REPORT ITU-R SM.2091-0[*,**]

Studies related to the impact of active space services allocated in adjacent or nearby bands on radio astronomy service

(2007)

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[*] Syria reserves its right not to accept any proposed protection criteria contained in this Report, as a result of the use of allocated frequency bands for FSS, RNSS, MSS and BSS in adjacent bands to the radio astronomy service.

[**] The Arab Administrations represented at RA-03 indicated that they do not accept the content of Recommendation ITU-R RA 769, which is referenced in this Report.

1 Introduction

The passive radio astronomy service (RAS) is studying natural phenomena producing radio emissions at frequencies fixed by the laws of nature.

Primary allocations have been made to various space services in the Earth-to-space direction such as the fixed-satellite service (FSS), radionavigation-satellite service (RNSS), mobile-satellite service (MSS) and broadcasting-satellite service (BSS) in bands adjacent or nearby to bands allocated to the RAS.

The studies in this technical report provide methodology and framework for documenting the results of the interference assessment between active services and the RAS operating in adjacent and nearby bands. The methodology is based on the equivalent power flux-density (epfd) concept for calculation of interference resulting from unwanted emissions from non-GSO satellite systems.

The list of bands that were considered under this study is given in Table 1. The result of these studies can be found in the following sections of this Report.

TABLE 1

List of compatibility studies with the RAS (passive)

RAS bands	Active service bands
150.05-153.0 MHz	137-138 MHz (non-GSO MSS)↓
322-328.6 MHz	387-390 MHz (MSS)↓
406.1-410 MHz	400.15-401 MHz (non-GSO MSS)↓
608-614 MHz	620-790 MHz (BSS)
1 400-1 427 MHz	1 452-1 492 (BSS)
1 400-1 427 MHz	1 525-1 559 MHz (MSS)↓
1 610.6-1 613.8 MHz	1 559-1 610 MHz (RNSS)↓
1 610.6-1 613.8 MHz	1 613.8-1 626.5 MHz (MSS)↓
1 610.6-1 613.8 MHz	1 525-1 559 MHz (non-GSO MSS)↓
2 690-2 700 MHz	2 655-2 690 MHz (BSS, FSS)↓
10.6-10.7 GHz	10.7-10.95 GHz (FSS)↓
22.21-22.5 GHz	21.4-22 GHz (BSS)
42.5-43.5 GHz	41.5-42.5 GHz (BSS, FSS)↓

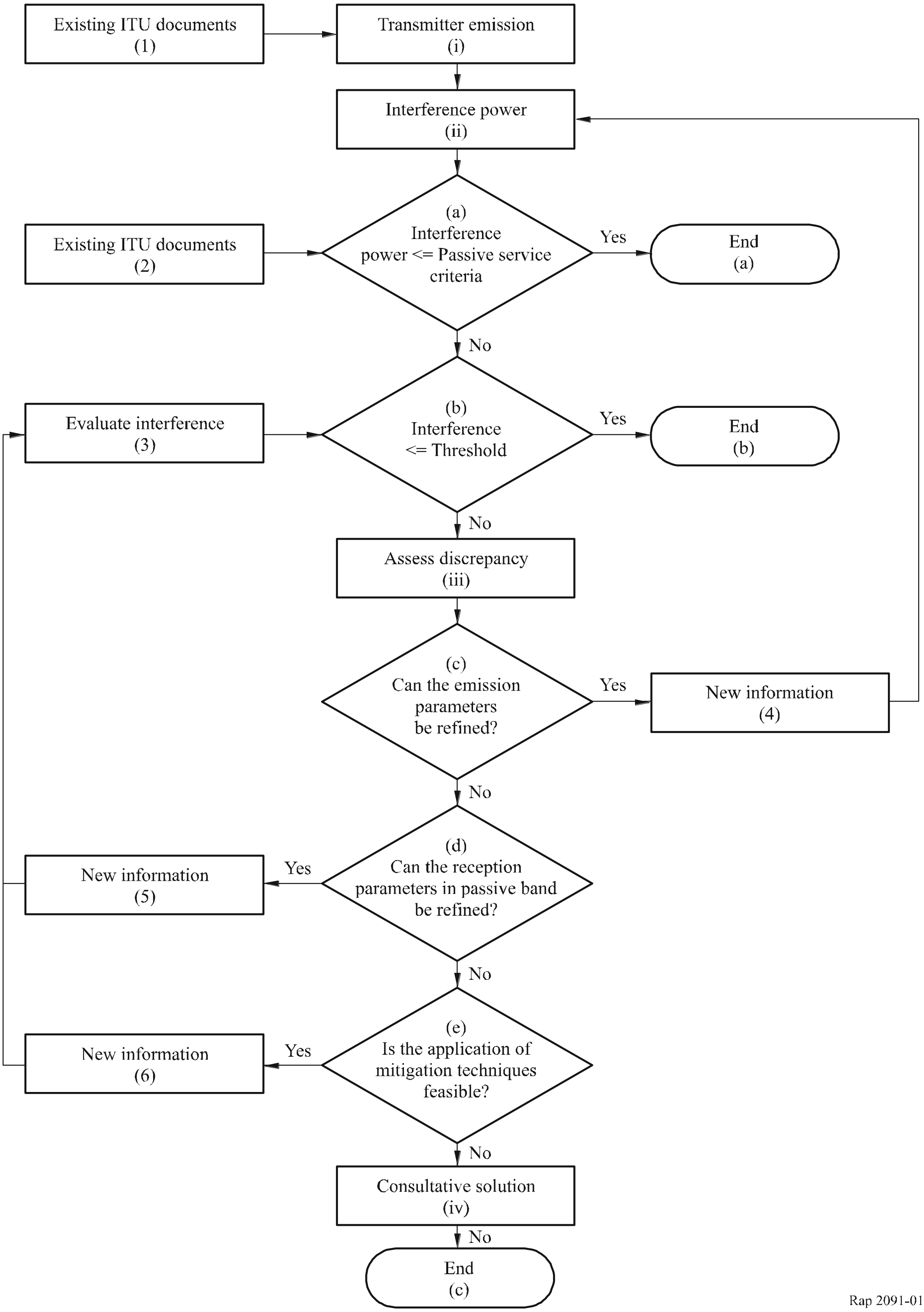
2 Methodology

2.1 General

The following general methodology defines a systematic means for deriving mutually acceptable compatibility criteria between operators of active and passive services operating in their allocated bands. The flow diagram (see Fig. 1) summarizes the methodology with each individual step described in detail in § 2.2 below. As the procedure is iterative, several cycles might be required before a solution is found.

FIGURE 1

Process for the evaluation of adjacent and nearby band operation of passive and active services



The first step is to determine the transmission parameters of the active service (box (i)). The starting point is the worst-case scenario that is used to determine whether there is the potential for detrimental interference to passive services by any and all types of active services operating in an adjacent or nearby band. This worst-case power level could often be determined from existing regulatory limits (box (1)), such as the pfd's found in Article 21 of the Radio Regulations (RR). Such regulatory limits for the power transmitted by the active service must then be used to determine the worst-case level of unwanted emission into the passive band (box (ii)).

The following step is to determine if this worst-case interference level is higher than the passive service interference threshold for the band under consideration (diamond (a)). These threshold levels are given in various ITU-R Recommendations (box (2)) such as Recommendations ITU-R RA.769, or ITU-R RS.1029. If this interference threshold is higher than the worst-case level of unwanted emissions in the band, then there is no adverse impact to the passive service operations. In this case the methodology follows the "Yes" line and the process terminates. At this point, as at all other end points in the methodology, the assumptions used to achieve the end point form the technical basis for a compatible working arrangement between the active and passive services involved. How these technical assumptions and their resulting conclusions are used is a regulatory exercise and is beyond the technical scope of this Recommendation. However, for the case of diamond (a), if the interference is assessed to be greater than the passive service criteria, then it is necessary to follow the "No" branch to diamond (b). On the first iteration, no new information is available so the path continues to box (iii). On later iterations, the threshold in diamond (b) may be different from the passive service criteria used in diamond (a) as a consequence of modified or additional parameters and burden sharing. These modified or additional parameters may result from diamonds (c), (d) or (e). Diamond (b) allows a further assessment whether compatibility has been achieved.

If such is the case the process follows along the "Yes" branch, and the procedure ends. If such is not the case, the discrepancy has to be assessed, whereby in reaching diamonds (c), (d) or (e) the following alternatives should be investigated:

- refine the emission parameters of the active service such as the actual system parameters, available prime power, etc. and/or;
- refine the reception parameters in the passive band, and/or;
- develop further mitigation techniques for both the active and passive services, which may include both alternatives (a) and (b).

When during the assessment of discrepancies, as indicated in box (iii), it is shown that the divergence between the two levels is large, then it is clear that the assumptions used in the first iteration are insufficient to resolve the issue and more detailed assumptions about the characteristics and operations of both services must be made. However, if the divergence is small, it may be possible to modify slightly one of the underlying assumptions so as to enable converging on a solution on the next iteration. A review of the data at hand may suggest what additional assumptions might be beneficial.

From this consideration, either one or more of the active service parameters, passive service parameters, the compatibility criteria or possible mitigation methods can be considered for modification in successive iterations. As many iterations will take place as necessary to either completely close the gap or to have exhausted all potential solutions. If all possible solutions have been exhausted and no compatible operation appears to be possible, then the method ends with a "consultative solution". This implies that the only possible solution is for a specific active system to consult with a specific passive service system operator, in order to achieve a one-to-one solution, if that is possible. Specifics of such a consultative solution are outside the purview of this Recommendation.

This methodology only addresses the potential interference from a single active service operating in its allocated band. Noting that Earth exploration-satellite service (EESS) (passive) may receive interference simultaneously from multiple services, additional consideration may be required to account for the aggregate effects of multiple active services.

2.2 Detailed description of the flow chart (see Fig. 1)

2.2.1 Box (1): Existing ITU documents

This box refers to documents that may be relevant for determining transmitter emissions. The following Articles of the RR and ITU-R Recommendations and Reports are relevant to determining transmitter power that may fall into passive bands, and are provided for reference. These regulations and recommendations are to be used as the starting point in the evaluation of potential active service unwanted emissions into passive service bands.

Radio Regulations

Articles 1, 5, 21, 22 and Appendix 3.

ITU-R Recommendations

ITU-R F.758:	Considerations in the development of criteria for sharing between the terrestrial fixed service and other services
ITU-R F.1191:	Bandwidths and unwanted emissions of digital fixed-service systems
ITU-R SM.326:	Determination and measurement of the power of amplitude-modulated radio transmitters
ITU-R SM.328:	Spectra and bandwidth of emissions
ITU-R SM.329:	Unwanted emissions in the spurious domain
ITU-R SM.1446:	Definition and measurement of intermodulation products in transmitter using frequency, phase, or complex modulation techniques
ITU-R SM.1539:	Variation of the boundary between the out-of-band and spurious domains required for the application of Recommendations ITU-R SM.1541 and ITU-R SM.329
ITU-R SM.1540:	Unwanted emissions in the out-of-band domain falling into adjacent allocated bands
ITU-R SM.1541:	Unwanted emissions in the out-of-band domain.

Some data may be needed beyond what these Recommendations provide. This includes:

- the duty cycle of the systems;
- the geographic distribution and densities of the emitters including deployment densities;
- the antenna aiming or scanning for radiodetermination systems or Earth-to-space transmissions;
- the beam coverage for space-to-Earth transmissions;
- relevant spectral masks; and
- antenna patterns.

Not all of the required data may be available. for all items listed above. Assumptions may be necessary for some parameters. Other information such as deployment may require the development of models.

2.2.2 Box (2): Existing ITU documents

This box refers to documents relevant to the selection of the appropriate passive service criteria for protection from interference. The various passive service criteria, each developed by the working party responsible for the respective passive services, serve as the input of diamond (a) on the flowchart. These Recommendations have been developed, over time, in order to assist other working parties dealing with active services in evaluating the potential for interference from their respective services into the passive services. The list of Recommendations to be considered is as follows:

ITU-R Recommendations

ITU-R RA.769:	Protection criteria used for radio astronomical measurements
ITU-R RA.1513:	Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy on a primary basis
ITU-R RS.1028:	Performance criteria for satellite passive remote sensing
ITU-R RS.1029:	Interference criteria for satellite passive remote sensing.

2.2.3 Box (3): Evaluate interference

The function of this box is to allow for the passive service to generate a new sharing criterion based on the information provided from boxes (5) and (6). As an example, lower side-lobe levels might be assumed than the 0 dBi receive antenna gain figure currently assumed for the RAS. If this were the case, the process of recalculating the sharing criteria would be done in box (3).

To evaluate interference from non-GSO FSS systems to stations in the RAS, the methodology of Recommendation ITU-R S.1586 should be used. Likewise, to evaluate interference from non-GSO MSS and RNSS systems to stations in the RAS, the methodology of Recommendation ITU-R M.1583 should be used.

2.2.4 Boxes (4), (5) and (6): New information

The function of the box is to accommodate new information brought into the sharing study while it proceeds through multiple iterations. An example of such a situation would be the making usage of RR Appendix 4 information submitted to the Radiocommunication Bureau (BR) in box (4) to justify the use of an in-band pfd less than the regulatory figure. Other information may consist of filter or antenna information in any of boxes (4), (5) and (6) that is brought into the process in order to close the gap. New information may also consist of additional input not considered previously, such as specific ITU-R Recommendations, regional recommendations, or regional standards. Examples for the relevant boxes are as follows:

Box (4)

At higher frequencies, transmit antenna patterns can have a significantly narrower beamwidth in order to maximize the power in a limited service area so as to increase throughput and overcome atmospheric effects. As a result, the majority of the surface of the Earth may receive an unwanted emission pfd level that is well below the detrimental level of the passive service. Instead of having the level applicable over the entire surface of the Earth, it may be possible to relax the level over a fraction of the Earth's surface. As a result, the probability that an RAS station will receive detrimental interference from a specific direction becomes very small.

In the band 40-42.5 GHz, Recommendation ITU-R S.1557 – Operational requirements and characteristics of fixed-satellite service systems operating in the 50/40 GHz bands for use in sharing studies between the fixed-satellite service and the fixed service, contains parameters that may be used for studies relevant to this band.

Box (5)

Characteristics such as band-specific receive antenna patterns are characteristics that could be used to decrease the difference between the passive service detrimental interference level and the received unwanted emission level.

Box (6)

Many mitigation methods that may minimize the impact of the active service on the passive service are listed in Recommendation ITU-R SM.1542. In any specific case, only some of the mitigation methods listed may apply to the situation at hand. In applying certain mitigation methods, it may often be necessary to determine how the burden resulting from its application will be partitioned.

2.2.5 Box (i): Transmitter emission

The purpose of this box is to establish the transmit in-band power density at the antenna flange.

2.2.5.1 General case

Generally the value can be found by:

$$p_{density} = e.i.r.p._{density} - G_t \qquad (1)$$

where:

$p_{density}$: transmit power density into the transmit antenna (dB(W/Hz))

$e.i.r.p._{density}$: transmit e.i.r.p. density (dB(W/Hz))

G_t: transmission antenna gain (dBi).

Transmit power density can also be computed as:

$$p_{density} = 10\ \log(p_t) - OBO - 10\ \log(BW_{nb}) - L_c \qquad (2)$$

where:

p_t: transmission amplifier maximum rated power (W)

OBO: output back off (dB)

BW_{nb}: necessary bandwidth (Hz)

L_c: circuit loss between the transmission amplifier and transmission antenna (dB).

It should be noted in equation (2) that the transmit power density is assumed to be uniformly distributed over the necessary bandwidth. If this assumption is erroneous, a correction can be introduced by appropriately modifying the bandwidth.

2.2.5.2 In-band satellite transmitted power level based on RR Table 21-4

To derive the transmit power density from the pfd limits, then:

$$P_{density} = pfd + 10\ \log(4\pi d^2) - G_t + L_c \qquad (3)$$

where:

pfd: downlink power flux-density (dB(W/(m^2 · MHz)))

d: slant path, from satellite to earth station (km)

G_t: transmission antenna gain (dBi)

L_c: circuit loss between the transmission amplifier and transmission antenna (dB).

If these values are used, the result will yield the highest possible transmitter emission level, which is in many cases unrealistic. This is because various factors such as the actual transmit antenna roll-off and spectral waveforms are not taken into the consideration. In making the above calculations, it should be kept in mind that the transmit antenna gain depends on each system and its applications. Typically, the satellite transmit antenna gain varies as follows:

- for non-GSO MSS systems the gain varies over a range from 17 dBi to 31 dBi depending on the satellite altitudes, elevation angles;
- for GSO MSS systems the gain varies over the range from 41 dBi to 45 dBi;
- for FSS satellite antenna gain of existing 4/6 GHz and 12/14 GHz, the gain varies in a range from 20 dBi to 42 dBi. However, the antenna gain of the future 4/6 GHz and 12/14 GHz satellite systems may be significantly higher than those of the existing systems; and
- for FSS satellite systems in the 20/30 GHz and 40/50 GHz bands, the satellite transmit antenna gain is in a range from 44 dBi to 60 dBi.

2.2.5.3 Power density based on total space station RF power

Calculating the transmit e.i.r.p. density depends on a satellite total transmit RF power, circuits loss between a transmit power amplifier and transmit antenna, transmit antenna gain, frequency reuse scheme, assigned bandwidth, number of beams, etc. The average transmits e.i.r.p. density can be computed as:

$$P_{density} = 10\ \log(P_{total}) - 10\ \log(N_{beam}) - 10\ \log\left(\frac{BW_{as}}{N_{freq}}\right) - OBO \tag{4}$$

where:

p_{total}: total RF transmit power (W)

N_{beam}: number of beams

BW_{as}: assigned bandwidth (Hz), e.g.,
500 MHz for 4/6 GHz-band; 1 000 MHz for 12/14 GHz band, etc.

N_{freq}: frequency reuse scheme

OBO: output back off (dB).

2.2.5.4 Power density based on ITU satellite filings

The satellite transmit power density can be obtained directly from RR Appendix 4 filings.

2.2.6 Box (ii): Interference power

The aim of this step is to derive the level of unwanted emission received by the passive service based on the in-band pfd determined in box (i). How this is assessed will vary depending on the characteristics of the transmitting service and those of the passive service receiving the interference. The potential interference to the passive service due to the unwanted emissions of the active service systems could be computed based on the following:

$$pfd_{(unwanted\ \ emissions)} = pfd_{in\text{–}band\_active} - OoB - L \tag{5}$$

where:

$pfd_{(unwanted\ emissions)}$: power flux-density level at the RAS receive sites

$pfd_{in\text{-}band\_active}$: in band pfd levels of the active service systems. The maximum allowable pfd limits shown in Table 21-4 may be used in the calculation. In some cases, there are no downlink pfd limits, and the maximum downlink pfd limits of the active system may be used

OoB: out-of-band rejection mask (for example based on Recommendation ITU-R SM.1541)

L: the attenuation by atmospheric gases and scintillation loss (see Recommendation ITU-R P.676 – Attenuation by atmospheric gases).

RR No. 1.153 and Recommendation ITU-R SM.1541 suggest methods for determining active services emissions within the OoB domain. In applying Recommendation ITU-R SM.1541, the range of the OoB domain is determined through the application of Recommendation ITU-R SM.1539. Recommendation ITU-R SM.329 is used to derive levels of unwanted emissions from active services that occur in the spurious domain.

2.2.6.1 EESS receiver

The EESS is vulnerable to interference from terrestrial transmitters, including single high level transmitters and the aggregate emissions of densely deployed low power level transmitters. Spaceborne transmitters could add to the energy received by the sensor via reflections off the Earth into the antenna main beam, or directly through the side or back of the antenna.

Inputs that are required to evaluate the resulting power from active systems at an EESS receiver, include:

- the gain of the EESS system;
- the pointing characteristics of the EESS system;
- the altitude of the EESS system; and
- the atmospheric absorption.

2.2.6.1.1 Transmitter geographical density

Systems deployed on the surface of the Earth are essentially stationary during the measurement period of the sensor. The interference potential increases when several transmitters appear in the main beam of the sensor antenna. The information required for the evaluation of the power received from active systems deployed within the EESS pixel is as follows:

- the size of the EESS pixel;
- the number of terminals to be deployed in the pixel size using the same frequency at the same time;
- an approximation of the gain of the terrestrial systems in the direction of the EESS satellite. Recommendation ITU-R F.1245 provides antenna pattern for FS P-P systems and Recommendation ITU-R F.1336 provides reference radiation patterns for point-to-multipoint (P-MP) systems. Since FS terminals are pointing in direction close to the horizon, the probability to have a FS system pointing directly within the main beam of an EESS satellite antenna is very low. As a first step approach, the average gain of FS systems in the direction of the EESS satellite to be used in the calculation of the aggregate power received at the EESS satellite, may be approximated by taking for each of the FS terminals a gain which is the gain calculated for a 90° off-axis angle.

In case of FS systems, the following parameters should be considered:

– the channel arrangement (if available) as a first step approach(examine the “closest” channels to the EESS band);

– Recommendation ITU-R F.1191 states that for digital FS systems, the necessary bandwidth is to be considered to have the same value as the occupied bandwidth and that the FS power outside the occupied bandwidth (lower and upper) should not exceed 0.5% of the total mean power of the given emission (see RR No. 1.153). Total mean power values are given in Recommendation ITU-R F.758.

2.2.6.1.2 Transmitter pointing toward sensors

In some cases, individual transmitters could interfere with measurements while the sensor is in the main lobe of the terrestrial station. Information required for the evaluation of the power received from the active system is as follows:

– the gain of the transmitter in the EESS direction; and

– the link path.

2.2.6.1.3 Satellite downlinks

In some cases, interference is possible from reflected signals off the surface of the Earth that could enter the main beam of the space station. Information required for the evaluation of the power received from the active system:

– the reflection coefficient of terrain or body of water;

– the gain of the space system in the direction of the Earth;

– the altitude of the space system or the pfd at the Earth.

2.2.6.2 RAS receiver

2.2.6.2.1 Unwanted emissions from the fixed service

Potential interference from high altitude platform station (HAPS) systems to the RAS is expected. No other issues, related to terrestrial sources of interference to radio astronomy bands have been identified in Recommendation ITU-R SM.1542.

2.2.6.2.2 Unwanted emissions from space systems

Interference power incident on the RAS station comes from either GSO or non-GSO satellite service downlinks. In the first case the interference will generally not vary in either location or time. In the second case, the interference power will vary both in time and location in the sky. As a result, both are treated separately.

2.2.6.2.2.1 Unwanted emissions from GSO satellite systems (downlink)

The pfd of unwanted emissions can be assessed as follows:

$$pfd_{unwanted\ emission} = \int_{f_1}^{f_2} \frac{p(f)\,.\,g(f)}{SL\,.\,ATM(f)}\,\mathrm{df} \qquad (6)$$

where:

$pfd_{unwanted\ emissions}$: pfd at the RAS station (W/m^2)

f_1, f_2: lower and upper edge respectively of the RAS receiver band (Hz)

$p(f)$: unwanted emission power density at the transmission antenna flange (W/Hz)

$g(f)$: gain of the transmission antenna in the direction of the radio astronomy site

SL: spreading loss (m^2)

$ATM(f)$: atmospheric absorption in the band $f_1 - f_2$ as a function of frequency.

It should be noted that the power density of the transmitted signal, the gain of the antenna sub-system, and the atmospheric absorption vary with frequency and as such are represented as functions of frequency. The pfd of unwanted emissions at the location of the RAS station is the integral of these functions as shown above over the passband frequency of the receiver. In cases where the unwanted emission power density, the antenna gain, and the atmospheric absorption are constant throughout the bandwidth of the passive service receiver, the function can be simplified as follows:

$$pfd_{unwanted\ emission} = \frac{p \, . \, g}{SL \, . \, ATM} (f_2 - f_1) \tag{7}$$

In cases where the active band is adjacent to the passive band, it may be possible to assume that the transmission antenna gain remains approximately constant in both the transmission band and the passive band. However this may often not be the case, particularly when the passive band is below the cut-off frequency of the waveguide feed network in the antenna sub-system.

2.2.6.2.2.2 Unwanted emissions from non-GSO satellite systems (downlink)

To evaluate interference from non-GSO FSS systems to stations in the RAS, the methodology of Recommendation ITU-R S.1586 should be used. Likewise, to evaluate interference from non-GSO MSS and RNSS systems to stations in the RAS, the methodology of Recommendation ITU-R M.1583 should be used.

2.2.7 Box (iii): Assess discrepancy

The purpose of this box is to provide for a review of the input data and the discrepancy before proceeding with another iteration of the methodology. If this box has been reached then the interference received is greater than the threshold, implying that changes must be made in the next iteration to close the gap between the two numbers.

In the first iterations through the loop, the focus should be on improving the accuracy of assessing the interference into the passive service. As preliminary sharing studies involve coarse assumptions about both systems, these will need to be refined so as to be able to appropriately assess the interference potential. More detailed system descriptions and calculation methodologies may require a greater degree of computational complexity, but in the end may reveal that interference potential is significantly less than coarser assumptions had indicated.

Once the study is deemed to be sufficiently precise and a gap still exists, it will be necessary for either or both sides to take restrictions in order to clear the problem. These restrictions may take the form of operational restrictions, characteristic changes of the equipment or a modification in the sharing criteria.

Once the possible areas for changes in the next have been identified in this box, the appropriate decision box will effect the change and lead to a new interference assessment.

2.2.8 Box (iv): Consultative solution

After several iterations of the methodology, there may still exist a gap between the active and passive service. If no further changes can be made to any of the system parameters, criteria or mitigation methods then there is no general solution that allows all users of the active band to share with all the passive service users. The only remaining solution that can then be explored is for sub-sets of the active band and passive band users to enter discussions and possibly achieve an agreement among them. For example, between two adjacent bands it may not be possible to find a solution between the FSS and RAS. However, a solution may be possible between the non-GSO FSS and the RAS.

The methodology in Fig. 1 may prove useful in carrying out the discussions in this section between sub-sets of operators sharing the band.

However, if smaller consultation groups cannot achieve an agreement, then the methodology comes to an end without having closed the gap. The resulting progress from the iterations through the methodology may have proved helpful in closing the gap and suggesting future areas for study. It may also serve as a basis for multiple solutions among which regulators may have to select.

2.2.9 Diamond (a): Interference power ≤ passive service criteria

The interference power assessed in box (ii) is compares to the appropriate passive service protection criteria from box (2). If the interference is greater then the detrimental level, the methodology proceeds to decision diamond (b). This method ends if the interference is less than or equal to these criteria.

2.2.10 Diamond (b): Interference power ≤ threshold

On later iterations the threshold in diamond (b) may indicate that the operating arrangement that provides adequate protection for passive service while minimizing the restrictions upon the active service is possible. Parameters used may result from the procedures in diamonds (c), (d) or (e). The burden following this arrangement would be distributed equitably between two services. In the case of multiple interfering active services, the iteration procedure should be followed for each individual service, possible resulting in different operating arrangements for each. The guiding principle is that the total burden on all parties involved should not render any of these parties incapable of operating effectively.

2.2.11 Diamond (c): Can the emission parameters be refined?

Following the review done in box (iii), it may be possible to modify the emission parameters of the active service. For example, regulatory limits used as lower levels that are more representative of current may replace the worst-case assumptions for future planned systems. These modified assumptions can then be taken into account in subsequent iterations.

2.2.12 Diamond (d): Can the reception parameters in passive band be refined?

Following the review done in box (iii), it may be possible to modify reception parameters of the passive service. For example, actual antenna patterns may be used instead of more conservative patterns. These modified assumptions can then be taken into account in subsequent iterations.

2.2.13 Diamond (e): Is the application of mitigation techniques feasible?

Once the parameters of the active and passive service can no longer be refined and there still remains a gap between the interference and sharing threshold, then mitigation methods can be considered as a way of reducing the gap. Three likely methods are included in this section, although additional methods do exist (e.g. the list in Annex 3 of Recommendation ITU-R SM.1542).

2.2.13.1 Active system

2.2.13.1.1 Filtering by the active system

One method of adequately protecting the passive services is the introduction of additional filtering in the RF chain of the transmitter to reduce the level of unwanted emissions. In some cases this may pose a minimal burden as the architecture of the transmitter allows for the insertion of a filter or the improvement of an existing filter. However in some cases, the applicability of filters may be affected by considerations of cost, weight and/or reduction in capacity.

2.2.13.1.2 Use of a guardband

One method of reducing the level of the unwanted emission from active service transmitter into the passive band is to introduce a guardband. The guardband allows reducing the interference power received by the passive service operator. Although this may be effective when both systems share adjacent bands, it may be of little value when the separation between the bands is large, as the additional bandwidth may not provide any substantial improvement in filter attenuation. Furthermore, the insertion of a guardband reduces the bandwidth available to one or both services.

To assess the impact of a guardband the following calculations should be undertaken. The interference power (W) received by the passive service is as follows:

$$I = \int_{f_1}^{f_2} \frac{p(f) \cdot g_1(f) \cdot g_2(f) \cdot |h(f)|^2}{FSL \cdot ATM(f)} \, \mathrm{d}f \tag{8}$$

where:

I: interference power received by the passive service receiver within its receive bandwidth (W)

f_1, f_2: lower and upper edge respectively of the passive service receiver band (Hz)

$p(f)$: unwanted emission power density as a function of frequency at the transmission antenna flange (W/Hz)

$g_1(f)$: gain of the transmission antenna as a function of frequency in the direction of the passive service antenna

$g_2(f)$: gain of the passive service antenna as a function of frequency in the direction of the transmission antenna

FSL: free space loss

$ATM(f)$: atmospheric absorption in the band as a function of frequency

$h(f)$: transfer functions of passive service receive filters.

Implementing a guardband involves shifting both the receiver and transmitter curves. As a result of the frequency shift some of the curves may change shape to accommodate the bandwidth available.

2.2.13.1.3 Use of geographic isolation

Another method to avoid detrimental interference is to make sure that the Earth-based passive service station is sufficiently removed from the boresight of the active service transmitter. If the Earth-based passive service stations are located in areas, which are removed from the space station service area then the interference, is minimized. Furthermore, if the Earth-based passive service stations are few in number and their positions are well known then it should be possible for the space station designer to position the beams so as to avoid the Earth-based passive service stations.

2.2.13.2 Passive system

See Recommendation ITU-R SM.1542.

2.2.14 End circles (a), (b), (c)

End (a): The methodology ending at this point has determined that compatibility has been demonstrated between the initial passive service parameters and the initial or refined active service parameters. It is a possible outcome at his point that no modifications were needed and the initial parameters analysed represent compatible systems.

End (b): The methodology ending at this point has determined that compatibility has been demonstrated between the initial or refined passive service parameters and the initial or refined active service parameters or by the consideration of other mitigation techniques.

End (c): The methodology ending at this point has determined that compatibility cannot be demonstrated with the initial or refined parameters for each service. It is necessary that the administrations sponsoring specific systems enter into negotiations relative to these systems.

3 Compatibility analysis between RAS systems operating in the 150.05-153.0 MHz band and mobile-satellite service (space-to-Earth) systems operating in the 137-138 MHz band

3.1 RAS

3.1.1 Allocated band

The 150.05-153.0 MHz band is allocated on a primary basis to the fixed service, the mobile service (except aeronautical mobile) and the RAS in Region 1. Additionally, this band is allocated to the radio astronomy service on a primary basis in Australia and India by RR No. 5.225.

RR No. 5.149 urges administrations to take all practicable steps to protect the RAS from harmful interference.

3.1.2 Type of observations

This band is used for continuum (broadband) observations.

It is needed to ensure the necessary spectrum coverage of continuum observations of cosmic radio sources. Given the octave spacing required for this coverage, it lies right in between the 73-74.6 MHz and 322-328.6 MHz bands, which are also used for this purpose by the radio astronomy service. It is also used for solar observations and for observations of the rapid, periodic emissions of pulsars.

3.1.3 Required protection criteria

The threshold levels for detrimental interference to radio astronomical observations are given in Recommendation ITU-R RA.769.

These are threshold levels above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), rises 10 dB or more above the level given in this Recommendation, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will then be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

For continuum observations, the entire 2.95 MHz width of the band 150.05-153.0 MHz is generally used. The pfd threshold for detrimental interference to single dish observations is –194 dB(W/m^2).

3.1.4 Operational characteristics

In general, continuum observations are made differentially: the area of sky surrounding the cosmic radio source may be mapped, and the background emission subtracted, or measurements made of the power coming from the direction of the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

3.2 MSS

3.2.1 Allocated transmit band

The bands 137-137.025 MHz and 137.175-137.825 MHz are allocated to the MSS (space-to-Earth) on a primary basis in all regions. The bands 137.025-137.175 MHz and 137.825-138 MHz are allocated to the MSS on a secondary basis in all regions.

RR Nos 5.208A and 5.209 apply to the MSS in this band.

RR No. 5.208A states that "In making assignments to space stations in the mobile-satellite service in the band 137-138 MHz, 387-390 MHz and 400.15-401 MHz, administrations shall take all practicable steps to protect the radio astronomy service in the bands 150.05-153 MHz, 322-328.6 MHz, 406.1-410 MHz and 608-614 MHz from harmful interference from unwanted emissions. The threshold levels of interference detrimental to the radio astronomy service are shown in Table 1 of Recommendation ITU-R RA.769-1.(WRC-97)".

RR No. 5.209 states that "The use of the bands 137-138 MHz, 148-150.05 MHz, 399.9-400.05 MHz, 400.15-401 MHz, 454-456 MHz and 459-460 MHz by the mobile-satellite service is limited to non-geostationary-satellite systems.(WRC-97)".

3.2.2 Application

Systems in the non-GSO MSS below 1 GHz are capable of transmitting digital packets of data at low data rates (2.8 to 19.2 kbit/s). These systems provide high quality wireless data communications. The low frequencies (below 1 GHz) and the low-Earth orbit result in small, low power earth stations and satellites and, consequently, in low system implementation costs. Networks are designed to be capable of providing coverage to all or most of the world (some systems do not include full coverage of the polar areas). Generally, these MSS systems operate in a near real-time mode when the same satellite covers both the user station and the feeder-link station. However, the systems can also operate in the store and forward mode when the user and feeder-link stations are not within the same satellite footprint, e.g. when a user is located in an open ocean area. In this mode, the systems operate with a time delay that can range from seconds to hours, depending on the next satellite pass over a feeder-link station.

3.2.3 Levels based upon regulatory provisions

There are no hard limits applicable to MSS in this band.

3.2.4 Operational characteristics

The technical and operational characteristics of four non-GSO MSS systems using, or planned to be used in, the band for either service or gateway downlinks are described in Recommendation ITU-R M.1184. Those are systems L, M, P and Q. The orbital characteristics of the actual system Q are different from the ones which are given in that Recommendation. The actual characteristics are given in Table 2, along with those of systems L, M and P.

TABLE 2

Orbital parameters of non-GSO MSS networks below 1 GHz

System	**L**	**M**			**P**	**Q**	
Number of satellites	48				6	26	
Altitude (km)	950	825		775	893	1 000	
Inclination (degrees)	50	45	0	70, 108	99	66	83
Orbit planes	8	3	1	2	2	4	2
Satellite/plane	6	8			3	6	1
Right ascension of ascending node (degrees)	0, 45, 90, 135, 180, 225, 270, 315	0, 120, 240	0	0, 180	9.8	0, 90, 180, 270	0, 90
Downlink emission power (W)	25	18.2			1	32	
Downlink e.i.r.p. (dBW)	19.7	13.6			3.8	17.8	
Necessary bandwidth (kHz)	25	25			855	25	
pfd in the MSS band (dB(W/m^2))	–111	–115			–126	–113	

3.3 Compatibility threshold

For the case of non-GSO constellations, an epfd threshold level of –238 (dB(W/m^2)) may be derived for the band 150.05-153 MHz from the pfd threshold level for interference detrimental to radio astronomy observations given in Recommendation ITU-R RA.769 and the maximum radio astronomy antenna gain given in Recommendation ITU-R RA.1631, which is 44 dBi for this frequency band.

3.4 Interference assessment

3.4.1 Methodology used to assess the interference level

Recommendation ITU-R M.1583 provides a methodology to evaluate the levels of unwanted emissions produced by a non-GSO system at radio astronomy sites. It is based on a division of the sky into cells of nearly equal solid angle and a statistical analysis where the pointing direction of the RAS antenna and the starting time of the satellite constellation are the random variables. For each trial, the unwanted emission level (expressed in terms of epfd) is averaged over a 2 000 s period.

The chosen RAS characteristics correspond to the Effelsberg radio telescope in Germany, which can observe in the band considered with an antenna diameter of 100 m and a maximum gain of approximately 44 dBi. The antenna pattern and maximum antenna gain are taken from Recommendation ITU-R RA.1631.

The geographical coordinates of the Effelsberg station are:

Latitude: 50.7° N Longitude: 7.0° E

The simulations were performed considering an RAS antenna elevation angle of 0°, in order to get completely general results.

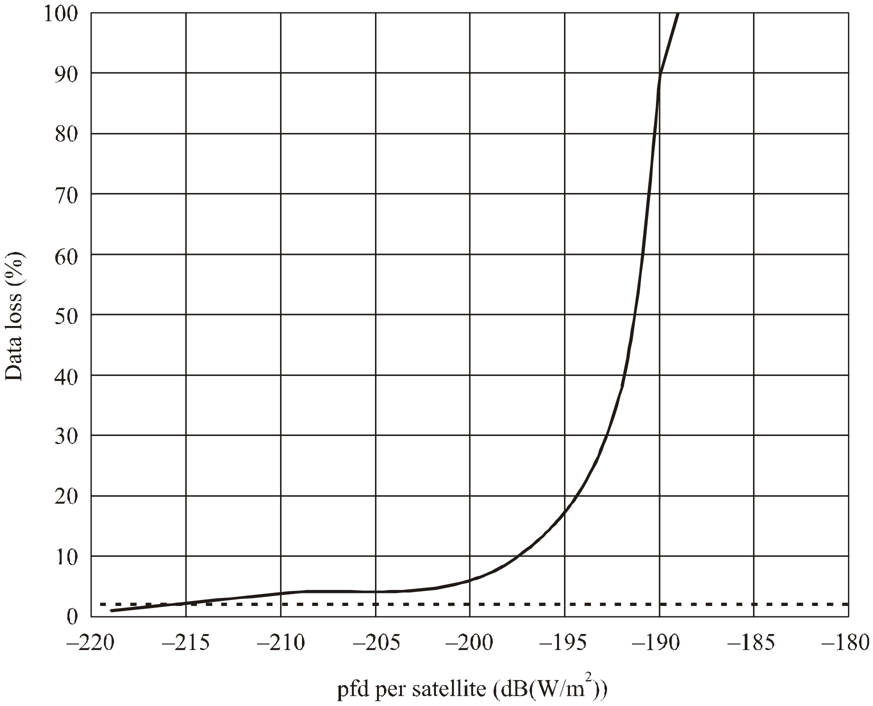
3.4.2 Calculation of interference level

3.4.2.1 MSS system L

Figure 2 shows the percentage of time when the epfd threshold level is exceeded at the radio astronomy station, for a given pfd value per MSS satellite (as explain in Recommendation ITU-R RA.1513, exceeding this threshold is equivalent to data loss).

FIGURE 2

Percentage of data loss vs. pfd per satellite at Effelsberg RAS site for MSS system L



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To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each satellite of MSS system L should generate a pfd of less than –216 dB(W/m^2) in the radio astronomy band.

Figure 3 shows for each cell of the sky, and for the pfd (per satellite) of –216 dB(W/m^2), the percentage of time when the epfd threshold is exceeded.

In Figs. 3, 5, 7 and 9, 0° azimuth is due North, and azimuth increases from West to East.

3.4.2.2 MSS system M

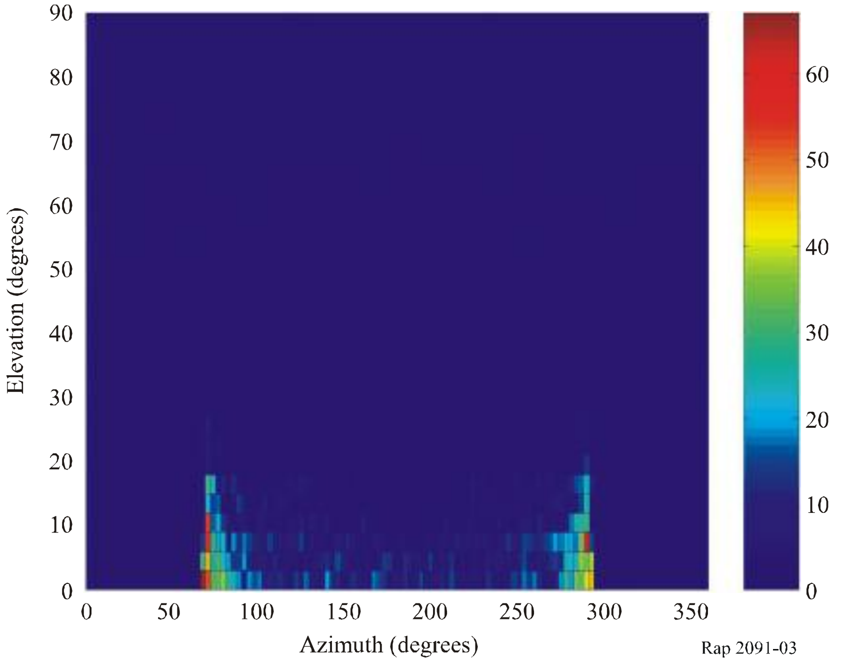
Figure 4 shows the percentage of time when the epfd threshold level is exceeded at the radio astronomy station, for a given pfd value per MSS satellite.

To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each satellite of MSS system M should generate a pfd of less than –212 dB(W/m^2) in the radio astronomy band.

Figure 5 shows for each cell of the sky, and for the pfd (per satellite) of –212 dB(W/m^2), the percentage of time when the epfd threshold is exceeded.

FIGURE 3

Percentage of data loss over the sky for the pfd value of –216 dB(W/m^2) at Effelsberg RAS site for MSS system L



Rap 2091-03

FIGURE 4

Percentage of data loss vs. pfd per satellite at Effelsberg RAS site for MSS system M

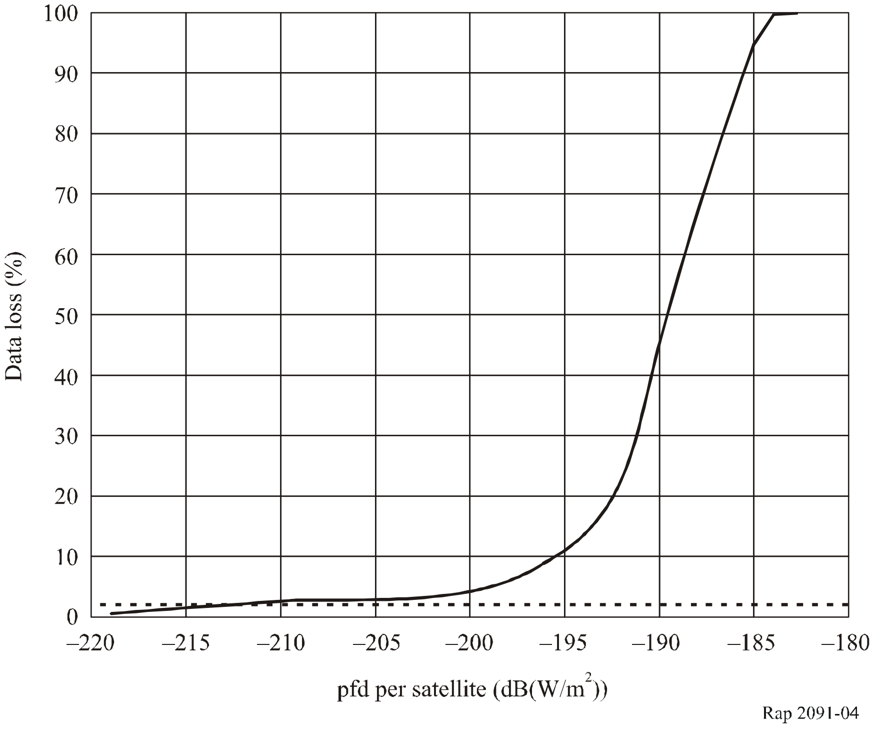


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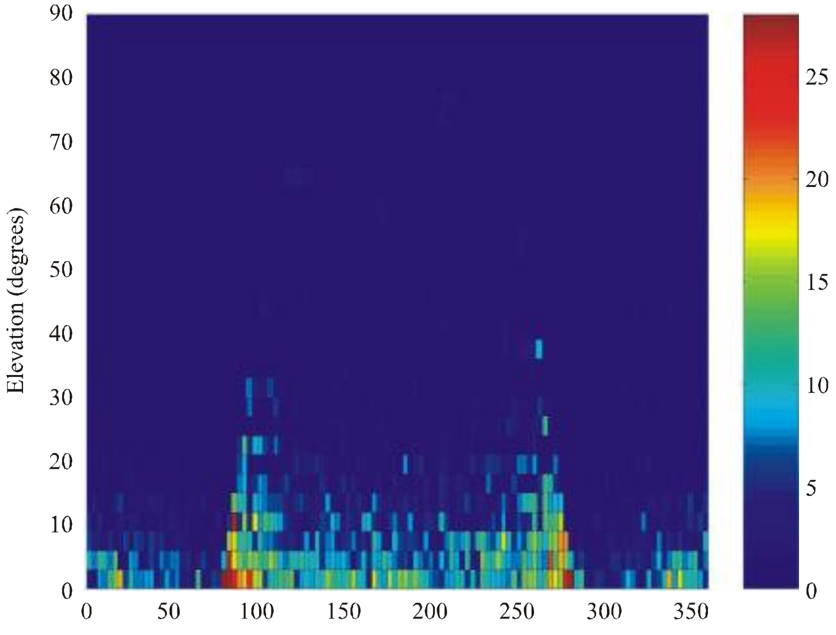
FIGURE 5

Percentage of data loss over the sky for the pfd value of –212 dB(W/m^2) at Effelsberg RAS site for MSS system M

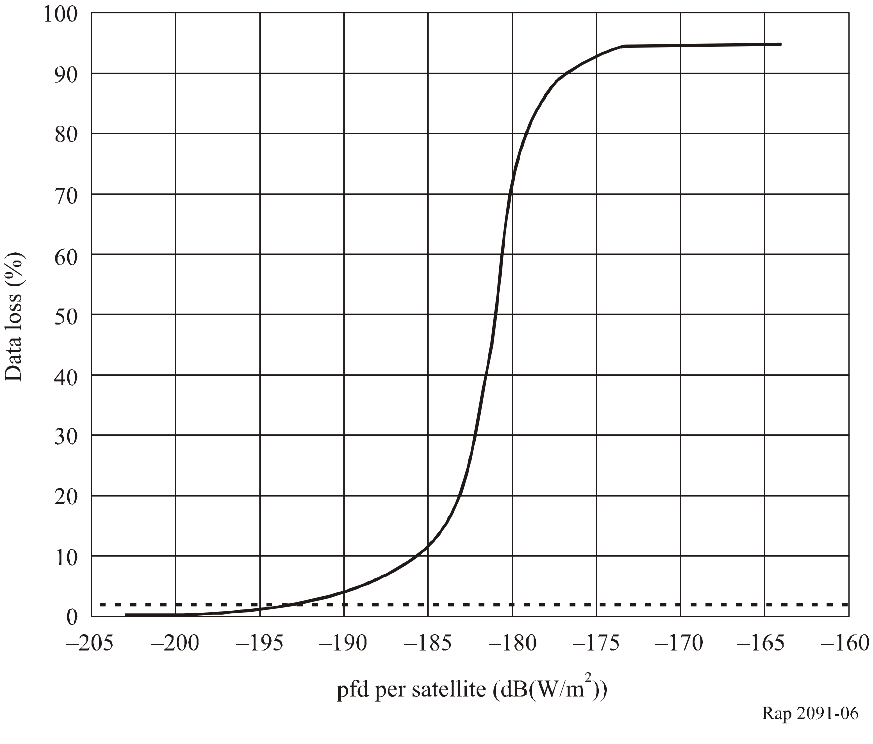


3.4.2.3 MSS system P

Figure 6 shows the percentage of time when the epfd threshold level is exceeded at the radio astronomy station, for a given pfd value per MSS satellite.

