International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Recommendation ITU-R F.1403

(05/1999)

Power flux-density criteria in ITU-R Recommendations for protection of systems in the fixed service in frequency bands shared with space stations of various space services

F Series

Fixed service

International Telecommunication Union

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Note*: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

Electronic Publication
Geneva, 2010

RECOMMENDATION ITU-R F.1403

Power flux-density criteria in ITU-R Recommendations for protection of systems in the fixed service in frequency bands shared with space stations of various space services

(Questions ITU-R 111/9, ITU-R 113/9, ITU-R 118/9 and ITU-R 201/9)

(1999)

The ITU Radiocommunication Assembly,

considering

a) that the fixed service (FS) shares many frequency bands on a co-primary basis with space radiocommunication services such as the fixed-satellite, broadcasting-satellite, mobile-satellite and space science services;

b) that criteria for the power flux-density (pfd) at the surface of the Earth produced by space stations of space services have been developed in order to control the interference into systems in the FS in the frequency bands shared with the space-to-Earth direction of these space services;

c) that these criteria are mainly expressed as hard limits on pfd produced by space stations but when it is not practicable, as coordination thresholds;

d) that in some cases of interference assessment from non-geostationary (non-GSO) satellites into digital systems in the FS in the 1-3 GHz range, coordination thresholds have been expressed in terms of fractional degradation in performance (FDP);

e) that various pfd criteria have been established since 1963 when certain frequency bands were allocated for the first time on a shared basis to the FS and the fixed-satellite service (FSS);

f) that a number of methodologies for interference assessment have been developed in order to derive appropriate pfd criteria;

g) that it is important to review the principles and advice which were incorporated in these methodologies,

recommends

1 that the following ITU-R Recommendations should be referred to for the pfd limits on space stations (mainly GSO) in the FSS:

SF.358 Maximum permissible values of power flux-density at the surface of the Earth produced by satellites in the fixed-satellite service using the same frequency bands above 1 GHz as line-of-sight radio-relay systems

SF.1005 Sharing between the fixed service and the fixed-satellite service with bidirectional usage in bands above 10 GHz currently unidirectionally allocated

SF.1008 Possible use by space stations in the fixed-satellite service of orbits slightly inclined with respect to the geostationary-satellite orbit in bands shared with the fixed service

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

2 that the following ITU-R Recommendations should be referred to for the pfd limits on non-GSO space stations in the FSS including those used for feeder links of systems in the mobile-satellite service (MSS):

SF.1320 Maximum allowable values of power flux-density at the surface of the Earth produced by non-geostationary satellites in the fixed-satellite service used in the feeder links for the mobile-satellite service and sharing the same frequency bands with radio-relay systems

SF.1482 Maximum allowable values of power flux-density produced at the Earth's surface by non-GSO satellites in the fixed-satellite service operating in the 10.7-12.75 GHz band

SF.1483 Maximum allowable values of power flux-density at the Earth's surface produced by non-geostationary satellites in the fixed-satellite service operating in the 17.7-19.3 GHz band

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

3 that the following ITU-R Recommendations should be referred to for pfd limits on space stations in space science services:

SA.1273 Power flux-density levels from the space research, space operation and Earth exploration-satellite services at the surface of the Earth required to protect the fixed service in the bands 2 025-2 110 MHz and 2 200-2 290 MHz

F.1502 Protection of the fixed service in the frequency band 8 025-8 400 MHz sharing with geostationary-satellite systems of the Earth exploration-satellite service (space-to-Earth),

4 that the following ITU-R Recommendations should be referred to for coordination thresholds for frequency assignments to GSO and non-GSO space stations in the MSS in the 1-3 GHz frequency range:

M.1141 Sharing in the 1-3 GHz frequency range between non-geostationary space stations operating in the mobile-satellite service and stations in the fixed service

M.1142 Sharing in the 1-3 GHz frequency range between geostationary space stations operating in the mobile-satellite service and stations in the fixed service

M.1143 System specific methodology for coordination of non-geostationary space stations (space-to-Earth) operating in the mobile-satellite service with the fixed service

F.1246 Reference bandwidth of receiving stations in the fixed service to be used in coordination of frequency assignments with transmitting space stations in the mobile-satellite service in the 1-3 GHz range

5 that the following ITU-R Recommendation should be referred to for coordination thresholds for frequency assignments to space stations in the broadcasting-satellite service (BSS) (sound) in the band 1 452-1 492 MHz:

F.1338 Threshold levels to determine the need to coordinate between particular systems in the broadcasting-satellite service (sound) in the geostationary-satellite orbit for space-to-Earth transmissions and the fixed service in the band 1 452-1 492 MHz

6 that the following ITU-R Recommendations should be referred to for the methodology for assessment of interference from GSO and non-GSO space stations into systems in the FS:

F.1107 Probabilistic analysis for calculating interference into the fixed service from satellites occupying the geostationary orbit

F.1108 Determination of the criteria to protect fixed service receivers from the emissions of space stations operating in non-geostationary orbits in shared frequency bands

SF.1572 Methodology to evaluate the impact of space-to-Earth interference from the fixed-satellite service to the fixed service in frequency bands where precipitation is the predominant fade mechanism

SF.1602 Methodology for determining power flux-density statistics for use in sharing studies between fixed wireless systems and multiple fixed-satellite service satellites

7 that Annex 1 should be referred to for the historical evolution of pfd criteria in ITU-R Recommendations for protection of systems in the FS shared with space stations of various space services, which might be used as guidance for future studies on pfd criteria in various sharing situations.

Annex 1

Historical evolution of pfd criteria in ITU-R Recommendations for protection of systems in the FS

1 Introduction

Power flux-density at the Earth's surface produced by space stations is an important factor for consideration in order to protect systems in the FS from emissions of space stations sharing the same frequency bands. Numerous ITU-R Recommendations have been established since 1963 dealing with this matter.

Some Recommendations give hard limits on pfd. This facilitates frequency sharing, because individual coordination is not required. But in some cases, it is difficult to establish hard limits, because no such limits can be found which adequately protect the FS and, at the same time, do not place undue constraints on system design of space services. In such cases, Recommendations present coordination thresholds and, if the pfd exceeds the coordination threshold, individual coordination is required with the affected administrations.

In addition to the pfd, a concept of FDP was introduced in Recommendation ITU-R F.1108 in order to assess the effects of interference from non-GSO satellites into the FS.

This Annex presents a historical evolution of pfd criteria adopted in various ITU-R Recommendations, many of which have been incorporated into the Radio Regulations (RR).

2 Power flux-density limits on FSS space stations

Power flux-density limits on space stations in the FSS are recommended in Recommendation ITU-R SF.358. It was in 1963 that the first version of this Recommendation was developed. It took more than twenty years before this Recommendation was almost finalized. It is applicable to both GSO and non-GSO space stations. However, it should be noted that only a limited number of non-GSO space stations were assumed in confirming the applicability of this Recommendation. Therefore, Recommendation ITU-R SF.358 should be regarded as applicable mainly to GSO space stations and, if a large number of non-GSO space stations are involved, a separate consideration is necessary (see, for example, Recommendation ITU-R SF.1320).

A detailed history about Recommendation ITU-R SF. 358 is given in Appendix 1 to Annex 1.

