REPORT ITU-R M.2118

Compatibility between proposed systems in the aeronautical mobile service* and the existing fixed-satellite service in the 5 091-5 250 MHz band

(2007)

Introduction

This Report is related to Agenda items 1.5 and 1.6 of WRC-07. It proposes a methodology based on Appendix 8 of the Radio Regulations and other ITU-R documents and Recommendations, for the compatibility analyses between possible new systems in the aeronautical mobile service and non-GSO MSS feeder links in the fixed-satellite service in the 5 091-5 250 MHz band.

1 Structure of the Report

This Report sets forth a general methodology for computing the aggregate $\Delta T_s/T_s$ seen by the FSS from new systems, and the $\Delta T/T$ levels seen by any one of the new systems due to the other new systems. The new systems include AM(R)S, systems of Aeronautical Mobile Telemetry (AMT) limited to flight testing, and aeronautical security[1]. The methodology is then applied, in detail, in each of three annexes. Annex 1 explores sharing with AM(R)S. Annex 2 discusses sharing by systems of AMT. Annex 3 describes a proposed aviation security system and the resulting sharing scenarios. In addition, the impact of FSS on these new AMS systems is also considered.

2 Methodology

The methodology is based on Appendix 8 of the Radio Regulations (RR), including Document 8B/195, and Recommendations cited above. It is based on a computation of an aggregate $\Delta T_s/T_s$, where T_s is the noise temperature of the satellite (that is, $T_s = T_{space\ station}$), performed using equation (1):

$$\frac{\Delta T_S}{T_S} = \frac{1}{T_S} \sum_{n=1}^{n=N} \frac{p_{e_n} g_{1_n}(\theta_{tn}) g_2(\delta_{e'_n})}{k l_{un}} \leq C \tag{1}$$

where C is the proposed criterion for sharing assessment.

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* Limited to aeronautical mobile telemetry for aircraft flight testing (referred to as AMT) and AMS for aeronautical security, and AM(R)S.

[1] *Terminology*: An aeronautical mobile service that supports aeronautical security transmissions ensure confidential and secure radiocommunications between aircraft and ground intended for systems used in response to interruption of aircraft operations that have not been permitted by the appropriate authorities.

The parameters are defined as follows (see Appendix 8):

T_s: receiving system noise temperature of the receiver channel under consideration of the space station, referred to the output of the receiving antenna for that channel of the space station (K)

ΔT_s: apparent increase in the receiving system noise temperature of the satellite S, caused by an aggregate interfering emission, referred to the output of the receiving antenna of this satellite (K)

$g_2(\delta)$: receiving antenna gain of satellite *S* in the direction δ (numerical power ratio)

$g_{1_n}(\theta_t)$: transmitting antenna gain of the earth station number *n* (AM(R)S or AMS) in the direction of satellite S′ (numerical power ratio)

p_{e_n}: maximum power density per Hz delivered to the antenna of the transmitting earth station number n (averaged over the worst 4 kHz band) (W/Hz)

$\delta_{e'}$: direction, from satellite *S*, of the transmitting earth station number n

θ_{tn}: direction, from the earth station number n, of the satellite *S*

k: Boltzmann's constant (1.38×10^{-23} J/K)

l_{un}: free-space transmission loss on the uplink (numerical power ratio), evaluated from the earth station number n, to satellite S

N: number of earth station (AM(R)S for AI 1.6 and AMS for AI 1.5)

n: index of the earth station.

In order to perform computations using equation (1), a scenario for the location of the earth stations (AM(R)S or AMS) is needed as well as a worst-case assumption on the maximum number of earth stations operating at the same time in the satellite receiver bandwidth and visibility.

The methodology consists in computing equation (1) for each time step of the above-defined scenario.

3 Proposed criteria for sharing assessment

In the studies of this document, the following criteria[2] are considered:

– In the band 5 091-5 150 MHz (aggregate $\Delta T_s/T_s$ for all other primary services of 6%):
  – A maximum $\Delta T_s/T_s$ of 3% for the ARNS;
  – A maximum $\Delta T_s/T_s$ of 2% for the AM(R)S or the AMS limited to aeronautical security applications;
  – A maximum $\Delta T_s/T_s$ of 1% for the AMS limited to AMT.
– In the band 5 150-5 250 MHz (aggregate $\Delta T_s/T_s$ of 6%):
  – A maximum $\Delta T_s/T_s$ of 3% for the MS (RLAN);

[2] In common with other applications using bands allocated to the FSS, in keeping with Recommendation ITU-R S.1432, WP 4A considers it appropriate for MSS feeder up-links to be designed to allow an aggregate of 6% of the total noise to interference from other primary services in the band 5 091-5 150 MHz. Thus on the assumption that there is unlikely to be significant MLS development in this band before 2018, it would seem reasonable to allow 3% of the MSS feeder up-link noise budget to interference from the aeronautical radionavigation service, and the other 3% for all other services.

– A maximum $\Delta T_s/T_s$ of 3% for other services:
  – A maximum $\Delta T_s/T_s$ of 1% for the AMS limited to AMT;
  – A maximum $\Delta T_s/T_s$ of 2% for other services (not precise).

4 List of characteristics used in the compatibility analyses

For an FSS system considered in the analyses that follow, the following criteria have been used:

TABLE 1

Parameter values used in satellite interference calculations

Parameter	HIBLEO-4 FL
Satellite orbit altitude h (km)	1 414
Satellite receiver noise temperature T (K)	550
Interference threshold H (dBm) in 1.23 MHz ($\Delta T_s/T_s$ = 3%)	−125.5
Interference threshold H (dBm) in 1.23 MHz ($\Delta T_s/T_s$ = 2%)	–127.3
Interference threshold H (dBm) in 1.23 MHz ($\Delta T_s/T_s$ = 1%)	–130.3
Polarization discrimination L_p (dB)	1
Feed loss L_{feed} (dB)	2.9
Satellite receiver bandwidth B (MHz)	1.23
Satellite receive antenna gain (dBi)	4

Some of the parameters that have been used for characterization of AMS systems in the analyses:

– *N*: maximum expected AMS operating at the same time in the satellite receiver bandwidth.
– Worst-case scenario AMS stations' location versus time.
– The antenna gain patterns (ground and airborne).
– The maximum power density per Hz delivered to the antenna of the transmitting earth station (averaged over the worst 4 kHz band) (W/Hz) (Pe).
– AMS typical emitter filter.
– AMS typical modulation.

Specific values for these parameters are given in the Annexes of this Report.

5 Conclusion

5.1 Impact into FSS conclusion

Analyses indicate, for the systems described in the annexes and visible within an FSS satellite antenna footprint, that interference to the FSS from the proposed AMT, AM(R)S, and a future aeronautical security system will represent a $\Delta T_s/T_s$ of less than 2.7% (criterion 3%) accounted by typically:

– 0.7% (criterion 1%) for AMT in the band 5 091-5 250 MHz;

– less than 2% (criterion threshold for AM(R)S plus AMS for security) in the band 5 091-5 150 MHz for:
  – either AM(R)S;
  – or AMS for aeronautical security.

In the band 5 091-5 150 MHz, in order not to exceed a $\Delta T_s/T_s$ of 2% allowable for AM(R)S plus AMS for security, AM(R)S and AMS for security cannot operate co-frequency at the same time (within the field of view of a single non-GSO satellite). The practical means for operating in a time sharing mode would require a very complex coordination procedure. Therefore it is proposed that AM(R)S and AMS for security operate in a non co-frequency basis.

With respect to the band 5 091-5 250 MHz, it should be noted that this band is already used by existing allocations and that the addition of new allocations, such as AMS and AM(R)S, will increase interference to the FSS feeder links unless significant steps are taken. These steps would need to include some kind of regulatory arrangement, where necessary, that would ensure the protection of the FSS, utilizing the 5 091-5 250 MHz band, from unacceptable interference.

5.2 Impact from FSS conclusion

5.2.1 Impact into AMS for telemetry limited to flight testing

The compatibility between the FSS ground transmitter and the AMS for telemetry limited to flight testing ground receiver can be handled at AMS for telemetry application level by ensuring sufficient distance separation between these stations. Due to the limited number of these ground stations this should be manageable.

5.2.2 Impact into AM(R)S

The compatibility between the FSS ground transmitter and the AM(R)S ground receiver located at airports can be handled by ensuring sufficient distance separation between these stations and/or appropriate frequency separation. Due to the limited number of FSS ground stations and the limited location of AM(R)S ground stations at airports this should be manageable.

5.2.3 Impact into AMS for security

The compatibility between the FSS ground transmitter and the AMS for security ground receiver can be handled at AMS for security application level by ensuring sufficient distance separation between these stations and/or appropriate frequency separation. Due to the limited number of these ground stations this should be manageable.

The compatibility between the FSS ground transmitter and the AMS for security airborne receiver can be handled at AMS for security application level as any interference suffered would not be frequent.

Annex 1

Aeronautical mobile (R) service

1 Introduction

1.1 The very high frequency (VHF) band 117.975-137 MHz is heavily utilized in the for air-ground communications associated with air traffic services and aeronautical operational control supporting safety and regularity of flight and operating in the aeronautical mobile (route) service (AM(R)S). In fact, use of the band is such that in some regions it is very difficult to find channels to meet current requirements. While regional efforts are underway to extend the capacity through measures such as channel splitting and/or functional reassignments, with the expected growth in air service, together with increasing desires for more data to the flight crews, the spectrum shortage issue will become even more challenging. This need was recognized at WRC-03 as evidenced by Agenda item 1.6 for WRC-07. In order to determine requirements for new AM(R)S spectrum, a number of aviation studies were completed.

1.2 Results of the studies provide guidance as to future AM(R)S requirements. In particular more spectrum is needed to support:

– surface applications;

– air-ground/air-air voice and data link applications;

– advanced surveillance/navigation applications;

– unmanned aerial vehicle (UAV) control.

The 5 091-5 150 MHz band has been identified to satisfy the requirements of the first category-surface applications.

1.3 Studies have turned up a number of AM(R)S applications for the airport surface. These range from uploads of routing and electronic flight bag information, to de-icing, and surface mapping to preclude runway incursion and aid in obstacle avoidance. In general those applications share the characteristics of short-range (e.g. 3 km) and high bandwidth per airport. Limitation to ground transmission, and geographic separation of airports would likely ease airport-to-airport channel reuse.