FIGURE 6

Percentage of data loss vs. pfd per satellite at Effelsberg RAS site for MSS system P

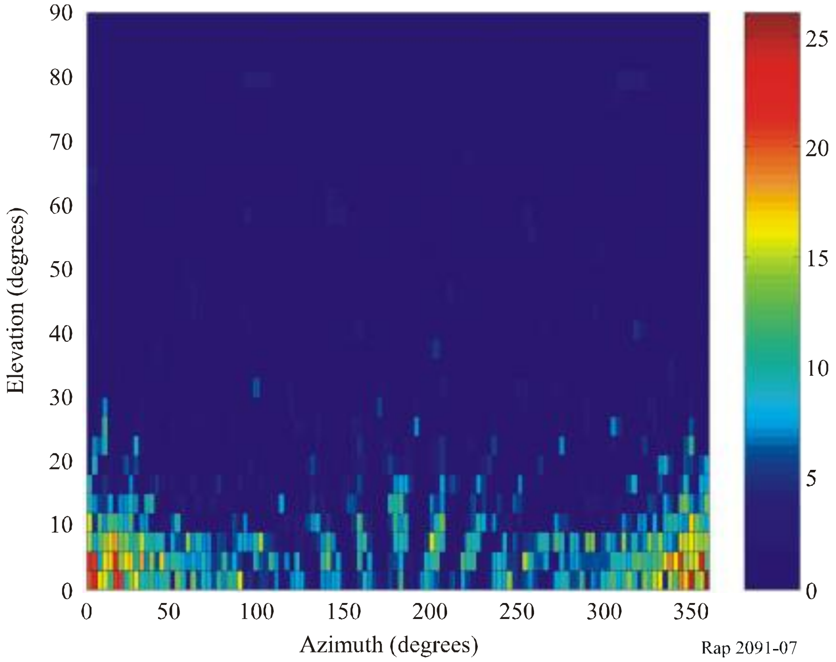


To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each satellite of MSS system P should generate a pfd of less than –193 dB(W/m^2) in the radio astronomy band.

Figure 7 shows for each cell of the sky, and for the pfd (per satellite) of –193 dB(W/m^2), the percentage of time when the epfd threshold is exceeded.

FIGURE 7

Percentage of data loss over the sky for the pfd value of –193 dB(W/m^2) at Effelsberg RAS site for MSS system P



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3.4.2.4 MSS system Q

Figure 8 shows the percentage of time when the epfd threshold level is exceeded at the radio astronomy station, for a given pfd value per MSS satellite.

To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each satellite of MSS system Q should generate a pfd of less than –212 dB(W/m^2) in the radio astronomy band.

Figure 9 shows for each cell of the sky, and for the pfd (per satellite) of –212 dB(W/m^2), the percentage of time when the epfd threshold is exceeded.

FIGURE 8

Percentage of data loss vs. pfd per satellite at Effelsberg RAS site for MSS system Q

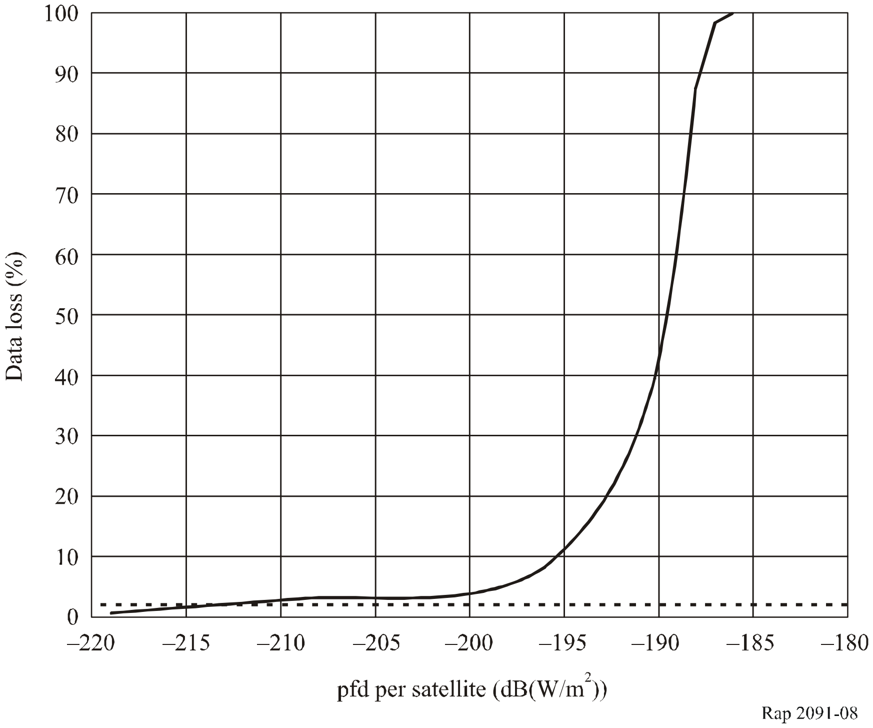
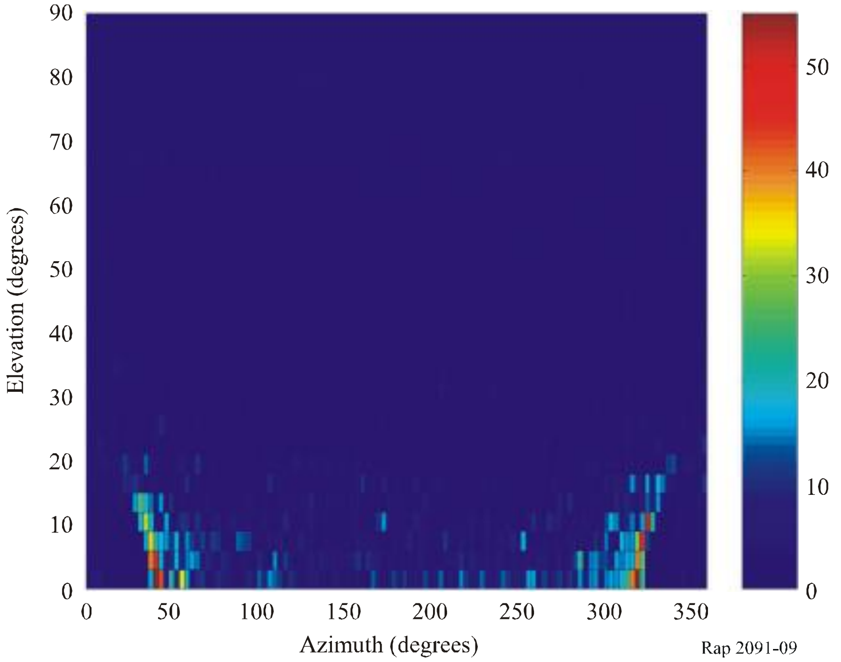


FIGURE 9

Percentage of data loss over the sky for the pfd value of –212 dB(W/m^2) at Effelsberg RAS site for MSS system Q



3.4.3 Values achieved

The unwanted emissions of MSS non-GSO satellites using the band 137-138 MHz falling into the RAS band 150.05-153 MHz fall in the spurious domain.

Table 3 shows, for each of the four non-GSO MSS systems below 1 GHz, the necessary attenuation so that the detrimental epfd threshold is not exceeded.

TABLE 3

Attenuation of non-GSO MSS networks below 1 GHz necessary to reach the detrimental epfd level

System	L	M	P	Q
Emission power in the MSS band (W)	25	18.2	1	32
pfd in the MSS band (dB(W/m^2))	–111	–115	–126	–113
43 + 10 × log (P)	57	56	43	58
Spurious attenuation from Appendix 3 (dBc in 4 kHz)	57	56	43	58
Spurious level from Appendix 3 (dB(W in 4 kHz))	–43	–43	–43	–43
Spurious level in the RAS band (dBW)	–14.3	–14.3	–14.3	–14.3
Spurious pfd in the RAS band (dB(W/m^2))	–139	–142	–140.3	–143
Required pfd in the passive band (dB(W/m^2))	–216	–212	–193	–213
Necessary attenuation (dB)	77	70	52.7	70

It has to be noted that for the calculation of the total amount of spurious emissions in the RAS band it was considered that spurious emissions have a constant level over the whole RAS band. This hypothesis is very stringent and clearly not realistic, as spurious emissions generally appear at some discrete frequencies. Therefore, further work is needed taking into account discrete component of spurious emissions, in order to get more realistic MSS unwanted emission levels in the RAS band.

3.5 Mitigation techniques

3.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for G/T, i.e. telescope gain divided by system temperature. This is to maximize the S/N for point sources. A key element of this approach is to reduce ground radiation entering through far side lobes. Inevitably this leads to some corresponding increase in the levels of near side lobes. Experience has shown that the majority of radio telescopes meet the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

3.5.2 Potential impact to the RAS

Antenna side-lobe performance: Attempts to decrease the sensitivity of the radio astronomy antenna to unwanted emissions coming from space stations are likely to increase the sensitivity of the radio astronomy telescope to ground radiation, and possibly reduce its main beam gain. Both of these effects will reduce the telescope's channel capacity of and thus lead to an increase of the total required integration time.

Blanking in time and/or frequency: Blanking involves a risk of compromising the integrity of the data and may lead to errors in their scientific interpretation. Blanking also causes a concomitant increase in the total integration time required to make the observation, this is equivalent to a loss in the channel capacity of the telescope.

4 Compatibility analysis between RAS systems operating in the 322-328.6 MHz band and mobile-satellite service (space-to-Earth) systems operating in the 387-390 MHz band

4.1 RAS

4.1.1 Allocated band

The 322-328.6 MHz band is allocated on a primary basis to the fixed service, the mobile service (except aeronautical mobile) and the radio astronomy service.

RR No. 5.149 urges administrations to take all practicable steps to protect the radio astronomy service from harmful interference.

4.1.2 Type of observations

This band is used for both continuum (broadband) and spectral line (narrow-band) observations, in single-dish as well as in very long baseline interferometry (VLBI) mode.

It is needed to ensure the necessary spectrum coverage of continuum observations of cosmic radio sources. Given the octave spacing required for this coverage, it lies in between the 150.5-153 MHz and 608-614 MHz bands, which are also used by the RAS for this purpose.

The band contains an important atomic spectral line: the hyperfine-structure line of deuterium at 327.4 MHz, that has been recently detected (May, 2005). The relative abundance of deuterium to hydrogen is directly related to the problems of the origin of the universe and the synthesis of the elements, and the determination of its abundance, or of a low upper limit on this value, will help in constraining cosmological theory.

The band is also used for observations of very highly redshifted emission of the 1 420.4 MHz spectral line of atomic neutral hydrogen (HI). This line is the most commonly observed radio spectral line in nearby galaxies. Observations in the 322-328.6 MHz spectral range allow the probing of the era of formation of galaxies and large-scale structures in the Universe, and will therefore help in constraining cosmological theory.

4.1.3 Required protection criteria

The threshold levels for interference detrimental to radio astronomical observations are given in Recommendation ITU-R RA.769. These are threshold levels above which radio astronomical data are degraded and may eventually be obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), rises 10 dB or more above the detrimental threshold level given in this Recommendation, then increased observing time will no longer be effective in ensuring that valid scientific data can be obtained. The radio astronomy station will then be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

The 322-328.6 MHz band is used for both continuum and spectral line observations. For single-dish continuum observations, the entire 6.6 MHz width of the band is used, for which case the pfd threshold for detrimental interference is −189 dB(W/m^2). For single dish spectral line observations, the pfd threshold for detrimental interference is –204 dB(W/m^2) in a 10 kHz bandwidth. VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, −147 dB(W/m^2), for the whole bandwidth of 6.6 MHz.

4.1.4 Operational characteristics

In general, observations are made differentially.

In the case of continuum observations, the area of sky surrounding the cosmic radio source may be mapped, and the background emission subtracted, or measurements made of the power coming from the direction of the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

In the case of spectral line observations, spectra are recorded at frequency ranges including the line emissions of interest (the line spectra), and then at a frequency that is offset from the line emissions, or at the same frequency but at a nearby position in the sky (the reference spectra). By subtracting the reference spectra from the line spectra, unwanted noise contributions and other contaminants can be removed from the data.

Spectral line observations are made using multi-channel spectrometers that can integrate simultaneously the power in many (typically up to 8 192) frequency channels distributed across the band. The number of channels and their individual bandwidths are chosen to adequately sample the spectrum of the net emission from the cosmic object(s) in the antenna beam.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data have been processed.

4.2 MSS

4.2.1 Allocated transmit band

The band 387-390 MHz is allocated to the mobile-satellite service (space-to-Earth) on a secondary basis in all regions.

RR Nos 5.208A and 5.255 apply to the MSS in this band.

RR No. 5.208A states that “In making assignments to space stations in the mobile-satellite service in the band 137-138 MHz, 387-390 MHz and 400.15-401 MHz, administrations shall take all practicable steps to protect the radio astronomy service in the bands 150.05-153 MHz, 322-328.6 MHz, 406.1-410 MHz and 608-614 MHz from harmful interference from unwanted emissions. The threshold levels of interference detrimental to the radio astronomy service are shown in Table 1 of Recommendation ITU-R RA.769-1. (WRC-97)”.

RR No. 5.255 states: “The bands 312-315 MHz (Earth-to-space) and 387-390 MHz (space-to-Earth) in the mobile-satellite service may also be used by non-geostationary-satellite systems. Such use is subject to coordination under No. **9.11A**.”

4.2.2 Application

Non-GSO MSS systems below 1 GHz are designed for digital transmissions and communication support.

4.2.3 Levels based upon regulatory provisions

There are no hard limits applicable to the MSS in this band.

4.2.4 Operational characteristics

4.2.4.1 Non-GSO MSS systems

There is no information in any ITU-R Recommendation, and particularly in Recommendation ITU-R M.1184, about MSS systems using the 387-390 MHz band.

The Russian system GONETS is identified in the ITU Master International Frequency Register (MIFR). Table 4 shows MSS system characteristics used in analysis.

With a view to attenuation of unwanted emissions in the 322-328.6 MHz band, special filters providing 50 dB attenuation are installed in GONETS-M satellites.

TABLE 4

GONETS-M characteristics

Parameter	Value
Orbit type	Circular
Altitude (km)	1 500
Inclination (degrees)	82.5
Number of satellites in the plane	8
Number of orbital planes	6
Spacing between satellites in the plane (degrees)	22.5
Planes separation(degrees)	60
Working frequencies band (MHz)	387-390
Maximum spectral power density (dB(W/Hz))	−32.3
Power of emissions in the 322-328.6 MHz band (dB(W/6.6 MHz))	−34.8
Spectral power density in 10 kHz segment of the 322-328.6 MHz band (dB(W/10 kHz))	–63
Filter attenuation (dB)	50
Maximum transmitting satellite antenna gain (dB)	3
Transmitting antenna pattern	ND

4.2.4.2 GSO case

There are some MSS GSO satellites found in the MIFR and listed in Table 5 but no technical parameters are available.

TABLE 5

Registered satellites in the MIFR in the active band 387-390 MHz

Administration	Satellite name
AUS	ADF/ADF West
F	SYRACUSE-4
G	SKYNET-5
RUS	VOLNA

As a result, a typical GSO satellite at 0° Longitude is considered for the interference assessment.

4.3 Compatibility threshold

4.3.1 Non-GSO systems

For the case of non-GSO constellations, an epfd threshold level of –240 (dB(W/m^2)) may be derived for continuum observations in the band 322-328.6 MHz from the pfd threshold level for interference detrimental to radio astronomy observations given in Recommendation ITU-R RA.769 and the maximum radio astronomy antenna gain given in Recommendation ITU-R RA.1631, which is 51 dBi for this frequency band. For spectral line observations, the corresponding epfd threshold level is –255 (dB(W/m^2)) in a 10 kHz band.

4.3.2 GSO systems

Recommendation ITU-R RA.769 contains threshold levels for interference detrimental to radio astronomical continuum (broadband) observations. They are recalled in Table 6.

TABLE 6

RA protection criteria

Active band (MHz)	Active service	Passive band (MHz)	Maximum power (RA.769) (dBW)	pfd (RA.769) (dB(W/m^2))	spfd (RA.769) (dB(W/(m^2 · Hz)))
387-390	MSS	322-328.6	–201	–189	–258

4.4 Interference assessment

4.4.1 Non-GSO case

4.4.1.1 Methodology used to assess the interference level

Recommendation ITU-R M.1583 provides a methodology to evaluate the levels of unwanted emissions produced by a non-GSO system at radio astronomy sites. It is based on a division of the sky into cells of nearly equal size and a statistical analysis where the pointing direction of the RAS antenna and the starting time of the satellite constellation are the random variables. For each trial, the unwanted emission level (expressed in terms of epfd) is averaged over a 2 000 s period.

The chosen RAS station has an antenna diameter of 100 m and a maximum gain of 51 dBi. The antenna pattern and maximum antenna gain are taken from Recommendation ITU-R RA.1631. It is located in the middle of France.

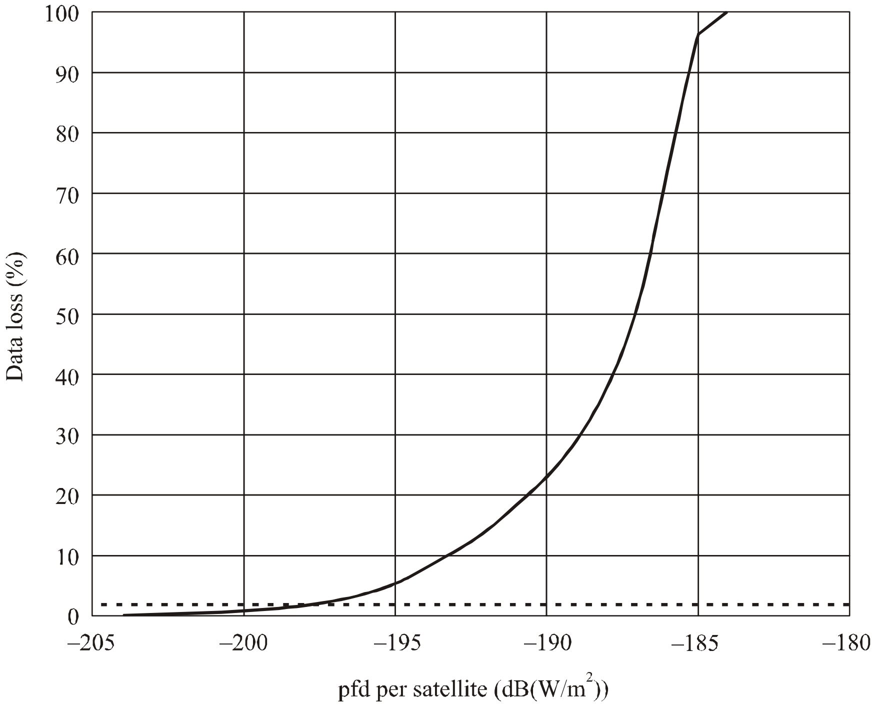
The simulations were performed considering an RAS minimum antenna elevation angle of 0°, in order to get completely general results.

4.4.1.2 Calculation of interference level

Figure 10 shows the percentage of time when the continuum epfd threshold level is exceeded at the radio astronomy station, for a given pfd value per MSS satellite (as explain in Recommendation ITU-R RA.1513, exceeding this threshold is equivalent to data loss).

FIGURE 10

Percentage of data loss vs. pfd per satellite at RAS site for MSS system GONETS-M



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To meet the continuum epfd threshold during more than 98% of the time in average over the whole sky, each satellite of MSS system GONETS-M should generate a pfd of less than –198 dB(W/m^2) in the 322-328.6 MHz radio astronomy band.

Figure 11 shows for each cell of the sky, and for the pfd (per satellite) of –198 dB(W/m^2), the percentage of time when the epfd threshold is exceeded.

In Fig. 11, 0° azimuth is due North, and azimuth increases from West to East.

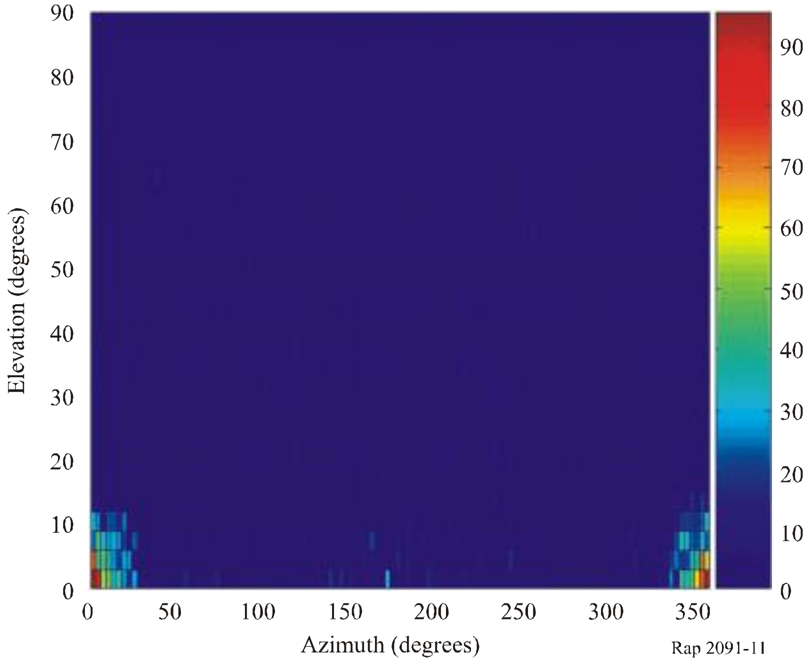
The pfd value required for spectral lines observations can be directly deduced without further simulations from the value required for continuum observations using formula (9):

$$pfd_{spectral} = pfd_{continuum} + epfd_{spectral} - epfd_{continuum} \tag{9}$$

To meet the spectral lines epfd threshold during more than 98% of the time in average over the whole sky, each satellite of MSS system GONETS-M should generate a pfd of less than –213 dB(W/m^2) in any 10 kHz bandwidth of the 322-328.6 MHz radio astronomy band.

FIGURE 11

Percentage of data loss over the sky for the pfd value of –198 dB(W/m^2) at RAS site for MSS system GONETS-M



Based on system performance, the spectral power density at the Earth surface from any GONETS M satellite in any 10 kHz part of the 322-328.6 MHz frequency band would be equal to –244.5 dB(W/(m^2 · 10 kHz)) (see § 4.3.1) that does not exceed the above criteria –213.5 dB(W/(m^2 · 10 kHz)).

4.4.2 GSO case

There is available information for the four existing satellites found in the MIFR. In that case, a typical GSO sa–244.5 dBW/m^2/10 kHz tellite is considered at a 0° Longitude.

For the studies contained in the following subsections,

– All characteristics of RAS stations are taken from the website http://www.astron.nl/craf/raobs.htm. They are located in CEPT countries.

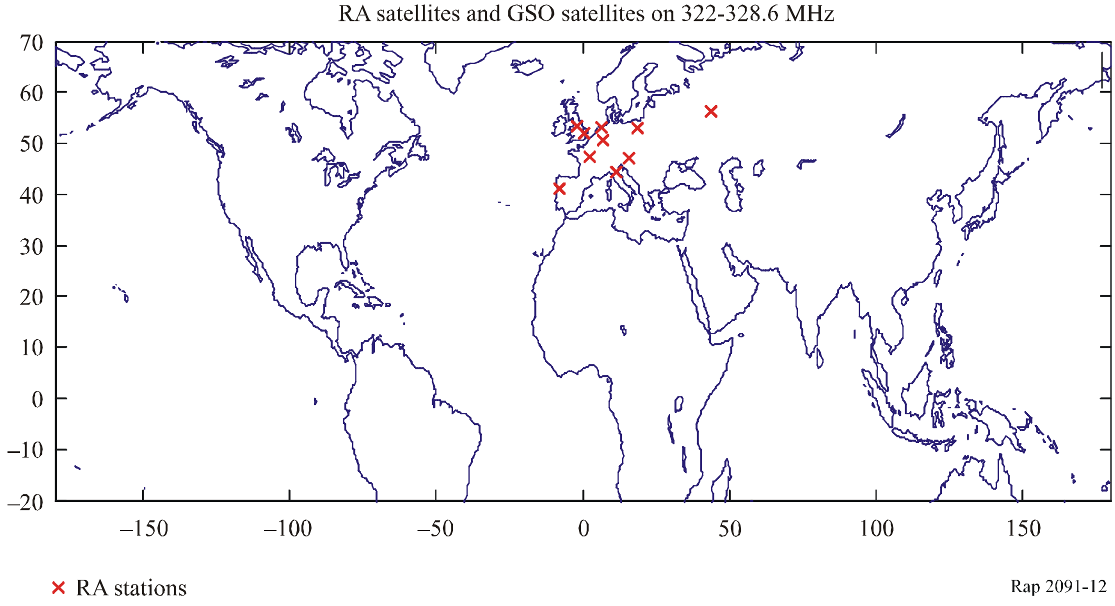
Taking into account the different locations of GSO satellite and relevant RA station, one can calculate the allowable e.i.r.p. in the RAS band in order to be compliant with the protection criterion for all RA stations presented in Fig. 12.

As a result, when some typical parameters of a GSO are available, an OoB attenuation factor can be identified given by the difference between the e.i.r.p. of the GSO satellite in the active service and the maximum allowable e.i.r.p. within the passive band.

The compliance of this needed attenuation factor with relevant data according to the relevant ITU-R Recommendations (RR Appendix 3 limit for example) can in that case conclude the interference assessment.

FIGURE 12

RAS stations and GSO satellites in the band 322-328.6 MHz



4.4.3 Values achieved

4.4.3.1 Non-GSO case

From the data provided in § 4.2.4 it is possible to calculate the pfd radiated in the RAS band by each MSS satellite, as indicated in Table 7.

TABLE 7

Maximum pfd radiated by GONETS-M satellite

Parameter	**Continuum (322-328.6 MHz band)**	**Spectral lines (any 10 kHz bandwidth in the 322-328.6 MHz band)**
Altitude (km)	1 500	
Power of emissions (dBW)	−34.8	−63
Additional filter attenuation (dB)	50	
Maximum transmitting satellite antenna gain (dB)	3	
Maximum pfd radiated per satellite (dB(W/m^2))	−216.3	−244.5

Analysis of the results shows (see § 4.4.1.2) that there is more than 18 dB of excess margin for the continuum observations and 31 dB for spectral line observations. This conclusion is also valid for radio astronomy VLBI observations in the 322-328.6 MHz frequency band.

It should be also noted that this methodology does not take into account the dynamic channel assignment of GONETS-M space stations. Additionally, GONETS-M space stations transmit information in short bursts, each being transmitted on a different frequency. In the study, all satellites were assumed to emit in the same frequency channel at all times. That is why the result obtained is for the worst-case interference scenario.

4.4.3.2 GSO case

The e.i.r.p. given in Table 8 are derived from the pfd threshold levels given in Table 8 (last column) considering free space losses. It is recalled that a satellite placed at a 0° Longitude is considered as no technical parameters were available for satellites registered in the MIFR.

TABLE 8

Maximum allowable EIRP in the RAS band at the satellite

Active band (MHz)	Passive band (MHz)	Maximum e.i.r.p. in the RAS band (dB(W/Hz))	Maximum e.i.r.p. in the RAS band (dBW)
387-390	322-328.6	–94.5	–26.3

4.5 Mitigation techniques

4.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for G/T, i.e. telescope gain divided by system temperature. This is to maximize the S/N for point sources. A key element of this approach is to reduce ground radiation entering through far side lobes. Inevitably this leads to some corresponding increase in the levels of near side lobes. Experience has shown that the majority of radio telescopes meet the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

4.5.2 Potential impact for the RAS

Antenna side-lobe performance: Attempts to decrease the sensitivity of the radio astronomy antenna to unwanted emissions coming from space stations are likely to increase the sensitivity of the radio astronomy telescope to ground radiation, and possibly reduce its main beam gain. Both of these effects will reduce the telescope's channel capacity of and thus lead to an increase of the total required integration time.

Blanking in time and/or frequency: Blanking involves a risk of compromising the integrity of the data and may lead to errors in their scientific interpretation. Blanking also causes a concomitant increase in the total integration time required to make the observation, this is equivalent to a loss in the channel capacity of the telescope.

5 Compatibility analysis between RAS systems operating in the 406.1-410 MHz band and mobile-satellite service (space-to-Earth) systems operating in the 400.15-401 MHz band

5.1 RAS

5.1.1 Allocated band

The 406.1-410 MHz band is allocated on a primary basis to the fixed service, the mobile service (except aeronautical mobile) and the RAS.

RR No. 5.149 urges administrations to take all practicable steps to protect the radio astronomy service from harmful interference.

5.1.2 Type of observations

This band is used for continuum (broadband) observations only.

It is needed to ensure the necessary spectrum coverage of continuum (broadband) observations of cosmic radio sources, and it lies right in between the 322.0-328.6 MHz and 608-614 MHz bands, which are also used for this purpose by the RAS.

5.1.3 Required protection criteria

The threshold levels for detrimental interference to radio astronomical observations are given in Recommendation ITU-R RA.769.

These thresholds levels are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), rises 10 dB or more above the level given in this Recommendation, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will then be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

The 406.1-410 MHz band is used for continuum observations only. In general, for continuum observations, the entire 3.9 MHz width of the band is used. For single dish observations, the pfd threshold for detrimental interference is –189 dB(W/m^2).

5.1.4 Operational characteristics

In general, continuum observations are made differentially: the area of sky surrounding the cosmic radio source may be mapped, and the background emission subtracted, or measurements made of the power coming from the direction of the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

5.2 MSS

5.2.1 Allocated transmit band

The 400.15-401 MHz band is allocated to the MSS (space-to-Earth) on a primary basis in all Regions.

RR Nos 5.208A and 5.209 apply to the MSS in this band.

RR No. 5.208A states that “In making assignments to space stations in the mobile-satellite service in the band 137-138 MHz, 387-390 MHz and 400.15-401 MHz, administrations shall take all practicable steps to protect the radio astronomy service in the bands 150.05-153 MHz, 322-328.6 MHz, 406.1-410 MHz and 608-614 MHz from harmful interference from unwanted emissions. The threshold levels of interference detrimental to the radio astronomy service are shown in Table 1 of Recommendation ITU-R RA.769-1. (WRC-97)”.

RR No. 5.209 states that “The use of the bands 137-138 MHz, 148-150.05 MHz, 399.9-400.05 MHz, 400.15-401 MHz, 454-456 MHz and 459-460 MHz by the mobile-satellite service is limited to non-geostationary-satellite systems. (WRC-97)”.

5.2.2 Application

Systems in the non-GSO MSS below 1 GHz are capable of transmitting digital packets of data at low data rates (2.8 to 19.2 kbit/s). The low frequencies (below 1 GHz) and the low-Earth orbit result in small, low power earth stations and satellites. Networks are designed to be capable of providing coverage to all or most of the world (some systems do not include full coverage of the polar areas). Generally, the MSS below 1 GHz systems operate in a near real-time mode when the same satellite covers both the user station and the feeder-link station. However, the systems can also operate in the store and forward mode when the user and the feeder-link stations are not in the same satellite footprint, such as a user located in an open ocean area. In this mode, the systems operate with some time delay that can range from seconds to hours, depending on the next satellite pass over a feeder-link station.

This kind of systems provides high quality wireless data communications for business, industry, government, and consumers worldwide.

5.2.3 Levels based upon regulatory provisions

There are no hard limits applicable to MSS in this band.

5.2.4 Operational characteristics

The technical and operational characteristics of four non-GSO MSS systems using or planned to use the band for either service or gateway downlinks are described in Recommendation ITU-R M.1184. Those are systems L, N, Q and S. The orbital characteristics of the actual system Q are different from the ones which are given in the recommendation. The actual characteristics are given in Table 9, along with those of systems L, N and S.

5.3 Compatibility threshold

For the case of non-GSO constellations, an epfd threshold may be derived from the pfd threshold given in Recommendation ITU-R RA.769 and the maximum antenna gain given in Recommendation ITU-R RA.1631, which is 53 dBi for this frequency band. The epfd threshold for the band 406.1-410 MHz is therefore –242(dB(W/m^2)).

TABLE 9

Orbital parameters of several non-GSO MSS networks below 1 GHz

System	**L**	**N**	**Q**		**S**
Number of satellites	48	3	26		6
Altitude (km)	950	800	1 000		692, 667
Inclination (degrees)	50	88	66	83	98.04
Orbit planes	8	3	4	2	2
Satellite/plane	6	1	6	1	3
Right ascension of ascending node (degrees)	0, 45, 90, 135, 180, 225, 270, 315	0, 15, 90	0, 90, 180, 270	0, 90	143.5, 53.5
Downlink emission power (W)	25	6.3	32		10
Downlink EIRP (dBW)	19.7	10	17.8		18
Necessary bandwidth (kHz)	35	85	45		300
pfd in the MSS band (dB(W/m^2))	–111	–119	–113		–110

5.4 Interference assessment

5.4.1 Methodology used to assess the interference level

Recommendation ITU-R M.1583 provides a methodology to evaluate the levels of unwanted emissions produced by a non-GSO system at radio astronomy sites. It is based on a division of the sky into cells of nearly equal size and a statistical analysis where the pointing direction of the RAS antenna and the starting time of the satellite constellation are the random variables. For each trial, the unwanted emission level (expressed in terms of epfd) is averaged over a 2 000 s period.

The RAS antenna diameter is 100 m which corresponds to a maximum antenna gain of approximately 53 dBi. The antenna pattern and maximum antenna gain are taken from Recommendation ITU-R RA.1631.

The geographical coordinates chosen are:

Latitude: 46.9° N Longitude: 2.4° E

The simulations were performed considering an elevation angle of 0° in order to get completely general results.

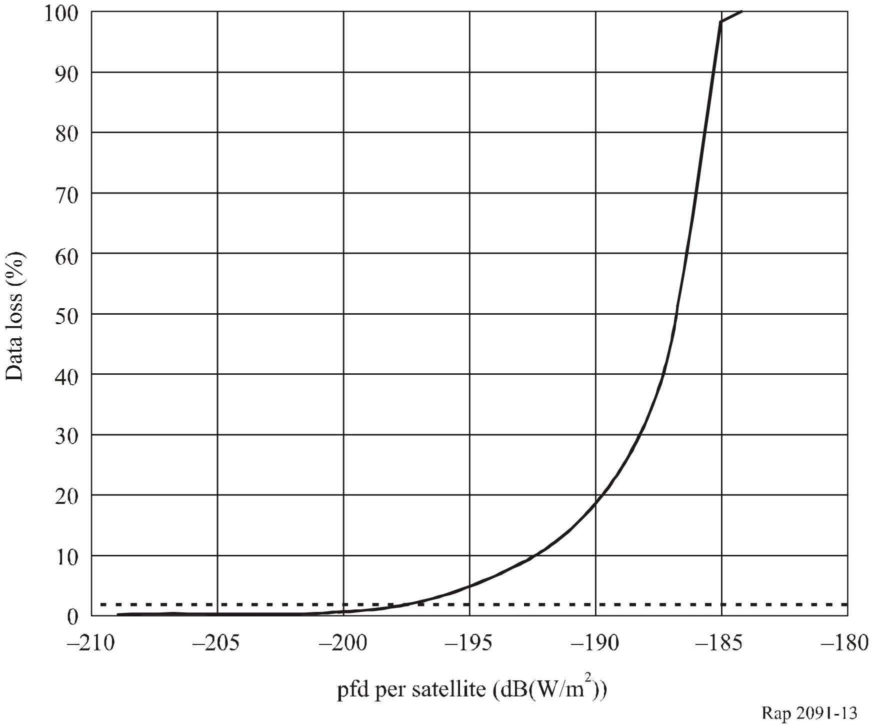
5.4.2 Calculation of interference level

5.4.2.1 MSS system L

Figure 13 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value per MSS satellite (as explain in Recommendation ITU-R RA.1513, exceeding this threshold is equivalent to data loss).

FIGURE 13

Percentage of data loss vs. pfd per satellite at RAS site

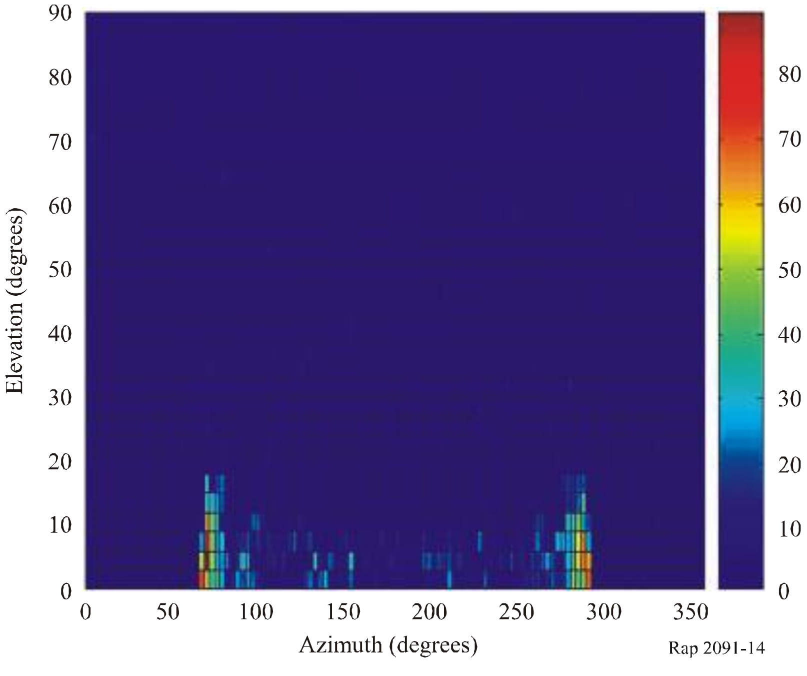


To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each MSS system L satellite should generate a pfd of less than –197 dB(W/m^2) in the radio astronomy band.

Figure 14 shows for each cell of the sky, and for the pfd (per satellite) of –197 dB(W/m^2), the percentage of time where the epfd threshold is exceeded.

FIGURE 14

Percentage of data loss over the sky for the pfd value of –197 dB(W/m^2) at RAS site



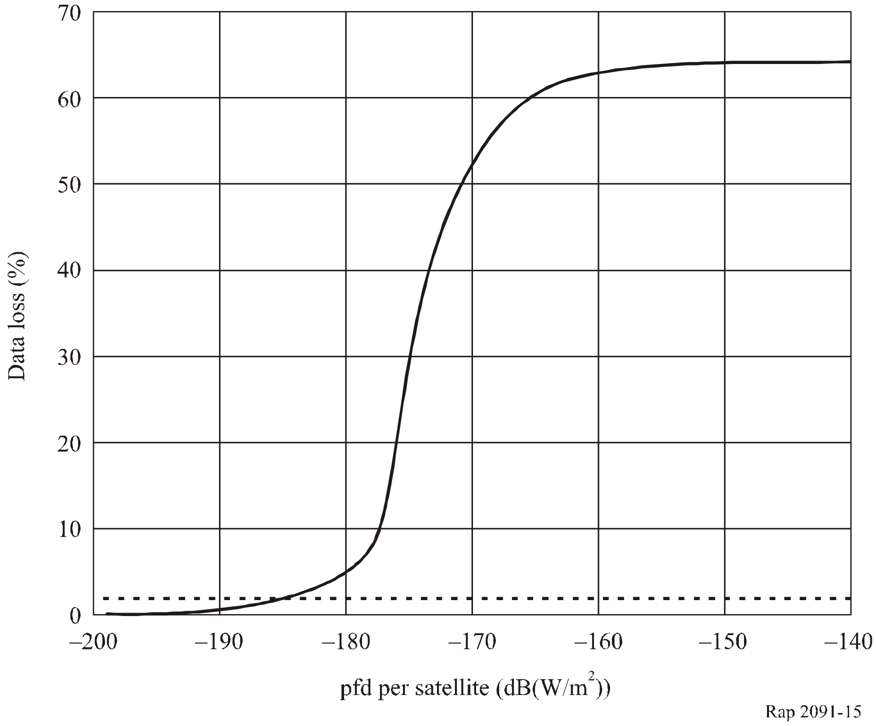
In Figs. 14, 16, 18 and 20, 0° azimuth is due North, and azimuth increases from West to East.

5.4.2.2 MSS system N

Figure 15 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value per MSS satellite.

FIGURE 15

Percentage of data loss vs. pfd per satellite at RAS site



To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each MSS system N satellite should generate a pfd of less than –185 dB(W/m^2) in the radio astronomy band.

Figure 16 shows for each cell of the sky, and for the pfd (per satellite) of –185 dB(W/m^2), the percentage of time where the epfd threshold is exceeded.

5.4.2.3 MSS system Q

Figure 17 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value per MSS satellite.

To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each MSS system Q satellite should generate a pfd of less than –195 dB(W/m^2) in the radio astronomy band.

Figure 18 shows for each cell of the sky, and for the pfd (per satellite) of –195 dB(W/m^2), the percentage of time where the epfd threshold is exceeded.

FIGURE 16

Percentage of data loss over the sky for the pfd value of –185 dB(W/m^2) at RAS site

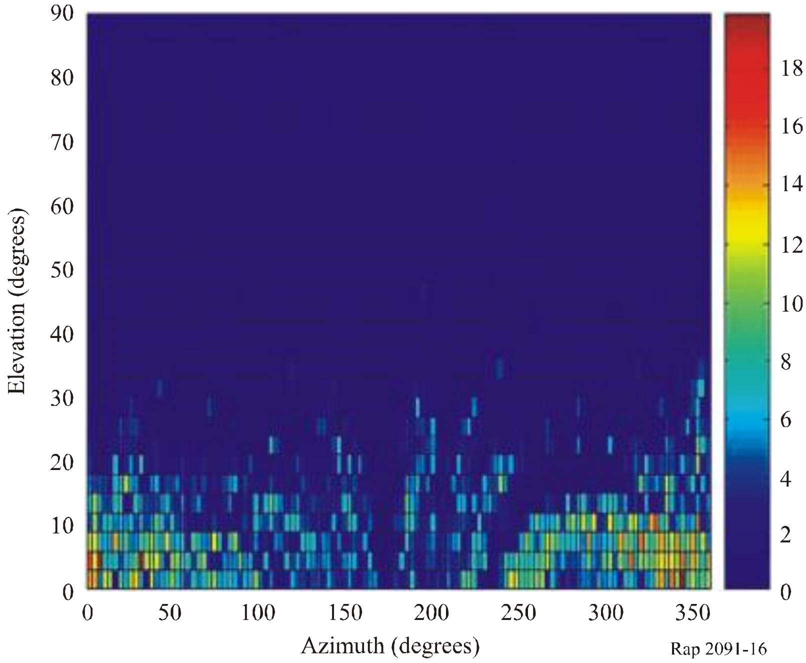


FIGURE 17

Percentage of data loss vs. pfd per satellite at RAS site

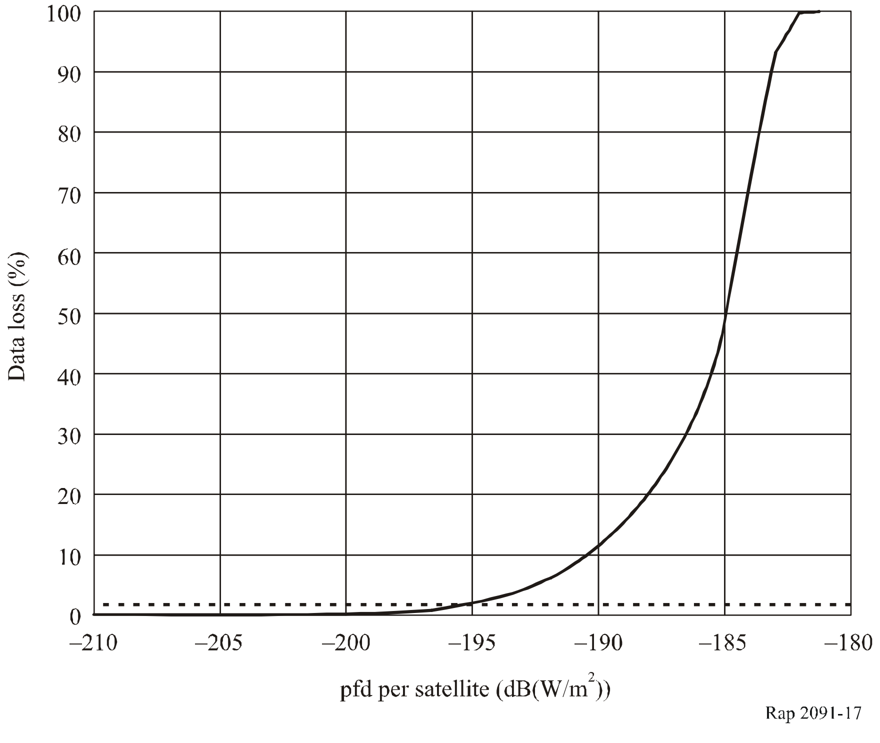
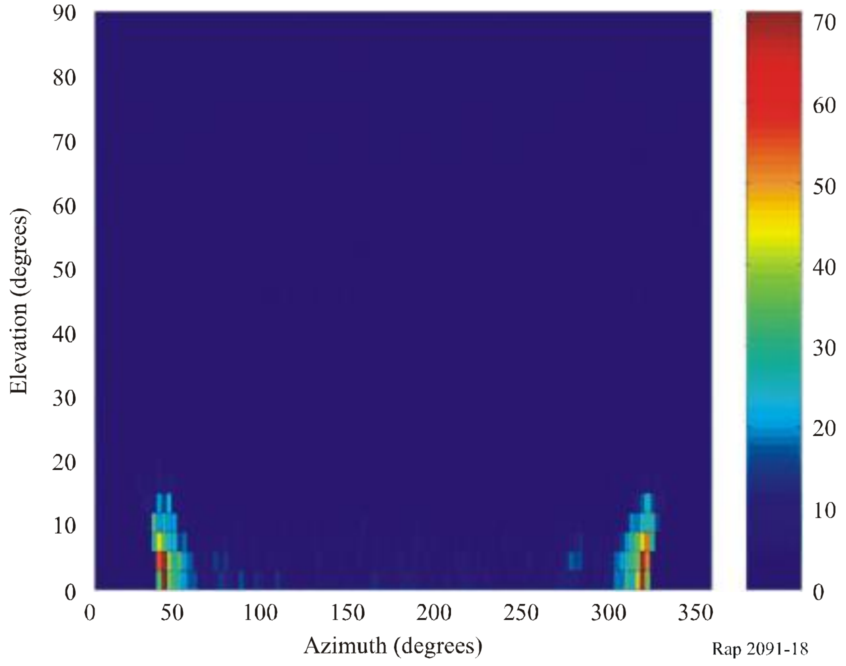


FIGURE 18

Percentage of data loss over the sky for the pfd value of –195 dB(W/m^2) at RAS site

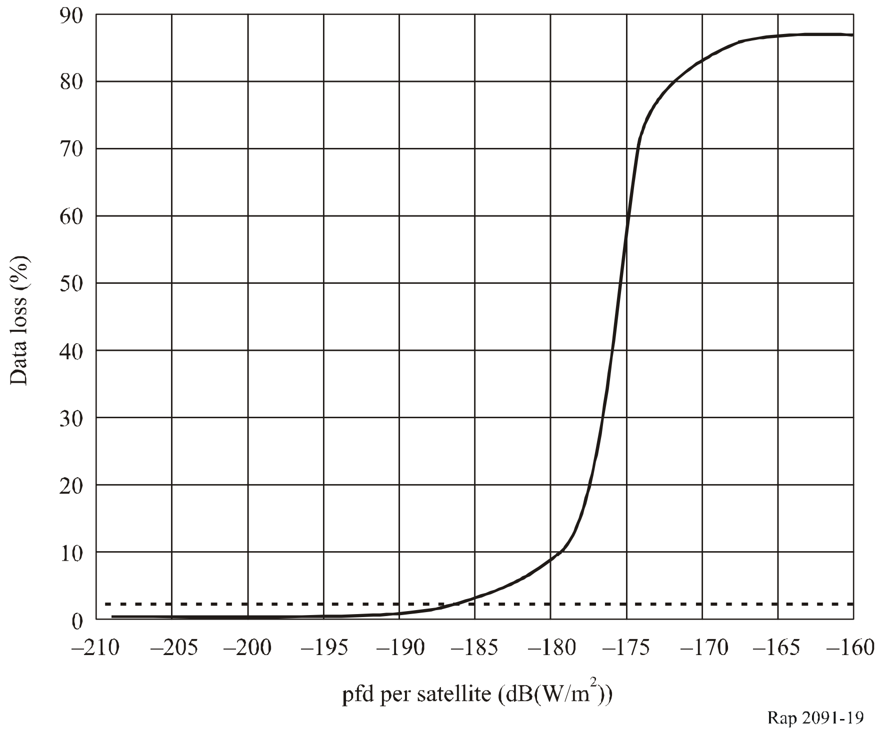


5.4.2.4 MSS system S

Figure 19 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value per MSS satellite.