3 FSS in bidirectional band usage and use by FSS space stations of orbits slightly inclined with respect to the GSO

The coexistence of the FS with the FSS was planned by the 1963 Extraordinary Administrative Radio Conference (1963 EARC) for unidirectional FSS transmissions and for GSO space stations. As a result, the permissible interference from the FSS was nearly invariant with time, except for propagation anomalies, and was generated from transmitting space stations or from transmitting earth stations.

However, in order to increase the capacity of the FSS and to increase the longevity of the space segment, the use of bidirectional transmission was considered for additional frequencies, and the use of slightly inclined orbits was also studied to save fuel and increase the useful life of the space stations.

The benefits to the FSS of additional frequencies through the use of bidirectional transmission comes at the expense of more interference sources for both the FS and the FSS, and the use of slightly inclined orbits comes at the risk of increasing the number of fixed receivers exposed to near direct interference from transmitting space stations.

3.1 Recommendation ITU-R SF.1005 (Geneva, 1993)

The sharing criteria that were established by the 1963 EARC assumed that the aggregate permissible interference into the model hypothetical reference circuit was small in comparison to the total noise of the system, and in fact, it could be accommodated within the total noise budget of existing systems without making any changes to systems already deployed throughout the world. Specifically, the permissible interference into fixed receivers from transmitting space stations could effectively be limited by controlling the pfd at the surface of the Earth, and the interference from transmitting earth stations could be controlled by limiting the e.i.r.p. at the horizon. The limits on the pfd and the e.i.r.p. could satisfy the assumption of small permissible interference, but allow the effective development of the FSS for the benefit of satellite technology throughout the world.

The use of bidirectional transmission by the FSS increases the interference sources; as a result, the assumption that the permissible interference from the FSS should be small could not be maintained without additional restrictions on the FSS. The additional restrictions, that were developed in Recommendation ITU-R SF.1005 – Sharing between the fixed service and the fixed-satellite service with bidirectional usage in bands above 10 GHz currently unidirectionally allocated (which is based on ex-CCIR Report 1005 developed in 1986), were that bidirectional operation would be limited for frequencies above 10 GHz; the pfd for angles of arrival within 5° above the horizon and the interference from transmitting earth stations should be lowered by 7 dB, 5 dB, and 3 dB for frequency bands, 10-15.4 GHz, 15.4-20 GHz, and above 20 GHz respectively; and for angles of arrival above 25° the pfd limits of Table 1 of Recommendation ITU-R SF.358 should continue to apply.

The application of bidirectional usage can be introduced with less interference impact on the FS provided that the FSS uses transmitting earth stations with high elevation angles (>40°), spot beams of approximately 2°, and does not extensively use the GSO.

3.2 Recommendation ITU-R SF.1008 (Geneva, 1994)

The coexistence of the FSS and the FS has taken place successfully for the last three decades mostly for space stations located in their nominal GSO locations. The probability that a FS receiver will intersect the GSO is low, and the probability that a transmitting space station will be located at that orbital location is significantly lower. As a result, the aggregate interference that the model radio-relay system is expected to receive is mostly from a single near, direct exposure and side-lobe interference from the rest of the visible space stations in the GSO.

However, in order to keep the space stations in their nominal orbital positions fuel needs to be expanded, and particularly, significant fuel needs to be used for north-south station-keeping. In fact, the lifetime of the space segment may be determined by the availability of fuel. If the north-south station-keeping was to be relaxed, the longevity of space stations can be extended, but the resulting inclination of the orbit would result in more terrestrial receivers exposed to near direct interference even though the duration of the exposure would be a fraction of the 24 h period, and the total average interference of the model hypothetical reference circuit may not increase.

The portion of the 24 h period during which the terrestrial receiver is exposed to main lobe interference will result in significant decrease in the thermal noise fade margin, and during these periods the receiver will be susceptible to slowly varying, non-dispersive, shallow fades. These fades can occur sufficiently frequently to make the affected receiver unavailable for an unacceptable amount of time. Recommendation ITU-R SF.615 provides the objectives for network unavailabilities from all sources of interference, and the contribution of the expected unavailability from even a few exposed receivers will exceed the aforementioned objectives by an order of magnitude. As a result, the receivers susceptible to main-lobe interference will have to be relocated in order to preserve the performance of the system.

Recommendation ITU-R SF.1008 – Possible use by space stations in the FSS of orbits slightly inclined with respect to the GSO in bands shared with the fixed service, limits the amount of inclination to less than 5° without imposing any additional restrictions on the FSS. The slight inclination of the orbit limits the additional terrestrial receivers that are exposed to main-lobe interference, and even though the number of affected stations increases with latitude, the number of susceptible receivers for latitudes as high as 60° is less than a few for a 50-hop system. However, for inclinations greater than 5°, the number of affected stations increases linearly, and a back-off on the pfd is recommended which increases linearly between five and ten degrees inclination, and reaches a maximum of 20 dB back-off at an inclination of 10°.

Finally, the inclination of the orbit may be designed at the planning stage of the satellite, and a satellite may be injected into an inclined orbit such that the lifetime of the satellite is maximized while minimizing the amount of the inclination, and thus, the impact on the FS and the need for tracking is reduced.

4 Power flux-density limits on BSS space stations in the 12 GHz band

The 1977 World Broadcasting-Satellite Administrative Radio Conference (WARC SAT-77) established the Regions 1 and 3 Plan for the BSS in the bands 11.7-12.2 GHz (in Region 3) and 11.7-12.5 GHz (in Region 1). The 1983 Regional Administrative Radio Conference (RARC-83) established the Region 2 Plan for the BSS in the band 12.2-12.7 GHz. Various parameters of BSS space stations were stipulated in the Plan. These frequency bands are shared with the FS. Therefore, it is necessary in the planning of FS systems to take due account of the BSS Plan and not to cause any harmful interference to BSS receiving earth stations.

When any change is made to the BSS Plan, there is a risk that a BSS space station in a new orbital location or at a new frequency assignment may cause unacceptable interference to existing FS systems. For this purpose, Annex 1 to RR Appendix 30 stipulates limits on the pfd to protect the terrestrial services in all three Regions.

5 New allocations to various space radiocommunication services by WARC-92

The World Administrative Radio Conference (WARC-92) was held in 1992 in Malaga-Torremolinos for dealing with frequency allocations in certain parts of the spectrum. This Conference allocated many frequency bands to various space radiocommunication services on a shared basis with the FS. It made the frequency sharing situations very much complicated and invited the ITU-R to carry out urgent studies to establish appropriate sharing criteria.

5.1 Allocation to BSS for HDTV near 20 GHz

WARC-92 allocated the band 21.4-22 GHz to the BSS in Regions 1 and 3 on a shared basis with the FS and the band 17.3-17.8 GHz to the BSS in Region 2, out of which the band 17.7-17.8 GHz is shared with the FS. These allocations to the BSS shall come into effect on 1 April 2007 (see RR Nos. 5.517 and 5.530).

Resolution 525 (WARC-92) specifies the conditions for the use of the band 21.4- 22 GHz in Regions 1 and 3 by the BSS after that date and on an interim basis prior to that date. This Resolution gives the values of pfd at the Earth's surface produced by emissions from a space station of an operational BSS (HDTV) system before 1 April 2007, as coordination thresholds. These values are identical to the values which were given in Recommendation ITU-R F.760 that had been developed by Radiocommunication Study Group 9 just prior to the WARC-92.

