RECOMMENDATION ITU-R RS.1416*, **

SHARING BETWEEN SPACEBORNE PASSIVE SENSORS AND THE INTER-SATELLITE SERVICE OPERATING NEAR 118 AND 183 GHz

(Question ITU-R 228/7)

(1999)

The ITU Radiocommunication Assembly,

considering

a) that Resolution 723 (WRC-97) resolves to address the allocations of frequency bands above 71 GHz to passive services;

b) that Recommendation ITU-R RS.515 indicates that the band 115-122 GHz is necessary for spaceborne passive sensing to obtain vertical temperature profiles;

c) that Recommendation ITU-R RS.515 indicates that the band 175-192 GHz is necessary for spaceborne passive sensing to obtain vertical water vapour profiles;

d) that weather forecasting is an important tool essential to all human economic activities, and also plays a predominant role in early identification and warnings of potentially dangerous phenomena;

e) that atmospheric temperature and water vapour profiles are essential data needed for weather forecasting on a global basis;

f) that the oxygen absorption band around 118 GHz and the water vapour absorption band around 183 GHz represent a unique natural resource for remote temperature and water vapour profile sensing in the atmosphere;

g) that these passive measurements are extremely vulnerable to interference because the natural variability of the atmosphere makes it impossible to recognize and to filter measurements contaminated by interference;

h) that contaminated passive sensor measurements can have a dramatic, adverse impact on climate studies and the quality of weather predictions,

recognizing

a) that the bands 116-126 GHz, 174.5-182 GHz, and 185-190 GHz are currently allocated to the inter-satellite service (ISS);

b) that Recommendation ITU-R RS.1029 provides interference criteria for the passive sensors in the bands 115-122 GHz and 175-192 GHz;

c) that studies conducted in the bands 116-122 GHz, 174.5-182 GHz and 185-190 GHz have shown that the inter-satellite links (ISLs) in a non-geostationary (non-GSO) satellite system can cause interference to the passive sensors well in excess of these protection criteria (see Annex 1);

d) that studies conducted in these bands have shown that ISLs in GSO satellite systems can share the band with passive sensors with suitable restrictions on the power flux-density (pfd) produced by GSO satellites at the sensor orbital altitude (see Annex 1);

e) that No. S9.7 of the Radio Regulations of the specifies that satellite stations using the geostationary-satellite orbit must consider and coordinate with other space radiocommunication systems,

recommends

1 that, in view of *recognizing* b) and c), passive sensors and ISLs of non-GSO satellite systems should not operate on a co-frequency basis in the bands 116-122 GHz, 174.5-182 GHz and 185-190 GHz;

---

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

[**] Radiocommunication Study Group 7 made editorial amendments to this Recommendation.

2 that, in view of *recognizing* d), passive sensors and ISLs of GSO satellite systems can share the 116-122 GHz band provided that the single-entry pfd at all altitudes from 0 to 1 000 km above the Earth's surface and in the vicinity of all geostationary orbital positions occupied by passive sensors, produced by a station in ISS, for all conditions and for all methods of modulation, does not exceed –148 dB(W/(m^2 · 200 MHz)) for all angles of arrival;

3 that, in view of *recognizing* d) and e), passive sensors and ISLs of GSO satellite systems can share the 174.5-182 GHz and 185-190 GHz bands provided that the single-entry pfd at all altitudes from 0 to 1 000 km above the Earth's surface and in the vicinity of all geostationary orbital positions occupied by passive sensors, produced by a station in the ISS, for all conditions and for all methods of modulation, does not exceed –144 dB(W/(m^2 · 200 MHz)) for all angles of arrival.

ANNEX 1

Feasibility of sharing between the Earth exploration-satellite service (EESS) (spaceborne passive sensors) and the ISS operating near 118 and 183 GHz

1 Introduction

The frequency bands near 118 and 183 GHz are allocated to the EESS on a primary basis for passive sensors as shown in Table 1. The allocation near 118 GHz is shared with other services. Near 183 GHz, the passive services have an exclusively allocated band. A need has been identified in this band to expand the frequency range over which passive measurements can be made, and therefore the passive sensors may have to share with active services in adjacent bands. It is important that frequency sharing be examined:

- to determine if currently allocated sharing at 118 GHz adequately protects the passive sensors; and
- to determine if the expansion of the range over which passive sensors operate near 183 GHz would create potential sharing problem with other services.

TABLE 1

EESS allocations at 116-126 GHz and near 183 GHz

Frequency band (GHz)	Allocation to services (all worldwide)
116-126	EESS (PASSIVE) FIXED INTER-SATELLITE MOBILE SPACE RESEARCH (PASSIVE)
174.5-176.5	EESS (PASSIVE) FIXED INTER-SATELLITE MOBILE SPACE RESEARCH (PASSIVE)
176.5-182	FIXED INTER-SATELLITE MOBILE
182-185	EESS (PASSIVE) RADIO ASTRONOMY SPACE RESEARCH (PASSIVE)
185-190	FIXED INTER-SATELLITE MOBILE

2 Equipment characteristics

2.1 Passive sensors

2.1.1 Low-Earth orbiting (LEO) scanning sensors

The LEO passive sensor used in this analysis is modelled from the advanced microwave sensing unit (AMSU). The AMSU-B is already deployed at 183 GHz and represents the current technology in microwave sensors.

The operation of the sensor is highly dependent upon a mechanically scanned antenna. The reflector moves within a cylindrical shroud. The cylinder has an opened area that allows the antenna to receive radiation across about ± 50° of the Earth's surface and into the night sky up to about 85° from nadir. The antenna scans the Earth, moves to the sky for a cold calibration measurement, and then moves inside the shroud for a warm calibration measurement. The angle at which the antenna takes the cold measurement is constrained by the Earth limb and the area of the shroud needed to cover the antenna for a warm measurement. The calibration measurements are used to measure the receiving system gain. The AMSU scanning scheme has the advantage over other schemes that all receiving components remain the same between atmospheric and calibration measurements.

This scanning and calibration method is used on LEO sensors. Because the orbit is sun-synchronous, the sensor can always make a cold measurement at the same location relative to the spacecraft. Most other arrangements would risk having the calibration antenna point toward the sun and not produce a cold measurement.

2.1.2 Geostationary orbiting sensors

Sensors have been proposed to operate in the geostationary orbit. A scanning type of antenna similar to the AMSU would sweep the visible portion of the Earth to about ± 8° from the spacecraft's nadir. If this sensor uses cold space for calibration it could either point its scanning antenna away from the Earth similarly to the AMSU or have a separate antenna for calibration pointed at any convenient location. The cold calibration antenna must not only avoid the Earth but also the sun and preferably the moon. The AMSU sensor in sun-synchronous orbit can calibrate at the same location relative to the spacecraft and always avoid pointing toward the sun. If the geostationary satellite points anywhere within its orbital plane, it is likely to point at some time toward the sun or the moon and corrupt the cold measurement. It is therefore assumed that the geostationary satellite would point the cold calibration antenna in some direction that does not cause the antenna to aim near the sun, Earth or moon. Most isolation for the calibration antenna would occur if pointed normal to the equatorial plane. This points the calibration antenna at least 67° from the ecliptic where the directional gain would be relatively low.

2.1.3 Push-broom sensors

At this time no push-broom sensors are in operation and no calibration method has been strictly defined. The push-broom sensor operates true to the analogy by having a series of small antenna beams across the spacecraft's track. Like bristles in the broom, the multiple beams sweep along the track. This system is not mechanical: each antenna beam is fixed. Therefore the Earth pointed beams cannot be used for cold calibration. If a separate antenna is used, it is not as constrained as the AMSU antenna in gain or calibration angle. The single constraint is that it must point toward cold space. If sun-synchronous orbits are used, the best direction is away from the sun, which is where the AMSU points. However the push-broom can use angles above the 85° limit imposed by the AMSU shroud.

2.1.4 Limb sounding sensors

Limb sounding sensors would have characteristics that differ from the AMSU-B, but are not addressed in this analysis.

2.1.5 Sensor characteristics

Sensor characteristics are given in Table 2 for the AMSU and GSO sensors. Two modes of operation for the sensor are considered in this analysis:

– the scanning mode; and

– the calibration mode.

The pointing angles for these two modes are given in Table 2.

TABLE 2

Passive sensor characteristics

Parameter	AMSU-B	GSO
Antenna main-beam gain (dBi)	45	66
Antenna back-lobe gain (dBi)	–14	–14
Antenna beamwidth at half power points (degrees)	1.15	0.102
Sensor altitude range (km)	500 to 1 000 850 (nominal)	35 786
Interference criteria per bandwidth (dB(W/200 MHz))	–160	–160
Antenna measurement scan angles (from nadir) (degrees)	± 50	± 8
Cold calibration angle (from orbital plane) (degrees)	90 ± 4	90
Cold calibration angle range (from nadir) (degrees)	65 to 85 83 (nominal)	90 (nominal)

The practical operational range for sensors in LEOs is between about 500 and 1 000 km. Operational or planned sensor systems in this band orbit at a nominal altitude of 833 km. However, orbits achieved by currently operating systems vary in altitude by as much as 20 km.

2.2 Inter-satellite systems

2.2.1 Modelled systems

The characteristics of an inter-satellite system modelled in this analysis are listed in Table 3. It is assumed to be a broadband digital system with a data rate of 200 Mbit/s, chosen to match the reference bandwidth of the sensor. This analysis is also applicable to broader band systems that have proportionally higher power.

