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European Radiocommunications Committee (ERC)
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FREQUENCY SHARING IMPLICATIONS OF FEEDER-LINKS FOR NON-GSO/MSS NETWORKS IN FSS BANDS

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1. INTRODUCTION

1.1 Relevant Radio regulations

A phrase in RR 22, which allows the Feeder-links of MSS networks to be implemented in FSS bands, reads as follows:-

> "*the fixed satellite service may also include feeder-links for other space radiocommunication services".*

The possibility of satellite networks based on non-geostationary orbits employing FSS bands is recognised in RR Article 11, but no coordination regime is currently prescribed for such networks. WARC-92 adopted a Resolution (COM5/8) as an interim measure to provide for the introduction of non-GSO networks in certain frequency bands between 1 and 3 GHz, but the FSS bands are not covered by that Resolution at present.

Protection for FSS networks using the GSO against interference from co-frequency networks using non-geostationary orbits is currently provided by RR 2613, reproduced here for convenience:-

> "*Non-geostationary space stations shall cease or reduce to a negligible level their emissions, and their associated earth stations shall not transmit to them, whenever there is insufficient angular separation between non-geostationary satellites and geostationary satellites resulting in unacceptable interference to geostationary satellite space systems in the fixed satellite service operating in accordance with these Regulations.*"

1.2 Bandwidth Required

A review of six non-GSO/MSS system proposals revealed that the requirement for feeder-link bandwidth varies between 50 MHz and 200 MHz for the up-paths, and the same (separately) for the down-paths.

2. TYPES OF NON-GSO NETWORK

Table 1 summarises the types under consideration, in comparison with a geostationary network. Although no proposals for MSS networks using satellites in high apogee elliptical orbits (HEOs) were found, preliminary calculations were made which satisfied the Team that, if HEOs were employed, interference to and from GSO networks would be unlikely to be a significant problem, because 'in-line' situations (see below) would not occur at times when the HEO links were 'active'.

3. THE PROBLEM

3.1 Interference to (and from) GSO/FSS networks

Figure 1 illustrates the case of an MSS satellite in a Polar (90° inclined) Low Earth Orbit (LEO), and an FSS satellite in the GSO instantaneously passing through the LEO plane. Both earth stations are assumed to be within the coverage areas of both satellites. The top half of Figure 1 illustrates an FSS earth station receiving from the geostationary satellite. If the LEO satellite is at position L(1) or L(3), interference from it enters via a sidelobe of the earth station's antenna pattern, but if it is in position L(2) the interference enters via the main beam of that antenna.

The lower half of Figure 1 shows an MSS feeder earth station tracking a LEO satellite. If that satellite is at position L(4) or L(6) when the GSO satellite crosses the LEO plane, then the feeder station's sidelobe emissions interfere with the GSO satellite, whereas if the position is L(5) the earth station's main beam will illuminate the GSO satellite.

A typical FSS/GSO earth station antenna might have an on-axis gain of 50-60 dBi, and sidelobes conforming to the 29 - 25Log(ϕ) envelope defined in ITU-R Recommendation 580. Similar gains might apply to a typical MSS feeder station antenna. Thus the difference in gain, and hence interference level, between the circumstances of L(2) and those of L(1) and (L3) if the off-axis angles of the latter are 3°, for example, is 55 - {29 - 25Log(3)} or about **38 dB**. Similar reasoning applies to the difference in interference level between the L(5) situation and the L(4) or L(6) situations.

It is therefore evident that, on both the up-path and the down-path, interference from non-GSO/MSS feeder-links to GSO/FSS networks will be characterised by short bursts of very high interference (hereafter termed 'events' for the sake of brevity), interspersed by much longer periods of moderate (very probably acceptable) interference. For convenience circumstances such as those identified by L(2) and L(5) are described as 'in-line' instances.

It is important to recognise that 'in-line' interference will occur in both directions, i.e. both MSS and FSS networks will suffer it (unless steps are taken to avoid it). This can be seen in Figure 1 by considering the GSO earth station to be transmitting, and the LEO earth station to be receiving. Calculations indicate that for the FSS/GSO networks the down-path 'in-line' interference will usually be more severe than its up-path counterpart, but for MSS/LEO networks the up-path 'in-line' interference will usually dominate.