FIGURE 19

Percentage of data loss vs. pfd per satellite at RAS site

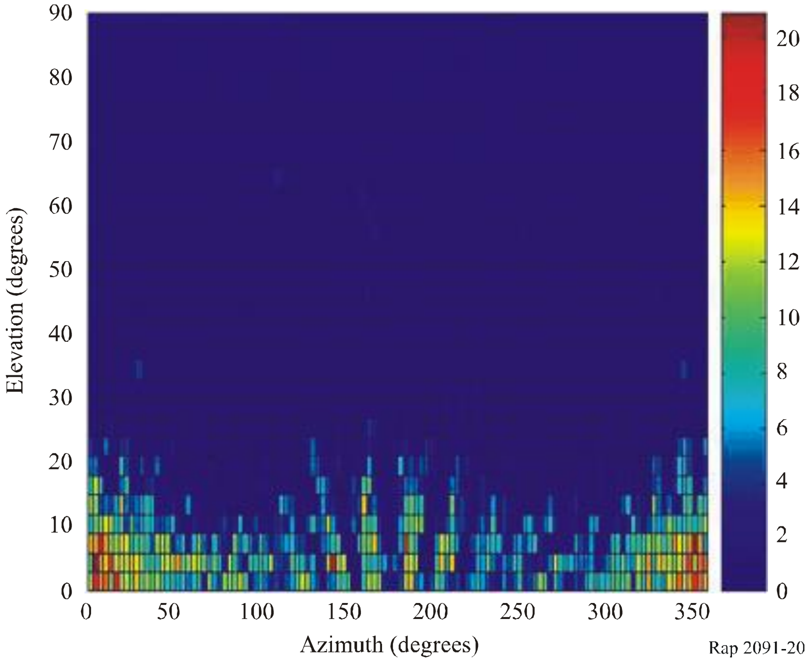


To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each MSS system S satellite should generate a pfd of less than –187 dB(W/m^2) in the radio astronomy band.

Figure 20 shows for each cell of the sky, and for the pfd (per satellite) of –187 dB(W/m^2), the percentage of time where the epfd threshold is exceeded.

FIGURE 20

Percentage of data loss over the sky for the pfd value of –187 dB(W/m^2) at RAS site



5.4.3 Values achieved

The unwanted emissions of MSS non-GSO satellites using the band 400.15-401 MHz falling into the RAS band 406.1-410 MHz fall in the spurious domain. Table 10 shows, for each of the four non-GSO MSS systems below 1 GHz, the necessary attenuation so that the detrimental epfd threshold is not exceeded.

It has to be noted that in order to calculate the total amount of spurious emissions in the RAS band it was considered that spurious emissions have a constant level in the whole RAS band. This hypothesis is very stringent and clearly not representative of the reality, as spurious emissions generally appear at some discrete frequencies. Therefore, further work is needed in order to take into account this discrete component of spurious emissions in order to get more realistic MSS unwanted emission levels in the RAS band.

TABLE 10

Attenuation of non-GSO MSS networks below 1 GHz necessary to reach the detrimental epfd level

System	L	N	Q	S
Emission power in the MSS band (W)	25	6.3	32	10
43 + 10 log P	57	51	58	53
Spurious attenuation from Appendix 3 (dBc in 4 kHz)	57	51	58	53
Spurious level from Appendix 3 (dBW in 4 kHz)	–43	–43	–43	–43
pfd in the MSS band (dB(W/m^2))	–111	–110	–113	–110
Spurious level in the RAS band (dBW)	–13.1	–13.1	–13.1	–13.1
pfd in the RAS band (dB(W/m^2))	–138	–131	–141	–133
Maximum pfd in the RAS band (dB(W/m^2))	–197	–185	–195	–187
Necessary attenuation (dB)	59	54	54	54

5.5 Mitigation techniques

5.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for G/T, i.e. telescope gain divided by system temperature. This is to maximize the S/N for point sources. A key element of this approach is to reduce ground radiation entering through far side lobes. Inevitably this leads to some corresponding increase in the levels of near side lobes. Experience has shown that the majority of radio telescopes meet the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

5.5.2 Potential impact on the RAS

Antenna side-lobe performance: Attempts to decrease the sensitivity of the radio astronomy antenna to unwanted emissions coming from space stations are likely to increase the sensitivity of the radio astronomy telescope to ground radiation, and possibly reduce its main beam gain. Both of these effects will reduce the telescope’s channel capacity of and thus lead to an increase of the total required integration time.

Blanking in time and/or frequency: Blanking involves a risk of compromising the integrity of the data and may lead to errors in their scientific interpretation. Blanking also causes a concomitant increase in the total integration time required to make the observation, this is equivalent to a loss in the channel capacity of the telescope.

6 Compatibility analysis between RAS systems operating in the 608-614 MHz band and broadcasting-satellite service (space-to-Earth) systems that may operate in the 620-790 MHz band

6.1 RAS

6.1.1 Allocated band

The band 608-614 MHz is allocated to the radio astronomy on a primary basis in Region 2, in India by RR No. 5.307 and in China by RR No. 5.305.

This band is also allocated by No. 5.306 to the radio astronomy service on a secondary basis in Region 1, except in the African Broadcasting Area (see RR Nos 5.10 to 5.13), and in Region 3.

RR No. 5.149 applies to this band in Regions 1 and 3. It urges administrations to take all practicable steps to protect the radio astronomy service from harmful interference.

6.1.2 Type of observations

This band is used for continuum (broadband) observations, both in single-dish and VLBI mode.

It is needed to ensure the necessary spectrum coverage of continuum (broadband) observations of cosmic radio sources, and lies in between the 406.1-410 MHz and 1 400-1 427 MHz bands, which are also used for this purpose by the RAS.

6.1.3 Required protection criteria

The threshold levels for detrimental interference to radio astronomical observations are given in Recommendation ITU-R RA.769.

These threshold levels are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), rises 10 dB or more above the level given in this Recommendation, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will then be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

The 608-614 MHz band is used for continuum observations only. For making single-dish continuum observations, the entire 6 MHz width of the band is used, for which case the threshold pfd limit for detrimental interference is –185 dB(W/m^2).

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, –143 dB(W/m^2), for the whole bandwidth of 6 MHz.

6.1.4 Operational characteristics

In general, continuum observations are made differentially: the area of sky surrounding the cosmic radio source may be mapped, and the background emission subtracted, or measurements made of the power coming from the direction of the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

VLBI observations are made by down-converting the signals to a base-band, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data have been processed.

6.2 BSS

6.2.1 Allocated transmit band

RR No. 5.311 applies to this band, which states: "Within the frequency band 620-790 MHz, assignments may be made to television stations using frequency modulation in the broadcasting-satellite service subject to agreement between the administrations concerned and those having services, operating in accordance with the Table, which may be affected (see Resolutions **33 (Rev.WRC-03)** and **507 (Rev.WRC-03)**). Such stations shall not produce a power flux-density in excess of the value −129 dB(W/m^2) for angles of arrival less than 20° (see Recommendation **705**) within the territories of other countries without the consent of the administrations of those countries. Resolution **545 (WRC-03)** applies. (WRC-03)"

Resolution 545 (WRC-03) asks for studies and the development of sharing criteria and regulatory provisions, prior to WRC-07, for the protection of terrestrial services, in particular terrestrial television broadcasting services, in the 620-790 MHz band from GSO BSS networks and non-GSO BSS satellite networks or systems that are planned to operate in this band.

6.2.2 Application

The purpose of the BSS systems which may use this band is to offer a broadcasting service on a national or regional basis. The band may be used by either GSO or non-GSO BSS systems.

A wide range of contents may be delivered through the system towards mobile terminals in a mass-market environment due to the use of highly efficient compression, coding and multiplexing techniques.

6.2.3 Levels based upon regulatory provisions

On a provisional basis, the maximum pfd produced at the surface of the Earth within the service area of a terrestrial broadcasting station by a space station in the BSS in the band 620-790 MHz should not exceed:

-129	dB(W/m^2)	for		$\delta \le 20°$
$-129 + 0.4\,(\delta - 20)$	dB(W/m^2)	for 20°	<	$\delta < 60°$
-113	dB(W/m^2)	for 60°	<	$\delta < 90°$

where δ is the angle of arrival (see Recommendation 705).

6.2.4 Operational characteristics

6.2.4.1 Non-GSO BSS systems

6.2.4.1.1 Constellation parameters

The system considered in this study will use satellites on highly elliptical orbits (HEO). The constellation parameters are optimized to offer satisfactory visibility conditions to any users within the service area. The example below illustrates the case of a Tundra constellation covering Western European countries with three satellites orbiting in a 24 h period:

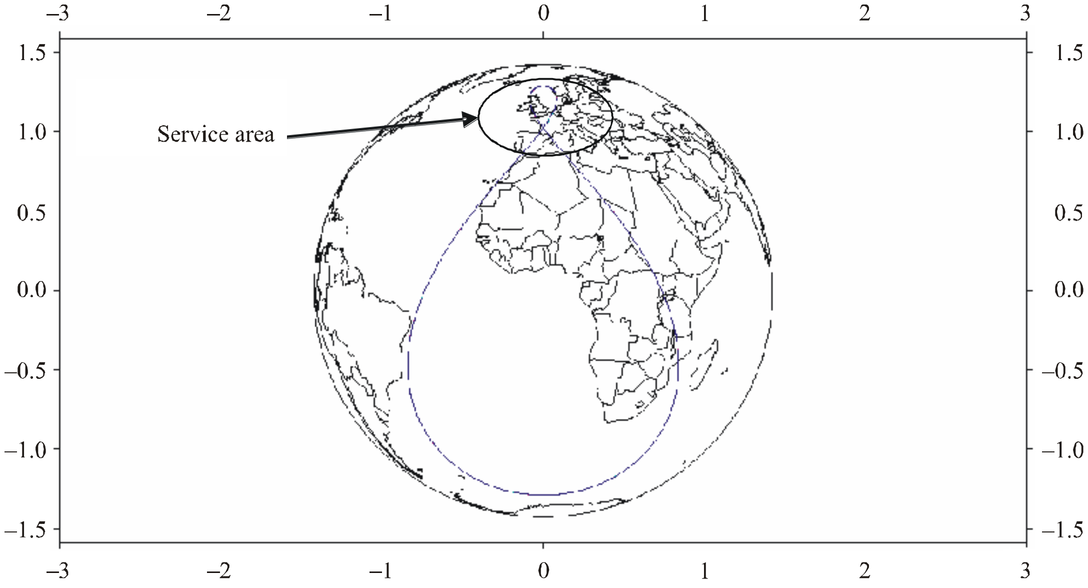
– Semi-major axis: 42 164 km

–	Eccentricity:	0.2684
–	Inclination:	63.4°
–	Argument of perigee:	270°
–	Right ascension of ascending node:	110°, 230° and 350°
–	Mean anomaly:	340°, 220° and 100°

Figure 21 illustrates the satellite's ground track on the Earth's surface.

FIGURE 21

HEO constellation ground track



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6.2.4.1.2 Times of satellite activity

With the orbital parameters of an HEO constellation, a given satellite is in visibility of the service area with an elevation angle greater than 60° only 1/3 of the time:

- Over its 24 h orbit period, the satellite will be in visibility of the service area with an elevation angle greater than 60° during a continuous period of 8 h, after which 16 h will be spent in "non-visibility".
- Satellites will be programmed to be inactive during their 16 h long periods of "non-visibility". This means that only one satellite will be transmitting towards the service area at any given time.

6.2.4.1.3 Satellite antenna and power management

The pfd on the ground will be kept constant, irrespective of time and location of the receiver within the service area. In order to do that, the satellite antenna will be designed to meet a number of requirements during the active transmissions periods:

- *Iso-flux transmission over the service area*

  The satellite will use an iso-flux antenna to optimize its power requirements and to cope with the pfd limits in the service area. It means that the satellite antenna gain within the service area will be such that the pfd at the Earth's surface will be kept constant, irrespective of the position of a receiver within the service area.

– *Beam zooming*

The solid angle with which a satellite sees the service area will vary with time, as function of its altitude. In order to cope with this “zooming effect” and to reduce the overall power requirements, the satellite will also adjust the power and the shape of its beam as function of its altitude.

6.2.4.2 GSO case

There are two GSO satellites registered in the MIFR. They belong to the Russian Federation and are named STATSIONAR.

The parameters of STATSIONAR satellites were taken into account in the compatibility studies to assess the impacts of future systems with similar characteristics and are given in Table 11:

TABLE 11

STATSIONAR parameters

Name	STATSIONAR-T	STATSIONAR-T2
Longitude (degrees)	99	99
Carrier frequency (MHz)	714	754
Bandwidth (MHz)	24	24
Peak power (dBW)	23	21.5
Peak power (dB(W/Hz))	−51	−52.3
Maximum antenna gain (dBi)	34	33.5
Position of the footprint centre (degrees)	$L = 91$, $l = 73$	$L = 95.24$, $l = 69.16$
Angle between pointing direction of GSO satellites and direction from GSO satellite towards RA station (degrees)	8.7	4.4
Antenna gain towards the most exposed RA station (dBi)	27.5	13.5
e.i.r.p. on active band towards the most exposed RA station (dB(W/Hz))	−23.5	−38.8

6.3 Compatibility threshold

6.3.1 Non-GSO systems

For the case of non-GSO constellations, an epfd threshold level of –241 (dB(W/m^2)) may be derived for the band 608-614 MHz from the pfd threshold level for interference detrimental to radio astronomy observations given in Recommendation ITU-R RA.769 and the maximum radio astronomy antenna gain given in Recommendation ITU-R RA.1631, which is 56 dBi for this frequency band.

6.3.2 GSO systems

Recommendation ITU-R RA.769 contains threshold levels for interference detrimental to radio astronomical continuum (broadband) observations. They are recalled in Table 12.

TABLE 12

RA protection criteria

Active band (MHz)	Active service	Passive band (MHz)	Maximum received power (RA.769) (dBW)	pfd (RA.769) (dB(W/m^2))	spfd (RA.769) (dB(W/(m^2 · Hz))
620-790	BSS	608-614	−202	−185	−253

6.4 Interference assessment

6.4.1 Non-GSO case

6.4.1.1 Methodology used to assess the interference level

Recommendation ITU-R S.1586 provides a methodology to evaluate the levels of unwanted emissions produced by a non-GSO system at radio astronomy sites. It is based on a division of the sky into cells of nearly equal size and a statistical analysis where the pointing direction of the RAS antenna and the starting time of the satellite constellation are the random variables. For each trial, the unwanted emission level (expressed in terms of epfd) is averaged over a 2 000 s period.

In the case of a HEO system the calculation is greatly simplified because there is only one satellite transmitting towards the Earth at any time.

6.4.1.2 Calculation of interference level

The studies show that the compatibility between unwanted emissions from HEO BSS systems operating in the band 620-790 MHz and the RAS in the band 608-614 MHz can be ensured if the pfd radiated by a HEO BSS satellite at any RAS station is lower than –188 dB(W/m^2) in the whole radio astronomy band.

This level ensures that the loss of data to the RAS over the part of the sky within which the radio astronomy station performs observations, taking into account the minimum elevation angle θ_{min} at which the radio astronomy station conducts observations in the frequency band (as defined in the Table A of Annex 2 to RR Appendix 4), will be less than 2%.

Figure 22 gives for the radio astronomy site of Jodrell Bank (UK), for each cell, over the whole sky, the number of 2 000 s long trials where the epfd criterion has been exceeded. The total number of trials per cell is 30, the vertical scale on the right represents the number of trials per cell for which the epfd criterion has been exceeded. For example, Fig. 22 shows that if the radio telescope points towards an azimuth of 350° and an elevation of 84° to 87° (see the corresponding cell in Fig. 22), all the observations performed will be affected by interference exceeding the detrimental level given in Recommendation ITU-R RA.769.

6.4.2 GSO case

For the studies contained in the next sections,

- All characteristics of RAS stations are taken from the website http://www.astron.nl/craf/raobs.htm. They are located in CEPT countries.
- All characteristics of GSO satellites are taken from the ITU MIFR.

Figures 23 and 24 illustrate where is the most sensible radio astronomy station and the attenuation below the maximum antenna gain towards it.

FIGURE 22

Simulation results for Jodrell Bank

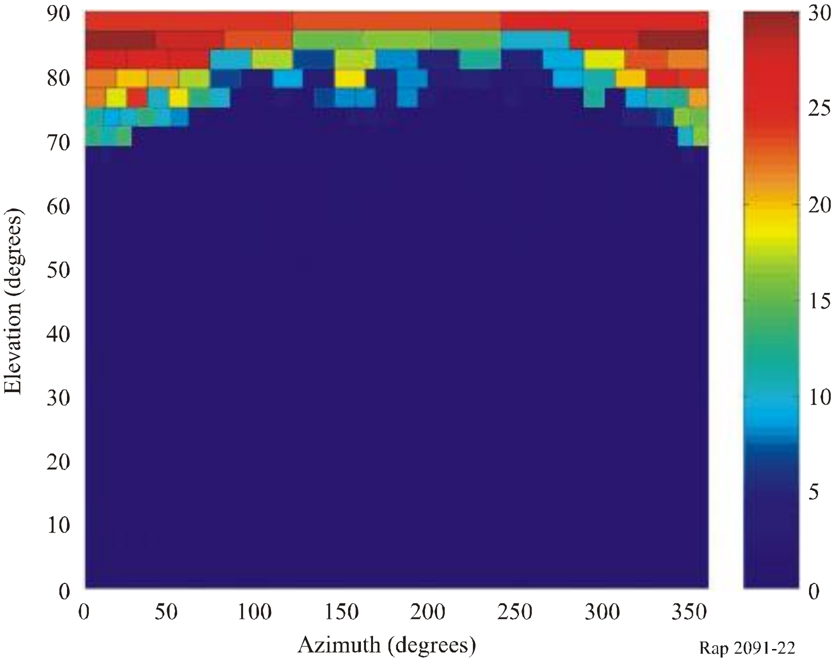


FIGURE 23

STATSTIONAR-T

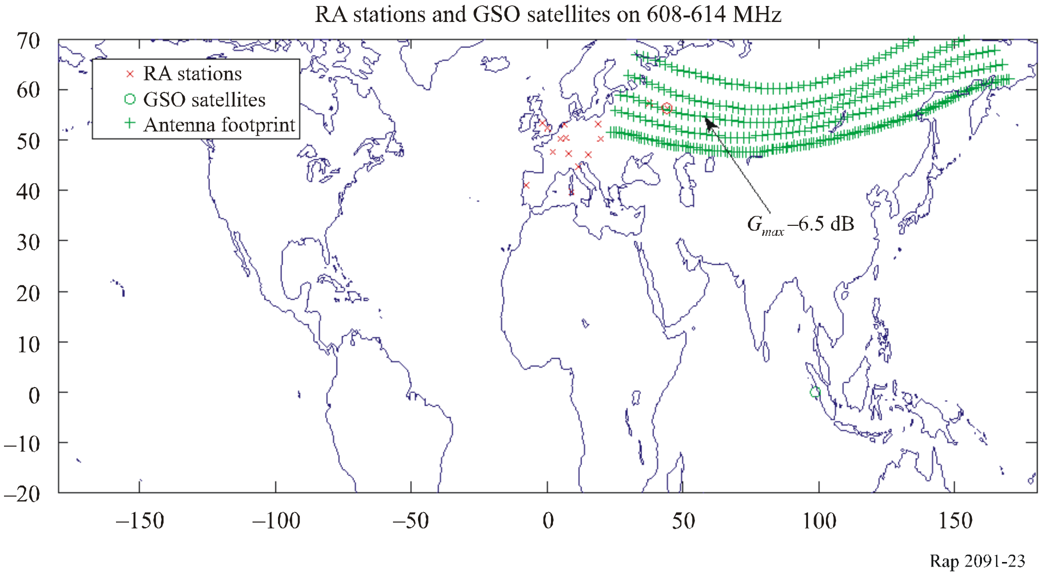
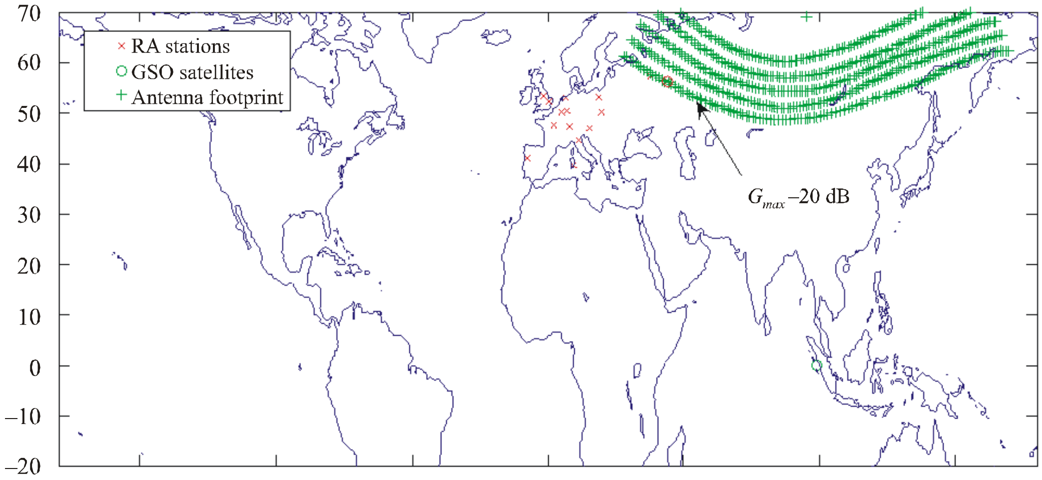


FIGURE 24

STATSTIONAR-T2

RA stations and GSO satellites on 608-614 MHz



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Taking into account the different locations of GSO satellite and most sensitive RA stations, the allowable e.i.r.p. in the RAS band is calculated in order to be compliant with the protection criterion.

As a result, an OoB attenuation factor can be calculated given by the difference between the e.i.r.p. of the GSO satellite in the active service and the maximum allowable e.i.r.p. within the passive band.

The compliance of this needed attenuation factor with relevant data according to the relevant ITU-R Recommendations (RR Appendix 3 limit for example) can conclude the interference assessment.

6.4.3 Values achieved

6.4.3.1 Non-GSO case

The unwanted emission pfd value of –188 dB(W/m^2) corresponds to an attenuation of 74 dB of the pfd radiated by the HEO BSS satellite at the Earth’s surface in a 6 MHz bandwidth under the assumption that the maximum pfd radiated by the HEO BSS system in the 620-790 MHz band is −113 dB(W/(m$^2 \cdot$ 8 MHz)), which is the maximum level indicated in Recommendation 705.

6.4.3.2 GSO case

The e.i.r.p. given in Table 12 are derived from the pfd threshold levels given in Table 12 (last column) considering free space losses.

TABLE 13

Maximum allowable e.i.r.p. in the RAS band at the satellite

Active band (MHz)	Passive band (MHz)	Maximum e.i.r.p. in the RAS band (dB(W/Hz))	Maximum e.i.r.p. in the RAS band (dBW)
620-790	608-614	−92	−24

Taking into account Tables 10 and 12 the attenuation factor must be greater than 69 dB (92 – 23.5 dB) for STATSIONAR-T and 53 dB (92 – 38.8 dB) for STATSIONAR-T2. Unwanted emissions falling into the RAS band belong to the spurious domain.

Regulatory provisions of BSS given by Table II of RR Appendix 3 indicate a maximum permitted emission power level attenuation greater than the minimum value between 60 dBc and 43 + 10 log *P*. P stands for the mean power in W. In this case, the attenuation factor will be 60 dBc.

Taking into account the levels contained in RR Appendix 3, unwanted emissions radiated by the STATSIONAR satellite into the RAS band towards RAS stations in CEPT countries will be up to 10 dB above the threshold levels contained in Recommendation ITU-R RA.769. However, experience has shown that the levels contained in RR Appendix 3 are very high and that real systems spurious emissions are well below these levels by up to 20 dB (see COSPAS-SARSAT). Therefore, it is considered that the threshold level of Recommendation ITU-R RA.769 can be met for this particular frequency band, by similar future systems having the same characteristics.

6.5 Mitigation techniques

6.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for G/T, i.e. telescope gain divided by system temperature. This is to maximize theS/N for point sources. A key element of this approach is to reduce ground radiation entering through far side lobes. Inevitably this leads to some corresponding increase in the levels of near side lobes.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

6.5.2 Potential impact on the RAS

Antenna side-lobe performance: Attempts to decrease the sensitivity of the radio astronomy antenna to unwanted emissions coming from space stations are likely to increase the sensitivity of the radio astronomy telescope to ground radiation, and possibly reduce its main beam gain. Both of these effects will reduce the telescope's channel capacity of and thus lead to an increase of the total required integration time.

Blanking in time and/or frequency: Blanking involves a risk of compromising the integrity of the data and may lead to errors in their scientific interpretation. Blanking also causes a concomitant increase in the total integration time required to make the observation, this is equivalent to a loss in the channel capacity of the telescope.

7 Compatibility analysis between RAS systems operating in the 1 400-1 427 MHz and 1 610.6-1 613.8 MHz bands and non-GSO mobile-satellite service (space-to-Earth) systems operating in the 1 525-1 559 MHz band

7.1 RAS

7.1.1 Allocated bands

The 1 400-1 427 MHz band is allocated to passive services only, on a primary basis: the RAS, the EESS (passive), and the space research service (SRS) − passive. This Annex discusses the radio astronomy case only.

RR No. 5.340 prohibits all emissions in this band.

The 1 610.6-1 613.8 MHz band is allocated to the RAS on a primary basis, along with other active services such as MSS or aeronautical radionavigation.

RR No. 5.149 urges administrations to take all practicable steps to protect the radio astronomy service in this band.

7.1.2 Type of observations

7.1.2.1 Band 1 400-1 427 MHz

The 1 400-1 427 MHz band is used more intensely than any other, in all ITU-R Regions. The main radio-astronomical use of band is to make spectral line observations of cosmic neutral atomic hydrogen (also referred to as HI), which has a rest frequency of 1 420.406 MHz. This material is by far the main constituent of our Galaxy and other galaxies, and occurs in huge, complex-structured clouds. This line is observed in both emission and absorption, and is broadened and shifted in frequency by Doppler shifts due to local and bulk motions in the cloud structures. Accordingly, HI observations can be used to map the distribution of material and its motions in our and other galaxies. In this way we can map the structure of our Galaxy, and how material is moving.

The 1 400-1 427 MHz allocation is sufficiently broad to encompass the Doppler-shifted emission from clouds in our galaxy and in nearby galaxies. Measurements of the polarization of the HI emission or absorption yield important information on galactic magnetic fields and thence an increased understanding of galactic structure.

The 1 400-1 427 MHz band is also used for continuum observations of broadband emissions produced by hot plasma formed when stars heat the surrounding clouds, and by the interaction of high-energy electrons in the galactic magnetic field (synchrotron emission).

7.1.2.2 Band 1 610.6-1 613.8 MHz

The 1 610.6-1 613.8 MHz band is used for spectral line observations of the OH (hydroxyl radical molecule). The OH line, which has a rest frequency of 1 612 MHz, is one of the most important spectral lines for radio astronomy, and is listed as such in Recommendation ITU-R RA.314. OH radical was the first cosmic radical to be detected at radio frequencies (1963), and continues to be a powerful research tool. OH produces four spectral lines, at frequencies of approximately 1 612, 1 665, 1 667 and 1 720 MHz, all of which have been observed in our own galaxy, as well as in external galaxies. The study of OH lines provides information on a wide range of astronomical phenomena, e.g. the formation of protostars and the evolution of stars. To interpret most observations made in the OH lines, it is necessary to measure the relative strength of several of these lines. Loss of the ability to observe any one of these lines may prevent the study of some classes of physical phenomena.

These OH lines are produced by a coherent process, in which a concentration of OH radicals radiate "in step", creating narrow-band emission. They are slightly broadened due to physical conditions in this concentration. Movement of these concentrations with respect to the Earth impose a Doppler shift on the line emission. The presence of several concentrations in the source, which are moving at different velocities, give rise to a more complicated spectrum, consisting of a number of superimposed Gaussian line profiles of different widths and amplitudes, and slightly-different frequencies (due to the different Doppler shifts). The width of the band allocation is required to accommodate the spreading and shifting of the spectrum by differential and total motions of the source.

In some stages of their evolution, certain classes of stars radiate only the 1 612 MHz line. The study of this line allows astronomers to gauge such physical properties of these stars as the rate at which gas is blown off by the stars and recycled into the interstellar medium. Some properties of these stars cannot be inferred from any other astronomical observation. Measurements of OH emitting stars have also been used to estimate the distance to the Galactic Centre, to measure the mass of the central bulge of our galaxy, and to study the spatial distribution of the molecular component in our galaxy and in external galaxies. Finally, extremely strong maser emission has been detected near the nuclei of a number of external galaxies. This OH megamaser emission from galactic nuclei allows astronomers to study the temperature and density of the molecular gas in their centre.

The OH spectral line is also observed in comets; there is very little flexibility in scheduling observations of these "targets of opportunity".

Spectral line observations are made using spectrometers that can simultaneously integrate the power in a large number of frequency channels (typically 256-4 096) distributed across the frequency band used. The width and number of channels has to be large enough to accurately reproduce the spectrum of the emission received by the radio telescope. Instantaneous bandwidths of typically ~0.2-20 kHz per frequency channel are used, depending on the scientific program.

The sources are small, and measurements of their size and structure often require observations using the VLBI technique.

7.1.3 Required protection criteria

7.1.3.1 Band 1 400-1 427 MHz

The threshold interference levels for detrimental interference to radio astronomical observations are given in Recommendation ITU-R RA.769.

These thresholds levels are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), rises 10 dB or more above the level given in this Recommendation, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will then be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

In the 1 400-1 427 MHz band, for single-dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 20 kHz, the threshold pfd for detrimental interference is –196 dB(W/m^2). For making single-dish continuum observations, the entire 27 MHz width of the band is used, for which case the threshold pfd for detrimental interference is –180 dB(W/m^2).

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, −166 dB(W/m^2), for a bandwidth of 20 kHz.

7.1.3.2 Band 1 610.6-1 613.8 MHz

In the 1 610.6-1 613.8 MHz band, for single-dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 20 kHz, the threshold pfd for detrimental interference is –194 dB(W/m^2).

7.1.4 Operational characteristics

The 1 400-1 427 MHz band is the most intensely used radio astronomy band of all. It is used worldwide, in all ITU Regions, and some radio telescopes, such as the Synthesis Radio Telescope at the Dominion Radio Astrophysical Observatory (DRAO), Penticton, Canada observe full-time in this band. Single-antenna radio telescopes are used to measure the integrated spectral pfd (spfd) of sources of small angular diameter and to map structures of large angular size that cannot be mapped using synthesis telescopes.

Observations in the 1 612 MHz band are carried out at a number of radio astronomy sites in numerous countries, worldwide. Observations in the 1 612 MHz band are sometimes conducted on targets of opportunity, e.g. on objects such as comets, which have been observed to produce transient emissions in this line. VLBI observations are also frequently conducted in this band, sometimes between the North American and European VLBI networks.

The higher angular resolution offered by synthesis telescopes make it possible to map the finer structure in the hydrogen clouds and sources of continuum emissions such as supernova remnants. These maps are then combined with the lower-resolution maps obtained using single-antenna radio telescopes to make high-quality 3-D images of our Galaxy and others. Synthesis radio telescopes, using multi-antenna arrays may require between one and a dozen 12 h “exposures” to make a complete map of an area of sky.

In order to facilitate mapping comparatively large source structures, some synthesis radio telescopes, such as the DRAO instrument, use arrays of comparatively small antennas. Instruments of this kind do not have the option of optimum side-lobe suppression and are therefore more vulnerable to interference.

Spectral line observations are made using multichannel spectrometers that can integrate simultaneously the power in many (typically 256 to 4 096) frequency channels distributed across the band. The number of channels and their individual bandwidths are chosen to adequately sample the spectrum of the net emission from the hydrogen cloud(s) in the antenna beam.

In general, observations are made differentially. In the case of continuum emissions, the area of sky surrounding the sky may be mapped, and the background emission subtracted, or measurements made of the power coming from the direction from the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

In the case of spectral line observations, spectra are recorded at frequency ranges including the line emissions of interest (the line spectra), and then at a frequency that is offset from the line emissions, or at the same frequency but at a nearby position in the sky (the reference spectra). By subtracting the reference spectra from the line spectra, unwanted noise contributions and other contaminants can be removed from the data.

Since the Galaxy is filled with clouds of neutral hydrogen, radio telescopes detect not only the emission or absorption in the clouds in the antenna main beam, but also a very significant contribution through the antenna side lobes. This "stray radiation" distorts spectra and reduces map detail. Removing this from the data involves large-scale measurement of the whole antenna beam (as far as possible), and estimation of the stray radiation correction. Interference and large "blocked" areas of sky will therefore affect the ability to make maps at parts of the sky large angles from interference sources.

An extended area of radio emission can be mapped by recording the emission from a grid of points covering the region of interest. Both continuum and spectral line observations may be made. In the case of single antenna radio telescopes, each grid point observation is an indication of the total power (in the continuum case) or the emission spectrum (in the spectral line case) coming from that position in the sky; the spacing between the grid points should not be more than half the antenna beamwidth. When observations are made using a synthesis radio telescope, where the area to be mapped exceeds the instantaneous mapping field, the grid points should not be further apart than half the beamwidth of one of the radio telescope antennas.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data has been processed.

7.2 MSS

7.2.1 Allocated transmit band

The allocated transmit band is 1 525-1 559 MHz (space-to-Earth).

RR No. 5.356 states that: "the use of the band 1 544-1 545 MHz by the mobile-satellite service (space-to-Earth) is limited to distress and safety communications (see Article **31**)".

7.2.2 Application

The bands 1 525-1 544 MHz and 1 545-1 559 MHz are only used by GSO systems and due to the antenna characteristics of MSS earth stations (omnidirectional antenna), it will be difficult for non-GSO systems to use these bands. However, Recommendation ITU-R M.1184 gives the characteristics of one non-GSO MSS system that may use these bands.

The band 1 544-1 545 MHz has been used by the Cospas-Sarsat global search and rescue satellite-aided system over many years. Cospas-Sarsat is a satellite system designed to provide distress alert and location data to assist search and rescue (SAR) operations, using spacecraft and ground facilities to detect and locate the signals of distress beacons operating on 406 MHz or 121.5 MHz. Non-GSO satellites (LEOSAR system) relay the 121.5 MHz signals as well as data extracted from the 406 MHz signals on the frequency 1 544.5 MHz for ground processing.

7.2.3 Levels based upon regulatory provisions

The required attenuation is 43 + 10 log P dBc or 60 dBc whichever is less stringent where P is the peak power at the input to the antenna (W) in any 4 kHz.

7.2.4 Operational characteristics

7.2.4.1 MSS system G based on Recommendation ITU-R M.1184

TABLE 14

Technical characteristics of non-GSO mobile-satellite systems (service forward link)

System parameter	**System G**	
	Link 1	**Link 2**
Polarization		
Feeder link	LHCP	LHCP
Service link	RHCP	RHCP
Direction of transmission	Space-to-Earth	Space-to-Earth
Frequency bands (GHz)		
Feeder link	14	14
Service	0.4	1.5
Orbit	Circular	Circular
Altitude (km)	1 500	1 500
Satellite separation (degrees)	30	30
Number of satellites	48	48
Orbital planes	4	4
Inclination angle (degrees)	74	74
Satellite antennas		
Number of beams (service link)	1	6
Beam size (km^2)	5×10^7	8.4×10^6
Average beam side lobes (dB)	–3	–2
Beam frequency reuse	1	0.6
Link characteristics		
Maximum e.i.r.p./beam (dBW)	–2	2.8
Average gain/beam (dBi)	3	13
e.i.r.p./carrier (dBW)	–15	–7.2
Unshadowed user e.i.r.p. (dBW)	Not applicable	Not applicable
Shadowed user e.i.r.p. (dBW)	Not applicable	Not applicable
e.i.r.p./CDMA channel (dBW)	–5	–10.2
User G/T (dB(K^{-1}))	–23.8	–14
Minimum elevation angle (degrees)	7	10
Transmission parameters		
Modulation	QPSK	QPSK
Coding	FEC	FEC
Access scheme	FDMA/CDMA	FDMA/CDMA
Duplex scheme	Full	Full
Frame length (ms)	Not applicable	Not applicable
Burst rate (kbit/s)	Not applicable	Not applicable

7.2.4.2 COSPAS-SARSAT

Although the nominal LEOSAR constellation comprises only four satellites (two COSPAS and two SARSAT), the satellites taken into account in the study include two Russian-built satellites with a COSPAS payload: NADEZHDA-1 and NADEZHDA-6, as well as five US-built satellites with a SARSAT payload: NOAA-14 to 18. Table 15 gives the orbital characteristics of these satellites.

TABLE 15

Characteristics of satellites in the COSPAS SARSAT system

Payload name	Satellite name	Launch date	Altitude (km)	Inclination (degrees)	Mean anomaly (degrees)	RAAN (degrees)
COSPAS-4	NADEZHDA-1	1989	1 000	82.96	302	151
COSPAS-9	NADEZHDA-6	2000	689	98.38	131	219
SARSAT-6	NOAA-14	1994	863	99.08	204	289
SARSAT-7	NOAA-15	1998	825	98.51	213	245
SARSAT-8	NOAA-16	2000	862	99.02	134	198
SARSAT-9	NOAA-17	2002	824	98.65	155	312
SARSAT-10	NOAA-18	2005	868	98.75	22	184

The payload specifications are available on the COSPAS-SARSAT website: http://www.cospas-sarsat.org/DocumentsTSeries/T3OCT03.pdf. This document contains specifications on the level of spurious emissions and on the antenna pattern of COSPAS and SARSAT payloads.

7.2.4.2.1 COSPAS

Figure 25 gives the typical spectrum of COSPAS signal within its allocated bandwidth. The level of COSPAS spurious emissions is limited to –60 dBW. However, no reference bandwidth is given. Figure 26 gives the antenna pattern of COSPAS downlink.

FIGURE 25

Spectrum of COSPAS 1 544.5 MHz signal

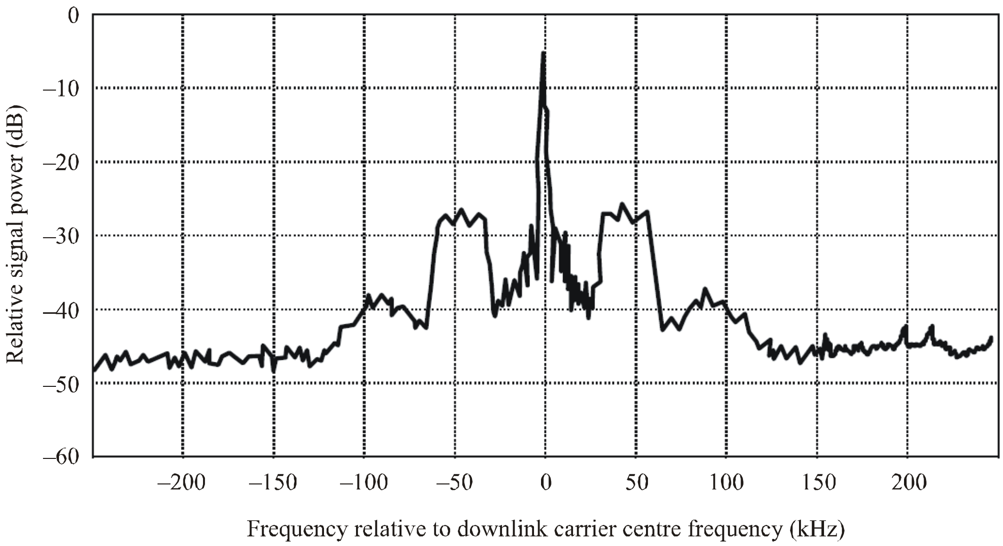

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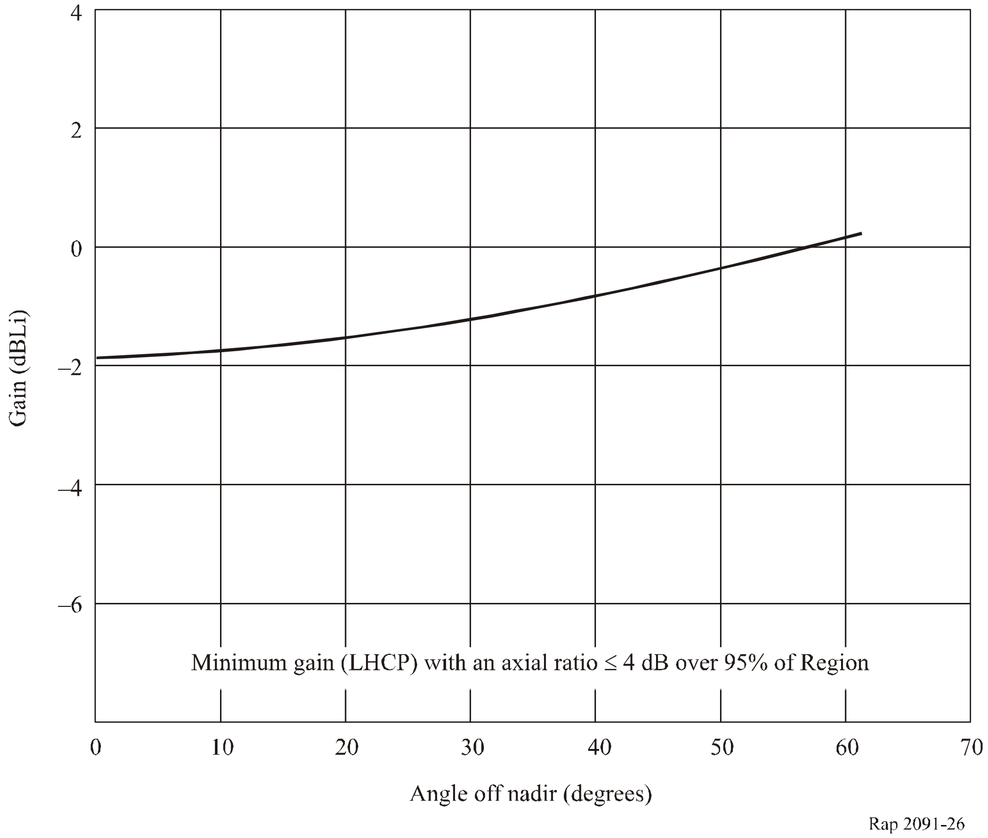
FIGURE 26

COSPAS antenna pattern



7.2.4.2.2 SARSAT

Figure 27 gives the typical spectrum of SARSAT signal within its allocated bandwidth. The level of SARSAT unwanted emissions is limited to the masks given in Figs. 28 and 29 for respectively discrete and noise-like emissions. However, no reference bandwidth is given for the discrete case. Figure 30 gives the antenna pattern of SARSAT downlink.

