REPORT ITU-R M.2119

Sharing between aeronautical mobile telemetry systems for flight testing[*] and other systems operating in the 4 400-4 940 and 5 925-6 700 MHz bands

(Question ITU-R 231/8)

(2007)

1 Introduction

This Report assesses frequency sharing between wideband aeronautical mobile telemetry (AMT) systems and other systems operating under primary allocations in the 5 925-6 700 MHz and 4 400-4 940 MHz bands. The Report is intended to address the technical and operational aspects of these sharing scenarios. These AMT systems are used to transmit supplementary data from aircraft to ground (aeronautical) stations in support of testing of aircraft at test ranges. Section 2 presents technical and operating parameters of AMT systems that are used in the analyses, which are presented in annexes and summarized in the sections below. Annex 1 addresses compatibility with FSS space station receivers in the 5 925-6 700 MHz band; Annex 2 addresses compatibility with FSS earth station transmitters in the 5 925-6 700 MHz band and earth station receivers operating in the 4 500-4 800 MHz band under RR Appendix 30B; Annex 3 addresses sharing between AMT ground station receivers and FSS satellite transmitters in the 4 500-4 800 MHz band; Annex 4 addresses sharing between AMT and the radio astronomy service in the 4 825-4 835 MHz band; and Annex 5 addresses sharing between AMT and FS/MS systems in the 5 925-6 700 MHz and 4 400-4 940 MHz bands.

2 Parameters of AMT systems

2.1 General characteristics

Table 1 provides representative values for parameters of AMT systems, which consist of aircraft transmitters and receiving ground stations that use high-gain antennas which track the aircraft. Link budgets encompassing these parameters show fade margins exceeding 13 dB, which is necessary to maintain a reliable telemetry link and minimize signal dropouts due to nulls in the aircraft antenna pattern, obstruction by the aircraft fuselage, and multipath fading at the tracking receive station. The specified permissible levels of interference are based on interference-to-noise power ratios (I/N) of –3 dB (long-term) and 0 dB (short-term.

2.2 AMT deployment scenario

The assumed AMT deployment scenario consists of 17 representative test areas or flight zones shown in the map of Fig. 1. These zones indicate approximate airspace volumes within which test aircraft operate. Among all worldwide deployments, this deployment would yield the maximum potential AMT aggregate interference at the geostationary satellite orbit (GSO). For purposes of aeronautical safety, administrations authorize flight testing only in designated areas.

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[*] This Report addresses only flight applications, and not other applications in these bands.

2.3 AMT frequency reuse

For worst case analyses, no more than two co-frequency aircraft could operate in each of the four largest or most active test zones (DFRC, Utah, WSTF, and PAX in Fig. 1) where sufficient separation between co-channel aircraft is possible in order to avoid interference between aircraft. Self-interference among AMT systems is avoided by rigorous scheduling of AMT frequency usage by frequency managers. Only one aircraft would use a given frequency in the other test zones, for a worst-case total of 21 co-frequency aircraft transmitters. Although aircraft testing using AMT is conducted only several hours per day, all 21 co-frequency aircraft are assumed to be operating simultaneously in order to avoid underestimating aggregate interference.

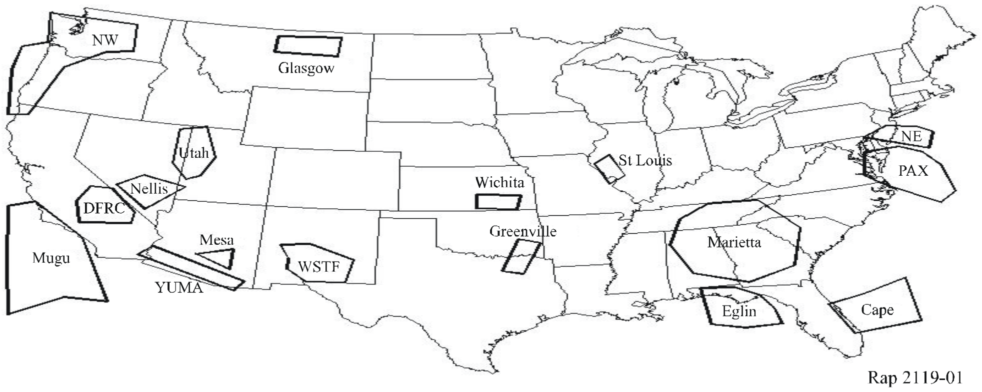
TABLE 1

Representative AMT system parameters

Parameter	Symbol	Value
Aircraft antenna pattern	–	Omni-directional
Peak aircraft antenna gain (dBi)	G_{tmax}	3
Average aircraft antenna gain (dBi)	G_{tave}	–4.8
Maximum aircraft e.i.r.p. density (dB(W/MHz))	–	–2.2
Average aircraft e.i.r.p. density (dB(W/MHz))	–	–10.0
Peak aircraft antenna input power density (dB(W/MHz))	P_t	–5.2
Ground receiver antenna aperture (m)	–	2 to 5
Ground receiver antenna pattern	–	Rec. ITU-R F.1245
Ground receiver antenna height (m)		30
Ground antenna elevation angles (degrees)		0-20
Nominal permissible long-term interference at receiver antenna output (dBW/MHz to be exceeded for no more than 20% of the time)		–145.5
Nominal permissible short-term interference at receiver antenna output (dBW/MHz to be exceeded for no more than 0.4% of the time)		–142.5

FIGURE 1

Map of assumed AMT test zones



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2.4 AMT aircraft antenna characteristics

The AMT aircraft transmitter antenna gain (and e.i.r.p.) in the direction of the receiving ground station fluctuates as a result of multipath and blockage effects of the aircraft fuselage. The aircraft antenna gain statistics were based on the Rayleigh model specified in Recommendation ITU-R M.1459, which yields 3 dBi peak gain, 1.5 dBi gain exceeded for 1% of the time, and –6 dBi gain for 50% of the time (average). It should be noted that the average aircraft antenna gain of –4.8 dBi in Table 1 was found by calculating the expected value of gain using the Rayleigh-like probability density function in Recommendation ITU-R M.1459 (thus the average gain and e.i.r.p. density is 3 – (–4.8) = 7.8 dB below the peak value rather than 9 dB using the –6 dBi/50% statistic). The antennas typically are of slot or blade (dipole) type. Installation locations of these temporary AMT antennas typically are on the underside of the aircraft so as to direct the radiation toward the ground during level flight. These temporary installations for testing are constrained by load-bearing aircraft structural features, such as stringers that cannot be cut; thus, the antenna locations cannot be freely optimized to achieve the best possible AMT transmission performance.

2.5 AMT e.i.r.p. and modulation

The total average power out of the telemetry transmitter, P_t, typically is 10W. It is common in test installations for a single transmitter to simultaneously feed two or more antennas on the aircraft fuselage. For example, a power split of 90%/10% is typical in which 90% of the total transmitter power is fed to an antenna on the bottom of the aircraft (since most of the time it is the one in view of the ground station) and 10% to an antenna on the top of the aircraft. Although the peak e.i.r.p. density in any direction (–2.2 dB(W/MHz)) is based on use of a single antenna with 3 dBi peak gain, the power splitting and two-antenna arrangement could theoretically produce the same peak e.i.r.p. in directions emanating from underside of the aircraft fuselage.

Wideband AMT systems are expected to operate at data rates upwards of 20 Mbit/s. The assumed peak e.i.r.p. is based on the highest power density associated with the modulation and coding techniques used in narrowband aircraft telemetry systems at frequencies below 3 GHz. Other modulation and coding choices tend to have more uniform spectral power density distributions such that the assumed 10 W AMT transmitter would produce a lower peak e.i.r.p. density.

3 Sharing between AMT and space station receivers in the 5 925-6 700 MHz band

AMT transmitters operate well below the power limits specified in Article 21 of the Radio Regulations (RR) for terrestrial stations in frequency bands shared with space services (Earth-to-space) above 1 GHz. FSS operators must take into account these regulatory provisions when designing their systems. The analyses in Annex 1 show that interference from AMT is below permissible levels specified in Recommendation ITU-R S.1432. Specifically, aggregate interference from AMT causes an increase in equivalent uplink noise temperature $\Delta T_s/T_s$ of no more than 2.7% in existing and planned FSS systems and $\Delta T_s/T_s$ is no more than 4.9% in more vulnerable, hypothetical FSS systems (assumed to have a very high uniform G/T of +7 dB/K over the satellite coverage area). These calculated values are conservative because they are based on the maximum expected number of co-frequency aircraft in the satellite uplink beam (21 aircraft), each aircraft simultaneously radiating its peak instantaneous e.i.r.p. towards the satellite, and no polarization discrimination or atmospheric losses. Under these assumptions, the interference averaged over existing and planned FSS systems is $\Delta T_s/T_s$ = 1.1%. Substitution of the average aircraft e.i.r.p. (–10.0 dB(W/MHz)) for the peak level and application of the central limit theorem of statistics yields an average aggregate $\Delta T_s/T_s$ level of 0.2% (averaged over existing and planned FSS systems).

4 Sharing between AMT and FSS earth stations in the 5 925-6 700 and 4 500-4 800 MHz bands

Studies in Annex 2 compare the coordination distances calculated in accordance with the methodology of RR Appendix 7 to the actual required separation distances based on conservative yet possible operational scenarios for AMT. While coordination distances are large, the separation distances required to prevent interference are shown to be smaller.

5 Sharing between AMT and FSS space stations in the 4 500-4 800 MHz band

Annex 3 evaluates potential interference to AMT ground stations from FSS satellite downlink transmissions in the 4 500-4 800 MHz band. This analysis shows that FSS downlink transmissions will not exceed permissible levels of interference to AMT ground stations except when the AMT receiver antenna is pointed in the direction of the satellite (main beam coupling). Although the random probability of such interference may be acceptably low for wideband AMT, this pointing situation can be avoided via selection of AMT ground station sites that would prevent or minimize pointing of the AMT antenna toward the GSO.

6 Sharing between AMT and radio astronomy observatories in the 4 825-4 835 MHz band

Annex 4 assesses potential interference to radio astronomy receivers from AMT aircraft transmitters in the 4 825-4 835 MHz band. This study shows that, in general, careful frequency planning/coordination is needed to prevent interference in co-frequency sharing situations where radio astronomy receivers are located within the radio horizon of the AMT aircraft (450 km). In such cases, time sharing may be feasible insofar as radio astronomy observations and flight testing are not continuous operations.

7 Sharing between AMT and the fixed and mobile service in the 4 400-4 940 MHz and 5 925-6 700 MHz bands

Annex 5 evaluates potential interference between AMT systems and systems in the fixed and mobile services (FS/MS). The MS systems are transportable (these and AMT systems are the only kinds of MS systems in the 4 GHz and 6 GHz bands for which parameters were available for analysis). Permissible levels of interference to FS/MS stations are not exceeded when the distance along the main-beam axis from the FS/MS receiver to the AMT area of operation is larger than 450 km or when the main-beam axis of the FS/MS antenna is separated from the aircraft flight zone by 12 km or more.

Further study would be needed (e.g. during bilateral coordination) to determine whether significantly smaller distance separations could result for actual co-frequency sharing situations. While it might be possible to operate AMT aircraft closer to a FS/MS receiver, this may require restrictions on the AMT system. These restrictions could include, for instance, frequency separation between AMT and FS/MS signals, limits on the region of aircraft operation, or the limits on the altitude range of operation. Because of the intensive use of the 4 GHz and 6 GHz bands by the FS, substantial frequency spectrum may not be available for AMT use in some flight test zones. The number of FS systems is generally growing throughout the world, e.g. by as much as 25% per year at 6 GHz in the territory of one administration. It remains to be seen, perhaps by AMT coordination trials, how much spectrum could be coordinated for AMT use in the 4 GHz and 6 GHz bands, particularly at test ranges where the FS/MS frequency usage is intense.

Separation distances are needed between FS/MS transmitters and AMT ground station receivers using the same frequencies in order to keep interference below permissible levels. In the worst hypothetical case, assuming that both the FS and AMT antennas are constantly pointed at each other, several hundred km of separation would be required (i.e. up to 425 km) for compliance with the short-term permissible level of interference. When this pointing condition is completely avoided, e.g. via selection of the AMT ground receiver site, distance separations of the order of 1-20 km enable co-frequency sharing.

8 Conclusions

Potential interference between typical wideband AMT systems and FSS space stations using the bands around 6 GHz is below permissible levels under assumptions provided in § 2 above. Additionally interference to AMT ground stations would be within acceptable levels as described in § 2 at 4 GHz assuming that the AMT systems are designed and deployed to prevent AMT ground station antenna pointing at the GSO FSS satellites.

However, the combined effects of all the local frequency sharing situations with FS/MS stations, radioastronomy observatories, and FSS earth stations may severely limit availability of spectrum resources for introduction and operation of AMT systems in the 4 400-4 940 MHz and 5 925-6 700 MHz bands. This is especially true for flight test zones that are located in areas where the bands are intensively used by systems in other services.

Annex 1

Potential aeronautical mobile telemetry (AMT) for flight testing interference to GSO satellites in the fixed-satellite service (FSS) (E-S) in the 5 925-6 700 MHz candidate band

1 Introduction

The 5 925-6 425 MHz portion of the band is heavily used by the FSS (Earth-to-space). This Annex evaluates potential interference from AMT aircraft transmitters into FSS satellite receivers. Note that potential AMT interference into FSS satellite receivers is an aggregate interference problem since all aircraft transmitters in the satellite field-of-view (FOV) will contribute to the total interference at the satellite. Thus, these analyses below consider all aircraft transmitters in worst-case AMT deployment situation described in § 2 of the main text.

2 Methodology and assumptions

2.1 FSS satellite characteristics

Recommendation ITU-R S.1432 apportions 27% of the total FSS system noise plus interference power to aggregate interference and 6% of the total FSS system noise plus interference power to interference from other co-primary services. Working Party 4A suggested that this 6% noise allowance should be further subdivided among AMT and other allocated services. The 6% noise apportionment for interference corresponds to a 8.2% increase in FSS equivalent satellite receive noise temperature, $\Delta T_S/T_S$ (100 × 6%/(100-27%)). Accordingly, this analysis determines aggregate $\Delta T_S/T_S$ levels that can be compared to the permissible levels of interference specified in Recommendation ITU-R S.1432. These calculations were performed for two sets of FSS satellite characteristics. The first set of characteristics in § 2.2.1 was derived from ITU satellite network filings for satellites that provide uplink coverage of the United States of America in the 5 925-6 700 MHz band. The second set of characteristics in § 2.2.2 was based upon the same set of ITU satellite networks used in § 2.2.1 but with the assumption that each uplink beam has a uniform uplink antenna gain pattern over the coverage area. This latter set of satellite beam characteristics was used to assess sharing between AMT and hypothetical future FSS satellites that may be particularly vulnerable to interfering signals generated by terrestrial transmitters.

2.1.1 FSS satellite characteristics from ITU published information

A search was made of the ITU-R space radiocommunication systems (SRS) database to identify the GSO FSS satellites with uplink beam coverage of the assumed AMT deployment at 5 925-6 700 MHz band. Satellites generating 99 such beams from orbit positions in the range 37 W-140 W longitude were identified. Table 1 lists the 99 beams along with the max beam G/T ratio (i.e. max satellite receive ant gain, G, to system noise temperature, T, ratio). The average G/T value in Table 2 is 2.48 dB/K. Note that the beams in Table 2 are sorted according to satellite longitude and that multiple beams can originate from the same orbit location.

Again using the SRS database and the ITU GIMS (graphical information management system) software, the receive antenna gain contour data for the 99 beams was extracted and imported into MATLAB data files for later use in the simulations. Figure 2 illustrates one of these beam patterns (USASAT-22B at 125W) overlaid on the AMT deployment scenario described in § 2.1 of the main text. Note that this beam pattern as well as many others can have multiple peak gain points.

Interpolation between gain contours using closest point of approach was performed in the satellite antenna coordinate system to determine the appropriate receive satellite antenna gain to apply to each individual AMT emitter (interferer) based on its location within the beam pattern.

