RECOMMENDATION ITU-R SA.1071*

USE OF THE 13.75 TO 14.0 GHz BAND BY THE SPACE SCIENCE SERVICES
AND THE FIXED-SATELLITE SERVICE

(Resolution No. 112, WARC-92)

(1994)

The ITU Radiocommunication Assembly,

considering

a) that the World Administrative Radio Conference for Dealing with Frequency Allocations in Certain Parts of the Spectrum (Malaga-Torremolinos, 1992) (WARC-92) allocated the frequency band 13.75 to 14.0 GHz to the fixed-satellite service (FSS) on a primary basis;

b) that this band is also allocated to the space research service on a secondary basis and may also be employed by the earth exploration-satellite and space research services on a secondary basis for radiolocation stations installed on spacecraft (see Radio Regulation (RR) No. 713);

c) that RR No. 855A places restrictions on the fixed-satellite and radiolocation and radionavigation services in order to allow these services to share this band;

d) that RR No. 855B provides for geostationary space stations in the space research service, for which information for advance publication was received by the ex-IFRB prior to 31 January 1992, to operate on an equal basis with stations in the FSS;

e) that for the case of interference between FSS satellites and geostationary data relay satellite (DRS) spacecraft for which advance publication information was received by the ex-IFRB prior to 31 January 1992, the regulatory procedures of RR Article 11 apply;

f) that orbital separations as small as 0.1° may be possible in the geostationary-satellite orbit (GSO) between receiving fixed-satellite space stations and transmitting DRS space stations for the interference conditions described in § 8;

g) that for the case of potential interference from an FSS earth station into a DRS earth station operating with a geostationary DRS spacecraft, the coordination contours can be determined in accordance with Recommendation ITU-R IS.848 and the separation distance requirement is considered to be a highly localized problem that may be addressed by the affected parties;

h) that RR No. 855B stipulates that prior to 1 January 2000 stations in the FSS shall not cause harmful interference to non-geostationary space stations in the space research and earth exploration-satellite services but after that date these non-geostationary space stations will operate on a secondary basis in relation to the FSS;

j) that there is a need to continue operation of existing DRS networks around 14 GHz, especially in the frequency band 13.772-13.778 GHz, well beyond the year 2000 in support of space research and earth exploration-satellite missions that cannot be supported by alternative means;

k) that there is a need to continue operation of a planned precipitation radar with protection from interference in the band for one year beyond the 1 January 2000 date specified in RR No. 855B;

l) that criteria are needed for use by the FSS in implementing uplinks in the band 13.75-14.0 GHz prior to the year 2000 while avoiding unacceptable interference to space stations in the science services;

* This Recommendation should be brought to the attention of Radiocommunication Study Group 4.

** In this Recommendation, space science services refers to the earth exploration-satellite service and the space research service.

m) that criteria are needed for use by the science services in implementing space stations in the band 13.75-14.0 GHz so that after the year 2000 they might operate while not causing harmful interference to, or requiring protection from, stations in the FSS, taking into account § j) and k);

n) that WARC-92 in Resolution No. 112 invited the CCIR to conduct the necessary studies with regard to technical compatibility between the primary allocation to the FSS (Earth-to-space) and the secondary allocations to the space research service and the earth exploration-satellite service in the band 13.75-14.0 GHz;

o) that maximum pfd levels likely to be produced at the GSO by space stations in the space science services are those given in Table 4;

p) that it would be desirable for future DRS networks operating in the space science services to be designed to operate at frequencies outside the 13.75-14.0 GHz band;

q) that the interference environment for space science services continuing to operate in the band after the protection periods is likely to be severe,

recognizing

1. that Radiocommunication Study Group 4 (in Task Group 4/4) has also studied the conditions for radio-frequency compatibility between the fixed-satellite and space science services in the 13.75-14.0 GHz band, and that the results of those studies (Recommendation ITU-R S.1069) have been taken into account in the development of this Recommendation,

noting

1. that systems of the space science services have a continuing need, as explained in Annex 1, to operate at frequencies in the vicinity of 14 GHz with bandwidths of as much as 500 MHz and that many of these systems cannot share spectrum easily with systems of the FSS (Earth-to-space),

recommends

1. that, during the time periods indicated in the appropriate following *recommends*, the permissible levels of interference specified in Annex 2 for the current space science services should be applied when considering specific sharing situations;

2. that, during the time periods indicated in the appropriate following *recommends*, the information in Annex 3 should be read as guidelines for the prevention of unacceptable interference to the space science services;

3. that to protect spaceborne altimeters from unacceptable interference until 1 January 2000 the following consultative steps should be taken:

3.1 upon publication of the RR Appendix 4 information of an FSS network intending to use the 13.75-14.0 GHz band, the administration with a spaceborne altimeter in the band should inform the notifying administration of the geographic constraints, if any, which may affect the location of earth stations in the FSS network;

3.2 the FSS network operator should review the information above and advise the operator of the spaceborne system about the location(s) of proposed earth stations in the network that would not meet the geographic constraints;

3.3 the consultation would then focus on these earth stations in order to ensure the protection required by the spaceborne altimeter;

4. that to protect spaceborne scatterometers using fan beams from unacceptable interference until 1 January 2000, FSS earth stations should not exceed an e.i.r.p. density toward the scatterometer orbit over the oceans of 25 dBW in any 2 kHz band between 13.99356 GHz and 13.99644 GHz. To meet this condition it may be advisable to avoid operation between these frequencies. Exceptionally, on a case-by-case basis the avoidance of unacceptable interference may be accomplished through consultation;

5. that to protect spaceborne precipitation radars from unacceptable interference:

5.1 until 1 January 2001:

5.1.1 the e.i.r.p. density of any FSS earth station at a latitude between ±55° should not exceed 61 dBW in any 600 kHz band between 13.793 GHz and 13.805 GHz;

5.1.2 the elevation angle of any FSS earth station using the band 13.75-14.0 GHz should not exceed 71°;

5.2 until 1 January 2000, implementation of individual FSS earth stations planned to use the band 13.75-13.86 GHz at latitudes between ±40° will require consultation on a case-by-case basis, in order to ensure that the appropriate protection is given (see Note 1);

5.3 the consultation process in § 5.2 should be extended until 1 January 2001, with a view to ensuring that whenever practicable the appropriate protection is given (see Note 1);

Note 1 – The consultation process in § 3 is also applicable to the consultations carried out under § 5.2 and § 5.3 to protect spaceborne precipitation radars from unacceptable interference. An administration planning an FSS network should provide detailed information regarding the emissions in the band 13.793-13.805 GHz with its RR Appendix 4 submission.

6. that to protect the links from DRS to low-Earth orbiting satellites operating in the space science service until such time that all data relay satellites in the GSO, for which information concerning advance publication was received by the ex-IFRB prior to 31 January 1992, cease to operate within the band 13.772-13.778 GHz, the e.i.r.p. density of transmissions from any FSS earth station within this band should not exceed 71 dBW per 6 MHz;

7. that administrations who continue to operate DRS networks in the space science services after 1 January 2000 are urged to implement DRS networks in bands other than 13.75-14.0 GHz as soon as practicable;

8. that after the time periods indicated in the appropriate foregoing *recommends*, the following guidelines should be taken into account by the operators of any space stations in the space research or earth exploration-satellite services that remain in operation in the 13.75-14.0 GHz band in order to avoid causing unacceptable interference to space stations in the FSS:

8.1 an emission from a non-GSO space station in the space science services would be likely to cause unacceptable interference to satellites of the FSS if its pfd incident on the GSO should exceed –130 dB(W/m^2) per 40 MHz anywhere in the frequency range 13.75-14.0 GHz;

8.2 the above value could probably be increased by up to 7 dB for short periods aggregating to no more than 0.02% of any month;

8.3 an emission from a GSO space station in the space science services would be likely to cause unacceptable interference to satellites of the FSS if its pfd incident on the GSO should exceed –127 dB(W/m^2) per 40 MHz anywhere in the frequency range 13.75-14.0 GHz within an angle of ±10°, subtended at the GSO and in the plane of the GSO, with respect to a line between the GSO and the Earth's centre (see Note 1);

8.4 for angles of incidence outside the angular range specified in § 8.3, interference pfds up to –97 dB(W/m^2) per 20 MHz anywhere in the frequency range 13.75-14.0 GHz could probably be tolerated (see Note 1);

Note 2 – § 8.3 and 8.4 refer to antipodal positions of a GSO space station in the space science services and a GSO spacecraft in the FSS.

9. that after the time periods indicated in the appropriate foregoing *recommends*, radiolocation stations installed on spacecraft (see § b)) should operate outside the frequency range between 13.75 GHz and 14 GHz (see Resolution No. 712 (WARC-92)) to the extent possible in order to avoid unacceptable interference to and from networks in the FSS, and that the necessary studies be conducted to determine the regulatory means to meet the requirements described in Annex 1.

ANNEX 1

Current and future use of the 13.75-14.0 GHz band by the space science services

1. Introduction

The purpose of this Annex is to address the continued need of the space research service and the earth exploration-satellite service to access frequencies near 14 GHz, the bandwidth requirements, and the scientific feasibility of performing the same measurements in bands other than the 13.4-14.0 GHz band. These requirements will be addressed from the viewpoint of the four major users of the band: scatterometers; altimeters; precipitation radars; and data relay satellites.

2. Scatterometers

2.1 Use of the 13.75-14.00 GHz band for scatterometers

Scatterometers are radar type devices that measure the near surface vector winds over the oceans. Wind data are critical to determination of regional weather patterns and global climate. No other instrument can provide all weather measurements of the global vector winds.

At the present time, good capability for acquisition of weather data exists over land, but not over the oceans where our only knowledge of surface winds comes from infrequent, and sometimes inaccurate, reports from ships. Since approximately two-thirds of the Earth’s surface is covered by oceans, data from scatterometers will play a key role in understanding and predicting complex global weather patterns, ocean circulation, and climate systems.

Two scatterometers currently in development in the United States are the NSCAT (NASA scatterometer) that will be launched in 1996 on Japan’s ADEOS (Advanced Earth Observing Satellite) and the NEXSCAT which will be launched around 1999 as part of the Earth Observing System (EOS). NSCAT, which has been designed to operate at a centre frequency of 13.995 GHz, has been built and is currently in system test and calibration. A change in frequency is not feasible. NEXSCAT is in the design phase but it is a derivative of NSCAT and is expected to use many of the same components. However, it is feasible to move the operating frequency to a frequency in the band 13.4-13.75 GHz.

2.2 Bandwidth requirements

Existing scatterometer designs use a fixed-frequency, continuous wave pulse to probe the sea surface. The transmitted frequency spectrum is narrow due to the low pulse repetition rate (62 Hz) and large pulse width (5 ms). When the frequency stability of the transmitter and Doppler shifts of frequency are included, the required radio-frequency bandwidth for present-day scatterometers is 1 MHz.

Future scatterometers may use spread spectrum modulation in order to obtain more precise definition of the surface cell where wind measurements are being taken. The bandwidth requirement for these future instruments could be 100 MHz.

2.3 Feasibility of using other bands

Scatterometer measurements, and the derived knowledge about wind vectors, are based on microwave scattering effects over water-surface capillary waves. Measurements at wavelengths comparable to that of the capillary waves caused by water-surface wind interaction is necessary in order to achieve the sensitivity required to measure wind speeds and directions for winds having velocities as low as 3 m/s. Measurements of winds with such velocity are needed to satisfy the requirements for determination of variation in weather and climate. The wavelength in the 13.4-14.0 GHz band is commensurate with the dimensions of the capillary waves produced by low speed winds with the result that the scatterometer is highly sensitive to local winds, especially low wind speeds. At the same time, a scatterometer operating in the 13.4-14.0 GHz band exhibits low sensitivity to non-wind effects such as swells and surface film/surface tension.