Figure 2 suggests that 'in-line' events will be statistical in nature. If no preventative measures are taken, interference from LEO satellite L_1 will be unacceptable if L_1 passes through a 'cone' of angle 2ϕ degrees subtended at GSO/FSS earth station E (note that ϕ was 3° in the example given in the previous page). Since the Earth and the GSO satellite are rotating in the Equatorial plane at 0.25 deg/min, while the LEO satellite is orbiting in an inclined plane at between 1 and 3.6 deg/min (depending on altitude) it is evident that on most of its revolutions L_1 will 'miss' the interference cone of earth station E, but every now-and-then a 'hit' will occur.

The duration of an individual 'event' will depend on whether L_1 passes through the middle of the cone or nearer to one of the edges, and on the angular velocity of the satellite relative to the earth station. Clearly, other LEO satellites in the same plane will also 'hit' the cone occasionally, as will satellites in other LEO planes. In general the 'hits' will occur at random intervals, and the number of down-path 'hits' in a given period will be proportional to the number of satellites in the LEO constellation. Up-path 'hits' (for interference to the GSO network) will also normally occur at random intervals, but the number in a period is influenced not only by the size of the constellation but also by the strategy of 'handover' for each feeder station from one LEO satellite to another. It is not possible to correctly compute the statistics for up-path 'hits' unless the handover strategy is known and built into the computations.

Careful consideration of Figure 2 suggests that, if the LEO is one for which the ground track repeats exactly after a given amount of time, it can be arranged for a given satellite never to be in line with particular earth stations and the GSO satellites to which they operate. In fact the Team's studies have shown that it is possible for a constellation of LEO satellites to avoid 'in-line' interference to and from certain earth stations by careful choice of orbit configurations and good station-keeping. However, owing mainly to the adverse operational impact on the MSS feeder-links of having to operate with such constraints, and also to the fact that avoiding 'hits' for some earth stations in this way would considerably increase the number of 'hits' in a period for other earth stations, the Team has concluded that avoidance of 'in-line' events by orbit coherence is unlikely to be feasible in practice. In fact, in the Team's opinion, frequency sharing would be assisted if non-coherence was deliberately ensured.

3.2 Interference to (and from) FS Terminals

Figure 3 shows that, if both up and down-paths of the LEO/MSS feeder-links share frequencies with the FS, the interference to (and from) the latter can involve both satellites and feeder stations. The following factors are evident:-

- If the LEO satellite uses spot beams for its feeder-links then interference into the main beams of FS receiving terminals (example A) is likely to originate from the sidelobes of the satellite antenna.

- Interference from the main beam of the satellite will normally enter the FS receivers via the sidelobes of the FS antennas (example B).

- Since the feeder station antenna will not normally operate at elevation angles below 10°, interference from it to FS receiving terminals will derive from its sidelobes (example C).

- The terrestrial terminals will be protected from interference from the satellite by the pfd limits recommended by the ITU-R for FS bands shared with the FSS.

- The interference from the MSS feeder stations will be the subject of RR Appendix 28-type coordination.

- Since the LEO satellites will move quite rapidly relative to the FS terminals, and the MSS feeder station antennas will track the satellites, the level of the interference will vary widely with time (by at least 14 dB in example C and 30 dB in example A).

- Careful choice of the geographical locations of the MSS feeder stations will maximise the worst case off-axis angles (ϕ_L) of the interference from MSS feeder stations.

4. CRITERIA FOR ACCEPTABILITY THRESHOLDS

At present the interference criteria on which most FSS networks are designed are long-term criteria (i.e. limits which apply for at least 80% of the time). Interference limits for digital signals are prescribed in ITU-R Recommendations 523 and 735, which both require single entry interference to be no greater than 6% of total noise in the receiver bandwidth, and aggregate interference not to exceed 20% of total noise, under clear sky conditions. These limits apply for the whole time the links are available, but Rec.579 recognises that equipment faults and severe propagation fades will occasionally occur, by setting unavailability limits of 0.2% of a year for equipment and 0.04% of any year for propagation. Rec.579 also regards outages of up to 10 seconds as 'available' time.