TABLE 2

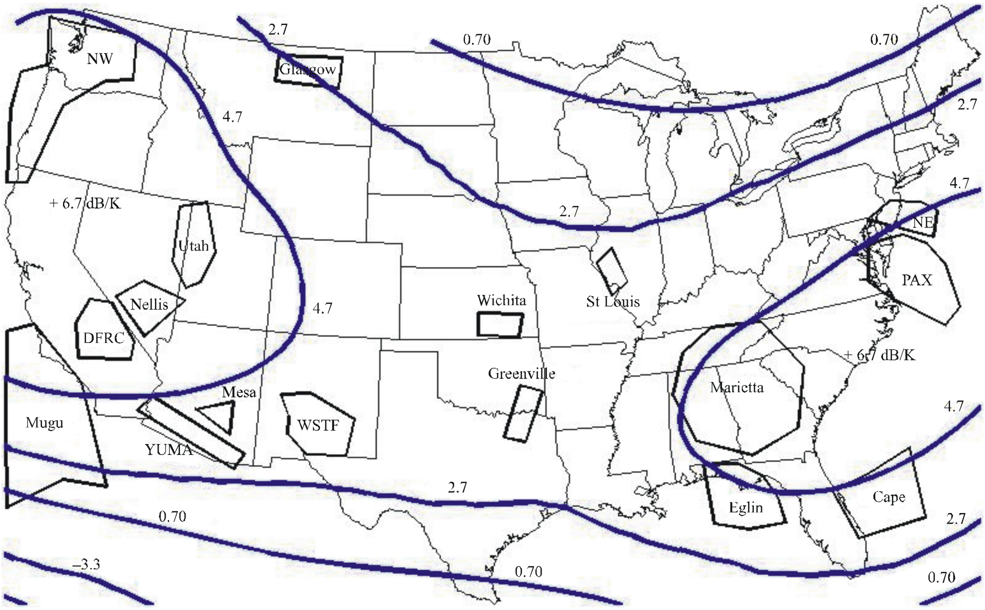
FSS satellites between 37 W and 140 W longitude with 6 GHz uplink beam coverage of CONUS (99 beams)

Beam #	Satellite name		Orbit Long	Beam ID	Gain (dBi)	Temp (K)	Polarization	Peak G/T (dB/K)	ITU Network ID
1	US SATCOM 1-R		-139	CON	31.8	627	?	3.83	90500452
2	USASAT-22I		-139	6UH	29.8	1350	H	-1.50	103500021
3	USASAT-22I2		-139	6UV	30	1350	V	-1.30	103500021
4	USASAT-22N		-139	UUH	30	630	H	2.01	101520005
5	USASAT-22G		-137	UUH	28.7	630	H	0.71	99500142
6	USASAT-22G2		-137	UUV	28.9	630	V	0.91	99500142
7	USASAT-22J		-137	UUH	30	630	H	2.01	99520295
8	USASAT-21A		-135	UUH	32.1	630	H	4.11	99500140
9	USASAT-21A2		-135	UUV	30.1	630	V	2.11	99500140
10	USASAT-22K		-135	UUH	30	630	H	2.01	99520242
11	USASAT-11D		-134	UH1	32.6	660	H	4.40	90504198
12	USASAT-11D2		-134	UV1	30.4	660	V	2.20	90504198
13	USASAT-22A	Galaxy-1R	-133	UH1	32.8	406	H	6.71	104500020
14	USASAT-22A2	Galaxy-1R	-133	UV1	30.5	406	V	4.41	104500020
15	USASAT-35Y	Galaxy-1R	-133	CR1H	33.2	630	H	5.21	99520518
16	USASAT-22H		-131	UUH	29.1	630	H	1.11	91980005
17	USASAT-35A		-131	UUH	30	630	H	2.01	99520243
18	USASAT-24N		-129	RC1	28	1000	H	-2.00	96520549
19	ASC-1		-128	B285	28.5	900	?	-1.04	90500615
20	USASAT-24O	Galaxy-13	-127	RC1	33.6	692	V	5.20	97520171
21	USASAT-24O2	Galaxy-13	-127	RC2	33.3	692	H	4.90	97520171
22	USASAT-35C	Galaxy-13	-127	CR1H	33.2	630	H	5.21	99520520
23	USASAT-22B	Galaxy-12	-125	UH2	32.8	406	H	6.71	101500395
24	USASAT-22B2	Galaxy-12	-125	UV2	30.5	406	V	4.41	90500318
25	USASAT-35D	Galaxy-12	-125	CR1H	33.2	630	H	5.21	99520519
26	USASAT-24P	Galaxy-10R	-123	RC2	29.4	550	H	2.00	97520161
27	USASAT-35E	Galaxy-10R	-123	CR1V	33.2	630	V	5.21	99520517
28	ANIK D-1		-118.7	B2	33	1000		3.00	90500176
29	ANIK E-D		-118.7	RC1	33.8	1000		3.80	96520119
30	CANSAT-18		-118.7	CNRH	30	705	H	1.52	101520037
31	ANIK D-2		-114.9	RC1	33	1000		3.00	90500178
32	CANSAT-17		-114.9	CNRH	30	705	H	1.52	101520036
33	CANSAT-6		-114.9	CNRH	30	705	H	1.52	100520449
34	ANIK E-B		-111.1	RC1	33.8	1000		3.80	90500184
35	ANIK F-2		-111.1	CNRH	31.1	703	H	2.63	100520282
36	CANSAT-19		-109.2	CNRH	30	705	H	1.52	103520282
37	ANIK E-A		-107.3	RC1	33.8	1000		3.80	90500182
38	USASAT-24F		-103	6V1	32.1	617	V	4.20	95520120
39	USASAT-24F2		-103	6H1	31.9	609	H	4.05	95520120
40	USASAT-35H		-103	DNH	27.1	512	H	0.01	99520537
41	USASAT-35I		-101	RCA	28	550	H	0.60	98520238
42	USASAT-7D		-101	CON	30.4	900	?	0.86	101500073
43	USASAT-24J	Galaxy-4R	-99	B1	31.6	552	H	4.18	91980048
44	USASAT-24J2	Galaxy-4R	-99	B3	30.6	552	V	3.18	91980048
45	USASAT-35J	Galaxy-4R	-99	CR1H	29.3	630	H	1.31	99520516
46	USASAT-24D		-97	6H	30.4	575	H	2.80	91980038
47	USASAT-24D2		-97	6V	30.2	575	V	2.60	91980038
48	USASAT-35K		-97	CNU	31.7	470	H	4.98	99520529
49	USASAT-24L	Galaxy-3C	-95	UH3	32.8	406	H	6.71	90500319
50	USASAT-24L2	Galaxy-3C	-95	UV3	30.5	406	V	4.41	90500319
51	USASAT-35L	Galaxy-3C	-95	CR1H	30.1	630	H	2.11	99520526
52	USASAT-12B		-93.5	UH3	33.1	660	H	4.90	90501103
53	USASAT-12B2		-93.5	UV3	30.4	660	V	2.20	90501103
54	USASAT-24S		-93	6H	32.5	750	H	3.75	97520044
55	USASAT-24S2		-93	6V	31.8	750	V	3.05	97520044
56	USASAT-35M		-93	CNU	31.7	470	H	4.98	99520530
57	USASAT-24K	Galaxy-9/11	-91	B1	31.6	552	H	4.18	93520129
58	USASAT-24K2	Galaxy-9/11	-91	B3	30.6	552	V	3.18	93520129
59	USASAT-35N	Galaxy-9/11	-91	CR1H/V	32.3	630	H	4.31	99520430
60	USASAT-24E		-89	6H	30.4	575	H	2.80	101500404
61	USASAT-24E2		-89	6V	30.2	575	V	2.60	101500404
62	USASAT-35O		-89	6NH	30.4	470	H	3.68	99520506
63	USASAT-24T		-87	6H1	33.3	617	H	5.40	96520212
64	USASAT-24T2		-87	6V1	31.7	617	V	3.80	96520212
65	USASAT-35P		-87	DNH	27.1	512	H	0.01	99520538
66	USASAT-3C		-86	6-H	27	900	H	-2.54	90500346
67	USASAT-24U		-85	6H1	33.3	617	H	5.40	96520211
68	USASAT-24U2		-85	6V1	31.7	617	V	3.80	96520211
69	USASAT-35Q		-85	DNH	27.4	605	H	-0.42	98520553
70	USASAT-24V		-83	RC1	32.2	430	M?	5.87	97520017
71	USASAT-35R		-83	CR1H/V	32.3	630	H	4.31	99520505
72	USASAT-24R		-81	CR1H/V	32.3	630	H	4.31	97520255
73	USASAT-35S		-81	CR1H/V	32.3	630	H	4.31	98520203
74	USASAT-24W		-79	DNH	29.8	617	H	1.90	97520404
75	USASAT-35T		-79	DNH	27.1	512	H	0.01	99520539
76	USASAT-24Q		-77	RC1	28	1000	H	-2.00	96520548
77	USASAT-12C		-76	CON	24.5	2200	?	-8.92	90500315
78	USASAT-22E	Galaxy-3R	-74	UH4	32.8	406	H	6.71	90500320
79	USASAT-22E2	Galaxy-3R	-74	UV4	30.5	406	V	4.41	90500320
80	USASAT-35V	Galaxy-3R	-74	CR1H/V	32.3	630	H	4.31	97520251
81	USASAT-35W		-72	DNH	27.5	603	H	-0.30	98520537
82	USASAT-8B		-72	F2	30.5	1500	?	-1.26	90500511
83	USASAT-24X		-69	6H	32.5	750	H	3.75	97520045
84	USASAT-24X2		-69	6V	31.8	750	V	3.05	97520045
85	USASAT-35X		-69	6NH	29	470	H	2.28	99520290
86	USASAT-24Y		-67	DNH	30.4	617	H	2.50	97520405
87	USASAT-25G	PAS-9	-58	NAH	29	800	H	-0.03	90500448
88	USASAT-26G3	PAS-9	-58	CMD	22	650		-6.13	103520284
89	INTELSAT5AWH		-55.5	WH	24.2	1122	?	-6.30	100500274
90	INTELSAT5AWZ		-55.5	WZ	29	1585	?	-3.00	100500274
91	INTELSAT6		-55.5	Z1	34.1	796	CR	5.09	97520350
92	INTELSAT7		-55.5	Z1	24.9	437	CR	-1.50	97520265
93	INTELSAT8		-55.5	Z1	34.9	703	CR	6.43	97520226
94	INTELSAT9		-55.5	9H1	27.8	700	CL	-0.65	98520139
95	USASAT-13I	PAS-1R	-45	NU	30.4	1100		-0.01	96500511
96	USASAT-25D	PAS-1R	-45	CR1H	27.8	630	H	-0.19	90500445
97	USASAT-25C	PAS-3R	-43	ARH	24.5	500	H	-2.49	93520023
98	USASAT-25A		-37.5	NAH	31.1	800	H	2.07	101500093
99	USASAT-25A1		-37.5	C1R	35	600		7.22	104520201

FIGURE 2

Illustration of USASAT22-B (Galaxy-12) uplink beam pattern overlaid on the 17 AMT test zones

(Numbers shown on the map are the satellite receive *G*/*T* values in dB/K)



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For a given FSS beam, the aggregate interference power flux density at the satellite was calculated as:

$$PFD = 10\log\left(\left(\sum_{i=1}^{N}\frac{eirp_{0_i}}{4\pi\cdot D_i^2}\right)\right) \qquad (\text{dB(W/(m}^2\cdot\text{MHz)))}$$

where

N: number of simultaneously active co-frequency AMT emitters

$eirp_{0_i}$: eirp spectral density of the *i*-th AMT emitter (W/MHz) in the direction of the satellite

D_i: distance between the *i*-th emitter and the satellite (m).

Aggregate interference power density at the satellite was calculated as:

$$I_0 = 10\log\left[\sum_{i=1}^{N}\frac{eirp_{0_i}}{4\cdot\pi\cdot D_i^2}\cdot g_{ri}\cdot\frac{\lambda^2}{4\pi}\right] \qquad (\text{dB(W/MHz)})$$

where g_{ri} is the satellite receive antenna gain (in non-dB, numerical units) in the direction of the *i*-th emitter calculated by interpolating between the appropriate gain contours in the pattern. Also, to be conservative, no polarization discrimination is assumed. The quantity λ is the wavelength (m).

The aggregate I_0/N_0 ratio is then $I_0/N_0 = I_0 - N_0$ (dB) where N_0 is the receiver thermal noise power density ($N_0 = 10*\log(k*T_{sys}*B)$) with $B = 1$ MHz since I_0 is in units of dB(W/MHz). T_{sys} is the satellite system noise temperature (K) according to the value in the ITU database.

Since the apparent satellite system noise temperature increase, ΔT_s, due to interference is defined as $i_0 = k\Delta T_s$ where i_0 is the (aggregate) interference power density (W/Hz) and k is Boltzmann's constant (k = 1.38exp-23 J/K), the ratio $\Delta T_s/T_s$ is calculated as (i_0/n_0) where both i_0 and $n_0 = kT_s$ are in units of W/Hz.

2.1.2 Hypothetical FSS satellite characteristics

The same methodology as described in § 2.2.1 was applied except that for each satellite network listed in Table 2, the associated receive beam was assumed to have a uniform gain pattern over the entire coverage area with a resultant constant *G*/*T* of 7 dB/K. Note also that this value is larger than any of the *G*/*T* values of the existing satellites shown in Table 2 except for USASAT-25A-1 (peak *G*/*T* = 7.22 dB/K). This uniform gain case allows assessment of sharing with hypothetical satellites in which the location of the *G*/*T* peaks over the service area are currently unknown and for which the peak *G*/*T* may be quite high. Given the trend towards smaller earth stations, satellite *G*/*T* values are expected to increase in order to accommodate the smaller earth station transmit antenna gain and hence, lower e.i.r.p.

3 Analysis results

Table 3 shows a summary of the results for the existing/planned FSS beams while Table 3 shows the corresponding results for the hypothetical satellite (constant *G*/*T*) case. Figs. 3a and 3b show the interference results for the (99) existing/planned FSS beams in terms of satellite noise temperature increase ($\Delta T_s/T_s$ ratio) vs. satellite beam longitude. The maximum $\Delta T_s/T_s$ ratio varies from 0.26% (17 emitters at EIRP$_0$ = –11.2 dB(W/MHz)) to 2.7% (21 emitters at EIRP$_0$ = –2.2 dB(W/MHz)) depending on the number of emitters and emitter EIRP$_0$. The mean $\Delta T_s/T_s$ varies from 0.11% to 1.1%.

For the constant *G*/*T* scenario (i.e. *G*/*T* = 7 dB/K assumed for all satellite receive beams), the $\Delta T_s/T_s$ varies from 0.5% (17 emitters at EIRP$_0$ = –11.2 dB(W/MHz)) to 4.9% (21 emitters at EIRP$_0$ = –2.2 dB(W/MHz)). The mean $\Delta T_s/T_s$ varies from 0.48% to 4.72%.

One might also consider the impact to satellites with global coverage beams (e.g. Inmarsat). While it is true that these satellites may have a larger number of interfering AMT aircraft in the uplink beam, the fact that they are global coverage beams means the resulting satellite *G*/*T* is so low that it would take an unrealistically large number of aircraft to cause appreciable interference. For example, the Inmarsat-3 global beam has a *G*/*T* of about –7 dB/K and Inmarsat-4 has a *G*/*T* of –4.6 dB/K. It would take approximately 310 concurrent co-frequency aircraft (each radiating at –2.2 dB(W/MHz) EIRP towards the satellite) in the Inmarsat-3 beam and 180 aircraft in the Inmarsat-4 beam to exceed an interference level of $\Delta T_s/T_s$ = 3%.