TABLE 3

ISL parameters

Parameter	Value
Antenna mainbeam gain (dBi)	45, 50, 55 or 60
Antenna back-lobe gain (dBi)	–10
System noise temperature (K)	2 000 at 118 GHz and 3 000 at 183 GHz
Performance criterion of link, C/N (dB)	12

The link performance is chosen as a C/N of 12 dB. This includes an E_b/N_0 of 10 dB for QPSK modulation and a 2 dB implementation loss. The system noise temperature is derived from the system design of ISLs in lower bands and the receivers built for the AMSU-B. A range of antenna gains between 45 and 60 dBi are examined. Generally, the 45 dBi antenna is chosen for low altitude links and the higher 55 or 60 dBi-antenna gain for higher altitudes and longer links. The antenna side-lobe patterns are modelled using the single feed circular beam antenna pattern from Recommendation ITU-R S.672.

The analysis was limited to scanning sensors and inter-satellite systems in circular orbits. ISLs are limited to a network of satellites with the same orbital altitude.

2.2.2 Operational systems in other bands

No known inter-satellite systems currently operate in the bands addressed in this analysis. In the ITU records Belarus, Malaysia, and the United States of America have advanced filed their intentions to operate space-to-space systems in the 116 to 126 GHz band. No advanced filings appeared for ISLs near 183 GHz. Of those that operate in other bands, most are either at the GSO or at LEOs nominally 700 to 800 km. A few operate above the sensor at orbits that range from 1 000 to 10 350 km. These systems use multiple satellite constellations to achieve full Earth coverage.

Table 4 lists several operating or proposed non-GSO ISL satellite constellations. The geocentric angles subtended by the links are listed for each constellation.

TABLE 4

Example non-GSO satellite constellations

System	Number of orbits	Number of satellites per orbit	Separation within the orbit (degrees)	Separation between orbits (degrees)	Orbital altitude (km)
System A	6	11	32.7	60	780
System B	3	4	90	120	10 350
System C	8	6	60	45	1 414
System D	4	8	45	90	775
System E	21	40	9	17.1	700
System F	6	8	45	60	950
System G	4	6	60	90	800
System H	2	5	72	180	500
System I	6	4	90	60	1 000

Existing or planned GSO satellite systems operating in other bands do not have, in general, evenly spaced satellites. For example, a look at one system shows five links with varying geocentric angles: 149°, 31°, 85°, 85° and 125°. Table 5 shows the maximum longitudinal spacing for ten GSO constellations along with their antenna gains.

TABLE 5

Parameters of example GSO inter-satellite systems

System	1	2	3	4	5	6	7	8	9	10
Antenna gain (dBi)	58.5	59	58	46	55.5	60.3	53	50.3	49.1	55.7
Maximum longitudinal spacing (degrees)	162.6	162.6	78.6	10.1	67.3	162.6	53.9	111.1	77.4	136.4

3 Approach

This analysis considers a broad range of parameters for ISL constellations and determines what restrictions on these parameters would permit co-channel sharing. Sharing is considered to be feasible only if the restrictions on the ISL parameters permit the development of systems similar to systems that are planned for other bands.

Unacceptable interference to the Earth-exploration satellite (passive) service is determined by two criteria. First is an interference threshold of –160 dB(W/200 MHz). Interference above this level is considered to be unacceptable. This power level corresponds to 20% of the sensitivity (Recommendation ITU-R RS.1029) of the sensor. Interference received above this level will increase the temperature reading that the satellite is making and corrupt long-term temperature averages. Another –3 dB will be added to the sensitivity to account for sharing with between space and terrestrial services. The second criterion is temporal and is applied when the first criterion, threshold level, is exceeded. The interference should not exceed the threshold for more than 0.01% of the time. This percentage is given in *recommends* 4 of Recommendation ITU-R RS.1029.

3.1 Analysis organization

The analysis is presented in two investigations. The first is interference to LEO sensors from ISLs in orbits from close to the Earth to the geostationary orbit. The second investigation is interference into sensors in the geostationary orbit from both GSO and non-GSO ISLs.

Each of these investigations starts with a static analysis that identifies the circumstances under which interference can occur. These circumstances are mainly the orbits of the ISLs and the position of the ISL transmitter relative to the sensor. These interference parameters are applied to a temporal analysis which identifies how many transmitters could operate without exceeding the temporal criterion. Circumstances are then investigated to determine if interference can be avoided by restricting operating parameters of the ISLs or the passive sensors. Finally the restrictions are determined for the number of ISLs, length of inter-satellite paths, and pointing restrictions of sensor antennas. These restrictions are compared to those of operating or planned systems in other bands to determine if the constraints are practicable.

3.2 Establishment of geometries causing interference

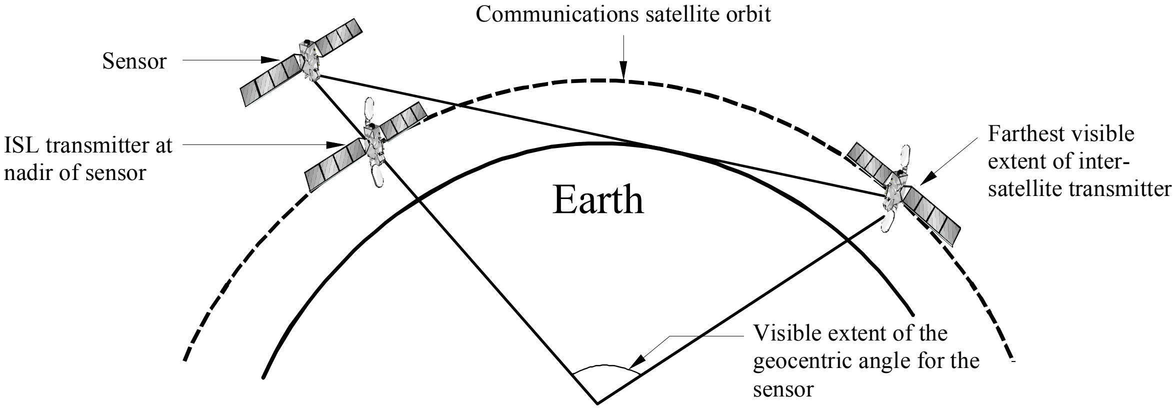
The analysis examines antenna coupling for all possible orientations of the sensor and ISL transmitter. The analysis of relative positions of the sensor satellite and the interfering satellites is performed to find those positions or orientations that cause interference. This investigation considers altitude differences, geocentric angles between the sensor and the ISL transmitter, and antenna orientations. The ISLs are first analysed with the path centre 200 km above the Earth to keep the path above the atmosphere. The inter-satellite path length in terms of geocentric angle is then reduced while observing the maximum interference orientations to determine the maximum length of the link that precludes unacceptable interference. The results of this analysis identify the specific orientations and configurations that cause interference. It bounds the relationship between geocentric angle and altitude that precludes interference.

An algorithm was set up to calculate the received power of an interfering satellite at the sensor for variations of altitude, inter-satellite path length, geocentric angle between the sensor and interfering satellite, and ISL antenna gain. The received power at the sensor was calculated from the geocentric angle between the sensor and the ISL transmitter. The geocentric angles varied from the horizon to the sensor's nadir as shown in Fig. 1.

The power of the transmitter is calculated to maintain a constant link performance, as specified in Table 3, taking into account the distance of the ISL path and the gains of the two antennas. The height of the inter-satellite path and the geocentric angle are related and define the length of the ISL path. This geometry is illustrated in Fig. 2.

FIGURE 1

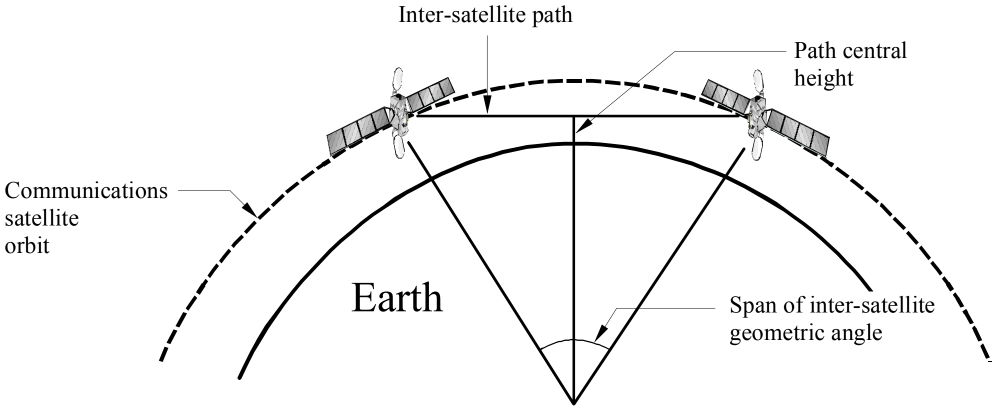
Visibility angles between the sensor and the ISL transmitter



1416-01

FIGURE 2

ISL geometry



1416-02

The path length of the ISL was evaluated using equation (1):

$$d_{link} = 2\sqrt{(R_e + Alt_{non\text{-}GSO})^2 - (R_e + Alt_{centre})^2} \tag{1}$$

where:

d_{link}: distance (m) from the ISL transmitting satellite to the ISL receiving satellite

R_e: radius of the Earth = 6 378 140 m

$Alt_{non\text{-}GSO}$: altitude of the non-GSO orbit (m)

Alt_{centre}: altitude of the centre of the non-GSO link path (m) (see Fig. 2).

