ERC REPORT 45

European Radiocommunications Committee (ERC) within the
European Conference of Postal and Telecommunications Administrations (CEPT)

SHARING BETWEEN THE FIXED AND EARTH EXPLORATION-SATELLITE (PASSIVE) SERVICES IN THE BAND 50.2 - 66 GHz

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Sharing between the Fixed and Earth Exploration-Satellite (passive) Services in the band 50.2 - 66 GHz

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1 EXECUTIVE SUMMARY

This report presents the results of the study on sharing between the Fixed Service (FS) and passive sensors of the Earth Exploration-Satellite (passive) Service (EESS) in the frequency band 50.2 - 66 GHz. The study has been focused on the bands 50.2 - 50.4 GHz and 54.25 - 58.2 GHz, which are allocated on a co-primary basis in the Radio Regulations.

The report gives the background on why these two services require allocations in this part of the spectrum. It also investigates the required protection criteria for the EESS and the operating requirements for the FS.

The findings are that sharing is possible at frequencies above 55.78 GHz. At frequencies between 54.67 - 55.78 GHz sharing would be possible with varying degrees of restrictions on the FS. Below 54.67 GHz, sharing is totally impracticable within the 15 MHz bandwidth of a push-broom sensor channel. The following should be noted about these conclusions:

- the calculations have been based on the need to protect cross-track push-broom sensors, which are expected to be brought into service soon after 2005; the current generation of passive sensors require less stringent restrictions on the FS,

- a number of indirect propagation mechanisms have been identified, but the impact of these could not be firmly established; the conclusions are based on the impact of the direct propagation mechanism, with the preliminary assumption that the interference caused by other mechanisms would be accepted by the remote sensors,

- fixed links are assumed to be located at an altitude of 0 km above sea level (asl); for areas more than 500 m asl, the restrictions on the FS are tightened further,

- the protection criteria of Recommendation ITU-R SA.1029 include a provision that the specified interference threshold could be exceeded for up to 5% of measurement cells; since the interpretation of this provision is unclear, SE20 could not implement it; furthermore, the provision was found unacceptable to the EESS experts in SE20; it is recommended that ITU SG 7 study this issue; sharing studies to date have assumed that the interference threshold will not be exceeded in any measurement cell.

A further study focussing on the band 55.22 - 55.78 GHz can be found in ERC Report 46.

2 INTRODUCTION

This report addresses the feasibility of sharing between the Fixed Service and the Earth Exploration-Satellite (passive) Service in the frequency range 50.2 - 66 GHz. The ERC has previously published two reports on this subject: ERC Report 17 on the band 57.2 - 58.2 GHz and ERC Report 19 on the band 54.25 - 57.2 GHz. In summary, the conclusions of these reports are that in the upper band sharing presents no problem, whereas in the lower band interference from fixed links to passive sensor satellites may occur, but these can be avoided through coordination or restrictions on the fixed links. However, some concerns were expressed that these reports were not complete, and in order to get a fuller understanding of the sharing conditions, the following topics were identified for further study:

* the reasons that these two services have to use shared bands
* the parameters assumed for the sensors
* the range of parameters possible for the FS
* the extent of the problem area within the band
* coordination methods
* the expected interference from in-direct propagation mechanisms
* cost implications of changing the frequency for FS and EESS
* satellite visibility statistics.

Further detailed study of the band 55.22 - 55.78 GHz can be found in ERC Report 46.

3 ALLOCATIONS

In the frequency range 50.2 - 66 GHz there are two sub-bands where the FS and the EESS have co-primary allocations in the Radio Regulations. These are:

* 50.2 - 50.4 GHz
* 54.25 - 58.2 GHz

CEPT Recommendation T/R 22-03 divides the band 54.25 - 58.2 GHz into two parts: 54.25 - 57.2 GHz is to be used for local connections and supporting infrastructure for large-scale mobile networks and 57.2 - 58.2 GHz is intended for low-power, short-range systems.