TABLE 3

Summary of aggregate interference results for the (99) FSS satellite uplink beams

Total No. of co-freq AMT emitters	**Emitter EIRP$_0$ and ant gain towards satellite**	**Aggregate PFD at satellites (dB(W/(m^2 · MHz)))**		**Aggregate I_0/N_0 at satellites (dB)**		**Noise temp ratio at satellites ($\Delta T_s/T_s$) (%)**	
		Average	Max	Average	Max	Average	Max
21	–11.2 dB(W/MHz) –6.0 dBi	–160.60	–160.44	–29.69	–24.62	0.14	0.34
21	–3.7 dB(W/MHz) +1.5 dBi	–153.09	–152.93	–22.19	–17.22	0.77	1.90
21	–2.2 dB(W/MHz) +3.0 dBi	–151.60	–151.45	–20.65	–15.65	1.10	2.73

TABLE 4

Summary of aggregate interference results for FSS satellite uplink beams with uniform G/T = 7 dB/K over CONUS coverage area

Total no. of co-freq AMT emitters	**Emitter EIRP_0 and ant gain towards satellite**	**Aggregate PFD at satellites (dB(W/(m^2 · MHz)))**		**Aggregate I_0/N_0 at satellites (dB)**		**Noise temp ratio at satellites ($\Delta T_s/T_s$) (%)**	
		Average	Max	Average	Max	Average	Max
21	–11.2 dB(W/MHz) –6.0 dBi	–160.59	–160.44	–22.26	–22.10	0.60%	0.62%
21	–3.7 dB(W/MHz) +1.5 dBi	–153.09	–152.93	–14.75	–14.60	3.35%	3.47%
21	–2.2 dB(W/MHz) +3.0 dBi	–151.60	–151.45	–13.27	–13.11	4.72%	4.88%

FIGURE 3a

$\Delta T_s/T_s$ interference results for 17 emitter scenarios

(Note that multiple FSS beams can occur at the same GSO longitude as indicated by the multiple symbols)

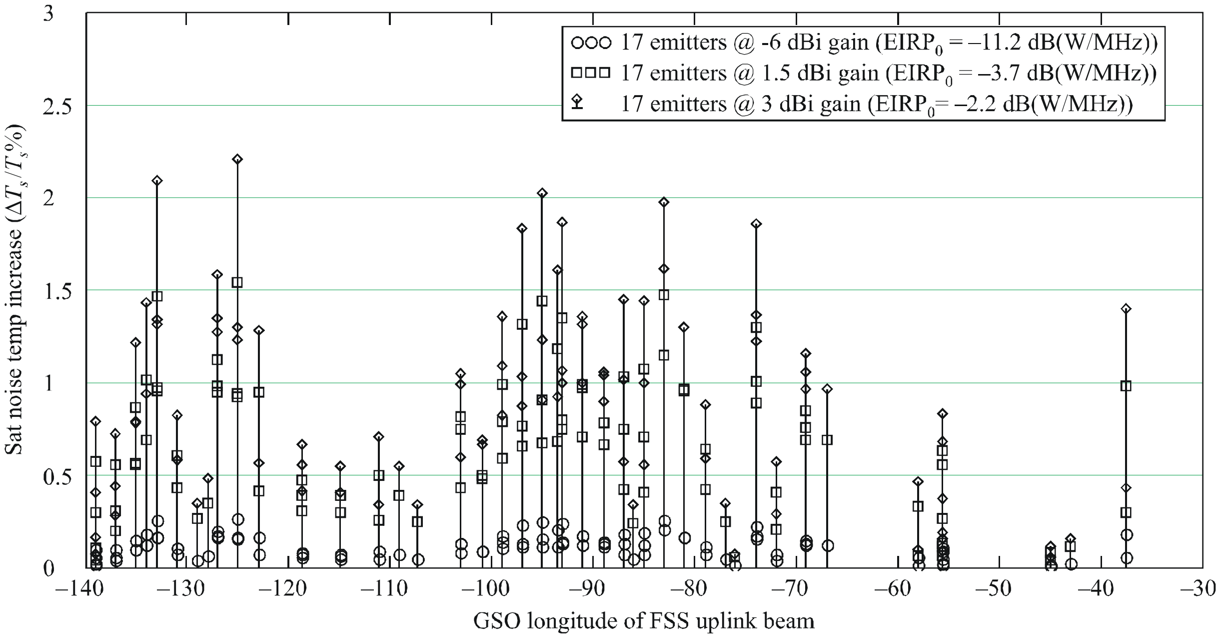

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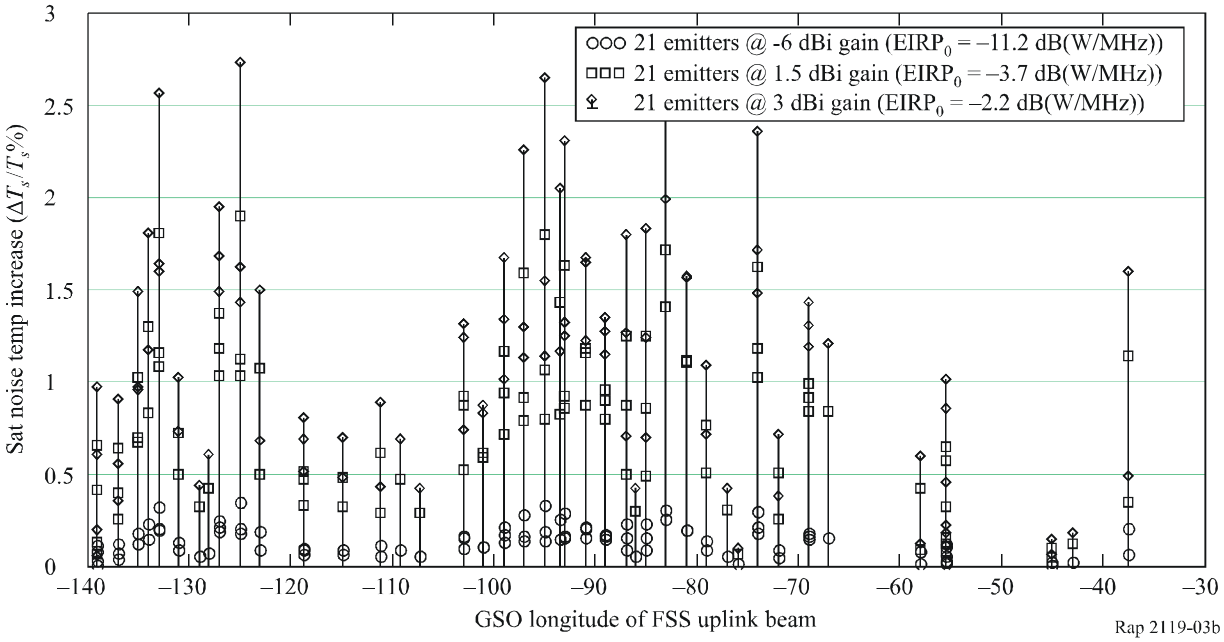
FIGURE 3b

$\Delta T_s / T_s$ interference results for 21 emitter scenarios



Annex 2

Sharing between FSS earth stations and AMT stations operating in the frequency bands 4 400-4 940 MHz and 5 925-6 700 MHz

1 Introduction

This Annex addresses distance separation constraints on sharing between FSS earth stations and AMT stations. The results are presented as contours of the RR Appendix 7 calculated distances and separation distances around a FSS earth station that may be necessary to protect the FSS earth station and AMT ground station receivers. The calculated distance results allow assessment of the general administrative coordination burden of sharing between FSS and AMT stations. Of the order of 100 telemetry ground receivers are expected to be needed in the telemetry test zones presented in § 2 of the main text. The separation distance calculations give an indication of the actual distance between the FSS and AMT stations that might be required to for co-frequency sharing.

The band 5 925-6 700 MHz (6 GHz) is allocated to the FSS (Earth-to-space) and the band 4 500-4 800 MHz (4 GHz) is allocated to the FSS (space-to-Earth) for use in accordance with RR Appendix 30B. In the 6 GHz case, the RR Appendix 7 calculated and separation distances between a transmitting earth station and a receiving AMT ground station are calculated. For 4 GHz, the Appendix 7 calculated and separation distances between an AMT aircraft transmitter and a receiving FSS earth station is investigated.

In RR Appendix 5, Table 5-1 indicates that for these frequency bands, coordination is triggered when the coordination area of the earth station covers the territory of another administration and that the method of calculation is to be found in RR Appendix 7. The coordination area represents the area surrounding an earth station sharing the same frequency band with terrestrial stations within which the permissible level of interference may be exceeded under some circumstances and, hence, coordination is required. The coordination area is determined using worst case assumptions for signal propagation and system parameters that typically lead to large distances that greatly exceed the actual required separation distances.

2 Methodology

The RR Appendix 7 calculations were performed using the “R1448” software provided by the ITU.

The separation distance around an FSS earth station is calculated based on the characteristics of the FSS and AMT stations, their antenna pointing directions, and the permissible level of interference. A parametric study was conducted to evaluate the effects of variations in system characteristics, propagation models, pointing directions, etc. The methodology consists of the following steps:

Step 1: Define the characteristics of the interfering and victim stations.

Step 2: Compute the required propagation loss based on the systems' characteristics and assumed pointing directions.

Step 3: Determine the required separation distance needed to obtain the required loss based on typical values and the propagation model under consideration in example calculations.

Step 4: Use example calculations with realistic parameters to show that required separation distances are much less than the coordination distance calculated under RR Appendix 7.

3 FSS system characteristics

The 6 GHz FSS uplink is assumed to be a 2.4 m antenna with a reference antenna pattern given in Recommendation ITU-R S.465-5 and operating at a power level that produces the maximum off-axis eirp levels specified in Recommendation ITU-R S.524-7.

Comparing these two models shows that the maximum allowable input power into the FSS antenna is 3 dB(W/4 kHz). A simple uplink link budget is shown in Table 5.

TABLE 5

FSS uplink link budget

Parameter	Description	Value
Transmit power density (dB(W/Hz))	3-10 log10(4e3)	–33.0
Transmit antenna gain (dBi)	2.4 m, 65% eff, Rec. 465	42.1
Rnge to satellite (km)	lat = 50; delta long = 40	39 418
Space loss (dB)	6 300 MHz	–200.3
Space station G/T (dB/K)	Assumed	0.0
C/N (dB)	$Pd + Gt + SL + G/T - k$	37.4

The earth station transmitter power level assumed here represents the worst case for interference into the AMT receiver and results in substantial FSS uplink margin. It is noted, however, that most earth stations transmit at power levels lower than those listed in Table 5.

The 4 GHz FSS downlink system characteristics are taken from RR Appendix 30B. For both the coordination and separation distance calculations, an *I*/*N* protection criterion of –13.9[1] dB The FSS *I*/*N* requirement of –15.2 dB was derived from Recommendation ITU-R S.1432 is assumed in the analysis of long-term interference in order to avoid underestimating required separation distances. For this band (4 500-4 800 MHz), RR Appendix 7 determines coordination distances based on much higher, short-term *I*/*N* values.

The characteristics of the FSS and aeronautical telemetry systems assumed in this analysis are summarized in Table 6.

TABLE 6

Baseline system characteristics

Parameter	FSS	AMT
Transmit		
Station	Earth Station	Aircraft
Frequency (MHz)	6312.5	4650
Power (dBW)	3.0	-1.2
Bandwidth	4 kHz	1 MHz
Line loss (dB)	0.0	-4.0
Antenna gain (dBi)	41.2	3.0
Antenna diameter (m)	2.4	n/a
Antenna efficiency (%)	65	n/a
Antenna pattern	S.465	omni
Height (m)	10	10000
Receive		
Station	Earth Station	Ground Station
Frequency (MHz)	4650	6312.5
Antenna gain (dBi)	49.1	46.0
Antenna diameter (m)	7.0	4.0
Antenna efficiency (%)	70	50
Antenna pattern	APP30B	F.1245
Height (m)	10	30
Noise temp (K)	170	400
Io/No requirement (dB)	-13.9	-3.0 dB 20% of time 0 dB 0.4% of time

---

[1] Recommendation ITU-R S.1432 recommends interference apportionment with respect to the total interference + thermal noise power. Recommendation ITU-R S.1432 recommends that 27% of this total noise power be apportioned to interference from all sources (i.e. 20% from other FSS systems + 6% from systems of other co-primary services + 1% from systems of secondary services). This means 73% of the total noise + interference represent receiver thermal noise power. Since there are two co-primary services in the band (i.e. MS and FS), the 6% allowance is split: 3% for MS and 3% for FS. This analysis uses the receiver thermal noise power in the *I*/*N* calculations – not the total thermal noise + interference power. Therefore, since the 3% allowance is referenced to the total thermal noise + interference power in Recommendation ITU-R S.1432, it should be adjusted to just thermal noise power in this analysis so that the appropriate threshold is $I_0/N_0 = 0.03/0.73 = 0.041$ (4.1%). Or, in terms of dB, $I_0/N_0 = –13.9$ dB. In this analysis it is assumed that the AMT interference power represents 3% of the total thermal noise + interference power (from all sources) and 4.1% of the receiver thermal noise power alone.

4 Required propagation loss

4.1 6 GHz sharing case

The separation distance around a transmitting FSS earth station necessary to protect an aeronautical telemetry receiving ground station is derived from the following expression:

$$I/N_{AMT} = Pd_{FSS} + L_{FSS} + G_{FSS}(\theta_{FSS}) + PL + G_{AMT}(\theta_{AMT}) - Nd_{AMT} \tag{1}$$

where:

I/N_{AMT}: required protection level into AMT receiver (dB)
Pd_{FSS}: transmit power density of FSS station (dB(W/Hz))
L_{FSS}: transmit line loss (dB)
$G_{FSS}(\theta_{FSS})$: gain of FSS station in direction of AMT station (dBi)
PL: propagation loss (dB)
$G_{AMT}(\theta_{AMT})$: gain of AMT station in direction of FSS station (dBi)
Nd_{AMT}: noise density of AMT receiver (dB(W/Hz)).

Note that the interfering signal is assumed to occupy the entire bandwidth of the wanted signal, so no frequency dependent rejection is accounted for in this analysis. Rearranging the above expression gives the required propagation loss:

$$PL = I/N_{AMT} - Pd_{FSS} - L_{FSS} - G_{FSS}(\theta_{FSS}) - G_{AMT}(\theta_{AMT}) + Nd_{AMT} \tag{2}$$

4.2 4 GHz sharing case

Similarly, the separation distance necessary to protect the FSS receiving earth station is determined from:

$$I/N_{FSS} = Pd_{AMT} + L_{AMT} + G_{AMT}(\theta_{AMT}) + PL + G_{FSS}(\theta_{FSS}) - Nd_{FSS} \tag{3}$$

where:

I/N_{FSS}: required protection level into FSS receiver (dB)
Pd_{AMT}: transmit power density of AMT station (dB(W/Hz))
L_{AMT}: transmit line loss (dB)
$G_{AMT}(\theta_{AMT})$: gain of AMT station in direction of FSS station (dBi)
PL: propagation loss (dB)
$G_{FSS}(\theta_{FSS})$: gain of FSS station in direction of AMT station (dBi)
Nd_{FSS}: noise density of FSS receiver (dB(W/Hz)).

Again, rearranging this expression gives the required propagation loss:

$$PL = I/N_{FSS} - Pd_{AMT} - L_{AMT} - G_{AMT}(\theta_{AMT}) - G_{FSS}(\theta_{FSS}) + Nd_{FSS} \tag{4}$$

5 Separation distance calculations

Three propagation models are used in this analysis: free space loss, the Empirical Propagation Model (EPM-73), and Recommendation ITU-R P.452. The required separation distance is determined from the propagation model under consideration.

5.1 Free space loss

Free space propagation loss (FSL) is found from the following expression:

$$PL = 20 \log_{10}\left(\frac{\lambda}{4\pi d}\right) \tag{5}$$

where:

λ: wavelength

d: distance

with consistent units of λ and d. Rearranging this expression to solve for d gives:

$$d = \frac{\lambda}{4\pi(10^{PL/20})} \tag{6}$$

5.2 Empirical propagation model (EPM-73)

EPM-73 is a propagation model which has the advantage of simplicity of calculations of basic transmission loss, and which provides a degree of accuracy which is similar to that obtained with other more sophisticated models. A complete description of this model is available in [IEEE, 1977].

The EPM-73 model requires the signal polarization, which can be either horizontal or vertical, as an additional input.

5.3 Recommendation ITU-R P.452-12

Recommendation ITU-R P.452-12 includes a complementary set of propagation models that ensure that the predictions embrace all the significant interference propagation mechanisms that can arise. Methods for analyzing the radio-meteorological and topographical features of the path are provided so that predictions can be prepared for any practical interference path falling within the scope of the procedure. In this analysis, a smooth Earth is assumed, i.e. the terrain height is assumed to be 0 km at all locations.

The approach in this procedure keeps separate the prediction of interference levels from the different propagation mechanisms up to the point where they can be combined into an overall prediction for the path. This overall prediction is made using a blending technique which ensures, for any given path distance and time percentage, that the signal enhancement in the equivalent notional line-of-sight model is the highest attainable.

Nominal values for radio meteorological parameters were taken from the data included in Recommendation ITU-R P.452-12 for central United States of America. Table 7 summarizes the values of the additional inputs required for each of the propagation models considered here.