The power of the ISL transmitter was calculated using equation (2):

$$P_t = -20 \log \left(\frac{0.3}{4\pi f \, d_{link}} \right) + 10 \log (k \, T \, B) \, 2 G_{ISL} + 12 \tag{2}$$

where:

P_t: ISL power (dBW)

f: tuned frequency of the sensor in (Hz)

k: Boltzman's constant = $1{,}38 \times 10^{-23}$ J/K

B: reference bandwidth of the sensor (Hz)

T: noise temperature of the ISL receiver (K)

G_{ISL}: gain of the ISL antennas (dBi) (assumed to be equal for transmitter and receiver)

12: performance level of the ISL receiver (rapport C/N = 12 dB).

The calculated transmitter power is then used to determine the received interference power considering the path length between the sensor and the transmitter plus the relative gains of the respective antennas toward each other. The received power at the sensor is calculated for all geocentric angular distances from the mutual horizon to the point where the satellites are in line with the centre of the Earth (see Fig. 1). The power to the sensor receiver was calculated using equation (3).

$$P_r = P_t + G_{ISL}(\varphi) + G_{sensor}(\alpha) + L_{fs} \tag{3}$$

where:

P_r: received interference power (dBW)

$G_{ISL}(\varphi)$: angle dependent gain of the ISL transmitting antenna

φ: off-main-beam angle from the ISL transmitting antenna to the sensor receiver

$G_{sensor}(\alpha)$: angle dependent gain of the sensor antenna toward the ISL transmitter

α: off-boresight angle of the sensor antenna toward he ISL transmitter

L_{fs}: free-space loss (dB) between the ISL transmitter to the sensor receiver.

The relationship of the received power vs. geocentric angle was plotted as parameters were varied. This identified the worst interference situations and showed what combinations of these parameters would eliminate interference.

3.3 Temporal analysis of interference-causing constellations

The output of the previous section identifies sensor and interfering satellite orientations that cause interference, primarily via main beam coupling. The temporal criterion of 0.01% is applied to these orientations.

The analysis considers interference from constellations orbiting above and below the sensor. The ISL constellation is analysed as if it were a random distribution of ISL satellites on a sphere.

Interference is considered to come from any position on the ISL constellation sphere for which the signal received at the sensor from that position exceeds the interference threshold. At each position, excessive interference comes from a small elliptical or circular area on the sphere whose area is determined from the antenna main beam gain and the distance of that sphere from sensor. These small areas are the intersections of the sensor antenna's main beam with the constellation sphere.

Because of the assumption of a random distribution of satellites on the ISL constellation sphere, an area ratio can represent the amount of interference over time. For a single satellite, this is the ratio of the interference area on the sphere to the total surface area of the sphere.

The temporal analysis provides the percentage of time that a single satellite in an ISL constellation exceeds the interference threshold. Comparison of this number to the temporal criterion of 0.01% determines the maximum number of ISL satellites allowed to exceed the interference power threshold.

The static analysis is repeated for the geostationary orbiting sensors but because ISLs in the GSO are fixed, no temporal analysis is needed. A temporal analysis will be presented using the area ratio technique for interference from LEO satellite constellations.

3.4 Comparison

In summary, the initial interference analysis provides restrictions in orbital altitude and geocentric angle that avoid interference. For those satellite configurations that do not conform to these restrictions, a temporal analysis determines the number of satellites that can exceed the power threshold while conforming to the 0.01% temporal criterion. Parameters of satellite constellations planned for other bands are compared to these restrictions in order to evaluate whether these restrictions are practical for satellite systems to share these bands with passive sensors.

4 Analysis

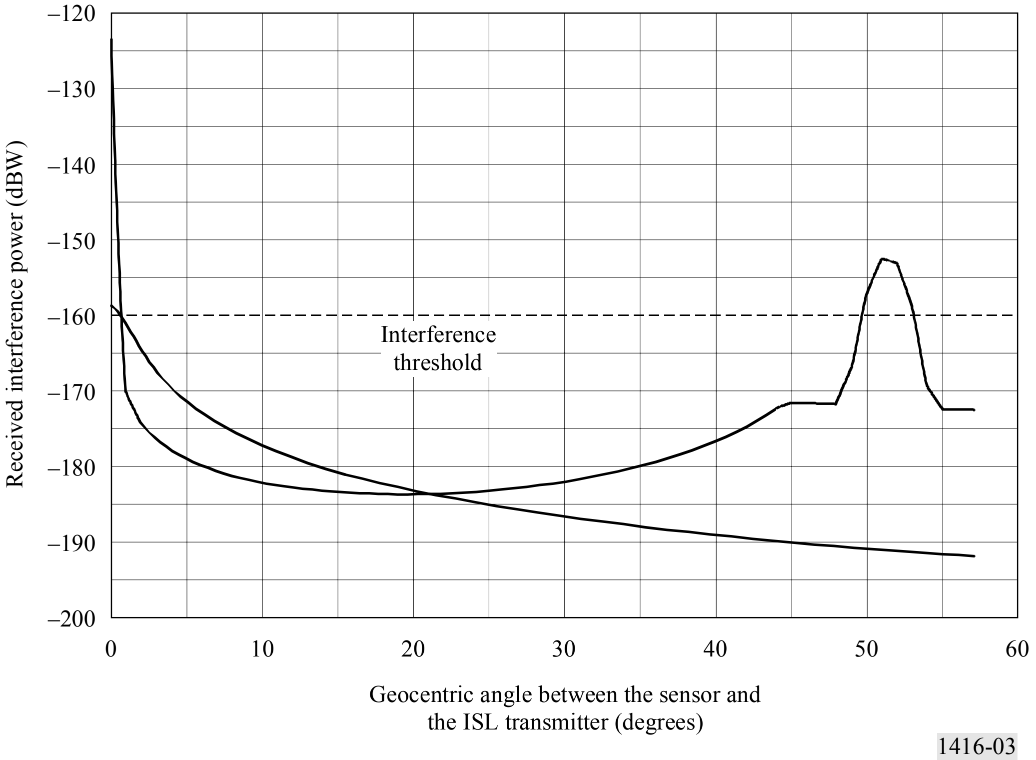
4.1 Interference to LEO sensors

4.1.1 Identification of circumstances causing interference

Initially it is necessary to determine under what circumstances, if any, the power levels of an ISL could exceed the interference threshold of the sensor. To investigate this, a series of calculations were performed with the sensor and ISL transmitter at various orientations to each other. To represent the worst case orientations, the sensor, ISL, and Earth centre are in the same plane. The ISL transmitter is approaching the sensor normal to the sensor's orbital plane. The ISL antenna is aimed in the direction of the sensor. Figure 1 shows the range of angles from the horizon to the nadir of the sensor over which calculations were performed. Figures 3 and 4 are graphs of interference power into the sensor from ISLs over the range of angles illustrated in Fig. 1. Figure 3 represents interference power for the sensor in the scan mode and Figure 4 shows it in the calibration.

