RECOMMENDATION ITU-R S.1759

Analysis of interference from HEO system space operation transmissions in FSS bands into GSO networks and corresponding guidelines to be used for designing and operating TT&C for HEO-type FSS system

(2006)

Scope

This Recommendation provides an analysis of interference from HEO-type FSS system space operation transmissions into GSO networks in FSS bands subject to Article 22 of the Radio Regulations (RR) epfd limits. It also presents techniques that may be taken into consideration in the design and operation of the TT&C links of HEO-type FSS systems in a manner that ensures adequate protection of co-frequency GSO links in accordance with RR Article 22.

The ITU Radiocommunication Assembly,

considering

a) that all FSS satellites have telemetry, tracking and command (TT&C) requirements;

b) that TT&C operations are carried out on FSS satellites while in transfer orbit as well as during regular (on-station) operations in various non-geostationary-satellite orbits (non-GSOs);

c) that telecommand signal transmissions originate and terminate under satellite operator control;

d) that TT&C carriers need higher performance reliability objectives than normal traffic carriers, which is recommended in Recommendation ITU-R S.1716;

e) that loss of the uplink command carriers to a satellite and downlink telemetry and ranging carriers during orbital manoeuvres, or when a critical malfunction occurs on-board a spacecraft, could result in the loss of a satellite;

f) that TT&C operation functions will normally be provided within the service band in which the space station is operating instead of within the *space operation service* (SOS) bands, and some space stations with service bands above 17 GHz may use TT&C in bands below 17 GHz;

g) that HEO-type FSS operators should be given some flexibility to operate TT&C in the most appropriate frequency band;

h) that most HEO-type FSS satellites transmit and receive service carriers only while they are within their "active" arcs having large angular separation from GSO links, but it would not be practicable to limit TT&C operations to those active arcs;

j) that there may be several possibilities to overcome the challenges of operating TT&C links for HEO-type systems in FSS bands subject to Article 22 of the Radio Regulations (RR) epfd limits while affording appropriate protection to GSO systems operating in these bands, *recognizing*

a) that in frequency bands subject to RR No. 22.2 it is necessary to ensure that HEO-type uplink and downlink TT&C transmissions do not cause unacceptable interference into GSO FSS and BSS networks;

b) that in certain frequency bands identified in RR Article 22, HEO-type satellites are required to meet epfd limits;

c) that in FSS frequency bands other than those identified in *recognizing* a), sharing between HEO-type FSS systems and GSO FSS networks is subject to the relevant provisions of Section II of RR Article 9,

recommends

1 that the technical and operational analysis and techniques given in Annex 1 may be taken into consideration by operators of HEO-type FSS systems in the design and the operation of their TT&C systems.

Annex 1

Analysis of interference from HEO system space operation transmissions in FSS bands into GSO networks and some interference mitigation techniques

Summary

Whereas a typical HEO (references to HEO system in this Annex denote HEO-type FSS system) satellite transmits and receives service carriers only while it is within its “active” arc or arcs, its TT&C carriers must remain active even outside that arc (or arcs) and are therefore likely to have difficulty in satisfying RR No. 22.2 including, where applicable, the RR Article 22 epfd limits. Computer simulations of the TT&C links in an example HEO system lead to an identification of possibilities for overcoming the problem.

1 Introduction

In recent years ITU-R Study Groups have received the results of numerous studies of interference between HEO systems and GSO networks, and in general these results showed that the epfd$\downarrow$ and epfd$\uparrow$ limits in Tables 22-1A, B, D and E and Table 22-2 of RR Article 22 would be met by the HEO systems concerned. In those studies the interference was calculated for the service links of the HEO systems, each of which is designed so that all its satellites sequentially follow a repeated ground track with the apogee at or near the highest latitude point, and each satellite transmits and receives only while it is within an “active” arc containing the apogee. One consequence of such configurations is that, insofar as the service links are concerned, no satellite is transmitting or receiving while it is passing through or near to the line between any geostationary satellite and any point on the Earth’s surface. In a recent review of twelve different HEO orbital configurations it was found that the minimum off-axis angle to any GSO link at which any HEO service link transmission occurred was greater than 25°. This characteristic of typical HEO systems generally enables them to meet the epfd limits without the application of additional interference-mitigation techniques.

Typically the "active" arc of a HEO system comprises only a quarter or a third of each orbital period; during the remaining portion continuity of the service links is maintained by the other satellites following the repeated ground track. But each and every satellite in a system requires its own telemetry and telecommand carriers, on frequencies exclusive to itself (within the system), and these carriers need to be able to be transmitted at any time during the life of the satellite in orbit. This is true for all types of geostationary and non-geostationary satellite, and is not a feature unique to HEO satellites. Clearly it would not be practicable to operate a satellite whose telemetry and telecommand carriers could be transmitted only during one quarter or one third of each period of 12, 18 or 24 h, and it is probable that, unlike the service links of HEO systems, there may be a need for the TT&C links to transmit during "in-line" transitions of GSO links. Hence it is considered to be necessary to make a separate assessment of the HEO TT&C links in the context of RR No. 22.2 including, where applicable, the RR Article 22 epfd limits. Furthermore, the following points should also be noted:

– This Annex is focused primarily on performing TT&C operations within the service band of the HEO system, instead of within the *space operation service* (SOS) bands, since it is common to adopt this method for the modern satellite system design. RR No. 1.23 also defines the SOS as follows: "**1.23** *space operation service:* A *radiocommunication service* concerned exclusively with the operation of *spacecraft*, in particular *space tracking, space telemetry* and *space telecommand*. *These functions will normally be provided within the service in which the space station is operating.*" This Annex briefly explores the possibility of performing TT&C operations within the SOS bands.
– Although the example HEO system is based on TT&C operations in the 12-18 GHz band (Ku-band), results in this Annex would also be applicable to TT&C operations in other frequency bands subject to the epfd limits of RR Article 22.
– In cases of TT&C operations in FSS frequency bands which are not subject to epfd limits, this Annex will also be helpful in the analysis of interference and the identification and assessment of techniques to mitigate the interference to GSO networks.