1.4 To accommodate future growth in surface applications, portions of the 5 GHz band have been selected for evaluation as a potential spectrum location for an airport radio local area network (RLAN). Initial studies have indicated that the 5 GHz band is well suited to the type of applications envisioned, and work is being accomplished to determine if IEEE 802.xx technologies – utilized in adjacent bands (i.e. above 5 150 MHz) for commercial, unlicensed terrestrial RLANs – can be leveraged[3].

[3] This proposed AM(R)S application will be implemented only at airports.

2 System characteristics

2.1 Assumed aviation system

2.1.1 In order to address the mix of aviation applications intended for the airport surface, development of an airport safety-rated RLAN is envisioned for the 5 091-5 150 MHz sub-band. One candidate architecture is the airport network and location equipment (ANLE) system. ANLE is visualized as a high-integrity, safety-rated wireless RLAN for use at airports, combined with an interconnected grid of multilateration sensors. Simple transmitters would be added to surface-moving vehicles, allowing for the development of a high-fidelity, complete picture of the airport surface environment. In order to speed development and reduce the cost of the ANLE, the system would be based on existing Institute of Electrical and Electronics Engineers (IEEE) "802-Family" standards[4].

2.1.2 While there are several protocols in the IEEE 802 family standards, analysis has focused on two candidates for the ANLE application: 802.11a and 802.16e:

– 802.11a currently operates in the 5 GHz unlicensed band using an orthogonal frequency division multiplexing (OFDM) modulation scheme. It operates using 20 MHz wide channels.

– 802.16e is designed to support non-line-of-sight (NLOS) communications in the 2-11 GHz band. Though below 6 GHz the standard allows various channel bandwidths, a 20 MHz channel has been defined to be compatible with the 802.11a standard, and is the channel bandwidth assumed for this analysis. One desirable feature of 802.16e is that it has been designed to allow for networking between users with relative speeds of up to 150 km/h – suitable for taxing aircraft.

2.1.3 Because of the "mobility" capabilities built into IEEE 802.16e, it is expected that it will prove to be the most compliant with aviation requirements. As a result, the remainder of Annex 1 will focus on that protocol.

3 Airport LAN characteristics

3.1 As noted above, a key parameter of the sharing study is ANLE transmitter power. Providing connectivity, with conservative margins to account for fading effects, over the assumed 3 km maximum range drives required transmitter power. ANLE transmitter and receiver antenna gain, ANLE receiver sensitivity, and path loss over the 3 km range in turn drive connectivity between the ANLE transmitter and the ANLE receiver.

3.2 The ANLE transmitter antenna gain versus elevation angle pattern considered in the analysis is adopted from International Telecommunication Union (ITU) Radiocommunication Sector, Recommendation ITU-R F.1336-1[5] and is shown in Fig. 1.

For this initial analysis, the radiation pattern was assumed to be omnidirectional in the horizontal plane. It must be noted that in practice, many if not all installed ANLE antennas are likely to have sectoral rather than omnidirectional horizontal-plane patterns. Sectoral antennas would allow ANLE

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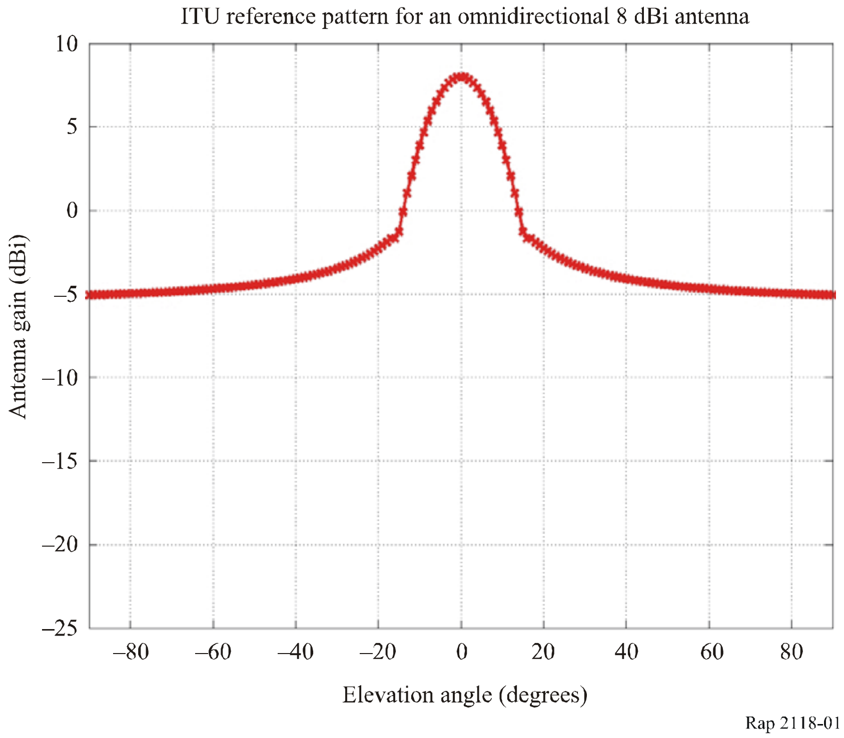
[4] While the system would be based on the IEEE standards, it is expected that system elements would be tailored for the aviation application. Such tailoring might include bandpass filtering to facilitate sharing with adjacent band MLS, improved receiver sensitivities, and sectorized antennas.

[5] Reference radiation patterns of omnidirectional, sectoral and other antennas in point-to-multipoint systems for use in sharing studies in the frequency range from 1 GHz to above 70 GHz, Recommendation ITU-R F.1336-1 (1997-2000 version).

transmitters to operate at lower power, thereby enhancing compatibility with FSS and reducing overall interference levels below the values estimated in this Report.

FIGURE 1

Potential ANLE 802.16e transmitter antenna pattern



3.3 The ANLE transmitter power required to cover a cell 3 km in radius can be estimated on the basis of a set of nominal parameter values. Based on the receiver minimum performance requirements from the IEEE 802.16e standard, the minimum receiver sensitivity level is −80.1 dBm. Receivers with better sensitivity however are technically feasible for 802.16e, and based on available literature[6], for the purpose of this analysis the assumed sensitivity level used will be –83.4 dBm.

3.4 The path loss is a function of the path distance *d*. For an ANLE system the propagation path loss is evaluated on the airport surface where the path loss characteristics – in particular considering multipath effects – could be different (higher attenuation) from simple free-space path loss.

The path loss exponent *n*, is used to characterize the environment. The path loss equation is defined as:

$$L_{path}(d) = L_{free}(d_0) + 10n \log_{10}(d / d_0) \qquad (2)$$

where:

- L_{free}: free-space path loss
- d_0: distance up to which path loss can be modelled using the free-space equation
- n: path loss exponent

[6] IEEE 802.16 Broadband Wireless Access Working Group. Interference scenarios in 2.4 GHz and 5.8 GHz UNII bands – reviewed document. IEEE C802.16-04/14. June 28, 2004.

and

$$L_{free}(d_0) = 32.44 + 20\log_{10}(f_{\text{MHz}}) + 20\log_{10}(d_{0\text{km}}) \quad (3)$$

with

f_{MHz}: operating frequency (MHz)

$d_{0\text{km}}$: propagation distance (km) up to which path loss can be described by free-space loss.

3.5 If $n = 2$, equation (2) reduces to the case where the entire path distance is treated as a free-space path. To determine required ANLE power, however, the values of 2.3 for n and 462 m for d_0 were assumed. It must be noted that the assumption that $n = 2.3$ is considerably more conservative than a free-space loss assumption; and, consequently it results in higher estimated values of necessary ANLE transmitter power.

3.6 Terrestrial communications systems traditionally implement link margins (L_m) to account for fading, such as that due to multipath effects, and line loss (the latter losses should be very small in the ANLE configuration, due to short, low-loss cable runs). In regard to the link margin L_m for the ANLE-like system, the available information is very sketchy and indirect. For this analysis, a conservative value of 11 dB is estimated, however measurements are on-going in airport environments to try to develop a better estimate.

3.7 Using the information above, the required ANLE transmitter power P_t, dB, referred to one milliwatt dBm, is computed using the following expression:

$$P_t = R_{xs} + L_{path}(d) + L_m - G_t - G_r \quad (4)$$

where:

R_{xs}: receiver sensitivity (dBm)

d: distance between transmitter and receiver (3 km)

G_t: transmitter antenna gain (dB) referred to lossless isotropic gain (dBi)

G_r: receiver antenna gain (dBi).

3.8 The ANLE transmitter power level required to establish a 3-km direct link in the system as determined using equation (4) is 32.2 dBm. Table 1 summarizes the ANLE system parameters and the transmitter power required.

TABLE 1

Estimated ANLE transmitter power needed for 3-km range

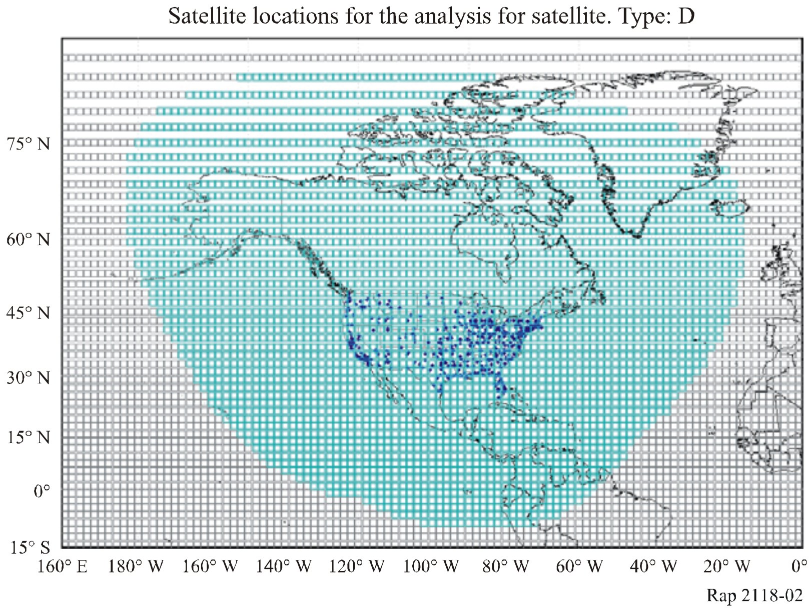
Parameter	ANLE (IEEE 802.16e)
Receiver sensitivity R_{xs} (dBm)	–83.4
Transmitter antenna gain G_t (dBi)	8.0
Receiver antenna gain G_r (dBi)	6.0
Assumed link margin L_m (dB)	11.0
Assumed path-loss exponent n	2.3
Transmitter power required P_t (dBm)	32.2

4 Compatibility assessment results

4.1 With the ANLE parameters outlined above, the compatibility assessment can be performed. Figure 2 shows (in light blue), for HIBLEO-4 FL, the full set of "relevant" 2° × 2° latitude/longitude cells such that a satellite directly above the centre of a given cell would be in view of at least one of the 497 towered airports in one administration (shown in dark blue in Fig. 2).