Possible alternative bands to the 13.4-14.0 GHz band have been considered. The two bands closest to 14 GHz that are currently available to the Earth exploration-satellite service are the 9.5-9.8 GHz and 17.2-17.3 GHz bands. Neither the 9.5-9.8 GHz band nor the 17.2-17.3 GHz band are as desirable for use by scatterometers as the 13.4-14.0 GHz band. This is a consequence of there not being a large body of data on radar scattering from the ocean surface at frequencies other than 14 GHz where the Seasat scatterometer operated and 5.3 GHz where the ERS-1 scatterometer is operating. Moving to a new band would require re-developing the algorithm that relates the radar return to the wind speed and direction. The algorithm developed for the 5.3 GHz band required a number of aircraft and tower experiments before launch and more than six months of refinements after the launch of ERS-1. An effort to develop a new algorithm would result in an interruption of the data flow to the science community for the period that is required to gain confidence in the new algorithm. A frequency change will result in some loss of the continuity of the long-term data set for the same reason. The experience with the ERS-1 scatterometer to date shows that the NSCAT or NEXSCAT requirement to measure wind direction at wind speeds below 5 m/s cannot be met with a scatterometer operating in the 5.3 GHz band. The low speed wind vectors are important to the studies of the variability of ocean currents. At frequencies above 14 GHz, atmospheric attenuation due to water content (e.g. cloud cover and rain) becomes more variable. At 17.2 GHz, it is probably possible to operate a wind scatterometer, however, operating at a frequency of 17.2 GHz or greater would result in degraded performance since the scatterometer would be more sensitive to atmospheric water content and surface film/surface tension effects. At frequencies above 20 GHz, the variability of the atmospheric attenuation would render the instrument useless without other means of measuring the atmospheric variability.

Another factor that makes continued use of the 13.4-14 GHz band for scatterometry important is the large amount of data that has been acquired at this frequency over the past 15 years. The Seasat scatterometer and the NASA aircraft scatterometer both operated at this frequency, as will the NSCAT. Continued use of this band for future EOS scatterometers will allow more meaningful cross-comparison of data sets acquired in the future with those from the past. A broader database acquired by instruments operating with similar parameters can be expected to produce a more accurate scientific model.

2.4 Long-term need for operation around 14 GHz for scatterometers

There is a long-term requirement to operate spaceborne scatterometers in the 13.4-14 GHz band. Scatterometer measurements will be used in operational systems to derive wind speed and wind direction data. These data will be used to measure and predict weather, ocean circulation, and climate, all key factors in management of the environment. As discussed above, only in the 13.4-14 GHz band can the required measurement sensitivity be achieved. In addition, only in this band is there an existing database acquired over a period of 15 years that can contribute to the value of future scatterometer data interpretation.

The NSCAT scatterometer has already been constructed to operate at 13.995 GHz and it is not possible to change its frequency. Protection of NSCAT operations until the year 2000 is essential. On the other hand, the NEXSCAT scatterometer is at a developmental stage and its frequency will be changed to 13.4 GHz in order to preclude frequency sharing constraints with respect to the fixed-satellite service. Likewise, any other new scatterometers developed for this frequency range should operate below 13.75 GHz. It is projected that a 100 MHz bandwidth will be needed for future scatterometers in order to improve measurements through the use of alternative modulation techniques.

3. Altimeters

3.1 Use of the 13.75-14.0 GHz band for altimeters

A spaceborne radar altimeter is a downward-looking pulsed-radar system mounted on an orbiting spacecraft. They are primarily ocean remote sensing instruments, although there is some interest in the tracking data that they acquire over land and ice surfaces, as implemented on the ERS altimeters. Current and planned radar altimeter missions are designed to meet over ocean requirements; land/ice tracking is a secondary data product.

Altimeters are used to measure range from the satellite to the ocean surface. This very precise height measurement, when combined with very precise orbit determination and corrections for other media effects, provides very accurate global maps of the ocean topography. From this knowledge of topography, the location, speed, and direction of ocean currents worldwide can be calculated. This provides an understanding of ocean circulation and its time variability that is crucial to understanding the Earth's climate change. Altimeter data can also provide measurements of surface-significant wave height (ocean waves), and backscatter at nadir from which wind speed (but not the wind vector) can be determined. The meteorological forecasting community plans to incorporate the above measurements into an operational system on the next planned NASA/CNES altimeter project.

Several spaceborne radar altimeters are currently operating in the allocated band of 13.4-14 GHz. There are also several planned missions, such as TOPEX follow-on, GEOSAT follow-on, EOS and ENVISAT-1, that will operate altimeters in this band. Radar altimeters are now an operational tool for earth/ocean/air sciences and, as such, will continue to be launched and used long into the future. The TOPEX-POSEIDON altimeters are centred at frequencies of 13.6 and 13.65 GHz and have emissions that extend from 13.44-13.76 GHz and 13.49-13.81 GHz, respectively. The ERS-1 altimeters are centred at 13.80 GHz and have emissions that extend from 13.635-13.965 GHz.

The 13.4-14 GHz band was chosen long ago based on such considerations as an allocation for radars on spacecraft, wide allocated bandwidth, science objectives, hardware availability, and compatibility with the radiolocation service. The first spaceborne altimeter to use this band was the Skylab S-193 experiment in the early 1970s; since then, there have been many altimeters using this band (GEOS-C, Skylab, GEOSAT, TOPEX-POSEIDON and ERS-1). This use represents a considerable investment in hardware design, hardware development, missions operations, data reduction, software design, scientific analysis, modelling and database construction.

A very large database has been obtained from these altimeters that allows the proper interpretation of current and future altimeter data. These data are very sensitive to the hardware transmission frequencies. A change in operating frequency could negate the applicability of a substantial amount of that existing database. Also, a significant amount of hardware for both inflight use and ground use has been developed in both the United States of America and in Europe that will support future missions. Much of this hardware is designed to operate within the 13.4-14 GHz band. Based on the above, the need for altimeters working within this frequency band will extend well into the future. It should be noted that the TOPEX follow-on alone is planned to operate on multiple satellites from 1998 for at least 20 years.

3.2 Bandwidth requirements

The bandwidths being employed by current and planned altimeters are of the order of 320 MHz (for TOPEX-POSEIDON) to 330 MHz (for ERS). As in any radar system, the precision of the altimeter's height (range) measurement is dependent on the bandwidth used. The TOPEX altimeter uses pulse compression (chirp full de-ramp stretch) to achieve its fine precision. In TOPEX, the 320 MHz allows for an effective compressed pulse width of 3.125 ns (46.5 cm basic resolution) before further processing and averaging is done. Ultimately, the precision on the Ku-band channel is less than 3 cm.

Several studies have been carried out in the United States of America that examined the need to extend the bandwidth for altimeters to as much as 600 MHz. These studies examined other effects on the accuracy of height measurement including EM-bias, sea-state bias, ionospheric effect, tropospheric effect and orbit determination. It has been concluded that these effects are large enough at the present time to dominate the error budget for the height measurement. A decrease in the 2-3 cm height uncertainty achieved by the TOPEX altimeter would not significantly change the total error. Therefore, the bandwidth of 320-330 MHz used by current altimeters will be adequate for missions currently in the planning or conceptual stages of development.

In the future, if systematic errors can be significantly reduced by modelling, new instruments, etc., then increasing the bandwidth to as much as 600 MHz may be desirable. Also, in the future, components for altimeters with such wide bandwidths may become much more available and affordable.

There are potential changes to the basic design of altimeters that may produce a need for wider bandwidths: multibeam altimeters, scanning altimeters, and synthetic aperture altimeters fall into this category. Another design that would require a wider bandwidth is for an altimeter that would decorrelate its along-track measurement by use of frequency agility or frequency hopping. Several such designs have been studied in concept but are not currently supported by any flight project.

Another reason that bandwidths greater than 320-330 MHz may be needed is to accommodate both an altimeter and a scatterometer on the same spacecraft.

An interference-free bandwidth of 500 MHz would be available if the lower limit of the band currently allocated for active sensors could be extended downward from 13.4-13.25 GHz. It is concluded that this allocation could accommodate both present and potential future needs for spaceborne altimeters.

3.3 Feasibility of using other bands

It is not at all desirable to move altimeter operations to other bands. First of all, there is a very large database from altimeters operating in the 13.4-14 GHz band. This database has established many facets required for altimetry, such as electromagnetic bias of the sea surface at 13.6 GHz, an exact model of the interaction of the surface features and the RF pulse, atmospheric effects on the RF attenuation and delay, and spacecraft attitude effects on the return waveshape just to name a few. Translating all of this data to another frequency would be a considerable task if it could be done at all without actual flight data. Currently, the TOPEX altimeter has a secondary frequency (5.3 GHz) for determining ionospheric effects. Some of the subtleties of operating in this new band are just now being learned.

The following requirements would be applicable to any new frequency chosen:

– at whatever frequency an altimeter was designed to operate, it would require 320 MHz of bandwidth to meet current precision requirements. Anything less would give degraded performance which would be unacceptable to the science community;

– the altimeter is intended to be an all weather instrument. It is required to obtain ocean surface data 90 to 95 per cent of the time. At allocated frequencies above 20 GHz, the altimeter measurement would be degraded by both clouds and rain. At a frequency of 13.6 GHz, these effects can be compensated for except during very heavy rains. At 35 GHz, these effects would degrade the altimeter operation. The attenuation and delay changes could not be adequately compensated for and mission objectives could not be met;

– at the lower frequencies (below 5.0 GHz), the hardware would become considerably larger and heavier. To obtain the required signal/noise ratios for precision tracking at lower frequencies would require larger antennas. Since future missions are being directed as smaller, lower cost, and more lightweight systems, this would not be feasible. Other problems, such as inadequate allocated bandwidth, exist in all of the lower frequency bands.

3.4 Continued need for frequencies around 14 GHz for altimeters

The only allocated band where altimetric mission requirements can be met is the 13.4-14 GHz band where extensive databases have evolved, and where simulators, models and space-qualified hardware have been developed. TOPEX-POSEIDON will continue to operate in the 13.75-14 GHz band until 1997.

Future designs could be accommodated if the lower band edge of the allocation could be shifted down in frequency from 13.4-13.25 GHz. The feasibility of doing this would depend on the results of studies to determine the conditions for sharing between the satellite-borne altimeters and aeronautical radionavigation systems for which the band is currently allocated.

4. Data relay satellite networks

4.1 Use of the 13.75-14 GHz band

In 1983, the United States of America launched the first satellite in its Tracking and Data Relay Satellite System (TDRSS) data relay satellite network. TDRSS relays commands, scientific data and spacecraft health and safety information for a number of NASA low-Earth orbit (LEO) satellites such as the space shuttle, Landsat and other non-NASA flight missions. There is also an agreement to support international or joint venture LEOs.

There are firm plans for this system to support space missions well beyond the year 2000 using operational tracking and data relay satellites located at 41°, 46°, 171° and 174° W longitude on the geostationary orbit. On-orbit backup TDRS satellites are located at 62° and 79° W longitude. A TDRS satellite will also be located at 85° E. This data relay satellite network is planned to be augmented by the addition and/or replacement of TDRS satellites by a functionally equivalent replacement TDRS and by TDRS 8, 9, 10 replenishment spacecraft, also functionally equivalent, beginning in the year 1998. Satellites will eventually be replaced by a next generation of TDRS after the year 2000.

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

4.2 Bandwidth requirements

The bandwidth requirements are pictured in Fig. 1. The figure shows two links in the 13.75-14 GHz band. The use of the band that is at issue is the forward link from the TDRSS to low-Earth orbit satellites used for command, control and ranging and for transmission of data and video. The centre frequency is 13.775 GHz.

The bandwidth is typically 6 MHz in the case of command and control data, where in most cases the low-rate information data is spread with a 3 chip/s pseudo-random noise (PN) code. A 50 MHz bandwidth is required for sending higher rate data to a spacecraft or video information to the space shuttle or space station. Reliable transmissions of commands in the 6 MHz around 13.775 MHz are most critical. The bandwidth required for this link is not expected to decrease in the foreseeable future.