FIGURE 27

Spectrum of SARSAT 1 544.5 MHz signal

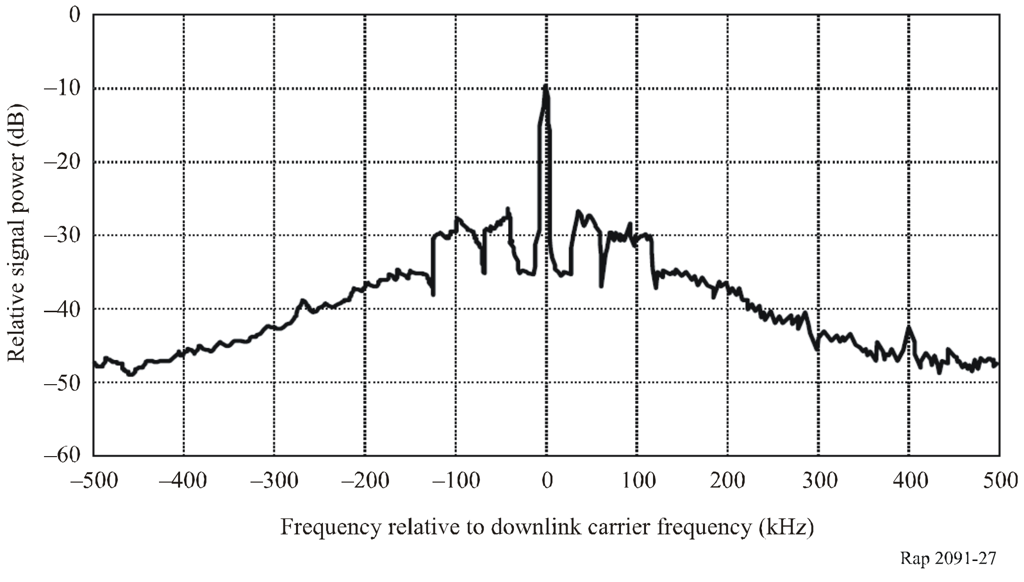


FIGURE 28

Discrete unwanted emission limits

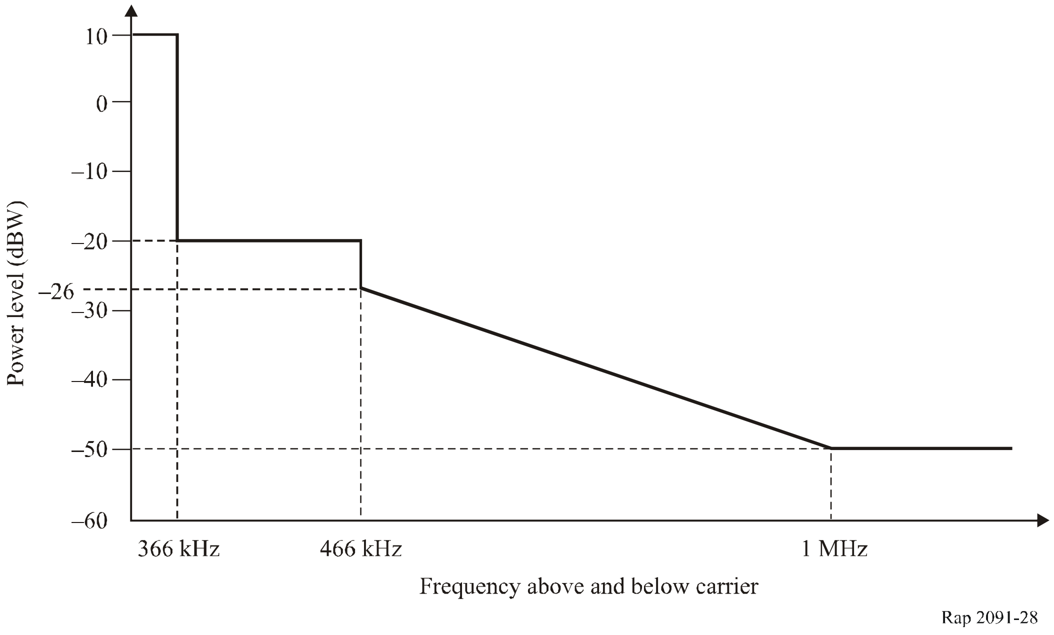


FIGURE 29

Noise-like unwanted emission limits

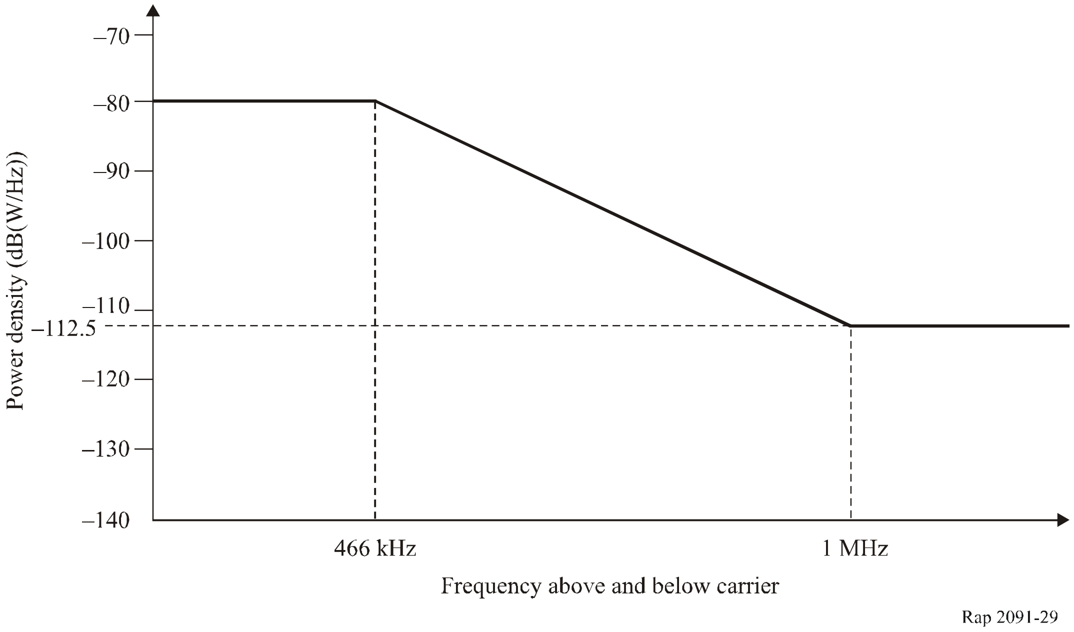
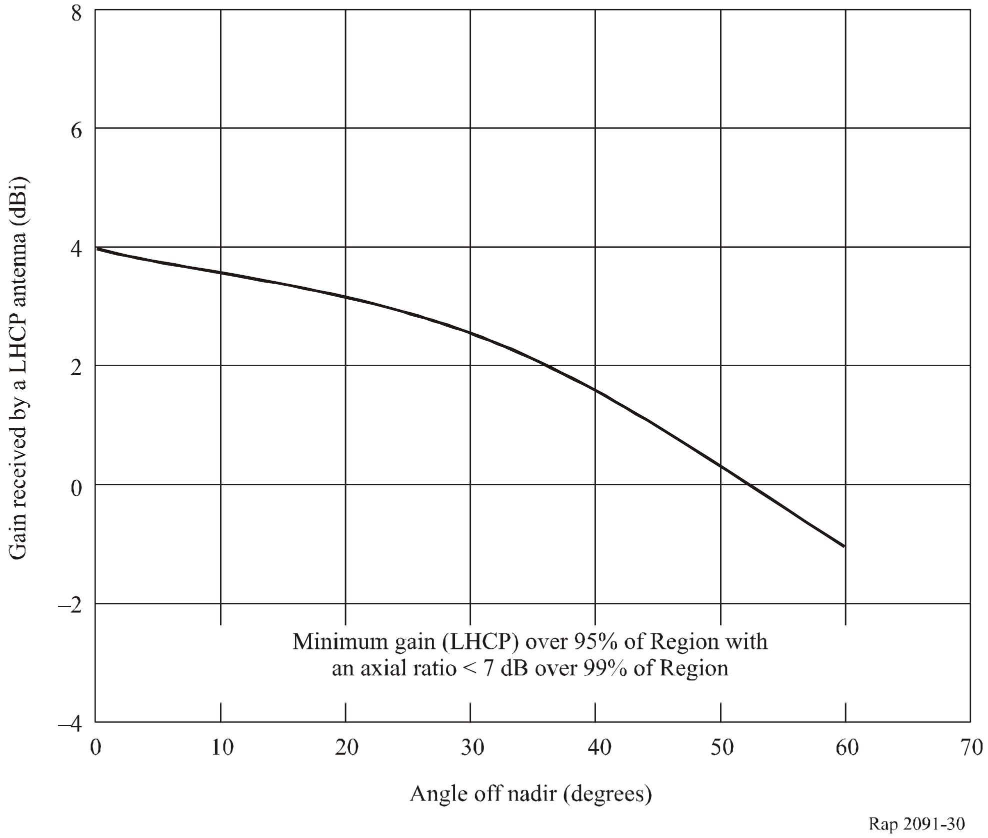


FIGURE 30

SARSAT antenna pattern



7.3 Compatibility threshold

For the case of non-GSO constellations, an epfd threshold may be derived from the pfd threshold given in Recommendation ITU-R RA.769 and the maximum antenna gain given in Recommendation ITU-R RA.1631, which is 63 dBi for this frequency band. The epfd threshold for the band 1 400-1 427 MHz is therefore –243 (dB(W/m^2)) in the entire band 1 400-1 427 MHz for single-dish continuum observations, –259 (dB(W/m^2)) in any 20 kHz bandwidth of the band 1 400-1 427 MHz for single-dish spectral line observations, and –258 (dB(W/m^2)) in any 20 kHz bandwidth of the band 1 610.6-1 613.8 MHz for single-dish spectral line observations.

7.4 Interference assessment

7.4.1 Methodology used to assess the interference level

Recommendation ITU-R M.1583 provides a methodology to evaluate the levels of unwanted emissions produced by a non-GSO system at radio astronomy sites. It is based on a division of the sky into cells of nearly equal size and a statistical analysis where the pointing direction of the RAS antenna and the starting time of the satellite constellation are the random variables. For each trial, the unwanted emission level (expressed in terms of epfd) is averaged over a 2 000 s period.

The RAS antenna diameter is 100 m which corresponds to a maximum antenna gain of approximately 63 dBi in the 1 400-1 427 MHz band and 64 dBi in the 1 610.6-1 613.8 MHz band. The antenna pattern and maximum antenna gain are taken from Recommendation ITU-R RA.1631.

The geographical coordinates chosen are:

Latitude: 46.9° Longitude: 2.4°

The simulations were performed considering an elevation angle of 0° in order to get completely general results.

7.4.2 Calculation of interference level

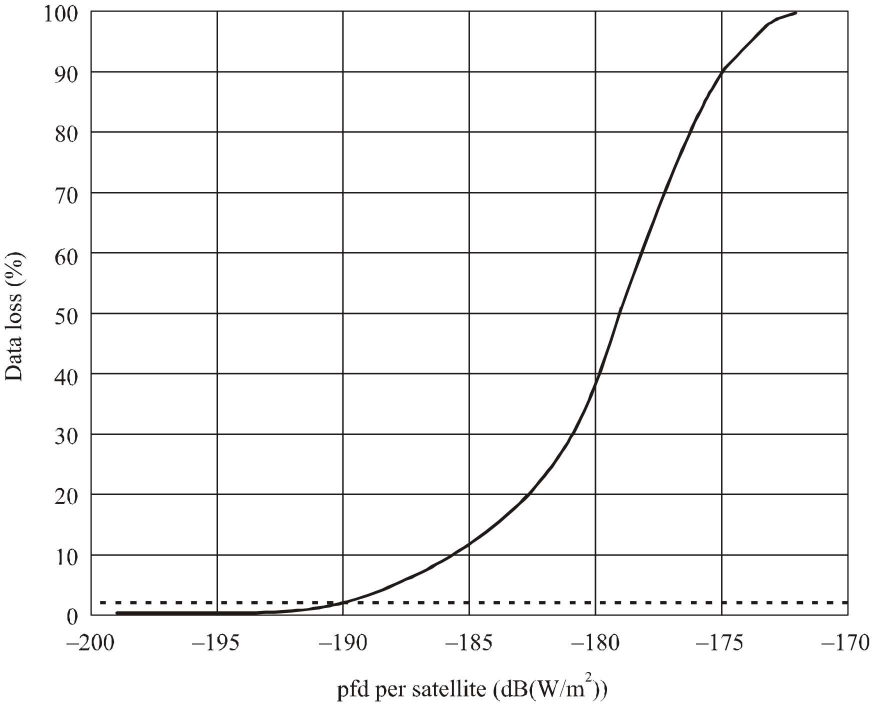
7.4.2.1 Continuum observations in the band 1 400-1 427 MHz

7.4.2.1.1 MSS system G based on Recommendation ITU-R M.1184

Figure 31 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value per MSS satellite (as explain in Recommendation ITU-R RA.1513, exceeding this threshold is equivalent to data loss).

FIGURE 31

Percentage of data loss vs. pfd per satellite at RAS site



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To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each MSS system G satellite should generate a pfd of less than –190 dB(W/m^2) in the radio astronomy band.

Figure 32 shows for each cell of the sky, and for the pfd (per satellite) of –190 dB(W/m^2), the percentage of time where the epfd threshold is exceeded.

0° azimuth is due North, and azimuth increases from West to East.

7.4.2.1.2 COSPAS-SARSAT

Figure 33 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value per satellite (as explained in Recommendation ITU-R RA.1513, exceeding this threshold is equivalent to data loss).

FIGURE 32

Percentage of data loss over the sky for the pfd value of –190 dB(W/m^2) at RAS site

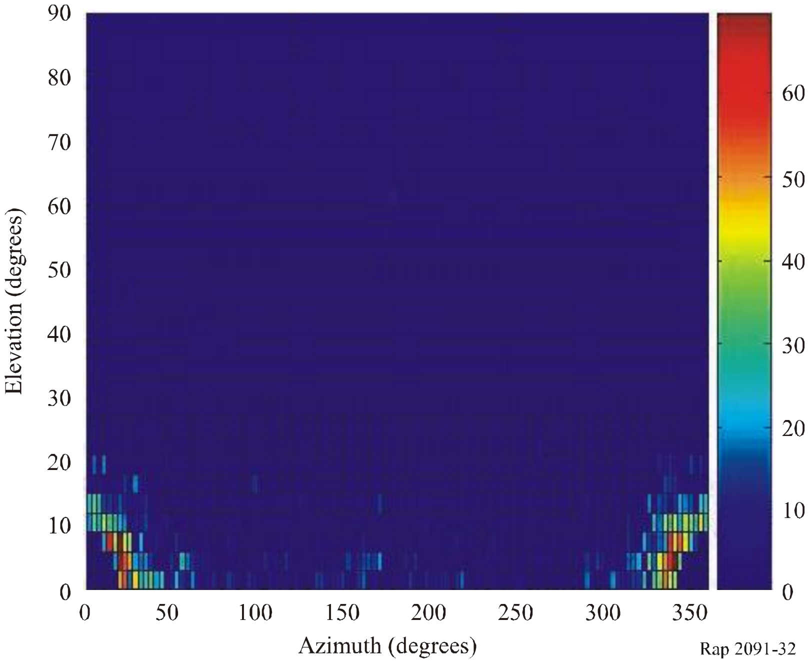
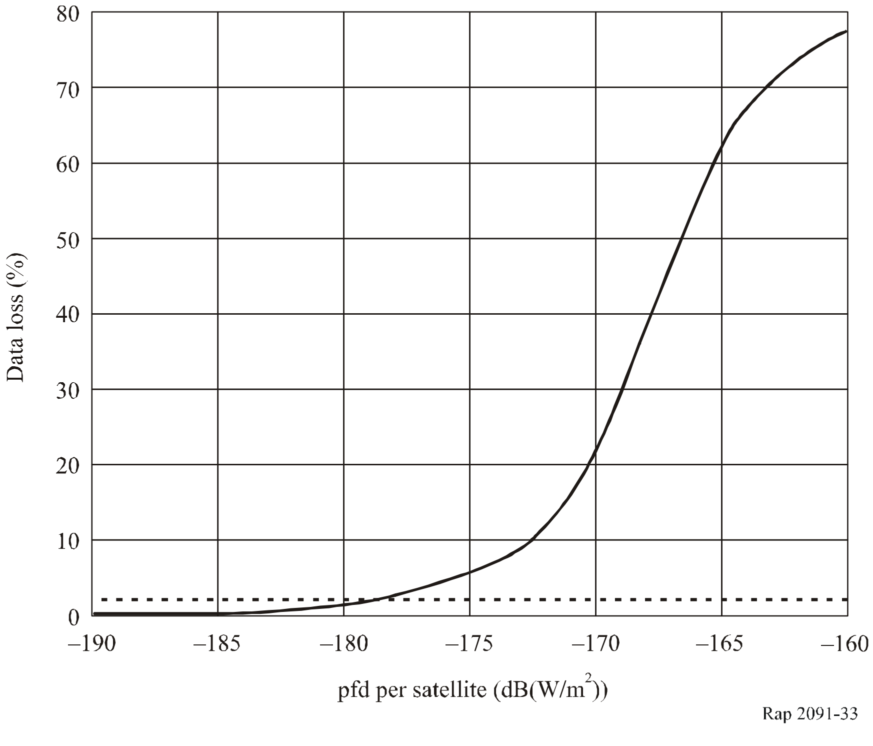


FIGURE 33

Percentage of data loss vs. pfd per satellite at RAS site

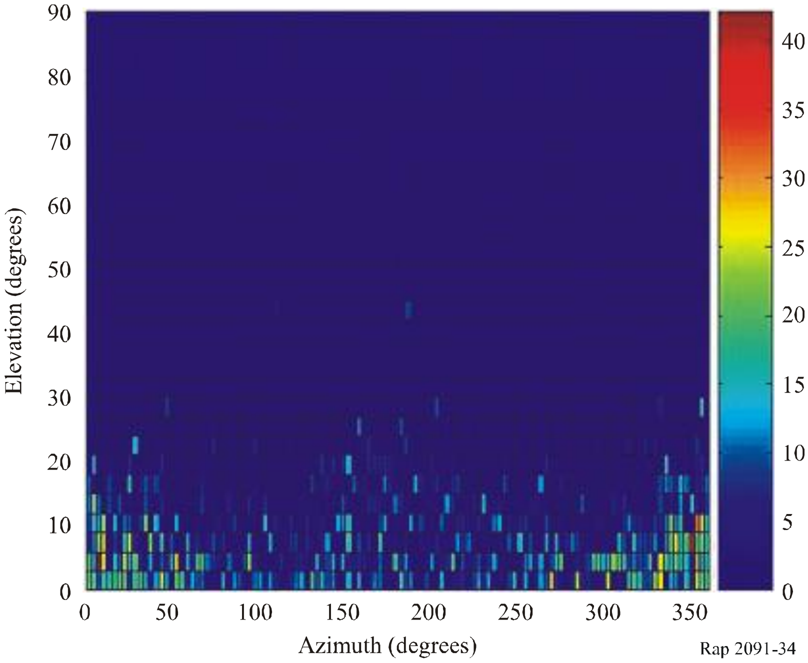


To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each LEOSAR satellite should generate a pfd of less than –179 dB(W/m^2) in the radio astronomy band.

Figure 34 shows for each cell of the sky, and for the pfd (per satellite) of –179 dB(W/m^2), the percentage of time where the epfd threshold is exceeded. 0° azimuth is due North, and azimuth increases from West to East.

FIGURE 34

Percentage of data loss over the sky for the pfd value of –179 dB(W/m^2) at RAS site



7.4.2.2 Spectral line observations in the band 1 400-1 427 MHz

This pfd value per satellite can be directly deduced without further simulations from the value required for continuum observations using the following formula:

$$pfd_{spectral} = pfd_{continuum} + epfd_{spectral} - epfd_{continuum} \tag{10}$$

To meet the epfd threshold of –259 dB(W/m^2) in 20 kHz during more than 98% of the time in average over the whole sky, each MSS system G satellite should generate a pfd of less than –206 dB(W/m^2) in any 20 kHz bandwidth of the radio astronomy band and each COSPAS-SARSAT satellite should generate a pfd of less than –194 dB(W/m^2) in any 20 kHz bandwidth of the radio astronomy band.

7.4.2.3 Spectral line observations in the band 1 610.6-1 613.8 MHz

The power received by the radioastronomy station receiver to be compared with the detrimental threshold level is:

$$P = average\left(pfd \cdot \frac{\lambda^2}{4\pi} \cdot \sum_{i=1}^{n} G_i\right) \tag{11}$$

where:

P: received power in the radioastronomy bandwidth (W)

pfd: pfd radiated by one satellite at the radio astronomy station in the radio astronomy bandwidth (assumed constant) (W/m^2)

λ: wavelength (m)

n: number of satellites in visibility and in activity

G_i: radio astronomy antenna gain in the direction of satellite i.

The average is calculated over the 2 000 s of RAS observation.

From this equation, we can see that the difference from one frequency to another is determined by: the value of λ, the radiotelescope antenna gain, the detrimental threshold level, and the propagation conditions. A study introduced in ITU-R WP 7D has already shown that the antenna gain has hardly any influence on the results: that is why the antenna diameter of 100 m is chosen for all frequencies in all studies. Moreover, for the frequencies considered here, the propagation conditions do not change a lot. We can therefore consider that the difference in pfd per satellite from one frequency to another will be mainly due to the wavelength and the detrimental threshold level.

We therefore can write:

$$pfd_2 \approx pfd_1 + P_2 - P_1 + 20 \log\left(\frac{\lambda_1}{\lambda_2}\right) = pfd_1 + P_2 - P_1 + 20 \log\left(\frac{f_2}{f_1}\right) \qquad (12)$$

where:

pfd_2: pfd per satellite to be respected at frequency 1 (dB(W/m^2))

pfd_2: pfd per satellite to be respected at frequency 2 (dB(W/m^2))

P_1: detrimental threshold level at frequency 1 (dBW)

P_2: detrimental threshold level at frequency 2 (dBW)

f_1: frequency 1 (MHz)

f_2: frequency 2 (MHz).

To meet the epfd threshold of –258 dB(W/m^2) in 20 kHz during more than 98% of the time in average over the whole sky, each MSS system G satellite should generate a pfd of less than –205 dB(W/m^2) in any 20 kHz bandwidth of the radio astronomy band and each COSPAS-SARSAT satellite should generate a pfd of less than –193 dB(W/m^2) in any 20 kHz bandwidth of the radio astronomy band.

7.4.3 Values achieved

The unwanted emissions of MSS non-GSO satellites using the band 1 525-1 559 MHz falling into the RAS bands 1 400-1 427 MHz and 1 610.6-1 613.8 MHz fall in the spurious domain.

7.4.3.1 MSS system G based on Recommendation ITU-R M.1184

Table 16 gives an evaluation of the pfd generated by MSS system G at a radio astronomy station based on the spurious emission mask contained in RR Appendix 3.

TABLE 16

Attenuation of non-GSO MSS networks in the band 1 525-1 559 MHz necessary to reach the detrimental epfd level

System G	
e.i.r.p. per beam and per carrier in the MSS band (dBW)	–7.2
pfd in the MSS band (dB(W/m^2))	–141.7
Antenna gain (dBi)	13.0
Emission power per beam and per channel in the MSS band (dBW)	–20.2
43 + 10 log *P*	22.8
Spurious attenuation from RR Appendix 3 (dBc in 4 kHz)	22.8
Spurious level from RR Appendix 3 (dB(W in 4 kHz))	–43
Spurious level in the band 1 400-1 427 MHz (dBW)	–5
Spurious pfd in the RAS band (dB(W/m^2))	–126
Required pfd in the passive band (dB(W/m^2))	–206

It has to be noted that in order to calculate the total amount of spurious emissions in the RAS band it was considered that spurious emissions have a constant level in the whole RAS band. This hypothesis is very stringent and clearly not representative of the reality, as spurious emissions generally appear at some discrete frequencies. Therefore, further work is needed in order to take into account this discrete component of spurious emissions in order to get more realistic MSS unwanted emission levels in the RAS band.

The same remark is valid for the 1 610.6-1 613.8 MHz band.

7.4.3.2 COSPAS-SARSAT

A calculation of the pfd radiated on the ground by both systems is given in Tables 17 (nadir case) and 18 (horizon case).

No reference bandwidth is given in the specification for either SARSAT or COSPAS for the discrete-like spurious emissions. However, information was received from the manufacturer of SARSAT payloads. Measurements of spurious emissions are made within a reference bandwidth of 10 kHz. The same assumption was taken for COSPAS.

TABLE 17

Maximum pfd radiated at nadir

System	**Spurious level (dBW)**	**Reference bandwidth (kHz)**	**Altitude (km)**	**Antenna gain (dBi)**	**Maximum pfd (dB(W/m^2))**
SARSAT	–38	27 000	825	4	–164
	–47	20	825	4	–172
COSPAS	–57	20	1 000	–2	–190
	–57	20	690	–2	–187

TABLE 18

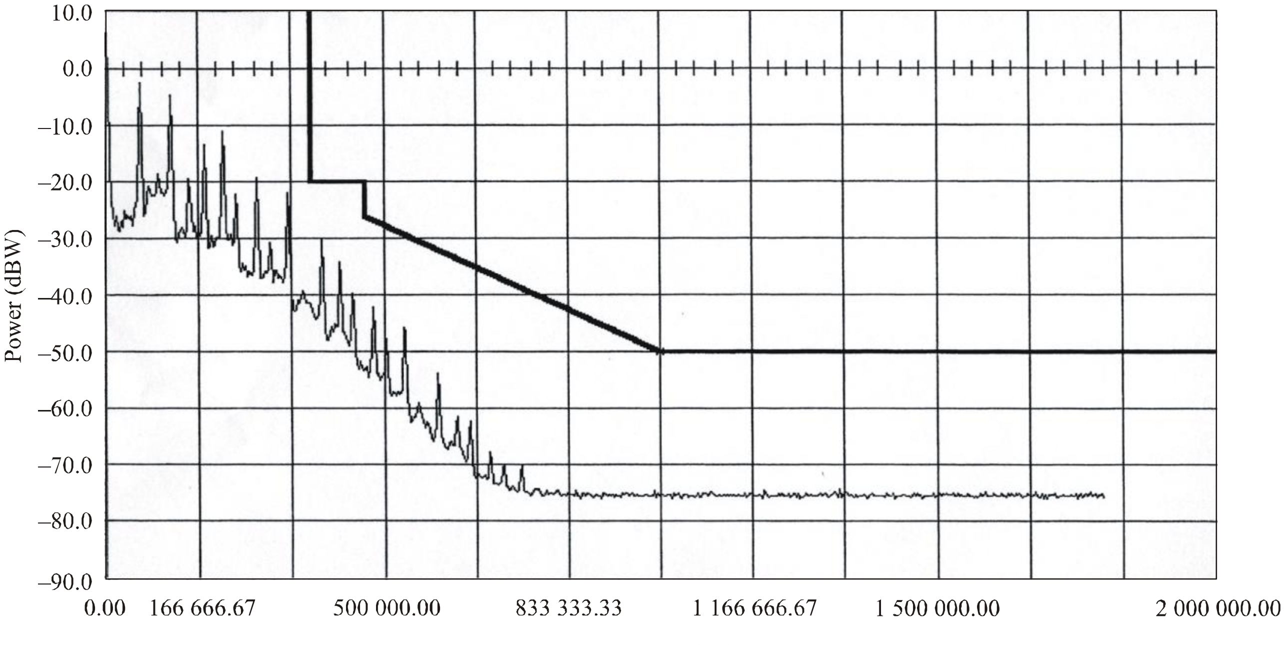
Maximum pfd radiated at an offset angle of 60° (horizon)

System	Spurious level (dBW)	Reference bandwidth (kHz)	Slant range (km)	Antenna gain (dBi)	Maximum pfd (dB(W/m^2))
SARSAT	–38	27 000	2 272	–1	–177
	–47	20	2 272	–1	–186
COSPAS	–57	20	2 973	0	–197
	–57	20	1 792	0	–193

Figure 35 has been provided by the manufacturer of SARSAT payloads. It shows that, in fact, the level of spurious is 25 dB below the specification. Therefore the actual pfd radiated on the ground in the radioastronomy bands would be 25 below the values given in Tables 17 and 18. It may therefore be considered that it is feasible to meet the pfd level per satellite determined in § 7.4.2 without any undue constraint on the payload. As SARSAT payloads represent the worst case, the same conclusion may be drawn for COSPAS payloads.

FIGURE 35

Measurement of SARSAT unwanted emissions



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7.5 Mitigation techniques for the RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for *G*/*T*, i.e. telescope gain divided by system temperature. This is to maximize the *S*/*N* ratio for point sources. A key element of this approach is to reduce ground radiation entering through far side lobes. Inevitably this leads to some corresponding increase in the levels of near side lobes.

Experience has shown that the majority of radio telescopes meet the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

7.6 Results of studies

7.6.1 Summary

Table 19 thereafter summarizes the epfd and pfd threshold levels required for the protection of radio astronomy stations from unwanted emissions of COSPAS SARSAT payloads in the 1 544-1 545 MHz.

TABLE 19

Threshold levels for the protection of RAS from COSPAS-SARSAT unwanted emissions

RAS band (MHz)	Type of observations	Reference bandwidth	epfd threshold (dB(W/m^2))	pfd threshold per satellite (dB(W/m^2))
1 400-1 427	Continuum	27 MHz	–243	–179
1 400-1 427	Spectral line	20 kHz	–259	–194
1 610.6-1 613.8	Spectral line	20 kHz	–258	–193

When taking into account the specifications of COSPAS and SARSAT payloads, it appears that the pfd generated on the ground and in the RAS bands by unwanted emissions exceeds the pfd threshold level per satellite given in Table 17 by 2 to 13 dB for continuum observations and 5 dB to 22 dB for spectral line observations.

However, the RAS bands are located 65 MHz and 117 MHz away from the COSPAS-SARSAT band, respectively. Moreover, the level of unwanted emissions actually measured on SARSAT payloads is about 25 dB lower than the specification. Therefore, SARSAT payloads meet the pfd limits given in Table 17. As SARSAT represents the worst case, this conclusion is also true for COSPAS.

7.6.2 Conclusions

It is feasible to meet the pfd level per satellite determined in Table 19 without any further constraints on the COSPAS-SARSAT system.

8 Compatibility analysis between RAS systems operating in the 1 400-1 427 MHz band and BSS (space-to-Earth) systems operating in the 1 452-1 492 MHz band

8.1 RAS

8.1.1 Allocated band

The 1 400-1 427 MHz band is allocated to passive services only, on a primary basis: the RAS, the EESS (passive), and the SRS (passive).

RR No. 5.340 prohibits all emissions in this band.

8.1.2 Type of observations

The 1 400-1 427 MHz band is used more intensely than any other, in all ITU-R Regions. The main radio-astronomical use of band is to make spectral line observations of cosmic neutral atomic hydrogen (also referred to as HI), which has a rest frequency of 1 420.406 MHz. This material is by far the main constituent of our Galaxy and other galaxies, and occurs in huge, complex-structured clouds. This line is observed in both emission and absorption, and is broadened and shifted in frequency by Doppler shifts due to local and bulk motions in the cloud structures. Accordingly, HI observations can be used to map the distribution of material and its motions in our and other galaxies. In this way we can map the structure of our Galaxy, and how material is moving.

The 1 400-1 427 MHz allocation is sufficiently broad to encompass the Doppler-shifted emission from clouds in our galaxy and in nearby galaxies. Measurements of the polarization of the HI emission or absorption yield important information on galactic magnetic fields and thence an increased understanding of galactic structure.

The 1 400-1 427 MHz band is also used for continuum observations of broadband emissions produced by hot plasma formed when stars heat the surrounding clouds, and by the interaction of high-energy (fast-moving) electrons in the galactic magnetic field (synchrotron emission).

8.1.3 Required protection criteria

The threshold levels for detrimental interference to radio astronomical observations are given in Recommendation ITU-R RA.769, which lists the levels of unwanted emissions that will increase the measurement error by 10%. The band is used for both spectral line and continuum observations. In the 1 400-1 427 MHz band, for single-dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 20 kHz, the threshold pfd limit is –196 dB(W/m^2). For making single-dish continuum observations, the whole 27 MHz width of the band is used, for which case the threshold pfd limit for detrimental interference is –180 dB(W/m^2).

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, -166 dB(W/m^2), for a bandwidth of 20 kHz.

The thresholds of detrimental interference levels to the RAS as defined and calculated in the Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes 10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

8.1.4 Operational characteristics

The 1 400-1 427 MHz band is the most intensely used radio astronomy band of all. It is used worldwide, in all ITU Regions, and some radio telescopes, such as the Synthesis Radio Telescope at the Dominion Radio Astrophysical Observatory (DRAO), Penticton, Canada observe full-time in this band. Single-antenna radio telescopes are used to measure the integrated spfd of sources of small angular diameter and to map structures of large angular size that cannot be mapped using synthesis telescopes.

The higher angular resolution offered by synthesis telescopes make it possible to map the finer structure in the hydrogen clouds and sources of continuum emissions such as supernova remnants. These maps are then combined with the lower-resolution maps obtained using single-antenna radio telescopes to make high-quality 3-D images of our Galaxy and others. Synthesis radio telescopes, using multi-antenna arrays may require between one and a dozen 12 h "exposures" to make a complete map of an area of sky. In order to facilitate mapping comparatively large source structures, some synthesis radio telescopes, such as the DRAO instrument, use arrays of comparatively small antennas. Instruments of this kind do not have the option of optimum side-lobe suppression and are therefore more vulnerable to interference.

Spectral line observations are made using multichannel spectrometers that can integrate simultaneously the power in many (typically 256 to 4 096) frequency channels distributed across the band. The number of channels and their individual bandwidths are chosen to adequately sample the spectrum of the net emission from the hydrogen cloud(s) in the antenna beam.

In general, observations are made differentially. In the case of continuum emissions, the area of sky containing the source may be mapped and the background emission subtracted, or measurements made of the power coming from the direction from the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

In the case of spectral line observations, spectra are recorded at frequency ranges including the line emissions of interest (the line spectra), and then at a frequency that is offset from the line emissions, or at the same frequency but at a nearby position in the sky (the reference spectra). By subtracting the reference spectra from the line spectra, unwanted noise contributions and other contaminants can be removed from the data.

Since the Galaxy is filled with clouds of neutral hydrogen, radio telescopes detect not only the emission or absorption in the clouds in the antenna main beam, but also a very significant contribution through the antenna side-lobes. This "stray radiation" distorts spectra and reduces map detail. Removing this from the data involves large-scale measurement of the whole antenna beam (as far as possible), and estimation of the stray radiation correction. Interference and large "blocked" areas of sky will therefore affect the ability to make maps at parts of the sky large angles from interference sources.

Extended areas of radio emission can be mapped by recording the emission from a grid of points covering the region of interest. Both continuum and spectral line observations may be made. In the case of single antenna radio telescopes, each grid point observation is an indication of the total power (in the continuum case) or the emission spectrum (in the spectral line case) coming from that position in the sky; the spacing between the grid points should not be more than half the antenna beamwidth. When observations are made using a synthesis radio telescope, where the area to be mapped exceeds the instantaneous mapping field, the grid points should not be further apart than half the beamwidth of one of the radio telescope antennas.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without demodulation, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data have been processed.

8.2 BSS

8.2.1 Allocated transmit band

The 1 452-1 492 MHz band is allocated to the BSS.

8.2.2 Application

Broadcasting of audio-only transmissions.

8.2.3 Levels based upon regulatory provisions

Not assessed.

8.2.4 Operational characteristics

The following characteristics were communicated as the expected maximum values and typical necessary bandwidth based on characteristics of BSS sound systems already implemented or most likely to be implemented. In addition, this Recommendation proposes typical values for antenna gains.

TABLE 20

Frequency band (MHz)	**Notified system**	**Necessary bandwidth (MHz)**	**Satellite antenna gain (dBi)**	**Expected maximum in-band pfd (dB(W/(m^2 · 4 kHz)))**
1 452-1 492	Digital System A	1.536	30	–128
	Digital System DS	1.84	30	–138

NOTE 1 – The results in this Annex are limited to GSO systems.

8.3 Compatibility threshold

See § 8.1.3.

8.4 Interference assessment

8.4.1 Methodology used to assess the interference level

With respect to non-GSO systems, the protection criteria for radio astronomy and the relevant methodologies are described in Recommendations ITU-R RA.769 and ITU-R RA.1513, as well as in Recommendation ITU-R S.1586 for FSS systems.

The OoB emission mask that was used for the calculation is described in § 8.4.3.1.

8.4.2 Calculation of interference level

See § 8.4.3.

8.4.3 Values achieved

It should be noted that the following sections cover only the case of GSO systems.

8.4.3.1 Spectral line observations

Based on the necessary bandwidth given in Table 20, and on the separation of the BSS and passive service bands, it appears that for the BSS allocation, the spurious limit applies: 43 + 10 log *P* or 60 dBc, whichever is less stringent, where *P* is the mean power (W) supplied to the antenna transmission line. This is detailed in Table 21.

TABLE 21

BSS allocation (MHz)	**Closest passive service allocation (MHz)**	**Notified system**	**Necessary bandwidth (MHz)**	**Start of OoB domain (MHz)**	**End of OoB domain (MHz)**	**Required attenuation in the passive allocation**
1 452-1 492	1 400-1 427	Digital System A	1.536	1 452	1 448.928	43 + 10 log *P* or 60 dBc
		Digital System DS	1.84	1 452	1 448.32	43 + 10 log *P* or 60 dBc

The expected unwanted emission level is deduced from the parameters in Table 22.

TABLE 22

BSS allocation (MHz)	**Necessary bandwidth (MHz)**	**Expected maximum in-band pfd (dB(W/ (m^2 · 4 kHz)))**	**Satellite antenna gain (dBi)**	**Total mean output power of the transmitter (dBW)**	**Required attenuation in the passive allocation (dBc)**	**Expected maximum unwanted emission levels (dB(W/ (m^2 · 4 kHz)))**
	(1)	(2)	(3)	(4)	(5)	(6)
1 452-1 492	1.536	–128	30	29.8	60	–162.4
	1.84	–138	30	20.6	60	–171.4

where the columns are related as follows:

$$(4) = (2) + 162 \text{ (free space loss)} - (3)_{in\text{-}band} - 36 + 10 \log ((1))$$

The level of (4) determines the required attenuation in the case of the spurious limit:

$$(6) = (4) - (5) + (3)_{out\text{-}of\text{-}band} - 162$$

It was assumed that the satellite antenna gains at the frequencies of the passive allocation are the same as at the operating frequencies of the satellite allocation (i.e. $(3)_{in\text{-}band} = (3)_{out\text{-}of\text{-}band}$ with the notations used below). One should keep in mind that this corresponds to a worst case.

The passive band is used for both spectral line and continuum observations. Spectral line observations are made using a channel bandwidth (one of the spectrometer channels) of (typically) 20 kHz, the threshold pfd is then –196 dB(W/m^2). This protection criteria needs to be compared with the following values:

$$-162.4 + 10 \log((20/4)) = -155.4 \text{ dB(W/(m}^2 \cdot 20 \text{ kHz))}$$

and with:

$$-171.4 + 10\log((20/4)) = -164.4 \text{ dB(W/(m}^2 \cdot 20 \text{ kHz))}$$

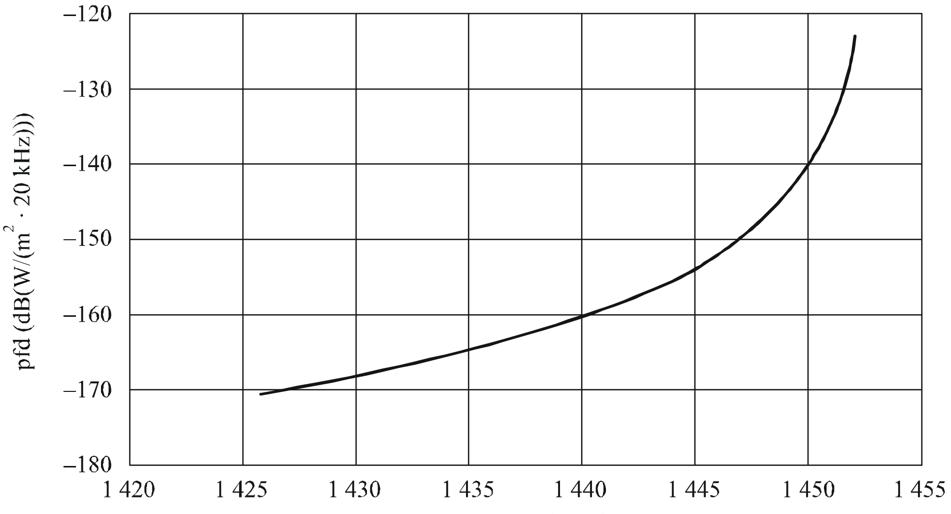
It means that at the end of the OoB domain, the discrepancy between the protection criteria and the spurious limit is of the order of 40 dB. Since the end of the OoB domain occurs at 1 448.928 MHz and the RAS allocated band starts at 1 427 MHz (more than 10 times the necessary bandwidth), it is likely that at the beginning of the RAS band, the discrepancy between the level of spurious emissions and the protection criteria will be significantly lower.

In particular, if we make the assumption that the decrease of the signal, within the spurious domain, will follow the new OoB mask as developed for BSS system (see Recommendation ITU-R SM.1541), then the attenuation will be given by:

$$32\log\left(\frac{F}{50}+1\right) \qquad \text{dBsd}$$

FIGURE 36

pfd level integrated over 20 kHz depending on the frequency



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In such a case the discrepancy at the edge of the RAS allocation is about 25 dB (about 20 dB in case of Digital System DS). This remaining interference would have to be avoided by additional mitigation technique (geographical isolation and filtering).

8.4.3.2 VLBI observations

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, –166 dB(W/m^2), for a bandwidth of 20 kHz.

According to the calculation conducted in § 8.4.3.1, the VLBI protection criteria are likely to be met.

8.4.3.3 Continuum observations

For making single-dish continuum observations, the whole 27 MHz width of the band is used, for which case the threshold pfd limit for detrimental interference is –180 dB(W/m^2).

Taking into account the two systems given in Table 20, the maximum in band pfd level is:

$$-128 + 10\log_{10}(1.536 \text{ MHz}/4 \text{ kHz}) = -102 \text{ dB(W/(m}^2 \cdot 1.536 \text{ MHz}/4 \text{ kHz))}$$

If this system follows the same decrease of the signal than the one proposed by Radiocommunication Working Party 4A in Document 1-7/149, then the rejection between the in-band power and the power integrated over 27 MHz will be higher than 80 dB. This means that the continuum observation protection criteria will be met. This also confirms that the VLBI protection criteria will be met.

8.5 Mitigation techniques

8.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for G/T, i.e. telescope gain divided by system temperature. This is to maximize the S/N for point sources. A key element of this approach is to reduce ground radiation entering through far side lobes. Inevitably this leads to some corresponding increase in the levels of near side-lobes. Experience has shown that the majority of radio telescopes meets the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

8.5.2 BSS

This service involves continuous transmission of signals continually or for long periods of time, with constant power and spectrum. Possible mitigation procedures are to avoid transmitting unwanted emissions in the direction of the radio astronomy stations that use this band, or to use filters to appropriately suppress unwanted emissions to a level where detrimental interference to radio astronomical observations in the 1 400-1 427 MHz is not caused.

8.5.3 Potential impact

8.5.3.1 RAS

Antenna side-lobe performance: Attempts to decrease the sensitivity of the radio astronomy antenna to unwanted emissions coming from space stations are likely to increase the sensitivity of the radio astronomy telescope to ground radiation, and possibly reduce its main beam gain. Both of these effects will reduce the telescope’s channel capacity of and thus lead to an increase of the total required integration time.

Blanking in time and/or frequency: Blanking involves a risk of compromising the integrity of the data and may lead to errors in their scientific interpretation. Blanking also causes a concomitant increase in the total integration time required to make the observation, this is equivalent to a loss in the channel capacity of the telescope.

8.5.3.2 BSS

Filters are an obvious way to suppress unwanted emissions, but the addition of such filters may affect the satellite design in a substantial manner. If a phased array active antenna is used, filters may be required for every driven antenna element. This will increase the weight of the satellite. Compensating for filter losses will require more powerful transmitters, which in turn will require more bus power, and so, larger solar power arrays. The increase in weight could be sufficient to require a larger launcher. The cost impact could be large. Consequently, the implementation of filters can be considered only at the design stage of a system. However, continuing technical improvements in the design of filters and active antennas may in time reduce the problem of implementing such solutions to manageable proportions.

8.6 Results of studies

8.6.1 Summary

The calculations provided in the previous section address compatibility between GSO BSS systems operating in the band 1 400-1 427 MHz and the RAS operating in the band 1 400-1 427 MHz. Further studies will be needed to address the case of non-GSO systems.

The calculations provided in the above sections show that BSS systems will meet the protection criteria of VLBI and continuum observations, as discussed in § 8.1.3. However, to meet the spectral line protection criteria, it is likely that mitigation techniques such as filtering would have to be implemented. Taking into account the fact that the existing guardband between the RAS and the BSS allocated bands is large compared to necessary bandwidth used by BSS systems, it is expected that the RAS protection criteria are technically achievable by using mitigation techniques such as filtering and geographical isolation. It should be noted that the economic impact of implementing such techniques is significant.

8.6.2 Conclusions

The protection criteria for radio astronomical observations in this band can be met for continuum and VLBI observations, and for spectral line observations when appropriate mitigation techniques are used.

9 Compatibility analysis between the RAS in the 1 400-1 427 MHz band and GSO mobile-satellite systems (space-to-Earth) operating in the 1 525-1 559 MHz band

9.1 RAS

9.1.1 Allocated band

The 1 400-1 427 MHz band is allocated to passive services only, on a primary basis: the RAS, the EESS (passive) and the SRS (passive). This Section discusses the radio astronomy case only.

RR No. 5.340 prohibits all emissions in this band.

9.1.2 Type of observations

The 1 400-1 427 MHz band is used more intensely than any other, in all ITU-R Regions. The main radio-astronomical use of band is to make spectral line observations of cosmic neutral atomic hydrogen (also referred to as HI), which has a rest frequency of 1 420.406 MHz. This material is by far the main constituent of our Galaxy and other galaxies, and occurs in huge, complex-structured clouds. This line is observed in both emission and absorption, and is broadened and shifted in frequency by Doppler shifts due to local and bulk motions in the cloud structures. Accordingly, HI observations can be used to map the distribution of material and its motions in our and other galaxies. In this way we can map the structure of our Galaxy, and how material is moving.