3.1 Use by the EESS

3.1.1 Why microwave sounding around 60 GHz?

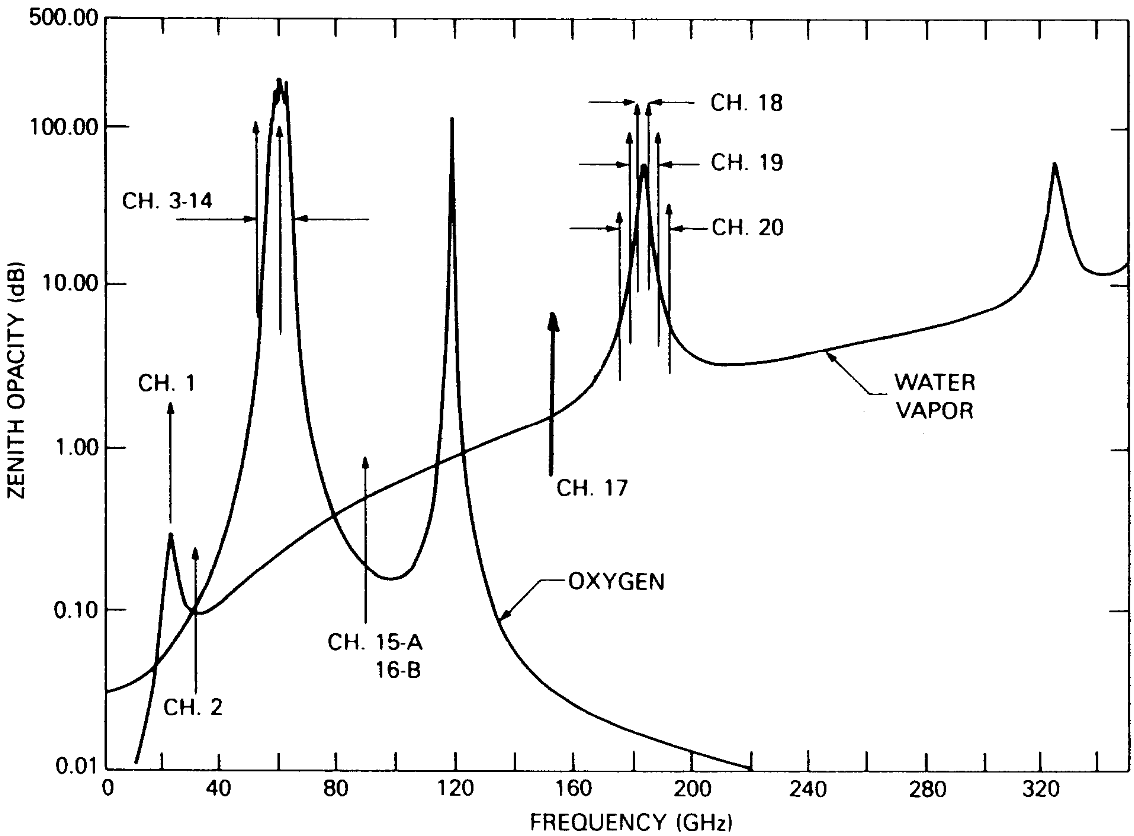

Figure 1: Zenith atmospheric opacity due to oxygen and water vapour

Atmospheric temperature profiles are amongst the essential parameters which are routinely used by meteorological services for **operational weather forecasting**, and by the scientific community involved in **climate and environmental monitoring studies**. These applications do not generate direct commercial return. However, they have an important impact on all economic activities, and contribute heavily to human welfare and life conservation.

Atmospheric temperature profiles are currently obtained from spaceborne sounding instruments working in the infrared spectrum and in the **microwave spectrum (including oxygen absorption around 60 GHz)**.

As compared to IR techniques, the **all-weather capability** (the ability for a spaceborne sensor to "see" through most clouds) is probably the most important feature that is offered by microwave techniques.

This is fundamental for operational weather forecasting and atmospheric science applications, because more than 60% of the Earth's surface, on average, is totally obscured by clouds, and only 5% of any 20x20 km spot (corresponding to the typical spatial resolution of the IR sounders) is completely cloud-free. This situation severely hampers operations of IR sounders, which have very little or no access to large, meteorologically active regions.

The next O_2 absorption spectrum around 118 GHz has a lower potential due to its particular structure (monochromatic, as compared to the rich multi-line structure around 60 GHz) and is more heavily affected by the attenuation caused by atmospheric humidity, as it is shown on Figure 1. It appears that **the 50/70 GHz band offers a unique possibility to perform all-weather measurements** of the vertical atmospheric temperature profiles from a satellite's orbit.