Owing to the severe but short-term nature of 'in-line' interference events, there is a need for the ITU-R to establish criteria for both the maximum permissible level of 'in-line' interference and for the level which may be regarded as an outage; maximum percentages of time for which they can be tolerated should be associated with these two levels. The Project Team's suggestions for digital carriers in GSO/FSS networks are:-

Permissible limit	-	12% of the clear-air long-term noise budget should not be exceeded for more than 0.1% (0.05%) of any year, and no individual excess should last for more than 30 seconds.
Outage threshold	-	120% (64%) of the clear-air long-term noise budget should not be exceeded for more than 0.01% of any year, and no individual excess should last for more than 10 seconds.

(The percentages in brackets relate to circuits designed to meet ITU-TS Recommendation G.826 while the un-bracketed percentages relate to circuits designed to meet ITU-R Rec.614, which is compatible with ITU-TS Rec.G.821.)

Except in cases where bit regeneration is performed within the satellite payload, these limits should be applied to GSO/FSS carriers from end-to-end (i.e. including both up-path and down-path interference contributions).

It has not been practicable for the Project Team to develop 'in-line' interference criteria for the non-GSO/MSS Feeder-links, but bearing in mind that Feeder-links are effectively **trunk** links it is conceivable that similar limits to those above (non-bracketed) would emerge from an appropriate study.

5. ANALYSES AND COMPUTER SIMULATIONS

Using parameters of carriers in the IRIDIUM, GLOBALSTAR and INMARSAT P21 (MEO) feeder-links for the non-GSO constellations described in Table 1, various members of the Project Team carried out either computer simulations or statistical analyses to deduce the 'in-line' event statistics for typical GSO/FSS networks sharing frequencies with the feeder-links of non-GSO/MSS networks. The combinations considered covered LEO and MEO constellations and all three FSS pairs of bands in common use. Carriers were selected from among the types most sensitive to interference, and those likely to cause the most interference, and results were obtained for both the GSO/FSS carriers and the non-GSO/MSS carriers in each role. A small excerpt from the many results obtained is given in Table 2, in which 3 of the six carriers labelled "IG" are typical INTELSAT GSO/FSS digital carriers and 3 are FM/TV carriers. The 5^{th} to 8^{th} columns in Table 2 show the important results; these were based on a 12% of total (long-term) noise threshold, and on the earth stations of both networks being located in Equatorial regions and near to the longitude of the geostationary satellite. This excerpt is included here for illustrative purposes only; for the same carrier combinations the event durations and aggregate time percentages are greater by a factor of at least 5 for earth stations in mid-European latitudes. The Team's conclusions were reached by considering the full range of results contained in the main report.

6. POSSIBLE SOLUTIONS

6.1 Implementation of RR 2613

From the lower part of Figure 1 it can be seen that up-path 'in-line' interference could be avoided by switching off the transmission (and reception) of each MSS feeder station whenever its antenna is pointing within $\pm\phi_U$ degrees of the GSO, where $\pm\phi_U$ corresponds to a sufficiently low sidelobe level to meet the first criterion in §4. Technically this could be done quite easily, since the azimuth and elevation angles toward the whole of the visible GSO can be accurately defined mathematically for each station. However, the need to switch off would probably impact adversely on the MSS operations.

The avoidance of down-path interference in this way presents significantly greater problems, however. The upper part of Figure 1 shows that, to protect the particular GSO earth station shown, the satellite would have to suppress its emissions in directions within $\pm\phi_d$ degrees of the 'in-line' pointing direction. The wording of RR 2613 effectively requires the non-GSO satellite to protect all possible 'in-line' GSO earth stations operating to any location in the GSO (or in quasi-geostationary orbits with up to 5° inclination) now and in the future. Figure 4 illustrates the nature of this task.

It is clear that 'in-line' circumstances can occur for any GSO satellite from S_1 to S_n operating to earth stations (E_1 to E_n) in line (or nearly in line) with L. So the emissions from L would have to be suppressed over the whole of the area surrounding the 'in-line' loci, and that area would move as L moves and its pointing directions with respect to L would change. Furthermore the degree of suppression would have to be 30-40 dB if it was necessary to match the 'loss' of earth station antenna discrimination described in §3.1. Since L is likely to need to illuminate the Earth's surface on either side of the 'protection zone', effectively a net antenna beam with a deep slot in the middle capable of automatic steering would be required.

A study by a Team member representing European industry involved in spacecraft manufacture concluded that the implementation of such a beam, whether by multi-feed beam shaping techniques or by multiple spot beams with a switching regime, would be complex and on the threshold of practicability. It could also have significantly adverse affects on the space sector costs and on MSS traffic handling. (The impact on the MSS service would be less in sub-bands which are, and will continue to be, only lightly used by GSO networks).