The 1 400-1 427 MHz allocation is sufficiently broad to encompass the Doppler-shifted emission from clouds in our galaxy and in nearby galaxies. Measurements of the polarization of the HI emission or absorption yield important information on galactic magnetic fields and thence an increased understanding of galactic structure.

The 1 400-1 427 MHz band is also used for continuum observations of broadband emissions produced by hot plasma formed when stars heat the surrounding clouds, and by the interaction of high-energy electrons in the galactic magnetic field (synchrotron emission).

9.1.3 Required protection criteria

The threshold interference levels for detrimental interference to radio astronomical observations are given in Recommendation ITU-R RA.769, which lists the levels of unwanted emissions that will increase the measurement error by 10%. The band is used for both spectral line and continuum observations. In the 1 400-1 427 MHz band, for single-dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 20 kHz, the threshold pfd for detrimental interference is –196 dB(W/m^2). For making single-dish continuum observations, the entire 27 MHz width of the band is used, for which case the threshold pfd for detrimental interference is -180 dB(W/m^2).

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, -166 dB(W/m^2), for a bandwidth of 20 kHz.

The thresholds of detrimental interference levels to the RAS as defined and calculated in the Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes 10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

9.1.4 Operational characteristics, type of observations

The 1 400-1 427 MHz band is the most intensely used radio astronomy band of all. It is used worldwide, in all ITU Regions, and some radio telescopes, such as the Synthesis Radio Telescope at the DRAO, Penticton, Canada, observe full-time in this band. Single-antenna radio telescopes are used to measure the integrated spfd of sources of small angular diameter and to map structures of large angular size that cannot be mapped using synthesis telescopes.

The higher angular resolution offered by synthesis telescopes makes it possible to map the finer structure in the hydrogen clouds and sources of continuum emissions such as supernova remnants. These maps are then combined with the lower-resolution maps obtained using single-antenna radio telescopes to make high-quality 3-D images of our Galaxy and others. Synthesis radio telescopes, using multi-antenna arrays may require between one and a dozen 12 h “exposures” to make a complete map of an area of sky.

In order to facilitate mapping comparatively large source structures, some synthesis radio telescopes, such as the DRAO instrument, use arrays of comparatively small antennas. Instruments of this kind do not have the option of optimum side-lobe suppression and are therefore more vulnerable to interference.

Spectral line observations are made using multichannel spectrometers that can integrate simultaneously the power in many (typically 256 to 4 096) frequency channels distributed across the band. The number of channels and their individual bandwidths are chosen to adequately sample the spectrum of the net emission from the hydrogen cloud(s) in the antenna beam.

In general, observations are made differentially. In the case of continuum emissions, the area of sky surrounding the sky may be mapped, and the background emission subtracted, or measurements made of the power coming from the direction from the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

In the case of spectral line observations, spectra are recorded at frequency ranges including the line emissions of interest (the line spectra), and then at a frequency that is offset from the line emissions, or at the same frequency but at a nearby position in the sky (the reference spectra). By subtracting the reference spectra from the line spectra, unwanted noise contributions and other contaminants can be removed from the data.

Since the Galaxy is filled with clouds of neutral hydrogen, radio telescopes detect not only the emission or absorption in the clouds in the antenna main beam, but also a very significant contribution through the antenna side-lobes. This “stray radiation” distorts spectra and reduces map detail. Removing this from the data involves large-scale measurement of the whole antenna beam (as far as possible), and estimation of the stray radiation correction. Interference and large “blocked” areas of sky will therefore affect the ability to make maps at parts of the sky large angles from interference sources.

An extended area of radio emission can be mapped by recording the emission from a grid of points covering the region of interest. Both continuum and spectral line observations may be made. In the case of single antenna radio telescopes, each grid point observation is an indication of the total power (in the continuum case) or the emission spectrum (in the spectral line case) coming from that position in the sky; the spacing between the grid points should not be more than half the antenna beamwidth. When observations are made using a synthesis radio telescope, where the area to be mapped exceeds the instantaneous mapping field, the grid points should not be further apart than half the beamwidth of one of the radio telescope antennas.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data has been processed.

9.2 MSS

9.2.1 Allocated transmit band

The allocated transmit band is 1 525-1 559 MHz (space-to-Earth).

9.2.2 Application

MSS.

9.2.3 Levels based on regulatory provisions

The required attenuation is $43 + 10 \log P$ dBc or 60 dBc whichever is less stringent where P is the peak power at the input to the antenna (W) in any 4 kHz.

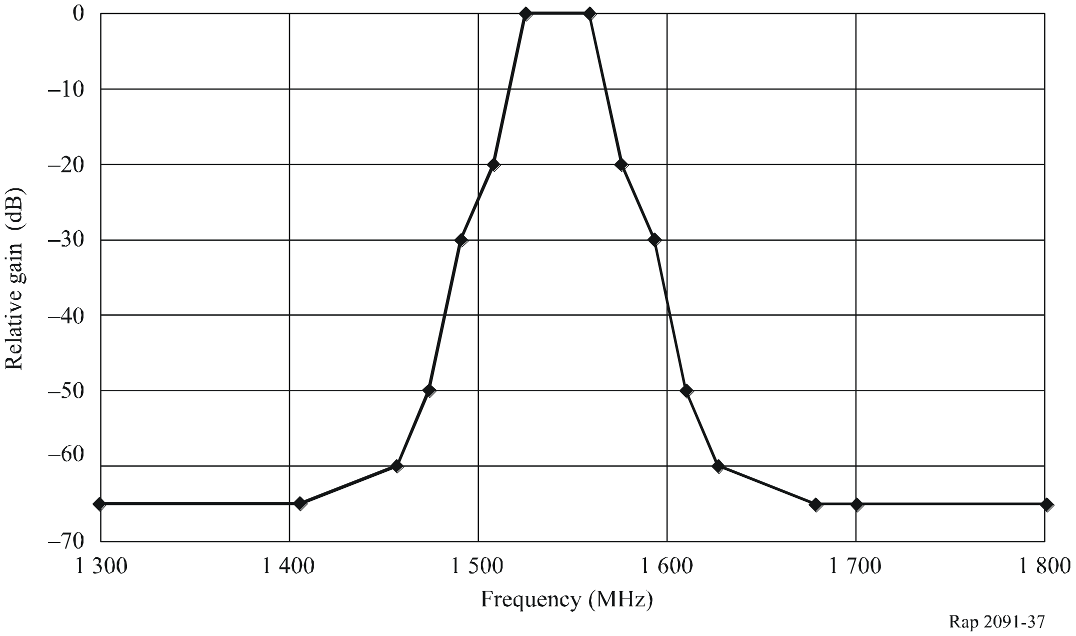
9.2.4 Transmitter characteristics

The antenna gain is 41 dBi.

The transmitter (Tx) output filter characteristic is shown in Fig. 37.

FIGURE 37

Tx output filter characteristics



9.2.5 Operational characteristics

The typical peak power into GSO MSS satellite spot beam at input to the antenna is 16 dBW over a bandwidth of 5 MHz.

9.2.6 In-band transmit level

The in-band transmit level is –15 dBW in a 4 kHz bandwidth.

9.3 Compatibility threshold

See § 9.1.3.

9.4 Interference assessment

9.4.1 Methodology used to assess the interference level

The parameters peak in band power spectral density, the peak antenna gain and the measured attenuation of the Tx output filter at different frequencies are used to determine the pfd at the surface of the Earth.

9.4.2 Calculation of interference level

Based on the expected performance of the Tx filter used for the 1 525-1 559 MHz band, the typical power levels at the output of this filter, e.i.r.p. density levels at the antenna output and the pfd at the surface of the Earth at different frequencies are as shown in Table 23.

TABLE 23

Expected values of the power spectral density (PSD), e.i.r.p. density and pfd at the surface of the Earth of Inmarsat-4 satellite

Frequency (MHz)	PSD at the output of filter (dB(W/4 kHz))	e.i.r.p. density at the output of the antenna (dB(W/4 kHz))	pfd at the surface of the Earth (dB(W/(m^2 · 4 kHz)))
1 300	–80	–39	–202
1 406	–80	–39	–202
1 457	–75	–24	–197
1 474	–65	–14	–187
1 491	–45	–4	–167
1 508	–35	6	–157
1 525	–15	26	–137
1 559	–15	26	–137
1 576	–35	6	–157
1 593	–45	–4	–167
1 610	–65	–14	–187
1 627	–75	–24	–197
1 678	–80	–39	–202
1 700	–80	–39	–202
1 800	–80	–39	–202

9.4.3 Values achieved

The value is –202 dB(W/m^2) in a 4 kHz bandwidth.

Translating these values for the continuum and spectral line observations, we obtain the following values:

- for single-dish continuum observations: –163 dB(W/m^2) in a 27 MHz bandwidth;
- for single-dish spectral line observations: –195 dB(W/m^2) in a 20 kHz bandwidth.

Based on the above parameters of one GSO mobile-satellite system of one operator the following margins/deficits are derived:

- for single-dish line observations there is a deficit of 1 dB in meeting the protection criterion given in Recommendation ITU-R RA.769;
- for single-dish continuum observations there is a deficit of 17 dB in meeting the protection criterion given in Recommendation ITU-R RA.769.

9.5 Mitigation techniques

9.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for *G*/*T*, i.e. telescope gain divided by system temperature. This is to maximize the *S*/*N* for point sources. A key element of this approach is to reduce ground radiation entering through far side-lobes. Inevitably this leads to some corresponding increase in the levels of near side-lobes.

Experience has shown that the majority of radio telescopes meets the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

9.5.2 MSS

In order to improve the levels given in Table 23, the following mitigation techniques should be taken into account in the design of new space station:

- the wideband frequency response of the antenna;
- the attenuation characteristics of intermediate filters;
- the gain frequency response of solid state power amplifiers;
- the modulation characteristics of individual carriers;
- the attenuation of inter-modulation products with respect to the power of the carriers.

9.5.3 Potential impact for MSS

The mitigation techniques in § 9.5.2 are deemed technically feasible for GSO systems.

9.6 Results of studies

9.6.1 Summary

Based on the parameters of one GSO mobile-satellite system of one operator and taking into account the mitigation factors listed in § 9.5.2, it is very likely that the unwanted emission levels from this satellite system meet the threshold levels for detrimental interference to single-dish radio astronomical observations as discussed in § 9.1.3.

9.6.2 Conclusions

The protection criteria are likely to be met for continuum, VLBI and spectral lines observations, with the use of appropriate mitigation measures.

10 Compatibility analysis between RAS systems operating in the 1 610.6-1 613.8 MHz band and RNSS systems operating in the 1 559-1 610 MHz band

10.1 RAS

10.1.1 Allocated band

The 1 610.6-1 613.8 MHz band is allocated to the RAS on a primary basis.

RR No. 5.149 urges administrations to take all practicable steps to protect the RAS.

10.1.2 Type of observations

The 1 610.6-1 613.8 MHz band is used for spectral line observations of the hydroxyl radical (OH). The OH line, which has a rest frequency of 1 612 MHz, is one of the most important spectral lines for radio astronomy, and is listed as such in Recommendation ITU-R RA.314. OH was the first cosmic radical to be detected at radio frequencies (1963), and continues to be a powerful research tool. OH produces four spectral lines, at frequencies of approximately 1 612, 1 665, 1 667 and 1 720 MHz, all of which have been observed in our own galaxy, as well as in external galaxies. The study of OH lines provides information on a wide range of astronomical phenomena, e.g. the formation of protostars and the evolution of stars. To interpret most observations made in the OH lines, it is necessary to measure the relative strength of several of these lines. Loss of the ability to observe any one of these lines may prevent the study of some classes of physical phenomena.

These OH lines are produced by a coherent process, in which a concentration of OH radicals radiate "in step", creating narrow-band emission. They are slightly broadened due to physical conditions in this concentration. Movement of these concentrations with respect to the Earth impose a Doppler shift on the line emission. The presence of several concentrations in the source, which are moving at different velocities, give rise to a more complicated spectrum, consisting of a number of superimposed Gaussian line profiles of different widths and amplitudes, and slightly-different frequencies (due to the different Doppler shifts). The width of the band allocation is required to accommodate the spreading and shifting of the spectrum by differential and total motions of the source.

In some stages of their evolution, certain classes of stars radiate only the 1 612 MHz line. The study of this line allows astronomers to gauge such physical properties of these stars as the rate at which gas is blown off by the stars and recycled into the interstellar medium. Some properties of these stars cannot be inferred from any other astronomical observation. Measurements of OH emitting stars have also been used to estimate the distance to the Galactic Centre, to measure the mass of the central bulge of our galaxy, and to study the spatial distribution of the molecular component in our galaxy and in external galaxies. Finally, extremely strong maser emission has been detected near the nuclei of a number of external galaxies. This OH megamaser emission from galactic nuclei allows astronomers to study the temperature and density of the molecular gas in their centre.

The OH spectral line is also observed in comets; there is little flexibility in scheduling observations of these "targets of opportunity".

Spectral line observations are made using spectrometers that can simultaneously integrate the power in a large number of frequency channels (typically 256-4 096) distributed across the frequency band used. The width and number of channels has to be large enough to accurately reproduce the spectrum of the emission received by the radio telescope. Instantaneous bandwidths of typically ~0.2-20 kHz per frequency channel are used, depending on the scientific program.

The sources are small, and measurements of their size and structure often require observations using the VLBI technique.

10.1.3 Required protection criteria

Recommendation ITU-R RA.769 specifies the protection criteria for radio astronomical observations and gives threshold levels of detrimental interference for primary radio astronomy bands. In the 1 610.6-1 613.8 MHz band, for single-dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 20 kHz, the threshold pfd limit is –194 dB(W/m^2). This band is used only for radio line observations, not for continuum observations.

For detrimental interference from non-GSO systems, the protection criteria and the relevant methodologies are described in Recommendations ITU-R RA.769 and ITU-R RA.1513, as well as in Recommendation ITU-R S.1586 for FSS systems and in Recommendation ITU-R M.1583 for MSS and RNSS systems.

The thresholds of detrimental interference levels to the RAS as defined and calculated in the Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes

10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

10.1.4 Operational characteristics

Observations in the 1 612 MHz band are carried out at a number of radio astronomy sites in numerous countries, worldwide. Observations in the 1 612 MHz band are sometimes conducted on targets of opportunity, e.g. on objects such as comets, which have been observed to produce transient emissions in this line. VLBI observations are also frequently conducted in this band, sometimes between the North American and European VLBI networks.

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, −166 dB(W/m^2), for a bandwidth of 20 kHz, which has been developed for VLBI observations, but not included in Recomendation ITU-R RA.769.

Spectral line observations are made using multichannel spectrometers that can integrate simultaneously the power in many (typically 256 to 4 096) frequency channels distributed across the band. The number of channels and their individual bandwidths are chosen to adequately sample the spectrum of the net emission from the source(s) in the antenna beam.

In general, observations are made differentially; spectra are recorded at frequency ranges including the line emissions of interest (the line spectra), and then at a frequency that is offset from the line emissions, or at the same frequency but at a nearby position in the sky (the reference spectra). By subtracting the reference spectra from the line spectra, unwanted noise contributions and other contaminants can be removed from the data.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data have been processed.

10.2 RNSS

10.2.1 Allocated transmit band

The band 1 559-1 610 MHz is allocated to the RNSS for transmissions from space to Earth.

10.2.2 Application

Radio navigation satellite systems, which are low power signals compared to most satellite system, are used for position estimation and timing by users, including radio astronomers and space-based passive systems. Therefore both services are intertwined. There are two main types of RNSS systems: non-GSO and GSO. GSO systems are primarily used for aviation navigation. Non-GSO systems are used throughout the world and by multiple administrations for navigation, position estimation, precise timing, and search and rescue.

10.2.3 Levels based upon regulatory provisions

There are no hard limits or threshold values listed in the Radio Regulations applicable to RNSS in the band 1 559-1 610 MHz.

10.2.4 Operational characteristics

10.2.4.1 GALILEO

10.2.4.1.1 Orbital characteristics

GALILEO orbital characteristics used for simulation are given in Table 24 hereafter:

TABLE 24

GALILEO constellation parameters

Parameter	Value
Number of satellites	27
Number of planes	3
Inclination	56
Altitude (km)	23 616

The orbital parameters of each satellite of the constellation are given in Table 25 below.

TABLE 25

GALILEO constellation parameters

Satellite number	Right ascension of the ascending node	True anomaly
1	0	0
2	0	40
3	0	80
4	0	120
5	0	160
6	0	200
7	0	240
8	0	280
9	0	320
10	120	13.33
11	120	53.33
12	120	93.33
13	120	133.33
14	120	173.33
15	120	213.33
16	120	253.33
17	120	293.33
18	120	333.33
19	240	26.66
20	240	66.66
21	240	106.66
22	240	146.66
23	240	186.66
24	240	226.66
25	240	266.66
26	240	306.66
27	240	346.66

10.2.4.1.2 Unwanted emissions of GALILEO satellites

Table 26 gives the level of unwanted emissions produced by GALILEO in the radio astronomy band 1 610.6-1 613.8 MHz.

TABLE 26

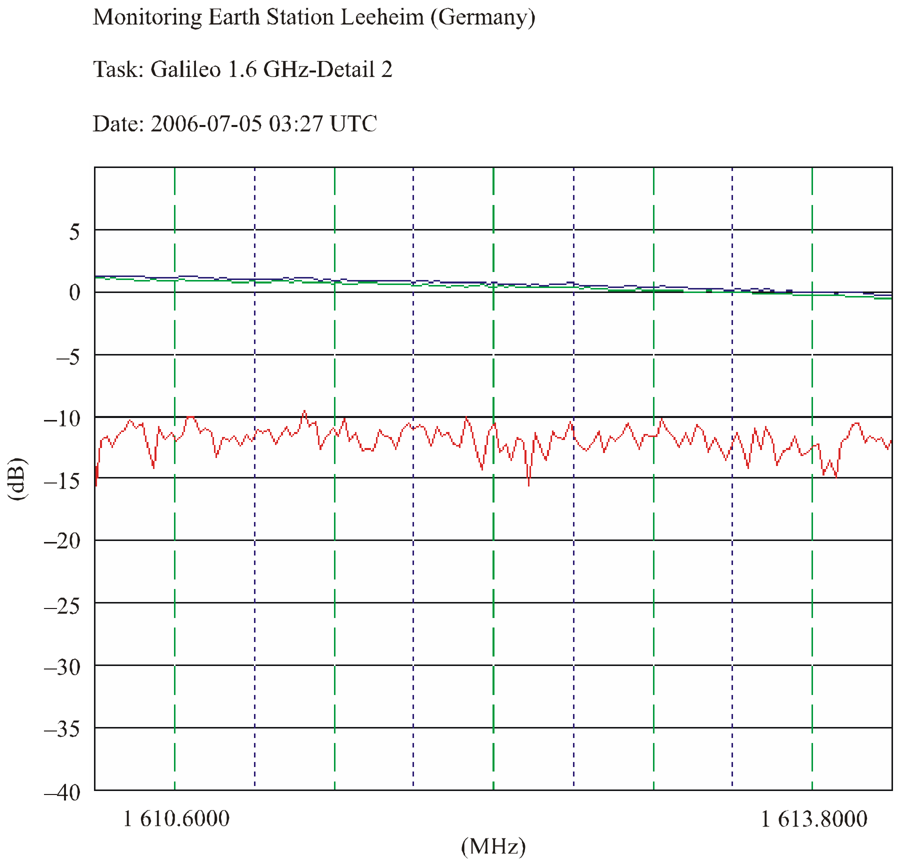
GALILEO unwanted emissions

Parameter	Value
e.i.r.p. spectral density (dB(W/kHz))	−68.5
Altitude (km)	23.616
spfd (dB(W/(m^2 · kHz)))	−227
pfd(dBW/(m^2 · 20 kHz)))	−214

Figure 38 shows the measurement results of GALILEO OoB emission in the RAS band made by Leeheim monitoring earth station. Current measurements can not indicate the level of out of band emissions, due to the limited sensitivity of the measurement station. The red line indicates the system sensitivity of around –191 dB(W/m^2) in a 20 kHz bandwidth.

FIGURE 38

Measured OoB emission levels of an experimental GALILEO satellite over the frequency range 1610.6 to 1613.8 MHz



Monitoring Earth Station Leeheim (Germany)

Task: Galileo 1.6 GHz-Detail 2

Date: 2006-07-05 03:27 UTC

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In Fig. 38 the blue curve (upper curve) indicates the measured emissions of the experimental Galileo satellite+clear-sky noise, the green curve (middle curve) indicates the clear-sky noise level, and the red curve (lowest curve) shows the difference between the blue and the green curve.

10.2.4.2 GPS

10.2.4.2.1 Orbital characteristics

GPS orbital characteristics used for simulation are given in Table 27 hereafter:

TABLE 27

GPS constellation

Parameter	Value
Number of satellites	24
Number of planes	6
Inclination	55
Altitude (km)	20 200

The orbital parameters of each satellite of the constellation are given in Table 28.

TABLE 28

GPS constellation parameters

Satellite	Right ascension of the ascending node	True anomaly
1	272.847	11.676
2	272.847	41.806
3	272.847	161.786
4	272.847	268.126
5	332.847	80.956
6	332.847	173.336
7	332.847	204.376
8	332.847	309.976
9	32.847	11.876
10	32.847	241.556
11	32.847	339.666
12	32.847	11.796
13	92.847	135.226
14	92.847	167.356
15	92.847	265.446
16	92.847	35.156
17	92.847	197.046
18	152.847	302.596
19	152.847	333.686
20	152.847	66.066
21	212.847	238.886
22	212.847	345.226
23	212.847	105.206
24	212.847	135.346

10.2.4.2.2 Unwanted emissions of GPS satellites

Beginning in early 1989 the first full-scale operational GPS satellites were designed with enhanced frequency synthesis techniques, which provided additional filtering through the use of an optimized L-band triplexer. This optimized filtering capability has been added to all Block II/IIA and subsequent satellites including Block IIR and IIR-M satellites to minimize unwanted emissions. The current triplexer is a contiguous 6-pole Chebychev filter and is applied to the emissions of both the L1 and L2 frequencies. The Block IIF series of modernized GPS spacecraft will use a quadruplexer design to incorporate the new L5 civil signal and will provide similar performance.

The unwanted emissions of the GPS satellites have an output flux density that is no greater than −258 dB(W/($m^2 \cdot$ Hz)) in the 1 610.6-1 613.8 MHz band. This value is explained in the link budget below, in Table 29.

TABLE 29

GPS unwanted emission characteristics

	Parameters	**Value**
1	Maximum OoB emission specification (dB(W/Hz))	−110
2	Worst case OoB emission level (from manufacturer) (dB(W/Hz))	−113
3	λΛ(c/1 612 MHz) (m)	0.19
4	Effective Rx. Antenna aperture ($\lambda^2/4\pi$) (dBm^2)	−25.4
5	D = distance from satellite to Rz antenna(m)	2.02E+7
6	Path loss ($\lambda^2/((d*4\pi)^2 2)$) (dB)	−182.7
7	Transmitter antenna gain (dB)	12
8	Received pfd(Row 2 − Row 4 + Row 6 + Row 7) (dB(W/($m^2 \cdot$ Hz)))	−258.3
9	Received pfd (dB(W/($m^2 \cdot$ 20 kHz)))	−215.3

10.2.4.3 Quasi Zenith Satellite System (QZSS)

10.2.4.3.1 Orbital characteristics

QZSS orbital characteristics used for simulation are given in Table 30 hereafter:

TABLE 30

QZSS constellation parameters

Parameter	**Value**
Number of satellites	3
Number of planes	3
Inclination (degrees)	45
Altitude of apogee (km)	39 970
Altitude of perigee (km)	31 602
Argument of perigee (degrees)	270

The orbital parameters of each satellite of the constellation are given in Table 31.

TABLE 31

QZSS constellation parameters (Epoch of 0:00 1 January 2000)

Satellite number	**Right ascension of the ascending node (degrees)**	**True anomaly (degrees)**
1	205	129.21
2	325	0
3	85	230.49

10.2.4.3.2 Unwanted emissions of QZSS satellites

Table 32 gives the level of unwanted emissions produced by QZSS in the radio astronomy band 1 610.6-1 613.8 MHz.

TABLE 32

QZSS unwanted emissions

Parameter	**Value**
e.i.r.p. spectral density (dB(W/Hz))	–86.9
minimum distance from satellite to the surface of the Earth (km)	31 602
spfd (dB(W/(m^2 · kHz)))	–218
pfd (dB(W/(m^2 · 20 kHz)))	–205

10.2.4.4 GLONASS

10.2.4.4.1 Orbital characteristics

GLONASS orbital characteristics used for the simulations are given in Table 33.

TABLE 33

GLONASS constellation parameters

Parameter	**Value**
Number of satellites	24
Number of planes	3
Inclination (degrees)	64.8
Altitude (km)	19 100

The orbital parameters of each satellite of the constellation are given in Table 34.

TABLE 34

GLONASS constellation orbital parameters

Satellite	**Right ascension of the ascending node (degrees)**	**True anomaly (degrees)**
1	0	0
2	0	45
3	0	90
4	0	135
5	0	180
6	0	225
7	0	270
8	0	315
9	120	0
10	120	45
11	120	90
12	120	135
13	120	180
14	120	225
15	120	270
16	120	315
17	240	0
18	240	45
19	240	90
20	240	135
21	240	180
22	240	225
23	240	270
24	240	315

10.2.4.4.2 Unwanted emissions of GLONASS satellites

The levels of the unwanted emissions of the GLONASS system into the 1 610.6-1 613.8 MHz radio astronomy band have been reduced over the years (see § 10.5.2). The measures taken to reduce the unwanted emission levels include:

a) Changing the GLONASS frequency band:

  - From 1998 through 2005: GLONASS satellites in service used frequency numbers $k = 0 ... 12$ (see Table 35) without any limitations. Frequency number $k = 13$ was used for test purposes.
  - After the year 2005: All GLONASS satellites in service use frequency numbers $k = (–7, ..., +6)$ (see Table 35).

Thus the frequency plan of the system has been modified resulting in the transfer of GLONASS fundamental emissions to the frequency band below 1 610.6-1 613.8 MHz.

TABLE 35

Distribution of carrier frequencies in GLONASS system in the frequency range 1.6 GHz

Frequency No. ***k***	**Carrier frequencies in L1 sub-band (MHz)**	**Frequency No.** ***k***	**Nominal carrier frequencies in L1 sub-band (MHz)**
13	1 609.3125	02	1 603.125
12	1 608.75	01	1 602.5625
11	1 608.1875	00	1 602.0
10	1 607.625	–01	1 601.4375
09	1 607.0625	–02	1 600.8750
08	1 606.5	–03	1 600.3125
07	1 605.9375	–04	1 599.7500
06	1 605.375	–05	1 599.1875
05	1 604.8125	–06	1 598.6250
04	1 604.25	–07	1 598.0625
03	1 603.6875		

b) Filtering: all GLONASS satellites placed in service after the end of the year 2005 are equipped with filters that suppress the satellite out-of-band emissions in the frequency band 1 610.6-1 613.8 MHz substantially, and in the band 1 660.0-1 670.0 MHz down to the level indicated in Recommendation ITU-R RA.769 (value per satellite).

The calculated relative suppression of GLONASS unwanted emissions due to these filters is shown in Table 36.

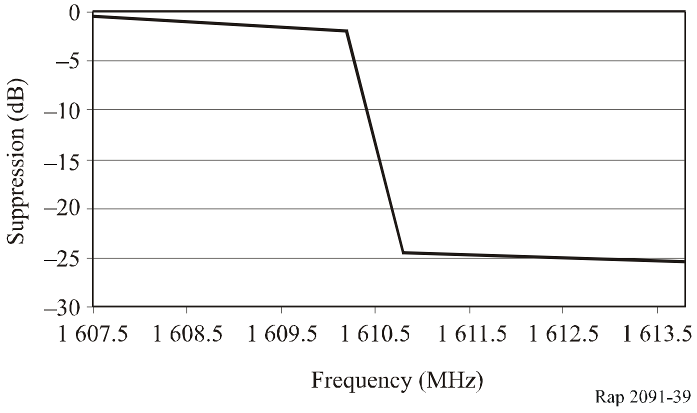
TABLE 36

Calculated suppression of GLONASS satellite emissions due to filters

Frequency (MHz)	**Suppression (dB)**
1 607.5	–0.5
1 610.2	–2
1 610.8	–24.5
1 613.8	–25.5

FIGURE 39

Calculated suppression characteristics of GLONASS satellite emissions due to filters in the band 1 610.6-1 613.8 MHz



These are the design characteristics of the new GLONASS satellite generation, including a filter that was implemented on one of the satellites launched in late 2003. Observations show that up to 19 dB of attenuation have been obtained. This attenuation is not sufficient to reach the Recommendation ITU-R RA.769 detrimental threshold level specified for the 1 610.6-1 613.8 MHz band.

Simulation of signals emitted by each GLONASS satellite in the 1.6 GHz range on frequency nominals from $k = -5$ to $k = 6$ as well as simulation of filter characteristics in accordance with the method below was carried out.

$$PFD(\beta_i) = L_F(f_c) + P_{si} + G_t(\theta_i) - L(\beta_i)$$

where:

$PFD(\beta_i)$: pfd emitted by i-th GLONASS satellite as a function of elevation angle β, dB(W/m^2) in a reference frequency band Δf

$L_F(f_c)$: attenuation of a filter mounted on GLONASS space station (see Fig. 39), (dB)

P_{si}: total power from navigation signal emitted by i-th GLONASS satellite, dBW in a reference frequency band Δf(dBw)

$G_t(\theta_i)$: antenna gain of GLONASS space station transmitting as a function of angle θ (dBi)

θ_i: angle between the main axis of GLONASS transmitting space station antenna and reception direction point at the Earth’s surface (degrees)

$L(\beta_i)$: spreading loss as a function of elevation angle β (dB/m^2)

β_i: GLONASS space station elevation angle at the reception point at the Earth’s surface (degrees)

N: number of GLONASS satellites in a constellation

i: index of a GLONASS satellite under consideration (1, 2 … N)

Δf: measurement reference frequency band (Hz)

f_c: central frequency of a measurement reference frequency band □ Δf (Hz).

Total power P_{si} from navigation signal emitted by i-th GLONASS satellite, dBW in a reference frequency band Δf is determined from the equation:

$$P_{si} = 10 \log 10 \left(PD \cdot \int_{-\frac{\Delta f}{2}}^{\frac{\Delta f}{2}} S_i(f) \mathrm{d}f \right)$$

$$S_i(f) = \frac{\sin \left[|f - (fx_i - fc)| \, \pi \cdot \frac{1}{fe} \right]^2}{\left[|f - (fx_i - fc)| \, \pi \cdot \frac{1}{fe} \right]^2}$$

where:

P_{si}:	total power from navigation signal emitted by i-th GLONASS satellite, in a reference frequency band Δf (dBW)
PD:	maximum spectral power density level of navigation signal (W/Hz)
$S_i(f)$:	spectral characteristic of navigation signal generated by i-th transmitting station
f:	current frequency (Hz)
fx_i:	carrier frequency of i-th GLONASS satellite (Hz)
f_c:	central frequency of a measurement reference frequency band Δf (Hz)
f_e:	−3 dB bandwidth of navigation signal (Hz)
Δf:	measurement reference frequency band (Hz).

In its turn the spreading loss $L(\beta_i)$ is determined from the equation:

$$L(\beta_i) = 10 \ \log 10 \left[4\pi (d(\beta_i))^2 \right]$$

$$d(\beta_i) = \sqrt{(H + R)^2 - \left(R \cos \left(\beta_i \cdot \frac{\pi}{180} \right) \right)^2} - R \sin \left(\beta_i \cdot \frac{\pi}{180} \right)$$

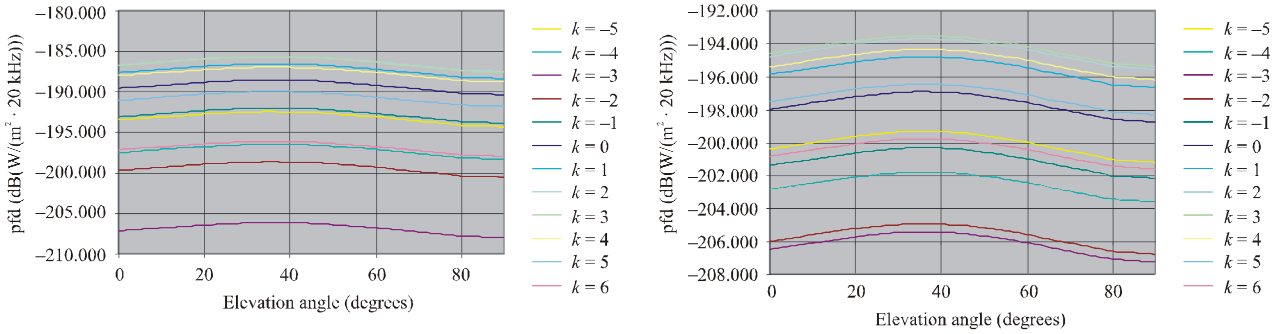
where:

$L(\beta_i)$:	spreading loss as a function of elevation angle β (dBm^2).
β_i:	GLONASS space station elevation angle at the reception point at the Earth's surface (degrees).
$d(\beta_i)$:	distance between transmitting space station and reception point at the Earth's surface as a function of elevation angle β (m).
H:	GLONASS space station orbit altitude over the Earth's surface (m).
R:	Earth's radius (m).

The pfd levels due to each GLONASS satellite (each carrier frequency) equipped by the above-mentioned filter were determined for all elevation angles of signal arrival for the three presented frequencies 1 610.6, 1 610.8 and 1 613.8 MHz, respectively (Fig. 40).

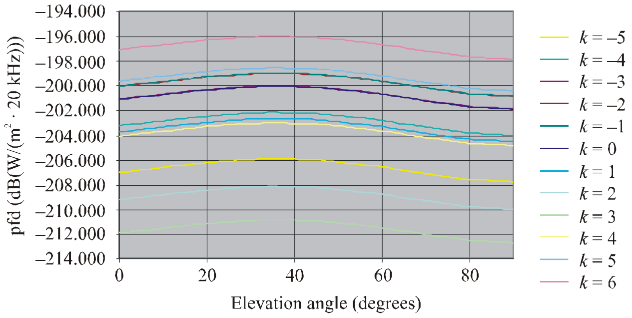
FIGURE 40

pfd levels for each GLONASS satellite (each carrier frequency)



a) at frequency 1 610.6 MHz

b) at frequency 1 610.8 MHz



c) at frequency 1 613.8 MHz

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For the epfd simulation, the pfd levels given in Table 37 were considered for each satellite of the constellation, for the worst-case frequency (1 610.6 MHz). This is an example of a frequency plan that does not necessarily reflect the actual frequency plan that may be used for the future GLONASS system. For simplification purposes, and since there are only small variations with elevation angle, the values are averaged over all elevation angles.

The OoB emissions characteristics of a new generation, filtered GLONASS satellite were recently measured at the Leeheim monitoring earth station. Figure 41 above shows the result of these measurements. The blue curve (upper curve) indicates the measured emissions of the GLONASS satellite + clear-sky noise, the green curve (middle curve) indicates the clear-sky noise level and the red curve (lowest curve) the difference between the blue and the green curve.

The measurements show that the modulation was improved between the old and new GLONASS satellites and that a filter was implemented in order to reduce the level of unwanted emissions by up to 19 dB in the 1 610.6-1 613.8 MHz RAS band. The filter implemented appears to be offset with regard to the centre of the 1 610.6-1 613.8 MHz band.

Implementation of the improved modulation resolves the existing problem with null spikes in the RAS band 1 660-1 670 MHz. The centre frequency of the GLONASS signal measured is 1 604.25 MHz, corresponding to the number $k = 4$ in Table 35. This frequency carrier is the operational channel closest to the RAS band. The pfd level measured at the frequency 1 610.6 MHz is around –173.8 dB(W/(m^2 · 20 kHz)).

Current measurements can not indicate the actual level of OoB emissions because the sensitivity of the monitoring station is not known and it is unsure whether the lowest pfd value measured at 1 613.8 MHz (–189 dB(W/(m^2 · 20 kHz))) corresponds to the emission of the GLONASS satellite or the noise of the monitoring station.

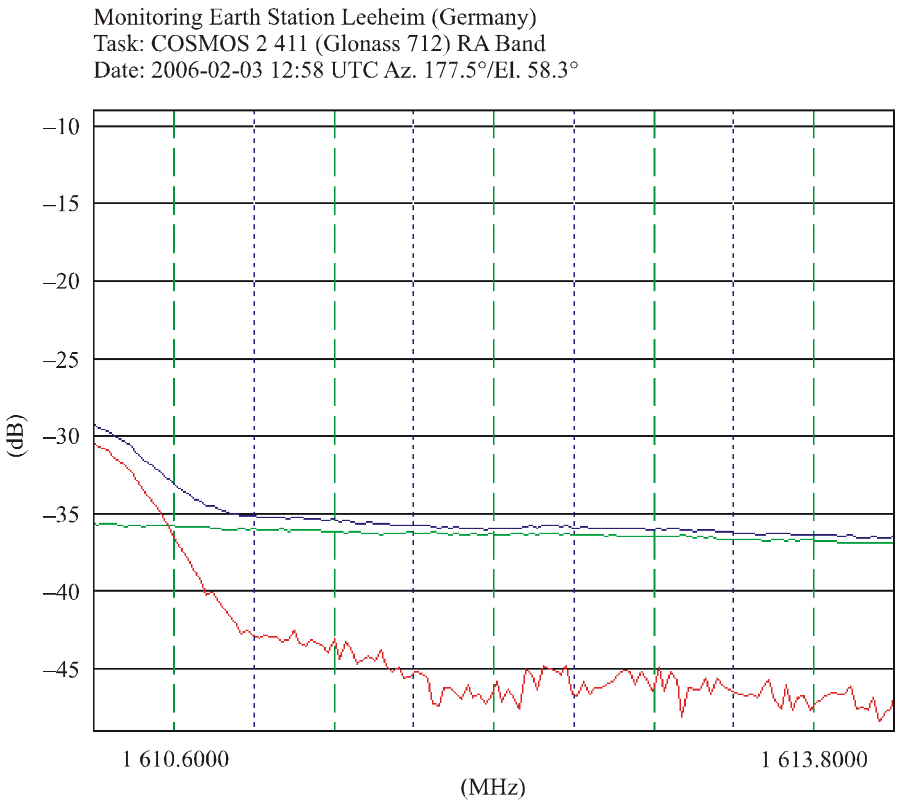
TABLE 37

GLONASS pfd levels per satellite

Satellite	**Carrier *k***	**pfd (dB(W/(m^2 · 20 kHz)))**		
		1 610.6 MHz	**1 610.8 MHz**	**1 613.8 MHz**
1	–5	–193	–200	–207
2	–4	–197	–203	–203
3	–3	–206	–206	–201
4	–2	–198	–206	–201
5	–1	–192	–201	–200
6	0	–188	–198	–201
7	1	–187	–197	–203
8	2	–186	–194	–209
9	3	–186	–194	–212
10	4	–187	–195	–204
11	5	–190	–197	–199
12	6	–197	–201	–197
13	–5	–193	–200	–207
14	–4	–197	–203	–203
15	–3	–206	–206	–201
16	–2	–198	–206	–201
17	–1	–192	–201	–200
18	0	–188	–198	–201
19	1	–187	–197	–203
20	2	–186	–194	–209
21	3	–186	–194	–212
22	4	–187	–195	–204
23	5	–190	–197	–199
24	6	–197	–201	–197

FIGURE 41

Measured OoB emission levels of a new generation GLONASS satellite over the frequency range 1610.6 to 1613.8 MHz



Monitoring Earth Station Leeheim (Germany)
Task: COSMOS 2 411 (Glonass 712) RA Band
Date: 2006-02-03 12:58 UTC Az. 177.5°/El. 58.3°

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10.3 Compatibility threshold

For the case of non-GSO constellations, an epfd threshold level of -258dB(W/m^2) may be derived for the band 1 610.6-1 613.8 MHz from the pfd threshold level for interference detrimental to radio astronomy observations given in Recommendation ITU-R RA.769 and the maximum radio astronomy antenna gain given in Recommendation ITU-R RA.1631, which is 64 dBi for this frequency band.

10.4 Interference assessment

10.4.1 Methodology used to assess the interference level

Recommendation ITU-R M.1583 provides a methodology to evaluate the levels of unwanted emissions produced by a non-geostationary-satellite system at radio astronomy sites. It is based on a division of the sky into cells of nearly equal solid angle and statistical analysis where the pointing direction of the RAS antenna and the starting time of the satellite constellation are the random variables. For each trial, the unwanted emission level (expressed in terms of epfd) is averaged over a 2 000 s period.

Regarding the simulation for GPS, GLONASS and GALILEO, the characteristics chosen correspond to the Effelsberg radio telescope in Germany which can observe in the considered bandwidth with an antenna diameter of 100 m and a maximum gain of approximately 64 dBi. The antenna pattern and maximum antenna gain are taken from Recommendation ITU-R RA.1631.

The geographical coordinates are:

Latitude: 50.7° N Longitude 7.0° E

Regarding the simulation for QZSS, the characteristics chosen correspond to the Kashima and Usuda radio telescope in Japan. The antenna pattern and maximum antenna gain of 64 dBi are taken from Recommendation ITU-R RA.1631.

The geographical coordinates of Kashima radio telescope are:

Latitude: 35.95° N	Longitude: 140.67° E

The geographical coordinates of Usuda radio telescope are:

Latitude: 36.12° N	Longitude: 138.35° E

Simulations were performed considering a minimum elevation angle of 0°of the telescope in order to get completely general results.

For the GLONASS case, the pfd radiated in the radio astronomy band may vary from one satellite to the other as each satellite may use a different carrier.

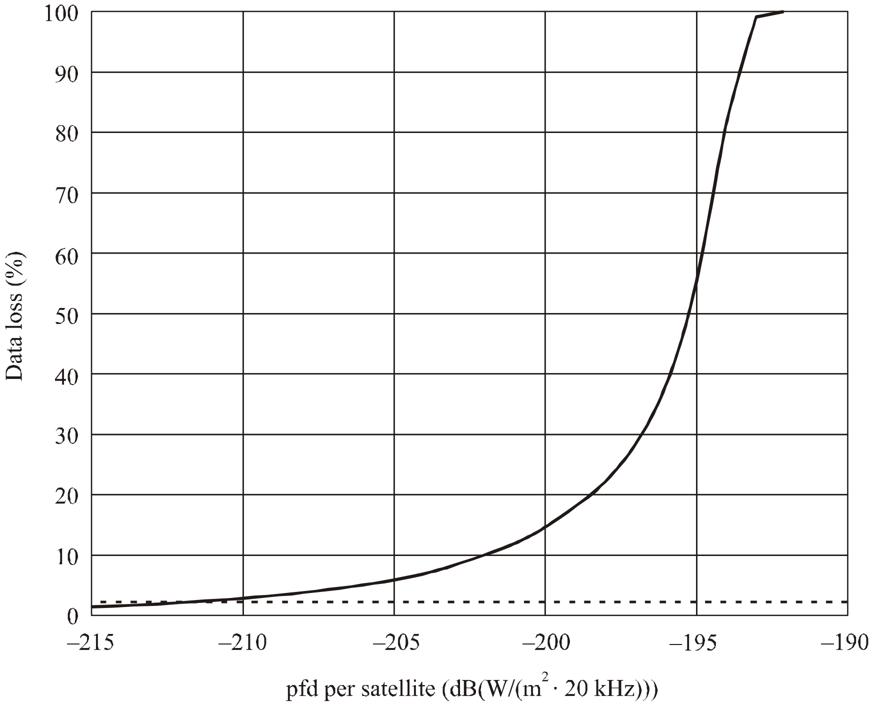
10.4.2 Calculation of the interference level

10.4.2.1 GALILEO

Figure 42 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value generated per GALILEO satellite (as explained in Recommendation ITU-R RA.1513, exceeding this threshold is equivalent to data loss).

FIGURE 42

Percentage of data loss vs. pfd per satellite (GALILEO)



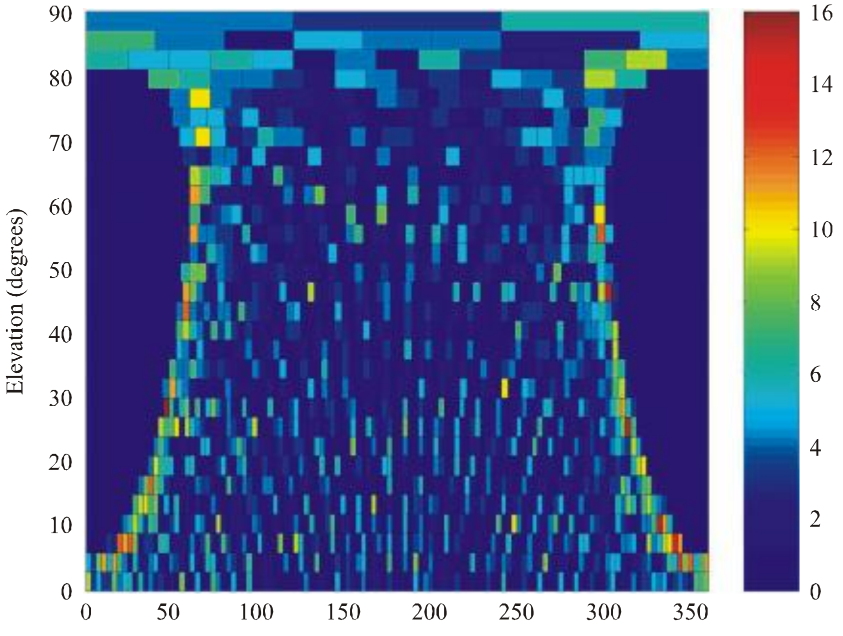
To meet the epfd threshold level during more that 98% of the time in average over the whole sky, each GALILEO satellite should generate a pfd of less than −212 dB(W/(m^2 · 20 kHz)) in the radio astronomy band.

Figure 43 shows for each cell of the sky, and for the pfd (per satellite) of –212 dB(W/(m^2 · 20 kHz)), the percentage of time where the epfd threshold is exceeded. One can see that it never exceeds 14% per cell, and therefore it never causes any sky blockage in any part of the sky.

In Figs. 43, 45, 47, 49 and 50, 0° azimuth is due North, and azimuth increases from West to East.

FIGURE 43

Percentage of data loss over the sky for the pfd of –212 dB(W/(m^2 · 20 kHz)) (GALILEO)



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10.4.2.2 GPS

Figure 44 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value generated per GPS satellite.

To meet the epfd threshold level during more than 98% of the time in average over the whole sky, each GPS satellite should generate pfd of less than –211 dB(W/(m^2 · 20 kHz)) in the radio astronomy band. This value is identical to the one found for GALILEO.