3.1.2 Why the lower slope

The lower slope of the 60 GHz absorption peak is preferred over the upper slope, since the water vapour absorption is greater on the upper slope. This results in sharper weighting functions at the lower slope, and thus better all weather capabilities.

3.1.3 *Current plans and instrumentation*

Since 1978, the Earth Exploration-Satellite Service has used sections of the 50.2 - 58.2 GHz band for passive microwave sounding of the atmosphere. These measurements are provided by the *Microwave Sounding Unit (MSU)* instrument which is flown on the operational series of polar-orbiting weather satellites operated by NOAA. MSU is a 4 channel radiometer (see Table 1 for channel characteristics) with two channels in the frequency band under discussion (at 54.76 - 55.16 GHz and 57.75 - 58.15 GHz).

On the basis of experience gained with the MSU data, NOAA is going to upgrade the microwave sounding capability on its operational polar-orbiting satellites, expected in 1996. This capability will be provided by two new instruments: the *Advanced Microwave Sounding Unit - A* (AMSU-A), for determining atmospheric temperature profiles, and the *Advanced Microwave Sounding Unit - B* (AMSU-B), for determining atmospheric water vapour profiles. Together, these two instruments have 20 microwave channels, of which 9 AMSU-A channels fall within the 54.25 - 58.2 GHz band and one in the 50.2 - 50.4 GHz band.

Channel	Frequency (GHz)	Bandwidth (MHz)	NE T (K)
1	50.3	± 200	0.21
2	53.74	± 200	0.22
3	54.96	± 200	0.18
4	57.95	± 200	0.21

Table 1: MSU channel characteristics

The channel characteristics of these instruments are given in Tables 2 and 3 respectively.
Figure 1 shows the atmospheric attenuation at microwave frequencies due to oxygen and water vapour together with the 20 AMSU channel positions
Further upgrading of the microwave sounding capability will be achieved (in the 2005 timeframe) by the addition of "stratospheric" channels in the frequency range 60.4 - 61.2 GHz. Such channels will increase the maximum height at which the atmospheric temperature is retrieved from approximately 45 km to approximately 70 km. This technique relies on a special interaction between the Earth's magnetic field and particular O_2 absorption lines (Zeeman splitting).

Channel	Frequency (GHz)	Bandwidth (MHz)	NE T (K)
1	23.8	± 135	0.2
2	31.4	± 90	0.2
3	50.3	± 90	0.3
4	52.8	± 200	0.2
5	53.596	± 200	0.2
6	54.4	± 200	0.2
7	54.94	± 200	0.2
8	55.5	± 165	0.2
9-14	57.290344	± 390	0.2
15	89	± 3000	0.5
Additional stratospheric channels on upgraded AMSU-A			
-	60.79267	± 361	1.5

Table 2: AMSU-A channel characteristics

The service provided by the MSU instrument is likely to continue until the end of 1997.

The first flight of the AMSU-A and AMSU-B instruments, on NOAA-K, is currently scheduled for 1995. They will be operated continuously until about 2005, before being replaced with new improved instruments on a converged series of US polar satellites.

Channel	Frequency (GHz)	Bandwidth (MHz)	NE T (K)
16	89	± 1500	0.3
17	150	± 1500	0.6
18a	182.311	± 250	0.6
18b	184.311	± 250	0.6
19a	180.311	± 500	0.6
19b	186.311	± 500	0.6
20a	176.311	± 1100	0.6
20b	190.311	± 1100	0.0

Table 3: AMSU-B channel characteristics

The following other microwave sounding instruments must also be mentioned:

- The *SSM/T* (Special Sensor Microwave/Temperature) has 7 channels (50.5 to 58.4 GHz), and is currently operated on the US defense meteorological polar satellites DMSP.

- The *SSMIS* is a new sensor under development for the DMSP series. It integrates into one unique instrument microwave channels previously distributed amongst three distinct sensors: *SSM/I* (surface sensing), *SSM/T* (atmospheric temperature profiles), and *SSM/H* (atmospheric humidity profiles). In particular, *SSMIS* has 13 channels within 50-61 GHz, and 3 channels around 183 GHz.

- The *MTZA* is a 10-channel (52 to 57 GHz) temperature sounder, which will be flown on the Russian METEOR-3M (from 1996 onwards).