FIGURE 3

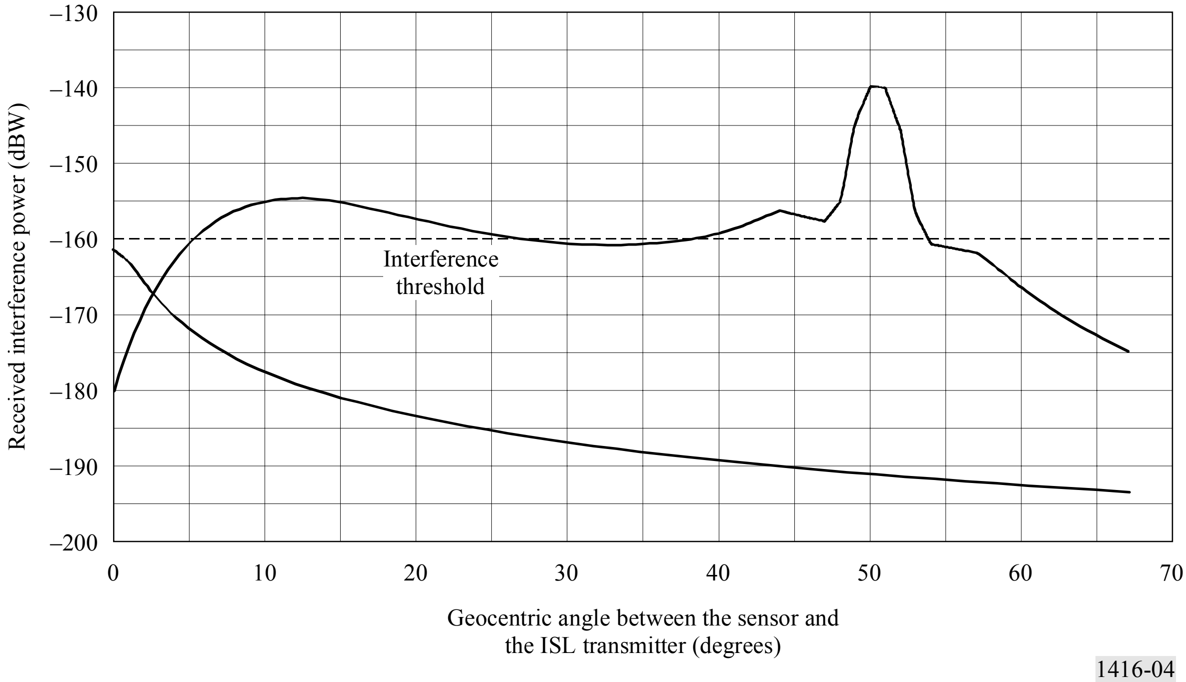
Interference power - Scan mode



1416-03

FIGURE 4

Interference power - Calibration mode



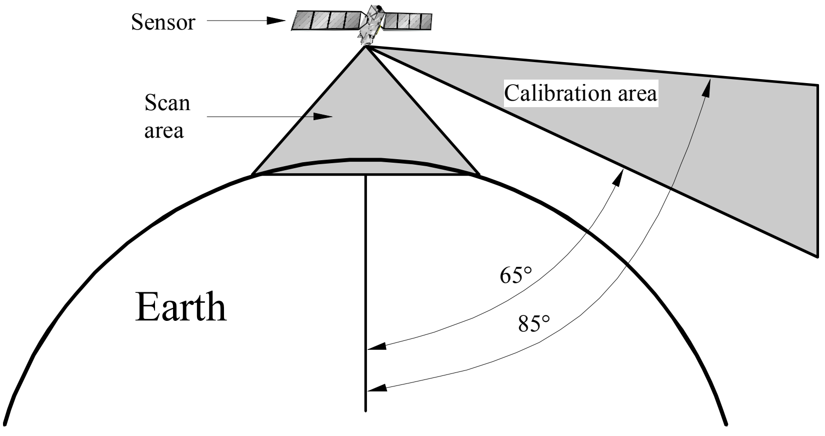
1416-04

Three lines are plotted on Figs. 3 and 4. The horizontal line at –160 dBW represents the interference threshold of the sensor. The lower curved line is a plot of the interference power received by the sensor assuming that both the sensor and ISL transmitter had 0 dBi gain omnidirectional antennas. The third line with peaks is a plot of interference power with directional gains for the sensor and ISL transmitter. The relative magnitudes of the interference curves show the effect of the high gain antennas. Observing from Fig. 3 the omnidirectional-gain-antenna curve only exceeds the threshold when the ISL transmitter is close to the sensor near 0°. The high gain antenna curve exceeds the interference threshold both when the ISL transmitter is near 0° and in the sensor antenna's main beam and when the ISL transmitter is nearer the horizon and its main beam illuminates the sensor. From Fig. 4 the interference level is above the threshold when the ISL transmitter is near the main beam of the sensor calibration antenna and again when the sensor is in the main beam of the ISL transmitter antenna.

In both Figures interference levels are high if the ISL transmitter gets near the main beam of the sensor antenna. Figure 5 illustrates the ranges over which the sensor antenna could be operating.

FIGURE 5

Sensor angles and ranges for the scan and calibration modes



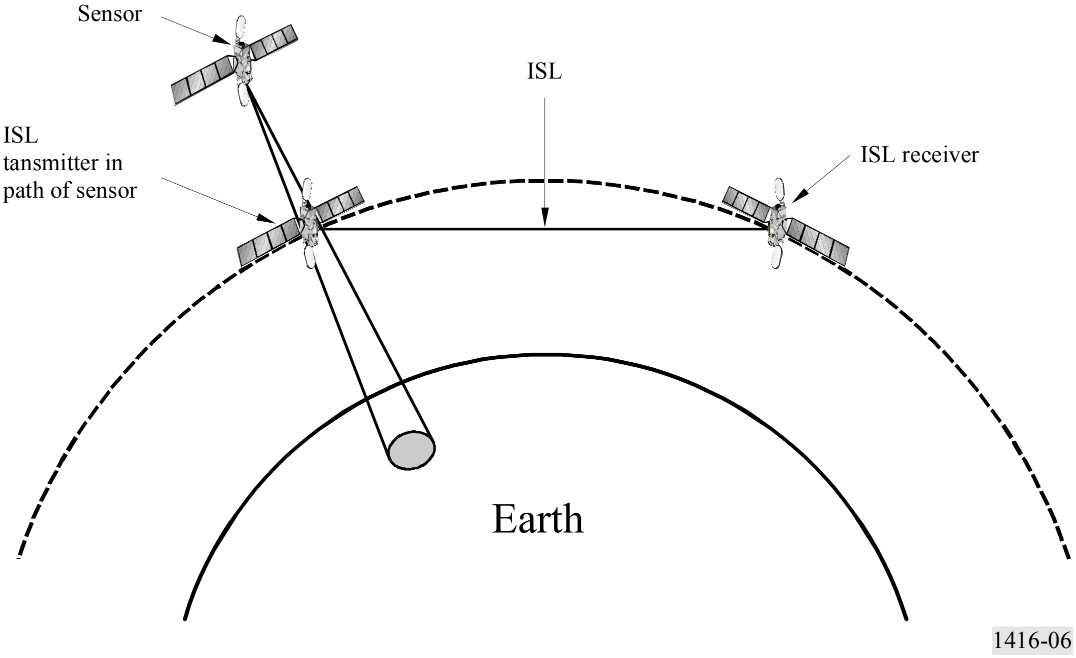
1416-05

Figure 5 can be applied to both the AMSU and push-broom sensors. The scan for the AMSU is the range over which the antenna sweeps during operation. For the push-broom sensor, multiple beams are continuously covering this area. The calibration area shown in the Figure is the range of angles that can be used by the AMSU sensor. In operation it will use only a single angle, nominally about 83°. The push-broom must use a separate antenna for cold calibration and is not as constrained as the AMSU. It can be pointed in any direction that will not include the Earth. But as a secondary consideration it must also avoid the sun. If a sun-synchronous orbit is used, as is assumed, it could point up to and beyond the horizontal. Also it could point along or oblique to the orbital plane.

Because excessive interference can occur when the ISL transmitter is in the sensor main beam, it occurs when it is in the shaded areas of Fig. 5. The scan mode therefore receives interference into the main beam of its antenna from constellations that orbit below the sensor. In contrast the calibration mode of the sensor is subject to interference into its main beam from satellite orbits both above and below its orbit. These interference orientations are illustrated in Figs. 6 and 7.

FIGURE 6

Interference when the ISL transmitting satellite is in the scanning beam of the sensor



Interference also occurs as determined earlier when the main beam of the ISL transmitter intercepts the sensor. Figures 8 and 9 illustrate the intersection of the ISL main beam from constellations both below and above the sensor.

4.1.2 Temporal analysis

4.1.2.1 Low altitude analyses

Three areas of interference were identified:

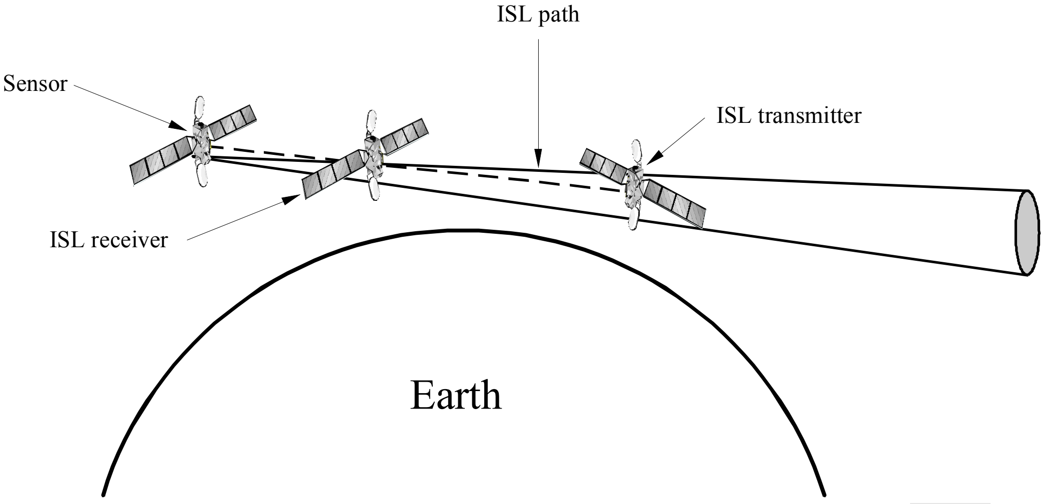
– below the sensor in the scan mode where the main beam of the sensor couples with the ISL side lobe;

– to the side of the sensor in the calibration mode, when the sensor calibration antenna couples to the side lobe of the ISL transmitter satellite; and

– where the ISL transmitter main beam couples to the sensor's side lobe.

FIGURE 7

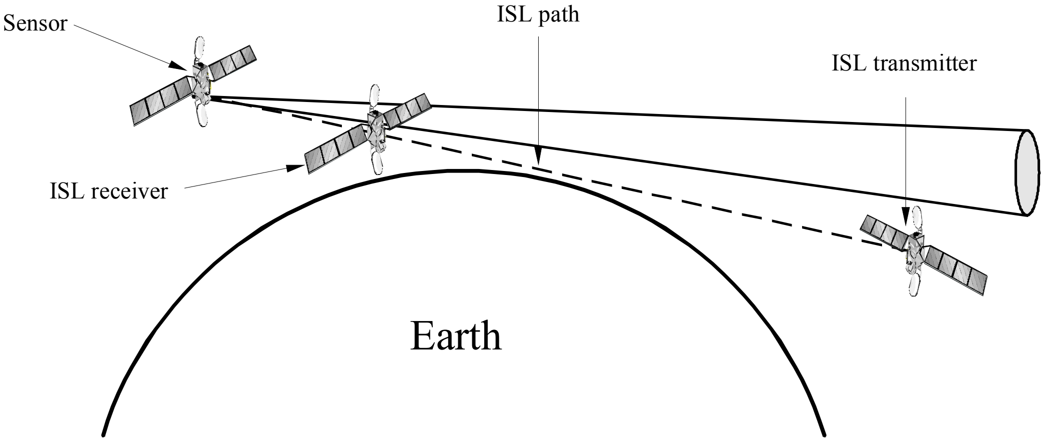
Interference when ISL transmitter is in calibration antenna main beam