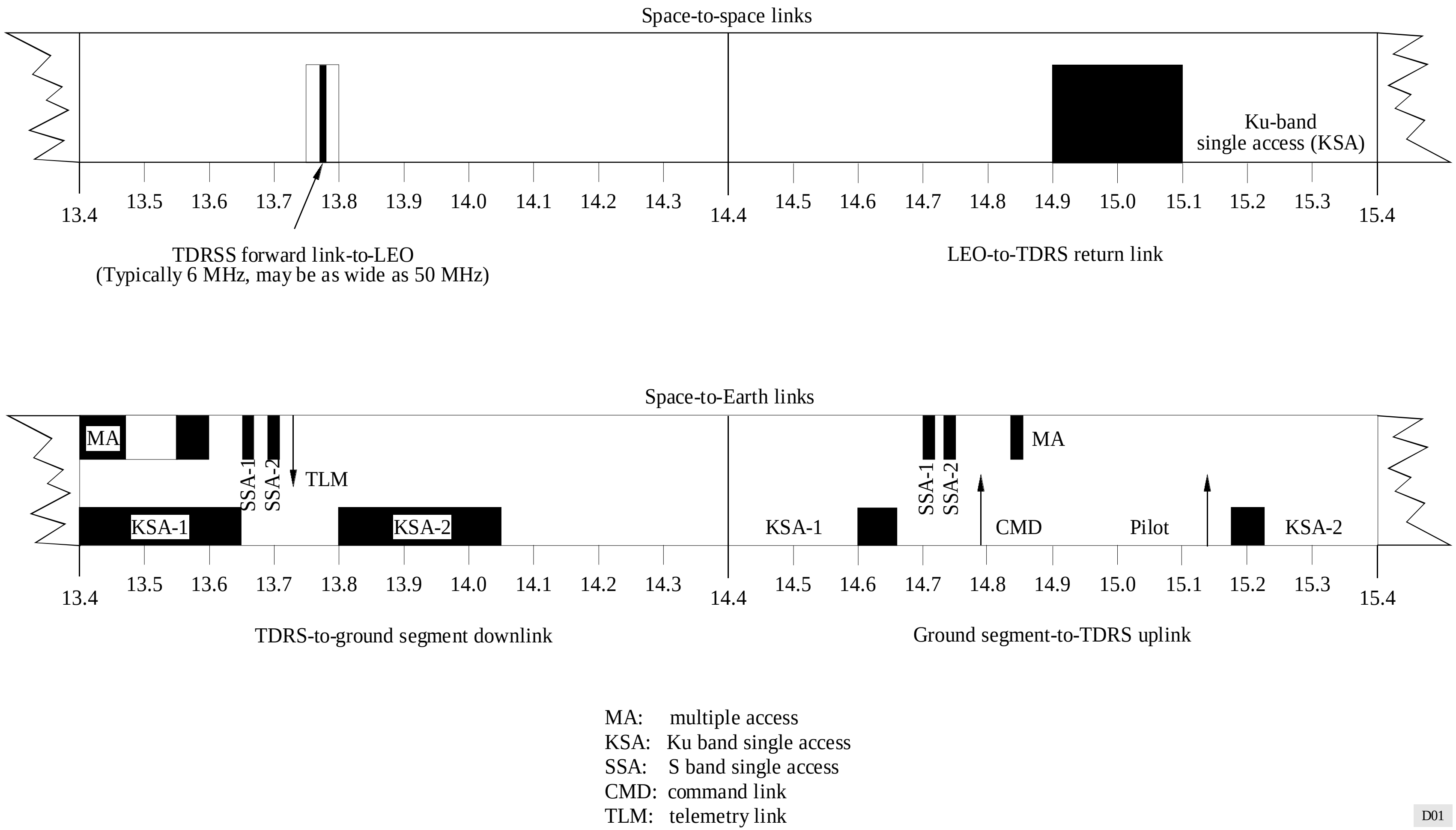
The second link is a feeder link used to transmit wideband signals received by the TDRS from LEO satellites to the TDRSS data relay satellite network earth station. The signals consist of primarily scientific data and spacecraft telemetry. The bandwidth of this link may be up to 225 MHz centred around 13.9 GHz. The bandwidth required for this link is not expected to decrease, especially with the advent of Earth observation satellites using high-resolution instruments within the next several years.

4.3 Feasibility of using other bands

The TDRSS data relay satellite network currently uses frequencies around 2 GHz and 13/15 GHz to operate and to receive data from low-orbiting satellites. The 13/15 GHz is also used for feeder links for the geostationary TDRSS data relay satellite network. The TDRS replacement and TDRS 8, 9, 10 satellites will use the same frequency plan as the current TDRS satellites. At the time of WARC-92, it was believed that the next generation of data relay satellites to be operated by the United States of America would add links in the 23/26 GHz bands for use with low-orbiting satellites in both the forward and return directions. The higher bands would accommodate data rates that are not as easily accommodated in the 13/15 GHz bands. There are now no firm plans to proceed with the next generation of spacecraft. It is clear that the need for reliable use of the 13.75-14 GHz band by the TDRS data relay satellite network will continue to exist for some time.

FIGURE 1

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



4.4 Continued need for the 13.75-14 GHz band

Elements of the United States TDRSS data relay satellite network require access to the 13.75-14 GHz band until well after the year 2000. An important use is the forward link operating in the lower portion of the band for relaying commands to spacecraft like the space shuttle and the mission to planet Earth's Earth observing system. Satellite systems currently in operation or planned for use in this band will likely have useful lifetimes in excess of 20 years. Experience has shown that there are satellites launched almost 30 years ago that are still returning useful data. While there will be the opportunity to continue to operate satellites beyond their design lifetime, the primary need for continued access to the 13.75-14 GHz band is one of economics. The economic investments that have been made to develop, implement and operate all the space and terrestrial elements of the TDRSS data relay satellite network, including those elements that use the 13 GHz bands, are in excess of many tens of billions of United States dollars and cannot be easily replicated within the next several decades.

5. Precipitation radars (PR)

5.1 The use of 13.75-14 GHz band by PR

Although there are several frequencies allocated to spaceborne radars (e.g. 10 GHz, 14 GHz, 17 GHz and 35 GHz), the 14 GHz band was selected as the most suitable frequency for precipitation radars, especially single-band radars such as the tropical rain measuring mission (TRMM) PR. The major system requirements which determine the frequency selection are:

a) dynamic range and sensitivity of rainfall measurements,

b) instantaneous field-of-view (IFOV) vs. antenna size, and

c) signal-to-ground clutter ratio.

It is concluded that using the frequencies higher than 14 GHz cannot satisfy the requirement a) and that the requirements b) and c) are difficult to meet with the use of the frequencies lower than 14 GHz.

The TRMM PR, which is the only spaceborne precipitation radar appearing before the year 2000, is under development by NASDA, Japan, and the change in frequency is not feasible. A TRMM-follow-on mission has also been studied in relation to global hydrological studies (such as GEWEX) and its target launch is around the year 2000. For this mission, the 14 GHz band is also essential, and it would be the best choice to use the same frequency as TRMM from the cost and schedule point of view and from data continuity considerations.

5.2 Bandwidth requirement

Since the range resolution requirement for the PR is not as severe as other spaceborne radars such as SAR and altimeters, the receiver bandwidth of the precipitation radar is expected to be fairly narrow (at most several megahertz). However, the following facts should be considered:

– *Frequency agility:* In order to achieve high accuracy in rain echo power estimates in a short time, the frequency agility technique, which uses multiple carrier frequencies several megahertz apart from each other and transmits pulses sequentially or alternatively, will be employed. Although the bandwidth of each frequency is the same as that of non-frequency-agility radar, the total bandwidth required is significantly larger. For example, the TRMM PR uses two frequencies 6 MHz apart from each other, and each frequency channel has a 3 dB bandwidth of 0.6 MHz. To achieve a sufficient attenuation of 60 dB, a total bandwidth of 12 MHz is required, which is used for the FSS earth station – PR interference study. In general, the number of frequency channels will be limited to three or four, so the total bandwidth required will be between 20-40 MHz depending upon the number of channels and the frequency separation.

– *Pulse compression radar:* For future missions, pulse compression techniques will be employed in order to achieve a higher resolution, a high sensitivity and/or high accuracy in rain echo power estimates. The bandwidth of a pulse-compression radar will be at least several times wider than non-pulse-compression radar, but much less than the bandwidth of spaceborne altimeters.

– *RF bandwidth:* Although the final bandwidth of a radar receiver is determined by a narrow band-pass filter, it is necessary to evaluate the response of the radar receiver to out-of-band interference signals, because the bandwidth of the receiver front-end up to the IF unit at which the narrow band-pass filtering is performed is generally much wider. This can cause the saturation of the receiver front-end. The out-of-band interference signal may also appear in the radar video signal due to the finite attenuation of the band-pass filters.

In summary, the bandwidth of future spaceborne precipitation radars would be at most 30-40 MHz. Consideration of the receiver RF bandwidth, which is generally much wider than the final pass band, is also necessary.

5.3 *Feasibility of using other bands*

This section considers the frequencies suitable for the TRMM and future space rain measurement missions (based upon the above general discussion). We begin with the case of single-band radar followed by a brief discussion on dual-band radar. The single-band radar is used not only for TRMM but is also considered as a baseline instrument for the TRMM-follow-on.

5.3.1 *Measurement dynamic range*

Frequencies higher than 17 GHz cannot satisfy the requirement of rain rate measurement dynamic range between about 1 mm/h and 50 mm/h which is based on a statistical study of tropical oceanic rainfall. The 17 GHz band is a possible candidate for the measurement of precipitation at higher latitudes where light rainfall would be dominant. For tropical rainfall, however, this frequency is too high to obtain a sufficient dynamic range. For this reason, TRMM and future TRMM-like missions should use a frequency lower than 17 GHz.

5.3.2 *IFOV*

In order to achieve an IFOV of the order of 5 km from a typical LEO altitude of 500 km, the beamwidth should be about 0.01 rad (~0.6°). That is, the antenna size should be about 100 λ or greater. In the case of the TRMM PR, the antenna size is about 2 m $\times$ 2 m^2 (~ 92 λ). This size has been determined from the scientific requirement for the IFOV, the limitation in antenna fabrication accuracy and the size of launching rocket fairing.

To achieve the same IFOV with a lower frequency, a larger antenna size will be required, which makes the antenna fabrication and the interfaces with the spacecraft and the rocket more difficult. A conclusion in the TRMM PR feasibility study was that the use of 10 GHz or lower frequencies was technically difficult. Although the situation may change to some extent depending upon the spacecraft and rocket capabilities, the use of frequencies lower than 10 GHz, which requires an antenna of about 5 m or larger, is not feasible for a PR on board a spacecraft.

5.3.3 *Signal-to-clutter ratio*

The requirement of the signal-to-clutter ratio (S/C) depends upon the minimum rainfall rate that should be measured. There are two types of surface clutters to be considered; one is the clutter caused by antenna side lobes and the other is that caused by range side lobes appearing in the receiver filter output pulse. The latter can be particularly serious in the case of pulse-compression radars. The maximum surface clutter can reach about 60 dB higher that the rain echo corresponding to the 1 mm/h rain, which requires very low antenna side-lobe levels. TRMM PR antenna aperture distribution adopts a Taylor weighting with $SL = -35$ dB to achieve low side-lobe level characteristics. A performance analysis has demonstrated that the PR can achieve the minimum S/C of about 4 dB for 0.7 mm/h rain rate. If the frequency is lowered to 10 GHz, however, the strength of rain echo relative to surface clutter will decrease by about 6 dB, which will cause loss of rain detection capability at light rain rates.

In summary, the use of frequencies lower than 10 GHz for spaceborne rain radar is difficult from the signal-to-clutter point of view.

5.3.4 Frequencies for dual-band radars

In the case of dual-band radars, which may be implemented after the year 2000 in order to achieve wider dynamic range and higher accuracy in precipitation retrieval, the selection of radar frequencies becomes more complicated. If the major objective is rain measurement, combinations of 10 and 24 GHz, 14 and 35 GHz, and 14 and 24 GHz would be desirable. If the objective is to measure both rain and cloud, the frequency selection would be an independent decision process of a single-band rain radar and a single-band cloud radar.

In either case, the frequencies near 14 GHz will remain essential for future dual (or multiple) band radars, as it provides global coverage (both tropical and higher latitude rain) as regards the dynamic range of measurement, and is technically feasible with respect to the requirements of spatial resolution and signal clutter.

5.4 Continued need for operation around 14 GHz

For the single-band radar (TRMM PR and perhaps TRMM-follow-on PR) for global rainfall measurement, frequencies near 14 GHz are essential because:

– from the measurement dynamic range point of view, 17 GHz is too high;

– a shift in frequency near 14 GHz to 10 GHz would require significant design changes in the radar to achieve the same resolution and sensitivity. Although advances in antenna technology may make the use of lower frequencies feasible for missions beyond the year 2000, the increase in antenna size and weight might force a redesign in spacecraft and require the use of an alternative launch vehicle.