Furthermore, although RR 2613 affords no protection to the non-GSO/MSS feeder-links, reliance on its implementation would necessitate the incorporation of features within the non-GSO systems to prevent 'in-line' interference from the GSO/FSS carriers adversely affecting the mobile satellite service.

If the non-GSO/MSS feeder-links share frequencies with GSO/FSS networks on the basis of RR 2613 and no coordination procedure is invoked, then EIRP limits on the up-path and pfd limits on the down-path will need to be set for the non-GSO/MSS feeder-links, in order to protect the GSO/FSS networks, and these limits will be difficult to meet. The establishment of a coordination procedure would require action by WRC-95.

The Team considers that, if a coordination regime is established, then a means of determining whether or not an existing or pending GSO/FSS network would be affected - e.g. a modified form of the RR Appendix 29 method - would have to be adopted. A large number of coordination exercises would probably be necessary for each incoming non-GSO network, and if these were successfully concluded and the network brought into service it may nevertheless be impracticable to protect **future** GSO/FSS networks adequately.

6.2 Alternatives to reliance on RR 2613

Possible alternatives to reliance on RR 2613, each of which would require action by WRC-95, are:-

i) allocation to the non-GSO/MSS Feeder-links of spectrum outside the FSS bands;

ii) exclusion of FSS carriers other than non-GSO/MSS Feeder-link carriers from designated sub-bands within the FSS allocations;

iii) allocation of designated sub-bands within the FSS allocations to the non-GSO/MSS Feeder-links in reverse-band mode; the Feeder-link carriers would be permitted to operate only in reverse-band mode and other FSS carriers would, as at present, be restricted to normal mode.

The Project Team's terms of reference exclude study of alternative (i). A study of alternative (ii) is also outside the Team's competence, except to state the obvious that it would create major difficulties for operators of the 'displaced' GSO/FSS networks, and that pressure to minimise the amount of spectrum involved and to avoid the heavily loaded parts of C and Ku-bands * would probably be strong.

Alternative (iii) has been investigated by the Team in some depth, using both 'normal' GSO/FSS carrier parameters and also using generalised parameters conforming to RR Appendix 30B. The modes of interference would be from non-GSO feeder-link earth station to GSO/FSS earth station (and vice versa), and from non-GSO/MSS satellite to GSO/FSS satellite (and vice versa). The study shows that the satellite-to-satellite interference would be well within acceptable limits even in the most unfavourable instantaneous relative locations of the two spacecraft.

Figure 5 illustrates the earth station-to-earth station interference. The worst case interference will occur when angles AZ and AZ' are both equal to zero and angles EL and EL' are both equal to 10° (earth stations do not normally operate below 10° elevation owing to increased propagation fades at low elevation angles). This situation will apply for only small proportions of time because, although the pointing of the FSS antenna will remain relatively fixed, the feeder station's antenna will be tracking satellites moving quite rapidly relative to the Earth's surface. Furthermore, in many cases it should be possible to site the MSS feeder station so that angle AZ is large enough to ensure substantial discrimination from the GSO/FSS earth station's antenna pattern. In these cases coordination along the lines of RR Appendix 28 would be required, but the studies indicated that coordination distances would usually be within 130 km, and that for most of the time the interference would be 14 dB lower than its level at the worst pointing direction instants. To limit the number of coordination exercises it would be advisable to avoid frequencies and/or geographical areas heavily used for VSAT or other small-dish networks.

Also, in central European countries, for example, the 0.01% of worst month rain attenuation at 30 GHz is about 15 dB greater than at 18 GHz; for this reason above 18 GHz the reverse band alternative might create design difficulties for the non-GSO satellite payloads.

* The use in this document of the terms 'C-band', 'Ku-band' and 'Ka-band' relate to the frequency allocations to the FSS in the vicinity of 4-7 GHz, 11-15 GHz and 18-30 GHz respectively.

7. CONCLUSIONS

7.1 Forward band frequency sharing between non-GSO/MSS feeder-links and FS networks is judged to be feasible on the basis of the Team's studies, which suggest that the interference between the satellites and the radio-relay terminals is likely to be within ITU-R criteria, and that the interference between the earth stations and the radio-relay terminals is unlikely to lead to excessive coordination distances. The Team has not repeated the studies for the case of reverse band working by the feeder-links, but has no reason to suppose that a different conclusion would be reached given freedom to locate the earth stations suitably to afford reasonable angular separation from the principal axes of nearby radio-relay terminals.