1416-07

FIGURE 8

Interference in calibration mode from ISL transmitter antenna main beam or constellation orbiting below the sensor

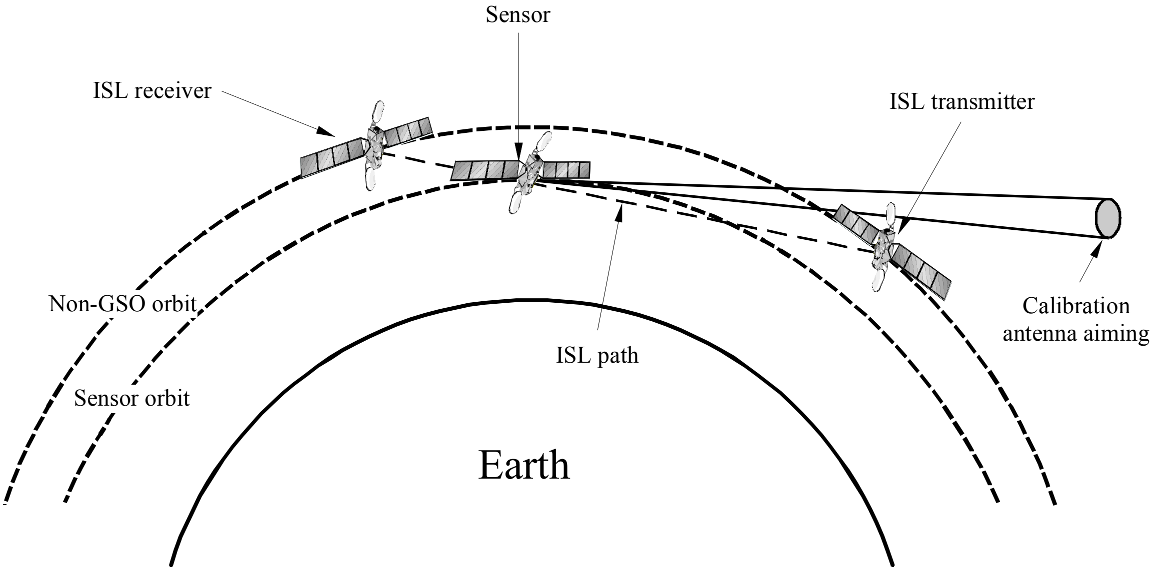


1416-08

Results of this analysis (see Fig. 10), show that a maximum of eight satellites in the entire orbital sphere can share the 118 GHz band, and five satellites can share the 183 GHz band, if they are in an orbit near 300 km altitude. The number that can share drops to two satellites at around 500 km altitude, and to zero at 900 km altitude. The curve is a composite of the three probabilities for the three interference areas caused by main beam coupling to the sensor's scanning antenna, the sensor calibration antenna, and the ISL transmitter antenna. The dominant interference mechanism is ISL main beam transmission into the sensor side lobes. At 749 km altitude, interference into the sensor antenna during calibration dominates the composite curve.

FIGURE 9

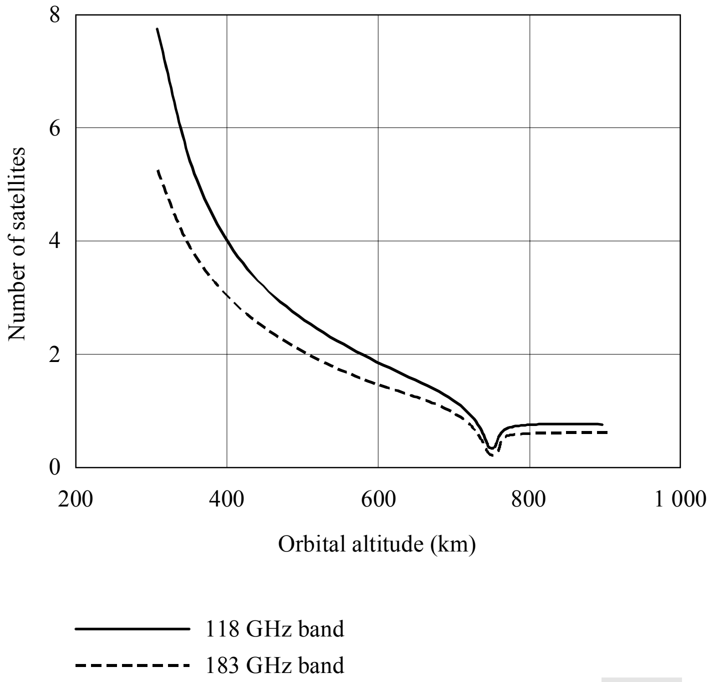
Interference in calibration mode from ISL transmitter antenna main beam or constellation orbiting above the sensor



1416-09

FIGURE 10

Number of satellites in LEO constellation that meet 0.01% criterion



1416-10

The calibration angle for the sensor influences the potential for sharing, as illustrated above. Generally, when interference can be received into the calibration antenna, only one satellite can share without violating the 0.01% criterion. As the calibration angle is changed from 65° to 85°, the maximum interference altitude moves upward. Table 6 shows the maximum-interference altitude for the range of calibration angles from 65° to 85° where the least number of satellites can share.

TABLE 6

Minimum interference altitude to sensor antenna in calibration mode

Calibration angle (degrees)	Minimum interference altitude (km)
65	308
70	555
75	749
80	888
85	971

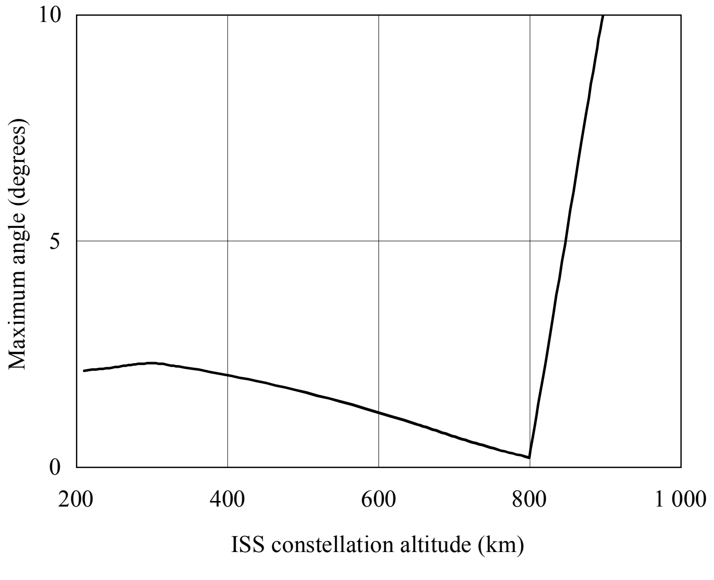
4.1.3 Analysis of interference avoidance for ISLs

The ISL path lengths considered up to now produce the maximum amount of interference because they were the longest paths requiring the most transmitter power. Anything that reduces the satellite e.i.r.p. will reduce the interference levels. Two factors that affect the e.i.r.p. are the antenna gain and path length. If the ISL were designed with matching transmit and receive antennas, every decibel increase in the antenna gain results in a 2 dB increase in the ISL received signal power. To maintain the same received signal power, the ISL transmitter power can therefore be reduced to 2 dB. In other words, each decibel increase in antenna main beam gain results in a 1 dB reduction in main-beam e.i.r.p. and a reduction in side-lobe radiation. The required e.i.r.p. is also proportional to the square of the distance, so reduction of the link length reduces the e.i.r.p. and therefore the interference power received. There exists a maximum ISL path length for each altitude for which no unacceptable interference occurs.

Figures 11 and 12 show the maximum geocentric angle for ISLs that precludes unacceptable interference. These results were obtained by calculating the interference power at the sensor, and reducing the ISL path length until this power falls below the threshold of –163 dBW. ISL transmit and receive antenna gain is 45 dBi.

FIGURE 11

Maximum geocentric angle for an inter-satellite system to avoid interference to the spaceborne sensors when a sensor is in the scanning mode at 850 km altitude

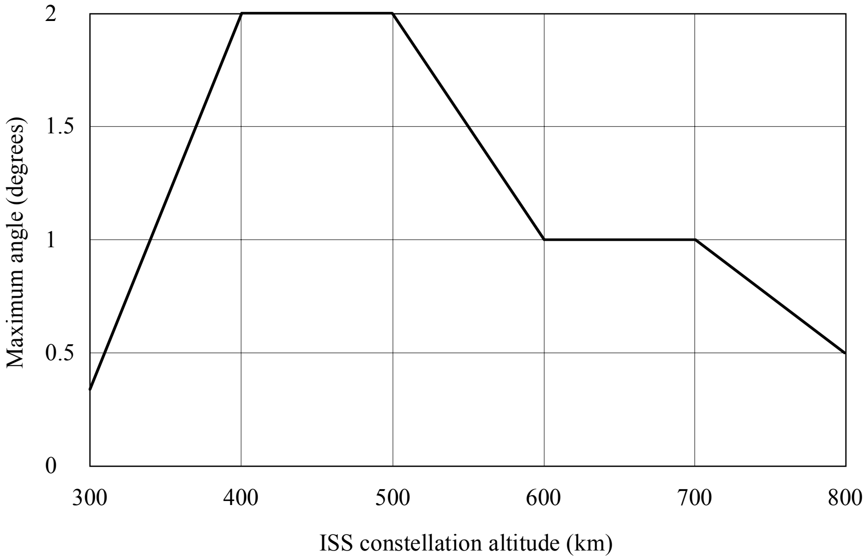


1416-11

Figure 11 depicts the case for the sensor at an altitude of 850 km in the scan mode with the ISL links below and slightly above it. The maximum geocentric angle is 2° or less for the scan mode until the ISL constellation is above the sensor's altitude. The maximum angle approaches zero when the altitudes of the ISL constellation and the sensor satellite are equal. In the calibration mode, shown in Fig. 12, the maximum angle is less than 1°. Therefore the calibration mode is more susceptible to interference.