FIGURE 2

Cells considered in analysis



Relevant cells for HIBLEO-4 FL

4.2 The next condition to be determined was how many of the ANLE airport networks would be operating on a given ANLE channel at any instant of time. This parameter – termed transmitter duty cycle – directly affects the aggregate power. A range of values from 1% to 15% was proposed by different parties in a HIPERLAN study for an adjacent band, and a compromise value of 5% was suggested[7]. Detailed design studies (beyond the scope of the present study) will be needed to ascertain a reasonable duty-cycle value for an ANLE network. In order to over-bound expected effects, however, a duty cycle of 50% is assumed for this analysis.

4.3 The final parameter, the bandwidth factor, B_f, is the ratio of the victim satellite receiver bandwidth (B_{LEO}) to the interfering ANLE transmitter bandwidth (B_{ANLE}), if $B_{LEO} < B_{ANLE}$; otherwise, $B_f = 1$. It determines the amount of interfering power falling into the victim's "filtered" bandwidth. As discussed above, the assumed channel bandwidth for ANLE is 20 MHz. This value is larger than the receiver bandwidth of HIBLEO-4 FL (1.23 MHz). Therefore, the bandwidth factor is much less than unity for this type of LEO receiver. Table 2 lists the computed bandwidth factor.

[7] European Radiocommunications Committee (ERC). Study of the Frequency Sharing between HIPERLANs and MSS feeder links in the 5 GHz band. ERC Report 67. February 1999, Marbella, European Conference of Postal and Telecommunications Administrations (CEPT).

TABLE 2

Bandwidth factor (dB)

	IEEE 802.16e
HIBLEO-4 FL	−12.1

5 Conclusion

For a given combination of ANLE system and satellite type, the aggregate interference power was computed at each orbit grid point. The maximum value of that aggregate interference power was then identified as the "hot point". On the basis of the assumed worst-case ANLE transmitter power (32.2 dBm/20 MHz), the results are listed in Table 3.

TABLE 3

Aggregate interference from ANLE (802.16e)

Satellite	Interference Threshold (dBm)	Aggregate interference power at hot point (dBm)	Aggregate interference margin below interference threshold (dB)
HIBLEO-4 FL	−125.5 (3%) −127.3 (2%)	−129.4 at 67° N 104° W	3.9 2.1

Annex 2

Aeronautical mobile telemetry

1 Introduction

To accommodate future growth in AMT applications, the 5 091-5 250 MHz band has been selected for evaluation as a candidate band for air-to-ground flight test telemetry operations. This band currently is allocated to the aeronautical radionavigation service (ARNS) and aeronautical mobile satellite (route) service (AMS(R)S) (reference RR footnote No. 5.367). It is also allocated to the FSS (Ref. RR No. 5.444A), limited to feeder links of non-geostationary mobile-satellite systems (non-GSO/MSS). Initial studies have indicated that this band is suited for the type of AMT applications envisioned. ITU-R has determined that the need for additional AMT spectrum is between 100 MHz and 1 GHz, with at least 650 MHz required specifically for air-to-ground flight test telemetry in designated areas. Aeronautical telecommand functions, which require relatively little spectrum, can continue to be accommodated below 3 GHz. Due to technical constraints, spectrum for AMT use must be below 7 GHz. In the following sections, compatibility is demonstrated with existing FSS feeder links.

2 AMT sharing analyses

2.1 A detailed analysis based on AMT operations in the 5 091-5 150 MHz band

AMT-equipped aircraft in a different Administration utilize omnidirectional transmit antennas having nominal gain factors of 2 dBi. A typical aircraft will have two such antennas, one on top and one beneath the fuselage, so as to provide geometric diversity and to ensure visibility from the ground AMT station of at least one of the antennas during aircraft maneuvers. Aerodynamic considerations typically limit the efficiency of these transmit antennas, so that typical maximum gain factors are 2 dBi or less. The theoretical maximum antenna gain is 3 dBi.

Aircraft operating AMT systems in the L-band and S-band telemetry frequencies have traditionally utilized transmitters having an output power of approximately 10 W or less. This power level represents a compromise based on transmitter technology, the availability of dedicated spectrum, and the desire to have sufficient link margin. Specifically, at the legacy L and S band telemetry frequencies, 10 W transmitters are practical given the size, weight, and DC power requirements related to installation of the transmitters in flight test aircraft. At these same frequencies, concerns with respect to interference into other systems are not a major factor in AMT system design. Finally, this choice of transmit power level provides the luxury of having significant link margin under worst-case conditions (for example, multipath fading while an aircraft is operating at maximum range from an AMT ground station).

In the discussion that follows, conservative assumptions will be used in calculations in order to demonstrate the ability to conduct successful AMT operations in the band 5 091-5 150 MHz without creating unacceptable levels of interference to incumbent FSS systems. The notion is that if sharing can be accomplished under these worst-case conditions, then introduction of further complexities into the sharing analyses is unnecessary.

For example, instead of using 2 dBi as the nominal maximum directive gain of an aircraft antenna, the theoretical maximum value of 3 dBi will be used. Also, when calculating effective radiated power levels, line and splitter losses that typically exceed 4 dB will not be taken into consideration. Thus, radiated power levels used in the computations below will be at least 5 dB higher than those encountered during actual flight test.

Furthermore, when computing aggregate interference levels from an ensemble of flight test aircraft to a non-GSO satellite receiver, the assumption will be made that all of the aircraft are co-located at a position in which the geometry with respect to the satellite yields the worst-case interference (i.e. the maximum possible level of received power into the satellite from the ensemble of aircraft).

Finally, when computing interference levels, no further reductions in transmitted power levels from aircraft are taken in order to account for dynamic power control, where power is reduced when an aircraft is flying in proximity to its telemetry receive ground station. Likewise, no reductions are taken to accommodate for situations in which there is excess link margin. Depending on fade conditions, one can need as much as 10 dB of additional link margin for a particular aircraft's flight test. This is why 10 W transmitters, for example, are used instead of 1 W transmitters, even though there are many situations in which a 1 W transmitter is adequate.

With respect to wideband AMT systems, the signals transmitted from aircraft will be coded and modulated utilizing modern techniques, and will typically have a post-modulation bandwidth of approximately 20 MHz. Typical installations implement a "90/10" power split, where the top antenna transmits only 10% of the total power. This is because, in the absence of unusual aircraft maneuvers, the signal from the top antenna is of little practical importance. During flight tests that involve unusual attitudes, adjustments are made to the geographic location of the flight test airspace, as needed, to ensure that the lower power signal from the top antenna is of adequate power for purposes of the test. However, having this antenna operational during all tests minimizes equipment changes and adjustments, and provides for telemetry during unexpected maneuvers (an eventuality for which AMT operators must always be prepared).

For the purpose of calculating aggregate AMT interference into the non-GSO FSS satellite, we assume an AMT deployment scenario similar to that used in other AMT sharing studies. This scenario consists of 17 representative test areas or flight zones in the US shown in the map of Fig. 3. These zones indicate approximate airspace volumes within which test aircraft operate and were developed in consultation with the US flight test telemetry community. The flight zones are based on the locations and Special Use Airspace (SUA) volumes (i.e. prohibited, restricted, warning, alert, and military-operations areas) used by civil, commercial, and national defense flight test ranges. The zones are not strictly defined by SUAs, however, since flight testing can occur in other classes of airspace in coordination with the aviation authorities. For safety purposes, administrations would authorize specific flight test areas, including areas that could differ in number, size, and shape from those in Fig. 3. One or two simultaneously active co-frequency AMT emitters are assumed to be located in each test area. This yields the maximum number of emitters in the airspace transmitting simultaneously on the same frequency channel, noting that additional emitters may operate in the airspace on other channels.

A worst-case scenario was examined consisting of a single emitter (per frequency channel) in each test zone with an additional co-frequency emitter in the four most active test areas (DFRC, Utah, WSTF, and PAX zones) where such co-frequency operation among AMT transmitters may be feasible. This yields a total of 21 concurrent co-frequency emitters across Continental United States (CONUS). The number of concurrent co-frequency emitters in a test area is limited by the amount of spectrum available as well as the number of receiving ground stations, isolation (coupling losses) between AMT systems operating in the same flight test area, and flight paths of the test vehicles.

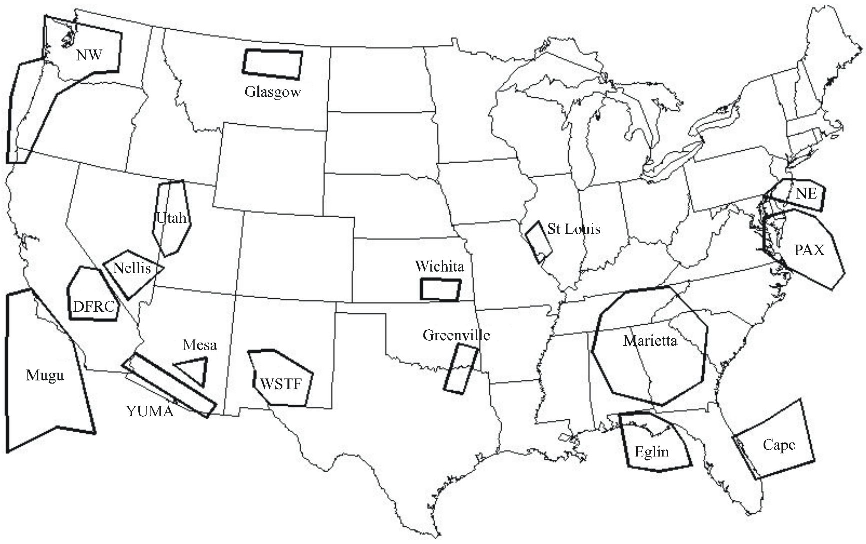
Thus, unless the flight paths of the vehicles are compatible with one another, a single user per channel per test area is the common rule. Even if flight paths and ground stations are compatible, co-channel usage within the same test area will be rare if there is sufficient spectrum available.