7.2 Frequency sharing between forward band non-GSO/MSS feeder-links and GSO/FSS networks will lead to 'in-line' interference instants. Unless RR 2613, and also mechanisms to inhibit 'in-line' interference in the direction of the non-GSO networks, are implemented within the non-GSO/MSS systems, or an alternative means of avoiding the 'in-line' interference is sanctioned by WRC-95, it is probable that unsatisfactory quality of service will result for both GSO and non-GSO networks.

Bearing in mind

a) the difficulties of implementing RR 2613 in the non-GSO satellites,

b) the probably adverse impact of RR 2613 implementation on the MSS continuity of service,

c) the need for a similar means in the non-GSO satellites of overcoming the even greater difficulties posed by 'in-line' interference **to** the MSS Feeder-links, and

d) the need for either very stringent EIRP and pfd limits to protect GSO/FSS networks, or a complex coordination regime with a large number of coordination exercises per non-GSO network,

in the judgement of the Team RR 2613 does not provide a satisfactory sharing mechanism.

The Project Team was not mandated to investigate the options requiring exclusive frequency allocations or the use of non-FSS bands. However, the report would not be complete without a mention of the fact that, should the option of allocating a pair of FSS sub-bands exclusively to non-GSO MSS Feeder-links be chosen by WRC-95, then selection from Ka-band would be likely to cause less disruption of existing services than selection from the lower frequency FSS bands. Of the two options within the Team's mandate it is considered that reverse band working by the non-GSO/MSS Feeder-links, preferably in frequency bands below 18GHz and preferably in sub-bands and/or geographical areas not heavily used by VSATs or other small-dish services, is a more promising option than implementation of RR 2613.

8. FUTURE STUDIES

Further work is considered to be necessary to

- consolidate the findings of the present study,
- investigate the impact of possible reverse band operation by the non-GSO/MSS feeder-links on frequency sharing with the Fixed Service, and
- study the feasibility of frequency sharing between the feeder-links of separate non-GSO/MSS networks.

Noting that ITU-R Study Group 4 will set up a new Task Group to pursue the 'in-line' interference studies, and that ITU-R Working Party 4-9S will tackle the question of non-GSO feeder-link sharing with the Fixed Service, and that both fora have only 1 year to reach conclusions which can be taken into account by WRC-95, it is recommended that experts within CEPT administrations should participate in these ITU-R fora.

Table 1 CLASSES OF ORBIT FOR SATELLITE PCNs

Class of Orbit	Geostationary	LEO (a)	LEO (b)	MEO (or ICO)	HEO
Typical MSS System	INMARSAT P 21	IRIDIUM	GLOBALSTAR	INMARSAT P 21	-
Orbit Shape	Circular	Circular	Circular	Circular	Elliptical
Orbit Height (km)	35786	780	1414	10000	1114 to 39366
Orbit Inclination	-5° to +5°	86°	52°	50°	63.4°
Orbit Period (hrs)	23.93	1.67	1.90	5.79	12.01
Angular Velocity (deg/min)	0.25	3.58	3.16	1.04	varies
No of Orbit Planes	1	6	8	3	3
No of Satellites per Plane	3	11	6	5 (4)	1
Total No of Satellites	3	66	48	15 (12)	3
Feeder-link Frequency band	C, Ku or Ka	Ka	C	C, Ku or Ka	C, Ku or Ka
Modulation /Access	Digital, TDMA per Carrier	Digital, TDMA per Carrier	Digital, CDMA per Carrier	Digital, TDMA per Carrier	-