The importance of frequencies near 14 GHz also holds for the future dual-band radars. This band has been used for several spaceborne scatterometers and altimeters. The heritage and databases in radar hardware and scattering cross-section data are very useful for continuing development of the spaceborne PR. Since the TRMM PR uses 13.8 GHz, many algorithms have been developed for this frequency, which can work only around 14 GHz. In addition, an airborne radar at this frequency has been developed by JPL/NASA and a second radar is under development by Communications Research Laboratory, Japan, for TRMM radar algorithm testing and validation.

Considering the past heritage, databases and on-going efforts, it is essential to keep frequencies near 14 GHz for current and future spaceborne PR.

6. Summary and conclusions

This Annex has addressed the use of the 13.75-14 GHz band, the bandwidth requirements, the feasibility of using bands other than the 13.75-14 GHz band to satisfy mission requirements, and the long-term need to access spectrum near the 13.75-14 GHz band from the view point of four major space applications now operational in the band: scatterometers; altimeters; precipitation radars (as well as precipitation radars for future applications); and data relay satellite networks. Based on these preliminary studies, the following are concluded:

– *For scatterometers:*

  – the current generation scatterometer (NSCAT) operates at a centre frequency of 13.995 GHz and is to be flown aboard the ADEOS spacecraft in 1996; a follow-on scatterometer (NEXSCAT) will be modified to operate at 13.402 GHz and is to be launched around 1999;

  – the current generation scatterometers require a radio-frequency bandwidth of 2.88 MHz;

  – future generations of scatterometers may require bandwidths up to 100 MHz near the 14 GHz band;

  – the use of bands above and below the 13.4-14 GHz band that are allocated for use by radars on-board satellites is not an acceptable alternative on the basis of economic investments that have been made to develop databases; data reduction algorithms, and ground and space-qualified equipment; and the optimality of the frequency band for the physical phenomenon being observed; and

  – continued use and protection of scatterometer bandwidths of 2.88 MHz centred at 13.995 GHz is required until the year 2000, after which scatterometers operating below 13.75 MHz will be available.

– *For altimeters:*

  – the current generation of altimeters use a bandwidth of approximately 320 MHz centred at 13.60, 13.65 and 13.80 GHz;

  – a bandwidth of up to 600 MHz may be required to accommodate both an altimeter and a scatterometer on the same spacecraft;

  – the use of bands above and below the 13.4-14 GHz band that are allocated for use by radars on board satellites is not an acceptable alternative on the basis of: economic investments that have been made to develop databases; data reduction algorithms, and ground and space-qualified equipment; and the optimality of the frequency band for the physical phenomenon being observed;

  – access to the 13.75-14 GHz band is required through 1997 for TOPEX-POSEIDON and through 2000 for ERS. Both the United States and the French altimeters to be used for the TOPEX follow-on, as well as the ERS follow-on altimeters on ENVISAT, can be moved down in frequency so that they will not require access to the 13.75-14 GHz band, and

  – if 330 MHz is the maximum bandwidth required, future altimeters will operate in the band 13.40-13.75 GHz. If newer designs materialize that require wider bandwidths, they could be accommodated in a band below 13.75 GHz if the lower band-edge of the allocation could be shifted down in frequency from 13.4-13.25 GHz. Further studies are suggested to determine the conditions for sharing between the satellite-borne altimeters and aeronautical radionavigation systems for which the band is currently allocated.

– *For precipitation radars:*

  – the current generation of precipitation radars to be flown on board TRMM in 1997 operate at 13.796 GHz and 13.802 (two-channel frequency agility) with a receiver bandwidth of 0.6 MHz and require a bandwidth of 12 MHz (13.793-13.805 GHz) free from interference for at least three and a half years;

  – a bandwidth of up to several tens of MHz may be required to accommodate precipitation radars of the next generation;

  – the use of bands above and below the 13.4-14 GHz band that are allocated for use by radars on board satellites is not an acceptable alternative on the basis of dynamic range of measurement, IFOV and spacecraft design requirement;

  – considering past heritage, databases and on-going efforts, it is essential to keep frequencies around 14 GHz for current and future spaceborne precipitation radars;

  – continued use of 12 MHz of receiver bandwidth centred around 13.799 GHz will extend beyond the year 2000;

  – precipitation radars on board future missions such as the TRMM follow-on satellite, could be available to operate at a centre frequency below 13.75 GHz. However, study of compatibility between radiolocation and the space research service in the band 13.4-13.75 GHz may be necessary.

– *For data relay satellite networks:*

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

  – this use is the culmination of investments of many tens of billions of United States dollars that have been made in extensive system trade-off studies, the development and qualification of space hardware, and the development and implementation of satellite systems and earth stations comprising the TDRSS data relay satellite network;

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

  – the next generation of data relay satellites is planned to add links in the 23-26 GHz band for use with low-Earth orbiting satellites; and

  – elements of the United States TDRSS data relay satellite network require access to the 13.75-14 GHz band until after the year 2012.

ANNEX 2

Permissible levels of interference in space science systems that use the 13.75-14 GHz band

1. Introduction

This Annex presents criteria for protection of space science systems operating in the 13.75-14 GHz band from Earth-to-space links operating in the FSS. The criteria consist of a permissible level of interference signal power in a specified reference bandwidth at the output of the receiving antenna that is not to be exceeded for more than a specified percentage of time and locations. The largest possible reference bandwidths are specified in order to enable the greatest possible sharing benefit from averaging interfering signal power over bandwidth. Although the criteria are based on current and planned space science system designs and associated operating requirements, it is anticipated that future space science systems can be designed to accept at least the same levels of interfering signals and associated spatial and temporal conditions.

2. Altimeters

The interfering signal power above which data are unacceptably degraded was derived for two families of altimeters. For one TOPEX-POSEIDON altimeter (13.44-13.76 GHz), based on a nominal operating signal-to-noise power ratio (S/N) of 13 dB (at baseband) and an established relationship between the S/N and height measurement noise, an aggregate interfering signal power level exceeding –117 dB(W/320 MHz) would cause an unacceptable increase in the height measurement noise (i.e. greater than 4%). For the other TOPEX-POSEIDON altimeter (13.490-13.810 GHz), the permissible level of interference is –130 dB(W/320 MHz). Interference to TOPEX-POSEIDON is of concern for observations made over only oceans and large bodies of water. For the ERS-1/2 altimeters (13.635-13.965 GHz for ERS-1), measurements conducted by ESA indicate that data will be significantly corrupted if the aggregate level of interfering signal power exceeds –120 dB(W/330 MHz) when observing land, ice and oceans.

The availability requirement for altimetry data is 95%, assuming that the associated individual outages are brief and randomly dispersed over all observation times and areas (i.e. most outages lasting 2 s or less). The above interfering signal power thresholds could be exceeded by Earth-to-space links in the FSS. In addition, outages may occur due to external causes (e.g. intense rainfall). Because the data loss from interfering earth stations will occur systematically (i.e. non-randomly) at the same locations, and because observations (and altimeter calibration operations) in certain areas are of relatively high importance, it is necessary to consider interference from planned FSS earth stations on a case-by-case basis. Specifically, it is necessary to determine the portion of the altimeter orbit(s) and associated observation areas for which altimeter data may be lost in cases where interference from a particular earth station exceeds the permissible level.

3. Scatterometers

The permissible level of interference differs for scatterometers using antennas that generate fan beams (i.e. current systems) and spot beams (i.e. contemplated designs for future systems) and depends on the speed of winds being observed (i.e. observations of winds with relatively low speed are more susceptible to data loss from interfering signals). The NSCAT scatterometer operates in a bandwidth of 2.88 MHz centred at 13.995 GHz. For scatterometers using fan beams, an aggregate interfering signal power level exceeding –174 dB(W/2 kHz) causes unacceptable measurement error for low-speed winds. Similarly, for spot beam antennas, the aggregate interfering signal power threshold is –155 dB(W/10 kHz).

The overall availability requirements for scatterometers are similar to those for altimeters except that scatterometers suffer greater intra-system outages, scatterometer observations are made only over oceans and large bodies of water, and systematic data losses over the same areas are more acceptable for scatterometers. Accordingly, Earth-to-space links in the FSS may exceed the applicable interfering signal power threshold such that data from 1% of the area of the ocean is lost systematically or 5% of the area of the ocean is lost randomly.

4. Precipitation radars

The science requirement for the TRMM PR is to achieve, after data processing, measurement of rain rates equal to or greater than rain rates of 0.7 mm/h. An increase in measurable rain rate to 0.75 mm/h would not materially affect the data and would be acceptable. Such an increase corresponds to a degradation in the system noise level of 10% due to noise-like interference. Therefore, the interference should be 10 dB below the system noise level. Since the system noise level is –140 dBW and the final bandwidth of the PR is 600 kHz, the criteria for the harmful interference level is –150 dB(W/600 kHz). Outside the 12 MHz band between 13.793 GHz and 13.805 GHz, the allowable interference level is much higher due to the band-pass filtering in the receiver; –115 dBW for 13.790-13.793 GHz and 13.805-13.808 GHz, –90 dBW for 13.75-13.79 GHz and 13.808-13.850 GHz, and –70 dBW for 13.85-13.86 GHz.

Scientists on the TRMM project have determined that the needed availability of rainfall data is a function of where the rainfall occurs. For most areas within the TRMM observing area between ±38° latitude, a loss of 0.2% of the possible data due to interference is acceptable.

In addition to the above global criterion, areas where the PR measurements are especially important must be taken into consideration. Measurements in such important areas should be protected from interference as much as possible to prevent data loss and degradation of data quality. The "important" areas can be classified into the following two categories:

– Tropical regions having intense rainfall and rainfall variability need to be protected from interference because the amount and the variability of rainfall in those areas make significant contributions to the large-scale atmospheric circulation, thereby controlling global climate. Among such regions, the belt area extending in an East-West direction north of the Equator (called inter-tropical convergence zone or ITCZ), and the wide belt area extending from the Maritime continent to the South Pacific (called Australian monsoon trough and South Pacific convergence zone or SPCZ) are of particular importance. These most important areas are generally bounded by latitudes of (0°-10°) and by (50° E-180° E) and (0°-10° S), as shown in Fig. 2.

– In order to satisfy accuracy requirements for most TRMM scientific research, a comprehensive "ground truth" programme is essential. For TRMM, several ground truth facilities have been constructed at key locations in the TRMM observing area. In Japan, at least one PR calibration site will also be constructed.

For specific FSS earth stations, consultations will be needed in order to determine location, magnitude, and impact of data loss in these limited areas to determine whether use of certain frequencies within the range 13.75-14 GHz by the FSS will be compatible with the TRMM mission requirements.