Recommendation ITU-R F.760 examines the in-beam interference at low angles of arrival and off-beam interference at high angles of arrival to a 64-QAM FS receiver. After considering correlation of rain fading between wanted and interfering signals, the Recommendation arrives at the proposed pfd values. This was the first case in which the values in an ITU-R Recommendation were incorporated into a Resolution attached to the RR as coordination thresholds.

5.2 Allocation to BSS (sound) in the 1-3 GHz range

WARC-92 allocated the band 1 452-1 492 MHz to the BSS (sound) on a worldwide basis (except for one administration, see RR No. 5.344). In addition, the bands 2 310-2 360 MHz and 2 535-2 655 MHz were also allocated to the BSS (sound) for use in certain countries (see RR Nos. 5.393 and 5.418). These bands are shared with the FS.

WARC-92 did not adopt any coordination thresholds for pfd values produced by BSS (sound) space stations to be used in coordination with the FS. Resolution 522 (WARC-92) invited the ITU-R to study the appropriate sharing criteria between BSS (sound) systems and the systems of other services sharing the bands.

5.3 Allocation to MSS in the 1-3 GHz range

WARC-92 allocated a number of frequency bands in the 1-3 GHz range to the MSS (Earth-to-space and space-to-Earth) on a shared basis with the FS. WARC-92 considered what pfd values are appropriate in the bands allocated to the MSS (space-to-Earth) in order to protect the FS. It was recognized that it was not possible to find an appropriate pfd limit that will adequately protect the FS and, at the same time, will not cause undue constraint on the design of MSS systems. Therefore, WARC-92 decided to establish coordination thresholds instead of pfd limits.

In the absence of any ITU-R Recommendation on this issue, WARC-92 was faced with the difficulty of arriving at appropriate coordination thresholds. After long debates, WARC-92 reached a provisional conclusion that in the bands allocated to the MSS (space-to-Earth), coordination of MSS space stations with respect to terrestrial services is required only if the pfd produced at the Earth's surface exceeds limits in RR No. 21.16 (3400-7850 MHz). Here, RR No. 21.16 means the pfd limits on FSS space stations in the band 3-8 GHz (–152 dB(W/m^2) and –142 dB(W/m^2)) in a 4 kHz band for low and high arrival angles, respectively).

At the same time, Recommendation 717 (WARC-92) invited the ITU-R to carry out further studies on frequency sharing criteria between the MSS and the FS and other terrestrial services.

5.4 Allocation to space science services

Before WARC-92, the bands 2025-2110 MHz and 2200-2290 MHz had been allocated to the space science services by a footnote to the Frequency Allocation Table in the RR. The allocation was subject to agreement being reached using the procedure given in RR Article 14 (edition of 1994). WARC-92 removed the Article 14 requirement and changed this footnote allocation to a primary allocation in the Table of Allocations. In the revised allocation table, the band 2025-2110 MHz is allocated to space operation, Earth exploration-satellite and space research services (Earth-to-space and space-to-space) and the band 2200-2290 MHz is allocated to space operation, Earth exploration-satellite and space research services (for space-to-Earth and space-to-space). Both bands are shared with the FS.

WARC-92 allocated additional bands to space science services. They included the band 25.25-27.5 GHz allocated to the inter-satellite service shared with the FS.

WARC-92 retained pre-WARC-92 pfd limits on space stations in the bands 2025-2110 MHz and 2200-2290 MHz to protect the FS (–154 dB(W/m^2) and –144 dB(W/m^2) in a 4 kHz band for low and high arrival angles, respectively). For the band 25.25-27.5 GHz, the same pfd limit as that on FSS space stations in the band 17.7-19.7 GHz (–115 dB(W/m^2) and –105 dB(W/m^2) in a 1 MHz band for low and high arrival angles, respectively) was applied.

6 Methodology for interference assessment

Various new frequency allocations to space services decided by WARC-92 made it necessary to establish sharing criteria to protect FS stations from emissions of space stations sharing the same frequency bands. Recommendations ITU-R F.1107 and ITU-R F.1108 were developed in order to present the methodology for assessment of interference into the FS from geostationary and non-geostationary space stations, respectively.

6.1 Recommendation ITU-R F.1107 (Geneva, 1994)

Recommendation ITU-R F.1107 presents geometric considerations and methods of calculating the total interference power received at FS receivers caused by geostationary space stations. The methodology is based on the approach adopted for many years for developing Recommendation ITU-R SF.358 which had established pfd limits on FSS space stations.

A number of satellites are assumed to be operating at the GSO with uniform spacing. They are assumed to produce the maximum pfd at the surface of the Earth allowed by an assumed pfd mask. The aggregate interference is evaluated through computer simulations using Monte Carlo methods for generating representative service implementations. The FS network is assumed to be composed of 50 hop routes randomly distributed over an approximately 65° by 22.5° longitude by latitude surface. All receivers have the same noise temperature, antenna characteristics and spacing.

Calculations over many FS routes result in an interference distribution. In the case of interference into analogue FS systems, the aggregate interference should not exceed 1 000 pW except for a small percentage (generally 10%). A computer program is attached to this Recommendation.

6.2 Recommendation ITU-R F.1108 (Geneva, 1994)

Recommendation ITU-R F.1108 gives a method for determining the criteria to protect FS receivers from the emissions of space stations operating in non-GSO orbits in shared frequency bands. Geometric considerations are given for non-GSO satellites employing circular orbits. Satellite orbit parameters are orbit altitude, number of satellite orbital planes, longitude of ascending node for each plane, orbit inclination and number of satellites per plane. Interference into FS routes are assessed by computer simulations using Monte Carlo methods.

In the case of simulation of interference into analogue FS routes, the FS system model is 50 hops, 2 500 km routes, with hop directions being selected by Monte Carlo methods. Recommendation ITU-R SF.357 is used as a short- and long-term limit of interference that is allowed into an analogue FS system.

A new concept, called FDP, was introduced in order to assess interference from non-GSO space stations into digital FS systems. The FDP is an average of interference-to-thermal noise ratio, where summation is taken over all interference events. The Recommendation establishes the equivalence of this average with the FDP of digital systems in cases where the performance is dominated by multipath fading. For determining the effect of interference on digital receivers employing diversity, a different formula was introduced for evaluating FDP. This formula was first introduced in the process of developing Recommendation ITU-R SF.1320 dealing with pfd limits on space stations in non-GSO MSS feeder link networks. The formula was later incorporated into Annex 4 to Recommendation ITU-R F.1108.

7 Coordination thresholds for MSS in the 1-3 GHz frequency range

Frequency sharing between MSS and FS in the 1-3 GHz frequency range was studied by Study Group 2 (Task Group 2/2) during 1992 and 1995. It resulted in the establishment of Recommendations ITU-R IS.1141, ITU-R IS.1142 and ITU-R IS.1143, approved in 1995. After Study Group 2 was disbanded in 1995, a joint rapporteur group of Radiocommunication Study Groups 8 and 9 continued the study, which resulted in the revised Recommendations ITU-R M.1141, ITU-R M.1142 and ITU-R M.1143 and the new Recommendation ITU-R F.1246 in 1997.