Table 2 STATISTICS OF 'IN-LINE' EVENTS FOR EQUATORIAL EARTH STATIONS

Interference Mode	Frequency Band	Interfering Carrier	Victim Carrier	Minimum Margin (dB)	Mean Event Duration (Sec)	No. of Events per Day	Aggregate Event Time (%)	No. of Interf. Satellites	No. of Interf. Earth Stations
Non-GSO Sat. to GSO E/S	C	LEO(b)	IG-1	-36.0	15.5	4.0	0.072	48	1
	Ku	MEO	IG-4	-24.0	64.2	0.44	0.033	15	1
	Ka*	LEO(a)	IG-6	-28.6	4.2	1.7	0.0083	66	1
Non-GSO E/S to GSO Sat.	C	LEO(b)	IG-2	-8.9	8.2	4.23	0.040	1 (48)	2
	Ku	MEO	IG-4	-35.0	137	1.9	0.301	1 (15)	2
	Ka*	LEO(a)	IG-6	-4.5	10.6	0.9	0.011	1 (66)	2
GSO Sat. to non-GSO E/S	C	IG-1	LEO(b)	-0.7	10.3	26.8	0.319	10 (48)	1
	Ku	IG-3	MEO	-36.4	190	13.0	2.859	10 (15)	1
	Ka*	IG-5	LEO(a)	-38.9	11.4	45.2	0.596	10 (66)	1
GSO E/S to non-GSO Sat.	C	IG-1	LEO(b)	-49.2	37.2	196	8.439	10 (48)	2
	Ku	IG-3	MEO	-32.5	62.8	8.6	0.652	10 (15)	2
	Ka*	IG-6	LEO(a)	-39.0	9.1	72.4	0.762	10 (66)	2

* Note that this table is based on clear-sky conditions but, for example, 2 to 3 dB of additional EIRP will need to be provided in central Europe for 1% of the time.