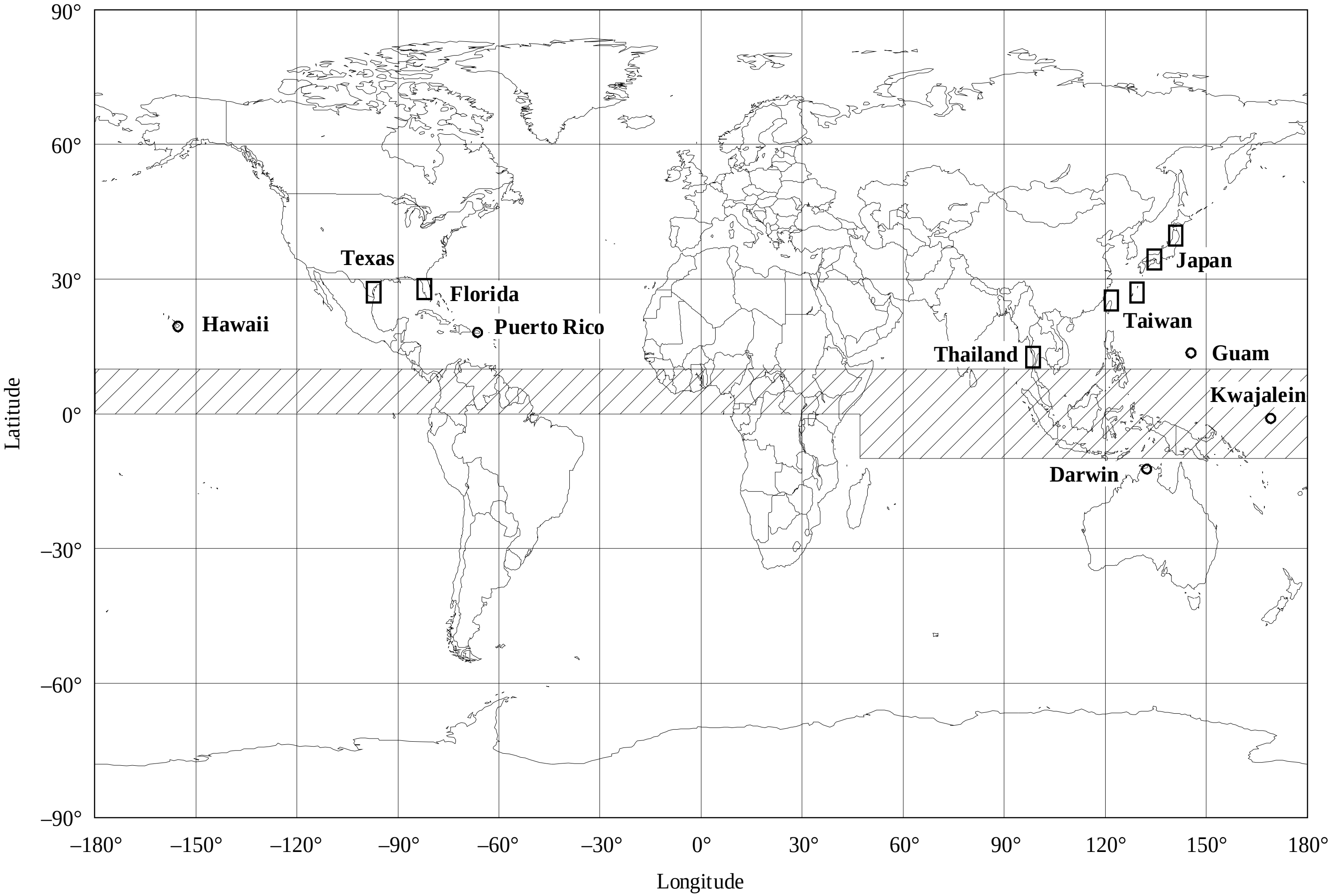
The location of the intense rainfall areas of primary importance mentioned above and the currently planned ground truth sites are shown in Fig. 2. Ten ground truth sites have been selected. There are two categories of sites, those with multiple radars and those with single radars. The multiple radar sites are designed to provide complete rainfall detection over a 500 by 500 km grid box for validation of monthly climatological means. The single radar sites will provide rainfall estimates to a radius of 120 to 150 km depending on the radar type. The coordinates of these critical radar sites are contained in Table 1. Although there are no existing plans for additional ground truth sites, there is the possibility that one or more additional sites could be added and would need to be taken into account when planning for FSS earth stations occurs.

5. Data relay satellite systems

The permissible level of degradation to a data relay satellite link is a 0.4 dB reduction in link power margin, which occurs with an I/N of –10 dB. An aggregate protection criteria of –178 dB(W/kHz) for no more than 0.1% of the time on the forward inter-orbit link of a low-orbiting satellite operating in a data relay satellite network may be used. This is equivalent to –140 dB(W/6 MHz). The I/N criterion of –10 dB is applicable over a bandwidth of up to 6 MHz centred at 13.775 GHz, although operations can extend over a bandwidth of up to 50 MHz centred at the same frequency. In order to achieve desired link availabilities, the interference threshold should not be exceeded for more than 0.1% of the time by Earth-to-space links in the FSS.

FIGURE 2

Location of the intense rainfall areas of primary importance and "ground truth" sites



Multiple radar sites

Single radar sites

Intense rainfall areas of primary importance to TRMM

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TABLE 1

Coordinates of TRMM ground truth sites

Location /Type	Name	Latitude	Longitude
1. Florida – multiple site	Melbourne, FL Miami, FL Jacksonville, FL Tampa, FL Key West, FL Tallahassee, FL	28° 06' N 25° 36' N 30° 30' N 27° 42' N 24° 33' N 30° 24' N	080° 39' W 080° 24' W 080° 39' W 082° 24' W 081° 45' W 084° 21' W
2. Australia – single site	Darwin, AUS	12° 27' S	130° 55' E
3. Kwajalein – single site	Kwajalein Atoll	08° 43' N	167° 43' E
4. Texas – multiple site	Houston, TX Texas A&M, TX Brownsville, TX Corpus Christi, TX San Antonio, TX	29° 28' N 30° 35' N 25° 54' N 27° 46' N 29° 42' N	095° 05' W 096° 30' W 097° 36' W 097° 30' W 098° 03' W
5. Marianas – single site	Guam	13° 39' N	145° 47' E
6. Japan – multiple site	Combined rain gauge and weather radar networks over the Japanese islands		
7. Thailand – multiple site	Phuket, THA Om Koi, THA Bangkok, THA	08° 00' N 17° 48' N 14° 10' N	098° 30' E 098° 25' E 100° 30' E
8. Hawaii – single site	Hawaii, HA	19° 00' N	156° 00' W
9. Taiwan – multiple site	Taipei, Kuanshan,	25° 10' N 25° 05' N	121° 45' E 121° 35' E
10. Puerto Rico – single site	Humacao, PR	18° 10' N	066° 21' W

ANNEX 3

Feasibility of operating space science systems and FSS uplinks in the 13.75-14 GHz band

1. Introduction

The feasibility of sharing the 13.75-14 GHz band between various types of space science systems and Earth-to-space links in the FSS is addressed in this Annex. Estimates of the potential levels and associated spatial and temporal characteristics of interference to known operational and developmental space science systems are presented. These results are compared with the criteria in Annex 2 in order to determine whether the e.i.r.p. and minimum antenna diameter limits of RR No. 855A assure adequate protection of each type of space science system. In cases where the permissible interference is expected to be exceeded, the bases for procedural measures are developed for the prevention of unacceptable interference. In all cases, the ramifications of the analytical results are interpreted with regard to the provisions of RR No. 855B.

2. Interference to active sensors

Several of the following analyses indicate that the aggregate interference criteria of Annex 2 may not be met (i.e., for all active sensors except spot beam scatterometers). In these cases, and in light of the provisions of RR No. 855B, the following measures should be applied for protecting active sensors until the year 2000:

– case-by-case consultation should be conducted for overlapping earth station and active sensors frequency assignments in cases where the associated peak interfering signal level at the receiver antenna output would exceed the permissible level specified in Annex 2;

– to facilitate the consultation, the locations and characteristics of all potentially interfering earth stations should be made available to administrations operating active sensors. This will enable active sensor operators to determine whether any data loss can be accepted over those areas;

– current and future ITU-R Recommendations, as well as the following subsections should be consulted for guidance on the fixed-satellite and space science system design and operating adjustments and considerations that may lead to a conclusion that interference will be at acceptable levels.

2.1 Altimeters

Potential interference from earth stations was evaluated for the ERS-1/2 and TOPEX-POSEIDON altimeters. In general, it was found that an earth station operating in accordance with RR No. 855A can cause co-channel interference in excess of the permissible level. Although the provisions of RR No. 855A were developed for protection of terrestrial radiolocation systems from earth station transmissions, it is concluded that these provisions facilitate sharing with the space science services but that case-by-case consideration of co-channel sharing situations is generally needed to assess the potential altimeter degradation within these current systems and determine appropriate mitigations. In some cases, it is planned to maintain altimeter spacecraft orbits that may preclude mainbeam illumination of the spacecraft and interference in excess of the permissible level; in these cases, interference might be avoided inherently or through earth station site selection constraints. This principle is illustrated for TOPEX-POSEIDON in Fig. 3, which shows that the area in the altimeter orbital sphere where the permissible level of interference may be exceeded is substantially smaller than the area between anticipated satellite locations ("interference areas" over land can be disregarded because only oceanic observations are made in this case). It was also found that in the long term (i.e. assuming extensive earth station usage of the band), it is unlikely that altimeter performance requirements of these current systems can be met in the shared band as a result of the systematic degradation that may occur in the relatively important areas of observation.