For FSS satellite systems operating in LEO, this means that a single satellite may “see” in the worst case as many as 21 aircraft operating simultaneously across CONUS within a single 20 MHz channel. Furthermore, as noted above, the conservative and simplifying assumption is made in this analysis that the aircraft are co-located at the peak gain point of the FSS antenna in computing the aggregate interference.

For terrestrial services, however, a receive system operated at or near a flight test range will only be able to see the 1 or 2 aircraft operating co-channel. Depending on the particular geometry of the range, it may often be the case that a terrestrial antenna will “see”, and thus receive interference from, only one aircraft at a time. This is because co-channel operation of multiple aircraft at a single range is typically accomplished by operating the aircraft in geographically distinct areas of the range.

FIGURE 3

Map of 17 flight test areas in CONUS



Using the AMT parameters described above, it is now possible to consider the impact of aeronautical mobile telemetry operations on incumbent services.

Sharing by AMT with the fixed-satellite service

Interference from AMT into the FSS service

A satellite in the FSS (non-GSO) in this band can be regarded as being able to view at one time, in the worst case, the entire territory of, for example, the United States. In this example, typical maximum-activity levels for AMT operations will involve up to 21 concurrent co-frequency aircraft flying in as many as 17 flight test zones across CONUS.

For this ensemble of 21 aircraft, one can reasonably assume that 20 of the aircraft are flying under nominal straight-and-level conditions at a given instant. (This is the case for the majority of time that a flight-test aircraft is in the air.) For these straight-and-level aircraft, an FSS satellite will have a view primarily of the signals from the top antenna on each aircraft. The remaining aircraft will be presumed to be operating in inverted flight, during which the lower antenna will be the primary interference source "seen" by the satellite.

At 5 GHz, body masking is considerably more effective than at lower frequencies, such as at the legacy L and S band frequencies. However, experimental measurements of body masking for flight test aircraft available for use in this study were conducted at S and X bands, but not at ~5 GHz. In order to illustrate the worst-case interference that might be seen by a satellite in LEO orbit, the analysis presented here will utilize the less favourable (to sharing) S band data. The data presented below were measured on an antenna range using a full-size, but small fuselage diameter aircraft (e.g. an aircraft the size a small business jet). This will provide a realistic, but conservative, estimate of the beneficial effects of body masking with respect to sharing between AMT and FSS satellites.

A conservative estimate, therefore, assumes 21 co-frequency aircraft in flight at one time with 20 of the aircraft flying "straight and level" and the remaining aircraft flying inverted. This is important because as noted above, AMT equipped aircraft typically operate with two antennas, with the top antenna radiating only 10% of the total power from the aircraft's telemetry transmitter while the bottom antenna radiates 90% of the power. This is accomplished by the use of a 90/10 power splitter, which divides the transmitter power between the two aircraft antennas.

Thus, the interfering signal seen by a LEO satellite will be larger when the aircraft is flying inverted since there is no body masking of the higher radiated power from the antenna mounted on the bottom of the aircraft fuselage.

The effects of body masking are shown in Fig. 4 and in Tables 4 and 5. Figure 4 shows the geometry of a flight test aircraft with respect to a spacecraft in low earth orbit. Even at high altitude, the aircraft is essentially at the surface of the earth as compared to the orbital altitude of the satellite. To compute the effects of body masking of the bottom antenna from the satellite (or the top antenna, in the case of an aircraft performing inverted flight), it is necessary to know the relative antenna gain, as a function of elevation angle θ, for each of the two aircraft antennas.

For a typical blade antenna installation, the gain as a function of azimuth, or yaw, angle is essentially constant, independent of the azimuth angle. In the elevation plane (i.e. pitch and/or roll directions), fuselage masking, as well as the normal gain pattern of a vertical monopole antenna such as a blade, yields the gain versus angle profiles given in Table 4. The values in the table were obtained from actual measurements made of a business jet size aircraft on an outdoor antenna range. The measurements were made at an azimuth angle of 90°, which represents a "broadside" view of the aircraft in which the swept wings of the aircraft do not block the view of the bottom antenna at high elevation viewing angles. Thus, the data in the figure represent a worst case (i.e. limited body shielding) representation of the AMT-to-LEO interference geometry. Furthermore, since the measurements were obtained at ~2 GHz, instead of at ~5 GHz, the body masking effects are less than they will be at the higher frequency. Thus, the data in Tables 4 and 5 represent a worst-case scenario from the point of view of interference to a LEO satellite.

The slant range versus elevation angle shown in Fig. 4 is computed from the equation

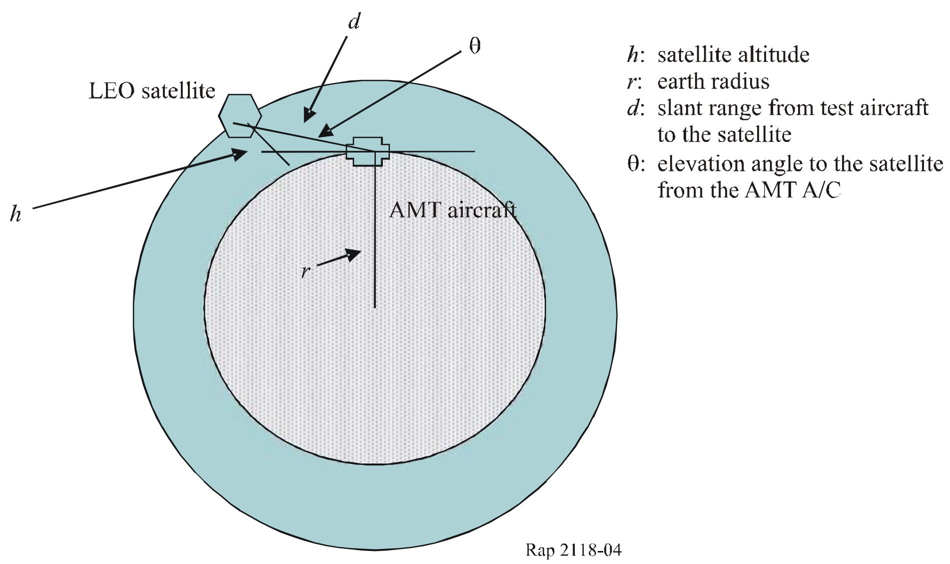
$$d = -r \cdot \sin\theta + \sqrt{r^2 \sin^2\theta + \left(2hr + h^2\right)}$$

By combining the slant range as a function of elevation angle with the antenna directive gain, also as a function of elevation angle, it is straightforward to compute the power flux-density seen at the antenna of a satellite in LEO orbit. This is given by:

$$pfd_{at\ satellite} = [P_{top}G_{top} + P_{bottom}G_{bottom}]/\left(4\pi d^2\right)$$

FIGURE 4

Satellite geometry of a LEO spacecraft with respect to a flight test aircraft



With regard to Table 4, the gain at 0° elevation is less than the 3 dBi theoretical value due to the curvature of the aircraft fuselage. The relative power includes the effects of slant range versus elevation angle and gain versus elevation angle. It represents the change in power from the worst case of $G = 3$ dBi and $d = h$, where h is the altitude of the LEO satellite. Because the altitude of the aircraft is insignificant with respect to the altitude of the spacecraft, as compared to the radius of the earth, a LEO satellite will never be visible to the aircraft at negative elevation angles. The negative elevation angles are provided so that data in Table 5, for an inverted aircraft, can be related to the data in Table 4.

TABLE 4

Relative power versus elevation angle and slant range for a small-fuselage aircraft in straight and level flight with a 90/10 bottom/top power split

Elevation angle, θ (degrees)	Slant range, d (km)	Gain G_{top} for the top antenna (dBi)	Gain G_{bottom} for the bottom antenna (dBi)	pfd_{top} seen by the LEO satellite from the top antenna (based on 1 W) (dB(W/m^2))	pfd_{bottom} seen by the LEO satellite from the bottom antenna (based on 9 W) (dB(W/m^2))	$pfd_{total} = pfd_{top} + pfd_{bottom}$ (dB(W/m^2))
90	1 414	−6	−25	−140	−150	−140
75	1 454	−3	−21	−137	−146	−136
60	1 586	0	−19	−135	−144	−134
45	1 844	3	−15	−133	−142	−132
30	2 306	3	−11	−135	−140	−134
15	3 118	0	−8	−141	−139	−137
0	4 470	−4	−4	−148	−135	−135
−15	N/A	−8	0			
−30	N/A	−11	3			
−45	N/A	−15	3			
−60	N/A	−19	0			
−75	N/A	−21	−3			
−90	N/A	−25	−6			

TABLE 5

Relative power versus elevation angle and slant range for a small-fuselage aircraft in inverted flight with a 90/10 bottom/top (relative to the A/C) power split. (This is the same as Table 4, except that the power levels seen by the satellite are reversed to account for the inversion of the aircraft)

Elevation angle, θ (degrees)	Slant range, d (km)	Gain G_{top} for the bottom antenna (dBi)	Gain G_{bottom} for the top antenna (dBi)	pfd_{top} seen by the LEO satellite from the bottom antenna (based on 9 W) (dB(W/m^2))	pfd_{bottom} seen by the LEO satellite from the top antenna (based on 1 W) (dB(W/m^2))	$pfd_{total} = pfd_{top} + pfd_{bottom}$ (dB(W/m^2))
90	1 414	−6	−25	−130	−159	−130
75	1 454	−3	−21	−128	−155	−128
60	1 586	0	−19	−125	−154	−125
45	1 844	3	−15	−124	−151	−124
30	2 306	3	−11	−126	−149	−126
15	3 118	0	−8	−131	−149	−131
0	4 470	−4	−4	−138	−149	−138
−15	N/A	−8	0			
−30	N/A	−11	3			
−45	N/A	−15	3			
−60	N/A	−19 dB	0 dB			
−75	N/A	−21 dB	−3 dB			
−90	N/A	−25 dB	−6 dB			

The total worst-case power flux-density seen at the antenna of a LEO satellite for an ensemble of 20 aircraft in straight and level flight and one aircraft in inverted flight can be computed from the data in Tables 4 and 5. Using the worst-case pfd from Table 4 (−132.7 dB(W/m^2)), multiplying by 20 aircraft, and adding the worst-case pfd from Table 5 (−123.8 dB(W/m^2)) for the single inverted aircraft, yields a total pfd from the ensemble of 21 aircraft of (−118.3 dB(W/m^2)).