FIGURE 12

Maximum geocentric angle for an inter-satellite system to avoid interference to the spaceborne sensors when a sensor is in the calibration mode at 83° and 850 km altitude



1416-12

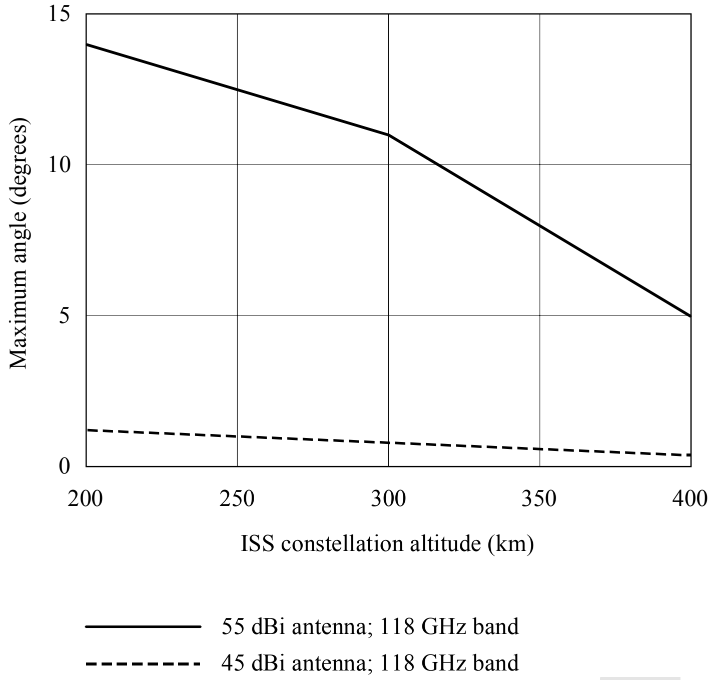
The range of usable orbits for the sensors is 500 to 1 000 km. From Fig. 11 it can be observed that sharing is not feasible with ISLs at the same altitude but the sharing possibilities increase as the ISL transmitter orbit becomes lower than the sensor. Since the sensor can be anywhere from 500 to 1 000 km ISLs cannot occupy this orbital range. The sharing possibilities would be below 500 km for a sensor at 500 km and above 1 000 km with the sensor at that altitude. Figures 13 and 14 show the angle restrictions when the sensor is at 500 km for the scan and calibration modes, respectively. Figures 15 and 16 similarly show the angle restrictions for the sensor at 1 000 km altitude with ISLs above it. In these Figures two antenna gains are investigated for the ISL. Plots are provided for both a 45 dBi and 55 dBi antenna on the ISL.

Increasing the antenna gain for the ISL increases the link angles that avoid interference. First, this is because less ISL transmitter e.i.r.p. is required. Secondly, the ISL transmitter antenna has a narrower beam, which decreases emissions off the main lobe.

For the case when the ISL is above the sensor at 1 000 km, the antenna gain seems to have little effect in the scan mode (Fig. 15) and the geocentric angle limit of the ISL is less restrictive. The antenna gain of the ISL has more effect in the calibration mode (Fig. 16). The 45 dBi antenna is still quite restricted while the 55 dBi antenna is not. Figures 14 and 16 show the increased sharing achievable with higher gain ISL antennas.

FIGURE 13

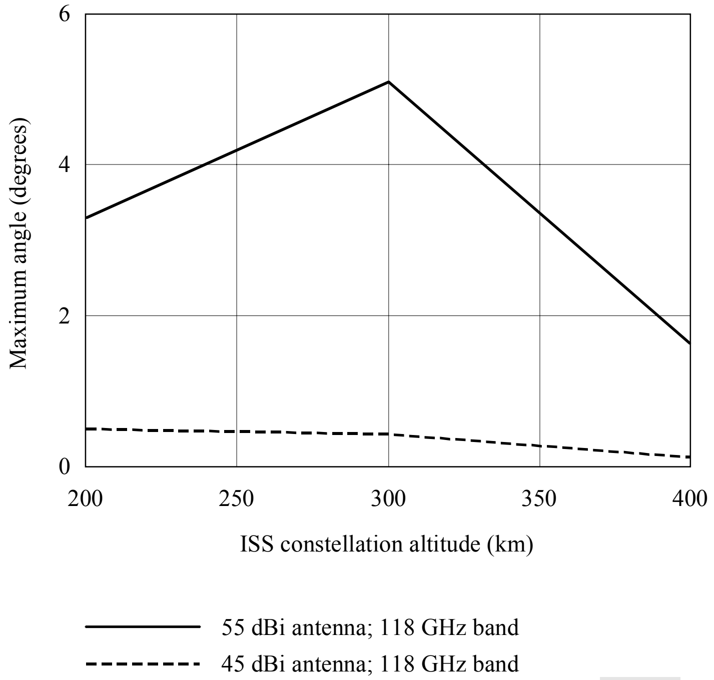
Maximum geocentric angle for an inter-satellite system to avoid interference to the spaceborne sensors when a sensor is in the scanning mode at 500 km altitude



1416-13

FIGURE 14

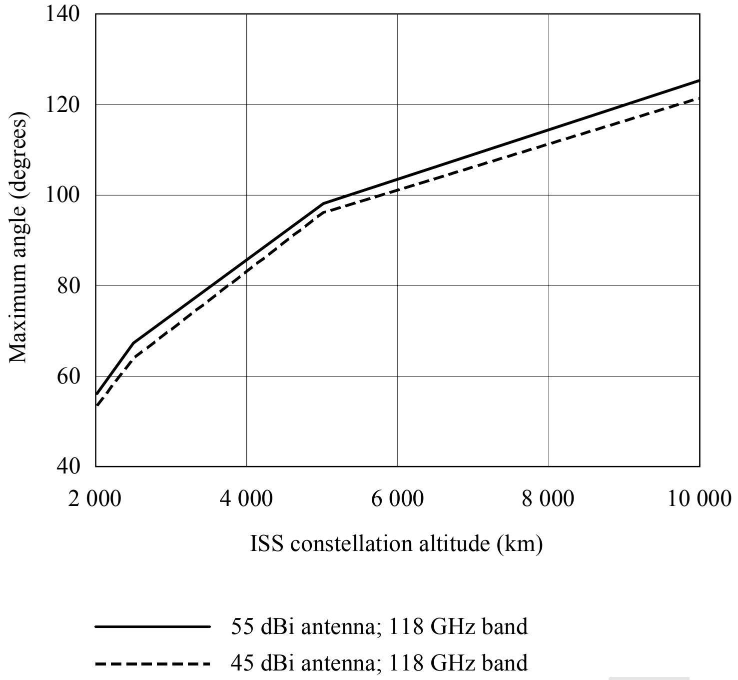
Maximum geocentric angle for an inter-satellite system to avoid interference to the spacecraft sensors when a sensor is in the calibration mode at 83° and 500 km altitude



1416-14

FIGURE 15

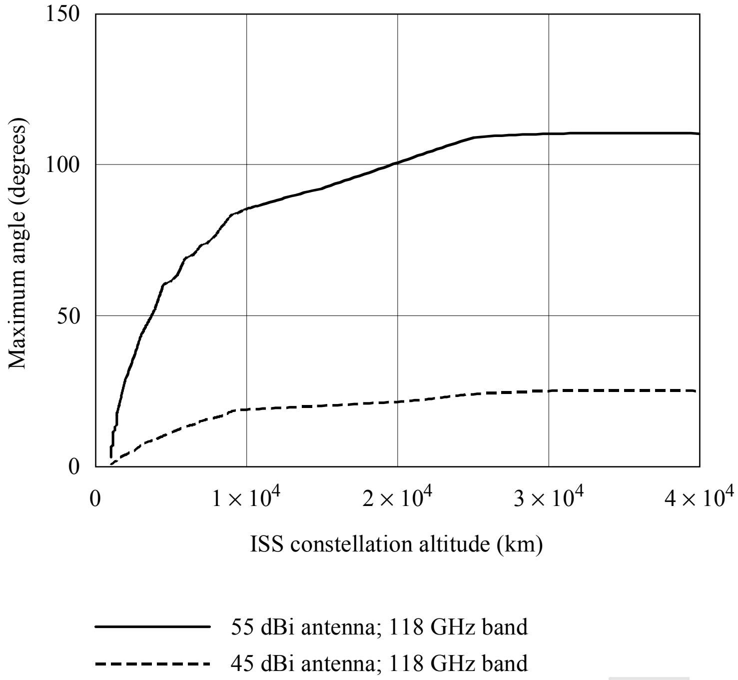
Maximum geocentric angle for an inter-satellite system to avoid interference to the spaceborne sensors when a sensor is in the scanning mode at 1 000 km altitude



1416-15

FIGURE 16

Maximum geocentric angle for an inter-satellite system to avoid interference to the spaceborne sensors when a sensor is in the calibration mode at 83° and 1 000 km altitude



1416-16

4.1.4 Restrictions on sensor calibration angle and antenna gain to facilitate sharing

The sensor antenna calibration proved to be the most constraining mode for restricting sharing with the ISS. The sensor calibration antenna gain and angle were fixed at 45 dBi and 83° for the analysis. Just as a different antenna gain reduced the sharing restrictions on the ISLs, adjustments of antenna gain and calibration angle might improve the sharing possibilities. However, with implementation of a different calibration antenna on future sensors, the gain is likely to decrease rather than increase. Tables 7 and 8 present the results of an investigation into the restrictions caused by sensor antenna gains and orientation.