FIGURE 3a

Topex-Poseidon orbit vs. potential interference zone

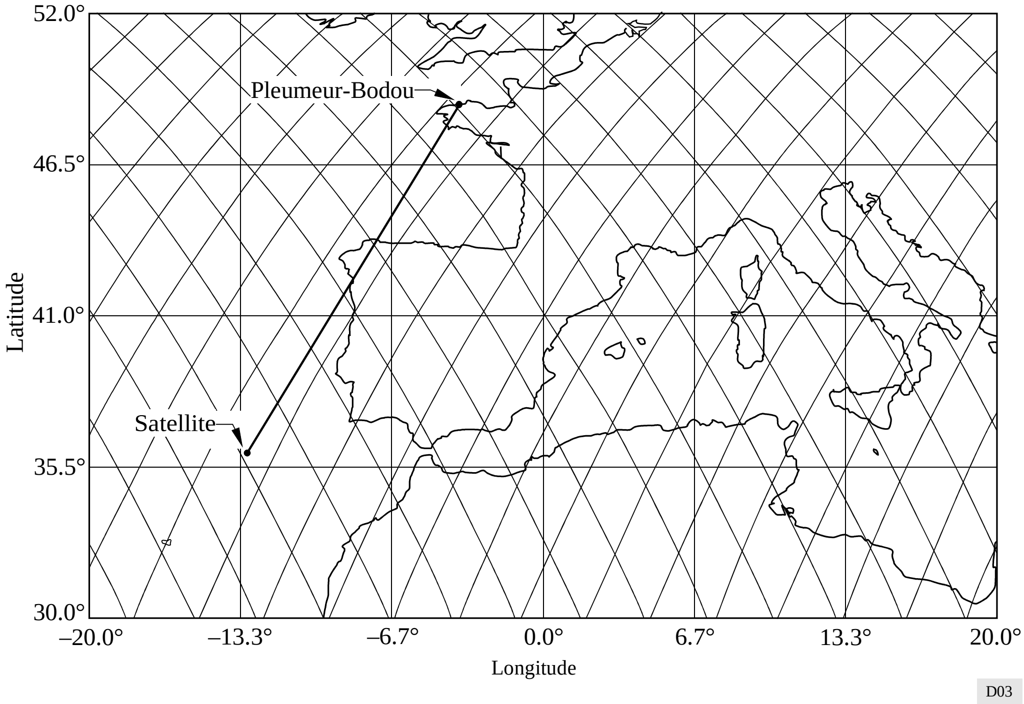


FIGURE 3b

Enlarged view of Fig. 3a

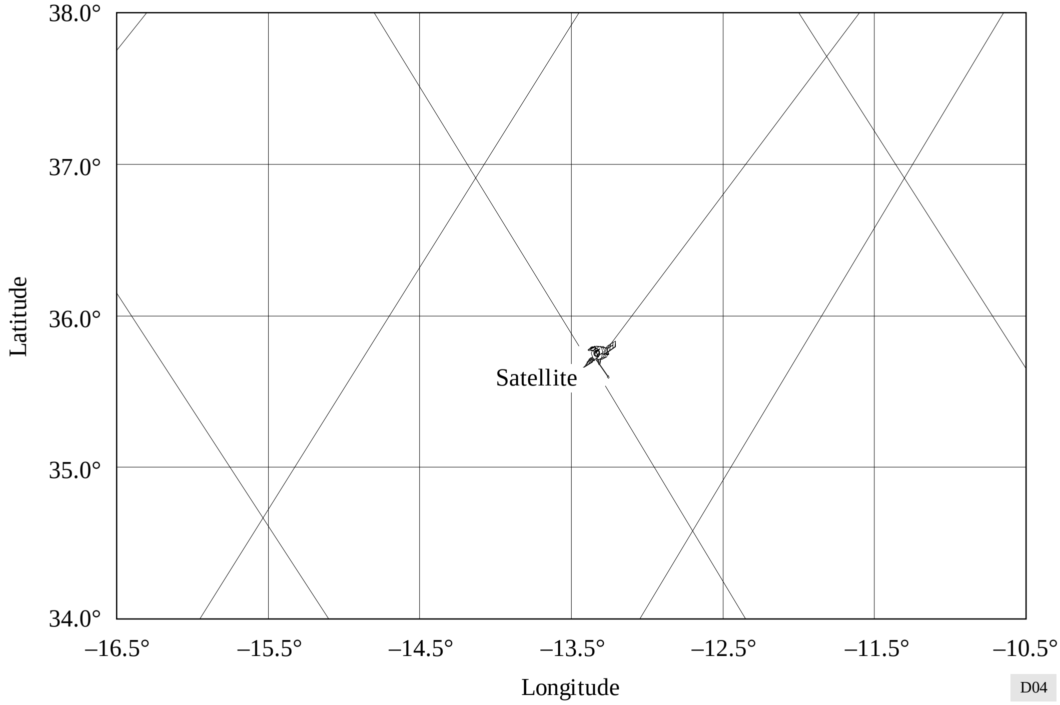
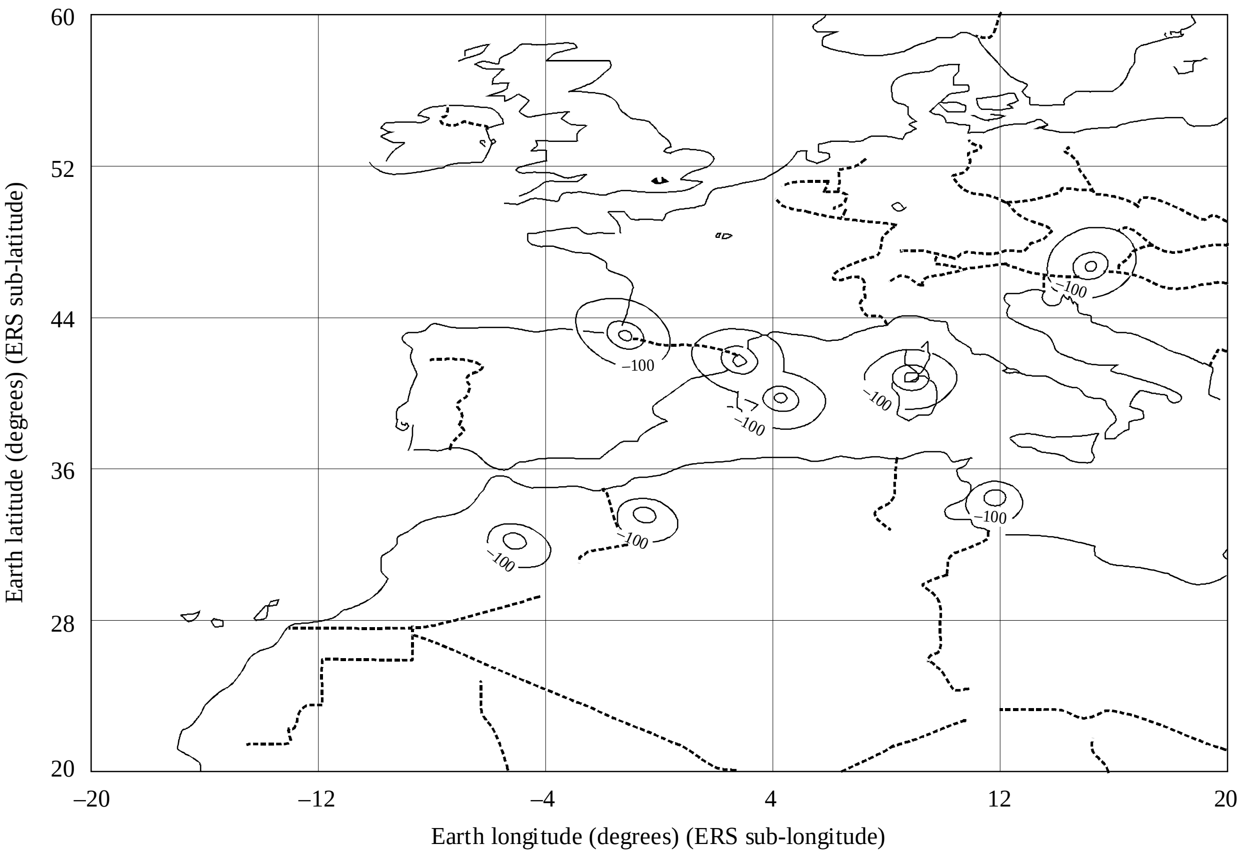


Figure 4 illustrates the areas in which the interference threshold for ERS-1/2 would be exceeded as a result of several earth stations operating on a co-channel basis with an antenna diameter of 4.5 m. Polarization discrimination is disregarded and the earth station antenna radiation pattern of RR Appendix 28 is assumed. The figure shows that for each earth station, the interference threshold would be exceeded in an area around each earth station site and a larger area corresponding with illumination of the altimeter by the mainbeam of the earth station antenna. The dimensions of these areas and the effect of varying earth station antenna diameter and total e.i.r.p. within the portion of the altimeter bandwidth overlapping the shared band (13.75 GHz to 13.965 GHz) are illustrated in Tables 2 and 3.

FIGURE 4

Interference level at sub-location (dBm)



Global view of interference areas originated by emissions from E/S in Stockholm, London, Dublin, Paris, Frankfurt, Rome, Madrid and Lisbon.

E/S (4.5 m antenna) - GEO satellite at 10° E.

Contours plotted in 10 dB steps. Contours of unacceptable data degradation: "–100" contour corresponds with an earth station e.i.r.p. of 95 dBW in the altimeter bandwidth: smaller concentric contours correspond with earth station e.i.r.p. levels of 85 dBW and 75 dBW within the altimeter bandwidth.

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Assuming that an earth station uses 85 dBW e.i.r.p. and a 4.5 m antenna diameter with the RR Appendix 28 radiation pattern, Fig. 5 shows the interfering signal power received by a TOPEX-POSEIDON altimeter over a 10 min time period as it passes through the mainbeam of the earth station (no polarization discrimination is considered and co-channel operation is assumed). The figure shows that even if the minimum earth station e.i.r.p. were used (68 dBW), the permissible level of interference could be exceeded. Figure 6 shows the cumulative time distribution of interfering signal power from 32 earth stations deployed throughout Europe, Africa, eastern portions of North America and eastern South America, and operating with satellites that provide trans-Atlantic and European regional coverage, which may represent one-third of the total long-term worldwide deployment of earth stations operating co-channel with an altimeter. The earth stations are assumed to have a total e.i.r.p. of 80 dBW within the altimeter bandwidth with an antenna diameter of

4.5 m, and no polarization discrimination is considered. Figure 6 shows that in the long-term, less than 0.001% of the observations may be degraded by more than the permissible level; however, the data loss is systematic and may occur at particularly important areas of observation.

TABLE 2

Potential dimensions of interference area around an earth station as a function of its e.i.r.p. within the altimeter bandwidth

		Potential interference area (elliptical)	
Earth station antenna		Pleumeur-Bodou satellite at 16° E (major/minor axis)	Pleumeur-Bodou satellite at 53° W (major/minor axis)
Diameter (m)	e.i.r.p. (dBW)		
4.5	75	No degradation	No degradation
4.5	85	35 km/30 km	35 km/30 km
4.5	95	50 km/45 km	50 km/45 km
11	75	No degradation	No degradation
11	85	15 km/15 km	15 km/15 km
11	95	40 km/35 km	40 km/35 km

TABLE 3

Potential dimensions of interference area under earth station main beam intersection with the altimeter orbital sphere as a function of earth station e.i.r.p. within the altimeter bandwidth

		Potential interference area (elliptical)	
Earth station antenna		Pleumeur-Bodou satellite at 16° E (major/minor axis)	Pleumeur-Bodou satellite at 53° W (major/minor axis)
Diameter (m)	e.i.r.p. (dBW)		
4.5	75	55 km/50 km	40 km/25 km
4.5	85	140 km/135 km	160 km/95 km
4.5	95	320 km/320 km	415 km/245 km
11	75	30 km/25 km	15 km/10 km
11	85	70 km/70 km	80 km/50 km
11	95	180 km/175 km	210 km/125 km

FIGURE 5

Interference versus TOPEX satellite position for different FSS earth station antenna beam elevation angles

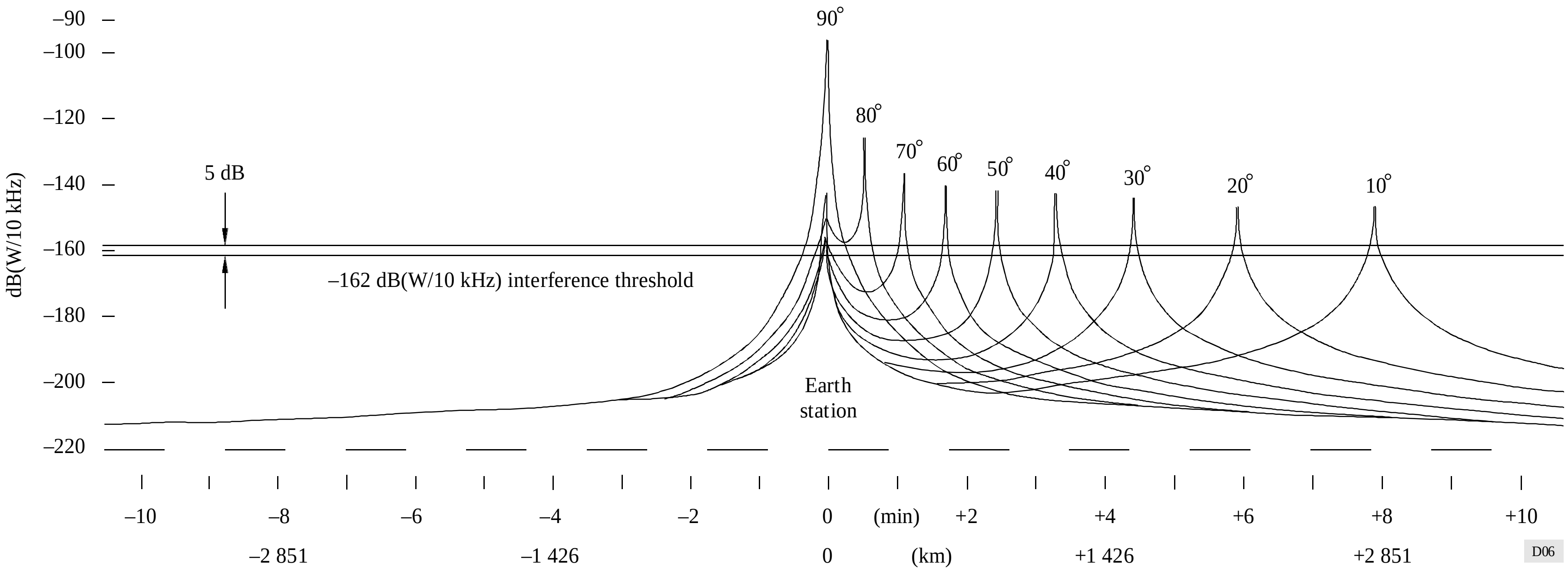
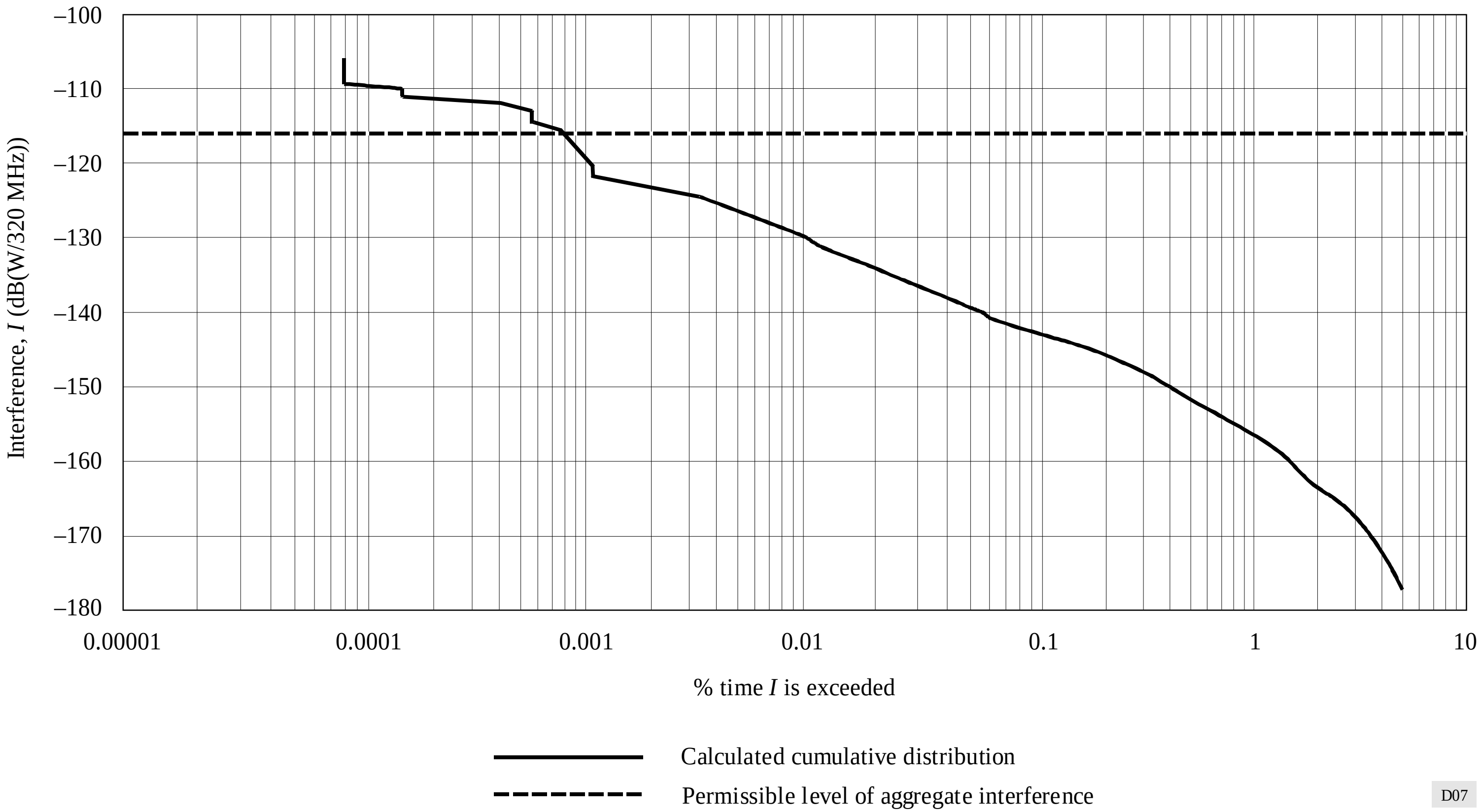