To compute the effect of this aggregate PFD on the system noise temperature of a LEO system, it is necessary to know typical FSS/non-GSO satellite system parameters. The relevant satellite receiver parameters of the HIBLEO-4 FL system, which currently operates in the 5 091-5 150 MHz band are shown in Table 4 of § 3 of the main body of this report, and will be assumed in this analysis.

To compute the interference into the satellite receiver, it is necessary to multiply the aggregate pfd value calculated above by the effective area of the 4 dBi satellite receive antenna gain. This is accomplished using the familiar equation:

$$P_R = P_T + G_T + G_R + \{20 \log(\lambda) - 20 \log(4\pi) - 20 \log(h)\} - 10 \log(1.23/20) \text{ dBW}$$

where the P_T, G_T, 20 log(d), and 10 log(4π) of the 20 log(4π) terms have already been considered. The factor of 1.23/20 represents the fraction of total AMT interference power (occurring in a 20 MHz bandwidth) that falls in the 1.23 MHz channel bandwidth of the satellite receiver. Note also that we assume no polarization discrimination or feed losses, which will further overestimate the interference from AMT.

Using the above equation and a wavelength of λ = 0.059 m (average value for 5 091-5 150 MHz band), the aggregate pfd value of –118.3 dB(W/m^2) produces a total interference of I = −162 dBW (in the 1.23 MHz channel) at the LNA input of the satellite receiver (I = –165.9 dBW if polarization and feed losses are included, and taking proper account of the 1.23 MHz/20 MHz bandwidth factor described above). Using the satellite receiver system noise temperature of T_s = 550 K, the satellite thermal noise power, given by $N = kTB$, is −140.3 dBW. This yields an I/N = −21.7 dB and $\Delta T_s/T_s$ = 0.68%. Thus, the worst-case aggregate interference from the ensemble of 21 aircraft is less than 0.7%. This is well below the overall $\Delta T_s/T_s$ level of 3% indicated in Table 6 that may be used to determine whether more detailed studies are warranted.

Furthermore, almost any enhancement that can be introduced to the above analyses (such as accounting for the geographic distribution of the aircraft in which case they will not all be along the same gain axis of the satellite antenna) will result in a lower aggregate AMT interference level into the FSS satellite. However, the premise here is that by demonstrating that AMT produces negligible interference to FSS even under these very conservative assumptions, there is no need for a higher fidelity analysis.

Interference from FSS feeder link transmitters into the AMT system

AMT ground station receive antennas are typically high gain (~40 dBi) parabolic dish tracking antennas. Typically, these antennas are located sufficiently close to the ground that interference from FSS feeder links will not be an issue. However, in rare conditions in which there is temporary main-beam line-of-sight conjunction between AMT receive antennas and FSS feeder link antennas, there are mitigation techniques available to AMT operators. These include the associated use, on the flight test aircraft, of legacy telemetry frequencies in the L and S bands for transmission of safety of flight information. (That is, the aircraft will be broadcasting separate AMT data on *L* or *S* band frequencies while also broadcasting in the 5 091-5 150 band.) These legacy *L* and/or *S* band frequencies can also be used to permit antenna tracking of the 5 GHz signal to be maintained during brief periods of interference (when the AMT tracking antenna points for a short interval at the FSS feeder link antenna while an aircraft travels through the flight test airspace, for instance). Furthermore, networked telemetry designs currently in development will permit the use of automatic resend requests (ARQs) to recover any data lost during a short-lived interference event.

2.2 Additional analysis for the 5 091-5 250 MHz band

a) *Aeronautical telemetry system characteristics:*

1 Expected typical transmitter power: 10 W maximum, but adjustable to lower levels.

2 Number of transmitters per aircraft: 2.

3 Antenna characteristics of the airborne transmitter and the ground receiver station:

– aircraft antenna: 2 semi-omnidirectional antennas: one forward located under the aircraft cockpit and one aft mounted on the top of its tail fin; 3 dBi maximum per antenna in the direction of the satellite;

– expected cable loss, 2 dB per antenna.

4 Expected data rate and bandwidth requirement for each channel:

– expected data rate of each channel: 10 to 20 Mbit/s;

– expected bandwidth required: 10 MHz;

– minimum spacing between 2 channels: 2 MHz.

5 Number of channels fitted per aircraft: one

– as five aircraft could be simultaneously under testing in the same area, five different channels are required.

6 Required spectrum characteristics:

– it is considered that these channels will require a guardband of 1 MHz. Then, if the five channels are contiguous, they involve the use of 5 × 12 MHz = 60 MHz;

– if the 12 MHz bandwidth channels are not contiguous, antenna and receivers constraints demand that the difference between the highest channel and the lowest channel will not exceed 10% of the mean carrier frequency.

b) *Operational characteristics:*

1 Number of aircraft under test at any one time: 5 (one Aircraft transmitter per channel).

2 Maximum range the aircraft will fly from the ground receiving station: 500 km corresponding at the aircraft viewed with 0° elevation angle when flying at the maximum altitude.

3 Proximity of aircraft to each other during airborne testing:

– five aircraft could be in the same cell having a radius of 10 km, albeit operating on a different sub-band each.

4 Weather conditions under which testing will be undertaken: all, without limits.

5 The number and location of test facilities: 16 stations in Western Europe (between 8 and 10 over France, 1 over Germany, between 2 and 4 over Spain and Portugal and 1 over the United Kingdom).

6 Flight altitudes: 0 to 45 000 ft. (0 to ~14 km).

c) *Preliminary assessment of AMT interference into the existing non-GSO satellite systems operating under the FSS allocation:*

AMT Antenna gain variation with elevation angle

The airborne antenna to be used in ITU Region 1 AMT application will be assumed to exhibit similar radiation pattern characteristics as the one used in Region 2 for small fuselage aircraft and described in the preceding § 2.1.

For ease of computation linear interpolation is used to calculate antenna gain as a function of the elevation angle θ – under which the satellite is seen from the aircraft – in between the values given in Tables 4 and 5 of the previous § 2.1, using a three-segment linear approach:

– θ in the range –90 to 30°: $G = -25 + \left(\frac{\theta + 90}{120}\right) \times 28$ (dBi)

– θ in the range 30 to 45° G = 3 (dBi)

– For θ in the range – to 45 to 90°: $G = -3 + \left(\frac{\theta - 45}{45}\right) \times 9$ (dBi)

This linear interpolation scheme yields the Table 6:

TABLE 6

ITU-R Region 1 AMT antenna radiation pattern versus elevation angle, calculated by interpolating Tables 4 and 5 values

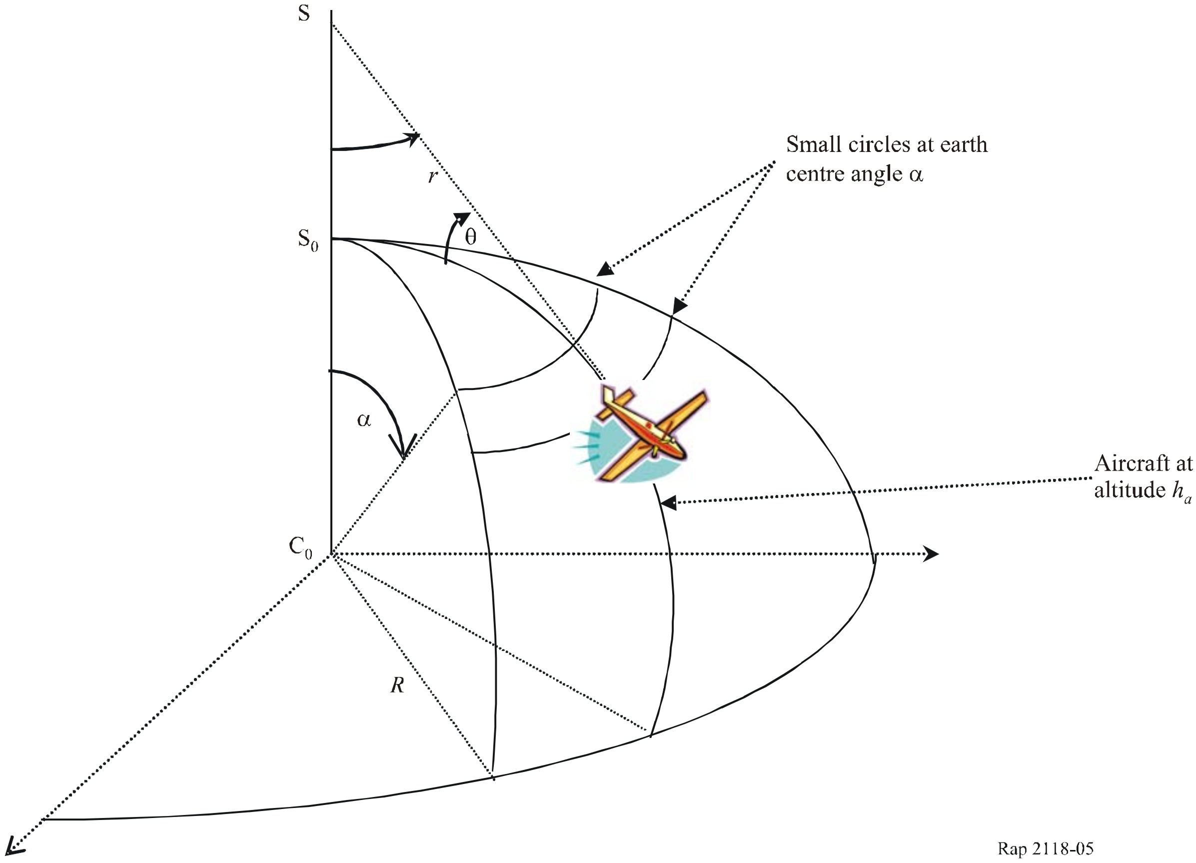
Elevation angle Theta	Top antenna gain (dBi)	Bott. antenna gain (dBi)
90	–6.0	–25.0
75	–3.0	–21.5
60	0.0	–18.0
45	3.0	–14.5
30	3.0	–11.0
15	–0.5	–7.5
0	–4.0	–4.0
–15	–7.5	–0.5
–30	–11.0	3.0
–45	–14.5	3.0
–60	–18.0	0.0
–75	–21.5	–3.0
–90	–25.0	–6.0

Comparison of this table with Table 4 and 5 above shows that the chosen linear interpolation scheme does provide good fitting as it produces equal or worst case overbounding values for the antenna gain for all values θ with the exception of that corresponding to θ = –75°, i.e. −21.5 vs. 21 dBi. The Table 7 designed to look for the worst-case highest interfering PFD into the satellite shows that it occurs for values of θ which are in the neighbourhood of +30 to 45°. Accordingly the underestimating of PFD arising from a calculated half dBi less gain at –75° can be rightfully disregarded as having an insignificant contribution.