3.1.4 Operations of the microwave temperature sounders

A network composed of two NOAA operational environmental satellites carrying identical payloads (Vis/IR imagers, IR and MW sounders...), is currently being maintained and operated for the benefit of the whole international meteorological and scientific communities.

Meteorological sensors have a wide field of view enabling each of them to yield two complete coverages per day of the Earth and of its atmosphere.

The two satellites are in co-ordinated "morning" (around 7.30 a.m local time at equator's crossing) and "afternoon" (around 1.30 p.m local time) sun-synchronous orbits respectively, in such a way that an almost 6-hourly repeat cycle is achieved by the network (4 global coverages daily, for each type of sensor).

Instruments are operated permanently. Besides the real time data dissemination to regional or local users, global data are stored on board the satellites, and dumped at regular intervals over a limited number of central ground data acquisition stations at selected geographical positions in order to avoid losing any data. Typically, each user station can acquire real-time data four times a day, during up to three successive satellite passages, depending on latitude.

From around 2000 onwards Europe, through EUMETSAT and ESA, will assume responsibility for the "morning" orbit service. The European METOP satellite will occupy the "morning" orbit position (probably with a slightly later local time at equator's crossing), and will replace the corresponding NOAA satellite which will be discontinued. The remaining "afternoon" NOAA satellite and the "morning" METOP satellite will continue to carry essentially identical meteorological core instruments.

In the long term, it can be anticipated that other meteorological satellites carrying similar instruments, for instance the Russian METEOR-3M, will be integrated into this network. This is going to improve the number of observations per day, and local times at equator's crossing will be adjusted accordingly.

3.1.5 Anticipated performance improvements

The need for improvements in the fields of climate understanding and modelling and weather forecast reliability and resolution, the further scientific expertise which will be gained through utilization of AMSU-A data, and the technological advances which can be anticipated in the fields of antenna and microwave technology, will render possible further enhancements of microwave sounders, in particular

- optimized selection of channel frequencies,
- improved radiometric and geometric resolution,
- improved vertical resolution.

This is a usual and unavoidable iterative practice in the field of instrument design for sensing complex geophysical parameters from a satellite's orbit, where improvements of instrument performance and scientific expertise are going along two parallel paths in a kind of "push-pull" process.

The following assumptions were made, which introduce technological improvements **as they can be anticipated now**, but which cannot be considered as absolute limits:

- Adoption of **microwave low-noise pre-amplifiers** based, for instance, on HEMT's (High Electronic Mobility Transistors). A receiver noise figure of 3dB can be expected. The receiver contribution to the system noise temperature Ts is then 300K.

- Adoption of a radiometer lay-out which enables **full optimization of the integration time t** (for instance a "push-broom" technique). Optimum **t** is taken as the full time that is necessary for the satellite to travel across the dimension of a pixel: therefore, **t** is directly proportional to the pixel's size and inversely proportional to the satellite velocity. For instance τ=1s for a 7 km pixel (satellite velocity typically around 7 km/s).

- The **improvement potential** which can be achieved by using these techniques will be optimally distributed amongst the parameters which characterize the performance of the instrument (ref.§4.1) in a way which is difficult to appreciate to-day, but which is likely to improve the vertical resolution (**sharper weighting functions and increased number of channels**, thus following the continuous improvement process of numerical weather forecast models), and the horizontal resolution.

This improved ("push-broom") sensor was introduced in 1993, in the ITU documentation. A sample of the achievable performances (as an example), and the permissible interference levels are presented in Recommendations ITU-R SA.515-2, ITU-R SA.1028, and ITU-R SA.1029 respectively, for the scanning sounder and for the "push-broom" sounder.

3.2 Rationale behind the choice of the band 54.25 - 58.2 GHz for the Fixed Service

- Congestion of the spectrum: fixed services are already using a certain amount of the spectrum below 50 GHz. Some new services are foreseen in the near future, for which the infrastruture is very dense and which have to be deployed in very short periods of time. This is only achievable by using fixed links. The Fixed Service bands below 50 GHz are used more and more for other services (like the Mobile Service) because of technical characteristics. All of these arguments lead to the need to find more and more bands for the fixed service higher in the spectrum (it is not an obligation to have exclusive bands for fixed services, sharing studies have to be made to enforce spectrum efficiency).