FIGURE 6

Interference to altimeters from 32 FSS earth stations with an e.i.r.p. of 80 dBW



2.2 Scatterometers

For the NSCAT scatterometer using a fan beam antenna, it was found that there will be a systematic loss of 0.5% of the data due to interference from one co-channel earth station operating at 85 dBW with a 4.5 m antenna having the radiation pattern of RR Appendix 28. Interference would exceed permissible levels if the e.i.r.p. of earth stations toward the scatterometer orbit over oceans were greater than 25 dBW in any 2 kHz segment of the bandwidth used by fan beam scatterometers, which is lower than the e.i.r.p. density of typical earth station emissions operating at the minimum e.i.r.p. level allowed under RR No. 855A. However, because scatterometers use small bandwidths (e.g. 13.99356 GHz to 13.99644 GHz or a bandwidth of 2.88 MHz for NSCAT), avoidance of co-channel operation is a practical means for protecting fan beam scatterometers.

Figure 7 presents the cumulative time distribution of interference to a spot beam scatterometer assuming the same deployment of 32 earth stations as in the preceding section, except that a total e.i.r.p. density of 77 dB(W/2 MHz) per earth station is assumed. Interference occurring over land is included even though observations only over oceans are of concern; thus, the interference probabilities are overstated. Nonetheless, the figure shows that if earth stations operate in compliance with RR No. 855A, interference to spot beam scatterometers will be below permissible levels and no case-by-case considerations would be needed.

2.3 Precipitation radars

Interference resulting from transmissions of FSS earth stations can potentially enter the PR receiver as a result of mainbeam-to-mainbeam antenna coupling, FSS mainbeam-to-PR side lobe coupling, FSS side lobe-to-PR mainbeam coupling, and FSS side lobe-to-PR side lobe coupling. Geometric considerations determine the range of latitudes where each of these interference modes is possible. Mainbeam-to-mainbeam antenna coupling can only occur if the FSS antenna elevation exceeds 71°. FSS mainbeam-to-PR side lobe coupling cannot occur from earth stations located at latitudes above 40° if the earth station has an elevation angle of at least 5°. Coupling between FSS side lobes and the PR mainbeam is possible at latitudes below 36°. Side lobe-to-side lobe coupling can occur anywhere that there is mutual visibility between the PR and an earth station which, for the TRMM orbit, is possible at latitudes up to 55°.

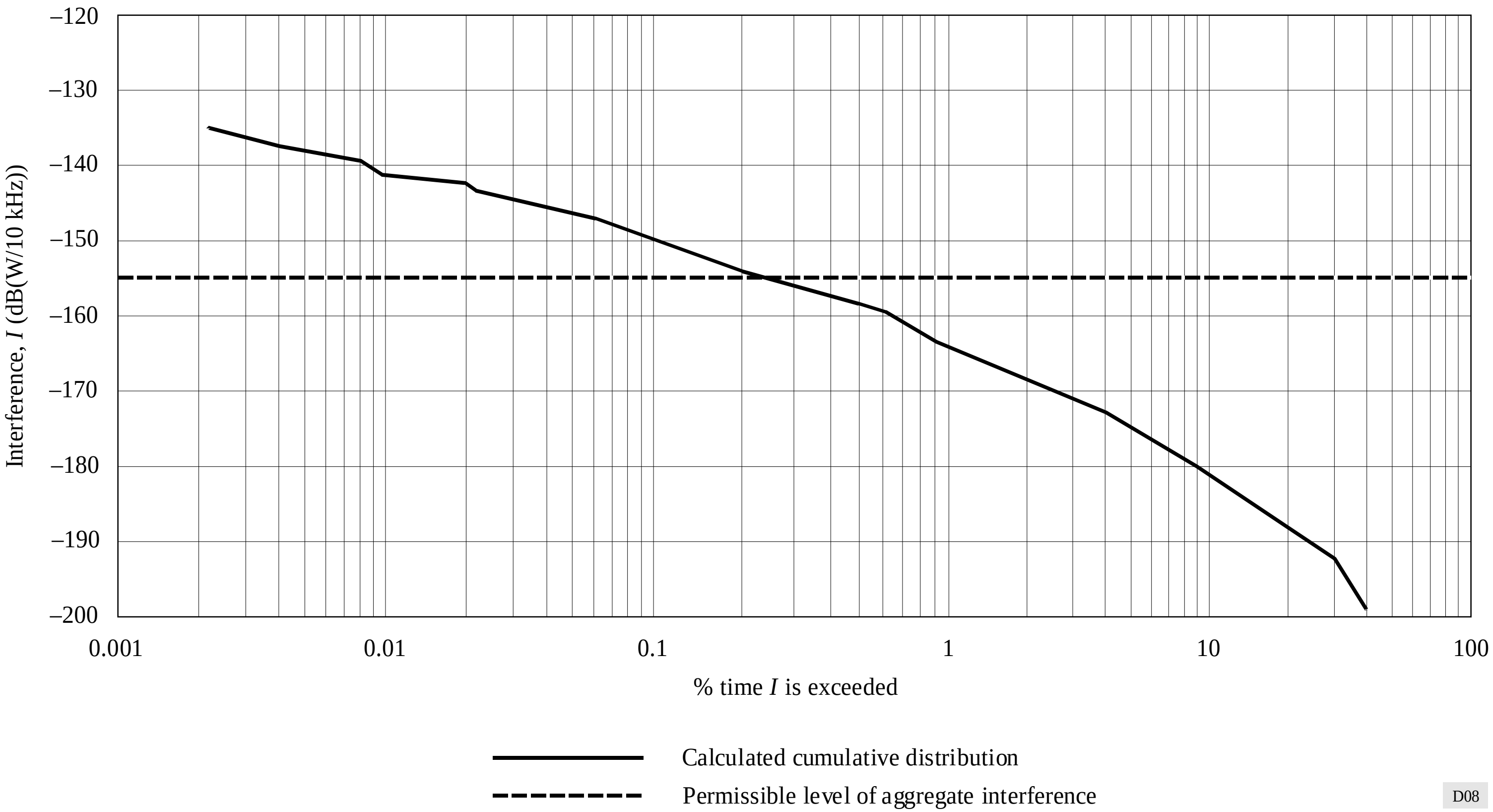
An in-band interference signal from an FSS earth station (ES) can degrade the PR observation accuracy in two ways; degradation of signal-to-noise and a bias error caused by the presence of a CW-like interference signal and the non-linearity of the PR receiver. It has been concluded that the allowable interference level (I_{max}), which is essentially determined by the former effect, is an interference signal to system noise power ratio of −10 dB or −150 dBW for 0.60 MHz. This value should be applied to 13.799 $\pm$ 0.006 GHz. It should be noted that interference may also occur due to the FSS signal outside the 12 MHz bandwidth around 13.8 GHz; the “leak” interference caused by the finite attenuation of receiver BPFs, and the saturation of amplifiers in the PR receiver. I_{max} is determined by either one of them. As for the “leak” interference, I_{max} can be at least 60 dB higher due to the attenuation of band pass filters in the PR receiver. Since the amplifiers sensitive to the saturation due to the interference are located before the narrow-band BPF, the frequency range to be considered is wider than the former. It is shown that I_{max} is determined by the “leak” for the frequencies between 13.7-13.9 GHz and by saturation for other frequencies.

Interference scenarios using one FSS earth station having an e.i.r.p. of 82 dBW have been analysed to give a perspective of the severity of interference potential for the PR. Interference levels in the event of mainbeam-to-mainbeam coupling would exceed the interference threshold of –150 dBW by a wide margin if within the final pass band of the PR. It should also be noted that this coupling will cause significant interference over the frequency band 13.75-14 GHz and therefore should be prevented.

Interference caused by coupling between an FSS mainbeam and the near side lobes of the PR and between the near side lobes of an FSS antenna and the mainbeam of the PR antenna would also exceed the interference threshold of the PR by as much as 84 dB. Interference could result from FSS transmissions in frequencies between 13.75 and 13.86 GHz. Coordination of individual earth stations located at latitudes below 40°, will therefore be essential to ensure that interference from mainbeams to side lobes does not affect measurements at critical locations on the Earth.

FIGURE 7

Interference to spot-beam scatterometer from 32 FSS earth stations, with an e.i.r.p. density of 77 dB(W/2 MHz) per earth station

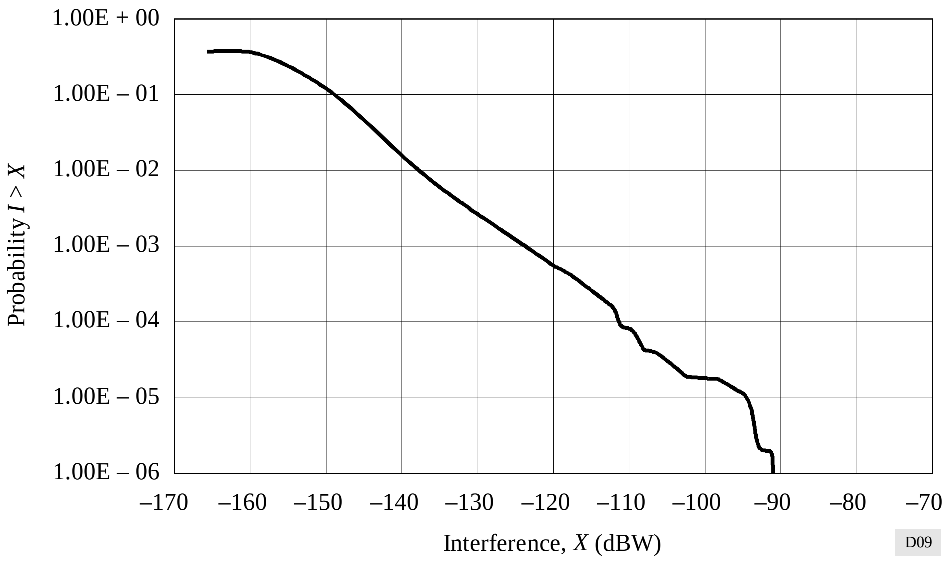


Even for interference resulting from coupling between near side lobes of an FSS antenna and near side lobes of the PR, the received power would exceed the interference threshold if the FSS transmissions were located in the final passband of the PR. The received power would not be sufficient to cause saturation in the PR.