The interference PFD into the non-GSO satellite is at most critical when the aircraft under test flies paths perpendicular to the satellite direction under stable level flight conditions and at the highest altitude of about 14 km (~ 45 000 feet). Under such conditions both the bottom and top antennas will achieve the highest gain towards the satellite, as their view of the satellite is direct and not shielded by wings nor fuselage, at least for small elevation angles. Assuming long extended flight paths they will run parallel to the Earth’s small circles, defined by constant α angles as it can be seen on Fig. 5.

FIGURE 5

Satellite AMT aircraft geometry



Inspection of above figure show that:

– α, the earth centre angle pointing to the AMT aircraft under test with respect to the satellite direction, varies in the range of ±35° with:

– *h* , the minimum satellite aircraft separation is 1 400 km (i.e. the difference between the satellite orbit of 1 414 km and the assumed aircraft altitude of 14 km)

– *R′* the earth radius augmented by the highest aircraft test flight altitude assumed to be h_a, i.e. *R′* = 6 380 km.

With the above defined constants, one can derive the satellite -aircraft range, *r*, and the satellite elevation angle θ, viewed from the aircraft as functions of α and the resulting interference PFD:

$$r = R' \times [1 + (1+k)^2 - 2(1+k)\cos\alpha)]^{1/2} \quad \text{with } k = h/R'$$

$$\theta = \cos^{-1}[(1+k)\frac{R'}{r}\sin\alpha]$$

$$PFD = \frac{P_{out} \times l \times Ga}{4\pi \times r^2}$$

, with G_a calculated per the above linear interpolation formula for top and bottom antennas, *l* the aircraft cabling loss and P_{out} the AMT transmitter power, taken as 2 dB and 10 W respectively in accordance with § 2.2.

TABLE 7

Interference PFD into the non-GSO satellite from AMT aircraft flying at different circular paths identified by constant earth centre angle α

α (degrees)	SAT range *r* (km)	θ, El. angle to satellite (degrees)	Top antenna gain (dBi)	Bott. antenna gain (dBi)	Top antenna. PFD at satellite dB(W/m^2 × 1.23 MHz)	Bott. antenna. PFD at satellite dB(W/m^2 × 1.23 MHz)	Combined PFD at satellite dB(W/m^2× 1.23 MHz)
35	4462.4	0.1	−4.0	−4.0	−140.0	−140.0	−137.0
34	4351.1	0.9	−3.8	−4.2	−139.5	−140.0	−136.7
33	4239.8	2.0	−3.5	−4.5	−139.1	−140.0	−136.5
32	4128.5	3.0	−3.3	−4.7	−138.6	−140.0	−136.2
31	4017.4	4.1	−3.0	−5.0	−138.1	−140.0	−135.9
30	3906.4	5.3	−2.8	−5.2	−137.6	−140.0	−135.6
29	3795.6	6.4	−2.5	−5.5	−137.1	−140.1	−135.3
28	3685.1	7.6	−2.2	−5.8	−136.5	−140.1	−134.9
27	3574.9	8.9	−1.9	−6.1	−136.0	−140.1	−134.6
26	3465.1	10.2	−1.6	−6.4	−135.4	−140.2	−134.1
25	3355.8	11.5	−1.3	−6.7	−134.8	−140.2	−133.7
24	3246.9	12.9	−1.0	−7.0	−134.2	−140.2	−133.2
23	3138.7	14.4	−0.6	−7.4	−133.6	−140.3	−132.7
22	3031.3	16.0	−0.3	−7.7	−132.9	−140.3	−132.2
21	2924.7	17.6	0.1	−8.1	−132.2	−140.4	−131.6
20	2819.0	19.3	0.5	−8.5	−131.5	−140.5	−131.0
19	2714.5	21.1	0.9	−8.9	−130.7	−140.6	−130.3
18	2611.3	23.0	1.4	−9.4	−130.0	−140.7	−129.6
17	2509.5	25.0	1.8	−9.8	−129.1	−140.8	−128.9
16	2409.5	27.1	2.3	−10.3	−128.3	−140.9	−128.1
15	2311.4	29.4	2.9	−10.9	−127.4	−141.1	−127.2
14	2215.6	31.8	3.0	−11.4	−126.9	−141.3	−126.7
13	2122.3	34.5	3.0	−12.0	−126.5	−141.6	−126.4
12	2032.1	37.2	3.0	−12.7	−126.1	−141.8	−126.0
11	1945.2	40.3	3.0	−13.4	−125.8	−142.2	−125.7
10	1862.3	43.5	3.0	−14.1	−125.4	−142.5	−125.3
9	1783.9	47.0	2.6	−15.0	−125.4	−143.0	−125.3
8	1710.6	50.7	1.9	−15.8	−125.8	−143.5	−125.7
7	1643.2	54.8	1.0	−16.8	−126.2	−144.1	−126.2
6	1582.3	59.1	0.2	−17.8	−126.8	−144.8	−126.7
5	1529.0	63.7	−0.7	−18.9	−127.4	−145.5	−127.3
4	1483.9	68.5	−1.7	−20.0	−128.1	−146.4	−128.1
3	1447.8	73.7	−2.7	−21.2	−128.9	−147.4	−128.9
2	1421.4	79.0	−3.8	−22.4	−129.8	−148.5	−129.8
1	1405.4	84.5	−4.9	−23.7	−130.8	−149.6	−130.8
0	1400.0	90.0	−6.0	−25.0	−131.9	−150.9	−131.9

From the Table 7 one picks up the worst combined interference into the non-GSO satellite, from top and bottom antennas, which can be read at lines α = 10° and 9°. These yield a combined top and bottom PFD of –125.3 dB(W/m^2 × 1.23 MHz), which value is then fed it into the satellite *I*/*N* analysis table here under:

TABLE 8

AMT interference into non-GSO satellite *I*/*N* computation

Parameters	Value	Comments
Max AMT PFD in dB(W/m^2 × 1.23 MHz)	−125.3	From Table 7
Omni antenna area at 5 120 MHz in dB(m^2)	−35.6	
SAT receive antenna gain (dBi)	4.0	From Table 4 of the main body of this Report
Polarization discrimination (dB)	1	From Table 4 of the main body of this Report
Satellite feed loss (dB)	−2.9	From Table 4 of the main body of this Report
AMT Interference (dBW)	−160.8	
AMT Transmit bandwidth (MHz)	10.0	
Interference density (dB(W/MHz))	−170.8	
Interference in SAT BW of 1.23 MHz (dBW)	−169.9	
Satellite thermal. noise within 1.23 MHz (dBW)	−140.3	Assumes a satellite receiver noise temp. of 550 K from Table 4 of the main body of this Report
Resulting *I*/*N* (dB)	−29.6	
Corresponding $\Delta T_s/T_s$ (%)	0.11	

2.3 Conclusion

The conclusion of the above *I*/*N* analysis is that the single aircraft in this scenario produces interference to the FSS satellite that is considerably less than the aggregate interference presented in the earlier example in § 2.1 in which there are 21 co-frequency aircraft. Thus, sharing with the FSS is feasible in both scenarios, even when other AMS systems are operating in the band.

The ability to share simultaneously with non-GSO feeder links of the MSS and the new AMS systems for flight testing proposed is a significant and unique feature of this band. In particular, the sharing criterion specified in equation (1) is insensitive to the particular manner in which any of the AMS/AMT systems for flight testing presented here are configured. This is because of the low gain, wide field of view antennas of the non-GSO feeder links, which makes computation of aggregate interference levels independent of whether, for example, one has four aircraft, each with a 10 W transmitter, or a single aircraft with two independent 10 W transmitters. Thus, in this particular band, it would be practical to combine multiple 10 W standard AMT transmitters to emulate a higher powered transmitter. This technique could be used to improve link margin in difficult situations without impacting the ability to share, provided that a corresponding power reduction was accomplished elsewhere in the field of view of the non-GSO satellite or the other AMS systems. Such flexibility is often not possible in other bands due to technical considerations of incumbent systems.

Annex 3

Civil aeronautical security requirements

1 Introduction

Among other things, Agenda item 1.6 for the WRC-07 addresses the use of the band 5 091-5 150 MHz for aviation systems and specifically includes security. The European Commission and Eurocontrol are co-funding a project to support the Eurocontrol strategic initiative to validate a high capacity air-ground communications capability for the transmission of encrypted cockpit voice, flight data and on-board video information.

The objective of this project work is to demonstrate the feasibility for enhancing ATM security by making available key security related information in encrypted form to decision-makers. This will necessitate a secure radio link between the ground and the aircraft. The technology being used is an adaptation of the IMT-2000 CDMA air interface standard.

Successful flight trials at C-band have already been conducted to a range of greater than 100 km. These demonstrate that the adapted CDMA standard can be used for aeronautical security applications in the band 5 091-5 150 MHz. Further validation flight trails are planned for the first half of 2006 using a European ground network and civil aircraft.

2 Key features of the new aeronautical security system

The proposed system is capable of supporting security. It acts primarily as an aeronautical security system, however it provides additional functionality.