Figure 45 shows for each cell of the sky, and for the pfd (per satellite) of −212 dB(W/(m^2 · 20 kHz)), the percentage of observations where the epfd threshold is exceeded. One can see that it never exceeds 18% per cell, and therefore it never causes any sky blockage in any part of the sky.

10.4.2.3 QZSS

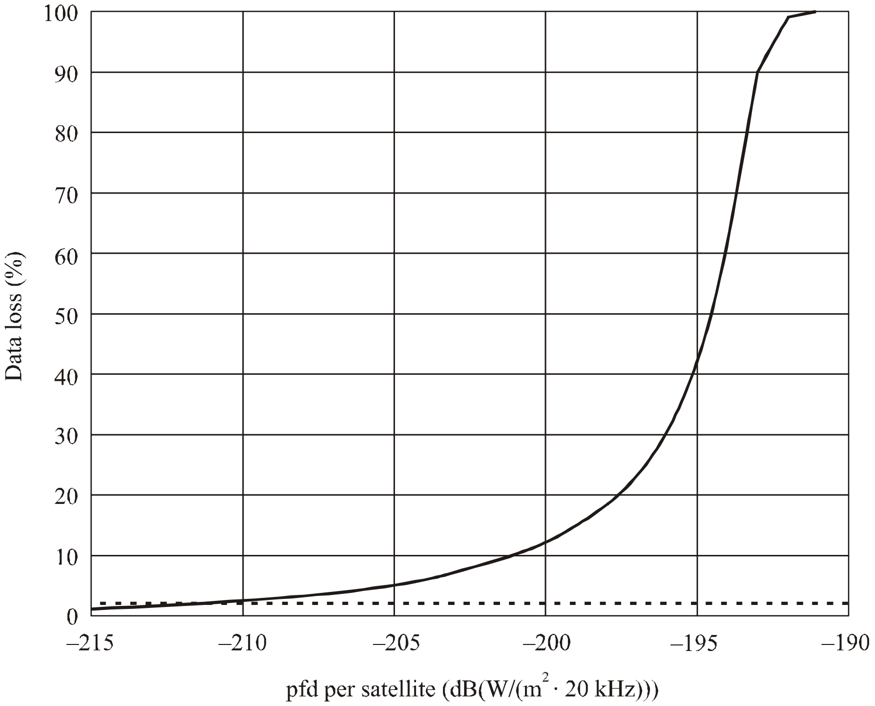
Because the simulation for the Kashima radio telescope results in the worst-case epfd levels, the calculation results for the Kashima radio telescope are shown here.

Figure 46 shows the percentage of time where the epfd threshold is exceeded at the radio astronomy location, for a given pfd value generated per QZSS satellite (as explained in Recommendation ITU-R RA.1513, exceeding this threshold is equivalent to data loss).

To meet the epfd threshold for more than 98% of the time in average over the whole sky, each QZSS satellite should not generate a pfd higher than –203 dB(W/(m^2 · 20 kHz)) in the radio astronomy band. For reference, in the case of the Usuda radio telescope, this pfd value is −202.5 dB(W/(m^2 · 20 kHz)).

FIGURE 44

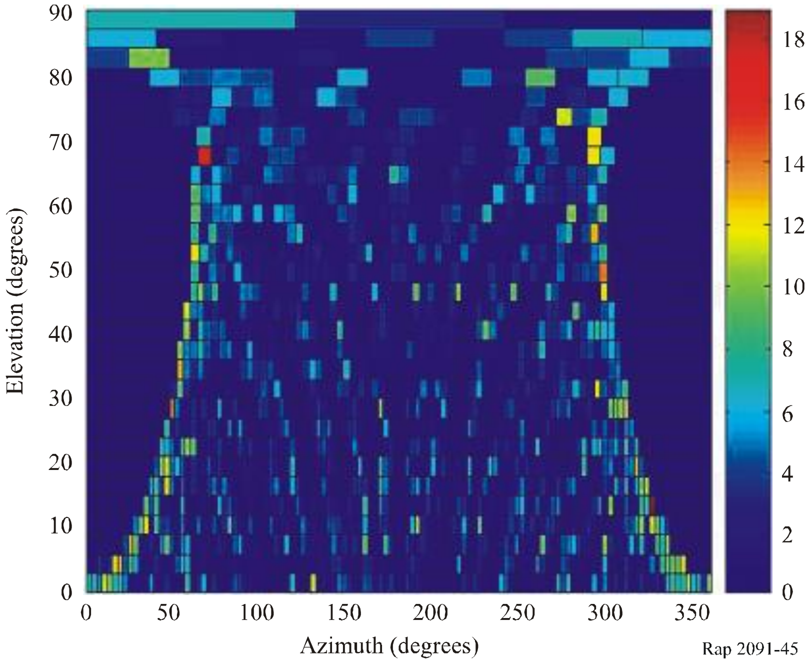
Percentage of data loss vs. pfd per satellite (GPS)



Rap 2091-44

FIGURE 45

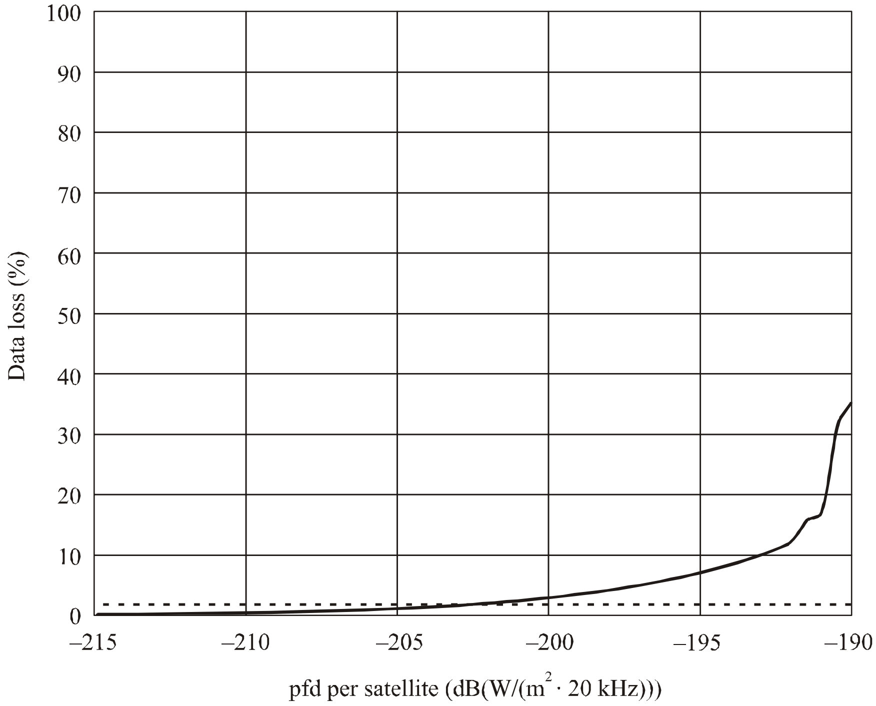
Percentage of data loss over the sky for the pfd of –212 dB(W/(m^2 · 20 kHz)) (GPS)



Rap 2091-45

FIGURE 46

Percentage of data loss vs. pfd per satellite (from QZSS into Kashima radio telescope)



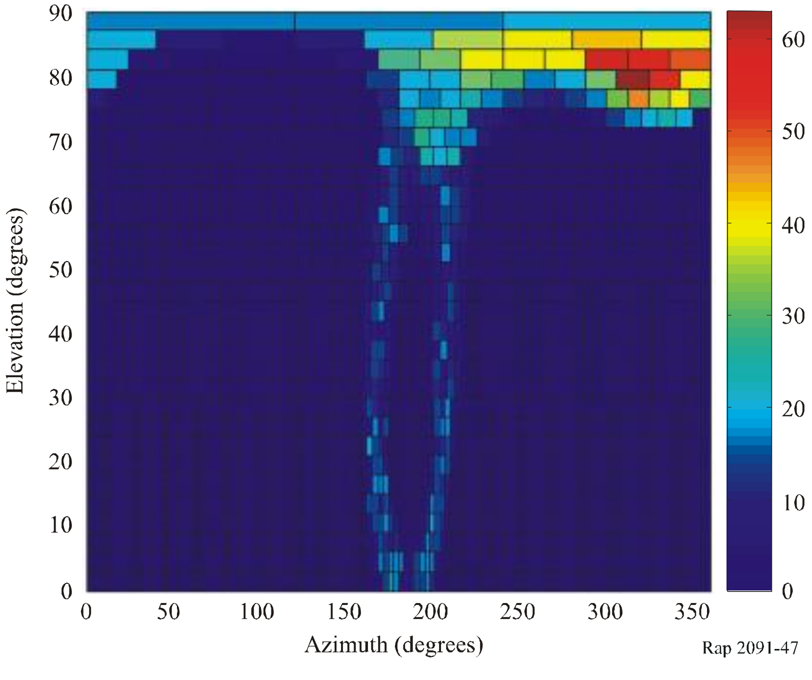
Rap 2091-46

Figure 47 shows for each cell of the sky, and for the aforementioned pfd per satellite, the percentage of time where the epfd threshold is exceeded for the Kashima radio telescope.

FIGURE 47

Percentage of data loss over the sky for the pfd of –203 dB(W/(m^2 · 20 kHz)) for the Kashima radio telescope (QZSS)

The maximum percentage of time where the epfd threshold is exceeded is 64%. And in 12.4% (288 cells) of the sky area the epfd threshold exceeds 2% of time.



Rap 2091-47

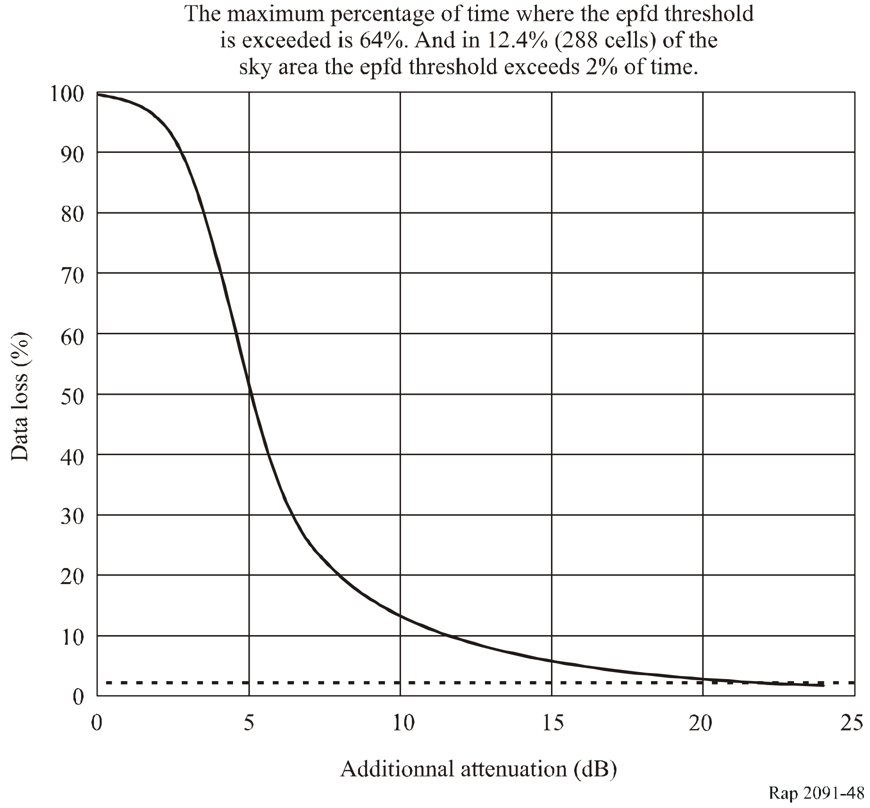
The level of unwanted emissions of QZSS satellites is calculated in § 10.2.4.3.2 as −205 dB(W/(m^2 · 20 kHz)), therefore this value is 2 dB below the pfd level determined above.

10.4.2.4 GLONASS

Figure 48 gives the percentage of data loss in a 20 kHz bandwidth centered on 1 610.6 MHz as function of the attenuation added to the attenuation that would be provided by the current filter design of GLONASS satellites as shown in Fig. 39.

FIGURE 48

Percentage of data loss vs. additional attenuation to the pfd of Table 34 for 1 610.6 MHz



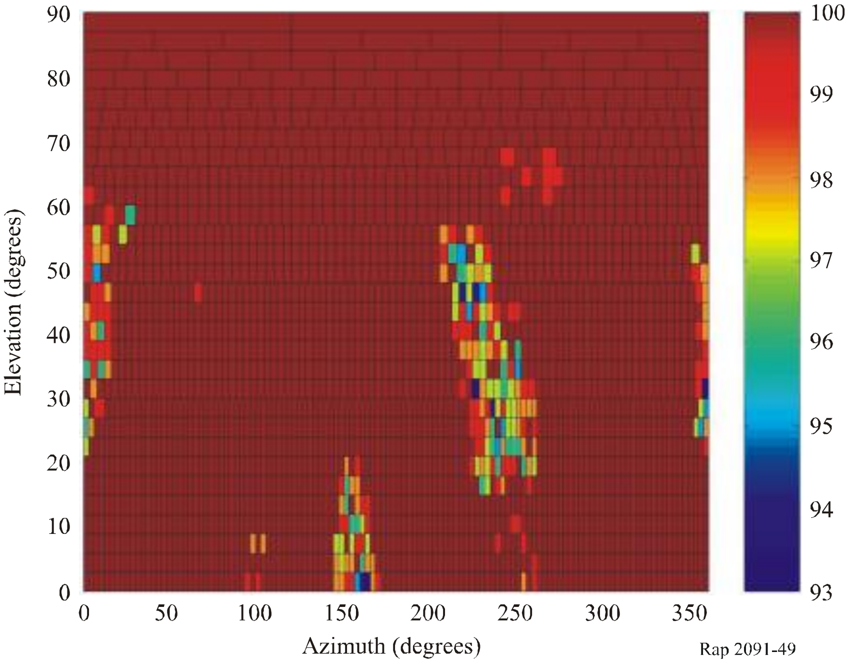
This Figure shows that the percentage of data loss will be around 99.8% over the sky if all future GLONASS satellites radiate at the same pfd levels as those of the GLONASS satellites equipped with the filter described in Fig. 39. In order to respect the 2% allowed data loss, an additional attenuation of 22 dB would have to be added.

Figures 49 and 50 show the percentage of data loss over the sky at a frequency of 1 610.6 MHz for, respectively, the pfd levels in Table 37 and for pfd levels that were attenuated by an additional 22 dB.

It should be noted, that upon deviation from frequency 1 610.6 MHz by only 200 kHz (the frequency 1 610.8 MHz), in order to ensure the 2% allowed data loss, an additional attenuation of 14.5 dB would have to be added instead of 22 dB, according to the characteristic of the filter (see Fig. 39).

FIGURE 49

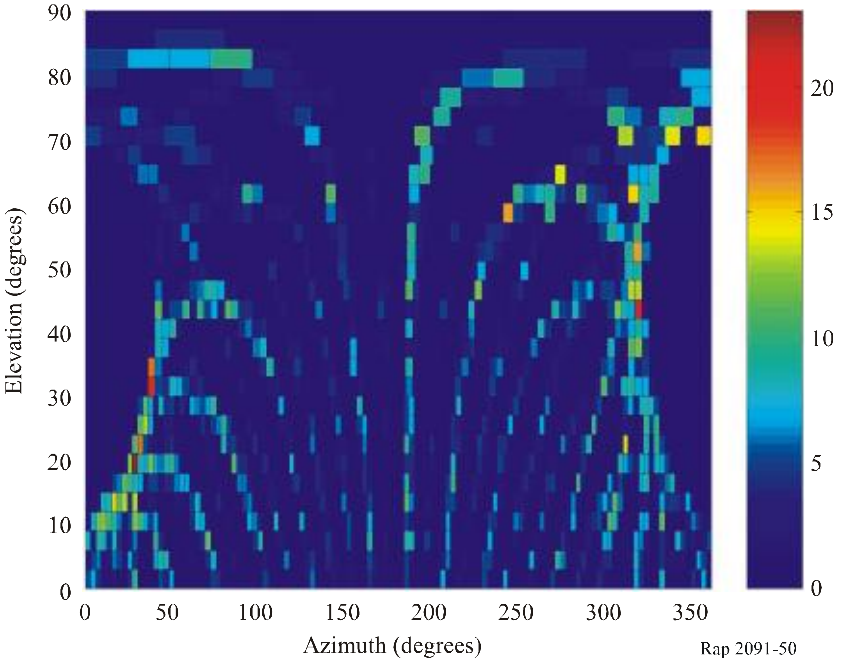
Percentage of data loss over the sky for the pfd levels given in Table 37, at 1 610.6 MHz



Rap 2091-49

FIGURE 50

Percentage of data loss over the sky for 22 dB additional attenuation, at 1 610.6 MHz



Rap 2091-50

10.4.3 Values achieved

The unwanted emission pfd levels given in Tables 26, 29, 32 and 37 for GALILEO, GPS, QZSS and GLONASS show that GALILEO, GPS and QZSS RNSS systems will meet the epfd threshold level derived from Recommendation ITU-R RA.769 with a margin of respectively 2, 3.3 and 2 dB.

However the GLONASS RNSS system will not meet the epfd threshold level derived from Recommendation ITU-R RA.769 in the 1 610.6-1 613.8 MHz band by 22 dB.

10.5 Mitigation methods

10.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for G/T, i.e. telescope gain divided by system temperature. This is to maximize the S/N for point sources. A key element of this approach is to reduce ground radiation entering through far side-lobes. Inevitably this leads to some corresponding increase in the levels of near side-lobes. Experience has shown that the majority of radio telescopes meets the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency. However it can only be applied when the percentage of data loss is sufficiently low.

10.5.2 Radionavigation-satellite service

At least two different mitigation techniques may be applied to reduce the amount of unwanted emissions of RNSS satellites:

– filtering;

– use of an improved frequency plan.

The paragraphs below give the example of application of both techniques to existing RNSS systems.

Initially two RNSS systems started operating in the 1 559-1 610 MHz band, both of which use spread spectrum modulation. Both systems started their operation without filtering their transmissions, and interference into the 1 610.6-1 613.8 MHz band from both systems was reported at radio astronomy stations.

The unwanted emissions into the 1 610.6-1 613.8 MHz band from one of the initial operating systems, which operates at lower frequencies in the RNSS band, was reduced to the satisfaction of the radio astronomy community by introducing filters in those satellites of its system that were launched after the interference was reported (see § 10.2.4.2.2 above) .

The other initial system started operating in the 1 610.6-1 613.8 MHz band, while this RAS allocation was still secondary. In order to improve the interference situation in the band, an Agreement was concluded between the satellite operator and the Inter-Union Commission on Frequency Allocations for Radio Astronomy and Space Science (IUCAF), representing the radio astronomy community worldwide (Document WRC-93/43). This Agreement contains a phased approach to meet the protection criteria of the RAS after some years. Subject to the above Agreement the channel plan has been revised and satellite transmissions switched over to frequencies further below the 1 610.6-1 613.8 MHz band. Also new satellites of the system were equipped with additional filters (see Fig. 39) reducing OoB emissions and providing for reduction of threshold levels subject to Recommendation ITU-R RA.769.

The mentioned filters are installed between the transmitting antenna and each transmitter generating radiation of L-band navigation signals by in-phase power summation.

10.5.3 Potential impact

10.5.3.1 RAS

Antenna side-lobe performance: Attempts to decrease the sensitivity of the radio astronomy antenna to unwanted emissions coming from space stations are likely to increase the sensitivity of the radio astronomy telescope to ground radiation, and possibly reduce its main beam gain. Both of these effects will reduce the telescope’s channel capacity of and thus lead to an increase of the total required integration time.

Blanking in time and/or frequency: Blanking involves a risk of compromising the integrity of the data and may lead to errors in their scientific interpretation. Blanking also causes a concomitant increase in the total integration time required to make the observation, this is equivalent to a loss in the channel capacity of the telescope.

If an RNSS system exceeds the epfd threshold level, derived from Recommendation ITU-R RA.769 in the 1 610.6-1 613.8 MHz band, use of this band by the RAS for observations of the hydroxyl molecule may not be possible.

10.5.3.2 RNSS

Hardware solutions such as filters may be difficult to implement. In active, multi-element antennas, filters may be needed for every antenna element. This will increase the weight of the satellite. The filter losses will require more powerful transmitters, which will in turn require more bus power, and so larger solar arrays. This will further increase the weight. In addition, a bigger, heavier satellite might need a larger launcher. The cost impact may be large. Technical improvements in filter design ameliorate this problem. Implementation of filters in the system is a more manageable task particularly when considered at the design stage of the system.

Also installation of filters on the GLONASS satellites has led to occurrence of the following basic problems:

- Phasing of transmitted emissions which forms the navigation signal on one frequency becomes very complicated. Lack of appropriate phasing results in distortion of the antenna radiation pattern and losses in navigation signal emission power.
- Additional losses in the filters passband have appeared thus reducing the level of emitted navigation signal.
- Additional delays of modulating signal in the L1-band have appeared that introduces the additional error for compensation of ionospheric inaccuracy for users.

The Russian Federation considers that previously agreed-on conditions between IUCAF and the GLONASS administration have been met.

Requirements of additional unwanted emission suppression in the radio astronomy band, beyond the attenuation provided by the filter shown in Fig. 39, would lead to an aggravation of the problems listed above. If navigation signals were excluded from the navigation solution, the safety of life related application of the GLONASS system would be impaired.

Since the production of GLONASS satellites equipped with filters has begun the characteristics of this filter will not change in the near future.

10.6 Results of studies

In this band, threshold levels of interference detrimental to radio astronomical observations as discussed in § 10.1.3 may be met by the active service for the VLBI and single-dish spectral line case, when mitigation methods are taken into account. No single-dish continuum observations are made in this band. The results of the analyses in § 10.4 show that for an existing system, a system under deployment and another planned RNSS system, all of which operate or plan to operate in the band 1 559-1 610 MHz, the unwanted emission levels that fall in the band 1 610-1 613.8 MHz may satisfy the protection criteria of the radio astronomy service, as a consequence of mitigation techniques. They also show that this is not the case for another existing system, that operates in the same band.

11 Compatibility analysis between RAS systems operating in the 1 610.6-1 613.8 MHz band and MSS (space-to-Earth) systems operating in the 1 613.8-1 626.5 MHz band

11.1 RAS

11.1.1 Allocated band

The 1 610.6-1 613.8 MHz band is allocated to the RAS on a primary basis.

RR No. 5.149 urges administrations to take all practicable steps to protect the RAS in this band.

11.1.2 Type of observations

The 1 610.6-1 613.8 MHz band is used for spectral line observations of the OH. The OH line, which has a rest frequency of 1 612 MHz, is one of the most important spectral lines for radio astronomy, and is listed as such in Recommendation ITU-R RA.314. OH radical was the first cosmic radical to be detected at radio frequencies (1963), and continues to be a powerful research tool. OH produces four spectral lines, at frequencies of approximately 1 612, 1 665, 1 667 and 1 720 MHz, all of which have been observed in our own galaxy, as well as in external galaxies. The study of OH lines provides information on a wide range of astronomical phenomena, e.g. the formation of protostars and the evolution of stars. To interpret most observations made in the OH lines, it is necessary to measure the relative strength of several of these lines. Loss of the ability to observe any one of these lines may prevent the study of some classes of physical phenomena.

These OH lines are produced by a coherent process, in which a concentration of OH radicals radiate "in step", creating narrow-band emission. They are slightly broadened due to physical conditions in this concentration. Movement of these concentrations with respect to the Earth impose a Doppler shift on the line emission. The presence of several concentrations in the source, which are moving at different velocities, give rise to a more complicated spectrum, consisting of a number of superimposed Gaussian line profiles of different widths and amplitudes, and slightly-different frequencies (due to the different Doppler shifts). The width of the band allocation is required to accommodate the spreading and shifting of the spectrum by differential and total motions of the source.

In some stages of their evolution, certain classes of stars radiate only the 1 612 MHz line. The study of this line allows astronomers to gauge such physical properties of these stars as the rate at which gas is blown off by the stars and recycled into the interstellar medium. Some properties of these stars cannot be inferred from any other astronomical observation. Measurements of OH emitting stars have also been used to estimate the distance to the Galactic Centre, to measure the mass of the central bulge of our galaxy, and to study the spatial distribution of the molecular component in our galaxy and in external galaxies. Finally, extremely strong maser emission has been detected near the nuclei of a number of external galaxies. This OH megamaser emission from galactic nuclei allows astronomers to study the temperature and density of the molecular gas in their centre.

The OH spectral line is also observed in comets; there is very little flexibility in scheduling observations of these "targets of opportunity".

Spectral line observations are made using spectrometers that can simultaneously integrate the power in a large number of frequency channels (typically 256-4 096) distributed across the frequency band used. The width and number of channels has to be large enough to accurately reproduce the spectrum of the emission received by the radio telescope. Instantaneous bandwidths of typically ~0.2-20 kHz per frequency channel are used, depending on the scientific program.

The sources are small, and measurements of their size and structure often require observations using the VLBI technique.

11.1.3 Required protection criteria

Recommendation ITU-R RA.769 specifies the protection criteria for radio astronomical observations and gives threshold levels of detrimental interference for primary radio astronomy bands. In the 1 610.6-1 613.8 MHz band, for single dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 20 kHz, the threshold pfd limit is -194 dB(W/m^2). This band is used only for radio line observations, not for continuum observations.

For detrimental interference from non-GSO systems, the protection criteria and the relevant methodologies are described in Recommendations ITU-R RA.769 and ITU-R RA.1513, as well as in Recommendation ITU-R S.1586 for FSS systems and in Recommendation ITU-R M.1583 for MSS and RNSS systems.

The thresholds of detrimental interference levels to the RAS as defined and calculated in the Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes 10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

11.1.4 Operational characteristics

Observations in the 1 612 MHz band are carried out at a number of radio astronomy sites in numerous countries, worldwide. Observations in the 1 612 MHz band are sometimes conducted on targets of opportunity, e.g. on objects such as comets, which have been observed to produce transient emissions in this line. VLBI observations are also frequently conducted in this band, sometimes between the North American and European VLBI networks.

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, –166 dB(W/m^2), for a bandwidth of 20 kHz, which has been developed for VLBI observations, but not included in ITU-R RA.769.

Spectral line observations are made using multichannel spectrometers that can integrate simultaneously the power in many (typically 256 to 4 096) frequency channels distributed across the band. The number of channels and their individual bandwidths are chosen to adequately sample the spectrum of the net emission from the source(s) in the antenna beam.

In general, observations are made differentially; spectra are recorded at frequency ranges including the line emissions of interest (the line spectra), and then at a frequency that is offset from the line emissions, or at the same frequency but at a nearby position in the sky (the reference spectra). By subtracting the reference spectra from the line spectra, unwanted noise contributions and other contaminants can be removed from the data.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data have been processed.

11.2 MSS

11.2.1 Allocated transmit band

The band 1 613.8-1 626.5 MHz was allocated to the MSS (space-to-Earth) on a secondary basis, worldwide at WARC-92. WARC-92 also took the following actions in regard to the RAS in the 1 610.6-1 613.8 MHz band:

a) an upgrading of the existing radio astronomy allocation from secondary to primary status in the 1 610.6-1 613.8 MHz band; and

b) the adoption of RR No. 5.372, that states: "Harmful interference shall not be caused to stations of the radio astronomy service using the band 1 610.6-1 613.8 MHz by stations of the radiodetermination-satellite and mobile-satellite services (No. **29.13** applies)." This footnote applies to the 1 610-1 626.5 MHz band.

11.2.2 Application

The band 1 610-1 626.5 MHz is allocated to MSS uplinks, worldwide on a primary basis, subject to some constraints.

The band 1 613.8-1 626.5 MHz is allocated to the MSS (space-to-Earth) service on a secondary basis, worldwide. The HIBLEO-2 system is currently the only system using this allocation in both Earth-to-space and space-to-Earth directions, while HIBLEO-4 uses the band in the Earth-to-space direction. HIBLEO-2 is a satellite system capable of operating in the 1 616-1 626.5 MHz band, but authorized to operate in the 1 621.35-1 626.5 MHz band only.

11.2.3 Levels based upon regulatory provisions

There are no regulatory limits on OoB emissions in the RR. However, RR Nos 5.28-5.31 state that, *inter alia*, stations of a secondary service by definition shall not cause harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date nor claim protection from harmful interference from stations of a primary service. This provision applies to protection from both in-band and OoB emissions and would apply to secondary MSS downlinks, regardless of specified pfd levels. Thus there is no obvious reason to codify specific pfd limits.

In RR No. 29.13 it is stated "Administrations shall take note of the relevant ITU-R Recommendations with the aim of limiting interference of the radio astronomy service from other services".

11.3 Compatibility threshold

See § 11.1.3.

11.4 Interference assessment

11.4.1 Methodology used to assess the interference level

See § 11.2.3 for references to the relevant ITU-R Recommendations dealing with non-GSO systems.

11.4.2 Calculation of the interference level

Unwanted emissions in terms of aggregate spfd of HIBLEO-2 satellite transmissions in the 1 610.6-1 613.8 MHz band have been theoretically estimated to range between –214 dB(W/(m^2 · Hz)) and –223 dB(W/(m^2 · Hz)) at some radio astronomy sites, under fully loaded conditions.

11.4.3 Values achieved

A collaborative test program, conducted by HIBLEO-2 and the United States National Radio Astronomy Observatory (NRAO), in 1998 measured spfd values ranging from –220 to –240 dB(W/(m^2 · Hz)) at these sites. These values refer to the so-called voice channels that are turned on when communication takes place. In addition the HIBLEO-2 system was found to radiate broadcast signals at all times. The spectra of the broadcasting channels showed 9-10 narrow (less than 40 kHz wide) peaks within the radio astronomy band. spfd peak values appeared to average –227 dB(W/(m^2 · Hz)) over 90 ms. Due to the mismatch between the satellite system transmission and other parameters and the radio astronomy receiver and antenna characteristics (e.g. radio telescopes are not adapted to track satellites; available receiver bandwidths are different from 20 kHz, etc.), it was difficult to estimate the spfd that would result under the conditions in Recommendation ITU-R RA.769, which specifies a detrimental interference level of -238 dB(W/(m^2 · Hz)).

11.5 Mitigation techniques

11.5.1 RAS

There are various methods that might be used to reduce unwanted emissions from the satellite transmitters at a radio telescope. When such methods are insufficient other solutions, such as an agreement between the operator of a satellite system and radio astronomy observatories may be considered.

No specific provisions for such coordination agreements between the RAS and active services are made in the RR. However, general provisions for coordination and consultation can be found in RR Article 9.

Coordination agreements can only be concluded with the explicit mutual assent of both parties involved, i.e. in principle the satellite operator and an afflicted astronomical observatory. For satellite downlinks, coordination at a national level between a satellite system operator and radio astronomy sites is only practicable when the footprint of the satellite transmission is smaller than the geographical dimensions of the nation in which coordination is sought, and when the visibility of the transmitting space station from a radio astronomy station does not extend beyond that nation’s border. International solutions need to be found when the local geographic density of radio astronomy stations operating at 1.6 GHz is such that at any given moment in time radio astronomy stations in more than one nation lie within the same satellite footprint or visibility of the same satellite.

In general, the conditions of such arrangements are not immutable over time, and need to be reviewed as required, for which milestones must to be defined. In case of disagreement, arbitration arranged by mutual agreement must be defined *a priori* in the text of the Agreement.

Several agreements were reached between the operators of the HIBLEO-2 system and various parts of the radio astronomy community. The common element in these agreements is that the aggregate emissions of the HIBLEO-2 system will meet the threshold levels given in Recommendation ITU-R RA.769 for single-dish observations in the 1 610.6-1 613.8 MHz band at the observatories concerned for a daily period of time, varying in duration from about 4 to 8 h. Some radio astronomy sites agreed to notify in advance their intentions to observe in this band.

11.5.2 MSS

There are various methods, such as filtering, that may be employed to reduce unwanted emissions. These should be considered in the design of new space station.

When such methods are insufficient, other solutions, such as an agreement between the operator of a satellite system and radio astronomy observatories may be considered (see § 11.5.1).

11.5.3 Potential impact

11.5.3.1 RAS

Coordination agreements between the operator of a satellite system and radio astronomy observatories, if feasible at all, may have a negative impact on the scheduling of observations, the flexibility of the observatory to accommodate the needs of the user community, and increase the administrative overhead. The net impact of a coordination arrangement upon the operability of an observatory should not render it ineffective of meeting required productivity standards.

11.5.3.2 MSS

Hardware solutions such as filters may be difficult to implement. In active, multi-element antennas, filters may be needed for every antenna element. This will increase the weight of the satellite. The filter losses will require more powerful transmitters, which will in turn require more bus power, and so larger solar arrays. This will further increase the weight. In addition, a bigger, heavier satellite might need a larger launcher. The cost impact may be large. Technical improvements in filter design may ameliorate this problem. Implementation of filters in the system is a more manageable task if considered at the design stage of the system.

It should be noted, however, that according to the coordination agreement signed between the operator of the HIBLEO-2 satellite system and the European radio astronomy community, the aggregate pfd level of the HIBLEO-2 system will not exceed the levels specified in Recommendation ITU-R RA.769 for radio astronomy stations within Europe from 1 January 2006. This indicates that adequate mitigation techniques are expected to be implemented by that date.

However, if satellite replenishment is extended beyond 1 January 2006 it will be difficult to use improved filtering on the inadequately filtered satellites still in orbit and the implementation of other mitigation techniques could have an adverse economic impact.

11.6 Results of studies

11.6.1 Summary

The mitigation of interference issues has been addressed by the setting up of agreements between the operators of the HIBLEO-2 system and various radio astronomy facility operators. Using such mitigation techniques, it should be possible for the protection criteria to be met for spectral line operations, as described in § 11.1.3, and for VLBI observations. No single-dish continuum observations are made in this band.

11.6.2 Conclusions

Appropriate mitigation techniques should make it possible to make effective spectral line and VLBI observations in this band.

12 Compatibility analysis between RAS systems operating in the 1 610.6-1 613.8 MHz band and GSO MSS (space-to-Earth) systems operating in the 1 525-1 559 MHz band

12.1 RAS

12.1.1 Allocated band

The 1 610.6-1 613.8 MHz band is allocated to the RAS on a primary basis.

RR No. 5.149 urges administrations to take all practicable steps to protect the radio astronomy service in this band.

12.1.2 Type of observations

The 1 610.6-1 613.8 MHz band is used for spectral line observations of the OH. The OH line, which has a rest frequency of 1 612 MHz, is one of the most important spectral lines for radio astronomy, and is listed as such in Recommendation ITU-R RA.314. OH was the first cosmic radical to be detected at radio frequencies (1963), and continues to be a powerful research tool. OH produces four spectral lines, at frequencies of approximately 1 612, 1 665, 1 667 and 1 720 MHz, all of which have been observed in our own galaxy, as well as in external galaxies. The study of OH lines provides information on a wide range of astronomical phenomena, e.g. the formation of protostars and the evolution of stars. To interpret most observations made in the OH lines, it is necessary to measure the relative strength of several of these lines. Loss of the ability to observe any one of these lines may prevent the study of some classes of physical phenomena.

These OH lines are produced by a coherent process, in which a concentration of OH radicals radiate “in step”, creating narrow-band emission. They are slightly broadened due to physical conditions in this concentration. Movement of these concentrations with respect to the Earth impose a Doppler shift on the line emission. The presence of several concentrations in the source, which are moving at different velocities, give rise to a more complicated spectrum, consisting of a number of superimposed Gaussian line profiles of different widths and amplitudes, and slightly-different frequencies (due to the different Doppler shifts). The width of the band allocation is required to accommodate the spreading and shifting of the spectrum by differential and total motions of the source.

In some stages of their evolution, certain classes of stars radiate only the 1 612 MHz line. The study of this line allows astronomers to gauge such physical properties of these stars as the rate at which gas is blown off by the stars and recycled into the interstellar medium. Some properties of these stars cannot be inferred from any other astronomical observation. Measurements of OH emitting stars have also been used to estimate the distance to the Galactic Centre, to measure the mass of the central bulge of our galaxy, and to study the spatial distribution of the molecular component in our galaxy and in external galaxies. Finally, extremely strong maser emissions have been detected near the nuclei of a number of external galaxies. This OH megamaser emission from galactic nuclei allows astronomers to study the temperature and density of the molecular gas in their centre.

The OH spectral line is also observed in comets; there is little flexibility in scheduling observations of these “targets of opportunity”.

Spectral line observations are made using spectrometers that can simultaneously integrate the power in a large number of frequency channels (typically 256-4 096) distributed across the frequency band used. The width and number of channels has to be large enough to accurately reproduce the spectrum of the emission received by the radio telescope. Instantaneous bandwidths of typically ~0.2-20 kHz per frequency channel are used, depending on the scientific program.

The sources are small, and measurements of their size and structure often require observations using the VLBI technique.

12.1.3 Required protection criteria

Recommendation ITU-R RA.769 specifies the protection criteria for radio astronomical observations and gives threshold levels of detrimental interference for primary radio astronomy bands. For single dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 20 kHz, the threshold pfd for detrimental interference is -194 dB(W/m^2).

This band is used only for radio line observations, not for continuum observations.

The thresholds of detrimental interference levels to the RAS as defined and calculated in Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes 10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

12.1.4 Operational characteristics

Observations in the 1 612 MHz band are carried out at a number of radio astronomy sites in numerous countries, worldwide. Observations in the 1 612 MHz band are sometimes conducted on targets of opportunity, e.g. on objects such as comets, which have been observed to produce transient emissions in this line. VLBI observations are also frequently conducted in this band, sometimes between the North American and European VLBI networks.

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, −166 dB(W/m^2), for a bandwidth of 20 kHz, which has been developed for VLBI observations, but not included in ITU-R RA.769.

Spectral line observations are made using multichannel spectrometers that can integrate simultaneously the power in many (typically 256 to 4 096) frequency channels distributed across the band. The number of channels and their individual bandwidths are chosen to adequately sample the spectrum of the net emission from the source(s) in the antenna beam.

In general, observations are made differentially; spectra are recorded at frequency ranges including the line emissions of interest (the line spectra), and then at a frequency that is offset from the line emissions, or at the same frequency but at a nearby position in the sky (the reference spectra). By subtracting the reference spectra from the line spectra, unwanted noise contributions and other contaminants can be removed from the data.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data has been processed.

12.2 MSS

12.2.1 Allocated transmit band

1 525-1 559 MHz (space-to-Earth).

12.2.2 Application

MSS.

12.2.3 Levels based upon regulatory provisions

RR Appendix 3.

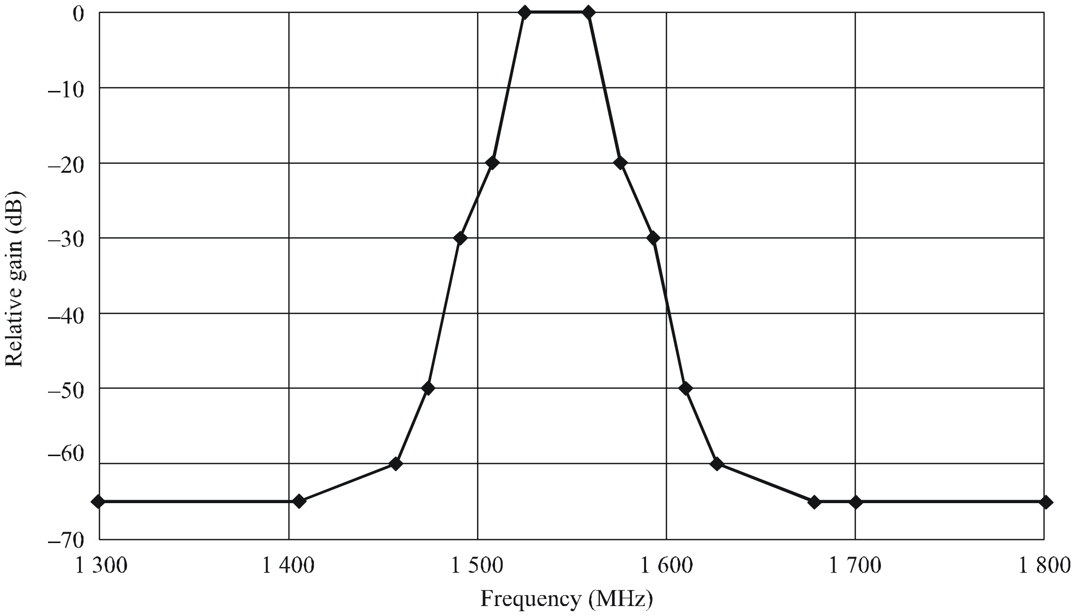
The required attenuation is 43 + 10 log *P* dBc or 60 dBc, whichever is less stringent, where *P* is the peak power at the input to the antenna (W) in any 4 kHz bandwidth.

12.2.4 Transmitter characteristics

The antenna gain is 41 dBi. The Tx output filter characteristic is shown in Fig. 51.

FIGURE 51

Tx output filter charateristic



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12.2.5 Operational characteristics

The typical peak power into an MSS GSO satellite spot beam at input to the antenna is 16 dBW over a bandwidth of 5 MHz.

12.2.6 In-band transmit level

The in-band transmit level is –15 dBW in a 4 kHz bandwidth.

12.3 Compatibility threshold

See § 12.1.3.

12.4 Interference assessment

12.4.1 Methodology used to assess the interference level

The parameters peak in band PSD, the peak antenna gain and the measured attenuation of the 1 525-1 559 MHz band output filter at different frequencies are used to determine the pfd at the surface of the Earth.

12.4.2 Calculation of the interference level

Based on the expected performance of the 1 525-1 559 MHz band, the typical power levels at the output of the Tx L band filter, e.i.r.p. density levels at the antenna output and the pfd at the surface of the Earth at different frequencies are as shown in Table 38.

12.4.3 Values achieved

The value achieved is –192 dB(W/m^2) in 4 kHz bandwidth.

Translating these values for single-dish spectral line observations, we obtain a pfd value of -185 dB(W/m^2) in a 20 kHz bandwidth for spectral line observations: Based on the above parameters of one GSO mobile-satellite system of one operator, it follows that there is a deficit of 9 dB in meeting the protection criteria for single-dish spectral line observations.

TABLE 38

Expected values of the PSD, e.i.r.p. density, and the pfd at the surface of the Earth of an Inmarsat-4 satellite in the frequency band 1 525-1 559 MHz

Frequency (MHz)	PSD at the output of filter (dB(W/4 kHz))	e.i.r.p. density at the output of the antenna (dB(W/4 kHz))	pfd at the surface of the Earth (dB(W/(m2 · 4 kHz)))
1 300	–80	–39	–202
1 406	–80	–39	–202
1 457	–75	–24	–197
1 474	–65	–14	–187
1 491	–45	–4	–167
1 508	–35	6	–157
1 525	–15	26	–137
1 559	–15	26	–137
1 576	–35	6	–157
1 593	–45	–4	–167
1 610	–65	–14	–187
1 627	–75	–24	–197
1 678	–80	–39	–202
1 700	–80	–39	–202
1 800	–80	–39	–202

12.5 Mitigation techniques

12.5.1 Radio astronomy service

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for *G*/*T*, i.e. telescope gain divided by system temperature. This is to maximize the *S*/*N* for point sources. A key element of this approach is to reduce ground radiation entering through far side lobes. Inevitably this leads to some corresponding increase in the levels of near side lobes. Experience has shown that the majority of radio telescopes meets the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in some cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

12.5.2 Mobile-satellite service

In order to improve the levels given in Table 37, the following mitigation techniques should be taken into account in the design of a new space station:

- the wideband frequency response of the antenna;
- the attenuation characteristics of intermediate filters;
- the gain frequency response of solid state power amplifiers;
- the modulation characteristics of individual carriers;
- the attenuation of inter-modulation products with respect to the power of the carriers.

12.5.3 Potential impact

12.5.3.1 RAS

On the basis of the analysis in § 12.4, and the nature of the mitigation techniques listed in § 12.5.1, there could be some loss of observing time when satellites travel through the main or inner side lobes of the antenna. The extent of this loss will depend upon the radio telescope antenna and the number of satellites. The data loss issue is discussed in Recommendation ITU-R RA.1513.

12.5.3.2 MSS

The mitigation techniques in § 12.5.2 are deemed technically feasible for GSO systems.

12.6 Results of studies

12.6.1 Summary

Based on the parameters of one GSO mobile-satellite system of one operator and taking into account the mitigation factors listed in § 12.5.2, it is likely that the unwanted emission levels from this satellite system meet the criteria discussed in § 12.1.3. No single-dish continuum observations are made in this band.

12.6.2 Conclusions

Protection criteria are met for the single-dish spectral-line case and for VLBI.

13 Compatibility analysis between the RAS systems (space-to-Earth) operating in the 2 690-2 700 MHz band and the BSS, and FSS (space-to-Earth) systems operating in the 2 655-2 690 MHz band

13.1 RAS

13.1.1 Allocated band

The 2 690-2 700 MHz band was allocated on a primary basis to the RAS, EESS (passive) and SRS (passive).

RR No. 5.340 states that in this band "all emissions are prohibited".

13.1.2 Type of observations

This band is primarily of interest for the study of continuum emission of radio sources.

A general consideration for the study of the continuum emission of radio sources is the requirement of sampled observations of these sources throughout a very wide frequency range. Observations at many different frequencies help to define the shape of the spectra of the emission from these sources, which in turn can give information on the physical parameters of the radiating sources such as densities, temperatures and magnetic fields, while they also give information on their lifetimes. The knowledge of these physical parameters is essential for our understanding of the physical processes that produce radio radiation. Many extragalactic radio sources show a "break" in their non-thermal spectrum in the region between 1 to 3 GHz and continuum measurements at ~2.7 GHz are essential to define such a spectral characteristic accurately.

This is a good frequency band for continuum measurements partly because the galactic background radiation is low, and also because radio astronomy receivers are of excellent quality and have very low noise at such frequencies.

It is also useful for galactic studies of ionized hydrogen clouds and the general diffuse radiation of the Galaxy. Since at such frequencies available radio telescopes have adequate angular resolutions (narrow beams, of the order of 10 arc min for large telescopes), many useful surveys of the galactic plane have been performed, including the regions of the galactic centre, which is invisible at optical wavelengths because of the interstellar absorption by dust particles. The centre of our Galaxy is perhaps its most important region and yet it can only be observed at infrared and radio wavelengths, since these wavelengths are not affected by the dust particles in the interstellar space (optical wavelengths are absorbed and scattered by such dust particles). The study of the nuclei of galaxies, including the nucleus of our own Galaxy, is emerging as an extremely important and fundamental topic in astronomy.