2 TT&C links of example HEO system

In order to make an assessment of the nature of the problem outlined in the Introduction a software model was constructed, enabling the statistics of interference from the TT&C links of an example HEO system to a variety of GSO uplinks and downlinks to be computed. The essential characteristics of the example HEO system, known as N-SAT-HEO2 in ITU-R parlance, are as follows:

– 3 satellites follow the same ground track, in planes inclined at 45° to the Equator and whose ascending nodes are spaced at 120° intervals in the Equatorial plane;
– the apogee height is 39 970 km, its latitude is 45° N and its longitude, common to all three planes, is 135° E;
– the perigee height is 31 602 km, and the orbit eccentricity is 0.099; this low eccentricity results in each of the satellites being above geostationary altitude throughout the "active" arc, and only about 412 km below geostationary altitude when crossing the Equator;
– while travelling North to South, the HEO satellites' ground track crosses the Equator at 123.7° E, and crosses at 146.3° E while travelling South to North;
– for the service links the "active" arc extends from 4 h before apogee to 4 h after apogee (i.e. for satellite latitudes above 26.5° N);

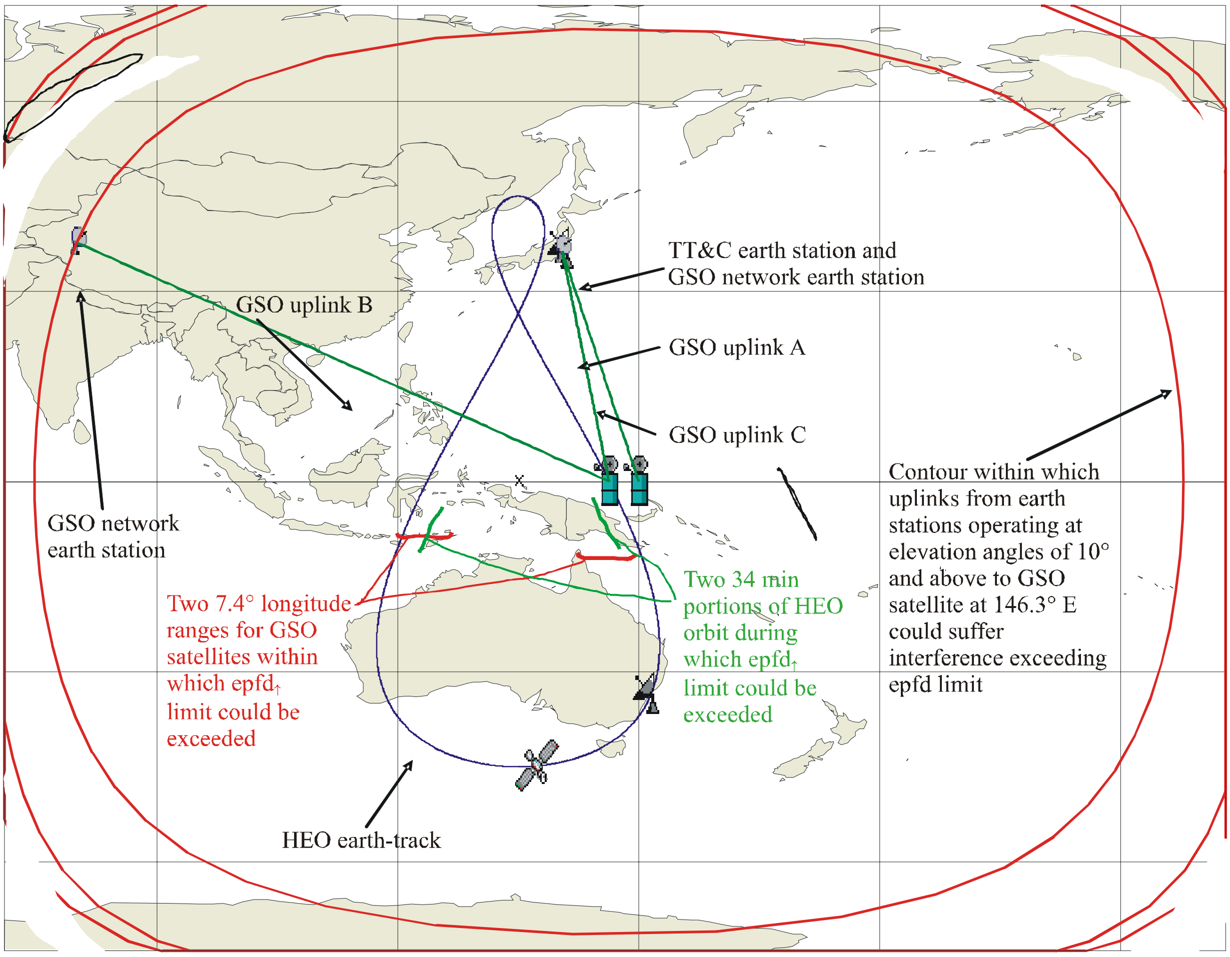
– there are four circularly polarized telemetry carriers, i.e. one per satellite plus a fourth for back-up, on separate frequencies in the 12 GHz FSS band, and each in a bandwidth of 605 kHz, although for most of the time the majority of the power falls within ±20 kHz of the carrier centre frequency; the overall downlink bandwidth is thus about 2.5 MHz; the satellite e.i.r.p. per telemetry carrier is 7 dBW; the system is designed so that each satellite can transmit its telemetry carrier continuously;
– there is one circularly polarized telecommand carrier on a separate frequency in the 14 GHz FSS band for each of the three satellites, in a bandwidth of 600 kHz, although again the majority of the power normally falls within ±20 kHz of the carrier centre frequency; the overall uplink bandwidth is thus about 2 MHz; the e.i.r.p. per telecommand carrier in normal mode is 50 dBW (80 dBW in emergency mode); the system is designed so that each of the three telecommand carriers may be transmitted at any time; for most of each orbit the telecommand carrier to each satellite is transmitted (when necessary) from a TT&C earth station in Japan (36.53° N/140.39° E) but, since perigee is not visible from that earth station, a TT&C earth station in Australia (33.9° S/151.17° E) assumes responsibility for telecommand transmission to (and telemetry reception from) each satellite while it is within ±4 h of perigee;
– the TT&C earth stations have antennas of 10 m diameter, designed to meet the antenna pattern in Recommendation ITU-R S.580, and track the satellite to which they are transmitting telecommand signals; as Recommendation ITU-R S.580 only provides the pattern from 1° or 100*(λ/D), whichever is smaller (in this case 100*(λ/D) is smaller), the main-lobe pattern from a different Recommendation needs to be used. The analysis performed for this example used a modified Recommendation ITU-R S.1428 pattern for the main-lobe.
– on each satellite the beam for transmission of the telemetry carrier and the reception of the telecommand carrier has a peak gain of 16 dBi, which corresponds to a half-power beamwidth of about 30°, and is modelled as meeting Recommendation ITU-R S.672; each satellite's TT&C antenna is fixed on the spacecraft and points to the subsatellite point except during the active arc when the satellite orientation is controlled to keep it pointing to Japan.

Illustrations of the system are given in Figs. 1 and 3, in which the three HEO satellites are seen to follow a single repeating ground track, and the TT&C earth stations in Japan and Australia are shown. Figure 1 illustrates a telecommand carrier interfering with three GSO uplinks, uplink A representing the worst case due to main beam-to-main beam interference (HEO TT&C earth station into GSO satellite) during the HEO equator-crossing; uplink B representing a link from a GSO earth station at 10° elevation to a satellite at worst-case longitude; and uplink C representing a link to a GSO satellite just far enough away from one of the two worst-case longitudes to enable the epfd↑ limit to be met. Note that for uplinks A and C, the GSO earth station is co-located with the HEO TT&C earth station. For uplinks A and B the GSO longitude = 146.3° E. For Uplink C the GSO earth station is located 3.7° to the East at 150.0° E.