TABLE 7

Additional data for propagation models

Propagation	FSL	EPM-73	Rec. ITU-R P.452
Polarization	N/A	H	N/A
Surface refractivity, N_0 (N-units/km)	N/A	N/A	330.0
Radio-refractive index lapse-rate, ΔN (N-units)	N/A	N/A	45.0

6 Results and example calculations

The coordination distance around an FSS earth station is computed for 3 latitudes in order to address different example operating environments. For each location, two satellite longitudes near the extremes of the visible GSO arc were considered. These were used so that worst-case (low) FSS earth station elevation angles (e.g. 10° for the assumption used in this study) would be addressed. The earth station locations are shown in Table 8.

TABLE 8

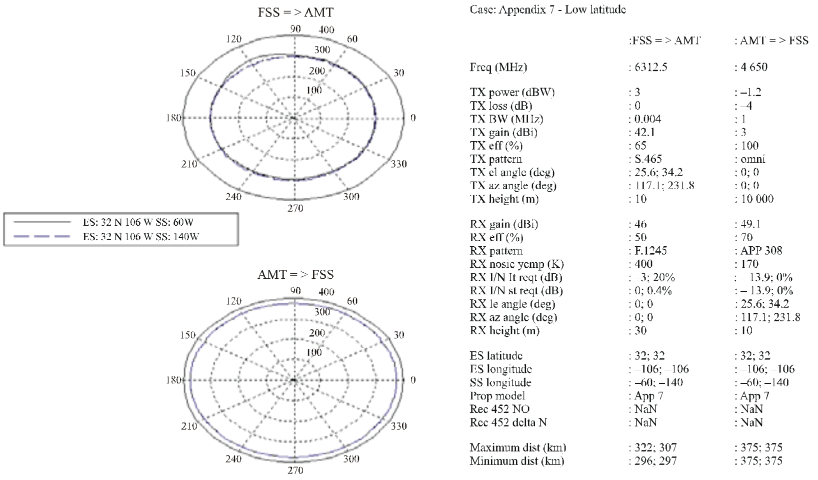
Earth station locations

Earth Station Location	Latitude	Longitude	Satellite Longitude
Low latitude	32.0	-106.0	-60, -140
Mid latitude	38.0	-101.0	-60, -140
High latitude	48.0	-107.0	-60, -140

The results are presented as plots of the coordination distance (Figs. 4a and 4b) and required separation distance (Fig. 5) around the FSS earth station necessary to protect both the FSS earth station and the telemetry receiving ground station.

FIGURE 4a

RR Appendix 7 calculated distance around FSS earth station
Low latitude case



Case: Appendix 7 - Low latitude

	:FSS = > AMT	: AMT = > FSS
Freq (MHz)	: 6312.5	: 4 650
TX power (dBW)	: 3	: –1.2
TX loss (dB)	: 0	: –4
TX BW (MHz)	: 0.004	: 1
TX gain (dBi)	: 42.1	: 3
TX eff (%)	: 65	: 100
TX pattern	: S.465	: omni
TX el angle (deg)	: 25.6; 34.2	: 0; 0
TX az angle (deg)	: 117.1; 231.8	: 0; 0
TX height (m)	: 10	: 10 000
RX gain (dBi)	: 46	: 49.1
RX eff (%)	: 50	: 70
RX pattern	: F.1245	: APP 308
RX nosie yemp (K)	: 400	: 170
RX I/N lt reqt (dB)	: –3; 20%	: – 13.9; 0%
RX I/N st reqt (dB)	: 0; 0.4%	: – 13.9; 0%
RX le angle (deg)	: 0; 0	: 25.6; 34.2
RX az angle (deg)	: 0; 0	: 117.1; 231.8
RX height (m)	: 30	: 10
ES latitude	: 32; 32	: 32; 32
ES longitude	: –106; –106	: –106; –106
SS longitude	: –60; –140	: –60; –140
Prop model	: App 7	: App 7
Rec 452 NO	: NaN	: NaN
Rec 452 delta N	: NaN	: NaN
Maximum dist (km)	: 322; 307	: 375; 375
Minimum dist (km)	: 296; 297	: 375; 375

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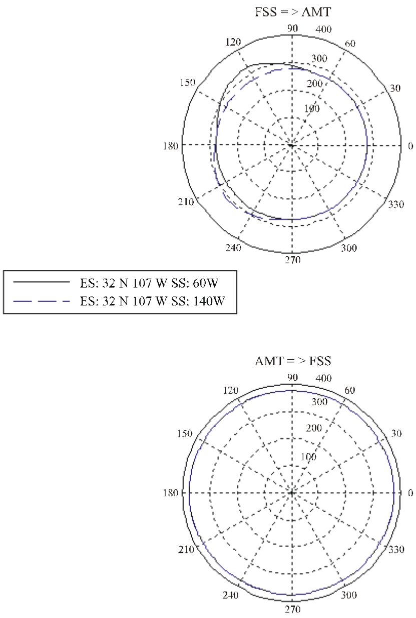
FIGURE 4b

RR Appendix 7 calculated distance around FSS earth station
High latitude case



Case: Appendix 7 - High latitude

	:FSS = > AMT	: AMT = > FSS
Freq (MHz)	: 6312.5	: 4 650
TX power (dBW)	: 3	: –1.2
TX loss (dB)	: 0	: –4
TX BW (MHz)	: 0.004	: 1
TX gain (dBi)	: 42.1	: 3
TX eff (%)	: 65	: 100
TX pattern	: S.465	: omni
TX el angle (deg)	: 17.8; 24.9	: 0; 0
TX az angle (deg)	: 124.7; 221.1	: 0; 0
TX height (m)	: 10	: 10 000
RX gain (dBi)	: 46	: 49.1
RX eff (%)	: 50	: 70
RX pattern	: F.1245	: APP 308
RX nosic ycmp (K)	: 400	: 170
RX I/N lt reqt (dB)	: –3; 20%	: – 13.9; 0%
RX I/N st reqt (dB)	: 0; 0.4%	: – 13.9; 0%
RX le angle (deg)	: 0; 0	: 17.8; 24.9
RX az angle (deg)	: 0; 0	: 124.7; 221.1
RX height (m)	: 30	: 10
ES latitude	: 48; 48	: 48; 48
ES longitude	: –107; –107	: –107; –107
SS longitude	: –60; –140	: –60; –140
P rop model	: App 7	: App 7
Rec 452 NO	: NaN	: NaN
Rec 452 delta N	: NaN	: NaN
Maximum dist (km)	: 328; 309	: 375; 375
Minimum dist (km)	: 277; 277	: 375; 375

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6.1 6 GHz case

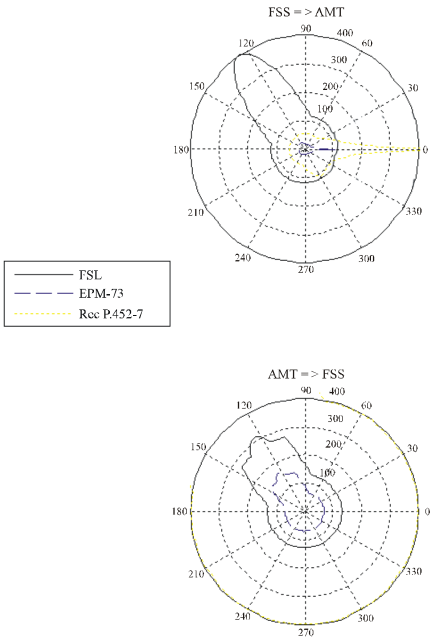
The RR Appendix 7 methodology assumes worst-case pointing of the telemetry ground station antenna along all azimuths around the FSS earth station and results in a nearly uniform coordination distance (for the cases considered here). The coordination distances can be on the order of 300 km.

In Fig. 5, the AMT ground station antenna pointing azimuth is always kept at 180°. As an example of the separation distances that may result, the worst-case location determined above is analyzed using the three propagation models described in the methodology section. For calculations using the Recommendation ITU-R P.452-12 propagation model, the separation distance is the maximum separation distance resulting from applying both interference criteria (–3.0 dB, 20% of time and 0 dB, 0.4% of time).

Large separation distances such as those seen along the 0° azimuth result when the AMT ground station is pointed directly at the FSS terminal. When AMT ground stations are deployed in the presence of existing FSS earth stations, this situation may be avoided through careful site selection in the coordination process. However, in the future deployment of FSS earth stations that may be pointed anywhere on the geostationary orbit, combined with the protection of AMT ground stations having variable pointing, it may not be possible to preclude this worst case situation. The FSL propagation model gives unrealistic results for interference between two ground-based stations. For this case the Recommendation ITU-R P.452-12 model is more appropriate. The separation distances along the ~120° azimuth are caused by coupling of the near-in side lobes of the FSS antenna into the AMT receiver. At higher FSS elevation angles, these distances would be reduced.

FIGURE 5

Separation distance around FSS earth station
High latitude case



Case: Appendix 7 - High latitude

	:FSS = > AMT	: AMT = > FSS
Freq (MHz)	6312.5	4 650
TX power (dBW)	3	–1.2
TX loss (dB)	0	–4
TX BW (MHz)	0.004	1
TX gain (dBi)	42.1	3
TX eff (%)	65	100
TX pattern	S.465	omni
TX el angle (deg)	17.8	0
TX az angle (deg)	124.7	0
TX height (m)	10	10 000
RX gain (dBi)	46	49.1
RX eff (%)	50	70
RX pattern	F.1245	APP 308
RX nosic ycmp (K)	400	170
RX I/N lt reqt (dB)	–3; 20%	– 13.9; 0%
RX I/N st reqt (dB)	0; 0.4%	– 13.9; 0%
RX le angle (deg)	0	17.8
RX az angle (deg)	0	124.7
RX height (m)	30	10
ES latitude	48	48
ES longitude	–107	–107
SS longitude	–60	–60
P rop model	FSL; EPM; 452-12	FSL; EPM; 452-12
Rec 452 NO	330	330
Rec 452 delta N	45	45
Maximum dist (km)	101 309; 106; 466	314; 156; 709
Minimum dist (km)	117; 19; 53	129; 68; 397

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6.2 4 GHz case

The 375 km distances shown for 4 GHz in Figs. 4a and 4b and Table 10 were calculated using the case-by-case methodology of RR Appendix 7 (WRC-03). This is because no predetermined distance was specified in Table 10 of Appendix 7 (which species a 500 km coordination distance for other cases involving aircraft transmitters).

The EPM-73 and Recommendation ITU-R P.452-12 models were not used to determine separation distances for the 4 GHz cases. This is because they are not intended for cases involving very high antenna heights (such as AMT vehicles sharing with FSS receive earth stations). For this case, interference into the FSS earth station receiver from the telemetry aircraft station should be based on FSL. Again, in Fig. 5, the separation distances along the ~120° azimuth are caused by coupling of the AMT transmitter into the near-in side lobes of the FSS antenna. At higher FSS elevation angles, these distances would be reduced.

TABLE 9

Assumed AMT and FSS characteristics

Parameter	FSS	AMT
Location		
Earth station latitude (deg)	38	38
Earth station longitude (deg)	-106	-106
Space station longitude (deg)	-101	n/a
Transmit		
Station	Earth Station	Aircraft
Frequency (MHz)	6312.5	4650
Power (dBW)	30.0	-1.2
Bandwidth	30 MHz	1 MHz
Line loss (dB)	0.0	-4.0
Antenna gain (dBi)	51.4	3.0
Antenna diameter (m)	7.0	n/a
Antenna efficiency (%)	65	n/a
Antenna pattern	S.465	omni
Height (m)	10	10000
Receive		
Station	Earth Station	Ground Station
Frequency (MHz)	4650	6312.5
Antenna gain (dBi)	49.1	46.0
Antenna diameter (m)	7.0	4.0
Antenna efficiency (%)	70	50
Antenna pattern	APP30B	F.1245
Height (m)	10	30
Noise temp (K)	170	400
Io/No requirement (dB)	-12.2	-3.0 dB 20% of time 0 dB 0.4% of time

TABLE 10

Summary of results

Appendix 7 distance calculations							
low	25.6	maximum	None	322	296	375	375
mid	26.4	maximum	None	315	288	375	375
high	17.8	maximum	None	326	277	375	375

Separation distance calculations							
ES latitude	ES elevation angle	ES transmit power	Varied parameter	Interference into AMT		Interference into FSS	
				Maximum distance (km)	Minimum distance (km)	Maximum distance (km)	Minimum distance (km)
high	17.8	maximum	None	466	53	314	129
mid	45.5	typical	None	439	37	113	106
mid	45.5	typical	AMT station height	431 - 451	29 - 44	113	106
mid	45.5	typical	FSS station height	432 - 444	31 - 43	113	106
mid	10 - 40	typical	FSS elevation angle	433 - 436	37	133 - 528	106
mid	45.5	typical	AMT ground station gain	411- 459	37 - 38	113	106

NOTE 1 – RR Appendix 7 distance calculation assume a FSS *I*/*N* of –13.9 dB while separation distance calculations in this example, except for high latitude case, use an *I*/*N* of –12.2 dB.

References

IEEE Trans. Electromag. Comp. [August 1977] Vol. EMC-19, **3**, p. 301-309.

Annex 3

Analysis of AMT for flight testing sharing with the FSS (space-to-Earth) in the 4 500-4 800 MHz band

1 Introduction

The 4 500-4 800 MHz band is allocated on a worldwide primary basis to the fixed-satellite service (FSS) (space-to-Earth). Under ITU Radio Regulation (RR) 5.441, the use of this band by the FSS is governed by the provisions of RR Appendix 30B (AP30B). The ITU SRS (space radiocommunication systems) database shows that there are 12 systems in the 4 500-4 800 MHz downlink band: 3 satellites over India and 9 satellites over Russia. In this sharing analysis, however, it is assumed that any of the allotments in Part A of the AP30B Plan have come into use. The objective of the following analysis is to assess potential interference from these FSS satellites to various AMT ground stations

2 Methodology and assumptions

2.1 AMT characteristics

AMT ground stations are assumed to be located within (17) flight test areas shown in Fig. 6 of the main text. Interference results were calculated for 2 m (6.6 ft), 3 m (10 ft), and 7 m (23 ft) diameter ground station antennas. The AMT ground station antenna pattern was based on Recommendation ITU-R S.465. The Recommendation ITU-R S.465 pattern was selected since it has the slower roll-off and hence greater sensitivity to off-axis interference[2]. For a given AMT antenna size and test zone, the aggregate FSS satellite downlink interference into the AMT ground station receiver was calculated as a function of the ground station antenna pointing angle. The pointing angle was varied in azimuth from 90° (due East) to 270° (due West) and in elevation from 0° (horizontal) to 90° (zenith). All GSO FSS satellites in the AMT ground station field-of-view (FOV) were included in the aggregate interference calculation. Free-space propagation conditions were assumed. To be conservative, no polarization discrimination was included.

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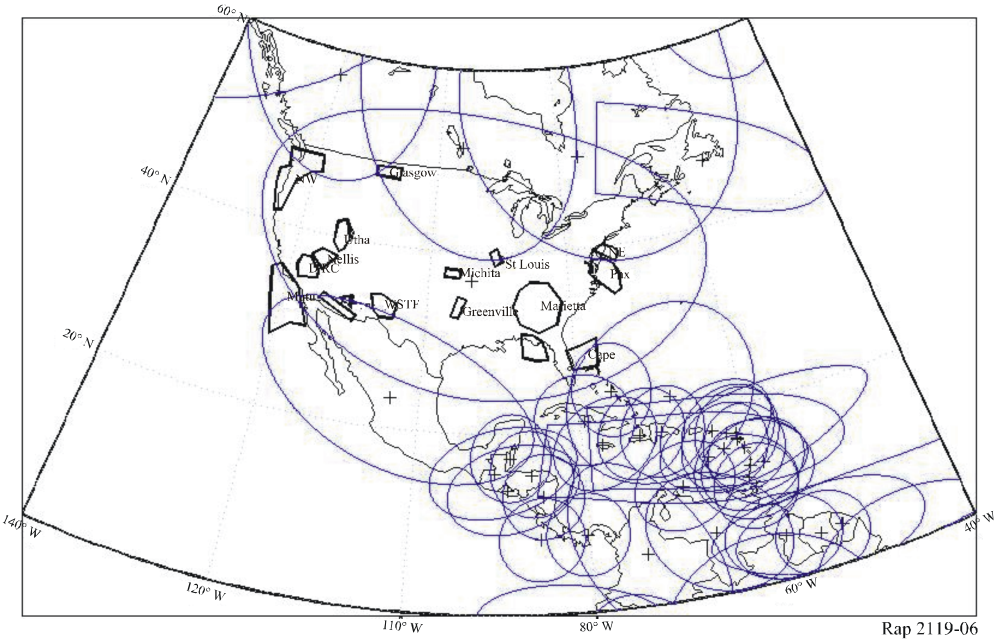
[2] The pattern in Recommendation ITU-R M.1459 was also considered, but is not general enough for this analysis since the equations are specific to telemetry antennas operating in the 1 452-1 525 MHz band with gain of either 29 dBi or 41.2 dBi.