Problems that can be studied in these objects include the state of matter and the possibilities of the existence of black holes in galactic nuclei; the explosive activities and the production of intense double radio sources from galactic nuclei; the influence of galactic nuclei on the morphological structure of galaxies; the formation of galaxies and quasars; and many other major astrophysical subjects.

An important study at radio wavelengths is the polarization of the radiation that is observed from radio sources. It is often found that radio sources are weakly linearly polarized, with a position angle that depends on frequency. This effect is due to the fact that the propagation medium in which the radio waves travel to reach us is composed of charged particles, electrons and protons, in the presence of magnetic fields. The determination of the degree and angle of polarization gives us information on the magnetic fields and electron densities of the interstellar medium and in certain cases on the nature of the emitting sources themselves. The degree of polarization of radio waves is higher at higher frequencies. The 2 690-2 700 MHz frequency band is important for polarization measurements.

13.1.3 Required service protection criteria

Recommendation ITU-R RA.769 specifies the protection criteria for radio astronomical observations and gives threshold levels of detrimental interference for primary radio astronomy bands. In the 2 690-2 700 MHz band, for single-dish continuum observations making use of the entire 10 MHz bandwidth, the threshold pfd limit is -177 dB(W/m^2).

This band is used only for continuum observations, not for spectral line observations.

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, -161 dB(W/m^2), for a bandwidth of 20 kHz.

For detrimental interference from non-GSO systems, the protection criteria and the relevant methodologies are described in Recommendations ITU-R RA.769 and ITU-R RA.1513, as well as in Recommendation ITU-R S.1586 for FSS systems.

The thresholds of detrimental interference levels to the RAS as defined and calculated in the Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes 10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

13.1.4 Operational characteristics

Observations in the 2 690-2 700 MHz band are carried out at a number of radio astronomy sites in numerous countries, worldwide. Observations in this band are sometimes conducted on targets of opportunity, e.g. on objects such as comets. VLBI observations are also frequently conducted in this band, sometimes between the North American and European VLBI networks.

Radio astronomical measurements are usually made differentially, the area of sky containing the source may be mapped, and the background emission subtracted, or measurements made of the power coming from the direction from the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

Extended areas of emission can be mapped by recording the emission from a grid of points covering the region of interest. In the case of single antenna radio telescopes, each grid point observation is an indication of the total power coming from that position in the sky; the spacing between the grid points should not be more than half the antenna beamwidth. When observations are made using a synthesis radio telescope, where the area to be mapped exceeds the instantaneous mapping field, the grid points should not be further apart than half the beamwidth of one of the radio telescope antennas.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data has been processed.

13.2 Active band

13.2.1 Allocated transmit band

The sub-band 2 655-2 670 MHz was allocated to the BSS on a primary basis.

The sub-band 2 670-2 690 MHz was allocated on a primary basis to the MSS (Earth-to-space), to the FSS (Earth-to-space) in Regions 2 and 3, and to the FSS (space-to-Earth) in Region 2.

The following relevant footnotes apply to the sub-band 2 655-2 670 MHz: RR Nos 5.149, 5.413, 5.415, 5.416 and 5.420, and the following footnotes apply to the sub-band 2 670-2 690 MHz: RR Nos 5.149, 5.419 and 5.420. Most relevant to the issue at hand are the following of these footnotes:

RR No. 5.149 urges administrations to take all practicable steps to protect the radio astronomy service from harmful interference.

RR No. 5.413 states that “In the design of systems in the broadcasting-satellite service in the bands between 2 500 MHz and 2 690 MHz, administrations are urged to take all necessary steps to protect the radio astronomy service in the band 2 690-2 700 MHz.”

RR No. 5.415 states that in this band, for the FSS operating in Regions 2 and 3: “… In the direction space-to-Earth the power flux-density at the Earth’s surface shall not exceed the values given in Article **21**, Table **21-4**.”

13.2.2 Application

There are operational BSSs in this band especially serving India. These services fall under the distribution definition of the BSS.

13.2.3 Levels based on regulatory provisions

pfd limits exist for BSS for community reception and for FSS systems, as set forth in RR Table 21-4.

13.2.4 Transmitter characteristics

13.2.4.1 FSS/MSS systems

Based upon the typical characteristics of systems operating in this band, FSS/MSS systems are supposed to use a necessary bandwidth of 20 MHz and to operate using the pfd limit given in RR Article 21: –137 dB(W/($m^2 \cdot$ 4 kHz)) (i.e. –100 dB(W/($m^2 \cdot$ 20 MHz))).

13.2.4.2 BSS systems

Based upon the typical characteristics of systems operating in this band, FSS/MSS systems are supposed to use a necessary bandwidth of 18 MHz and to operate using the pfd limit given in RR Article 21: –137 dB(W/($m^2 \cdot$ 4 kHz)) (i.e. –100.5 dB(W/($m^2 \cdot$ 20 MHz))).

13.2.5 Operational characteristics

Only GSO systems are addressed in the following calculations.

13.2.6 In-band transmit level

The BSS community reception and FSS pfd levels conform to the levels in RR Table 21-4.

13.3 Compatibility threshold

See § 13.1.3.

13.4 Interference assessment

13.4.1 Methodology used to assess the interference level

13.4.1.1 MSS/FSS cases

Recommendation ITU-R SM.1541 provides a mask for unwanted emissions within the OoB domain covering the case of FSS/MSS systems.

13.4.1.2 BSS case

The BSS is a full-time service, in that the areas served will be provided the signal all the time, with the same spectrum and power. On the other hand, there are no radio astronomy stations that use the band under consideration all the time. If interference problems arise, the GSO satellite systems will be steady emitters at unchanging positions in the sky, while celestial sources will be carried past them by the Earth's rotation, so the interference may not completely preclude the observation of the sources.

Interference to single-antenna radio telescopes will degrade the observations by an amount that is a function of the angle between the satellite(s) and the antenna boresight, and can be evaluated using methodologies such as the epfd approach (see § 13.1.3).

Calculation of levels of unwanted emissions using the OoB mask for BSS systems which are now retained within Recommendation ITU-R SM.1541 have shown that, following this dBc mask, in some cases the level of emissions within the OoB domain may be higher than the emissions levels within the necessary bandwidth. Therefore, a new OoB mask was developed for BSS system.

The OoB emissions of a station operating in the bands allocated to the BSS should be attenuated below the maximum PSD, in a reference bandwidth of 4 kHz (for systems operating above 15 GHz a reference bandwidth of 1 MHz may be used in place of 4 kHz) within the necessary bandwidth, by the following:

$$32 \log\left(\frac{F}{50}+1\right) \qquad \text{dBsd}$$

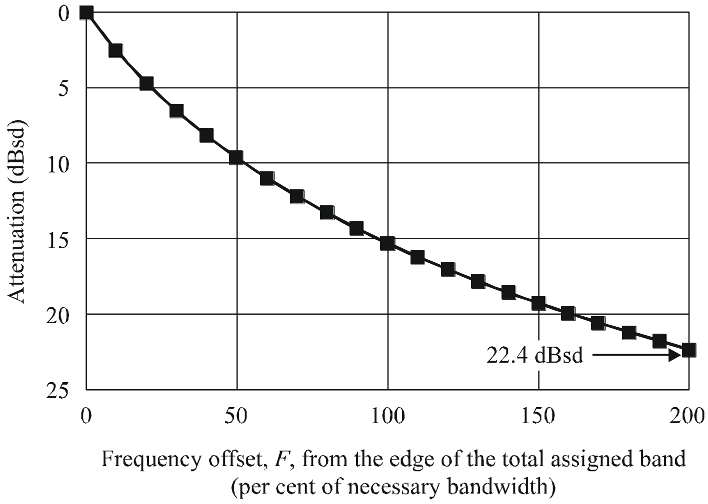
where F is the frequency offset from the edge of the total assigned band, expressed as a percentage of necessary bandwidth. It is noted that the OoB emission domain starts at the edges of the total assigned band.

The OoB emission mask rolls off to the spurious boundary or the point where it is equal to the RR Appendix 3 spurious emission limit, whichever is less attenuation. The spurious emission attenuation for space services is 43 + 10 log P or 60 dBc in a reference bandwidth of 4 kHz, whichever is less attenuation, or equivalently, 19 + 10 log P or 36 dBc in a reference bandwidth of 1 MHz, whichever is less attenuation.

FIGURE 52

OoB mask for BSS systems

(Attenuation within the OoB domain for BSS systems (dBsD))



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13.4.2 Calculation of the interference level

In cases where application of RR No. 1.153 provides improvements in the consideration of compatibility, this footnote should be taken into account:

"**1.153** *occupied bandwidth*: The width of a frequency band such that, below the lower and above the upper frequency limits, the *mean powers* emitted are each equal to a specified percentage β/2 of the *mean power* of a given *emission*.

Unless otherwise specified in an ITU-R Recommendation for the appropriate *class of emission*, the value of β/2 should be taken as 0.5%."

If the lower edge of the occupied bandwidth was at or above the lower limit of the satellite service allocation, the total power of the unwanted emissions at frequencies below the allocated bandwidth would be no greater than 0.5% of P, where P is the in-band power. Therefore, the total power of unwanted emission at frequencies in the 50.2-50.4 GHz EESS band would be no greater than P - 23 dB.

13.4.3 Values achieved

13.4.3.1 FSS/MSS case

The application of Recommendation ITU-R SM.1541 for the FSS/MSS systems using a necessary bandwidth lead to an integrated pfd over the whole RAS band of 108.5 dB(W/(m^2 · 10 MHz)). The application of RR No. 1.153 leads to a total pfd of –123 dB(W/(m^2 · 10 MHz)). This means the protection criteria for continuum observations will not be met.

The pfd integrated over 20 kHz, at the edge of the RAS band, is equal to -130 dB(W/(m^2 · 20 kHz)), i.e. about 30 dB above the VLBI protection criteria.

13.4.3.2 BSS case

Based on the pfd limit given in Article 21 (–137 dB(W/(m^2 · 4 kHz))), assuming a necessary bandwidth of 18 MHz and by applying the mask described in § 13.4.1.2, for a BSS system operating below 2 670 MHz, the maximum pfd falling into a 10 MHz reference bandwidth is equal to -121 dB(W/(m^2 · 10 MHz)), i.e. about 56 dB above the criteria given for continuum observations.

The application of RR No. 1.153 leads to a pfd of –123.5 dB(W/(m^2 · 10 MHz)). This means the protection criteria for continuum observations will not be met.

The pfd due to a BSS system operating below 2 670 MHz and integrated over 20 kHz, at the edge of the RAS band, is equal to –146 dB(W/(m^2 · 20 kHz)), which is about 15 dB above the VLBI protection criteria.

13.5 Mitigation techniques

13.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for G/T, i.e. telescope gain divided by system temperature. This is to maximize the S/N for point sources. A key element of this approach is to reduce ground radiation entering through far side-lobes. Inevitably this leads to some corresponding increase in the levels of near side-lobes. Experience has shown that the majority of radio telescopes meet the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

Guardband: A guardband is a technique to provide adequate separation in frequency between the active and passive services. In general, it will equitably straddle the boundary between the frequency bands of the active and passive services.

Geographical isolation: The geographic isolation of specific radio astronomy sites can be a factor in favour of protecting observations at these sites, given the orbital location of a specific BSS/FSS satellite, as there will be relatively few satellites.

13.5.2 FSS/BSS

This service involves continuous transmission of signals continually or for long periods of time, with constant power and spectrum. Possible mitigation procedures are to avoid transmitting unwanted emissions in the direction of the radio astronomy stations that use this band, or to use filters to appropriately suppress unwanted emissions to a level where detrimental interference to radio astronomical observations in the 2 690-2 700 MHz is not caused.

13.5.3 Potential impact

13.5.3.1 RAS

Antenna side-lobe performance: Attempts to decrease the sensitivity of the radio astronomy antenna to unwanted emissions coming from space stations are likely to increase the sensitivity of the radio astronomy telescope to ground radiation, and possibly reduce its main beam gain. Both of these effects will reduce the telescope’s channel capacity of and thus lead to an increase of the total required integration time.

Blanking in time and/or frequency: Blanking involves a risk of compromising the integrity of the data and may lead to errors in their scientific interpretation. Blanking also causes a concomitant increase in the total integration time required to make the observation, this is equivalent to a loss in the channel capacity of the telescope.

Guardband: In the case of broadband continuum measurements, the use of a guardband would effectively lead to a loss of channel capacity, since the integration time would need to be increased to compensate for the loss of bandwidth.

Geographical isolation: When considered on a case-by-case basis it is likely that there would be little impact on the radio astronomy sites concerned. This does necessarily provide protection of radio astronomy as a service, however.

13.5.3.2 FSS/BSS

Filters are an obvious way to suppress unwanted emissions, but the addition of such filters may affect the satellite design in a substantial manner. If a phased array, active antenna is used, filters may be required for every driven antenna element. This will increase the weight of the satellite. Compensating for filter losses will require more powerful transmitters, which in turn will require more bus power, and so, larger solar power arrays. The increase in weight could be sufficient to require a larger launcher. The cost impact could be large. Consequently filters can be considered only at the design stage of a system. However, continuing technical improvements in the design of filters and active antennas may in time reduce the problem of implementing such solutions to manageable proportions.

Since some multi-beam satellite systems are planned for operation in the frequency range of interest, the number of beams in the multi-beam system or the number of elements multiplies the cost and weight implications of additional RF filtering in the phased-array antenna system. This is due to the fact that in a multi-beam system the output amplifiers are generally not shared between beams, and so would have to be filtered separately. In a phased array type system the final stage of amplification takes place at the various elements of the array, each of which would have to be filtered separately. In this way the weight impact of an individual filter is multiplied by the number of beams in the system or the number of elements in the phased array. The filter insertion loss could impact system capacity.

Geographic isolation would involve the use of satellite antenna pattern roll-off to achieve the required isolation to meet an agreed sharing criterion at a particular radio astronomy receiver site. This technique tacitly assumes that an FSS system will not have a global, or even regional, coverage area, which is a limiting assumption in itself. Many systems have regional or sub-regional beams where geographic isolation is not feasible. Other spot beam systems may be able to use geographic isolation; however, this is not an attractive solution from the satellite system perspective as it could result in areas of the Earth being unavailable to the satellite service. Such limitations of the FSS service area could have serious revenue-generating implications. However, this solution does have the benefit of taking into account the actual protection requirements of specific radio astronomy sites, without the need to resort to the worst-case criteria at every radio astronomy site.

13.6 Results of studies

13.6.1 Summary

The interference calculation performed shows that, on the basis of the protection criteria discussed in § 13.1.3, if no mitigation techniques are applied, there is a possibility of detrimental interference to radio astronomy observations in the 2 690-2 700 MHz band by services in the adjacent band, at a level that would effectively prevent any useful astronomical measurements being made in that band.

Satellite operators will continue to work closely with the radio astronomy community to minimize the impact of satellite OoB emissions. In many instances normal satellite transponder filtering will be sufficient to ensure there is no harmful impact to the radio astronomy bands. When this is not the case, the impact of additional satellite filtering will be considered along with other mitigating techniques such as geographical pattern isolation and radio astronomy ground station isolation. This can be accomplished on a case-by-case basis depending on the radio astronomy site location and the orbital location.

13.6.2 Conclusion

Protection criteria are not met for single-dish continuum or spectral-line observations, or for VLBI.

14 Compatibility analysis between RAS systems operating in the 10.6-10.7 GHz band and FSS (space-to-Earth) systems operating in the 10.7-10.95 GHz band

14.1 RAS

14.1.1 Allocated band

The 10.6-10.7 GHz band is allocated to the RAS, EESS (passive) and SRS (passive) on a primary basis; the 10.68-10.7 GHz sub-band is allocated exclusively to these services, worldwide.

The following footnotes are of relevance to these bands: RR No. 5.149 for the band 10.6-10.68 GHz and RR No. 5.340 for the band 10.68-10.7 GHz.

14.1.2 Type of observations

14.1.2.1 Single dish observations

Astronomical uses of the band include the observation of non-thermal synchrotron sources that are just detectable at this frequency range. These observations provide information at the highest frequency where such sources can be easily detected, and this allows the determination of some physical parameters of these sources. The 10.6 GHz band is also extremely important for monitoring the intensity variability of radio galaxies, including quasars. These objects, believed to be the most distant celestial objects that astronomers can detect, have been found to vary in intensity with periods varying from hours to years, and to produce surprisingly large amounts of energy. The energy emitted during one such burst from a quasar is equivalent to the complete destruction of a few hundred million stars in a period of a few weeks or months. The fundamental physics that can produce such events are not yet fully understood and observations of the size and variability of these sources are crucial in solving these enigmas. Such observations are best performed in the frequency range 10 to 15 GHz.

The variability of quasars is pronounced at these frequencies, and their observation facilitates the discovery and the monitoring of such events, the physics of which is as yet poorly understood by astronomers. Observations lead us to estimate the sizes of these sources, which turn out to be very small for the amount of energy they produce. The 10.6 GHz band provides some of the best angular resolutions (~2 arc min) for many large, single-dish radio telescopes.

14.1.2.2 VLBI observations

The extremely small sizes of quasars (as small as milliarcseconds) are revealed from the VLBI observations. Such observations are also being made in the frequency band 10.6-10.7 GHz, though at present the 8.4 GHz is a more frequently used band for VLBI observations. The 8-10 GHz range provides a better angular resolution than observations made at lower frequencies and enable scientists to determine more accurately the sizes and small-scale structure of radio galaxies.

14.1.3 Required protection criteria

Recommendation ITU-R RA.769 specifies the protection criteria for radio astronomical observations and gives threshold levels of detrimental interference for primary radio astronomy bands. In the 10.6-10.7 GHz band, for single-dish continuum observations making use of the entire 100 MHz bandwidth, the threshold pfd limit is –160 dB(W/m^2) This band is used only for continuum observations, not for radio line observations.

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, –145 dB(W/m^2), for a bandwidth of 50 kHz.

For detrimental interference from non-GSO systems, the protection criteria and the relevant methodologies are described in Recommendations ITU-R RA.769 and ITU-R RA.1513, as well as in Recommendation ITU-R S.1586 for FSS systems and in Recommendation ITU-R M.1583 for MSS and RNSS systems.

The thresholds of detrimental interference levels to the radio astronomy service as defined and calculated in the Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealised circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes 10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

14.1.4 Operational characteristics

Observations in the 10.6-10.7 GHz band are carried out at a number of radio astronomy sites worldwide; these are made using single-antenna and array radio telescopes.

In general, observations are made differentially. In the case of continuum emissions, the area of sky containing the source may be mapped and the background emission subtracted, or measurements made of the power coming from the direction of the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

Extended areas of radio emission can be mapped by recording the emission from a grid of points covering the region of interest. In the case of single antenna radio telescopes, each grid point observation is an indication of the total power coming from that position in the sky; the spacing between the grid points should not be more than half the antenna beamwidth. When observations are made using a synthesis radio telescope, where the area to be mapped exceeds the instantaneous mapping field, the grid points should not be further apart than half the beamwidth of one of the radio telescope antennas.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data have been processed.

14.2 FSS

14.2.1 Allocated transmit band

The active service band considered is from 10.7 to 10.95 GHz.

14.2.2 Application

The band 10.7 to 10.95 GHz is allocated to the FSS on a primary basis. This allocation is governed by RR Appendix 30B that uses a plan to assign and guarantee capacity to all member nations. Given the general policy of first-come, first-served in unplanned bands, the creation of the RR Appendix 30B Plan allowed developing nations to preserve access to the GSO arc at a future time. Any imposition of constraints such as guardbands or filtering on the FSS would impact the RR Appendix 30B Plan allotments.

14.2.3 Levels based upon regulatory provisions

Levels of unwanted emissions into the band 10.6-10.7 GHz from the FSS are based on regulatory in-band pfd limits. The conversion from in band to OoB power is done using the RR Appendix 3 spurious emission levels and the OoB emission levels from Recommendation ITU-R SM.1541. A level of –154 dB(W/(m^2 · 4 kHz)) is the level of unwanted emissions that would be received in the band 10.6 to 10.7 GHz based on regulatory levels. A level of -166 dB(W/(m^2 · 4 kHz)) was provided, which is based on practical experience.

14.2.4 Transmitter characteristics

FSS GSO systems operating in the band are governed by RR Appendix 30B. FSS non-GSO systems operating in the band are governed by RR Article 22.

14.2.5 Operational characteristics

In order to share with the terrestrial fixed service, the in-band pfd limit from RR Table 21-4 for the FSS ranges from −116 to −126 dB(W/(m^2 · MHz)) which represents a range from −176 to -186 dB(W/(m^2 · Hz)) between 0° and 90° above the horizontal plane.

14.3 Compatibility threshold

See § 14.1.3.

14.4 Interference assessment

14.4.1 Methodology used to assess the interference level

Based on experience acquired with some radio astronomy sites and some satellite systems in these bands, information was provided by the radio astronomy community and satellite operators on unwanted levels that could be expected in the band 10.6-10.7 GHz.

14.4.2 Calculation of the interference level

The calculations performed are all based on information provided in § 14.4.3, as indicated in § 14.4.1.

14.4.3 Values achieved

14.4.3.1 European example for GSO satellite systems

In Europe, the RAS in the frequency band 10.6-10.7 GHz experiences severe harmful interference by OoB emissions from one FSS system. Specifically, this harmful interference has effectively rendered observations in this band completely impossible at the Effelsberg radio observatory in Germany. The issue has been brought to the attention of the German Administration, which confirmed the observed interference by observations at the Leeheim Satellite Monitoring Station of the German Administration and supported by this evidence also to the attention of the operator.

For example, one real case of interference to RAS operations is described below, with a particular GEO FSS satellite system operating at lower nominal centre frequency of 10.714 MHz with a transponder bandwidth of 26 MHz.

Figure 53 shows the results of RAS measurement at 10.6 GHz by the Effelsberg 100 m radio telescope, looking towards 3C84, one of the strongest point-like cosmic radio sources. This measurement was made before 1995. The field size is 30' × 12', the flux from the source is 20.5 Jy (~ -247 $dB(W/(m^{-2} \cdot Hz^{-1})))$.

FIGURE 53

Map of the galactic object “3C84” in the 10.6-10-7 GHz band with the Effelsberg 100 m radio telescope*

* The source 3C84 has an angular diameter much smaller than the antenna beamwidth, so the image above shows the antenna beam profile, including side-lobes. Since the map has been made to measure the source brightness and not its structure, this is not a problem.

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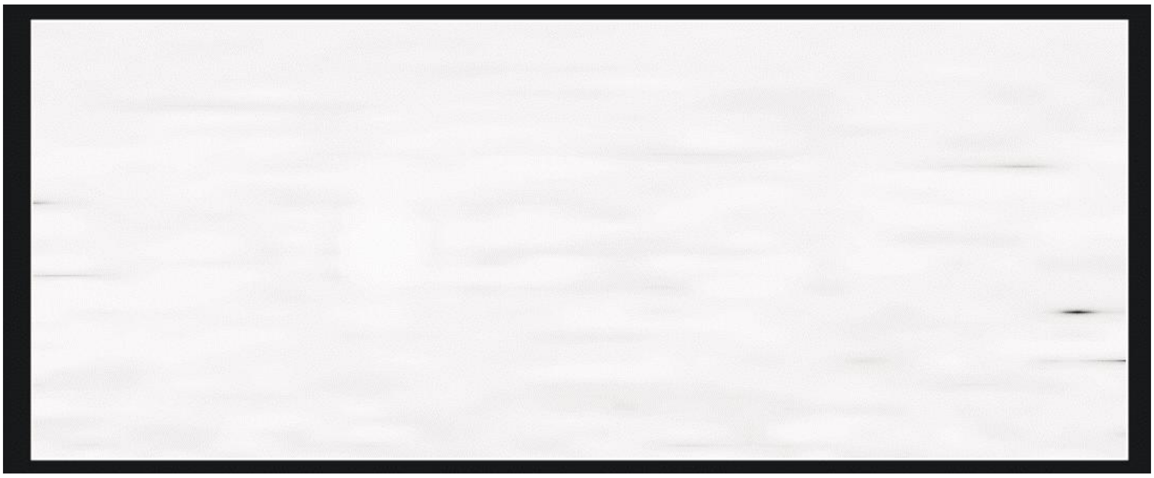
Then in the year 1995 a GSO FSS satellite was put into operation at certain orbital position, where other satellites had been already operating for some time. The satellite has a lower transmitting centre frequency of 10.714 GHz and a transponder bandwidth of 26 MHz. The resulting noise fluctuation generated by unwanted FSS emissions from that orbital position into adjacent RAS band 10.6-10.7 GHz was so strong, that it completely masked any astronomical signals.

Therefore, Fig. 54 shows a consequent map in the same 30' × 12' field of the sky as shown in Fig. 53, but after the satellite was put into operation in the year 1995, its orbital position being spaced 10° from the mapped field of the sky. For comparison, the 3C84 picture from Fig. 53 has been added onto the map in Fig. 54. However, this very strong point source is now no longer visible against the flux caused by the satellite’s emissions.

FIGURE 54

Map of the sky field as in Fig. 53, but with interference received at Effelsberg radio telescope



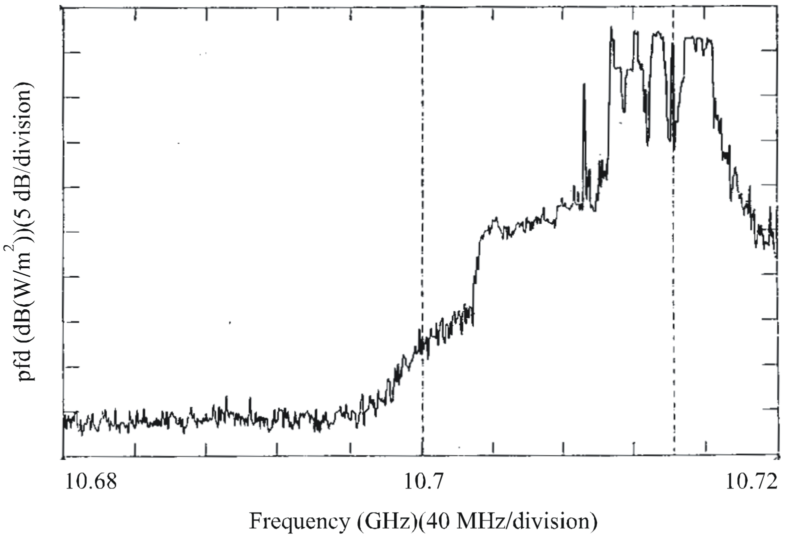
Rap 2091-54

To investigate this case of interference, the satellite monitoring station at Leeheim of the German Regulatory Authority measured a spectrum of the FSS transmissions from the given satellite orbital location (see Fig. 55), in order to determine the level of unwanted emissions into the RAS band. However it should be noted, that the sensitivity and the dynamic range of the monitoring station are not sufficient to verify interference at the levels given as protection criteria for the RAS in Recommendation ITU-R RA.769.

NOTE 1 – In Fig. 54, the galactic object is no longer visible due to interference received.

FIGURE 55

Measurement of interference source conducted at Leeheim monitoring station (1995)



Rap 2091-55

It may be seen from Fig. 55 that at the 10.7 GHz edge of the RAS allocation, in the passive exclusive band, the unwanted emission level is measured to be –151 dB(W/m^2) in a reference bandwidth of 100 kHz. This corresponds to –201 dB(W/(m^2 · Hz)), whereas Recommendation ITU-R RA.769 gives a 39 dB lower number, –240 dB(W/(m^2 · Hz)), as interference threshold, and additionally considers desirable that more stringent limits of 15 dB be applied in case of GSO satellites. This huge discrepancy occurs at the high edge of the 10.6-10.7 GHz band, and is lower in the rest of the band.

Down from the edge of 10.7 GHz until about 10.69 GHz, where the interfering signal reaches the noise floor of the Leeheim monitoring station (pfd ~ -160 dB(W/m^2)), its roll-off is about 10 dB per 4 MHz. If one assumes that this roll-off rate continues down to 10.6 GHz, the estimated total power emitted from that orbital location into the 10.6-10.7 GHz band would be -145.6 dB(W/m^2), which is 14.4 dB above the -160 dB(W/m^2) threshold given in Recommendation ITU-R RA.769 for the 10.6-10.7 GHz band, and therefore renders the entire 10.6-10.7 GHz completely unusable for radio astronomy observations, as shown in Fig. 54.

Though the operator of the satellite system did improve the system to some extent and filters were installed at the Effelsberg radio telescope an effective solution of this problem is not yet possible.

The following values of levels of unwanted emissions from typical FSS systems falling into the RAS band were provided. Two operators identified that any limit lower than the levels in Table 39 would impose undue constraint on FSS systems currently operating in the 10.7-10.95 GHz frequency band.

TABLE 39

Levels of unwanted emissions falling into the 10.57-10.7 GHz frequency band at specific points

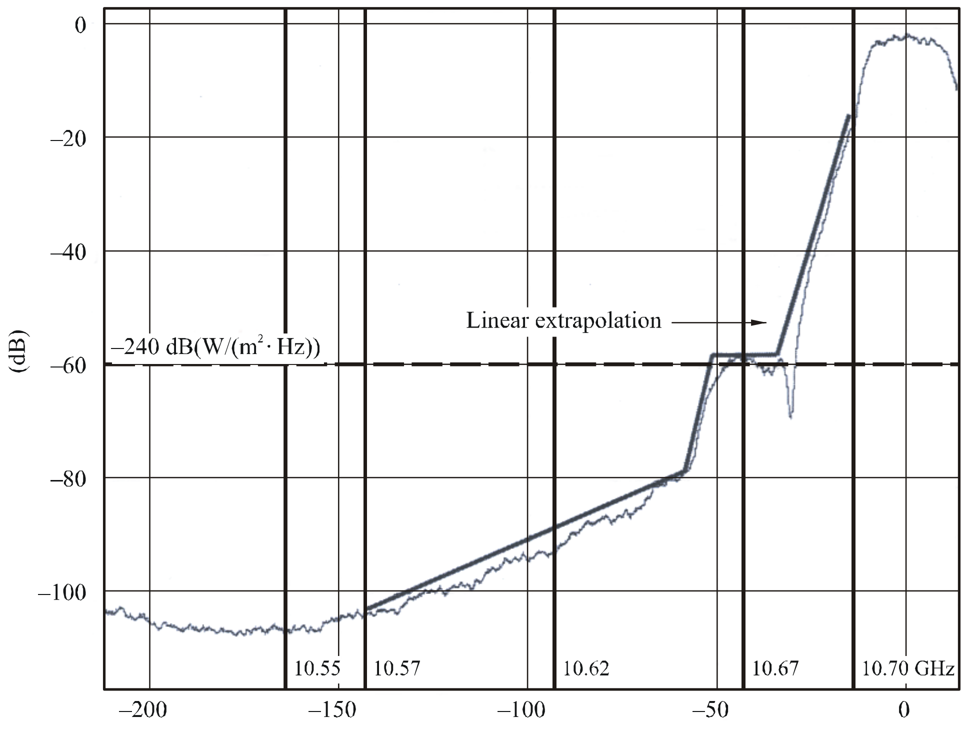
Boundary (GHz)	**Unwanted emission spfd level (dB(W/(m^2 · Hz)))**
10.570	–285
10.656	–256
10.662	–237
10.680	–237
10.700	–195

Figure 56 shows the spfd levels of a digital modulation with a symbol rate of 22 Msymbol/s, a roll-off of 35% and a transponder bandwidth of 26 MHz operating at 10 714 MHz. For practical reasons, the real power decrease was extrapolated by a linear power decrease in order to estimate the power falling into the entire 100 MHz radio astronomy band depending of the frequency offset.

Due to the nature itself of the digital modulation, the digital modulation necessary bandwidth is very close to the transponder bandwidth. Therefore, the spfd levels falling into the upper part of the RAS frequency band is much greater than the spfd levels observed for an analogue modulation (see Fig. 57.

FIGURE 56

Digital OoB emission mask

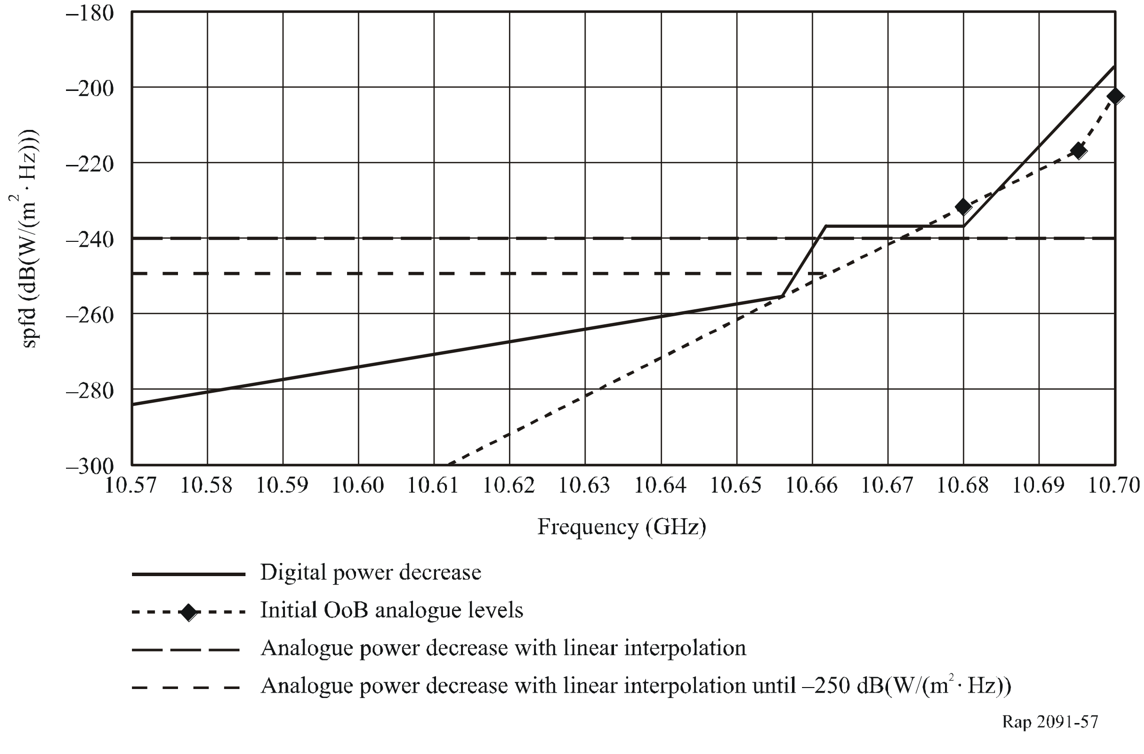


Symbole rate: 22 Msymbol/s, 35% roll-off

Rap 2091-56

FIGURE 57

Comparison of spfd levels depending on the type of modulation

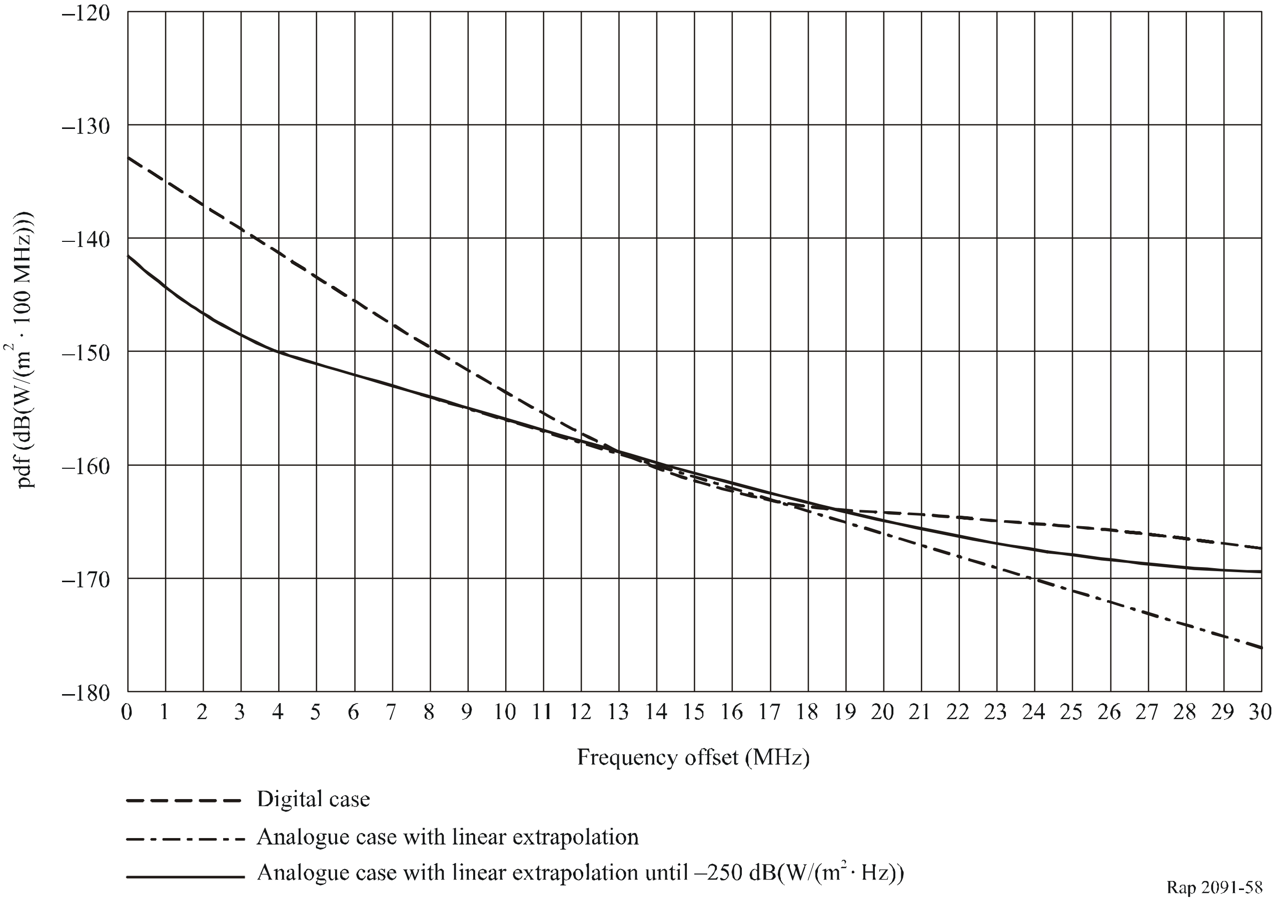


Rap 2091-57

From Fig. 57, it is possible to calculate the power falling into a 100 MHz reference bandwidth depending on the frequency where the integrations starts (see Fig. 58).

FIGURE 58

pfd integrated over a 100 MHz bandwidth depending on the type of modulation



In Fig. 58, a frequency offset of 0 MHz means that the integration over 100 MHz starts from 10.7 GHz (and thus ends up at 10.6 GHz), similarly a frequency offset of 30 MHz means that the integration over 100 MHz starts from 10.67 GHz (and thus ends up at 10.57 GHz).

From Fig. 58, under the assumptions that were made with regard to the signal decrease, the threshold level for continuum observations, i.e. –160 dB(W/(m^2 · 100 MHz)), would be met with the implementation of a guardband of at least 15 MHz between the two services. A different assumption with regard to the signal decrease could result in a larger required guardband.

Therefore, to reach a conclusion on a possible frequency separation that would make both services compatible in this example, the assumptions in terms of signal decrease should be validated.

14.4.3.2 Region 2 example for GSO satellite systems

In November 1993 the United States National Radio Astronomy Observatory (NRAO) conducted a survey of the geostationary belt from 152° W to 7° W in the 10.68-10.7 GHz band, using its 43 m telescope at Green Bank, West Virginia, (since decommissioned) to determine the levels of emission that may be present, and determined that this portion of the sky was free of emissions to at least the –250 dB(W/(m^2 · Hz)) level.

One case in Region 2 concerns two identical GSO satellites operating in the 10.75-10.95 GHz band, and using the 10.75-10.95 GHz band in accordance with RR Appendix 30B to provide feeder links for an MSS application. In another case, an operator provided data on the expected performance of their space station in the 10.6-10.7 GHz band.

In the case of the two identical GSO satellites mentioned above, special filters providing attenuation just over 40 dB in the 10.6-10.7 GHz band were installed at significant expense to the operators, to satisfy domestic concerns of protection of the passive services. The satellites generate interference into the 10.68-10.7 GHz band from two independent sources:

– radiated thermal noise generated in a travelling wave tube amplifier (TWTA). The worst case thermal tube noise e.i.r.p. was measured to be −27 dB(W/4 kHz) at the peak of the antenna pattern in the 10.68-10.7 GHz band, resulting in a spfd of -226.2 dB(W/($m^2 \cdot$ Hz)), after subtraction of a spreading loss of -163.2 dB(W/m^2); and

– intermodulation (IM) products among carriers generated by non-linearities in the TWTA. The 10.75 to 10.95 GHz downlink band is subdivided into 27 sub-bands, each carrying varying numbers of radio carriers. Under peak loading conditions, approximately 600 carriers will be on simultaneously and distributed across the sub-bands. In order to estimate the level of IM falling in the radio astronomy band, a worst-case simulation was done in which the sub-bands were filled with Gaussian noise to simulate the presence of many carriers, and the TWTA was run at maximum loading level. The simulation used measured TWTA input-output transfer characteristics and resulted in a peak IM product spfd level (including all IM product orders) in the 10.69-10.70 GHz band of –223.0 dB(W/($m^2 \cdot$ Hz)). The average worst case IM spfd over this band is -231 dB(W/($m^2 \cdot$ Hz)). Values for the remainder of the RAS band are approximately 5 dB less (i.e. peak of –228.0 and average of –236.0 dB(W/($m^2 \cdot$ Hz)).

The IM is generated by hundreds of independent radio carriers that are modulated by random, independent bit streams. Each modulator applies a 24-bit maximal pseudo-random noise sequence on top of the information stream, assuring minimal cross-correlation between carriers. There are thousands of individual independent products distributed across the radio astronomy band. The radio carriers themselves are turned on only when speech is present, further adding to the randomness of the composite IM signal. It therefore appears that the IM products will behave very much like wideband Gaussian noise.

The radio carriers are demand assigned when needed, otherwise they are turned off. As a result, these worst-case conditions will occur during normal business day busy hours typically occurring in a twelve-hour period during the day. At night, weekends and holidays the peak loading will be greatly reduced. This reduction in loading moves the operation of the TWTA into a more linear region, reducing the IM level. Fewer radio carriers also reduce the number of IM products. During these off-peak periods the IM spfd is reduced by at least 40 dB, or in the vicinity of −260 dB(W/($m^2 \cdot$ Hz)).

Total interference estimate: the tube noise and IM noise combined are wideband Gaussian distributed. The worst-case average spfd across the 10.6 to 10.69 GHz band is estimated to be -225.6 dB(W/($m^2 \cdot$ Hz)), rising to -221.3 dB(W/($m^2 \cdot$ Hz)) at 10.7 GHz. During light traffic loading periods the average spfd across the entire band is estimated to be -226.2 dB(W/($m^2 \cdot$ Hz)).

14.4.3.2.1 Computer simulation

One study based on a computer simulation demonstrated that the bringing into use of any RR Appendix 30B allotment would cause interference above the continuum pfd threshold level listed in § 14.1.3 for all radio telescopes having visibility of the space station. The study highlighted the fact that the largest portion of the unwanted emission power falling into the 10.6-10.7 GHz band occurs on the band edge. It should be pointed out that the use of Recommendation ITU-R SM.1541 to establish the OoB level overestimates the unwanted emission level, as this represents integration over a worst-case mask. Additional studies are required based on a mask representing typical unwanted emission performance.

14.4.3.3 Non-GSO satellite systems

As yet no non-GSO satellite system operates in the 10.7-10.95 GHz band, but several are planned to begin operations in the near future. Preliminary calculations were performed for one of these systems (F-SATMULTI1 B), using the epfd method (see Recommendations ITU-R RA.1513 and ITU-R S.1586). These calculations show that using the assumptions in Recommendation ITU-R RA.769, filtering values between 30 dB and 40 dB, would be required to protect the RAS in the 10.7 GHz band from spurious emissions of this system to the -240 dB(W/(m^2 · Hz)) level within a 100 MHz bandwidth. This result is consistent with the first GSO example described above.

14.5 Mitigation techniques

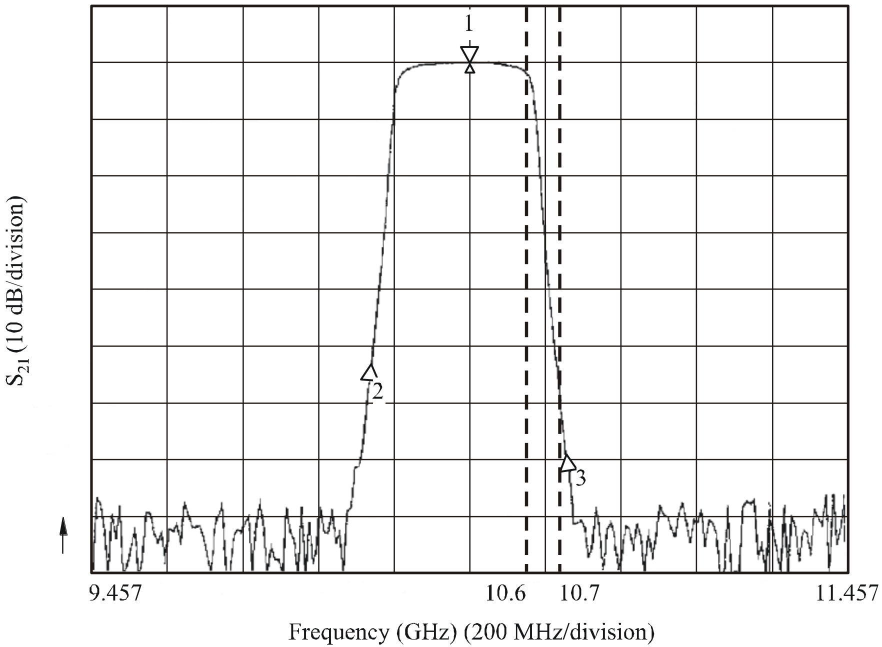
14.5.1 RAS

In order to continue RAS observations in the interference situation described in § 14.4.3.1, a filter was introduced into the receiver front-end of the radiotelescope. The specification for the filter was designed so as to suppress the main transmission from an interference source by 70 dB, while leaving sufficient pass-band with minimal insertion loss.

Amplifiers based on field effect transistors could be retuned to the somewhat lower frequency without loss of gain or increase in noise figure and a good commercially available filter design could be found. Figure 59 shows the transfer function for the filter, as provided by the filter manufacturer.