Similarly, Fig. 3 illustrates a telemetry carrier interfering with three GSO downlinks, D, E and F of similar nature to the three uplinks. Downlink F has a GSO satellite and corresponding earth station on the equator, both located at longitude = 121.4° E calculated to be just far enough away (2.3°) from 123.7° E (one of the two worst-case longitudes) to enable the epfd↓ limit to be met. For downlinks D and E the GSO satellite longitude = 123.7° E. The GSO earth station for downlink D is on the equator also at longitude = 123.7° E. The GSO earth station for downlink E is located at a point where its elevation angle towards its GSO satellite is 10°. Note that links D and F each have 90° elevation angle.

FIGURE 1

GSO orbital positions and earth station locations for uplink epfd analysis



Note that the idea behind the selection of the three example GSO links for each case is to span the circumstances under which the epfd limits would be exceeded by the TT&C carriers of the HEO system concerned unless steps were taken to avoid it. Hence:

– Link A is worst-case for the uplink because the GSO satellite is located at an Equator-crossing longitude for the HEO system and this will result in the GSO satellite periodically being in the mainbeam of the high gain HEO TT&C earth station;

– similarly, Link D is worst-case for the downlink due to the HEO satellite periodically entering the mainbeam of the GSO earth station receive antenna;

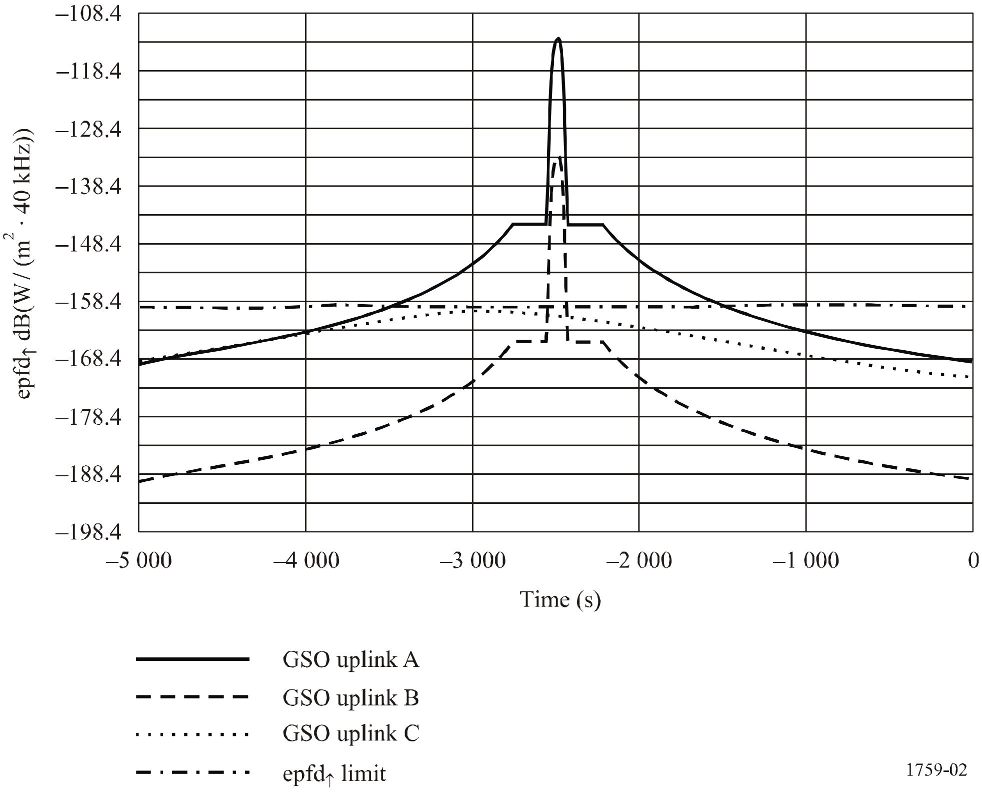
– Links B and E involve GSO satellites in worst-case longitudes insofar as interference from the HEO system is concernned, but the interference path length is a maximum for Link E and in both links the GSO earth stations are operating at minimum elevation; and

– Links C and F involve GSO satellites that are just far enough away in longitude from an HEO Equator crossing points for the corresponding epfd limit to be met on the shortest interference path

Figure 2 is a time plot of the epfd↑ in uplinks A, B and C as one of the HEO satellites traverses the Equatorial plane, showing that the limit is substantially exceeded in the first two for limited durations but is just met in the case of Link C. Figure 4 is a CDF of the epfd↓ statistics for the three GSO downlinks over a complete orbit period, and here again the limit mask can be seen to be exceeded in links D and E but just met in Link F.

FIGURE 2

Variation of epfd↑ during "in-line"transitions



3 Impacts of interference from TT&C of example HEO system

The impacts of the telecommand carrier are described by Fig. 1 and quantified in Fig. 2, and are summarized as follows:

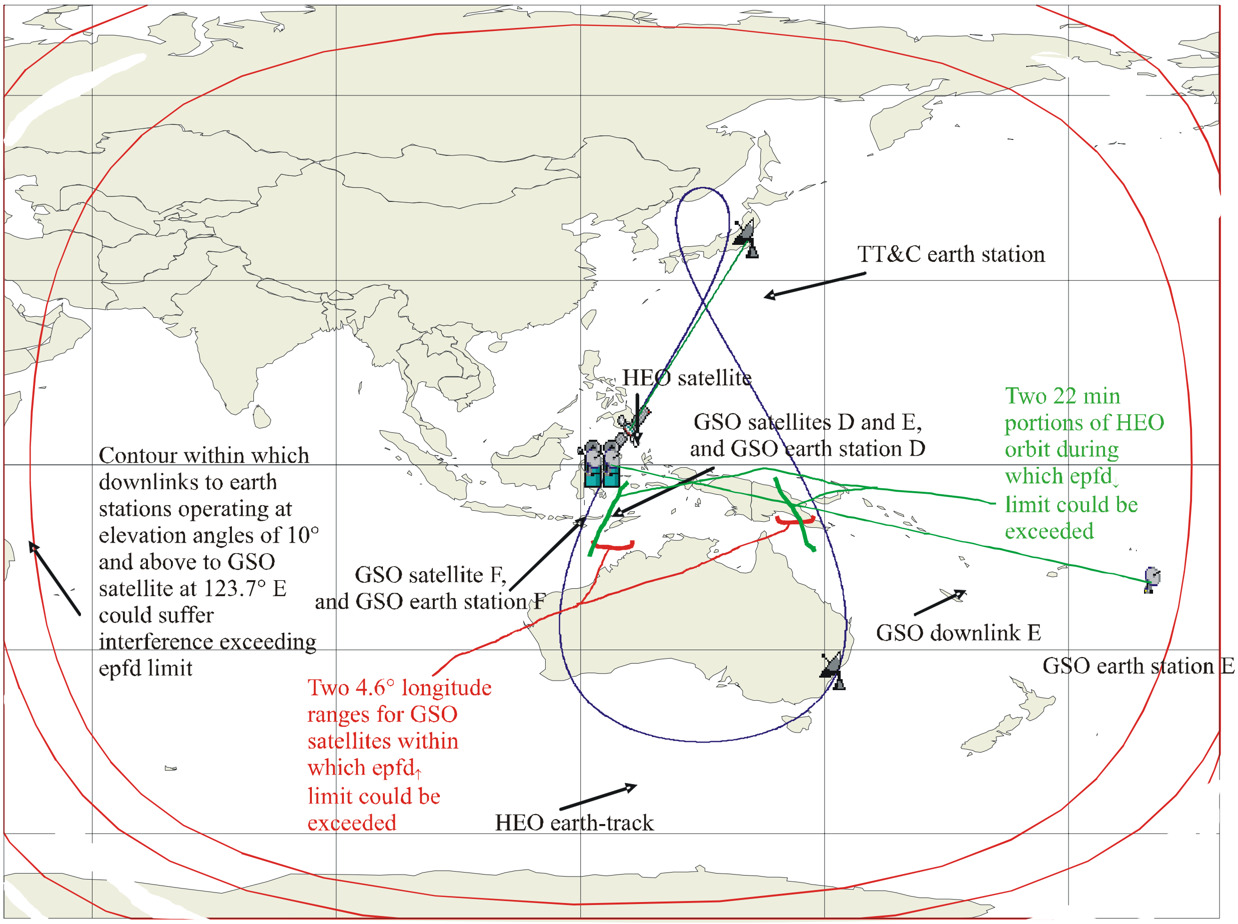
The epfd↑ limit would be exceeded in certain 40 kHz sub-bands within an overall bandwidth of about 2 MHz. Only uplinks to GSO satellites at longitudes within two ranges of 8.0° would be affected, comprising about 14% of available orbit slots in the region. In these cases the limits would be exceeded for two periods of up to 37.7 min per orbit period, comprising a maximum of 5.25% of the time. In the worst cases the limit would be exceeded by several tens of dB for durations of several tens of minutes, and although the proportion of earth stations whose uplinks would be affected would be limited, those earth stations could be at any geographical location in the region.