2.2 FSS characteristics

FSS satellite locations; (elliptical) beam parameters (i.e. bore-sight aim point latitude and longitude, major and minor axis beam-widths, orientation angle); and maximum e.i.r.p. spectral densities were taken from the FSS Plan (see RR Appendix 30B). The FSS Plan is based on the use of satellite antennas with elliptical or circular beams. The gain pattern is defined in Annex 1 of RR Appendix 30B. FSS satellite antenna beams that fall on or near the flight test areas are shown in Fig. 6. Note that the interference calculations involve determining the appropriate half-power-beamwidth in the direction of interest (i.e. in the direction of the AMT ground station in this case) for each of the visible FSS beams.

FIGURE 6

RR Appendix 30B (Annex 1) FSS satellite antenna pattern



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3 Analysis results

A software program was developed to calculate the aggregate FSS interference to noise power density ratio (I_0/N_0) at the AMT ground station receiver from all visible FSS satellites as a function of the earth station antenna pointing angle. Table 11 is a summary of the results for the 17 test areas for 3 different antenna sizes: 2 m; 3 m; and 7 m. For each antenna size, 3 columns of data are given:

- the maximum I_0/N_0 over the entire 90°-270° azimuth and 0°-90° elevation pointing angle range;
- the maximum I_0/N_0 when the antenna is pointed below 20° elevation; and
- the maximum I_0/N_0 when the antenna is pointed below 5° elevation.

The 20° and 5° elevation data are important since it is estimated that most telemetry ground station antennas spend approximately 98% of the time pointed below 20° elevation and 85% of the time pointed below 5° elevation. For 2-3 m antenna sizes, which are common, the worst case I_0/N_0 ranges from 4.4 to 7.9 dB for pointing elevations above 20° and –3.7 to –9.5 dB for pointing elevations below 20°. For a 7 m antenna, which is rare, the peak I_0/N_0 can reach 15 dB, but drops to 1 dB to 3.5 dB for pointing below 20°. The highest interference occurs for the test zones closest to the United States of America beam aim point (i.e. Wichita, Greenville, St. Louis).

TABLE 11

Aggregate interference from 4 GHz FSS GSO satellites into AMT ground stations

					2 meter (6.6 ft) G/S Antenna (37.6 dBi gain; 2.3°HPBW)			3 meter (10 ft) G/S Antenna (41.1 dBi gain; 1.6°HPBW)			7 meter (23 ft) G/S Antenna (48.4 dBi gain; 0.67°HPBW)		
AMT TEST ZONE	Ground Station Latitude (°N)	Ground Station Long (°E)	Worst Case G/S Ant Pointing Angle (AZ/EL)		Worst Case Io/No (dB) (at worst case pointing)	Worst Case Io/No (dB) below 20° EL	Worst Case Io/No (dB) below 5° EL	Worst Case Io/No (dB) (at worst case pointing)	Worst Case Io/No (dB) below 20° EL	Worst Case Io/No (dB) below 5° EL	Worst Case Io/No (dB) (at worst case pointing)	Worst Case Io/No (dB) below 20° EL	Worst Case Io/No (dB) below 5° EL
Pt Mugu	31.40	-119.76	167.2	52.6	1.3	-25.5	-35.4	4.8	-22.2	-32.8	11.9	-15.1	-27.8
DFRC	35.87	-117.74	152.8	44.8	2.3	-25.5	-35.0	5.8	-22.2	-32.0	13.1	-15.2	-25.0
Nellis	37.21	-115.53	156.8	44.2	2.8	-11.8	-11.8	6.4	-8.3	-8.3	13.7	-1.2	-1.2
Utah	39.82	-113.58	160.8	42.2	3.2	-12.2	-12.2	6.7	-8.8	-8.8	13.9	-1.5	-1.5
NW	44.96	-123.08	150.2	33.8	1.8	-22.0	-25.6	5.3	-19.0	-22.4	12.5	-12.5	-15.6
YUMA	32.56	-112.86	158.6	50	2.6	-10.8	-10.8	6.1	-7.3	-7.3	13.4	-0.1	-0.1
Mesa	33.33	-111.34	161.6	49.6	3.0	-10.8	-10.8	6.5	-7.3	-7.3	13.8	0.1	0.1
WSTF	33.22	-106.53	170	50.8	3.6	-10.0	-25.2	7.1	-6.5	-23.1	14.2	0.6	-17.6
Glasgow	47.90	-108.50	170	34.4	2.7	-9.0	-14.3	6.2	-5.5	-10.8	13.3	1.6	-3.6
Wichita	37.49	-96.92	186.6	46.4	**4.4**	-8.8	-27.3	**7.9**	-5.4	-24.7	**15.1**	1.6	-18.2
Greenville	33.62	-95.86	189.2	50.6	**4.4**	**-7.1**	-28.9	**7.9**	**-3.7**	-27.5	15.0	**3.5**	-24.2
St. Louis	39.26	-90.42	196.4	43.2	4.3	-7.6	-32.2	7.8	-4.1	-31.6	**15.1**	3.1	-24.8
Eglin	29.56	-85.32	209.6	51.4	3.6	-20.1	-20.7	7.1	-16.6	-17.9	14.3	-9.5	-16.3
Cape	28.13	-79.18	220.4	49.2	2.7	-9.5	**-9.5**	6.2	-6.0	**-6.0**	13.4	1.1	**1.1**
PAX River	36.70	-74.36	220	39	3.2	-17.9	-17.9	6.7	-14.5	-14.5	14.1	-7.6	-7.6
NE	39.48	-74.11	218.6	36.6	3.1	-12.2	-12.2	6.6	-8.7	-8.7	13.7	-1.5	-1.5
Marietta	34.36	-84.45	207.8	46.4	4.1	-20.1	-20.1	7.6	-16.6	-16.6	14.8	-9.4	-9.4

NOTES:

a) Worst interfering satellite beam for Pt Mugu test area is MEX at 113°W. Worst beam for other test zones is United States of America at 101°W.

b) Data for 20° and 5° pointing elevation are included since it is estimated that most telemetry ground station antennas spend approximately 98% of the time pointed below 20° elevation and 85% of the time pointed below 5° elevation.

4 Conclusions

This analysis has considered potential downlink interference from FSS satellites with AP30B technical characteristics into telemetry ground terminals. Currently, there are very few FSS satellites operating downlinks in the 4 500-4 800 MHz band. (The latest data indicates 3 satellites over India and 9 over Russia.) Aggregate interference results were calculated for AMT ground stations at 17 major test areas in the United States of America. The results indicate that *if* a US FSS satellite and perhaps satellites of neighbouring administrations were to operate in the 4 500-4 800 MHz band according to the RR Appendix 30B Plan, they could cause significant interference (i.e. 4 dB to 15 dB I_0/N_0) into an AMT ground station at certain pointing angles – mostly above 30° elevation. However, given the fact that most telemetry stations operate at elevation angles below 20° the vast majority of the time and antenna sizes will typically be in the 2-3 m range, FSS interference in these cases is less than –3 dB (I_0/N_0). A relatively high interference threshold of –3 dB can be tolerated in this case since the band will not be used to support critical safety-of-life or safety-of-flight data. It is envisioned that these critical communications would continue to be conducted within the current telemetry spectrum below 3 GHz. It would be possible to avoid excessive interference to specific ground stations by establishing appropriate no-fly zones around the station to prevent main-beam pointing towards the worst interfering satellites.

The relative gain fall-off (dB) is given by:

$$G_{std}\,(\psi, \psi_0, \psi_{major}, \psi_{minor}) := \left|\begin{array}{ll} G_{max} \leftarrow 44.45 - 10\log(\psi_{major}\psi_{minor}) & \\ \beta \leftarrow \dfrac{\psi}{\psi_0} & \\ X \leftarrow -12\cdot\beta^2 & \text{if } 0 \le \beta \le 1.45 \\ X \leftarrow -(22 + 20\log(\beta)) & \text{if } \beta < 1.45 \\ X \leftarrow -G_{max} & \text{if } X < -G_{max} \end{array}\right.$$

where:

Ψ: off-axis angle (degrees)

Ψ_0: beam cross-sectional HPBW in the direction of interest (degrees)

G_{max}: maximum antenna gain (dBi)

Ψ_{major}: major axis HPBW (degrees) (full angle)

Ψ_{minor}: the minor axis HPBW(degrees) (full angle).

Annex 4

Potential aeronautical mobile telemetry (AMT) interference to radio astronomy in the 4 825-4 835 MHz band

1 Problem statement and objective

The 4 825-4 835 MHz band is allocated on a secondary basis to the radio astronomy service (RAS); however, under RR 5.443, the RAS has primary status in this band in Argentina, Australia, and Canada. It should also be noted that under RR 5.442, the aeronautical mobile service (AMS) is currently excluded from the 4 825-4 835 MHz band. However, because AMT operations are generally limited to a relatively few number of specific geographic test areas and RA sites are also relatively few in number, it may be possible for AMT applications to share the band with RAS in certain administrations. Recommendation ITU-R RA.314-10 identifies the frequency 4 829.66 MHz as an important spectral line for Formaldehyde (H2CO) measurements and lists a suggested minimum band of 4 813.6-4 834.5 MHz. This Annex examines sharing between RAS and AMT in the U.S. by considering those RA sites operating in the 4 825-4 835 MHz band and their proximity to AMT test areas. Line-of-sight (LoS) situations between RAS sites and test areas are identified; required separation distances under LoS conditions are calculated; and AMT e.i.r.p. out-of-band emission limits necessary to protect RAS are examined.

2 Assumptions

The assumptions used in the analysis are as follows:

2.1 AMT characteristics

1 AMT aircraft are assumed to be transmitting within the 17 geographic test zones shown the map of Fig. 1 of § 2 of the main text.

2 When in LoS, the radiated e.i.r.p. spectral density ($EIRP_0$) of the AMT emitter in the direction of the RAS site is assumed to be –11.2 dB(W/MHz). This represents a telemetry transmitter with 10 W power; 20 Mbit/s information data rate/25.22 Mbit/s coded data rate; –6 dBi average antenna gain; 4 dB cable/line losses; and SOQPSK modulation along with FEC (forward error correction) coding (Turbo Product Code with $r = 0.793$).

2.2 Radio astronomy characteristics

1 The (11) RA observatories considered in this analysis are shown in Fig. 7. The Allen Telescope Array (ATA) in Hat Creek, CA; Green Bank Telescope (GBT) in Green Bank W VA; and very large array (VLA) in Socorro, NM are the sites most vulnerable to interference. The other sites which conduct interferometry measurements have much higher immunity to interference (ref Table 3 in Recommendation ITU-R RA.769-2 which shows 30 dB higher interference threshold for VLBI).

2 From Recommendations ITU-R RA.769-2 and ITU-R SA.509, the RA antenna side-lobes are modelled by $G_r(\psi) = 32\text{-}25 \log(\psi)$ dBi where ψ is the off-axis angle from the main beam axis and is in the range $1° < \psi < 48°$. Note that interference to radio astronomy receivers is almost always received through the antenna side lobes so that the main beam response to interference is not usually considered.

3 The relevant receiver parameters are taken from Table 2 of Recommendation ITU-R RA.769 (i.e. Threshold levels of interference detrimental to radio astronomy spectral-line observations). These include:

a) Nominal spectral line frequency ($f = 4\,830$ MHz).

b) Spectral line channel bandwidth ($\Delta f = 50$ kHz).

c) Antenna noise temperature ($T_A = 12$ K).

d) Receiver noise temperature ($T_R = 10$ K).

e) System sensitivity (in terms of noise temp increase):
$\Delta T = (T_A + T_R)/\sqrt{\Delta f \cdot 2000} = 2.2e-3$ (K) where the integration time is $t = 2\,000$ s (33.33 min).

f) System sensitivity (in terms of power spectral density):
$\Delta P = 10 \log(k\Delta T) = -255$ dB(W/Hz).

g) Threshold interference power (introduces 10% error in measurement of ΔP in bandwidth Δf): $\Delta P_H = 10 \log(0.1\Delta P \Delta f) = -218$ (dBW).

h) Threshold interference power flux density (PFD at antenna at incident angle ψ with side-lobe gain $G_r(\psi)$ that results in power ΔP_H): $\text{PFD}(\psi) = 10 \log[\Delta P_H/A_e(\psi)]$ (dB(W/m^2)) where ΔP_H is expressed in units of W and $A_e(\psi)$ is the effective area of the antenna at off-axis angle ψ given by: $A_e(\psi) = 10^{[Gr(\psi)/10]}\, \lambda^2/(4\pi)$ (m^2). Note that the value in Table 2 of Recommendation ITU-R RA.769 is for the case of a 0 dBi side-lobe gain (i.e. $\psi = 19.05°$) which gives PFD (19.05) = –183 dB(W/m^2).

i) Threshold interference spectral PFD is given by: $S_H(\psi) = 10 \log[\text{PFD}(\psi)/\Delta f]$ (dB(W/(m$^2 \cdot$ Hz))) where PFD(ψ) is expressed in non-dB units (i.e. W/m^2). Again, for the case of a 0 dBi side-lobe gain assumed in Table 2 of Recommendation ITU-R RA.769, we get $S_H(19.05)$ = –230 dB(W/(m^2 · Hz)) or –170 dB(W/(m^2 · MHz)).

j) For the case of VLBI, the tolerable interference level from Recommendation ITU-R RA.769 is 1% of the receiver thermal noise power to prevent serious errors in the measurement of cosmic signals. Based on the values of T_A =12 K and T_R =10 K in Table 1 of Recommendation ITU-R RA.769, this represents an interference threshold of I_0 = 10 log[k*(T_A + T_R)*0.01] = –235.18 dB(W/Hz). The corresponding PFD is then PFD$_{VLBI}(\psi)$ = 10 log[$I_0/A_e(\psi)$] (dB(W/(m^2 · Hz))) where I_0 is first converted to units of W/Hz. For the case of 0 dBi side-lobe gain in which ψ = 19.05°, we have PFD$_{VLBI}(19.05)$ = –200 dB(W/(m^2 · Hz)) or –140 dB(W/(m^2 · MHz)) which is the value shown in Table 3 of Recommendation ITU-R RA.769. Thus, the interference threshold for VLBI is about 30 dB higher than non-VLBI making VLBI more immune to interference.

3 Analysis results

It is very difficult for the RAS to share frequencies with any other service in which direct LoS paths from the (interfering) transmitters to the observatories are involved. For an AMT emitter within LoS of an RAS antenna radiating an e.i.r.p. spectral density in the direction of the RAS site, the received power flux density (PFD) at the RAS antenna at a distance D (m) under free-space propagation conditions is PFD$_0$ = 10 log[eirp$_0/(4\pi D^2)$] (dB(W/(m^2 · MHz))) where eirp$_0$ is in units of W/MHz. Solving for D and setting PFD$_0$ to the threshold level $S_H(\psi)$ above, necessary to protect the RAS, the required separation distance is: $D_{sep}(\psi)$ = [eirp$_0/(4\pi * s_h(\psi))$]^(1/2) (m) where $s_h(\psi)$ is the threshold spectral PFD expressed in units of W/(m^2 · MHz). If we assume a nominal

AMT emitter e.i.r.p. spectral density of –11.2 dB(W/MHz), the required separation distance between the RAS site and a co-frequency AMT aircraft must exceed the aircraft radio horizon distance (450 km).

It is also of interest to find the maximum allowable e.i.r.p. spectral density emission that will protect the RA under LoS conditions. For a non-VLBI site, the e.i.r.p. varies from –35 to –63 dB(W/MHz) for –10 dBi side-lobe gain and –45 to –73 dB(W/MHz) for 0 dBi side lobes. For VLBI, the EIRP values are 30 dB lower in both cases.