A statistical analysis of the interference to the PR as a result of FSS earth station emissions was made for an initial assumption of 32 FSS earth stations operating in the Atlantic Ocean Region (AOR). Each earth station was assumed to have a 4.5 m antenna and an e.i.r.p. of 82 dBW (the same model for FSS earth stations as used for the analyses of interference to altimeters, scatterometers and data relay satellites). The results are contained in Fig. 8 where it can be seen that the interference threshold of –150 dBW would be exceeded for about 20% of the time.

FIGURE 8

Probability of interference to the TRMM precipitation radar from 32 FSS earth stations distributed in Atlantic Ocean Region, with an e.i.r.p. of 82 dBW



An extension of the statistical analysis for the AOR to a worldwide population of FSS earth stations has been made using the assumption that the worldwide population of potentially interfering earth stations by the year 2000 would be approximately 25. In this case, and assuming that many of these earth stations would use antennas conforming to the improved side lobe pattern of 29 – 25 log φ, then the availability criteria for the PR could be met if the e.i.r.p. density in the band 13.793-13.805 GHz band were limited to 61 dBW for earth stations having line-of-sight to the PR. However critical locations would still need to be considered on a case-by-case basis.

The revised assumptions were based on information from Task Group 4/4 regarding the expected implementation schedule and side lobe pattern for FSS earth stations in the 13.75-14 GHz band.

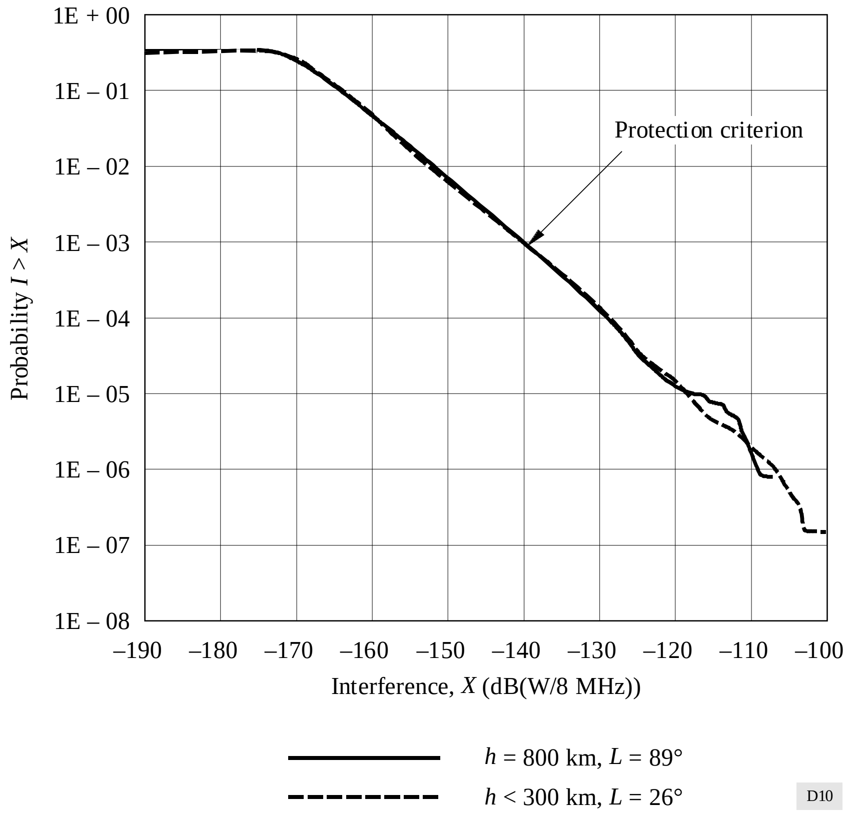
3. Interference to data relay satellite systems

A statistical analysis was performed of the interference to a receiver on board a low-orbiting satellite in a highly inclined 800 km orbit, and to a receiver on board a satellite in a moderately inclined 300 km orbit. These satellites are operating in a data relay satellite network and receive interference from FSS earth station emissions. It was assumed that there were a total of 32 FSS earth stations deployed in the Atlantic Ocean Region in the manner described previously. The earth stations employed an antenna of 4.5 m in diameter and transmitted at an e.i.r.p. level of either 68 dBW or 85 dBW in a 6 MHz bandwidth.

The results of the statistical analysis are shown in Fig. 9. Applying the protection criteria of –140.2 dB(W/6 MHz) for no more than 0.1% of the time, it is seen that an e.i.r.p. density limit of 71 dB(W/6 MHz) will accommodate 32 FSS earth stations with emissions centred around 13.775 GHz.

FIGURE 9

Probability of interference to a data relay satellite forward link from 32 FSS earth stations operating in the AOR: e.i.r.p. density = 71 dB(W/6 MHz)



From these results it is concluded that 32 FSS earth stations transmitting at an e.i.r.p. level of 71 dBW in a 6 MHz bandwidth centred at 13.775 GHz would not degrade the link margin by more than 0.4 dB for more than 0.1% of the time. An e.i.r.p. requirement of somewhat less than 71 dB(W/6 MHz) would be consistent with a larger number of transmitting earth stations.

The effect of the diameter of the transmitting FSS earth station on feasibility of operating a data relay satellite link centred at 13.775 GHz to a low-orbiting satellite was also evaluated. The following parameters for the satellite were assumed:

– the altitude is 800 km,

– the orbit inclination is 89°,

– the receiving antenna gain in the direction of the interference is 0 dBi.

For the FSS earth station, the following parameters were assumed:

– the station latitude is 38°,

– the transmitting antenna elevation angle is 15°,

– the transmitting antenna azimuth angle from due South is 70.2° (this is a computed value based on the station latitude and elevation angle),

– 1 m and 4.5 m transmitting antenna diameters,

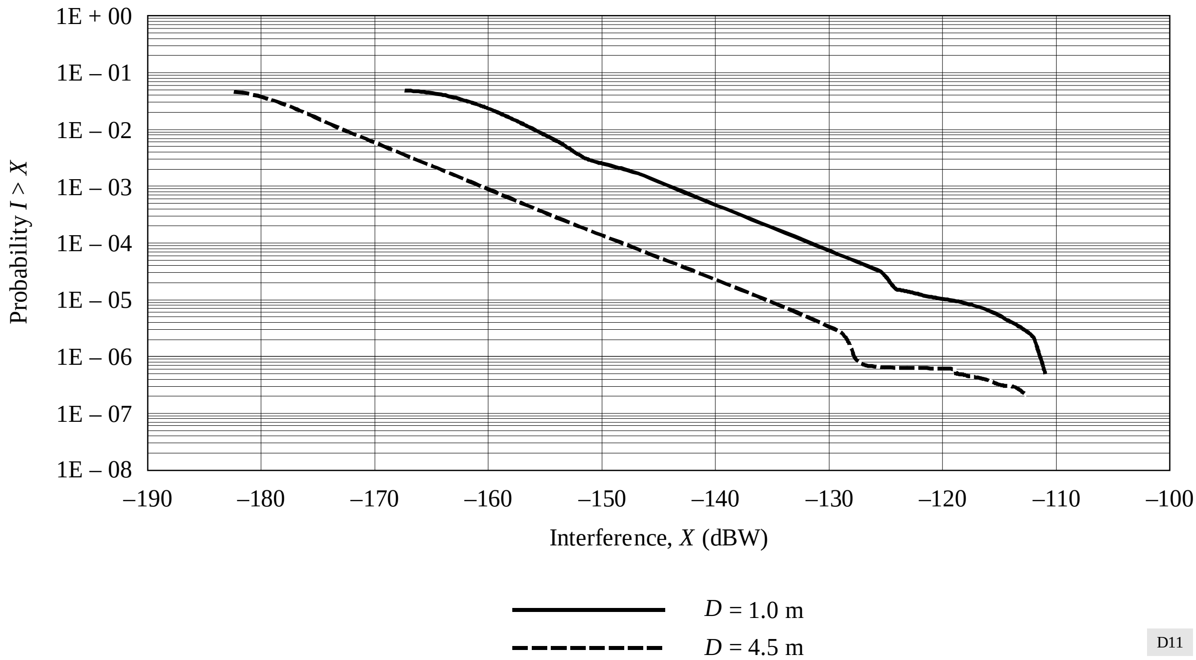
– the e.i.r.p. for both the 1 m and 4.5 m transmitting antennas is 68 dBW,

– the reference radiation pattern of the transmitting antennas is as given in RR Appendix 29.

The results of the analysis are shown in Fig. 10. The statistics associated with the 1 m diameter antenna are shown by the solid line while the statistics of the 4.5 m diameter antenna are shown by the dashed line. The figure shows that the 1 m diameter antenna creates approximately 16 dB more interference than the 4.5 m antenna does. Thus, it would take 40 FSS earth stations operating 4.5 m diameter antennas in a cluster to create as much long-term interference to low-orbiting satellites as would a single FSS earth station employing a 1 m diameter antenna. It is therefore concluded that the relaxation of the minimum antenna diameter as specified in RR No. 855A would significantly increase the potential interference to low-orbiting satellites operating in data relay satellite networks.

FIGURE 10

Comparison of the interference statistics of a 1 m and 4.5 m diameter FSS earth station transmitting antenna to a data relay satellite forward link



4. Interference to geostationary FSS satellites

4.1 Orbit separation for the United States of America tracking and data relay satellite (TDRS)

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

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

The maximum pfd levels produced by space science systems at a location in the geostationary-satellite orbit (GSO) are tabulated in Table 4. The maximum pfd level from a particular type of space science system occurs when the space science satellite is located either nearly antipodal from the GSO location (i.e. the signal path between satellites is tangential to the Earth) or at the minimum distance from the GSO location. If the different applications within the scientific space services were to operate as described in this Annex and in Annex 1, the maximum power flux-densities at the geostationary orbit from these scientific satellite systems would be as indicated in Table 4.

TABLE 4

Maximum pfd levels produced at the geostationary orbit by space stations in the space science services

Type of space station transmitter	Maximum antenna input power density	Case of near-antipodal satellite positions				Case of minimum separation distance			
		Spacecraft antenna gain (dBi)	pfd at the geostationary orbit (dB(W/m^2)) in the reference bandwidth			Spacecraft antenna gain (dBi)	pfd at the geostationary orbit (dB(W/m^2)) in the reference bandwidth		
			Total	1 MHz	4 kHz		Total	1 MHz	4 kHz
Altimeter	17 dBW per 320 MHz	0	–147.2	–172.2	–196.2	0	–144.7	–169.8	–193.7
Spot beam scatterometer	19 dBW per 180 Hz	10	–135.0	–135.0	–135.0	0	–142.9	–142.9	–142.9
Fan beam scatterometer	19 dBW per 180 Hz	28	–117.0	–117.0	–117.0	–14	–156.9	–156.9	–156.9
Precipitation radar	28 dBW per 800 kHz	0	–135.8	–135.8	–158.8	0	–134.0	–134.0	–157.0
DRS to user spacecraft	–5 dBW (Note 4)	53	–121.4	–121.6	140.2	0	–133.3	–133.5	–152.1

Note 1 – The altimeter is assumed to be at 800 km altitude and have a uniform spectral power density over the emission bandwidth.

Note 2 – The scatterometers are assumed to be at 800 km altitude and the peak envelope power is used.

Note 3 – The precipitation radar is assumed to be at 350 km altitude and the peak envelope power is used.

Note 4 – The DRS spacecraft is assumed to be located 1° from the FSS satellite in the minimum separation distance case. Reductions in the DRS antenna input power due to the effects of power control are not taken into account. The pfd levels specified for DRS spacecraft are based on an integration of power density in a $\sin^2 x/x^2$ power spectral distribution over the reference bandwidth. A DRS data rate of 300 kbit/s is assumed in the above table with no spreading by a PN code, which yields the worst case pfd levels when considering all possible data rates.