The impacts of the telemetry carrier are described by Fig. 3 and quantified in Fig. 4 and Appendix 1 to Annex 1 (see Fig. 5 and Table 1), and summarized as follows:

The epfd↓ limit masks would be exceeded in certain 40 kHz sub-bands within an overall bandwidth of about 2.6 MHz. Only downlinks from GSO satellites at longitudes within two ranges of 4.6° would be affected, comprising about 9% of available orbit slots. In these cases the epfd↓ limit mask for 1.2 m antennas would only be exceeded for two periods of up to 16.5 min per orbit period, comprising a maximum of 2.3% of the time. In the worst cases the maximum epfd↓ level in the limit mask (i.e. the short-term end) would be exceeded by several dB, and the medium term part of the mask would be exceeded by 10-20 dB. Although the proportion of earth stations whose downlinks would be affected would be limited, those earth stations could be at any geographical location in the region.

FIGURE 3

GSO orbital positions and earth station locations for downlink epfd analysis



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4 Techniques for mitigation of potential interference

The following two sections present techniques which have been identified to partially or fully mitigate potential interference from HEO TT&C uplink and downlink transmissions to GSO networks. For each technique studied, the following are provided:

a) how each technique could potentially be implemented,

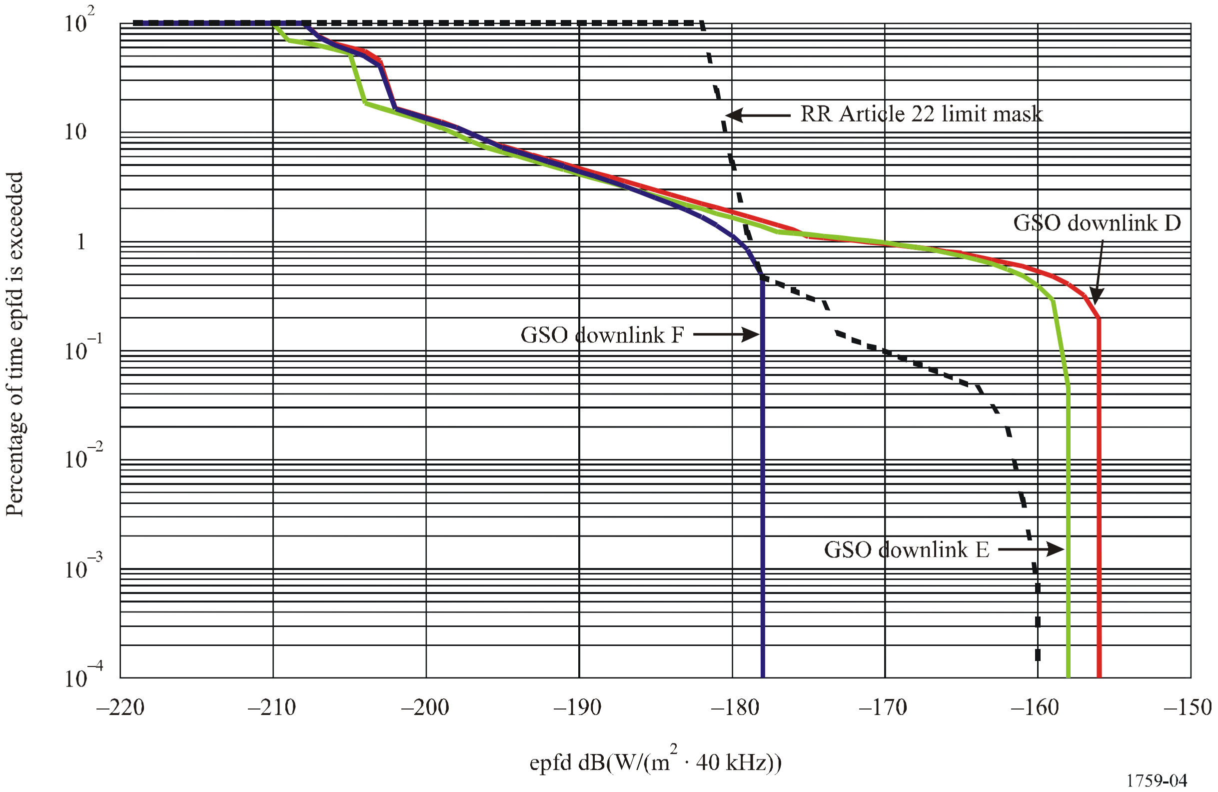
b) the potential advantages of each technique for HEO operators, and

c) the potential challenges and disadvantages to the implementation of each technique for HEO operators.

During the design of a HEO TT&C system, HEO operators could choose to implement one or more of the identified interference mitigation techniques, considering the advantages and the disadvantages, including the design challenges to keep the reliability and to reduce the cost impact, of each.

FIGURE 4

Cumulative epfd↓ statistics for selected GSO links with 1.2 m antennas



4.1 Uplink possibilities

4.1.1 Pausing telecommands: Interference would be avoided if it was possible for the non-emergency telecommand signals to HEO satellites to be transmitted at times of the day other than the critical periods exemplified in Fig. 1. Should it be necessary for a function to be executed within a satellite during a critical period, consideration could be given to the possibility of sending the command prior to the critical period and associating the appropriate delay with its execution.

4.1.1.1 Implementation

– Current TT&C systems typically include a software function to control the execution timing of uplinked telecommands to provide flexibility for satellite operations. Therefore, the above mitigation technique could easily be implemented by appropriate use of this software function.