Table 7 presents the results of an investigation to determine how close the transmitter and receiver used on the ISL should be to avoid excessive interference. Altitudes both above and below the sensor are investigated. The sensor was set at 850 km and the calibration angle fixed at 90° from nadir. The less restrictive calibration angle could be deployed if separate antennas were used for calibration. The maximum geocentric angle is given in the Table 7 for combinations of ISL orbital altitude and calibration antenna gain.

TABLE 7

Maximum ISL geocentric angle that fully protects passive microwave sensors in an 850 km orbit

Non-GSO orbit height (km)	Calibration antenna gain			
	45 dBi	40 dBi	35 dBi	30 dBi
300	2°	5°	10°	20° (maximum distance)(1)
400	2°	4.4°	8°	21°
500	1°	3.3°	5°	13°
600	1°	1.9°	3°	8°
700	0.5°	1°	2°	3.8°
800	0.2°	0.2°	0.5°	0.9°
1 500	2°	4°	7°	12°
2 000	4°	7°	12°	18°
2 500	7°	11°	14°	25°
3 000	8°	13°	20°	30°
5 000	13°	21°	31°	45°
10 000	17°	27°	40°	59°
15 000	21°	33°	49°	67°
GSO	134°	143°	149°	153°

(1) The entry indicating (maximum distance) means that the link would pass through the atmosphere before the interference criteria were achieved.

Again from Table 7 it can be observed that the lower calibration antenna gains would increase the sharing possibilities. Also the closer the ISL orbit is to the sensor orbit, the more restrictive the angles become. Restrictions become even greater when considering that the analysis considered only an 850 km orbit and the sensors could be in an orbit from 500 to 1 000 km. However, the angles are not very restrictive for ISLs at the GSO considering that the maximum angle a GSO link can span without blockage form the Earth is 162.6°.

Table 7 illustrates the sensitivity of calibration antenna gain and pointing angle to interference from ISLs in orbits lower than the sensor. The minimum calibration angle that keeps the interference level below the threshold is presented for combinations of altitude and calibration antenna gain. The AMSU has an antenna gain of 45 dBi but the push-broom sensor could be using lower gains. In this example the sensor is in an 850 km orbit.

TABLE 8

Minimum calibration angle from nadir to fully protect calibrating microwave sensors from ISLs with the sensor in an 850 km orbit

Non-GSO orbit height (km)	Calibration antenna gain			
	45 dBi	40 dBi	35 dBi	30 dBi
300	145°	115°	97°	86°
400	170°	130°	105°	91°
500	175°	135°	110°	93°
600	>180°	145°	115°	96°
700	>180°	145°	120°	100°
800	>180°	145°	120°	100°

NOTE 1 – Entries showing >180° indicate that excessive interference cannot be avoided.

From Table 8 it can be observed that the lower the calibration antenna gain, the lower the calibration angle can be without receiving excessive interference. None of the angles determined in this investigation were as low as the range for the AMSU. This implies that protection cannot be achieved for sensors similar to the AMSU from lower ISLs orbits.

One clear observation in this analysis is that lower calibration angle gains increase sharing possibilities with ISLs. However, the calibration antenna must view only cold space and lower gain antennas would have broader antenna side-lobe patterns and expose the calibration antenna partially to the Earth, the atmosphere or the sun. Additionally a wider antenna view would expose the receiver to interference from multiple ISLs. Only a single link is considered here. Although 30 dBi may not be the smallest antenna usable for calibration, it has a 6.5° beamwidth and is likely to be near the limit.

4.1.5 Limitations on ISLs in the GSO

Some GSO systems can meet the interference criteria as noted from the wide angles shown in Table 7. In order for sharing to be considered feasible, limits must be placed on the GSO systems to protect the passive sensors. The worst scenario is coupling directly into the sensor's main beam during calibration. Therefore, setting a pfd limit based upon main beam coupling would protect the sensor. The interference threshold of –163 dBW per 200 MHz translates to a pfd of –145 dB(W/m^2) at 118 GHz and to –141 dB(W/m^2) at 183 GHz. Calculations are shown in Table 9.

TABLE 9

Determination of pfd to protect passive sensors from emissions from ISLs in geostationary orbit

Item	118 GHz band	183 GHz band
Sensor interference threshold (dBW)	–163	–163
Antenna gain (dBi)	45	45
Effective aperture (dB/m^2)	–63	–67
Factor for multiple GSO systems (dB)	3.0	3.0
pfd threshold (dB(W/(m^2 · 200 MHz)))	–148	–144

4.1.6 Compatibility summary on LEO sensors

Compatibility is determined by comparing the operational restrictions evaluated above with sample systems that are either planned or operational in this or other bands. These systems are described in § 2. The following conclusions can be drawn from the analysis and comparison to other systems.

- ISL transmitters can produce interference over the sensor's threshold when near-main-beam antenna coupling occurs. Interference power levels can be below the threshold in other orientations.
- Of the example ISL transmitters that exceed the threshold, fewer than eight can be in orbits below the sensor without exceeding the temporal criterion for sharing.
- Although a lower calibration antenna gain does reduce the potential for interference to passive sensors in the calibration mode, the gain cannot be reduced sufficiently to permit ISLs with reasonably long range links distances as determined by comparing the calculated restrictions with typical systems planned or operating in other bands.
- Restricting the angle off nadir where the sensor calibration antenna is aimed also reduces interference from ISLs at certain orbits, but the restrictions are not within the operating range of sensors already being deployed and may not be feasible.
- Closer spacing of spacecraft with ISLs can reduce the potential for interference but the permissible maximum geocentric angles may not be practicable for communications satellite systems.
- The push-broom sensor has fewer restrictions on its calibration antenna than the AMSU sensor, but the additional capability does not appear to significantly improve its immunity to interference from ISLs.
- GSO ISLs can share with sensors provided their pfd at the sensor's orbit does not exceed certain limits.

The general conclusion of this section is that the restrictions either on the sensor or ISL parameters that would be needed to provide adequate protection may be too restrictive for typical systems that may be planned or implemented.

4.2 Interference to geostationary orbiting sensors

4.2.1 Identification of interference situations

Sensors in geostationary orbit will operate with a scanning type of antenna that would sweep the visible portion of the Earth to about ±8° from the spacecraft's nadir. If this sensor uses cold space for calibration it could either point its scanning antenna away from the Earth similarly to the AMSU or have a separate antenna for calibration pointed at any convenient location. The cold calibration antenna must not only avoid the Earth but also the sun and preferably the moon. The AMSU sensor in sun-synchronous orbit can calibrate at the same location relative to the spacecraft and always avoid pointing toward the sun. If the geostationary satellite points anywhere within its orbital plane, it is likely to point at some time toward the sun or the moon and corrupt the cold measurement. It is therefore assumed that the geostationary satellite would point the cold calibration antenna in some direction that does not cause the antenna to aim near the sun, Earth or moon. Most isolation for the calibration antenna would occur if pointed either due north or south at 90° from the equatorial plane. This points the calibration antenna at least 67° from the ecliptic where the directional gain would be relatively low.

As noted, the calibration antenna would likely be aimed away from the Earth and away from the geostationary orbital plane. Since interference is predominantly due to near main beam coupling, the calibration antenna is unlikely to receive excessive interference. The interference modes that would likely effect the GSO satellite sensor would be:

1 The Earth facing antenna in the scan mode from the main beam of lower orbiting satellites.

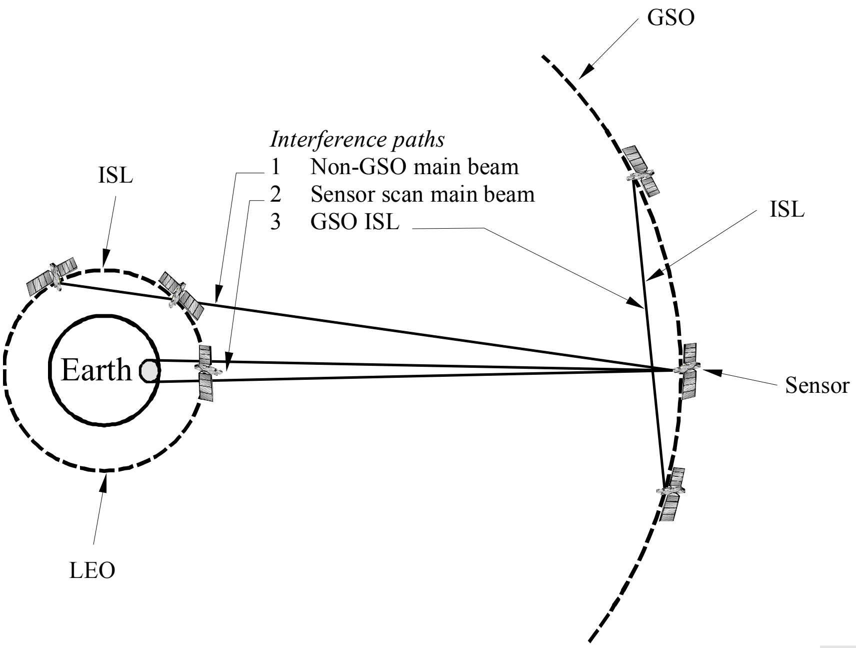
2 The Earth facing antenna in the scan mode from side lobes of lower orbiting satellites.