7.1 Recommendation ITU-R M.1141

The methodology of Recommendation ITU-R F.1108 was applied to the assessment of interference from non-GSO MSS space stations to FS systems in various frequency bands in the 1-3 GHz range. As a result, the coordination thresholds provisionally adopted by the WARC-92 were confirmed as applicable to certain frequency bands with respect to sharing with analogue FS systems. Somewhat higher coordination thresholds were adopted for other frequency bands.

On the other hand, FDP of 25% was mainly adopted as coordination thresholds with respect to sharing with digital FS systems.

Several trends arising from the analysis were observed as follows:

– the average received interference can be strongly dependent on the FS pointing azimuth for some non-GSO constellations. For constellations with polar or near polar orbits, the effect of FS pointing azimuths is much less pronounced;

– FS stations at higher latitudes generally experience more interference over time than FS stations located at lower latitudes. This is more significant for constellations with polar orbits, however actual operational requirements may include reducing satellite emissions due to coverage overlap and hence the interference effect will be reduced.

Recommendation ITU-R IS.1141 was approved in 1995 to give coordination threshold criteria for sharing between the MSS (space-to-Earth) non-GSO systems and the FS in the 1-3 GHz range and was renamed as Recommendation ITU-R M.1141 in 1997.

7.2 Recommendation ITU-R M.1142

The methodology of Recommendation ITU-R F.1107 was applied for assessment of interference from GSO MSS space stations to FS systems in various frequency bands in the 1-3 GHz range. As a result, the coordination thresholds provisionally adopted by the WARC-92 were confirmed as applicable to various frequency bands in the 1-3 GHz range with respect to sharing with FS systems, except for the band 2 520-2 535 MHz for which a lower threshold is recommended.

Recommendation ITU-R IS.1142 was approved in 1995 to give coordination threshold criteria for sharing between the MSS (space-to-Earth) GSO systems and the FS in the 1-3 GHz range and was renamed as Recommendation ITU-R M.1142 in 1997. Annex 1 to the Recommendation presents fixed system considerations that may facilitate successful coordination.

7.3 Recommendation ITU-R M.1143

In order to apply Recommendation ITU-R M.1141 for coordination threshold criteria of non-GSO MSS space stations with respect to sharing with digital FS systems, it is necessary to calculate FDP. Recommendation ITU-R IS.1143 (Geneva, 1995) was developed mainly for this purpose. First, interference is evaluated for FS systems with reference characteristics described in Annex 2 to the Recommendation. If the thresholds set forth in Recommendation ITU-R M.1141 are exceeded for these FS reference parameters, the system specific methodology described in Annex 1 to Recommendation ITU-R IS.1143 is used to assess the need for coordination of non-GSO MSS networks (space-to-Earth) with FS assignments. This methodology takes into account more specific characteristics of the non-GSO MSS system and reference FS characteristics. If the applicable maximum interference criteria are not exceeded, then (unless otherwise subsequently advised by the administration responsible for the FS systems), coordination is not considered to be necessary.

Recommendation ITU-R IS.1143 was renamed as Recommendation ITU-R M.1143 in 1997.

7.4 Recommendation ITU-R F.1246 (Geneva, 1997) (reference bandwidth)

Recommendations ITU-R IS.1141 (Geneva, 1995) and ITU-R IS.1142 (Geneva, 1995) adopted a 4 kHz reference bandwidth for defining the coordination thresholds, in terms of pfd, for analogue systems in the FS with respect to frequency sharing with non-GSO and GSO MSS space stations, respectively. On the other hand, Recommendation ITU-R IS.1141 (Geneva, 1995) adopted a 1 MHz reference bandwidth for defining FDP of digital systems in the FS with respect to frequency sharing with non-GSO MSS space stations. However, Recommendation ITU-R IS.1142 (Geneva, 1995) adopted a 4 kHz reference bandwidth for defining the coordination thresholds, in terms of pfd, for digital systems in the FS with respect to frequency sharing with GSO MSS space stations. The need for resolving this inconsistency and for a study on the applicability of 1 MHz reference bandwidth to analogue FS systems was recognized. At the same time, it was noted that some MSS system spectrum may not be uniform over a 1 MHz bandwidth.

An intensive study by Radiocommunication Study Groups 8 and 9 on the effects of MSS interference into FS systems led to Recommendation ITU-R F.1246 which recommends the use of 1 MHz reference bandwidth for digital FS systems and of both 4 kHz and 1 MHz reference bandwidths for analogue FS systems employing frequency division multiplex/frequency modulation (FDM-FM). Based on this Recommendation, the coordination thresholds in Recommendations ITU-R IS.1141 and ITU-R IS.1142 were appropriately modified. (These Recommendations were renamed as Recommendations ITU-R M.1141 and ITU-R M.1142.) The same conclusions were also incorporated into RR Appendix 5.

8 Power flux-density limits for non-GSO MSS feeder links (Recommendation ITU-R SF.1320)

The World Radiocommunication Conference of 1995 (WRC-95) allocated the bands 6 700-7 075 MHz and 19.3-19.6 GHz in the reverse band direction (space-to-Earth and Earth-to-space, respectively) to the FSS and designated these bands for use by non-GSO MSS feeder links. In addition, the band 19.3-19.6 GHz was also designated for additional use by the FSS for feeder links (space-to-Earth) to non-GSO MSS networks. WRC-97 later extended the latter band range by 100 MHz to cover the band 19.3-19.7 GHz and clarified its use by both GSO FSS and non-GSO MSS feeder-link satellite networks. These bands are also allocated to the FS which have been using these spectrum ranges in a variety of short haul and long haul radio-relay applications. Extensive studies were jointly performed by Radiocommunication Study Groups 4 and 9 in Working Party 4-9S in preparation for WRC-95 to establish the bandsharing feasibility. The link designs envisaged for candidate non-GSO MSS feeder links were conducive to the establishment of pfd limits, rather than trigger thresholds to coordinate with the FS. This was of significant benefit since the bands were already extensively used by the FS in many countries and frequency coordination would place heavy administrative burdens on these countries.

One way to deal with the time-varying nature of interference from non-GSO MSS space stations into the FS was to perform interference analyses employing the FDP methodology contained in Recommendation ITU-R F.1108. Further, in accordance with Recommendation ITU-R F.1094, a maximum performance degradation of 10% is permitted for services sharing spectrum with the FS on a co-primary basis. To establish pfd limits which not only are necessary and sufficient to protect the FS but also do not place undue constraints on non-GSO MSS feeder-link networks, a number of bandsharing assumptions required assessment.

For the case of the 7 GHz band, studies showed that the pfd limits applicable to the 4 GHz and 5 GHz bands (−152/−142 dB(W/m^2) in any 4 kHz band) would not be sufficient to ensure that the FDP of 7 GHz FS systems would be maintained within the maximum 10% degradation limit. For example, peak FDPs in the range of 50% to 250% would be experienced by the FS at critical pointing azimuths, while FDPs in excess of 10% would be experienced in a large range of FS station azimuths. Further analysis using a pfd mask 10 dB tighter produced peak FDP values near 4% at critical FS station azimuths. The average FDPs in this case were less than 1%. This tighter pfd mask, in the absence of other mitigating factors, was sufficient to protect the FS in the 7 GHz band. It was recognized that performance degradation to the FS could also be experienced from GSO FSS networks in the uplink direction but most cases may be treated through earth station/terrestrial station frequency coordination agreements on a domestic or bilateral basis. At the same time, it is expected that the majority of FS stations in future will employ digital modulation and a wider reference bandwidth of 1 MHz could be assumed in interference analyses. Thus, it was necessary to determine an acceptable increase in pfd from –138/–128 dB(W/m^2) in any 1 MHz band which would be deemed both necessary and sufficient to protect the FS.