– If it is necessary to activate some commands during a critical period, these commands could be uplinked prior to the critical period, stored in the satellite and activated at the appropriate time.

4.1.1.2 Advantages

– Considering that the above mitigation technique uses a capability that is already typically included in modern TT&C implementations, no additional equipment or software functionality would be required for HEO satellites and their TT&C earth stations.

– This technique by itself provides a straight-forward means for HEO telecommand links to fully comply with the RR Article 22 epfd↑ limits.

4.1.1.3 Disadvantages

– The critical period includes the ascending node and descending node of the HEO orbit, which are the optimum orbital positions for station-keeping manoeuvres. Station-keeping manoeuvres generally require a real-time interactive sequence of uplinked telecommands and downlinked satellite telemetry and status information. Before activating the satellite thrusters it is generally necessary to check real-time telemetry information at the TT&C earth station. As a result, station-keeping manoeuvres would have to be performed when the satellite is several orbital degrees outside of the optimum position. This operational constraint would require additional fuel consumption, which would add to the mass of the HEO satellites.

4.1.2 Spread spectrum for telecommands: In principle it would be possible for the epfd↑ levels to be reduced by adding spread-spectrum modulation to the telecommand carriers of HEO systems. To reduce the maximum epfd↑ in Fig. 2 to the regulatory limit would require around 45 dB of spreading.

4.1.2.1 Implementation

– This interference mitigation technique could be implemented by adding a spread-spectrum (SS) modulator to the TT&C earth stations and a SS demodulator to each HEO satellite.

– Effective use of the SS modulation technique dictates that SS modulation be used only outside the active arc so as to not interfere with the HEO system's service links. Use of the SS modulation technique could be further confined to only be used during the critical periods. When the HEO satellite leaves the active arc (or approaches a critical period) in its orbit, a TT&C earth station would send commands to switch to SS demodulation. When the satellite approaches the active arc (or passes beyond a critical period), a TT&C station would then send commands to switch back to the conventional modulation. With this changeover operation, the bandwidth of the SS modulation would only need to be extended within the band used for service links at those times when the satellite is outside of the active-arc. This SS band extension provides the possibility to reduce the epfd↑. In the case of the example HEO system, 32 dB reduction of epfd↑ could be achieved using 60 MHz bandwidth per telecommand carrier. If the implementation of this technique is not sufficient to meet the epfd↑ limit of RR Article 22, use of additional mitigation techniques would be required.

4.1.2.2 Advantages

– With the above SS band extension technique, the bandwidth for service uplinks, which is normally not used outside of the active-arc, would be used effectively to reduce the epfd↑.

4.1.2.3 Disadvantages

– Although using SS modulation for TT&C is not a new technique, currently it is not very common. Therefore, implementation of this technique would require development of new SS equipment for HEO satellites and TT&C earth stations.

4.1.3 Earth station diversity: In principle the peak epfd↑ levels could be reduced by TT&C earth station diversity. However, for the example HEO system it was found that, whilst optimum timing of handover between the two TT&C earth stations separated by more than 8 000 km would reduce the maximum epfd↑ level by about 15 dB, the limit would still be exceeded by many dB.

4.1.3.1 Implementation

– This interference mitigation technique would require locating TT&C earth stations at two or more positions with sufficient distance between them. To maintain a sufficient separation angle from GSO networks, station handover would be carried out corresponding to the location of the satellites.

4.1.3.2 Advantages

– This method could reduce the maximum epfd↑ level and if used in conjunction with other mitigation techniques could potentially help a HEO system meet the epfd↑ limit.

4.1.3.3 Disadvantages

– Although effective for LEO satellite systems, which have the geometry to easily maintain a sufficient separation angle from GSO networks, the geometry of HEO systems generally does not allow much angular separation from the GSO to be achieved during the periods when the telecommand carriers would exceed the epfd↑ limit. Therefore, this method has limited effectiveness for HEO systems.

– One or more additional TT&C earth stations with wide geographic separation (over which a reliable terrestrial communication link must be established) are required, and not all HEO systems include this feature.

4.1.4 High gain telecommand receive antenna: In the example HEO system the telecommand carriers would be received via a wide satellite beam (16 dBi peak gain). If the service uplinks of such a system were received via a higher gain beam (e.g., 30 dBi peak gain), consideration could be given to the possibility of transferring telecommand reception to that beam, thus enabling the TT&C earth station e.i.r.p. to be reduced (e.g., by 14 dBi), which would reduce the maximum epfd↑ level by the same amount. However, this requires control of the high gain beam even outside of the active arc, which may complicate the satellite design.

4.1.4.1 Implementation

– This interference mitigation technique could be implemented by inclusion of one or more high-gain, steerable-beam TT&C receive antennas on the HEO satellites. These on-board antennas would continuously track the TT&C earth stations. The HEO satellites would include provision for handover of the TT&C stations using a beam handover implementation.

4.1.4.2 Advantages

– No additional equipment would be required for TT&C earth stations. At the same time, the required gain for TT&C earth stations could be decreased.

4.1.4.3 Disadvantages

– The satellite's TT&C receive antenna would have to be a large aperture antenna with a high-precision tracking function capable of spanning a wide steering angle.

4.1.5 Use of SOS bands for telecommand: If the TT&C transmissions of the above mentioned HEO system should use the frequency bands allocated to the SOS instead of the above-mentioned frequency bands, the problem of non-compliance with RR Article 22 would be removed. While this would remove the problem concerning the epfd limits in RR Article 22 since they do not apply in the SOS bands, the physical interference phenomenon in the SOS band would be retained.

4.1.5.1 Implementation

– This interference mitigation technique could be implemented by the installation of independent RF equipment (antenna, HPA/SSPA, LNA, converter, etc.) for the TT&C system (on satellites and earth stations) using a different frequency band than the service links.

4.1.5.2 Advantages

– The HEO system TT&C operations would not be constrained by the epfd limits of RR Article 22.

– Considering that SOS bands are allocated in S-band or lower frequency bands, it would be easier to maintain sufficient TT&C link margin.

4.1.5.3 Disadvantages

– As each allocated bandwidth for the SOS is narrower than the bands subject to epfd limits, sharing these frequency bands with other systems may be difficult.

– The satellite and earth station TT&C operations would not be able to share the RF equipment used for service links.

4.1.6 Telecommand frequency selection: Considering that the TT&C uplinks for each satellite system occupy only a few MHz of bandwidth, the problem would be reduced in scope if the telecommand carriers of all non-GSO systems could be confined to the same frequency range of a few MHz.

4.1.6.1 Implementation

– To the extent possible, the telecommand frequencies chosen should be outside of the transponder bandwidths and TT&C frequency bandwidths of GSO satellites near the HEO equator crossing longitudes.

4.1.6.2 Advantages

– With respect to GSO systems which exist when the HEO system is filed, this option is straightforward.

4.1.6.3 Disadvantages

– Considering that HEO systems are non-GSO systems, the current RR do not allow this method to solve the problem in bands where the epfd$\uparrow$ limits of RR Article 22 apply. Therefore, in such bands this method could only limit the scope of the problem.