3 The sensor in either mode from ISL links of satellites in the geostationary orbit.

Figure 17 illustrates the three possible modes.

FIGURE 17

Interference modes to sensors in geostationary orbit



1416-17

4.2.2 Static analysis of interference from non-GSO ISLs

Prior analyses for the low orbiting sensor indicated that interference powers were the strongest when the main beam of either the sensor or non-GSO transmitter pointed directly at the other satellite. These alignments are illustrated as interference paths 1 and 2 in Fig. 17. These two paths will be investigated together by first determining the sensor's threshold sensitivity toward the non-GSO transmitter location.

The nine systems shown in Table 10 will be evaluated as if they were systems operating in these bands. The transmitter power for each link was determined by using equation (2) and angular separation from Table 10. A 45 dBi antenna was assumed for each link. For the interference path, the power plus full 45 dBi antenna gain was assumed to be radiated from a point 90° separation from the sensor sub-satellite point. For interference path 2 a backlobe gain was assumed to be –10 dBi with the non-GSO transmitter at an altitude above the sub-satellite point. The sensitivity of the sensor toward the interference path 1 was calculated assuming the sensor was scanning +8° in that direction. The sensor antenna gain is assumed to be 20 dBi (the directional sensitivity is –183 dBW). To the sub-satellite point the sensor is assumed to be pointed at nadir and the full 66 dBi gain of the sensor antenna adds to its sensitivity (–226 dBW).

Table 10 shows the results of these calculations and the comparison to the sensitivity of the GSO. The first four columns give parameters of these systems. The next four columns give the power level (dBW per 200 MHz) at the GSO for these systems. In the last two columns these power levels are compared to the threshold sensitivity levels of the sensor toward their direction.

TABLE 10

Determination of compatibility between GSO sensor and non-GSO ISLs

System	Number of satellites	Degrees separation	Orbital altitude (km)	Power at GSO from side-lobe emissions (dBW)		Power at GSO from main lobe emissions (dBW)		Sharing with GSO sensor due to side-lobe emissions?	Sharing with GSO sensor due to main lobe emissions?
				118 GHz	183 GHz	118 GHz	183 GHz		
System A	66	32.7	780	–218.0	–212.4	–160.9	–159.1	No	No
System B	12	90	10 350	–205.2	–188.6	–151.4	–149.7	No	No
System C	48	60	1 414	–213.3	–207.7	–156.4	–154.7	No	No
System D	32	45	775	–215.6	–210.1	–158.6	–156.8	No	No
System E	840	17.1	700	–223.3	–217.8	–166.2	–164.5	No	No
System F	48	45	950	–215.5	–209.9	–158.5	–156.7	No	No
System G	24	60	800	–213.9	–208.3	–156.8	–155.0	No	No
System H	10	72	500	–213.3	–207.7	–156.2	–154.4	No	No
System I	24	60	1 000	–213.7	–208.1	–156.7	–154.9	No	No

In all cases of the examined non-GSO systems, interference exceeded the sensor's allocated interference threshold.

4.2.3 Temporal analysis of non-GSO interference

It has already been established that a single ISL transmitter can transmit interfering levels of power when in the sensor's main beam even though the ISL antenna far side lobes are involved. Therefore any ISL that passes into the sensor's main beam can cause interference.

The proposed passive sensor has a footprint of 2 000 km^2 on the Earth and a similarly sized footprint at lower orbital altitudes. Assuming a nominal altitude of 800 km, the area ratio of the entire sphere to the footprint of the satellite is 0.0036%. If the satellites were evenly distributed, there would have to be 323 733 satellites for one to be in the sensor's field of view at all times. To reduce that to one satellite in the sensor's view for less than 0.01% of the time, there would have to be less than 33 satellites in LEO operating in any 200 MHz band.

4.2.4 Interference from other GSO ISLs

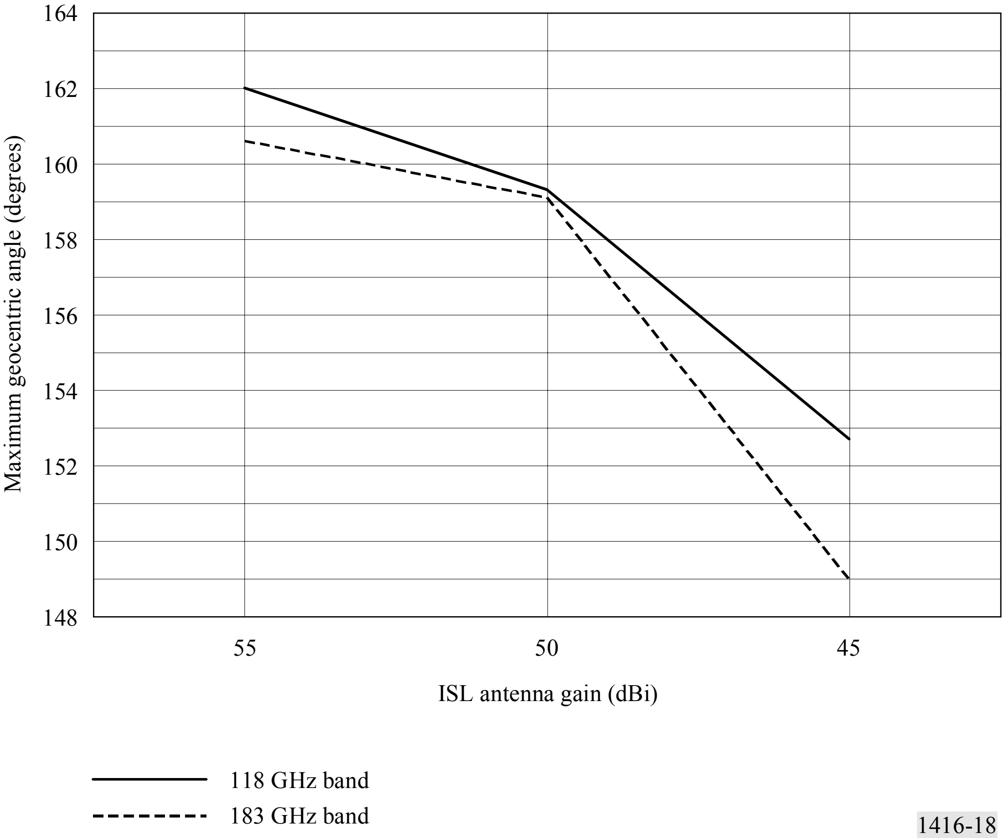
Interference from other GSO satellites is designated as interference path 3. In this case neither the main beam of the active satellite or the passive sensor point directly at each other unless the sensor is collocated with the intended receiver. The positional relationship between the satellites will not change with time for these satellites. Sharing is possible if the off-main-beam gain of the ISL transmitter is sufficiently low to prevent interfering signal levels at the sensor. This is controlled by the gain pattern of the ISL transmit antenna, the geocentric angle of the ISL link, and the geocentric angle between the sensor and ISL transmitter.

To determine if any ISL link might interfere with the sensor, links with antenna gains from 60 to 45 dBi were investigated. The geocentric angle was varied at angles up to 162.2° to determine where interference would occur. In the case of a 60 dBi antenna, no interference levels exceeded the threshold. The interference level only exceeded the threshold at wide spacing for the 55 dBi-, 50 dBi- and 45 dBi-gain antennas. Figure 18 shows the maximum spacing that avoids interference to the sensor over the threshold.

ISLs for systems in geostationary orbit can share with geostationary orbiting sensors provided the maximum geocentric angle relative to the antenna gain does not exceed the values plotted in Fig. 18.

FIGURE 18

Maximum allowable geocentric angle for GSO ISLs



1416-18

4.2.5 Comparison and conclusions on sharing with geostationary orbiting sensors

– Geostationary orbiting sensors can receive levels of power over the interference threshold from LEO ISLs when near-main-beam antenna coupling occurs.

– All of the example LEO systems that were examined would cause interference to a geostationary orbiting sensor if deployed in these bands.

– LEO constellations with 33 or less ISLs in this band could operate without violating the temporal criterion for sharing.

– All but a few very long GSO ISLs can share with geostationary orbiting sensors without exceeding the interference threshold at any time. All example systems planned or operating in other bands could share if they were implemented in this band.

5 Conclusions

5.1 Sharing in the 116-126 GHz frequency band

Sharing with the ISS in the range from 116 to 126 GHz is not feasible except for ISLs between the GSO satellites. The analysis has shown that non-GSO ISLs that do not exceed the sensor's interference threshold are likely to be impractical in both path length and allowable number of circuits when compared with example systems planned or implemented in other bands. Inter-satellite systems at the geostationary orbit can share with the sensors provided their power at the sensor's orbital altitude of 1 000 km is restricted to:

$$-148 \text{ dB(W/(m}^2 \cdot 200 \text{ MHz))}$$

5.2 Sharing in the frequency bands between 174.5 and 190 GHz

Sharing with the ISS in the frequency bands between 174.5 and 190 GHz is similarly not feasible except for ISLs in the geostationary orbit. Inter-satellite systems at the geostationary orbit can share with the sensors provided their power at the sensor's orbital altitude of 1 000 km is restricted to:

$$-144 \text{ dB(W/(m}^2 \cdot 200 \text{ MHz))}$$

5.3 Restricting sensor techniques to facilitate sharing

It is unlikely that adequate protection for the passive sensors can be achieved by adjusting or restricting measurement techniques of the passive sensors.