Account was taken of a number of factors, including on the one hand, up to 6 dB increase in pfd due to FS station latitude and antenna elevation angle; the effects, if any, of polarization discrimination near the main lobe of the FS station antenna; use of a pfd mask, and escalation rate of the pfd mask; and on the other, up to 3 dB decrease due to the effect of multiple non-GSO MSS feeder-link networks. It was concluded that, all factors considered, a 4 dB increase in the pfd and a 10 dB escalation factor between low and high arrival angle limits, will provide the necessary protection to the FS while also providing added flexibility to future non-GSO MSS feeder-link networks.

In addition, in a separate study presented at the WRC-95, it was demonstrated that a pfd mask of –154/–144 dB(W/m^2) in any 4 kHz band would also protect the FS. Such pfd levels would facilitate the implementation of narrow-band carriers by one non-GSO MSS feeder link network. This study was intensely reviewed by the Conference which concluded that both limits, i.e., –154/–144 dB(W/m^2) in any 4 kHz band and –134/–124 dB(W/m^2) in any 1 MHz band, simultaneously applied, would be required to permit bandsharing at 7 GHz. Narrow-band satellite carriers could be implemented cost-effectively, provided their aggregate pfd did not exceed –134/–124 dB(W/m^2) in any 1 MHz band. WRC-95 also decided, but without technical debate, that the pfd limits (in a 1 MHz reference bandwidth) in the sub-band 6 700-6 825 MHz required a 3 dB decrease relative to the band 6 825-7 075 MHz to protect more sensitive FS stations.

For the case of the 19 GHz band, it was necessary to address Recommendation ITU-R SF.1005 which states that in the frequency range 15.4-20 GHz, in bands where the FSS is allocated in a bidirectional mode, the pfd should be lowered from the limits given in Recommendation ITU-R SF.358 by 5 dB, i.e., reduced to –120/–110 dB(W/m^2) in any 1 MHz band. Studies showed that if no account were taken of atmospheric attenuation, the current pfd limits applicable to the 19 GHz band, i.e., –115/–105 dB(W/m^2) in any 1 MHz band, would not be sufficient to protect the FS. Applying Recommendation ITU-R F.1108 in this case resulted in peak FDPs in the range of 11% to 55%. However, in this frequency range, precipitation plays a dominant role in propagation and FS link design. Consequently, the FDP approach in Recommendation ITU-R F.1108 will not be of sufficient value in drawing conclusions on the adequacy of the pfd values to protect the FS. Hence, it was necessary to assess results of other interference methodologies in addition to the FDP approach, such as the cumulative distribution of interference functions (cdf).

As with the 7 GHz band, a number of mitigating factors were studied. For example, the minimum satellite operating angles of candidate non-GSO MSS networks are in the range of 5° to 8°. Atmospheric loss at low slant path angles is typically several decibels, sufficient to offset the tightening of pfd limits as required in Recommendation ITU-R SF.1005. Also, polarization isolation between satellite and terrestrial systems could range up to 3 dB for main-lobe interference cases. Results of cdf analyses, taking into account atmospheric loss but assuming non-GSO networks were to operate with a 0° minimum angle at the pfd limits, showed that the long-term and short-term interference objectives of the FS were met but with small margins (of the order of 2 to 4 dB for the bidirectional case). One study showed that the FS short-term interference objective (for the bidirectional case) was exceeded by about 4 dB, although no atmospheric loss was taken into account. It was concluded that, all factors considered, the existing pfd limits for the band 19 GHz band are necessary and sufficient to protect the FS from non-GSO MSS feeder-link space station interference.

It is important to note that the 19 GHz band may also be used by GSO FSS (space-to-Earth), as well as by non-GSO MSS feeder links in the reverse direction (Earth-to-space). Considering that there is interference margin, albeit small, resulting from the introduction of non-GSO MSS feeder link networks (space-to-Earth), this margin is available to the FS for frequency coordination cases with non-GSO MSS feeder-link earth stations operating in the reverse direction.

Recommendation ITU-R SF.1320 approved in 1997 gives a detailed analysis on the derivation of pfd limits on non-GSO MSS feeder link networks.

9 Review of pfd limits for space science services in the 2 GHz bands (Recommendation ITU-R SA.1273)

Recommendation ITU-R SA.1273 addresses the pfd limits in the 2 025-2 110 MHz and 2 200-2 290 MHz bands to protect FS stations from the emissions of space science services satellite systems. This Recommendation, which was prepared jointly by Radiocommunication Study Groups 7 and 9, is the result of several years of study to determine suitable pfd limits based on the characteristics and performance requirements of FS and space science services systems operating or projected to operate in the bands. Two types of networks are operated by the space science services in the 2 GHz bands – a ground network and a space network. The ground network employs earth stations for telemetry, tracking, command and acquisition of mission data from scientific satellites in all types of orbits. Transmissions from the earth stations to the satellites are in the 2 025-2 110 MHz band. Transmissions from the satellites to the earth stations are in the 2 200-2 290 MHz band.

The space network substitutes a geostationary data relay satellite (DRS) for the earth stations that are used in the ground network. The DRS is used to establish radiocommunication links for telemetry, tracking, command and the acquisition of mission data to satellites that are typically in orbits that are lower than the GSO. The 2 025-2 110 MHz band is used for links from the DRS to the low-orbiting user satellite (i.e., forward links), whereas, the 2 200-2 290 MHz band is used for links from the low-orbiting satellite to the DRS (i.e., return links).

Extensive use was made of Monte Carlo and deterministic simulations of satellite systems and FS systems to determine suitable pfd limits. In the 2 025-2 110 MHz band, these simulations included random orientation of the receiving antenna of FS stations and the computation of the aggregate interference from all DRS stations in view of the receiving FS station as they tracked a set of satellites in random orbits. These simulations confirmed that the existing pfd limits, when expressed in a reference bandwidth of 1 MHz, were suitable to protect typical FS stations operating in the band.

Simulation techniques based on Recommendation ITU-R F.1108 were used to evaluate pfd limits that are applicable to the 2 200-2 290 MHz band. These simulations assumed random orientation of the FS receiving antenna and simultaneous co-channel emissions from 15 low-orbiting satellites in random orbits. The simulations showed that the pfd limit could be relaxed by 3 dB and the reference bandwidth increased from 4 kHz to 1 MHz.

Recommendation ITU-R SA.1273 recommends that in the 2 200-2 290 MHz band; the pfd limit applicable to satellite emissions in the space-to-Earth direction range from –130 dB(W/m^2) to –120 dB(W/m^2) in any 1 MHz band; and for satellite emissions in the space-to-space direction, the pfd may range from –127 dB(W/m^2) to –117 dB(W/m^2) in any 1 MHz band. In the 2 025-2 110 MHz band, the pfd limits applicable to space-to-space emissions of geostationary DRS be limited to the range –130 dB(W/m^2) to –120 dB(W/m^2) in any 1 MHz band. The lower values apply to elevation angles below 5°. Between 5° and 25°, the pfd limit linearly increases to the larger value. It should be noted that the pfd limits in Recommendation ITU-R SA.1273 differ from the limits given in Table 21-4 of RR Article 21.