FIGURE 7

Radio astronomy sites operating in the 4 825-4 835 MHz band

Annex 5

Frequency sharing between aeronautical high bit-rate telemetry for flight testing and systems in the fixed and mobile services

1 Introduction

Section 2 of this Annex describes the analysis and present results pertaining to potential interference to FS/MS systems from AMT aircraft telemetry transmitters. Section 3 addresses potential interference from FS/MS transmitters to receiving AMT ground stations. The focus of the analyses is on the band 5 925-6 700 MHz because this band is particularly heavily used by FS/MS stations.

2 Potential interference to fixed mobile stations

2.1 System parameters used in the simulations

All of the results presented in this contribution were derived from the same set of parameters for the FS/MS and AMT systems. In particular, the FS/MS parameters used are those in Table 12, which were derived from Recommendation ITU-R F.758. The parameters assumed for the AMT transmitter are summarized in Table 13.

TABLE 12

FS parameters

Parameter	Symbol	Value
Frequency (GHz)	f_{GHz}	6.3
Antenna gain (dBi)	G_r	46 and 38
Feeder loss (dB)	L_f	3.0
Antenna height (m)	h_r	100
Antenna elevation angle (degrees)	α	0, 2.2, 5.0
Receiver noise temperature (K)	T_{eff}	750
Receiver noise floor (dB(W/MHz))	N_T	–139.9

The interfering signal power at a fixed service receiver is determined by the following equation:

$$I_r = P_t + G_t + G_r(\theta) - L_b - L_f \qquad (7)$$

where $G_r(\theta)$ is the receiver antenna gain at the off-bore-sight angle θ as determined from Recommendation ITU-R F.1245. The propagation loss is determined as:

$$L_b = 92.4 + 20\log(f_{GHz}) + 20\log(d_{slkm}) \qquad (8)$$

where d_{slkm} is the slant path distance (km) from the AMT transmitter to the FS receiver.

The interference power is assumed to propagate on a straight line path within the plane of the great circle determined from the positions of the AMT transmitter, the FS receiver and the centre of the Earth where the Earth is assumed to have a radius (8 504 km) that is 4/3 of its actual value (6 378 km). This allows the effect of atmospheric refraction to be taken into account.

2.2 Methodologies and interference criteria

2.2.1 Review of interference criteria

Before discussing the simulation methodologies it is necessary to determine the appropriate interference criteria to be applied in this sharing situation. Although no FS interference criteria have been developed for AMT use of the 5 925-6 700 MHz frequency band, criteria have been developed for portions of this band or for nearby bands in sharing studies with other services employing moving emitters of potential interference. Table 13 summarizes the criteria as given in these relevant ITU-R Recommendations. This table is discussed in the following paragraphs.

TABLE 13

Recommended fixed service interference criteria

Recommendation ITU-R	Year developed	Frequency band (interferer)	Short-term criterion	Long-term criterion
SF.1320	1997	6 700-6 825 MHz (MSS space-to-Earth links in the FSS)	–	FDP $\leq$ 4%
F.1494	2000	10.7-12.75 GHz (non-GSO FSS space-to-Earth links)	$I/N < 20$ dB (hard limit) (Note: I/N is the interfering signal to noise power ratio)	FDP < 10%
SF.1650	2003	5 925-6 425 MHz (earth stations on vessels)	$I/N < 23$ dB for all but 1.2 10^{-5}% of a month (SES)	–
			$I/N < 19$ dB for all but 4.5 10^{-4}% of a month (ES)	

By way of explanation, FDP is the fractional degradation in performance as defined in Recommendation ITU-R F.1108. It can be used where multipath fading is the primary limit on the performance of a fixed service link. Although Recommendation ITU-R F.1108 suggests a value of 10%, Recommendation ITU-R SF.1320 used a lower value (FDP of 4%) because it addressed the addition of space-to-Earth interference in a frequency band where the FS was already exposed to interference from Earth-to-space operations by the FSS and because of the wide-spread use of diversity operation by the FS in this band. The fractional degradation in performance of a diversity (FDPD) FS system will be more than twice as great as the non-diversity FDP, as shown in Annex 4 of Recommendation ITU-R F.1108 and § 2 of the Annex to Recommendation ITU-R SF.1320. It is notable that the band 6 425-7 025 MHz is administered for FS use as the upper 6 GHz band by most administrations in accordance with Recommendation ITU-R F.384 (in the US, the upper 6 GHz band is 6 525-6 875 MHz). Since the centre reference frequency for the band is 6 770 MHz and the FSS operates in the Earth-to-space direction throughout the entire band, the same interference considerations should apply to both halves of the band. The same long-term criterion should be used for the entire band from 5 925 to 6 700 MHz because the FSS operates in the Earth-to-space direction throughout this entire band.

While precipitation fading may affect the performance on many paths near 10 GHz, the interference criteria of Recommendation ITU-R F.1494 were developed under the assumption that system performance in the absence of interference was limited only by multipath fading. The approach taken in Recommendation ITU-R F.1494 was to develop short-term interference criteria for severely errored seconds (SES) and for errored seconds (ES). By imposing a hard limit on I/N, the recommended short-term interference criterion prevents any performance degradation relative to the error performance objectives (EPO) for either SES or ES because of short-term interference events.

Since diversity is not used much by the FS in the frequency bands above 10 GHz, the entire performance degradation of 10%, as specified by Recommendation ITU-R F.1108, can be allocated to the long term interference in this band.

Typical FS systems in the 6 GHz bands have the same fade margins as typical systems in the 10.7-12.75 GHz bands and are even more likely to implement automatic transmit power control (ATPC). Hence, the interference criteria applied in Recommendation ITU-R SF.1650 were developed using an approach similar to that used in Recommendation ITU-R F.1494. The difference is that the interference considerations in Recommendation ITU-R SF.1650 are limited to short-term interference events so that only short-term interference criteria were needed. The two criteria listed in Table 13 are those required to meet SES and ES error performance objectives.

Although the interference criteria of Recommendation ITU-R SF.1006 were considered for inclusion in Table 13, Recommendation ITU-R SF.1006 was developed in 1993, before the criteria of Recommendation ITU-R F.1108 were developed to address moving sources of interference and before current performance criteria for FS systems were in place. In particular, Recommendation ITU-R SF.1649 notes that the short-term criteria of Recommendation ITU-R SF.1006 are only compliant with ITU-T Recommendation G.821. On the other hand, Recommendation ITU-R SF.1650 provides FS short-term protection criteria for up-to-date links designed to meet the requirements of ITU-T Recommendations G.826 and G.828. Furthermore, Recommendation ITU-R SF.1006 was developed for use in bilateral or multilateral discussions between administrations to address interference when stations are within a coordination area. Its criteria contain parameters that need to be agreed between the two parties to a coordination and it has never been used in any sharing study.

In conclusion, from the various FS frequency sharing situations addressed in existing Recommendations, the short-term interference criteria applied in Recommendation ITU-R SF.1650 and the long-term interference criteria applied in Recommendation ITU-R SF.1320 appear to be the most applicable for the AMT sharing situation in the 5 925-6 700 MHz band.

2.2.2 Application of interference criteria

In the case of short-term interference from AMT systems, the distribution of interference power is determined by the physical location statistics of all of the AMT systems. While both short- and long-term interference criteria would need to be met by AMT interference, it is not clear whether one of them will always be controlling. As a first step in determining the effects of short-term interference events from AMT systems, short-term interference will be examined by determining where I/N exceeds 19 and 23 dB, as given in Table 13, using the maximum value of transmit antenna gain. This does not determine whether short-term interference criteria are exceeded, but only identifies the extent of regions where short-term interference may be a problem.

Air-traffic considerations may limit AMT operations at some test ranges to a limited number of altitudes within a test range and aircraft may be required to file flight plans indicating the tracks over the Earth where they will operate. This consideration can be accommodated by a simulation that evaluates the long-term interference resulting from AMT operations over defined paths. Details of the approach used are provided in § 2.4.

2.3 Short-term interference analysis

The short-term interference examination in this study begins by determining the regions relative to a fixed service receiver where of AMT operations would cause the interference-to-noise ratio at the FS receiver to exceed 19 or 23 dB. To this end, the FS receiver is located at a point on a spherical Earth with a local coordinate system in which it appears to be at the North Pole. In this coordinate system all the great circle paths through the location are equivalent to lines of constant longitude on the Earth. One can determine the desired regions by stepping along one of these great circles in

0.1 km increments. At each point one can determine the *I*/*N* that would be produced by an AMT transmitter at a given altitude directly over this point. The calculation assumes straight-line propagation over an Earth with a radius 4/3 times the true Earth radius. This process is continued until the test point reaches the distance at which the AMT transmitter at the specified altitude is no longer visible at the fixed service receiver. Figure 8 shows the results of this calculation assuming the maximum FS/MS transmit gain (46 dBi), the three elevation angles, and with 19 dB as the critical value of *I*/*N*.

Note that the scale of the x-axis, or cross-main-beam axis, is greatly exaggerated. The width of the regions where *I*/*N* exceeds 19 dB varies with the altitude of the AMT transmitter and with the FS antenna elevation angle. The widths, as shown in Fig. 8, vary from 2 to 5 km and the lengths from 150 at low elevation angles to 30 at the higher angles. Furthermore, the regions are spread along the main-beam axis out to a distance of 450 km when the elevation angle of the receiving antenna is 0° but to a distance of only 170 km when the elevation angle of the receiving antenna is 5°. The contours shown in Fig. 8 define the regions within which an AMT transmitter would be expected to cause the fixed service receiver to experience one bit error or more per second. The receiver would be expected to experience severely errored seconds (SESs) if there was a portion of any of these regions from which an AMT transmitter would cause the *I*/*N* to be greater than 23 dB.

It is apparent that the region where *I*/*N* exceeds 19 dB is a column in altitude with a tilt along the main-beam axis of the receiving antenna. The column has a long thin profile at any altitude cut and its dimensions in this cut depend on the altitude and the elevation angle of the FS receiving antenna. The tilt of the column, as evidenced by the distance along the main-beam axis of the various altitude contours, depends on the same parameters.

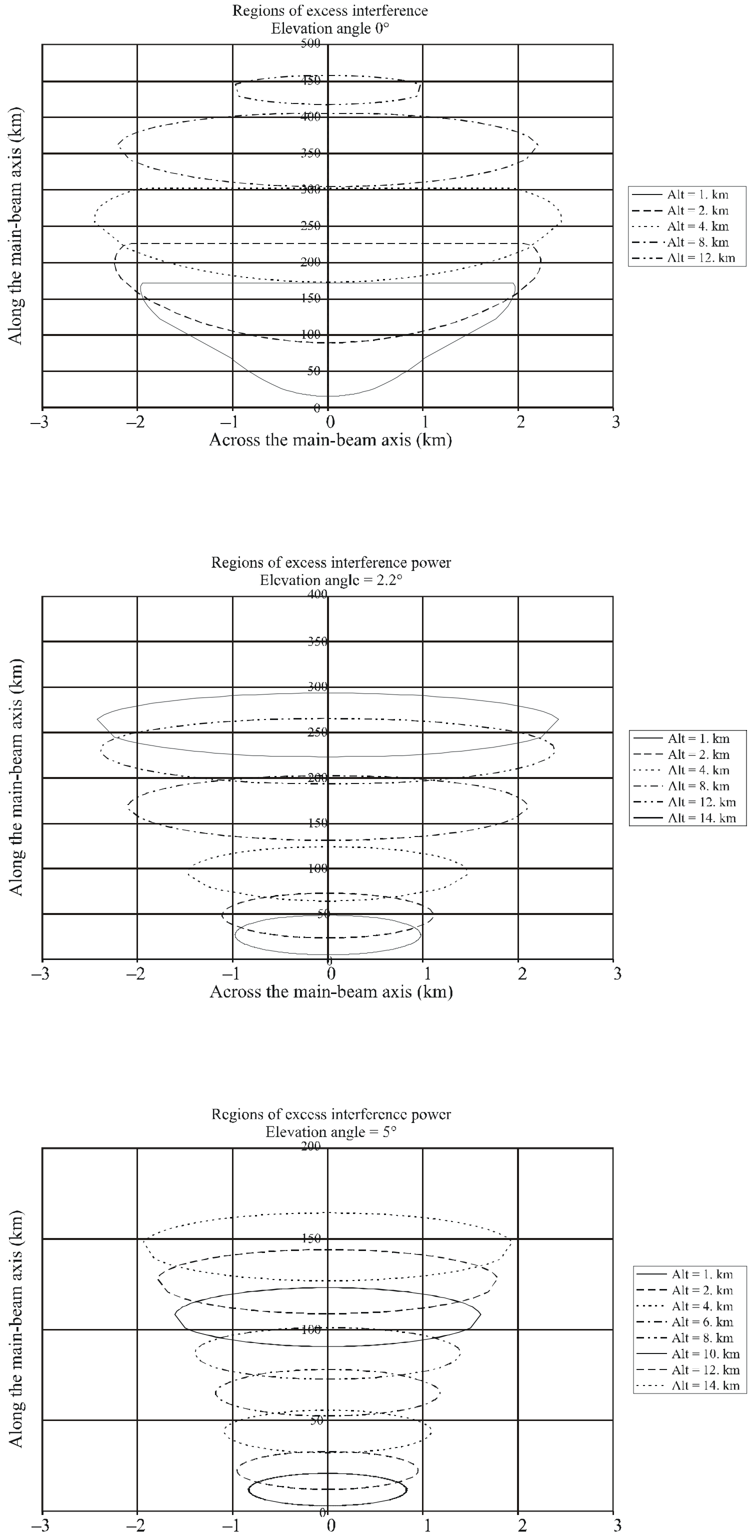
Figure 9 repeats the plots of Fig. 8, but also shows the regions where *I*/*N* exceeds 23 dB. These regions, within which an AMT transmitter would be expected to cause the FS receiver to experience Severely Errored Seconds (SESs), fill a large portion of the 19-dB contours at many altitudes. The widths of the SES contours, as shown in Fig. 9, vary from 1.5 to 3 km and the lengths from 120 km at low elevation angles to 20 km at the higher angles. The regions extend along the main-beam axis out to a distance of 300 km when the elevation angle of the receiving antenna is 0°, but, as before, to a distance of 170 km when the elevation angle of the receiving antenna is 5°. Note that when the elevation angle of the FS antenna is 0° there are no regions at altitudes of 5 km or higher where AMT operations will result in severely errored seconds.

Consider the case where an AMT transmitter is operating in the air space above the projection of the FS receiving antenna main-beam axis on the surface of the Earth. If the aircraft was moving at a speed of 900 km/hr, or 0.25 km/s, which is somewhat less than the speed of sound, a single pass through one of the SES regions in Fig. 9 would take from 6 to 12 s. The short term interference criterion for SESs in Table 13 is 1.2×10^{-5}%, or 0.3 s per month. Thus, in a single pass across the main-beam axis of the FS antenna within 300 km of that antenna, the AMT transmitter would exceed the allocation for SES events by a large factor. Even more significantly, consecutive SES events of this duration would cause a FS link to become unavailable, or could crash a network, such as a cellular back-haul network, containing it. Note that for slower aircraft speeds or crossing angles less than 90° the duration of a consecutive-SES event, corresponding to a single main-beam axis crossing, would be even greater.

The situation with respect to errored seconds is similar. The percentage of time specified for errored seconds in Table 13 is 4.5×10^{-4}, or 12 s in a month. For the 900 km/hr aircraft speed used above, a single pass across the main beam axis of the FS antenna could cause the FS receiver to exceed the errored second allocation for a month if the region width is 3 km or more. These widths can occur at distances out to 450 km from the FS antenna.