- Propagation characteristics: the propagation characteristics have two impacts. The first is the length of the link, the second is the reuse of the frequencies. The propagation characteristics of the 54.25-58.2 GHz band are ideally suited to short range links. The anticipated developments in large-scale mobile networks -PCN, or other networks based on micro cells- will require large numbers of links for the supporting infrastructure. The propagation characteristics of the 54.25-58.2 GHz band give the possibility for reuse of frequencies a large number of times in an area corresponding to a network coverage area. These physical characteristics (length of hop and reuse of frequencies) are only available around the oxygen absorption lines.

- Shape of oxygen absorption curve: in the lower part of the oxygen absorption peak (below 60 GHz) the curve presents a flatter slope compared to the upper part slope. Taking into account that duplex operation is necessary for the envisaged infrastructure, that the minimum duplex separation economically achievable is within the range 1 - 1.5 GHz, that due to the duplex separation a tranche of 2 - 3 GHz band is necessary for one plan, that the propagation between the lower and the upper part of the channelling plan has to differ as little as possible, the flatter slope of the curve is more convenient.

- Medium and long term view: in 1990, the CEPT produced a Recommendation (T/R 22-03) giving some guidance for the use of the frequency range 54.25-66 GHz. This long-term objective has already been used by industry and standardization bodies to develop components, sets or standards to such a level that it is impossible to change the frequency bands without losing years of work and large investments of money (ETSI is going to finalise ETS 300 407 (around 55 GHz) and ETS 300 408 (around 58 GHz)).

4 SHARING PARAMETERS

4.1 Parameters for the passive sensors

4.1.1 Description of the principles of microwave sounding

Sounders are designed to accurately measure atmospheric parameters, and to optimize to the best vertical and horizontal sampling of the atmosphere on a global basis. Their performances are characterized by the following main parameters:

- The **ground resolution** (the "pixel", or the elementary measurement cell) which depends on antenna aperture and on altitude. The pixel is typically the 3dB footprint of the antenna.

- The **vertical resolution** (represented by the sharpness of the weighting functions), which depends in particular on the channel bandwidth B(Hz),

- The **radiometric resolution** ΔTe(K) represents the smallest scene temperature variation that the radiometer can detect. It is expressed by the following equation (for a total-power radiometer):

$$\Delta Te = \frac{Ts}{\sqrt{Bt}}$$

Where:

* Ts(K) is the radiometer system noise temperature, which includes the receiver temperature and the antenna contribution. The antenna contribution itself is essentially the **temperature of the scene** as seen by the main lobe of the antenna,
* B(Hz) is the receiver (channel) bandwidth,
* τ(s) is the **integration time**, during which the elementary measurement cell is "seen" by the radiometer.

- The radiometer threshold Δp(W), the smallest power variation that the instrument is able to detect, is expressed by the equation:

$$\Delta p = k\Delta TeB$$

Where $k=1.38x10^{-23}$ J/K is the Boltzmann constant.

Note 1: The integration time t allocated to each pixel is an important parameter. It depends basically on the **size of the pixel**, on the **velocity of the satellite**, and because the instrument has to sample a great number of pixels within a scanning line (cross-track or conical about nadir), on the **efficiency** of the scanning. The scanning efficiency is **lower** if the pixels in a line are sampled **in sequence** (case of a mechanically scanned sensor); it is **higher** if all pixels in a line are sampled simultaneously (case of a "push-broom" type instrument).

Note 2: The design of the instrument must realize a difficult trade-off between **radiometric resolution** (requiring a **wide** channel bandwidth), and **vertical resolution** (requiring a **narrow** channel bandwidth). On AMSU-A, this difficulty is overcome at the expense of hardware complexity in the following way:
Some channels are built with the sum of up to **4 narrow-band sub-channels** carefully selected at, ideally, **almost identical absorption levels** of the O_2 spectrum, on the slopes of neighbouring absorption peaks.

4.1.2 Comparison between cross-track and conical push-broom sensors

For the push-broom instrument, two configurations can be envisaged:

- cross-track viewing in a plane normal to the satellite sub-track, extending ±50° on each side of the nadir direction;

- conical wiewing around the nadir direction, providing a constant incidence angle of about 53° at the level of the ground, corresponding to about 45° with respect to the nadir direction at the level of the satellite.

The conical viewing instrument has advantages in the domain of data processing. However, it provides uniformly degraded data due to the high (constant) incidence angle. In addition, the swath width is limited by the geometry.