10 Coordination thresholds for BSS (sound) in the band 1 452-1 492 MHz

As described in § 5.2, the WARC-92 allocated certain frequency bands in the 1-3 GHz range to the BSS (sound). A number of BSS (sound) projects were submitted to the Radiocommunication Bureau. Since the bands are shared with the FS, it became necessary to establish thresholds levels to determine the need to coordinate BSS (sound) systems and FS systems. It was noted that FS systems are generally used for short-haul point-to-point systems and local access systems on point-to-multipoint basis. In certain unfortunate situations, BSS (sound) space stations may appear in the main beam directions of FS receiving stations, resulting in significant interference. It was a difficult task to establish coordination thresholds taking into account such situations.

After an extensive study with participation of both FS experts and BSS experts, Recommendation ITU-R F.1338 was approved by the 1997 ITU Radiocommunication Assembly. The Recommendation presents, as coordination thresholds, the pfd levels equivalent to those applicable to the adjacent MSS bands, but at the same time recognizes the need to apply different pfd levels depending on the situation. Annex 1 to the Recommendation presents some FS system considerations that may facilitate successful coordination.

Recommendation ITU-R F.1338 is a first step on this issue and further study is under way.

11 Concluding remarks

Since 1963, the pfd criteria have been one of the most important issues for frequency sharing between the FS and various space services. In particular, since the WARC-92 which made various new frequency allocations to space services, a number of new ITU-R Recommendations have been developed in order to establish appropriate pfd criteria to protect the FS.

In many cases, criteria were developed only after long and controversial discussions among experts representing the interfering service and the interfered-with service. It was because the issue was complicated and difficult to analyse.

In the future, frequency sharing situations may become more complex and it may become necessary to establish pfd criteria appropriate for new situations. This Recommendation is expected to provide good guidance for such future analyses.

Appendix 1
to Annex 1

Development of pfd limits on FSS space stations

The Extraordinary Administrative Radio Conference (Geneva, 1963) allocated the bands 3 700-4 200 MHz and 5 925-6 425 MHz to the FSS on a shared basis with the FS. This was the first allocation to the FSS for operational purpose. Radio-relay systems in the FS had been operating for more than 10 years and, therefore, the frequency sharing criteria between the two services were among the most important issues discussed by the Xth ex-CCIR Plenary Assembly (Geneva, 1963) before the Conference.

Study Groups 4 and 9 jointly tackled this issue and developed Recommendation 358 (currently Recommendation ITU-R SF.358) which proposed the maximum allowable values of pfd at the surface of the Earth produced by FSS space stations. Since then, efforts continued to improve this Recommendation and to expand the application to other frequency bands. This Appendix gives an overview of such efforts.

1 Ex-CCIR Recommendation 358 (Geneva, 1963)

1.1 Sharing criteria to protect radio-relay systems

The first radio-relay system route operating in the 4 GHz band was placed into service in 1947 between New York and Boston in the United States of America. Since then, many countries throughout the world introduced radio-relay systems into their telecommunications networks both as long haul systems and short haul systems.

When satellite technology emerged, one of the key issues was how to protect the existing radio-relay systems from emissions of space stations. For this purpose, the ex-CCIR developed Recommendation 357 (currently Recommendation ITU-R SF.357) (Communication-satellite systems sharing frequency bands with line-of-sight radio-relay systems – Maximum allowable values of interference in a telephone channel of a radio-relay system). (Note that the term *fixed-satellite* service was defined by the World Administrative Radio Conference for Space Telecommunications (Geneva, 1971) (WARC-71). Until that time, the term *communication-satellite systems* had been used.)

This Recommendation recommended:

1 that communication-satellite systems which share frequency bands with line-of-sight radio-relay systems, should be designed in such a manner that, in any telephone channel of a 2 500 km hypothetical reference circuit for radio-relay systems, the interference noise power at a point of zero relative level, caused by the aggregate of earth stations and the transmitters of communication-satellite systems should not exceed:

1.1 1 000 pW psophometrically-weighted mean value in any hour;

1.2 1 000 pW psophometrically-weighted one minute mean power for more than 20% of any month;

1.3 50 000 pW psophometrically-weighted one minute mean power for more than 0.01% of any month.

Behind Recommendation 357, we find that Recommendation 393 (currently Recommendation ITU-R F.393) specified the allowable noise power in the hypothetical reference circuit for radio-relay systems for telephony using FDM. Recommendation 393 recommended:

1 that the noise power at a point of zero relative level in any telephone channel on a 2 500 km hypothetical reference circuit for frequency-division multiplex radio-relay systems should not exceed the provisional values given below, which have been chosen to take account of fading:

1.1 7 500 pW psophometrically weighted mean power in any hour;

1.2 7 500 pW psophometrically weighted one-minute mean power for more than 20% of any month;

1.3 47 500 pW psophometrically weighted one-minute mean power for more than 0.1% of any month;

1.4 1 000 000 pW unweighted (with an integrating time of 5 ms) for more than 0.01% of any month.

Note that the hourly mean noise clause was later deleted, but the rest can be still found in the current version of Recommendation ITU-R F.393. On the other hand, we can find that there was another Recommendation which specified the maximum allowable noise in real circuits whose length is shorter than 2 500 km. It was Recommendation 395 (currently Recommendation ITU-R F.395), which included the following objectives:

– noise power in a telephone channel of a real FDM radio-relay system of length L km, where L is between 280 km and 2 500 km, should not exceed $3L$ pW one-minute mean power for more than 20% of any month;

– noise power in a telephone channel of a real FDM radio-relay system of length L km, where L is between 50 km and 280 km, should not exceed $50\sqrt{L}$ pW one-minute mean power for more than 20% of any month.

From the above facts, an important factor is that Recommendation 357 was developed on the basis of Recommendation 393, but that Recommendation 395 was not taken into account. Recommendation 395 specified the maximum allowable noise power in real circuits whose length may be as short as 50 km. Even in those days, it was recognized that Recommendation 395 would not be complied with if the interference from satellites were taken into account due to the fact that in the most unfavourable situation where a satellite appears in the main beam of a radio-relay receive antenna, the interference may well exceed the limit allowed by Recommendation 395. Therefore, it was unanimously agreed that the maximum allowable interference from FSS systems should be specified only for the 2 500 km long hypothetical reference circuit.

1.2 Power flux-density limits

An intensive study in 1963 for developing appropriate pfd limits on FSS space stations which will meet the interference objective of Recommendation 357 led to the formulation of Recommendation 358. This historic Recommendation recommended:

1 that frequency sharing between communication-satellites and line-of-sight radio-relay systems be considered to be feasible under the conditions of § 2 or 3 below;

2 that for communication satellite systems which use wide-deviation frequency modulation the power-flux density set-up at the surface of the Earth by the emissions of a satellite should not exceed:

-130 dB(W/m^2) for all angles of arrival, and that signals radiated by a satellite should be continuously modulated by a suitable wave-form if necessary, so that the power flux-density measured in any 4 kHz bandwidth particularly during periods of light loading should not exceed:

–149 dB(W/m^2) per 4 kHz for all angles of arrival,

3 that for communication-satellite systems using other types of modulation, the power flux-density set up at the Earth's surface by the emissions of a satellite, measured in any 4 kHz bandwidth, should not exceed:

–152 dB(W/m^2) per 4 kHz for all angles of arrival;

4 that the above be provisional pending further study.