FIGURE 8

Regions where *I*/*N* exceeds 19 dB for transmit antenna gain of 3 dBi and antenna elevation angles of 0°, 2.2° and 5°



Regions of excess interference
Elevation angle 0°

Regions of excess interference power
Elevation angle = 2.2°

Regions of excess interference power
Elevation angle = 5°

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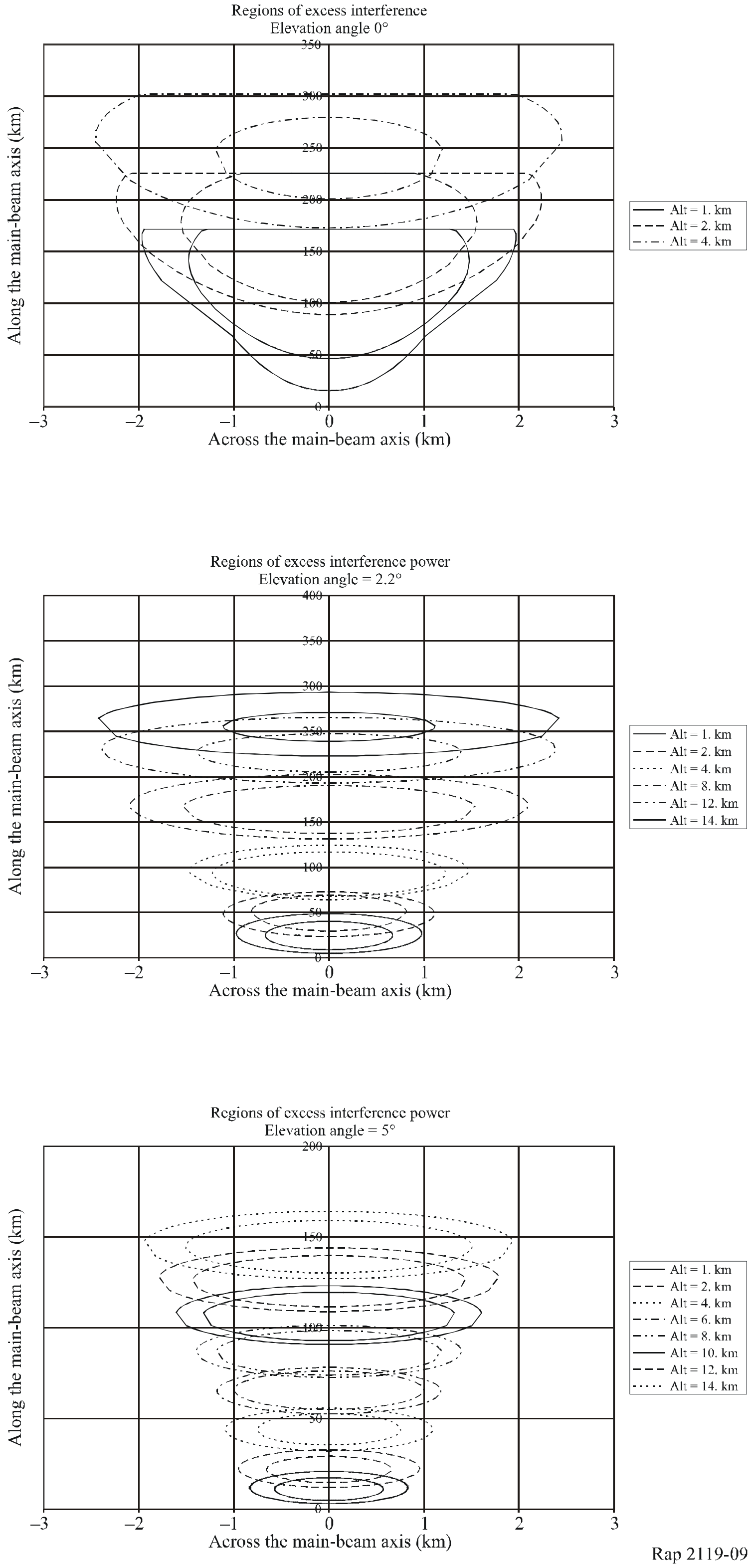
FIGURE 9

Regions where *I*/*N* exceeds 19 and 23 dB for transmit antenna gain of 3 dBi and antenna elevation angles of 0°, 2.2° and 5°



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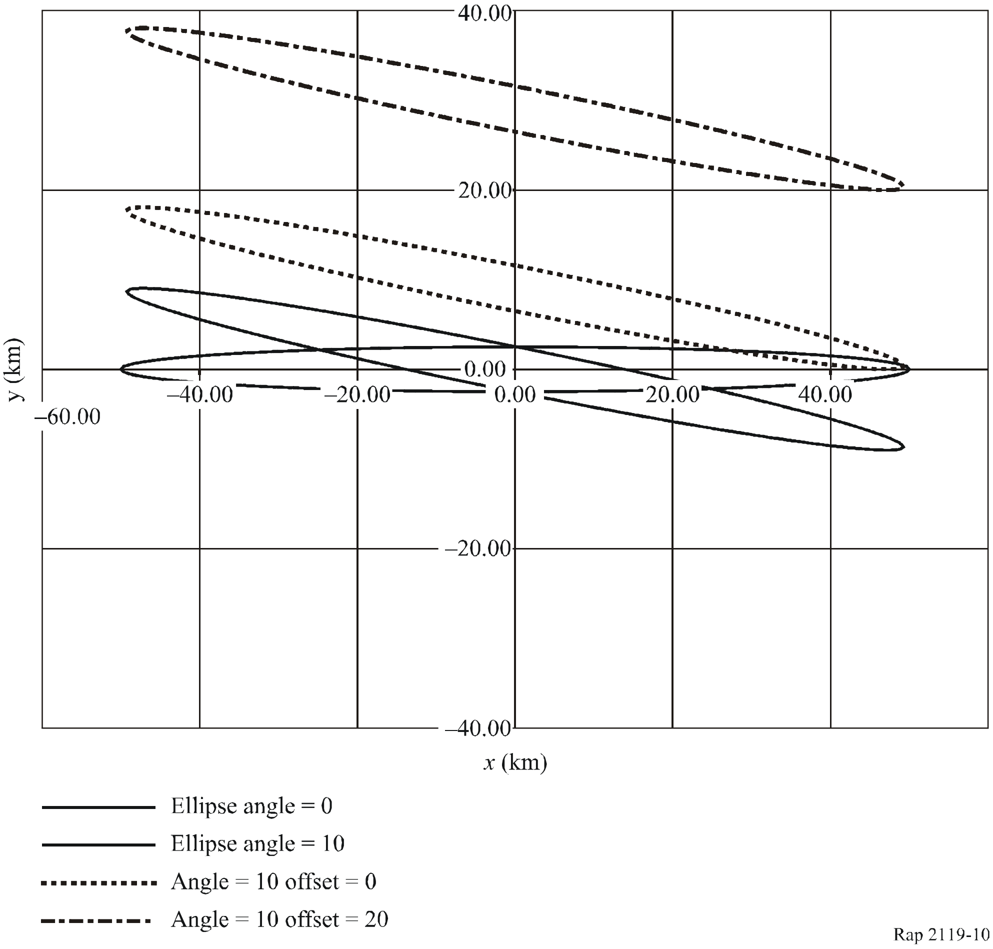
2.4 Long-term interference analysis

To simulate AMT operations for evaluation of long-term interference effects, it is assumed in this section that for any long-term interference evaluation AMT operations are limited to a single elliptical circuit or loop. This loop is long and narrow with a length of 100 km and a width of 5 km and may have any orientation and location with respect to the main-beam axis of the FS receiving antenna. While more complex scenarios can be envisioned, this approach provides a means of examining the range of FDP levels resulting from operations on a large number of different locations and orientations of this simple track.

The large number of tracks is generated by considering various locations for the elliptical path with respect to the great circle below the main beam of the receiving antenna. For reference, some of the ellipses used are shown in Fig. 10. The first ellipse is aligned along the x-axis, which is taken to be the main-beam axis of the FS antenna. The second ellipse in Fig. 10 is centred on the same point but is rotated by 10°. The third is also rotated by 10°, but is offset in the cross main-beam, or y-direction so that it is tangent to the main-beam axis. For the purposes of discussion here this will be described as having an offset of 0 km. The last ellipse is also rotated by 10°, but is offset so that its closest point to the main-beam axis is 20 km away.

FIGURE 10

Elliptical tracks used in determination of fractional degradation of performance (FDP)



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Several different scenarios were considered. As a worst case scenario, it was assumed that the centres of all ellipses were at 25 km intervals from 25 to 500 km along the main beam axis. At each of these 20 distances nineteen ellipses were considered, This set of ellipses was comprised of one for each of the nineteen rotation angles taken at 5° intervals between zero and ninety degrees. The FDP was determined for an AMT transmitter operating at a fixed altitude above each of these elliptical tracks. The set of altitudes considered consisted of integral values of altitude (in km) from 1 km to 13 km. Thus, FDP was determined for a total of (13 × 19 × 20 =) 4 940 elliptical tracks.

The FDP was determined in accordance with Recommendation ITU-R F.1108. Because an aircraft using AMT generally would not be flying on a given track for 100% of the time, the FDP equation was modified to be conditional on aircraft flight along the flight track under consideration. This conditional value of FDP, or FDP_C , is determined by the following equation.

$$FDP_C = \frac{\sum f_{Ci} I_i}{N_T} \tag{9}$$

Here:

I_i: interference power at the i-th sampling point (W/MHz)

f_{Ci}: fraction of time associated with the i-th point along the track, conditioned on being on the track all the time.

The noise power, N_T , which is defined in Table 12, has the same units as I_i. The summation is taken over all samples on the track.

Because of the need for AMT systems to avoid co-frequency interference with each other, it is assumed that the simultaneous co-frequency operation of more than one system on any of these tracks does not occur. However, a given track may be used sequentially by more than one AMT aircraft. Assuming that a given track can be used for 40 h a week, the FDP for a track can be derived from the conditional value in equation (9) as:

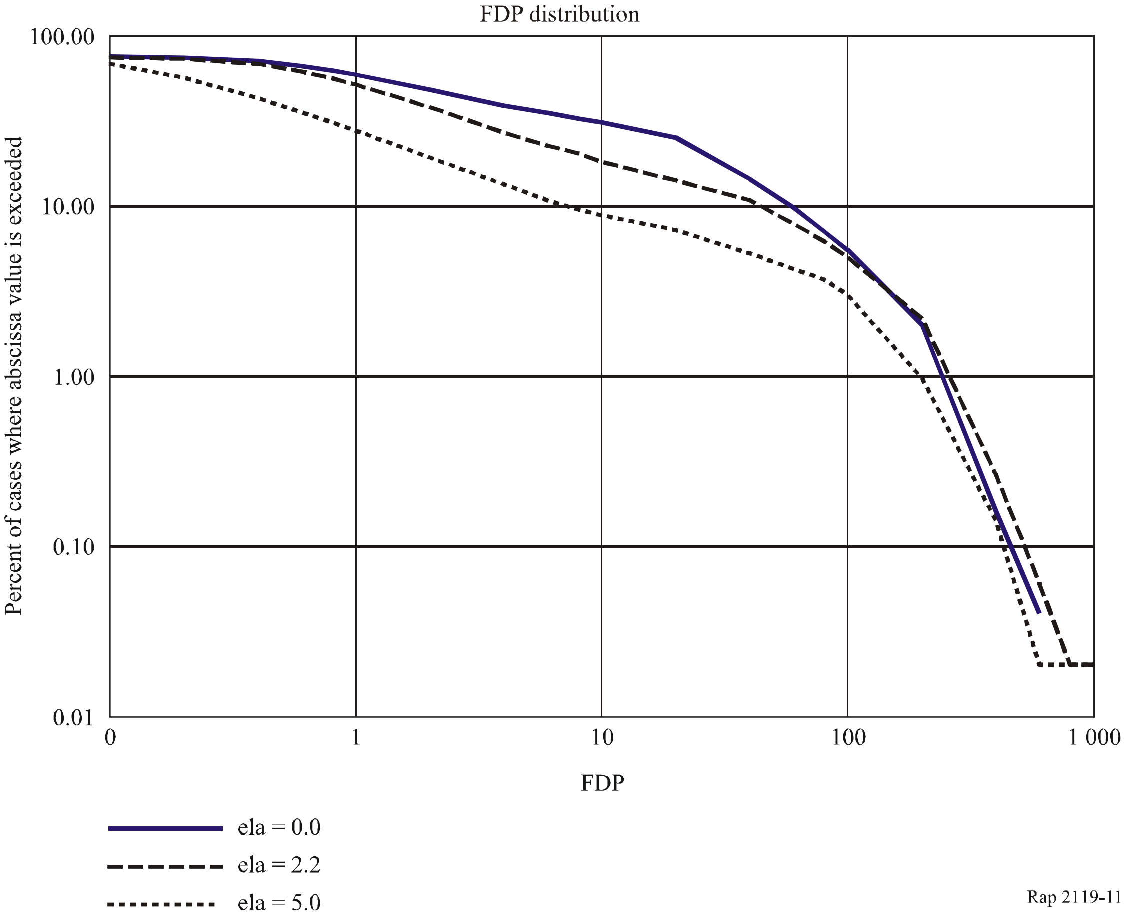
$$FDP = \left(\frac{40}{7 \times 24} \right) \frac{I_{av}}{N_T} \tag{10}$$

where I_{av} is the average value of the interference power as derived from the summation in the numerator of the expression in equation (9).

Figure 11 provides a plot of the cumulative distribution of the calculated FDP values from equation 10. The distribution gives the percentage of the 4 940 values that exceed the value given on the abscissa. The distribution was developed on the basis of all of the 4 940 ellipses even though some of the ellipses were entirely beyond the horizon of the FS station for AMT operations at lower altitudes. Figure 11 shows the distributions for receiving antenna elevation angles of 0°, 2.2° and 5.0°. These distributions show that the desired value of FDP of 4% is exceeded for most of the tracks when the elevation angle of the FS antenna is zero degrees and for a substantial fraction of the tracks when the elevation angle is 2.2° or 5°. Values of FDP greater than 100% would result from operation on 4 to 6% of the tracks. A FDP value greater than 100% would be representative of a case where the error performance degradations due to AMT interference would exceed the degradations due to all other causes.

FIGURE 11

Complimentary cumulative distribution of FDP for the scenario where all tracks are centred on the main-beam axis



Since the short-term interference would be significantly reduced if the AMT operating area was far enough away from the main-beam axis of the FS antenna, a further set of FDP distributions was developed for the case where all of the elliptical tracks were offset from the main-beam axis. Because all of the elliptical tracks are on one side of the offset line the symmetry that was present on the previous case no longer exists. Consequently it is necessary to augment the set of values of the angular rotation of the tracks. For these cases the values of angular rotation considered vary from 0° to 175° in five-degree steps. Otherwise the set of tracks considered is similar to the centred set used for Fig. 11, where the centres of all ellipses lie on the main-beam axis. For the offset case the centres of the ellipses are located at the same x-axis values as before, but the y-axis values are chosen, for each rotation angle, to insure that all points of the elliptical track are on the far side of the offset line from the main-beam axis, as described previously in conjunction with Fig. 10. The resulting set of tracks for each offset distance and each elevation angle is ($13 \times 36 \times 20 =$) 9 360 tracks.

Figure 12 shows the percentage of the 9 360 tracks for which the FDP value specified on the abscissa would be exceeded. The Figure shows the distributions for three FS antenna elevation angles and for offset distances of 0, 4 and 8 km. The distribution for zero degree elevation angle from Fig. 11 is also included for a comparison. Note that this distribution is more favourable at values of FDP greater than 200 because of the higher likelihood of AMT operations close to the main-beam axis when this axis is taken as a limiting point of operations. Otherwise the distributions are well ordered and seem to indicate that an offset distance of 8 km or more would be required for the FDP of a FS receiver to have an acceptable value. Thus, if the AMT flight paths would maintain this separation, it would be possible to operate without producing unacceptable interference at the specified FS receiver. Referring back to Figs. 8 and 9, it is apparent that short-term interference would not be a problem at this separation distance. To the contrary it appears that an acceptable value of offset distance is determined by long-term rather than short-term interference considerations.

One would expect the dominance of long-term interference considerations to be more significant for FS antennas with smaller values of maximum gain. To examine this possibility, the calculations presented in Figs. 9 and 12 were repeated for a FS receiving antenna with a 38 dBi maximum gain. The results of these calculations are presented in Figs. 13 and 14. Note that the transverse dimensions of the short-term interference regions are comparable to those of Fig. 9; however, the regions do not extend along the main-beam axis for more than 180 km. Also, the 19 dB *I*/*N* contours, for the case where the receiving antenna elevation angle is 0°, do not exist for altitudes above 2 km. Regarding long-term interference, for the 38 dBi antenna, it appears that the minimum offset would need to be increased to about 12 km.

