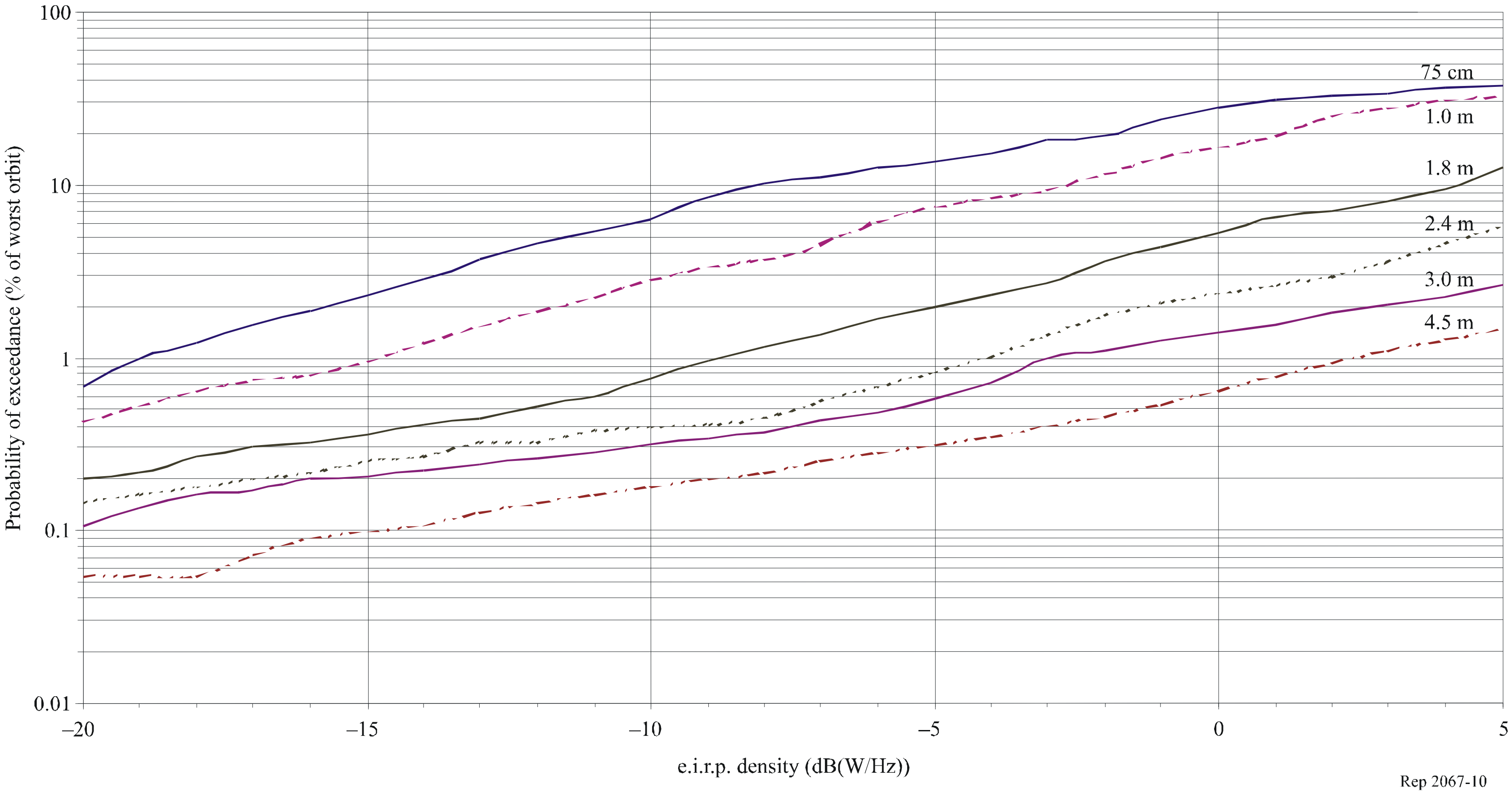
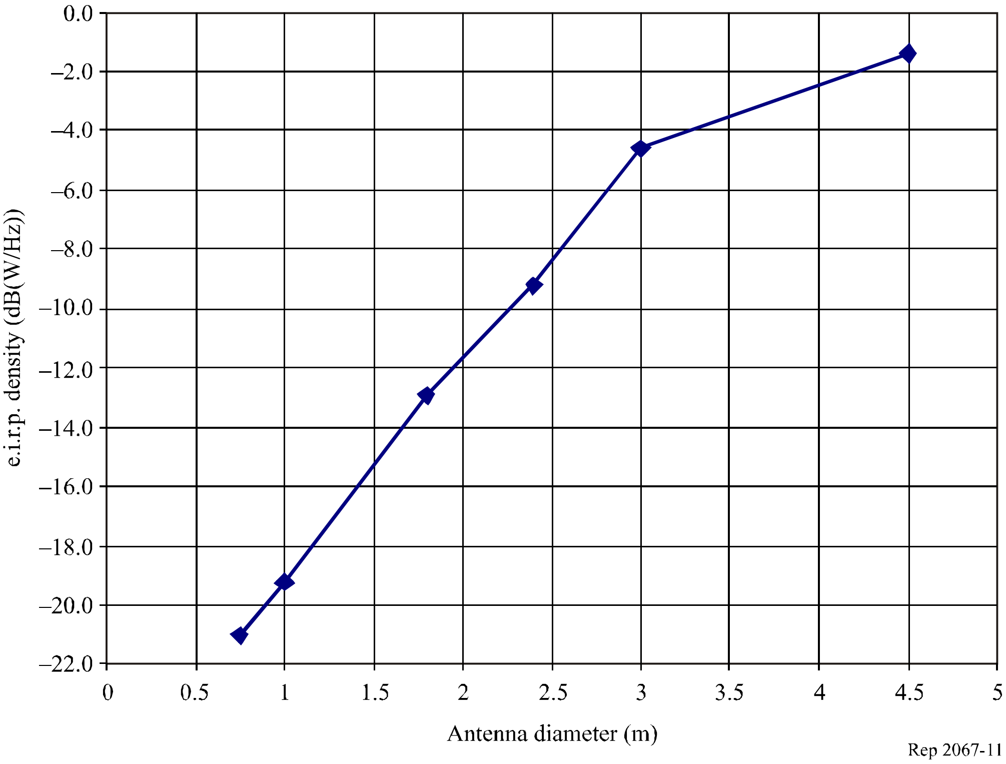