The justification for the above limits is described in ex-CCIR Report 209 (Geneva, 1963) – Communication-satellite systems – Frequency sharing between communication-satellite systems and terrestrial systems. Some texts are summarized below from Report 209:

It would appear that communication-satellite systems may well require a very large amount of spectrum space to meet future traffic requirements. However, that part of the radio-frequency spectrum between about 1 and 10 GHz, technically most suitable for such systems, is already widely used for terrestrial services. It follows that the problem of finding sufficient spectrum space for communication-satellite systems would be greatly facilitated if it were possible to share frequency bands with other compatible services. Such sharing would have to be based on mutually acceptable standards of protection against interference with some allowance for future developments in the services concerned.

The permissible power of a satellite transmitter should be high enough to give reasonable freedom to the designers of communication-satellite systems to meet the performance requirements of such systems, but must not be so high as to degrade significantly the performance of existing or future line-of-sight radio-relay systems below that of Recommendation 393. It can be shown that a practical limit can be set which meets both of these requirements.

However, a limitation expressed in terms of the satellite transmitter power would be inconvenient, due to the need to cover a range of altitudes and it is considered preferable to define the permissible power-flux (W/m^2) produced at the surface of the Earth by a satellite. This would allow the use of larger radiated powers in satellites in the higher orbits.

In addition to the permissible power-flux, it is also desirable to define the permissible power-flux spectral density (W/m^2 per 4 kHz) in the normal bandwidth of a telephone channel. The object of this requirement is to prohibit the concentration of radiated energy into a small frequency band which could cause excessive interference. A discussion of the relation between power-flux and interference caused by it in a radio-relay system is given in Annex II and provisional values for the permissible power-flux are given in Recommendation 358.

The rationale for the pfd limit of –149 dB(W/m^2) per 4 kHz bandwidth was given in Annex II to Report 209, which can be summarized as follows:

– assumptions for a radio-relay receiver are effective antenna area of 10 m^2 (43 dB gain at 4 GHz, which is larger than 5 m^2 and 40 dB of the average antenna), 3 dB polarization discrimination between circular and linear, and 3 dB feeder loss;

– thus, pfd of –149 dB(W/m^2) per 4 kHz bandwidth in a direct exposure is translated to −145 dBW per 4 kHz bandwidth at receiver input;

– assuming the noise figure of 4 dB (which is much smaller than a typical value of 10 dB), the thermal noise power is –164 dBW per 4 kHz bandwidth;

– assuming the thermal noise without fading (per hop) in a telephone channel of 5 to 10 pW, the interference noise (19 dB higher than the thermal noise) corresponds to 400 to 800 pW;

– since the probability of two hops being affected is negligible (less than 1%), the above interference compares favourably with the 1 000 pW given as the upper limit in Recommendation 357.

Apparently interference entries through radio-relay antenna side lobes were considered negligibly small. No explanation is given either for the total pfd limit of –130 dB(W/m^2) or for the pfd limit of –152 dB(W/m^2) in a 4 kHz bandwidth. But it is interesting to note that the limit of –152 dB(W/m^2) in a 4 kHz bandwidth for the 4 GHz band still appears in the latest version of Recommendation ITU-R SF.358.

It is difficult to understand why Recommendation 358 (Geneva, 1963) specified the same pfd limit for all angles of arrival, but this point was remedied in 1966.

As a whole, Recommendation 358 laid a good foundation for the successful frequency sharing between FSS and FS. Particularly impressive is that Report 209 assumed a noise figure as small as 4 dB while a typical noise figure in those days was about 10 dB.

2 Ex-CCIR Recommendation 358-1 (Oslo, 1966)

In 1966, Recommendation 358 underwent a major revision and the *recommends* part of Recommendation 358-1 (Oslo, 1966) simply reads as follows:

1 that in frequency bands in the range 1 to 10 GHz shared between communication-satellite systems and line-of-sight radio-relay systems, the maximum power flux density produced at the surface of the Earth by emissions from a space station, for all conditions and methods of modulation, should not exceed:

$$\left(-152 + \frac{\theta}{15}\right) \text{ dB relative to 1 W/m}^2 \text{ in any 4 kHz band,}$$

where θ is the angle of arrival of the wave (degrees above the horizontal);

2 that the aforementioned limit should be assumed to relate to the power flux density under free space propagation conditions.

Report 387 (Oslo, 1966) – Power flux-density at the surface of the Earth from communication satellites, gives the following information:

– according to a survey about the extent to which existing antennas of radio-relay systems are directed towards the GSO the percentage of the total antenna-beam directions which so intersect varies between the networks considered, but out of some 6 000 antenna-beam directions reported, about 2% are oriented within 1° of the GSO;

– in wide-deviation frequency-modulation systems, carrier energy-dispersal can be used such that the total pfd limit (–130 dB(W/m^2)) is exceeded without exceeding the limit on pfd in any 4 kHz band (–149 dB(W/m^2)). Hence the former limit is restrictive without providing additional protection to radio-relay systems;

– by allowing an increase in the limiting value of pfd in any 4 kHz band as the sub-satellite point is approached, the design of satellite systems with simpler earth stations would be facilitated. Such a relaxation would assist the satellite system designer, yet not increase the potential interference to radio-relay systems;

– for most satellite antennas, the radiation pattern of the antenna is likely to provide some 3 dB less gain towards the horizon than towards the centre of the Earth and the path length (and hence, attenuation) to the horizon is greater than to the point immediately below the satellite; the combination of these factors means that the pfd at the sub-satellite point could be some 6.5 dB greater than at the horizon for a satellite at 8 000 km, and some 4.2 dB greater for a satellite at 20 000 km (note that satellite antennas in these days were of low gain with global coverage).

These factors were the rationale for the revised Recommendation. The value of –152 dB(W/m^2) in a 4 kHz band was derived for the following reference radio-relay station:

– antenna of 7.5 m^2 effective area (about 42 dB gain);

– 3 dB feeder attenuation;

– 3 dB polarization discrimination;

– overall system noise temperature, 750 K;

– 25 pW thermal noise (psophometrically weighted) in a telephone channel of a free-space path of 50 km;

– operating frequency, 4 GHz.

Under these assumptions, the interference of 1 000 pW corresponds to the pfd of –150.6 dB(W/m^2) in a 4 kHz band.

3 Ex-CCIR Report 387-1 (New Delhi, 1970)

The 1969 joint meeting of Study Groups 4 and 9 received a proposal to replace the pfd limit in any 4 kHz band in Recommendation 358-1 with the following:

$$-152 + 0.5\,\theta \quad \text{dB(W/m}^2\text{)} \qquad \text{for } 0° \le \theta < 20°$$

$$-142 \quad \text{dB(W/m}^2\text{)} \qquad \text{for } 20° \le \theta \le 90°$$

where θ is the angle of arrival above the horizontal plane.