– The BR IFIC may not contain complete information on the telecommand frequencies used by potentially affected GSO networks.

4.1.7 Intersatellite links: If intersatellite links are implemented between the satellites in a HEO system, or between these satellites and a data relay satellite system, then telecommands can be transmitted to a HEO satellite that is in or near the active arc or to a data relay satellite and then relayed via the intersatellite links to other satellites.

4.1.7.1 Implementation

– This technique could be implemented by additional equipment on each HEO satellite for the intersatellite TT&C links.

4.1.7.2 Advantages

– Commanding of all satellites at all times would be possible from the primary TT&C earth stations with no potential for uplink interference to GSO networks.

– Minimal impact to TT&C earth stations; no need for remote TT&C earth stations.

4.1.7.3 Disadvantages

– The satellites would be burdened with additional equipment for the intersatellite link, and for acquisition and tracking control of an intersatellite link antenna.

– The satellites would need a backup TT&C method in case there is an intersatellite link failure.

– This technique may pose additional design challenges because the HEO system would be required to avoid the potential for interference into GSO networks that might be caused due to the HEO system's intersatellite link geometry.

4.2 Downlink possibilities

4.2.1 Pausing the telemetry: The problem would be removed if it was possible for the telemetry carrier transmission from each HEO satellite to be ceased for the durations of the critical periods (e.g. for two periods of 22 min per day as in Fig. 3). Should this solution be implemented then, if a malfunction within the satellite occurred during one of the critical periods, the personnel at the TT&C earth station would not become aware of it until the resumption of transmission of the telemetry carrier.

The Appendix 1 to Annex 1 provides an iterative method that can be used to determine the minimum HEO telemetry switch-off period. This includes determination of the precise times/orbit locations at which the telemetry carrier of a particular HEO satellite is switched off (and on) in order to meet the relevant $epfd_{\downarrow}$ limit.

4.2.1.1 Implementation

– Current TT&C systems typically include a software function that enables control of downlink telemetry transmissions to provide flexibility for satellite operations. Therefore, the above mitigation technique could easily be implemented by appropriate use of this software function to command the satellite to stop telemetry transmissions during the critical period and resume telemetry transmissions immediately after the critical periods.

– During the critical periods, the position and attitude of the satellite will be estimated at the TT&C earth stations using orbital prediction algorithms.

4.2.1.2 Advantages

– This technique requires no additional equipment for the HEO satellites or TT&C earth stations.

– This technique by itself provides a straight-forward means for HEO telemetry links to fully comply with the RR Article 22 $epfd_{\downarrow}$ limits.

4.2.1.3 Disadvantages

– Telemetry data would not be available to the TT&C earth stations during the periods when the epfd↓ mask would otherwise be exceeded. Those periods include the ascending node and descending node of the HEO orbit, which are the optimum orbital positions for station-keeping manoeuvres. Station-keeping manoeuvres generally require a real-time interactive sequence of uplinked telecommands and downlinked satellite telemetry and status information. Before activating the satellite thrusters it is generally necessary to check real-time telemetry information at the TT&C earth station. As a result, station-keeping manoeuvres would have to be performed when the satellite is several orbital degrees outside of the optimum position. This operational constraint would require additional fuel consumption, which would add to the mass of the HEO satellites.

– If some failure with the HEO satellite attitude control system or any other problem affecting the satellite's orbit were to occur during a switch-off period, the satellite operator would not receive reliable data concerning the problem for some time due to the halted telemetry transmissions. This could hinder the satellite operator's potential for implementing corrective action.

– Pausing telemetry leads to a significant decrease in operational availability. According to Recommendation ITU-R S.1716, the typical availability for telemetry downlinks in the 14/12 GHz band is on the order of 99.99%, which means 0.01% of unavailability. In the case of the example HEO system, the unavailability caused by pausing telemetry is 3.1% ((22 min × 2)/24 h × 100) in addition to the unavailability due to the attenuation due to rain and etc., which is more than 300 times worse than the typical value recommended in Recommendation ITU-R S.1716.

4.2.2 Spread spectrum for telemetry: In principle it would be possible for the epfd↓ statistics to be reduced by adding spread-spectrum modulation to the telemetry carriers of HEO systems. Taking the example results in Fig. 4, about 20 dB of spreading would be required to meet the limit mask completely in the worst case, which would require about 4 MHz of bandwidth per telemetry carrier. An alternative possibility might be to add spreading just within the assigned carrier bandwidth; in the present example this is 605 kHz, which would allow about 12 dB of spreading.

4.2.2.1 Implementation

– This interference mitigation technique could be implemented by adding a spread-spectrum (SS) demodulator to the TT&C earth stations and a SS modulator to each HEO satellite.

– Effective use of the SS modulation technique dictates that SS modulation be used only during the periods for which the epfd↓ levels would otherwise be critical. When the HEO satellite approaches a critical period in its orbit, a TT&C earth station would send commands to switch to SS modulation, and when the satellite goes outside of the critical period, a TT&C station would then send commands to switch back to the conventional modulation. With this changeover operation, the bandwidth of the SS modulation would only need to be extended within the band used for service links at those times when the satellite is outside of the active-arc. This SS band extension provides the possibility to reduce the epfd↓. In case of the example HEO system, 20 dB reduction of epfd↓ could be achieved using 4 MHz bandwidth.

4.2.2.2 Advantages

– With the above SS band extension technique, the bandwidth for service downlinks, which is normally not used outside of the active-arc, would be used effectively, and the technique has the potential for meeting the epfd↓ masks without additional mitigation.

4.2.2.3 Disadvantages

– Although using SS modulation for TT&C is not a new technique, currently it is not very common. Therefore, implementation of this technique would require development of new SS equipment for HEO satellites and TT&C earth stations.

4.2.3 High gain telemetry transmit antenna: In the example HEO system each telemetry carrier would be transmitted via a wide satellite beam (30° beamwidth). If the service downlinks of such a system were transmitted via a higher gain beam (e.g. 6° beamwidth), consideration could be given to the possibility of transferring the telemetry signals to that beam, thus confining the epfd↓ limit excess to a smaller geographical area. For the example system this would be practicable only if both TT&C earth stations were covered by the higher gain beam (or beams). However, this requires the control of the high gain beam even outside of the active arc, which may complicate the technical design of the satellites.

4.2.3.1 Implementation

– This interference mitigation technique could be implemented by inclusion of a high-gain, steerable-beam transmit antenna on each HEO satellite. These on-board antennas would be used for service downlink transmissions during the active arc portion of the HEO orbit. They would be used for telemetry downlink transmissions during the critical periods at which times they would continuously track the TT&C earth stations.

4.2.3.2 Advantages

– Any TT&C epfd↓ limit excess would be confined to a smaller geographical area which would reduce the number of potentially affected GSO earth stations.

– No additional equipment is required for the TT&C earth stations.

– The satellite transmit power would be reduced due to the higher transmit antenna gain which would save on-board power consumption.

4.2.3.3 Disadvantages

– The satellite's high gain transmit antenna would have to be a large aperture antenna with a high-precision tracking function capable of spanning a fairly wide steering angle.