Figure 1. (not to scale) **'IN-LINE' INTERFERENCE**

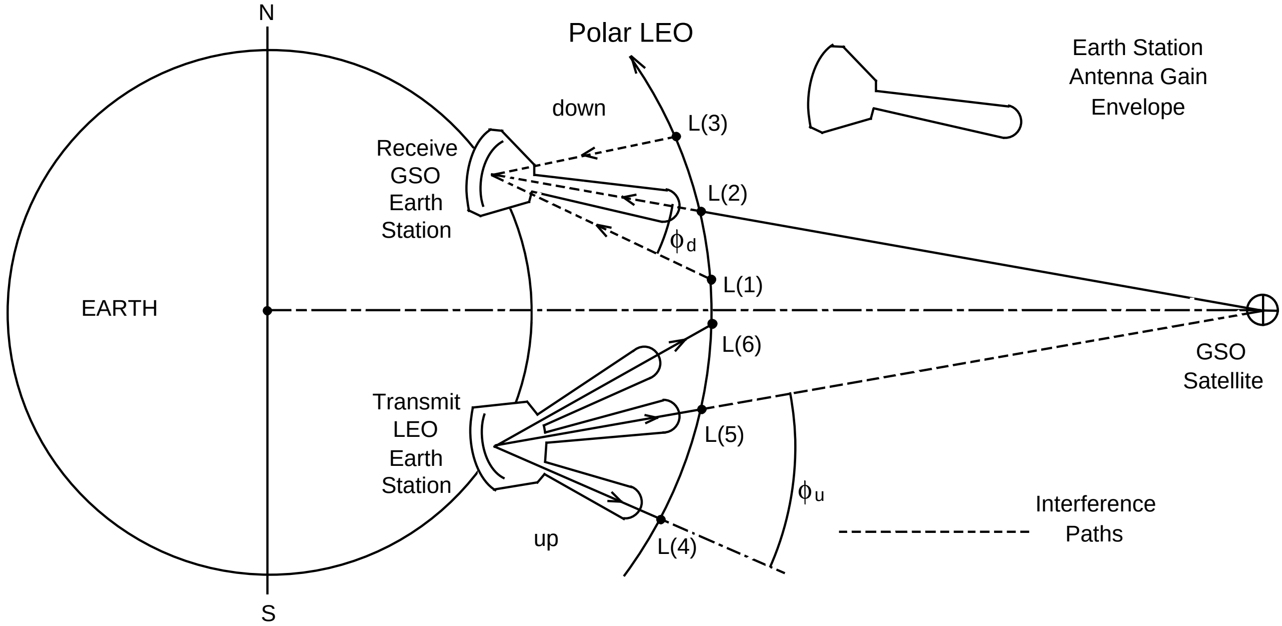

Figure 2. **STATISTICAL NATURE of 'IN-LINE' INTERFERENCE**

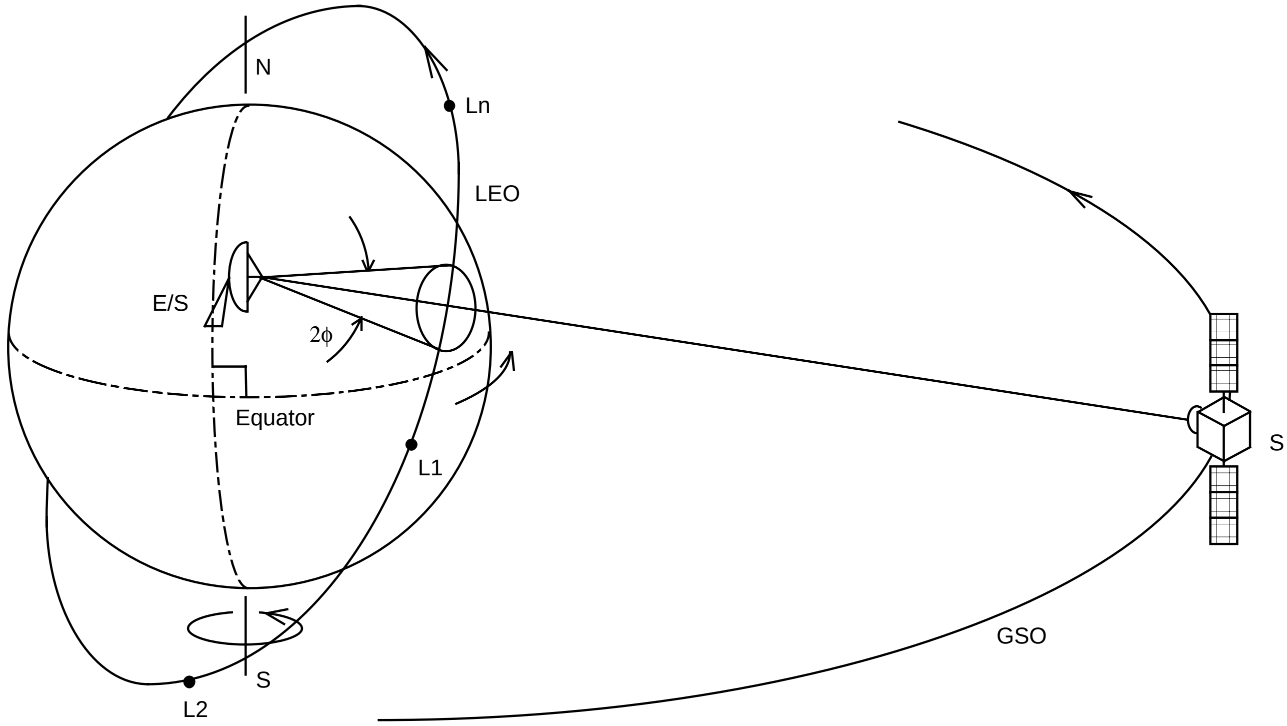