The reason for the proposal was to allow satellites employing spot beams. However, this was not accepted by the meeting and after intensive discussions, the following pfd mask for 4 kHz reference bandwidth was derived as a candidate for further study:

-152	$dB(W/m^2)$	for $0° \leq \theta < 5°$
$-152 + 0.5\ (\theta - 5)$	$dB(W/m^2)$	for $5° \leq \theta < 25°$
-142	$dB(W/m^2)$	for $25° \leq \theta \leq 90°$

Here, the pfd limit is constant for 0° – 5° angles of arrival. The rationale for adopting a constant value for this range is described in Recommendation ITU-R SF.358, Annex 1, § 2.3.

The revised candidate pfd mask was incorporated in the revised Report 387-1 (New Delhi, 1970), inviting administrations to carry out further study.

4 Ex-CCIR Special Joint Meeting (Geneva, 1971)

This meeting was a special meeting of Ex-CCIR Study Groups (similar to the current Conference Preparatory Meeting) to prepare for WARC-71. The pfd limits for FSS space stations were among important issues to be considered by this meeting.

Various contributions were submitted reporting on the simulation results concerning the candidate revised pfd mask for the 4 GHz band described in Report 387-1 (New Delhi, 1970). Most of them reported that the candidate mask was acceptable, but one administration reported that the candidate pfd limit for high arrival angles was too high, when a relatively poor radiation pattern of actual antennas of asymmetrical type in the vertical plane was taken into account.

Finally the meeting accepted the pfd mask proposed in Report 387-1. The results of these studies are now summarized in Appendix 1 to Annex 1 to Recommendation ITU-R SF.358. Satellites were assumed to be located on the GSO with a uniform spacing (3° or 6°). Each satellite was assumed to produce the maximum pfd at the surface of the Earth as permitted by a pfd mask at all angles of arrival.

In order to simulate routes of radio-relay systems of 50 hops, a station in the centre of the route was assumed to be at a certain latitude (typically 40°). Its longitude was chosen as a random parameter. Then the azimuth angle of the route trendline was chosen randomly from 0° to 360°. The antenna direction (azimuth) of each station was randomly chosen within ±25° of the trendline. This determines the location of the adjacent station. Thus, the locations of all stations can be determined. The interference from all visible satellites was summed up.

The results of simulation studies showed that for most radio-relay routes, the aggregate interference was below 1 000 pW. Only for some routes (less than 10%), the interference slightly exceeded 1 000 pW.

Then, the meeting endeavoured to establish new pfd masks for the frequency bands other than the 4 GHz band. It was noted that there were many operational radio-relay systems in the frequency range between 2 GHz and 15 GHz.

The meeting took into account that the pfd limit may be increased as the operating frequency increases from 10 to 30 GHz, for several reasons:

– greater atmospheric absorption;
– higher receiver noise temperatures;
– limits on the effective aperture of FS antennae imposed by manufacturing tolerances and by minimum beamwidths to ensure accurate pointing.

In conclusion, the meeting decided to apply the pfd mask proposed in Report 387-1 to the band 3-8 GHz, and the following masks were adopted for other frequency bands;

– 2 dB more stringent for the band 1.7-2.3 GHz, provisionally;
– 2 dB less stringent for the band 8-11.7 GHz;
– 4 dB less stringent for the band 11.7-15.4 GHz.

However, for the band 15.4-23 GHz, an entirely different approach was taken. There were no FS systems operating at frequencies above 15.4 GHz, although research and development activities were vigorously under way in various administrations. Therefore, it was difficult to identify model FS systems to be protected. In addition no protection criteria existed.

The meeting received four contributions proposing pfd limits in the band 15.4-23 GHz. It was agreed that mainly digital systems would operate in this band. This recognition led to the adoption of 1 MHz reference bandwidth instead of 4 kHz bandwidth adopted for lower frequency bands.

Interestingly enough, three contributions proposed almost the same pfd limits. On the other hand, one contribution proposed a much higher pfd limit. The meeting discussed whether there were sufficient technical materials to support a definitive pfd limit. The meeting was bold enough to say yes and, on the basis of a majority proposal, adopted the pfd mask of –115 dB(W/m^2) and –105 dB(W/m^2) in any 1 MHz band for low and high angles of arrival, respectively, which still appears in the latest version of Recommendation ITU-R SF.358.

5 World Administrative Radio Conference for Space Telecommunications (Geneva, 1971)

WARC-71 made new frequency allocations to various space services including FSS, BSS, MSS and space science services. The pfd limits included in the Report of the ex-CCIR Special Joint Meeting (Geneva, 1971) formed an important basis for consideration by the WARC-71. Most of them were incorporated into the RR without change as the pfd limits for the newly allocated FSS bands. In addition, they were also adopted as the pfd limits for certain bands allocated to space science services.

An exception was the 2 500-2 690 MHz band which was allocated to the BSS for television by community reception. For this band, the WARC-71 adopted the pfd limit of –152 dB(W/m^2) and –137 dB(W/m^2) in 4 kHz band for low and high angles of arrival, respectively. This decision took into account a special requirement of BSS systems and was based on an estimate that not many BSS systems will operate in this band.

6 Ex-CCIR Recommendation 358-2 (Geneva, 1974)

Ex-CCIR Recommendation 358-2 revised in 1974 incorporated the conclusions of the ex-CCIR Special Joint Meeting (Geneva, 1971) and the WARC-71 without any additional changes of substance. Since then this Recommendation has been maintained as Recommendation ITU-R SF.358 without major modifications.

It should be noted that Recommendation ITU-R SF.358 was developed to protect FS systems primarily from emissions of FSS space stations on the GSO, but it is also applicable to FSS space stations employing non-GSOs. Analyses confirmed that this Recommendation was appropriate for a limited number of non-GSO satellites.

7 Advance of digital radio-relay systems

Ex-CCIR Recommendation 358-2 (Geneva, 1974) was intended to protect analogue radio-relay systems. However, the technology of digital radio-relay systems showed a rapid progress since late 1960s. The first ex-CCIR Recommendation dealing with performance of digital radio-relay systems was Recommendation 594 adopted in 1982, which specified the overall error performance objective of digital radio-relay systems over the 2 500 km hypothetical reference digital path.

In 1986, ex-CCIR Recommendation 615 (later Recommendation ITU-R SF.615 was deleted in 2003) was developed which specified the maximum allowable interference to digital radio-relay systems from FSS systems. Several studies were carried out in order to determine whether Recommendation 358-2 was adequate to protect digital radio-relay systems. As a result, one important factor emerged. The progress of the technology for digital radio-relay systems made it possible to improve the spectrum efficiency by introducing multi-state modulation, which made the system more vulnerable to interference from space stations. Under this condition, it was found necessary to introduce orbital avoidance in the design of digital radio-relay systems in order to maintain the interference from FSS space stations within the allowable value of ex-Recommendation ITU-R SF.615. This factor is discussed in more detail in Appendix 3 to Annex 1 to Recommendation ITU-R SF.358.

The pfd limits of ex-CCIR Recommendation 358-2 (Geneva, 1974) were intended to protect analogue radio-relay systems for which orbital avoidance had not been implemented. But since the advent of digital radio-relay systems employing multi-state modulation, it has become a general practice to avoid the GSO in site selections of FS receiving stations shared with FSS (space-to-Earth) (see also Note 2 of Recommendation ITU-R SF.406 and RR No. 21.2).