Its primary functionality includes:

– to provide mutual authentication of ground and air networks;

– to provide the exchange of encrypted information between aircraft and ground for secure communications;

– to provide real time information to and from the aircraft including basic aircraft parameters, such as position, and video. This independent information from aircraft close to an airport could also be used for runway incursion determination calculations and would complement the Airport Wireless Surface Network (AWSN).

To optimize spectrum efficiency, any excess capacity experienced could be used for alternate functions, including:

– to provide enhanced connections between pilot and controller should confidentiality of information be essential;

– to provide enhanced data flow between aircraft and ground systems;

– to support passenger related applications (e.g. provision of real time confidential medical data);

– to provide functionality for UAV operations. For example, in the landing phase it may be necessary to download, in real time and with minimal latency, information to recreate a virtual cockpit for the ground-based pilot. This could involve video streaming in the last instances of flight.

3 Radio spectrum compatibility issues for security applications

3.1 Issues

Compatibility with the following operational and potential systems is essential:

– Microwave Landing System (MLS)
– AM(R)S
– ANLE (AWSN – Airport Wireless Surface Network)
– Existing FSS feeder links
– Aeronautical telemetry

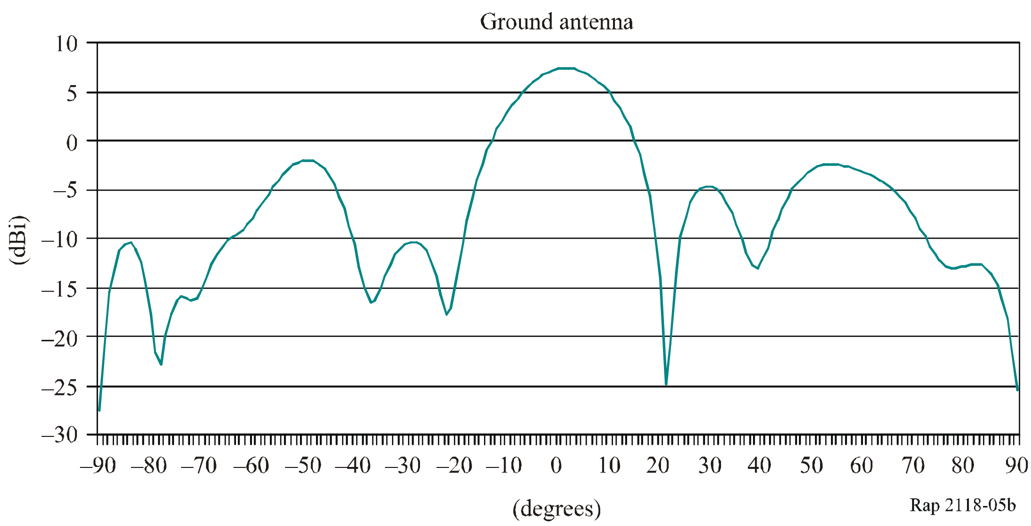
3.2 Compatibility with FSS

3.2.1 Impact of aeronautical security into FSS

3.2.1.1 Methodology and parameters

Ground antenna

The elevation polar pattern used in the analysis is based upon a manufactured unit as is shown below:



Interference estimation

The received interference by the HIBLEO-4FL satellite is determined by:

$$Pr = Pt + (Gt - Lc) + Gr - Lfree(d) - Lfeed - Lp + Bf - Dc$$

where:

- Pr: received power (dBm)
- Pt: transmitter power (dBm)
- Gt: ground antenna gain (dBi)
- Lc: ground feeder loss
- Gr: satellite gain (assumed to be 6 dBi)
- $Lfree$: free-space path loss (dB)

Lfeed: feed loss (dB)

Lp: polarization discrimination (dB)

Bf: bandwidth factor (dB)

Dc: Duty cycle reduction

$$Lfree = 32.44 + 20 \log(\text{freq}) + 20 \log(d)$$

where:

freq: frequency (MHz)

d: distance (km).

Simulation assumptions

It was assumed that the transmitter power was 40 dBm and that a total of 200 ground stations would be required. For the purposes of simulation it was assumed that there would be a maximum of 70 stations in each band. It was further assumed that at any given time the transmissions would be from base stations and aircraft on an equal basis.

Given that the system can operate using a 5 MHz or 10 MHz bandwidth, both situations were considered.

Furthermore, it was assumed that these stations would be uniformly spread along a line beneath the satellite orbit. In practice many ground antennas would be directional in azimuth thereby reducing interference.

Simulation parameters

The following parameters were used:

Number of ground stations	70
Transmitter power	40 dB(m/5 MHz)
Feeder loss including switch and connectors	4 dB
Number of aircraft (The maximum number transmitting at the same time is limited to the number of ground stations)	70
Airborne transmitter power	40 dB(m/5 MHz)
Airborne feeder loss	4 dB
Satellite antenna gain	4 dBi
Frequency	5 100 MHz
Polarization discrimination	0 dB
Transmitter bandwidth	5 MHz
Satellite receiver bandwidth	1.23 MHz
Satellite range	1 414 km
Aggregate FSS Interference threshold ($\Delta T/T = 2\%$) available for AS if no AM(R)S operating cofrequency	−157.3 dB(W/1.23 MHz)

3.2.1.2 Study results

Using the methodology described in Annex 1, with the system characteristics stated above, the studies results are:

– with a 5 MHz bandwidth the result gives a worst-case $\Delta T_s/T_s$ of less than 2% (−157.8 dB(W/1.23 MHz));

– With a 10 MHz bandwidth the results gives a worst-case $\Delta T_s/T_s$ below 1% (−160.8 dB(W/1.23 MHz)).

In both cases the aggregate $\Delta T_s/T_s$ are below the aeronautical security applications maximum aggregate FSS Interference threshold ($\Delta T/T$ = 2%) available for AS if no AM(R)S operating co-frequency (–157.3 dB(W/1.23 MHz)).

3.2.1.3 Alternative approach

This approach reuses the methodology employed specifically in Annex 2. It analytically develops a worse-case derivation. It also assumes the ground station antenna radiation pattern to conform to Recommendation ITU-R F.1336-1.

3.2.1.3.1 Assumptions used

Same as in the first approach: the ground stations are assumed to be equally spread over the great circle on the earth spanning the satellite sub-point, and goes through the centre of the proposed system service area. The service area spans an arc on this great circle of 2 000 km corresponding to an angle α of 18° as viewed from the centre of the Earth with respect to the satellite sub-point.

3.2.1.3.2 Satellite and ground stations geometry

The parameters and variables used in Fig. 6 are:

– Earth great circle angle α defined from the satellite direction; the offset angle α_0 points to the mid-point P_0 of the GS spread area.

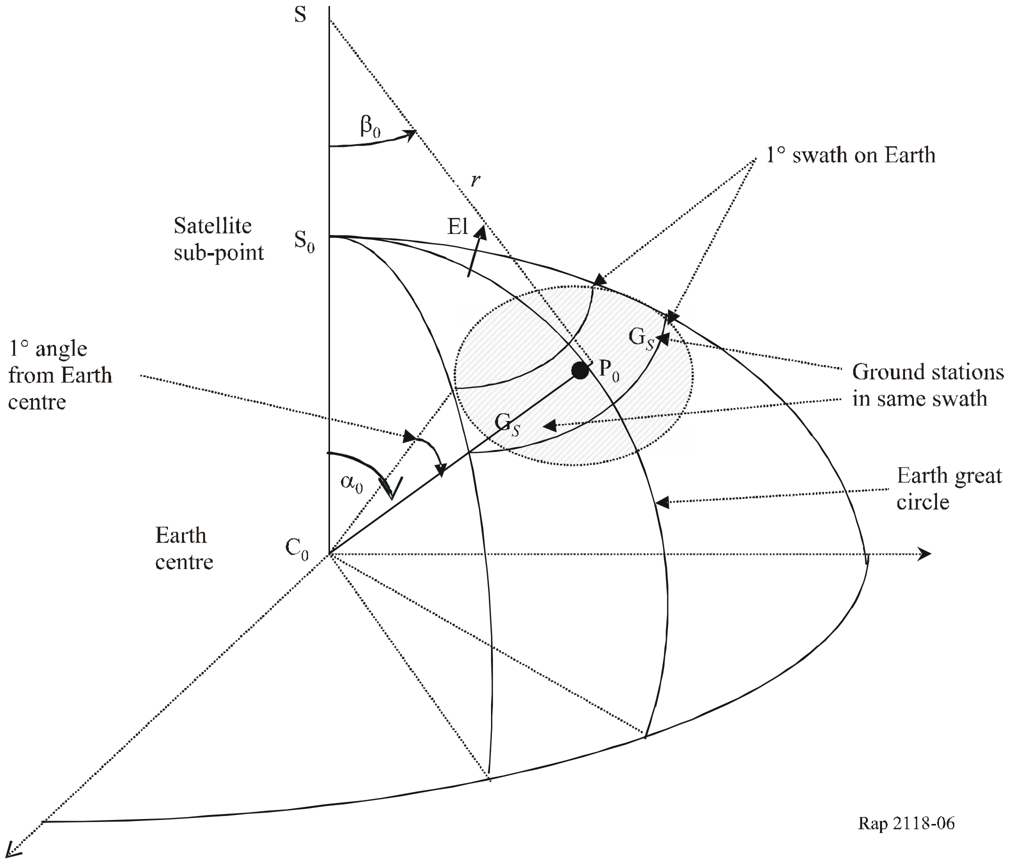
– Satellite angle, β and satellite – GS range, *r*.

– GS elevation angle to the satellite, *El*.

The number of GS in each 1° “band” or swath, as viewed from the earth centre and across the great circle arc through the service area mi-point, P_0 is assumed to follow a quadratic model of the form $N(\alpha) = N_{max}\,[1 - k'\,(\alpha\text{-}\alpha_0\,)^2]$. The constants N_{max} and k' are calculated such as to yield the assumed number of GS (see § 3.2) over the α range of ±9° or 1 000 km (with the 2 extreme swaths at + and – 10° void of GS).