Figure 3. INTERFERENCE BETWEEN NON-GSO/MSS FEEDER-LINKS AND FS TERMINALS

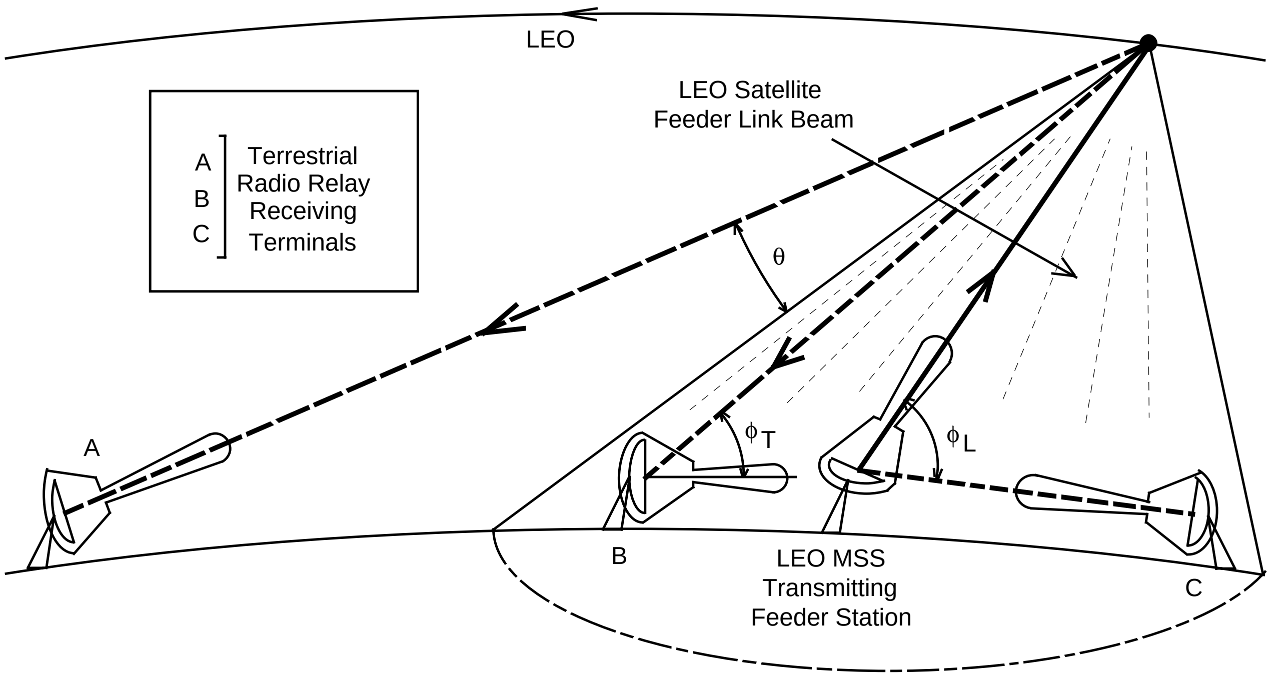

Figure 4. RR2613 "PROTECTION ZONE"

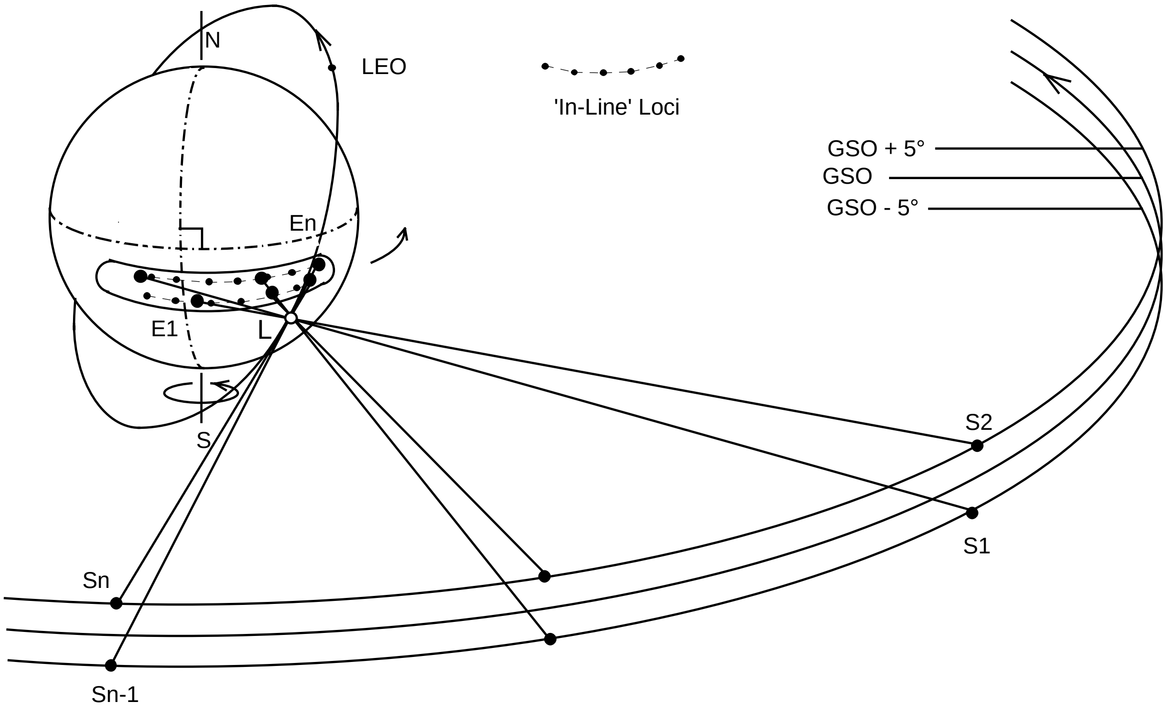

Figure 5. REVERSE BAND OPTION