FIGURE 59

Filter attenuation curve of the band-rejection filter implemented at the radiotelescope mentioned in § 4.3.1



Rap 2091-59

Marker 3 in Fig. 59 is set to the nominal centre frequency of interfering satellite transmission, that is 10.714 GHz. Note that the RAS band allocation, 10.6-10.7 GHz is marked by the dashed lines.

It should be noted that the above-described filter, which has been designed to protect the RAS receiver, provides minimal insertion loss at a frequency separation of roughly 200 MHz from the centre frequency of a rejected signal. As filter technology progresses, better figures may be achievable, but the currently available instrumentation requires a frequency shift of at least 100 MHz to be made.

It should be also noted that usable RAS observations could be made at Effelsberg in a frequency band around 10.5 GHz, which is allocated to the terrestrial fixed service, and in which interference is reported only occasionally. This may not be applicable in other countries due to their particular use of the fixed service in this band.

14.5.2 The active service

A number of possible mitigation methods may be implemented to minimize the impact on the passive service. These are listed in Recommendation ITU-R SM.1542. Certain specific cases that have been applied to protect the passive services operating in the band 10.6-10.7 GHz are listed below:

– One administration found that, while interference limits in Recommendation ITU-R RA.769 provided protection against interference to RAS operations, more flexibility could be exercised by requiring that non-GSO FSS service providers coordinate and reach a mutually acceptable agreement with the RAS facilities that use the 10.6-10.7 GHz band, that ensure that these facilities are adequately protected from interference. To that effect, a footnote was added to the relevant National Table of Allocations. The text of this footnote is as follows:

  "In the band 10.7-11.7 GHz, non-geostationary-satellite orbit licensees in the fixed-satellite service (space-to-Earth), prior to commencing operations, shall coordinate with the following radio astronomy observatories to achieve a mutually acceptable agreement regarding the protection of the radio telescope facilities operating in the band 10.6-10.7 GHz."

  NOTE 1 – In this place in the footnote, a Table of Radio Astronomy sites follows.

– One contribution suggests that the possibility to set a guardband between the FSS band and the RAS band should be considered (see considerations on this issue in § 14.4.3.1). Results of the band-by-band studies may conclude that the only option is to seek the implementation of a guardband between the FSS and RAS. However, the apportionment of the burden of the guardband between the services needs consideration.

  It should be kept in mind that any guardband imposed on the FSS would impact the RR Appendix 30B Plan. Similarly, any guardband imposed on the RAS would result in an increase in measurement time thus reducing the usage of RAS stations.

  Similarly, if an extension of the RAS allocation below 10.6 GHz is considered to allow the RAS service to operate properly in a 100 MHz bandwidth, this may impact services operating below 10.6 GHz.

14.5.3 Potential impact

14.5.3.1 RAS

From the radio astronomy side, it is technically not possible to filter the interference mentioned in § 14.4.3.1. Even a well designed BSS/FSS system would force radio astronomy observatories to insert filters into the receiver front ends. The receiver front ends in use today at radio observatories normally contain cooled high electron mobility transistor (HEMT) amplifiers, which are inherently broadbanded. The passband of the first stage amplifier drops slowly outside the edge of the designed bandwidth. Satellite transmitters, especially, which come close enough to the observing direction, may cause non-linearity of the receiving system and therefore filtering may be required before the first amplifier stage of the receiver front-end. In designing radio astronomy receivers, however, one always tries to avoid transmission loss, which raises the receiver noise temperature. This loss would occur when insufficient guardband is taken into account to protect radio astronomy observations, also because at the frequencies under consideration the filter technology is not developed sufficiently.

14.5.3.2 FSS

Filters may be used to suppress unwanted emissions, but the addition of filters may affect the satellite design in a substantial manner:

- The insertion loss introduced by the filter can result in a loss of capacity. To compensate for the loss requires an increase in HPA size, with consequential impacts to the space station design (cost, weight, power, reliability).
- The insertion of a filter impacts the phase response of the in-band signal. If the phase tolerance levels of the receiver are exceeded, the performance of the link will be impacted even though there is sufficient power at the receiver.
- The addition of a filter increases the complexity of the space station design and testing program.

Furthermore, if a phased-array active antenna is used, filters may be required for every antenna element.

For multi-beam satellite systems planned for operation in the frequency range of interest, the number of beams or the number of elements in the phased-array antenna system multiplies the cost and weight implications of additional RF filtering in the multi-beam system. This is due to the fact that in a multi-beam system the output amplifiers are generally not shared between beams, and so would have to be filtered separately. In a phased array type system the final stage of amplification takes place at the various elements of the array, each of which would have to be filtered separately. In this way the number of beams multiplies the weight impact of an individual filter in the system, or number of elements in the phased array. The filter insertion loss could impact system capacity.

Geographic isolation would involve the use of satellite antenna pattern roll-off to achieve the required isolation to meet an agreed sharing criterion at a particular radio astronomy receiver site. This technique tacitly assumes that an FSS system will not have a global, or even regional, coverage area, which is a limiting assumption in itself. Many 10-14 GHz band systems have regional or sub-regional beams where geographic isolation is not feasible. Other spot beam systems may be able to use geographic isolation; however, this is not an attractive solution from the satellite system perspective at is could result in areas of the Earth being unavailable to the satellite service. Such limitations of the FSS service area could have serious revenue-generating implications. However, this solution does have the benefit of taking into account the actual protection requirements of specific radio astronomy sites, without the need to resort to the worst-case criteria at every radio astronomy site.

14.6 Results of studies

14.6.1 Summary

In Region 2, currently available design practices and mitigation methods have protected the radio astronomy service in the 10.6-10.7 GHz band from the limited number of FSS space stations currently deployed. In cases where the usage of the RR Appendix 30B Plan may have interfered with radio astronomy observations, domestic pressure in another country ensured that the situation was corrected. However the deployment of future space stations that do not intentionally seek to protect radio telescopes could adversely impact their operations.

In Region 1, the juxtaposition of bands allocated to the RAS and the FSS or BSS, for use in transmitting signals in the space-to-Earth direction, has given rise to a difficult interference situation in some countries – one that can only be solved through the provision of a guardband between the two services. In this band, the protection criteria listed in § 14.1.3 are satisfied by the active service for the VLBI case, but not for the single-dish continuum case. Mitigation methods have been used in Region 2 to meet the single-dish continuum level. However, in Region 1 there are currently persistent cases of detrimental interference.

No data was received and no studies were done for Region 3.

14.6.2 Conclusion

In Region 1 the protection criteria are met for the VLBI case, but not for single-dish continuum or spectral line observations. In Region 2 the protection criteria are met for the VLBI case.

15 Compatibility analysis between RAS systems operating in the 22.21-22.5 GHz band and BSS (space-to-Earth) systems operating in the 21.4-22 GHz band

15.1 RAS

15.1.1 Allocated band

The 22.21-22.5 GHz band is allocated on a primary basis to the RAS.

RR No. 5.149 urges administrations to take all practicable steps to protect the radio astronomy service from harmful interference.

15.1.2 Type of observations

The frequency band is used by the RAS for both continuum observations as well as spectroscopic line observations of the water molecule, whose spectroscopic band in this frequency range is one of the most important for radio astronomy (see Recommendation ITU-R RA.314, Table 40 and the List of Important Spectral Lines of the International Astronomical Union).

The water molecule transitions in this band are observed using both single-dish and VLBI techniques.

15.1.3 Required protection criteria

Recommendation ITU-R RA.769 specifies the protection criteria for radio astronomical observations and gives threshold levels of detrimental interference for primary radio astronomy bands.

For the 22.21-22.5 GHz band, the pfd threshold limit given in Recommendation ITU-R RA.769 for single-dish line observations made using a channel bandwidth (one of the spectrometer channels) of 250 kHz is –162 dB(W/m^2). A pfd threshold limit of –146 dB(W/m^2) is defined for single-dish continuum observations in this band, made using the entire 290 MHz bandwidth.

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, –128 dB(W/m^2), for a bandwidth of 250 kHz.

For detrimental interference from non-GSO systems, the protection criteria and the relevant methodologies are described in Recommendations ITU-R RA.769 and ITU-R RA.1513, as well as in Recommendation ITU-R S.1586 for FSS systems and in Recommendation ITU-R M.1583 for MSS and RNSS systems.

The thresholds of detrimental interference levels to the RAS as defined and calculated in the Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealised circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes 10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

15.1.4 Operational characteristics

Observations in the 22.21-22.5 GHz band are carried out at a number of radio astronomy sites in numerous countries, worldwide. They may be of continuum emissions, spectral lines, or VLBI experiments. Observations in this band are sometimes conducted on targets of opportunity, e.g. on objects such as comets. VLBI spectral line observations are also frequently conducted in this band.

Spectral line observations are made using multichannel spectrometers that can integrate simultaneously the power in many (typically 256 to 4 096) frequency channels distributed across the band. The number of channels and their individual bandwidths are chosen to adequately sample the spectrum of the net emission from the sources in the antenna beam.

In general, observations are made differentially. In the case of continuum emissions, a map may be made of the area of sky containing the source, and the background emission subtracted, measurements are made of the power coming from the direction from the source (on-source) and at one or more nearby positions in the sky (off-source). By subtracting the off-source values from the on-source values, the emission originating in the source is separated from other contributions to the receiver output.

In the case of spectral line observations, spectra are recorded at frequency ranges including the line emissions of interest (the line spectra), and then at a frequency that is offset from the line emissions, or at the same frequency but at a nearby position in the sky (the reference spectra). By subtracting the reference spectra from the line spectra, unwanted noise contributions and other contaminants can be removed from the data.

Extended areas of radio emission are mapped by recording the emission from a grid of points covering the region of interest. Both continuum and spectral line observations may be made. In the case of single antenna radio telescopes, each grid point observation is an indication of the total power (in the continuum case) or the emission spectrum (in the spectral line case) coming from that position in the sky; the spacing between the grid points should not be more than half the antenna beamwidth. When observations are made using a synthesis radio telescope, where the area to be mapped exceeds the instantaneous mapping field, the grid points should not be further apart than half the beamwidth of one of the radio telescope antennas.

VLBI observations are made by down-converting the signals to a baseband, digitizing them without rectification, and recording them on tape or other storage media, along with precise timing signals. The data are then taken to a VLBI data processing centre, where the signals are synchronized and correlated. Consequently, the full impact of interference might not be known until the observing period is over and the data has been processed.

15.2 BSS

15.2.1 Allocated transmit band

The frequency range of the active service allocation is from 21.4 to 22 GHz.

15.2.2 Service

WARC-92 has reallocated the band 21.4-22.0 GHz in Regions 1 and 3 to the BSS high definition digital television (HDTV) service to be implemented after 1 April 2007. This band has been identified for the development of a future allotment plan.

15.2.3 Levels based on regulatory provision

Annex to Resolution 525 (Rev.WRC-03), Section III – Interim procedure relating to operational BSS (HDTV) systems introduced before 1 April 2007.

For the purpose of introducing operational BSS (HDTV) systems in the band 21.4-22.0 GHz in Regions 1 and 3 before 1 April 2007, the procedure contained in Resolution 33 (Rev.WRC-03) shall be applied if the pfd at the Earth's surface produced by emissions from a space station, on the territory of any other country, exceeds:

- -115 dB(W/m^2) in any 1 MHz band for angles of arrival between 0° and 5° above the horizontal plane; or
- -105 dB(W/m^2) in any 1 MHz band for angles of arrival between 25° and 90° above the horizontal plane; or
- values to be derived by linear interpolation between these limits for angles of arrival between 5° and 25° above the horizontal plane.

Annex to Resolution 525 (Rev.WRC-03), Section IV – Interim procedure relating to BSS (HDTV) systems introduced after 1 April 2007.

For the purpose of introducing and operating BSS (HDTV) systems in the band 21.4-22.0 GHz in Regions 1 and 3 after 1 April 2007, and before a future conference has taken decisions on definitive regulatory procedure, all relevant provisions of RR Articles 9 to 14 except RR No. 9.11 shall be applied.

15.2.4 Transmitter characteristics

The following characteristics were used:

- the antenna gain of the BSS system is the same in the BSS and in the RAS band;
- maximum spfd/pfd levels are used for the unwanted emissions from BSS systems falling into the RAS band;
- spectral regrowth of digital modulated signal due to transponder non-linearity;
- TWT noise falling into the RAS band; and
- improved characteristics of the OMUX filters.

15.2.5 Operational characteristics

This Section 15 only addresses the case of GSO systems. The case of non-GSO systems would have to be further studied.

15.2.6 In-band transmit level

See § 15.2.3.

15.3 Compatibility threshold

See § 15.1.3.

15.4 Interference assessment

15.4.1 Methodology used to assess the interference level

See § 15.2.4.

15.4.2 Calculation of interference level

Maximum levels of unwanted emissions from considered BSS systems operating in the band 21.4-22 GHz and falling into the 22.21-22.5 GHz radio astronomy band are given in Table 40.

TABLE 40

Maximum levels of unwanted emissions from BSS systems

Band (GHz)	Maximum unwanted narrow-band emission spfd level (dB(W/(m2 · Hz)))	Maximum unwanted wideband emission pfd level (dB(W/(m2 · 290 MHz)))
22.21-22.5	–221	–146

15.4.3 Values achieved

A comparison between the threshold pfd levels for the protection of the RAS in the 22.21-22.5 GHz band, as given in Recommendation ITU-R RA.769 (see § 15.1.3) and the unwanted emission levels produced by BSS systems provided in Table 40 lead to the results given in Table 41.

TABLE 41

Difference between Recommendation ITU-R RA.769 RAS threshold pfd levels and BSS unwanted emission levels

Type of observation	Continuum observations	Spectral line observations	VLBI observations
Difference between Recommendation ITU-R RA.769 RAS threshold pfd levels and BSS unwanted emission levels (dB)	0	+5	+37

From this calculation it follows that for single-dish continuum, single-dish spectral line observations and the VLBI observations, the threshold levels of Recommendation ITU-R RA.769 are met.

15.5 Mitigation methods

15.5.1 RAS

There are various methods, including those described below, which might be considered to reduce unwanted emissions from the satellite transmitters at a radio telescope.

Antenna side-lobe performance: The aperture illumination of radio telescopes is usually optimized for *G*/*T*, i.e. telescope gain divided by system temperature. This is to maximize the *S*/*N* for point sources. A key element of this approach is to reduce ground radiation entering through far side lobes. Inevitably this leads to some corresponding increase in the levels of near side-lobes. Experience has shown that the majority of radio telescopes meets the envelope side-lobe mask given in Recommendation ITU-R SA.509 over most directions.

Blanking in time and/or frequency: This technique may be applied in cases where interference into the radio astronomy frequency band can be fully and unambiguously identified in time and/or frequency.

15.5.2 BSS

Filters: This would involve the active system implementing additional RF filtering.

15.5.3 Potential impact

15.5.3.1 RAS

Antenna side-lobe performance: Attempts to decrease the sensitivity of the radio astronomy antenna to unwanted emissions coming from space stations are likely to increase the sensitivity of the radio astronomy telescope to ground radiation, and possibly reduce its main beam gain. Both of these effects will reduce the telescope channel capacity of and thus lead to an increase of the total required integration time.

Blanking in time and/or frequency: Blanking involves a risk of compromising the integrity of the data and may lead to errors in their scientific interpretation. Blanking also causes a concomitant increase in the total integration time required to make the observation, this is equivalent to a loss in the channel capacity of the telescope.

15.5.3.2 BSS

For multi-beam satellite systems planned for operation in the frequency range of interest, the number of beams in the multi-beam system, or number of elements, multiplies the cost and weight implications of additional RF filtering in the phased-array antenna system. This is due to the fact that in a multi-beam system the output amplifiers are generally not shared between beams, and so would have to be filtered separately. In a phased array type system the final stage of amplification takes place at the various elements of the array, each of which would have to be filtered separately. In this way the number of beams or number of elements in the phased array multiplies the weight impact of an individual filter in the system. The filter insertion loss could impact system capacity.

15.6 Results of studies

The calculations show that the protection criteria discussed in § 15.1.3 are met for all observation modes (VLBI, single-dish continuum, and spectral line).

16 Compatibility analysis between RAS systems operating in the 42.5-43.5 GHz band and FSS and BSS (space-to-Earth) systems operating in the 41.5-42.5 GHz band

16.1 RAS

16.1.1 Allocated band

The RAS shares the 42.5-43.5 GHz band with the fixed service, FSS (Earth-to-space) and mobile (except aeronautical mobile) service on a primary basis.

16.1.2 Type of observations

The 42.5-43.5 GHz band is used by the RAS for both continuum and spectral line observations. The band is very important for radio astronomy, because at approximately twice the frequency of the 23.6-24 GHz continuum band, it provides an effective point for the sampling of continuum emission at octave intervals, essential for the determination of the spectral index of radio sources. Observations of the continuum emission provide critical information on the physical state of the interstellar medium associated with star-forming regions. The 43 GHz band is also used extensively for studies of the cosmic microwave background (CMB). The band also includes the spectral lines associated with the silicon monoxide (SiO) molecule at rest frequencies of 42.519, 42.821, 43.122 and 43.424 GHz that are among the astrophysically most important lines, but which are not all listed in Recommendation ITU-R RA.314.

These are lines essential for studies of cosmic phenomena, such as the birth and death of stars.

16.1.3 Required protection criteria

Recommendation ITU-R RA.769 specifies the protection criteria for radio astronomical observations and gives threshold levels of detrimental interference for primary radio astronomy bands. In the 42.5-43.5 GHz band, for single dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 500 kHz, the threshold pfd for detrimental interference is -153 dB(W/m^2). For making single-dish continuum observations using the entire 1 GHz bandwidth, the threshold pfd limit is -137 dB(W/m^2).

VLBI observations, where signals from widely separated antennas are recorded and correlated after the observations, are much less susceptible to interference. This is reflected in the threshold pfd level for VLBI observations in this band, -116 dB(W/m^2), for a bandwidth of 500 kHz.

For detrimental interference from non-GSO systems, the protection criteria and the relevant methodologies are described in Recommendations ITU-R RA.769 and ITU-R RA.1513, as well as in Recommendation ITU-R S.1586 for FSS systems. The thresholds of detrimental interference levels to the RAS as defined and calculated in the Recommendation ITU-R RA.769 are protection criteria above which radio astronomical data are degraded and may be eventually obliterated. In principle, under rather idealized circumstances, if these levels are very slightly exceeded then it may be possible to compensate at the radio astronomy observatory by increased observing time. In doing so, the channel capacity of the telescope is reduced, with a corresponding reduction in scientific throughput. If the level of interference, under the assumptions of Recommendation ITU-R RA.769 (e.g. antenna performance, etc.), becomes 10 dB or more above the Recommendation ITU-R RA.769 definition, then increased observing time will no longer be effective in ensuring that valid scientific data are provided to the scientist. The radio astronomy station will be unable to operate in the affected frequency band, and its ability to provide service will have been lost if no appropriate mitigation techniques can be applied.

The following ITU-R Recommendations deal directly with, or may be relevant to, the protection of radio astronomy stations observing in the 42.5-43.5 GHz band:

Recommendation ITU-R RA.314 – Preferred frequency bands for radio astronomical measurements.

Recommendation ITU-R RA.517 – Protection of the radio astronomy services from transmitters operating in adjacent bands.

Recommendation ITU-R RA.611 – Protection of the radio astronomy service from spurious emissions.

Recommendation ITU-R RA.769 – Protection criteria used for radio astronomical measurements.

Recommendation ITU-R RA.1237 – Protection of the radio astronomy service from unwanted emissions resulting from applications of wideband digital modulation.

Recommendation ITU-R RA.1513 – Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy on a primary basis.

Recommendation ITU-R S.1586 – Calculation of unwanted emission levels produced by a non-geostationary fixed-satellite service satellite system at radio astronomy sites.

RR Nos 5.149, 5.547, 5.551AA and 5.551G apply to this band.

16.1.4 Operational characteristics

Radio astronomy observations in the 42.5-43.5 GHz band are carried out in all ITU Regions. Table 42 shows a list of radio astronomical observatories, which operate or are planned to operate in the 42.5-43.5 GHz band. Planned facilities are those under construction in Mexico (The Large Millimeter Telescope, a joint U.S.-Mexico project), Chile (The Atacama Large Millimeter Array) and Italy (Sardinia Telescope) or the implementation of this frequency band at the UK MERLIN interferometer array.

TABLE 42

Radio astronomy stations operating in the 42.5-43.5 GHz band

Region 1						
Country	**Site**	**Longitude**	**Latitude**	**Altitude (m)**	**Diameter (m)**	**Remarks**
Finland	Metsähovi	24° 23' 17"	60° 13' 04"	61	13.7	S
France	Bordeaux Plateau de Bure	–00° 31' 37" 5° 54' 26"	44° 50' 10" 44° 38' 01"	73 2 552	2.5 6 × 15	S S
Germany	Effelsberg	06° 53' 00"	50° 31' 32"	369	100	S
Italy	Medicina Noto Cagliari	11° 38' 43" 15° 03' 00" 09° 14' 40"	44° 31' 14" 36° 31' 48" 39° 29' 50"	44 85 570	32 32 64	S S S
Russian Federation	Dmitrov	37° 27' 00"	56° 26' 00"	200	32	S
Spain	Pico Veleta Yebes	–03° 23' 34" –03° 06' 00"	37° 03' 58" 40° 31' 30"	2 870 931	30 40	S S
Sweden	Onsala	11° 55' 35"	57° 23' 45"	10	20	S
United Kingdom (planned)	Cambridge Darnhall Jodrell Bank Knockin Pickmere	00° 02' 20" –02° 32' 03" –02° 18' 26" –02° 59' 45" –02° 26' 38"	52° 09' 59" 53° 09' 21" 53° 14' 10" 52° 47' 24" 53° 17' 18"	24 47 78 66 35	32 47 76 25 25	S S S S S

TABLE 42 (*end*)

Region 2						
Country	**Site**	**Longitude**	**Latitude**	**Altitude (m)**	**Diameter (m)**	**Remarks**
Brazil	Atibaia, SP	– 46° 33' 28"	–23° 11' 05"	805	13.7	S
Chile	San Pedro de Atacama	–67° 44' 00"	–23° 02' 00"	5 000	64 × 12	S
Mexico	Sierra Negra	–97° 18' 00"	18° 59' 00"	4 500	50	S
United States of America	Goldstone, CA Green Bank, WV Socorro, NM St. Croix, VI Hancock, NH North Liberty, IA Ft. Davis, TX Los Alamos, NM Pie Town, NM Kitt Peak, AZ Owens Valley, CA Brewster, WA Mauna Kea, HI Kitt Peak, AZ Mauna Kea, HI Westford, MA	–116° 47' 40" –79° 50' 24" –107° 37' 06" –64° 35' 01" –71° 59' 12" –91° 34' 27" –103° 56' 41" –106° 14' 44" –108° 07' 09" –111° 36' 45" –118° 16' 37" –119° 41' 00" –155° 27' 19" –111° 36' 50" –155° 28' 20" –71° 29' 19"	35° 14' 50" 38° 25' 59" 34° 04' 44" 17° 45' 24" 42° 56' 01" 41° 46' 17" 30° 38' 06" 35° 46' 31" 34° 18' 04" 31° 57' 23" 37° 13' 54" 48° 07' 52" 19° 48' 05" 31° 57' 10" 19° 49' 33" 42° 37' 23"	[] 1 071 946 16 309 241 1 615 1 967 2 371 1 916 1 207 255 3 720 1 916 3 720 [122]	34 100 27 × 25 25 25 25 25 25 25 25 25 25 25 12 10.4 36	S S S VLBI VLBI VLBI VLBI VLBI VLBI VLBI VLBI VLBI VLBI S S S
Region 3						
Australia	Parkes Mopra Narrabri, NSW Tidbinbilla	148° 15' 44" 149° 05' 58" 149° 32' 56" 148° 58' 59"	–33° 00' 00" –31° 16' 04" –30° 59' 52" –35° 24' 18"	415 866 237 677	64 22 6 × 22 34	S S S S
Japan	Nobeyama Kashima Mizusa Ogasawara Ishigakijima	138° 28' 32" 140° 39' 46" 141° 07' 57" 130° 26' 25" 142° 13' 00" 124° 10' 06"	35° 56' 29" 35° 57' 15" 39° 08' 01" 31° 44' 53" 27° 05' 30" 24° 24' 38"	1 350 50 117 569 273 60	45 34 20 20 20 20	S S S S S S
Korea (Republic of)	Taejon Yonsei U. Ulsan U. Tamna U.	127° 22' 18" 126° 56' 35" 129° 15' 04" 126° 27' 43"	36° 23' 54" 37° 33' 44" 35° 32' 33" 33° 17' 18"	120 260 120 100	13.7 20 20 20	S S S S
Other						
United States of America funded	Antarctica	N/A	–90° 00' 00"	3 000	Various	S

NOTE 1 – S refers to stations were single-dish operations are made, and VLBI refers to stations used exclusively for VLBI.

Scientific interest in the 43 GHz band is extremely high. Most interest comes from observations of very weak radio sources that push the technological limits, corresponding to antenna noise temperatures of the order of 2-20 μK involving integrations of the order of 2 000-4 000 s. Long integration times are essential to observe the faint sources that scientists are interested in. Correlation and differencing observing modes have been developed and are used successfully to counter atmospheric fluctuations to enable such long integration times.

The very large array (VLA) of the U.S. National Radio Astronomy Observatory (NRAO), possibly the most heavily used radio telescope in the world, spent nearly 20% of its total observing time in this band in the last few years. Similar statistics hold for NRAO's very long baseline array (VLBA). The VLA and VLBA receive two to three times as many requests for observing time than they can accommodate.

The percentage of time that each station spends at 42 GHz varies from station to station and from year to year. Many radio telescopes now have frequency flexibility, enabling them to switch operations from one frequency band to another on a time-scale of one minute or less. This enables flexible scheduling, to take best advantage of the observing conditions (weather, etc.). From the point of view of inter-service compatibility studies therefore, it is safest to assume that any radio astronomy station in Table 42 might observe at 43 GHz at any time.

16.2 FSS and BSS

16.2.1 Allocated transmit band

The active service band considered is the band 41.5-42.5 GHz.

16.2.2 Application

Based on ITU filings, more than 250 FSS and BSS systems are planned for operation within the 40 GHz band and the corresponding 47 GHz uplink band. The typical parameters of FSS systems planned to operate in the 50/40 GHz bands are shown in Table 43.

TABLE 43

Typical downlink system characteristics of GSO and non-GSO FSS systems planned to operate in the 37.5-42.5 GHz band (Recommendation ITU-R S.1557)

Parameters	GSO FSS	Non-GSO FSS (MEO)
Satellite antenna beam size (degrees)	0.3 to 0.6	0.6 to 1.8 depending on the satellite altitude
Typical space station DC power (kW)	10 to 15	3 to 5
Typical satellite transmit RF power into the antenna	2.5 kW to 3.5 kW	700 W to 1.1 kW
Number of beams	30 to 60	10 to 20
Bandwidth (GHz)	2.0 to 5.0, including HDFSS and gateway/hub	
Frequency reuse scheme	4 or 7 times (most systems use 4-times frequency reuse scheme)	
Link availability: – Gateway/hub (%) – HDFSS (VSAT) (%)	 – > 99.9 – 99.5 to 99.7	
Payload	Transparent transponder or processing payload	

TABLE 43 (*end*)

Parameters	GSO FSS	Non-GSO FSS (MEO)
Minimum operation elevation angle (degrees)	> 15	> 20
Modulation	QPSK/8-PSK/16-QAM	
BER	1×10^{-8} to 1×10^{-10}	
Coding	Concatenated code	
Required E_bN_0 (dB)	6 to 12.5 depending on modulation and coding	
Interference degradation (dB)	2 to 4	
System margin (dB)	1 to 3	
Earth terminal antenna size: – Gateway/hub (m) – HDFSS (VSAT) (m)	 – 1.8 to 2.7 – 0.3 to 0.6	 – 1.5 to 2.7 – 0.3 to 0.6
Earth terminal system noise temperature (K)	600 to 800	

HDFSS: high density fixed-satellite service.

VSAT: very small aperture terminal.

16.2.3 Levels based on existing ITU documents

Relevant ITU-R Recommendations are as follows:

Recommendation ITU-R S.1557 – Operational requirements and characteristics of fixed-satellite service systems operating in the 50/40 GHz bands for use in sharing studies between the fixed-satellite service and the fixed service.

Recommendation ITU-R SF.1484 – Maximum allowable values of power flux-density at the surface of the Earth produced by non-geostationary satellites in the fixed-satellite service operating in the 37.5-42.5 GHz band to protect the fixed service.

Recommendation ITU-R SF.1573 – Maximum allowable values of power flux-density at the surface of the Earth by geostationary satellites in the fixed-satellite service operating in the 37.5-42.5 GHz band to protect the fixed service.

Recommendation ITU-R SM.1540 – Unwanted emissions in the out-of-band domain falling into adjacent allocated bands.

Recommendation ITU-R SM.1541 – Unwanted emissions in the out-of-band domain.

16.2.4 Transmitter characteristics

Most FSS systems being proposed for operation in the 50/40 GHz bands plan to provide high data rates ranging from video conferencing quality through very high transmission rates of STM-1 (155 Mbit/s) to 10 × STM-4 (6.22 Gbit/s). Since propagation impairments in this frequency range are severe, special design considerations apply to this frequency band, which do not necessarily apply at lower frequencies. In order to achieve link availability and the high data rate in the 40 GHz band, most proposed FSS systems will operate with high gain satellite antennas. The 3 dB beam-width of the transmit and receive antennas are in a range from 0.3° to 0.65°. Also, due to satellite weight and power constraints, the number of active beams at any instant in the satellite field-of-view of all proposed FSS systems planned to operate in these bands will be very small, typically less than 5%. In the relevant study (Recommendation ITU-R S.1557), the FSS and the BSS systems planned to operate in the 40 GHz band are assumed to have similar system parameters.

Table 43 indicates that most proposed FSS systems plan to use at least 2 GHz of spectrum in the space-to-Earth direction, and most systems will use a 4-times frequency reuse scheme. This means that 500 MHz will be allocated to each beam. However, some proposed systems plan to use 2 GHz of spectrum for each beam. The actual bandwidth for each beam will depend on the applications and the separation between beams.

16.2.5 Operational characteristics

See Recommendation ITU-R S.1557 and § 16.2.4.

16.2.6 In-band transmit level

The FSS and BSS systems planning to operate in the 40 GHz band will only be able to transmit at the pfd limits in RR Table 21-4 for a very small percentage of time. The actual downlink pfd levels during clear-sky conditions will depend on each satellite system design such as, transparent transponder, on board processing payload, modulation, coding, etc. In the study it was assumed that FSS systems will typically operate at the pfd level of –117 dB(W/m^2) for elevation angles from 25° to 90° in clear-sky conditions.

The value of –117 dB(W/(m^2 · MHz)) represents a clear-sky level that is 12 dB below the peak pfd level listed in RR Table 21-4. Due to the power limitations of the space station, the full power is only reached for very short periods of time on beams where propagation effects must be overcome. Furthermore, the clear-sky level provides protection to certain sensitive fixed service systems deployed in the band. Additional details are available in Recommendations ITU-R S.1557 and ITU-R SF.1572.

16.3 Compatibility threshold

See § 16.1.3.

16.4 Interference assessment

16.4.1 Methodology used to assess the interference level

The example presented in Fig. 60 is a worst-case example based on a necessary bandwidth of 500 MHz and a spectral roll-off at the maximum level identified in Recommendation ITU-R SM.1541. As, well this example assumes that the necessary bandwidth extends to the edge of the FSS allocation.

16.4.2 Calculation of interference level

The spectral performance curve in Fig. 60 was numerically integrated in order to derive the aggregate unwanted emission power in order to assess the impact in the continuum band of 1 GHz.

Values were taken directly from the curve (with 3 dB removed in order to reflect the change in bandwidth from 1 MHz to 500 kHz) so as to verify compliance with the single-dish spectral line threshold and with the VLBI level.

The calculation assumes a beam at the sub-satellite point. As a result, the actual pfd values would be lower for radio telescopes where the elevation angle to the satellite is less than 90°.

The calculation does not take into account the impact of atmospheric attenuation[1].

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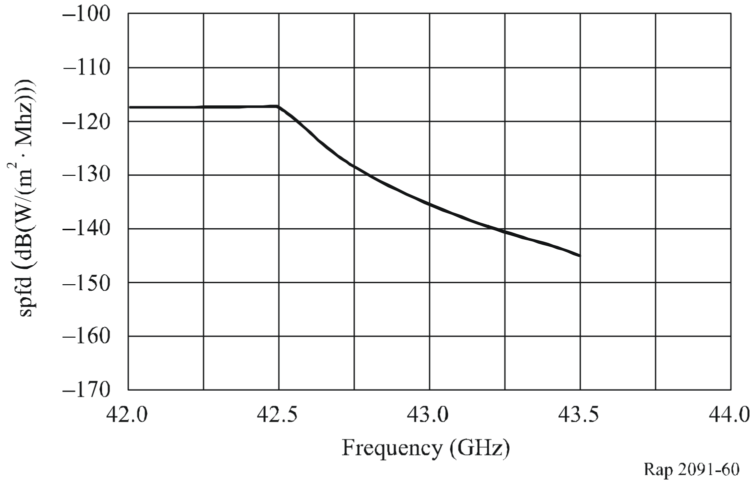
[1] See Recommendation ITU-R P.676. The value will vary from 1 to 2 dB at sea level.

FIGURE 60

Spectral performance



16.4.3 Values achieved

Based on this curve, the following worst-case levels are achieved in the band 42.5 to 43.5 GHz:

– –97 dB(W/(m^2 · GHz)), which is 37 dB above the continuum threshold for the band 42.5-43.5 GHz.

– –120 dB(W/(m^2 · 500 kHz)) at 42.5 GHz, which is 36 dB above the spectral line threshold.

As a result, compliance to the radio astronomy criteria would require the application of one or more mitigation methods.

16.5 Mitigation techniques

16.5.1 RAS

The possible mitigation methods for the RAS are either:

– a guardband; or

– other mitigation methods as listed in Recommendation ITU-R SM.1542.

16.5.2 FSS and BSS

16.5.2.1 Satellite filtering

Case 1: Multibeam space station

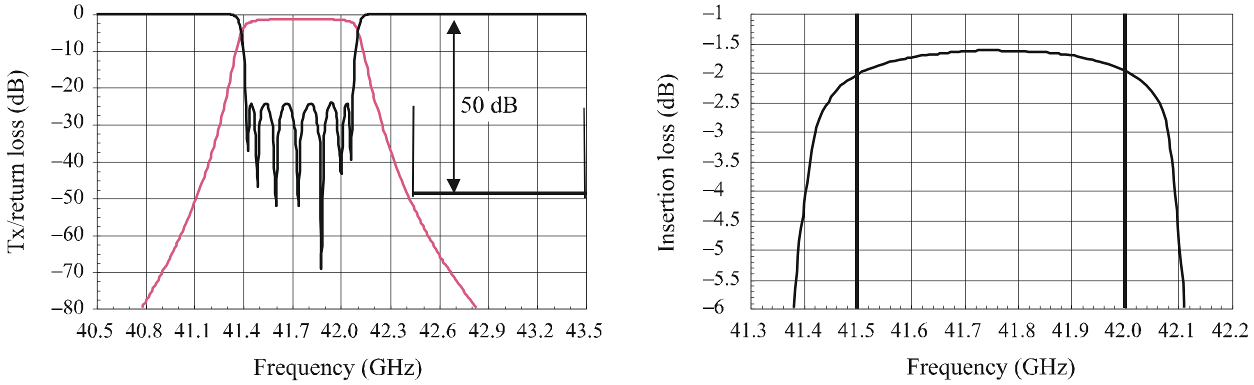
For wideband carriers, the curve in Fig. 61 shows as an example, the performance of a typical filter design in this band with a 7-pole filter.

Case 2: Phased array space station

For wideband carriers on a phased array, the performance of a typical filter design in this band with a 15-pole filter is shown in Fig. 62.

FIGURE 61

Tx/return loss/insertion loss



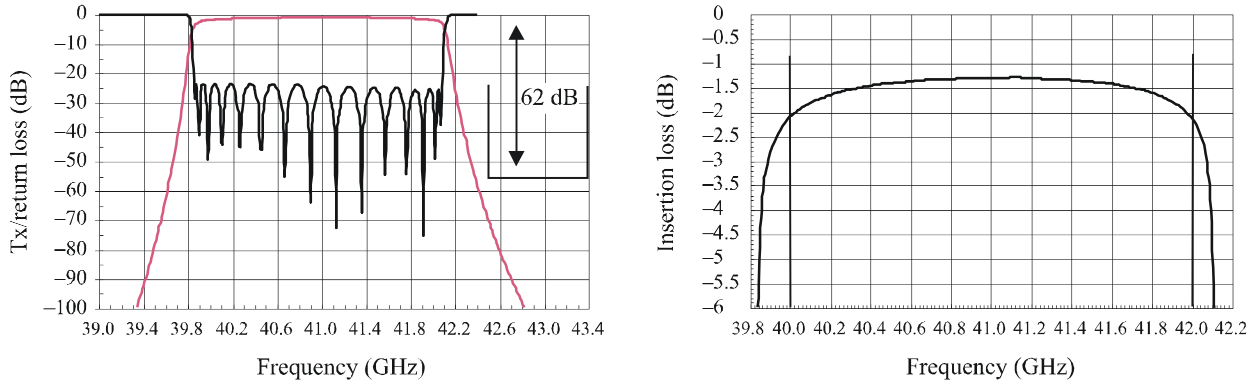
N = 7 TE101 filter

Size (W × H × L): 1.125" × 1.125" × 3.80"/Weight: 0.24 lb (copper)

Rap 2091-61

FIGURE 62

Tx/return los/insertion loss



N = 15, TE101 band-pass filter (BPF) cascade with WR22 lowpass filter/WR22 waveguide filters

Size (W × H × L): 1.125" × 1.125" × 5.50"/Weight: 0.33 lb (for copper)

Rap 2091-62

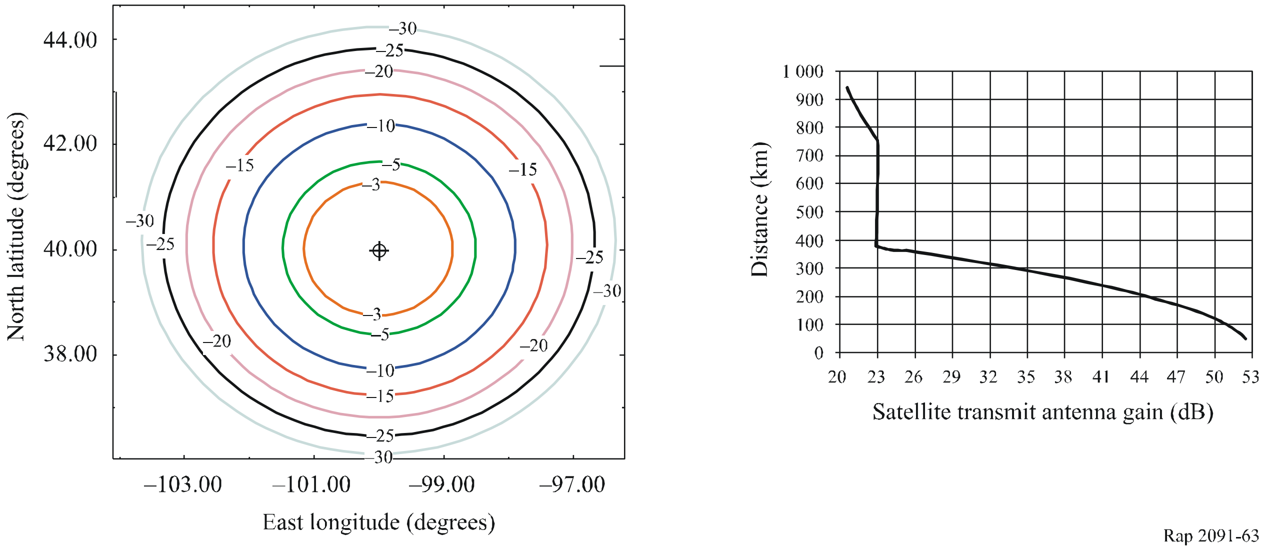
16.5.2.2 Geographic isolation

If FSS and BSS systems operating in the 40.5-42.5 GHz band are not able to implement the additional transmit filters needed to meet the detrimental interference criteria of RAS stations operating in the 42.5-43.5 GHz band, geographical isolation should be considered as an interference mitigation technique.

Based on Table 43, the satellite transmit antenna beam size is in a range from 0.3° to 0.6°. The left-hand portion of Fig. 63 shows the gain contours for a GSO space station antenna having a peak gain of 53 dBi and a 3 dB beamwidth of 0.4°. The geographical isolation advantage relative to the peak gain can be found for any distance by using the right-hand curve in Fig. 63.

FIGURE 63

Satellite antenna contours and distance between beam centre and edge of coverage vs. satellite transmit antenna gain



Rap 2091-63

16.5.2.3 Spectral shape of FSS/BSS signal

The waveform used by the FSS/BSS for the transmission of information could be selected that minimizes spectral roll-off, thus limiting the amount of unwanted emissions transmitted. As well it may be possible to design or operate the high power amplifier in such a way as to further minimize the unwanted emission level from the FSS/BSS signal.

16.5.2.4 Guardband

A guardband between the two services would allow for roll-off of the signal and filter.

16.5.2.5 Additional mitigation methods

Additional mitigation methods are listed in Recommendation ITU-R SM.1542.

16.5.3 Potential impact

16.5.3.1 RAS

Guardband at edge of RAS band – In the case of broadband continuum measurements, the use of a guardband within the radio astronomy band would effectively lead to a loss of data, since the integration time would need to be increased to compensate for the loss of bandwidth. This method has limited practicability as described in § 16.1.3.

The band also includes the spectral lines associated with the silicon monoxide (SiO) molecule at rest frequencies of 42.519, 42.821, 43.122 and 43.424 GHz that are among the astrophysically most important lines, but which are not all listed in Recommendation ITU-R RA.314. Thus there is limited scope for a guardband within the radio astronomy band, without impacting the capability to observe one or more of the SiO spectral lines.

16.5.3.2 FSS and BSS

16.5.3.2.1 Satellite filtering

In the multibeam example above, based on a 7-pole transmit filter, the insertion loss is 2.0 dB, which corresponds to a 37% degradation in system capacity. Such filtering would increase the weight of the space station by 120 g or more per beam, depending on the transmitter power.

In the phased array example above, based on a 15-pole transmit filter, the insertion loss is 2.0 dB, which corresponds to a 37% degradation in system capacity. Such filtering would increase the mass of the space station by 160 g or more per element, depending on the transmitter power. For a space station with a 2 818-element phased array antenna, an additional 450 kg would be added to the payload mass, with consequential cost and performance penalties.

In addition, most systems operating with phased array antennas prefer to use solid state power amplifiers (SSPAs). If additional transmit filters are required, and depending on the actual transmit power, due to an additional loss, TWTAs may be required. It is difficult to implement phased array antennas with TWTAs.

16.5.3.2.2 Geographic isolation

This mitigation method is only useable if the number of radio telescopes in the service area of the satellite is small and if their locations are taken into account while the space station antenna sub-system is being designed. Also this mitigation method limits the ability of the space station to be re-located or for the beam to be re-oriented to other portions of the satellite field of view.

16.5.3.2.3 Spectral shape of FSS/BSS signal

The high power amplifier (HPA) linearity and the point in the dynamic range at which the HPA is operated determine the spectral shape of the space station emission. Improving the unwanted emissions from the HPA can be achieved through operation at a lower input power or improving the amplifier linearity. However, maintaining the operation of the amplifier in the linear range reduces unwanted emissions at the cost of decreased HPA efficiency. Both methods have an impact on the throughput of the space station as well as its cost and weight.

16.5.3.2.4 Guardband

The usage of any guardband imposes a reduction of capacity on the FSS/BSS if the guardband is implemented within its allocation.

16.6 Results of studies

16.6.1 Summary

The majority of the RAS sites around the world utilize this band for single-dish measurements. A combination of appropriate mitigation techniques would be required to meet the levels of protection for single-dish measurements.

One study considered frequency separation without the use of any other mitigation method. This study assumed FSS and BSS systems operating up to 42 GHz and unwanted emission levels from Recommendation ITU-R SM.1541. The study shows that the detrimental level of interference for VLBI given in Recommendation ITU-R RA.769 is met. However, the threshold pfd limits for single-dish line or continuum observations are not met, and interference would be sufficiently severe as to effectively prevent any useful astronomical measurements unless additional mitigation methods are used.

The worst-case scenario presented in § 16.4.1, using no mitigation methods, is based on a necessary bandwidth of 500 MHz and a spectral roll-off at the rate identified in Recommendation ITU-R SM.1541. In addition, this example assumes that the necessary bandwidth extends to the edge of the FSS allocation at 42.5 GHz.

The unwanted emissions resulting from the worst-case example considered exceed the limits in RR No. 5.551G as well as the single-dish spectral line and continuum criteria from Recommendation ITU-R RA.769. However, the VLBI criterion is met across the entire band 42.5 to 43.5 GHz. The shortfall may be addressable through the use of mitigation methods. A diverse range of mitigation methods can be considered for application in practical systems; a combination of such methods is likely to be required.

If, for some systems, the provisional FSS spectral representation as described in the technical Appendix to Annex 1 of Recommendation ITU-R SM.1633 is considered instead of Recommendation ITU-R SM.1541, the shortfall with the continuum criteria is reduced. This does not necessarily alleviate the shortfall on band-edge unless additional mitigation methods are considered. It was however indicated that this spectral representation is based on experience at lower frequency bands.

It is expected that, using one or more of the mitigation methods identified in § 16.5, FSS/BSS systems may be able to meet the Recommendation ITU-R RA.769 protection criterion for continuum measurements. In addition, it may be difficult for FSS systems to meet the spectral line criterion in some parts of the 42.5-43.5 GHz band. It is doubtful whether FSS systems that are required to meet the RR No. 5.551G criteria would be practical, since these requirements would impose severe operational constraints and significantly increasing satellite system costs.

As a result, it is unlikely that the complete needs of both services can be met. Further work may be needed to refine the study.

16.6.2 Conclusions

In this band, the threshold level for detrimental interference to radio astronomical observations as given in Recommendation ITU-R RA.769 can be met by the FSS and BSS for the VLBI case. For the continuum case, it may be possible for FSS/BSS systems to meet the threshold with the use of mitigation methods. Meeting the spectral line threshold across part of the band may be possible. It is uncertain if mitigation methods will be sufficient to meet the spectral line criteria at the lower edge of the RAS allocation.

As nearly two-thirds of the RAS sites around the world (see Table 42) utilize this band for single-dish measurements, it is therefore important that a combination of appropriate mitigation techniques is applied to meet these levels of protection for single-dish measurements.