FIGURE 6

Satellite and ground stations geometrical configuration



Inspection of the two-dimensional geometry of Fig. 7shows:

– α extends ±35° approximately centered on the satellite sub-point S_0;

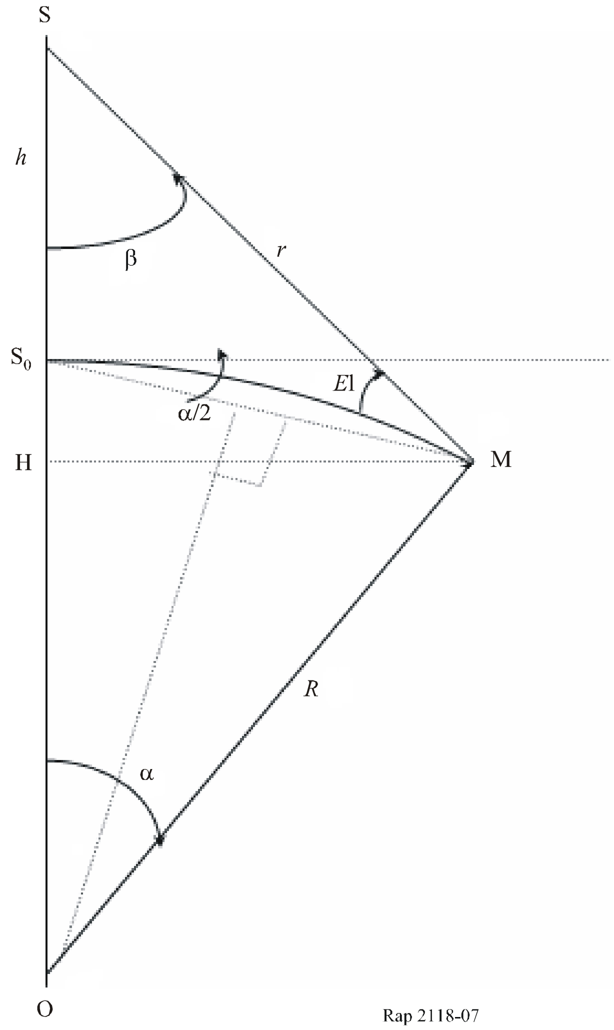
– β extends ±55° approximately;

– the worst-case interference situation into the satellite occurs for low values of *El*, i.e. when the GS antenna gain towards the satellite is the highest. The same situation applies to the airborne transmitters for aircraft banking with respect to stable flight conditions with an assumed angle of ±20° (refer to pre-WRC-03 RNSS vs. ARNS (DME) compatibility studies);

– α_0 is associated with the worst-case interference situation into the satellite, as the GS antennas' gain is the highest because the elevation angles *El* to the satellite are the lowest.

FIGURE 7

Satellite GS geometry in two dimensions



The relationships between all above variables are easily established:

$\beta = \sin^{-1}\left(\frac{r}{R}\sin\alpha\right)$ and with $k = h/R$:

$r = R \times [1 + (1+k)^2 - 2(1+k)\cos\alpha)]^{1/2}$ and $El = \cos^{-1}[(1+k)\sin\beta] = \cos^{-1}[(1+k)\frac{R}{r}\sin\alpha]$

h = 1 414 km; R = 6 370 km

Assuming a uniform distribution of ground stations GS, across the area of 2 000 km diameter depicted as the shaded area of Fig. 6, the number of GS $n(\alpha)$ in one-degree swath as viewed from the Earth centre, approximately follows a quadratic representation in α:

$n(\alpha) = N_{max}[1 - k'(\alpha - \alpha_0)^2]$ and $n(\alpha) = 0$ for $\alpha > \alpha_0 + \frac{\Delta\alpha}{2}$ or $\alpha < \alpha_0 - \frac{\Delta\alpha}{2}$, with $\alpha_0 = 35°$ and $\Delta\alpha = 18°$.

3.2.1.3.3 Alternative approach analysis results

The Table 9 here under gives the assumed GS distribution per one-degree “bands” or “swath”.

TABLE 9

Ground stations distribution per 1° Earth great-circle "band"

α angle wrt service area centre	Non-normalized. GS area density factor	Normalized. GS area density factor	*Nr* of GS in Alpha "band" of 1° *N*(α)
−10	0	0.0000	0.0
−9	0.19	0.0143	1.0
−8	0.36	0.0271	1.9
−7	0.51	0.0383	2.7
−6	0.64	0.0481	3.4
−5	0.75	0.0564	3.9
−4	0.84	0.0632	4.4
−3	0.91	0.0684	4.8
−2	0.96	0.0722	5.1
−1	0.99	0.0744	5.2
0	1	0.0752	5.3
1	0.99	0.0744	5.2
2	0.96	0.0722	5.1
3	0.91	0.0684	4.8
4	0.84	0.0632	4.4
5	0.75	0.0564	3.9
6	0.64	0.0481	3.4
7	0.51	0.0383	2.7
8	0.36	0.0271	1.9
9	0.19	0.0143	1.0
10	0	0.0000	0.0
S/total	13.3	1.0000	70.0

The Table 10 establishes the satellite range (r), offset angle (α), the elevation angle and the transmit antenna gain. The latter follows a quadratic equation modelled after the diagram of Annex 1 (on ANLE vs. non-GSO/FSS), § 3.2.

The combined PFD of all GS in the same "band" or swath is then computed in Table 10, using the values of $N(\alpha)$ lifted from the preceding Table 9.

TABLE 10

Computation of the interference PFD into the non-GSO satellite in the band 5 091-5 150 MHz

α (degrees)	*r* (km)	β (degrees)	El. (to satellite) (degrees)	GS Ant Gt (dBi)	*N*(α), GS quantity	PFD (dB(W/m^2))
35	4 462.5	54.9	0.1	8.0	0.0	N/A
34	4 351.4	54.9	1.1	8.0	1.00	−130.6
33	4 240.4	54.9	2.1	7.8	1.9	−127.7
32	4 129.4	54.8	3.2	7.6	2.7	−126.2
31	4 018.5	54.7	4.3	7.3	3.4	−125.3
30	3 907.8	54.5	5.5	6.8	3.9	−124.8
29	3 797.3	54.4	6.6	6.2	4.4	−124.7
28	3 687.1	54.2	7.8	5.5	4.8	−124.8
27	3 577.2	53.9	9.1	4.7	5.1	−125.1
26	3 467.7	53.6	10.4	3.7	5.2	−125.7
25	3 358.7	53.2	11.8	2.5	5.3	−126.6
24	3 250.2	52.8	13.2	1.0	5.2	−127.8
23	3 142.3	52.3	14.7	−0.6	5.1	−129.3
22	3 035.2	51.8	16.2	−2.5	4.8	−131.1
21	2 929.0	51.2	17.8	−4.7	4.4	−133.4
20	2 823.7	50.5	19.5	−5.0	3.9	−133.8
19	2 719.6	49.6	21.4	−5.0	3.4	−134.2
18	2 616.8	48.7	23.3	−5.0	2.7	−134.8
17	2 515.5	47.7	25.3	−5.0	1.9	−136.0
16	2 416.0	46.6	27.4	−5.0	1.0	−138.4
15	2 318.4	45.3	29.7	−5.0	0.0	N/A

The PFD values are then summed to yield the aggregate GS PFD. As for the airborne interference contribution, three assumptions are made:

– the number of active transmitters is the same as that of the GS;

– most aircraft are in stable flight condition which results in their antenna being shielded from and to the satellite by the aircraft fuselage and wings; only those aircraft in banking flight configuration are likely to have their antenna visible by the satellite. The proportion of these is assumed to be 10% at most;

– the aircraft antennas being of smaller dimensions than the GSs, the maximum. The gain figure to the non-GSO satellite is 3 dB less than the GSs, i.e. 5 dBi (this is consistent with the pre-WRC-03 RNSS vs. DME compatibility study).

The Table 11 presents the final part of the analysis, with the combination of the GS aggregate PFD and that of the aircraft aggregate PFD, estimated at 13 dB lower value, in accordance with the above assumptions. The TDD 50% activity factor introduces an overall 3 dB reduction in both the GS and airborne aggregate PFD.

TABLE 11

Aggregate interference analysis, with 5 MHz of transmit bandwidth

Parameters	Value	Comments
Aggregate GS PFD (dB(W/m^2))	−115.0	Summing of Table 10, PFD column
Aggregate banking A/C PFD (dB(W/m^2))	−128.0	10% a/c assumed in banking, 5 dBi ant.
Aggregate GS+ Aircraft (A/C) PFD (dB(W/m^2))	−114.8	Summing of the above 2 lines
Omni-antenna area at 5 120 MHz (dBm^2)	−35.6	
SAT antenna gain (dBi)	4.0	See Table 4 of the main body of this Report
Satellite feed loss (dB)	−2.9	See Table 4 of the main body of this Report
TDD activity factor (50%)	−3.0	
Aggregate interference level (dBW)	−152.3	
Interference density (dB(W/MHz))	−159.3	
Interference in SAT BW of 1.23 MHz (dBW)	−158.4	
Satellite thermal noise in ref BW (dBW)	−140.3	See Table 4 of the main body of this Report
Resulting *I*/*N* (dB)	−18.1	
Corresponding $\Delta T_s/T_s$ (%)	1.5	

The alternate method shows an aggregate interference level of −158.4 dBW into the non-GSO satellite, representing a $\Delta T_s/T_s$ of 1.5%.

3.2.2 Impact of FSS into aeronautical security

It is understood that the FSS feeder link would potentially cause interference to the aeronautical security system during aircraft transit of the beam. However, any interference suffered would not be frequent and could be mitigated for at application level.

3.3 Sharing with FSS general conclusions

Analyses indicate, for the systems described in the annexes and visible within an FSS satellite antenna footprint, that interference to the FSS from a future aeronautical security system will represent a $\Delta T_s/T_s$ of less than 2%.

In order not to exceed a $\Delta T_s/T_s$ of 2%, stations operating under AM(R)S and AMS for security cannot operate co-frequency at the same time (within the field of view of a single non-GSO satellite). The practical means for operating in a time sharing mode would require a very complex coordination procedure. Therefore it is proposed that stations operating under AM(R)S and AMS for security operate on a non co-frequency basis.

The compatibility between the FSS ground transmitter and the AMS for security ground receiver can be handled at AMS for security application level by ensuring sufficient distance separation between these stations and/or appropriate frequency separation. Due to the limited number of these ground stations this should be manageable.

The compatibility between the FSS ground transmitter and the AMS for security airborne receiver can be handled at AMS for security application level as any interference suffered would not be frequent.