FIGURE 12

Complementary cumulative distribution of FDP for several values of offset of the elliptical tracks from the FS antenna main-beam axis

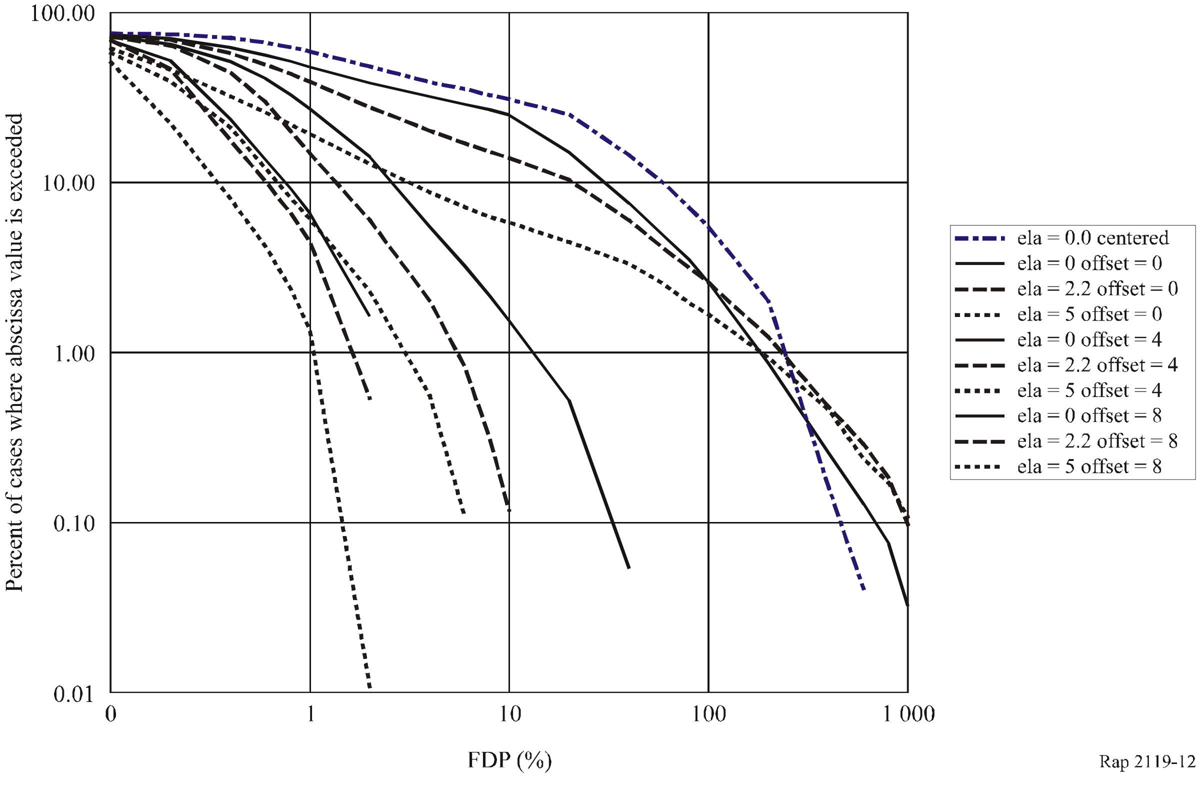


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FIGURE 13

Regions where *I*/*N* exceeds 19 and 23 dB for transmit antenna gain of 3 dBi, receiving antenna gain of 38 dBi and receiving antenna elevation angles of 0°, 2.2° and 5°

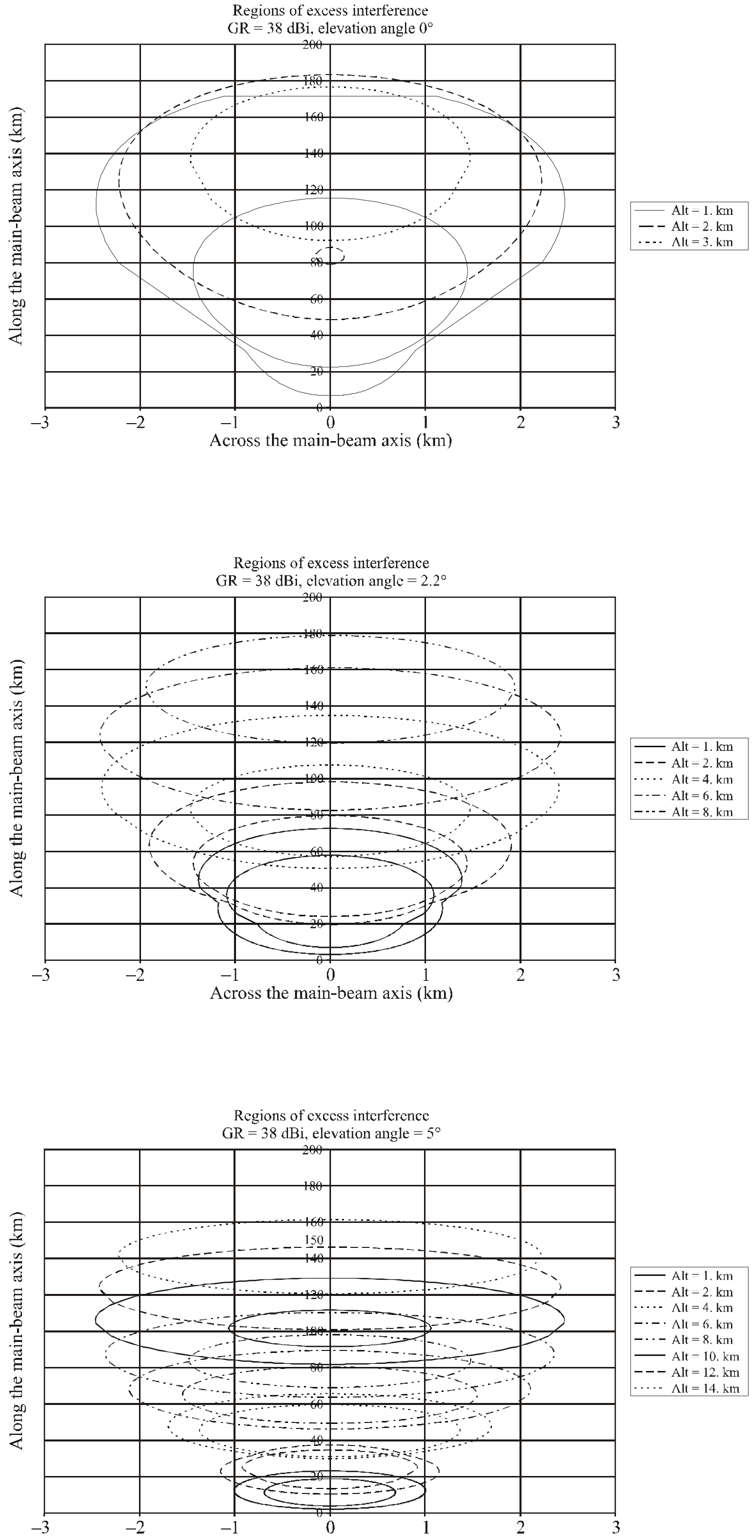

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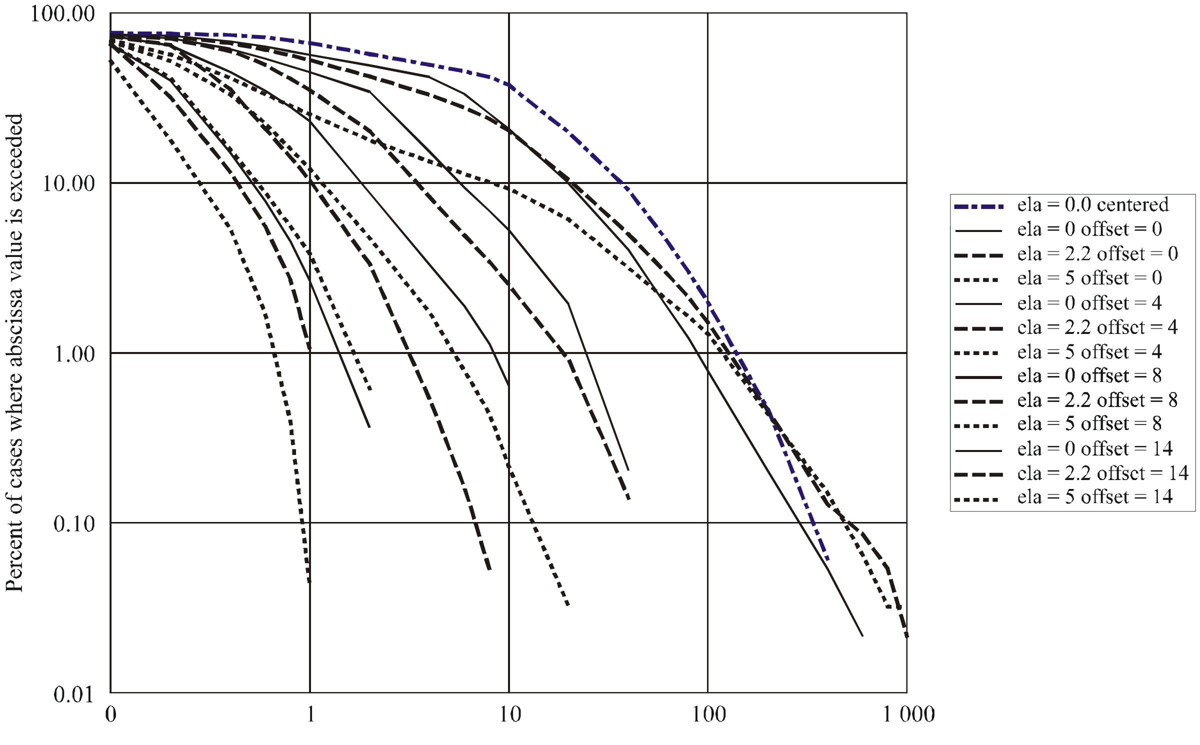
FIGURE 14

Complementary cumulative distribution of FDP for several values of offset of the elliptical tracks from the FS antenna main-beam axis with receiving antenna gain of 38 dBi



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It would be possible to develop distributions such as those given in Figs. 12 and 14 for many different spatial distributions of AMT aircraft, and this may be an appropriate step in the course of case-by-case studies (e.g. during coordination). An alternative or supplement for such studies would be to develop an AMT-aircraft exclusion region based on an approach similar to that used in § 4 for short-term interference. In the case of long-term interference, the worst case exposure would result if the AMT aircraft were to operate in a nominally-fixed position (such as at relatively small separation distances, off-main-beam azimuths and altitudes) relative to the receiving antenna for a significant fraction of a month. The boundary of the smallest AMT exclusion region that effectively protects a fixed station could be determined by finding the locations where:

– the critical FDP value would be met exactly, and

– it is confirmed that all aircraft locations outside those locations would not yield unacceptable short-term interfering signal levels.

2.5 Summary and conclusions

From the consideration of short-term and long-term interference, it appears that AMT systems for flight testing as currently described can cause harmful interference to fixed service receivers located at distances as great as 450 km for the worst-case geometries. Interference to a fixed service receiver may be at acceptable levels when there is sufficient separation of the FS receiver in antenna main-beam azimuth and in range from the AMT area of operation. In this context, distance separation for co-channel sharing may be sufficient when the distance along the main-beam axis from the FS receiver to the AMT area of operation is larger than 450 km or when the main-beam axis of the FS antenna is outside of the area of operation by 12 km or more.

An alternative view of these results is that there would need to be an area associated with a fixed service receiver within which AMT operations would be excluded. Depending on the details of the transmitting and receiving systems involved, the largest necessary exclusion area would extend along the main beam axis of the FS receiving antenna for 450 km with a width of 24 km. Further study would be needed (e.g. during coordination) to determine whether significantly smaller areas could result for realistic co-channel sharing situations. Because of the large distances involved, it may be desirable to develop a recommendation to provide guidance to be used in bilateral or multi-lateral discussions of AMT implementation.

It is interesting to note that the most severe interference concern for the AMT systems with the current parameters is short-term interference into FS receivers with antenna elevation angles near 0°. These low elevation angles are the angles most often found in FS systems. FS systems with low elevation angles are usually the least sensitive to interference power arriving from angles above the local horizontal, as is the case for emissions from space stations. Because of the high levels of incoming interfering power flux-density from AMT transmitters, these low elevation angle receivers would receive high levels of interference from AMT operations unless consultation ensures that compatible operating parameters for both the FS and the MS for AMT can be established and maintained.

While it might be possible to operate AMT systems closer to a FS receiver through the implementation of frequency coordination, such close operation with existing FS receivers might only be achievable by implementing restrictions on the AMT system. These restrictions could include, for instance, limits on the region of operation or the altitude range of operation. Difficulties in finding such a solution could result from the need to accommodate more than one existing FS receiver because of the intensive use of the 6 GHz bands by the FS. For instance, in the US there were 40 514 transmitters in the lower 6 GHz band (5 925-6 425 GHz) and 30 835 transmitters in the upper 6 GHz band (6 525-6 875 MHz) on 1 April 2006. About half of the links in the upper 6 GHz band would use frequencies below 6 700 MHz. Consequently, there would be almost 57 000 receivers in the band 5 925-6 700 MHz counting the 635 Broadcast Auxiliary Service links in the band between the upper and lower 6 GHz bands. It remains to be seen, perhaps by some coordination trials, how many of the existing AMT test ranges could be coordinated for use in the 6 GHz bands, where the usage is so intense.

The need for frequency coordination is a burden that must be shared, or otherwise resolved, by co-primary services occupying the same frequencies in the same geographic area. WP 8B needs to give some attention to the problem of how the mobile service would coordinate in the 5 925-6 700 MHz band. The number of fixed systems in this band is generally growing throughout the world, e.g. by as much as 25% per year in the territory of one administration. This means that more and more new transmitters are introduced each year and would need to be coordinated in these bands. The burden of dealing with such a large number of stations would weigh heavily on both services.

Although the 4 400-4 940 MHz band was not considered explicitly in this study, the results would not be expected to differ significantly. The 4 and 6 GHz bands are used in the fixed service for similar purposes, ATPC is widely used, and various types of diversity operations are often employed. While the antenna gains and short-term interference criteria in the 4 GHz band could differ by a dB or two from the values in the 6 GHz bands, the results presented in § 3 and 4 indicate that such small differences would not significantly alter the size of the resultant exclusion areas.

3 Potential interference to AMT ground stations from FS transmitters

3.1 FS Transmitter and AMT ground terminal receiver parameters

The FS transmitter parameters assumed in the analysis are shown in Table 14. Of the many FS systems described in Recommendation ITU-R F.758-4, these transmitters represent those with the highest EIRP power spectral density. Both are 45 Mbit/s/64-QAM transmitters.

TABLE 14

FS transmitter parameters for 4 600 MHz and 6 300 MHz

Parameter	4 600 MHz	6 300 MHz
Antenna input power (dBW)	2.0	3.0
Antenna gain (dBi)	44 dBi (4.25 m)	46 dBi (3.9 m)
Bandwidth	10 MHz	10 MHz
Antenna input power density	–68 dBW/Hz	–67 dBW/Hz
EIRP density	36 dBW/MHz	39 dBW/MHz
Antenna height above ground	100 m	100 m
Antenna elevation angle	0°-5° (baseline is 2°)	0°-5° (baseline is 2°)
Antenna gain pattern	Rec. ITU-R F.1245	Rec. ITU-R F.1245

3.2 Methodology

Using the propagation model in Recommendation ITU-R P.452-12 and assuming a smooth Earth surface, required separation distance contours were calculated about the AMT ground terminal receiver for both the long-term and short-term AMT interference protection criteria. A parametric analysis was performed by varying several factors including AMT antenna size, AMT antenna elevation angle, FS antenna elevation angle, and FS antenna pointing azimuth. In all cases, the AMT receiver antenna was held stationary, whereas in actual operation it would track the transmitting aircraft. Thus, the distances resulting from the short-term analysis are larger than those actually needed since the short-term permissible interference level may be exceeded for 0.4% of the time (rather than 0% of the time in this static analysis). If AMT receiver site is selected to avoid or minimize AMT receiver main beam pointing at the FS/MS transmitter, the distance separation results for compliance with the AMT long-term permissible levels would also result in compliance with the permissible short-term levels.

3.3 Analysis results

The distance separation results for the various co-frequency sharing cases are as follows:

At 4 600 MHz, maximum separation distances (which occur when the AMT and FS antennas are both oriented towards each other) range from 70-138 km for compliance with permissible long-term interference levels (and short-term levels assuming worst-case AMT antenna pointing is avoid, e.g. through careful receiver site selection). Required separation distances are les than 11 km if the AMT receiver antenna never points near the FS/MS transmitter.

At 6 300 MHz, maximum separation distances range from 67-129 km. Separation distances of less than 9.2 km are required if the AMT receiver antenna never points near the FS/MS transmitter.