– Even if the HEO satellite design already incorporates a high gain beam for service downlinks, this technique requires control of that high gain beam even outside of the active arc, which may complicate the technical design of the satellites.

4.2.4 Use of SOS bands for telemetry: If the TT&C transmissions of the above mentioned HEO system should use the frequency bands allocated to the SOS instead of the above mentioned frequency bands, the problem of non-compliance with RR Article 22 would be removed. While this would remove the problem concerning the epfd limits in RR Article 22 since they do not apply in the SOS bands, the physical interference phenomenon in the SOS-band would be retained.

4.2.4.1 Implementation

– This interference mitigation technique could be implemented by the installation of independent RF equipment (antenna, HPA/SSPA, LNA, converter, etc.) for the telemetry system (on satellites and earth stations) using a different frequency band than the service links.

4.2.4.2 Advantages

– The HEO system TT&C downlink operations would not be constrained by the epfd limits of RR Article 22.

– Considering that SOS bands are allocated in S-band or lower frequency bands, it would be easier to maintain sufficient TT&C link margin.

4.2.4.3 Disadvantages

– As each allocated bandwidth for the SOS is narrower than the bands subject to epfd limits, sharing these frequency bands with other systems may be difficult.

– The satellite and earth station TT&C operations would not be able to share the RF equipment used for service links.

4.2.5 Telemetry frequency selection: Considering that the TT&C downlinks for each satellite system occupy only a few MHz of bandwidth, the problem would be reduced in scope if the telemetry carriers of all non-GSO systems could be confined to the same frequency range of a few MHz.

4.2.5.1 Implementation

– To the extent possible, the telemetry frequencies chosen should be outside of the transponder bandwidths and TT&C frequency bandwidths of GSO satellites near the HEO equator crossing longitudes.

4.2.5.2 Advantages

– With respect to GSO systems which exist when the HEO system is filed, this option is straightforward.

4.2.5.3 Disadvantages

– Considering that HEO systems are non-GSO systems, the current RR do not allow this method to solve the problem in bands where the epfd↓ limits of RR Article 22 apply. Therefore, in such bands this method could only limit the scope of the problem. The present RR do not allow HEO TT&C downlinks to exceed the epfd↓ limits of RR Article 22, with the possible exception allowed by No. 22.5CA: *"**22.5CA** 2) The limits given in Tables **22-1A** to **22-1E** may be exceeded on the territory of any country whose administration has so agreed (see also Resolution **140 (WRC-03)**"*. However, considering that the TT&C downlink of the example HEO system uses a global beam, it should be noted that the total number of countries whose agreement is required could be very large.

– The IFIC may not contain complete information on the telemetry frequencies used by potentially affected GSO networks.

4.2.6 Intersatellite links: If intersatellite links are implemented between the satellites in a HEO system, or between these satellites and a data relay satellite system, then telemetry can be transmitted via intersatellite link to a HEO satellite that is in or near the active arc or to a data relay satellite and from there to the earth.

4.2.6.1 Implementation

– This technique could be implemented by additional equipment on each satellite for the intersatellite TT&C links.

4.2.6.2 Advantages

– Transmission of telemetry from all satellites at all times would be possible to the primary TT&C earth stations with no potential for downlink interference to GSO networks.

– Minimal impact to TT&C earth stations; no need for remote TT&C earth stations.

4.2.6.3 Disadvantages

– The satellites would be burdened with additional equipment for the intersatellite link, and for acquisition and tracking control of an intersatellite link antenna.

– The satellites would need a backup TT&C method in case there is an intersatellite link failure.

– This technique may pose additional design challenges because the HEO system would be required to avoid the potential for interference into GSO networks that might be caused due to the HEO system's intersatellite link geometry.

RR No. 22.5CA, adopted by WRC-2000 and modified by WRC-03, states "The (epfd↓) limits given in Tables 22-1A to 22-1E may be exceeded on the territory of any country whose administration has so agreed." This provides for solutions to the downlink problem to be sought through the prior agreement between an administration seeking to operate telemetry carriers from HEO satellites in an FSS band subject to the epfd↓ limits, and the administrations of each of the countries covered by the beam via which the telemetry carriers are to be transmitted. However, this procedure could take a long time (for concerned administrations to reach agreement). Therefore, it would be preferable to first consider the above possibilities.

In any bilateral meetings under the provision of RR No. 22.5CA the above possibilities might be also taken into account at the discretion of the parties concerned.

5 Conclusion

The foregoing considerations show that there may be several possibilities to overcome the challenges of operating TT&C links for HEO systems operating in bands subject to RR Article 22 epfd limits while affording appropriate protection to GSO systems operating in these bands. It is noted that these techniques would also be helpful with respect to other FSS bands shared between non-GSO and GSO networks. Further study will be required to determine which of these potential interference mitigation techniques will be most appropriate for any specific HEO system.

Appendix 1 to Annex 1

Methodology to determine the minimum telemetry carrier switch-off periods of a HEO satellite to comply with RR Article 22 epfd↓ limits

Following is a description of an iterative method that can be used to determine the precise times/orbit latitudes at which the telemetry carrier of a particular HEO satellite is switched off (and on) in order to meet the relevant epfd↓ limits.

As explained in § 4.2.1 of Annex 1, any exceedence with respect to the RR Article 22 epfd↓ limit mask for a given size of GSO earth station antenna in a given frequency band may be avoided by switching off each telemetry carrier during a period around each instant when its satellite crosses the Equatorial plane. The minimum duration of the period, and its precise switch-off and switch-on times, to just meet the epfd↓ limit mask concerned will depend on the orbital characteristics of the HEO system and the transmission characteristics of its telemetry carriers.

Assuming that, as for the example system described in § 2 of Annex 1 (N-SAT-HEO2), each HEO satellite in the system has its own telemetry carrier frequency and otherwise all the telemetry carriers have identical transmission parameters, it is necessary only to determine the minimum switch-off period duration for one satellite. The period will be the same for each of the other satellites in the system, and the precise switch-off and switch-on times will simply differ by intervals determined by the orbit characteristics and the number of satellites following the same ground-track.

Taking N-SAT-HEO2 as an example, a computer simulation may be set up to model a worst-case interference scenario as illustrated in Fig. 3 of the Annex, and used to calculate the epfd↓ level into a reference (e.g., 1.2 m) GSO earth station antenna at a worst-case location and operating to a GSO satellite at a worst-case longitude. (As explained in the Annex, for N-SAT-HEO2 the two worst-case situations are when both the GSO satellite and its reference earth station are at 0° latitude and a longitude corresponding to one of the HEO equator-crossings, either 123.7° E or 146.3° E.) This simulation is run for one complete orbit period (86 163 s = 1 sidereal day) with the epfd↓ calculated for each time step (10 s time steps are sufficiently accurate for this example). The results are then plotted in the form of a cumulative distribution function (CDF) of time percentage against epfd↓. In the present case this is the curve for Link D in Fig. 4 of the Annex.