FIGURE 11

Earth station e.i.r.p. densities to satisfy the sharing criteria: *I* > –139 dB(W/10 MHz) for no more than 0.1% of the time



3.4 Summary and conclusions

These parametric results are based on homogeneous earth station populations with uniform transmit levels.

Additional simulations were run to determine the effect of geographic distribution on the results and these effects were found to be negligible when averaging over many orbits was employed.

From the analyses presented here, it is concluded that adopting a maximum e.i.r.p. spectral density mask applicable to the emissions of GSO FSS earth stations (Earth-to-space) protects SRS operations. The GSO FSS earth station e.i.r.p. spectral densities are derived from scenarios where the full channel loading is used and are provided in reference to dB(W/Hz). As a result, these e.i.r.p. spectral densities can be used to evaluate the degradation of TDRSS forward link receivers over a bandwidth of 10 MHz as well as any other desired bandwidth.

4 Interference to geostationary FSS satellites from data relay satellite systems operating in the 13.75-14 GHz band

The feasibility of sharing the 13.75-14 GHz band between data relay satellite systems and Earth-to-space links in the FSS requires that both data relay satellite systems and FSS systems are protected from interference. Section 3 addressed the protection of data relay satellite systems and this section addresses the protection of FSS systems in the GSO.

4.1 Orbit separation for the United States of America tracking and data relay satellites

An analysis has been performed to determine the carrier-to-interference power ratio (C/I) on the uplinks of an adjacent FSS satellite as a result of emissions from a geostationary TDRS. It was shown for the case of the forward inter-orbit link that the C/I will be greater than 53 dB for an orbit separation angle of 0.1°. For the case of the space-to-Earth feeder link, the C/I will be in excess of 64 dB at a separation of 0.1°. For both cases it was assumed that the e.i.r.p. of the FSS earth station was 68 dBW.

4.2 Power flux-density levels at the geostationary-satellite orbit

The maximum pfd levels produced by space research systems at a location in the geostationary-satellite orbit are tabulated in Table 6. The maximum pfd level occurs when the space research satellite is located either nearly antipodal from the GSO location (i.e. the signal path between satellites is tangential to the Earth) or at the minimum orbital separation distance from the GSO location. The maximum pfd levels of the interference to GSO FSS satellites for these two cases under the conditions indicated are given in Table 6.

TABLE 6

Maximum pfd levels produced at the geostationary orbit by space stations in the space research service

Type of space station transmitter	Maximum antenna input power density	Case of near-antipodal satellite positions				Case of minimum separation distance			
		Spacecraft antenna gain (dBi)	pfd at the geostationary orbit (dB(W/m^2)) in the reference bandwidth			Spacecraft antenna gain (dBi)	pfd at the geostationary orbit (dB(W/m^2)) in the reference bandwidth		
			Total	1 MHz	4 kHz		Total	1 MHz	4 kHz
DRS to user spacecraft	–5 dBW (Note 1)	53	–121.4	–121.6	140.2	0	–133.3	–133.5	–152.1

NOTE 1 – The DRS spacecraft is assumed to be located 1° from the FSS satellite in the minimum separation distance case. Reductions in the DRS antenna input power due to the effects of power control are not taken into account. The pfd levels specified for DRS spacecraft are based on an integration of power density in a $\sin^2 x/x^2$ power spectral distribution over the reference bandwidth. A DRS data rate of 300 kbit/s is assumed in the above table with no spreading by a PN code, which yields the worst case pfd levels when considering all possible data rates.