Noting that the Equator-crossing at 123.7° E occurs when the satellite (starting at perigee) is about three-quarters of the way around its 23-h 56-min orbit, the above simulation may be re-run using a large time-step until about 17 h into the orbit. From that point, the simulation can then be stepped using a small time-step until the epfd↓ level reaches the value at which the Link D curve intersects the Article 22 mask (i.e. about –179 dBW/m^2 per 40 kHz in this example). The time at which this "mask intersection" occurs may be noted. The simulation may then continue to be advanced using a small time-step until the epfd↓ level reaches a peak when the satellite is directly over the equator and then returns once more to the Link D "mask intersection value" and that time noted. The simulation may then be stopped and the model modified to effectively switch-off the telemetry carrier between the two times noted. (In the simulation, the switching off of the telemetry carrier may be modelled by setting the EIRP to a negligible value for the interval between the two times.) The simulation may then be run in the form thus modified, and the results converted to a new CDF. It will be found that this CDF is significantly below the RR Article 22 mask at all points. (See curve (c) in Fig. 5.)

The model may then be further modified to reduce the switch-off period to about one-third of the period in the previous paragraph, but with approximately the same time centre, and the simulation re-run to produce the corresponding CDF. It is likely that this CDF will exceed the RR Article 22 mask for significant epfd ranges. (See curve (d) in Fig. 5.)

The results from the foregoing two paragraphs will enable the approximate switch-off and switch-on times to produce a CDF just meeting the RR Article 22 mask to be estimated by selecting times that are in-between those resulting in curves (c) and (d). A further run using these times may then be made. If the resulting CDF is still not optimum, a further iteration of the process should yield a sufficiently accurate result.

The above steps were carried out for N-SAT-HEO2 and a 1.2m GSO earth station antenna, for a telemetry carrier at 12.25 GHz. The resulting CDFs are shown in Fig. 5, where curve (b) is the same as the curve for Link D in Fig. 4 (i.e. worst case geometry with no switching off of the telemetry carrier). It will be seen that (e) is the optimum curve since it just barely stays within the epfd↓ limit mask. Although only three iterations were needed to produce the optimum curve in this case, it is unlikely that more than four – or at most five – iterations would be needed for any other practical case. Thus, taking both Equator crossings into account, the switch-off periods for the present example would be as shown in Table 1.

FIGURE 5

1.2 m epfd↓ statistics for various telemetry carrier switch-off periods

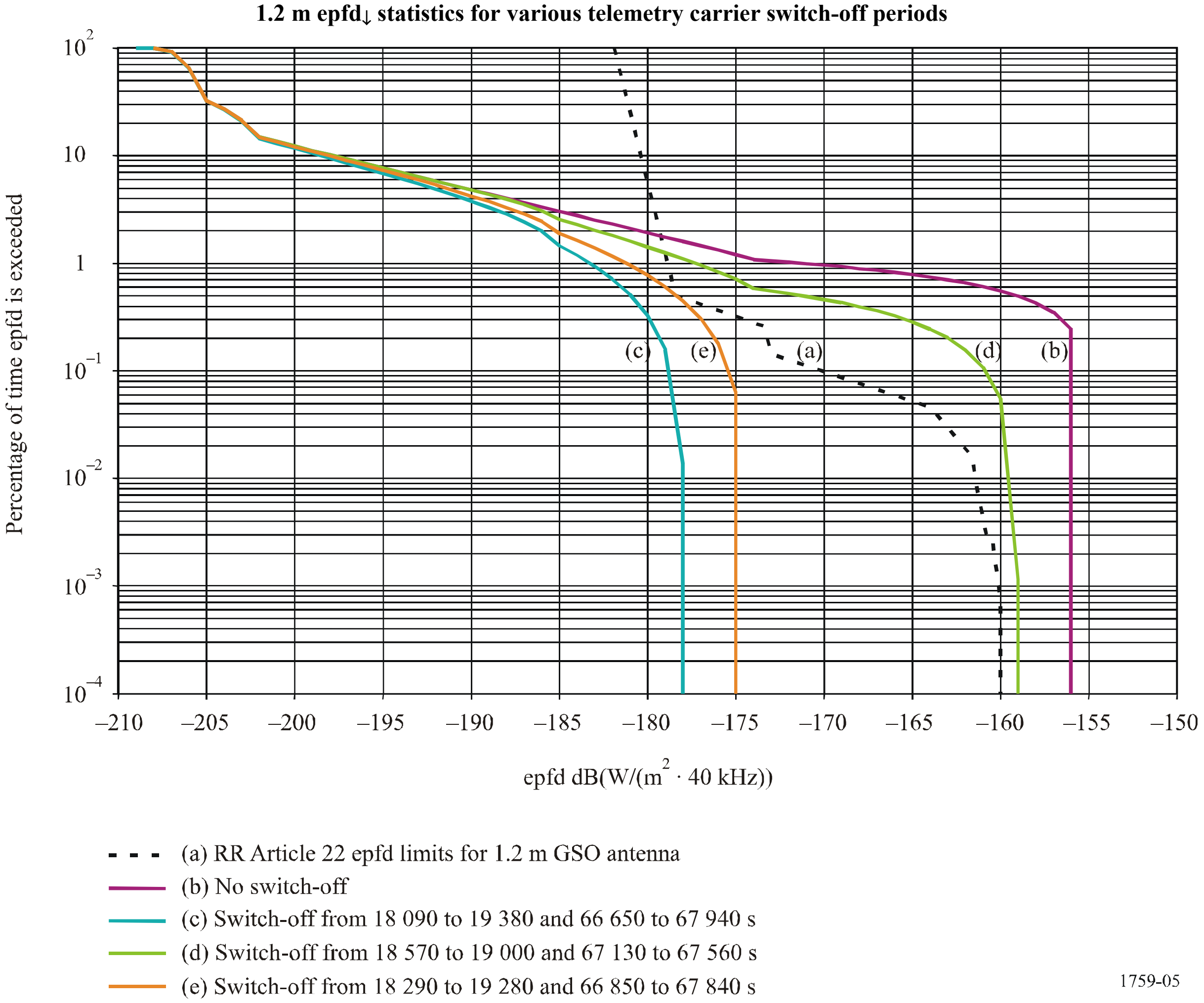


TABLE 1

Switch-off periods to ensure example HEO system's telemetry carriers would just meet epfd↓ limits for 1.2 m in the 12-18 GHz band (Ku-band) GSO earth station antenna

Satellite	Perigee time (s)	1st switch-off time (s)	1st switch-on time (s)	2nd switch-off time (s)	2nd switch-on time (s)
1	0	18 290	19 280	66 850	67 840
2	28 680	9 370	10 360	47 000	47 990
3	57 490	38 180	39 170	75 810	76 800

Note from Table 1 that each of the three satellites in the example HEO system would have to switch off for the same duration in the vicinity of its two crossings of the equatorial plane per orbit to meet the epfd limit mask. Each switch-off period is 990 s = 16.5 min corresponding to 1.15% of the orbital period (one sidereal day). Taking account of both switch-off periods per orbit results in a total "telemetry outage" corresponding to 2.30% of each satellite's orbit. Each switch-off period would occur while the satellite concerned is within the latitude range of approximately ±1.487°.

For each successive orbit the switch-off and switch-on times would be found by simply adding 86163 s (a sidereal day).