The cross-track viewing instrument provides on average better soundings and has a wider swath, thus achieving global coverage. Therefore a cross-track viewing push-broom instrument is preferred.

It is expected to develop such an instrument within about 10 years.

4.1.3 Interference threshold

Recommendation ITU-R SA.1029 gives interference criteria for passive remote sensing. It defines the harmful interference level at the input of the radiometer, P_h (W), as

$$P_h = 0.2k\Delta T_e B$$

Based on the performance criteria given in Recommendation ITU-R SA.1028 this gives the interference threshold, in the reference bandwidth 100 MHz:

* -161 dBW for a scanning sensor
* -166 dBW for a push-broom sensor

4.1.4 Other sensor parameters

A number of other parameters are needed for the sharing analysis. Typical values are given below for present and future sounders.

	Mechanical scanning	**Push-broom**
Interference threshold	-161 dBW/100 MHz	-166 dBW/100 MHz
Bandwidth	400 MHz	15 MHz
Integration time	0.2 s	2.45 s
Antenna diameter	15 cm	45 cm
IFOV 3dB points	3.3°	1.1°
Cross-track width	+/- 50°	+/- 50°
Antenna gain	36 dBi	45 dBi
Side lobes	- 10 dBi	-10 dBi
Beam efficiency	> 95%	> 95 %
Radiometric resolution	0.3 K	0.1 K
Swath width	2300 km	2300 km
Pixel size (nadir)	49 km	16 km
Number of pixels/line	30	90
Orbit altitude (circular)	850 km	850 km
Orbit inclination (sun-synchronism)	98.8 °	98.8 °
Year in service	1995	>2005

It should be noted that the push-broom sensor described above is not yet developed and thus the parameters described will be subject to review and possible alteration, taking advantage in particular of the experience gained through the exploitation of AMSU-A data.

4.2 Parameters for the fixed links

The important parameters for the sharing analysis are output power, antenna pattern, elevation angle, altitude and density of links.

prETS 300 407 for the band 54.25 - 57.2 GHz specifies a maximum output power of 1 W and two alternative antenna patterns: a standard pattern with 3 dBi far sidelobe gain and a high performance antenna with -10 dBi far sidelobe gain. prETS 300 408 for the band 57.2 - 58.2 GHz specifies a maximum output power of 10 mW and a maximum EIRP of 15 dBW. The maximum output power that is achievable with today's technology is around 0.1 W. Equipment operating in these bands are typically using output powers around -16 dBW. Future equipment can be expected to use high performance antennas.

Typical elevation angles for these types of links will be very close to 0°.

Channel plans for these bands are given by draft new ITU-R Recommendation F.1100. The bandwidths range from 14

MHz to 140 MHz.

Most fixed link locations will be at close to 0 km altitude. However, there are some large cities at higher altitudes.

4.3 Propagation

Interference from fixed links to passive sensors can be caused through different propagation mechanisms. The following mechanisms have been identified.

* direct coupling
* reflections from roof tops
* scattering from vertical surfaces
* rain scattering
* tropospheric scattering
* re-radiation.

For all mechanisms the oxygen absorption plays an important part. Since this changes dramatically over the frequency band under consideration, the band is split into nine sub-bands, and calculations are carried out at the absorption minima (valley) of each sub-band. The oxygen absorption on the zenith path for each sub-band is given below in Table 4.

Slot no.	Frequency band (GHz)	Valley frequency (GHz)	Oxygen absorption from 0 km (dB)	Oxygen absorption from 1 km (dB)
1	50.2 - 50.4	502	16	13
2	54.25 - 54.671	5425	153	128
3	54.671 - 55.221	5474	237	203
4	55.221 - 55.784	5531	370	322
5	55.784 - 56.255	5589	574	509
6	56.255 - 56.363	5629	864	785
7	56.363 - 56.968	5657	802	715
8	56.968 - 57.2	5719	988	883
9	57.2 - 58.2	5729	977	872

Table 4: Zenith oxygen absorption for specific sub-bands in the range 50-60 GHz

5 SHARING ANALYSIS

5.1 Interference through direct coupling

5.1.1 Calculation of critical elevation

As the satellite orbits the Earth, its sensor antenna scans in the plane perpendicular to the satellite velocity - known as "crosstrack" scanning. Thus, the satellite sensor cuts a swath either side of the sub-satellite path (see Figure 2).

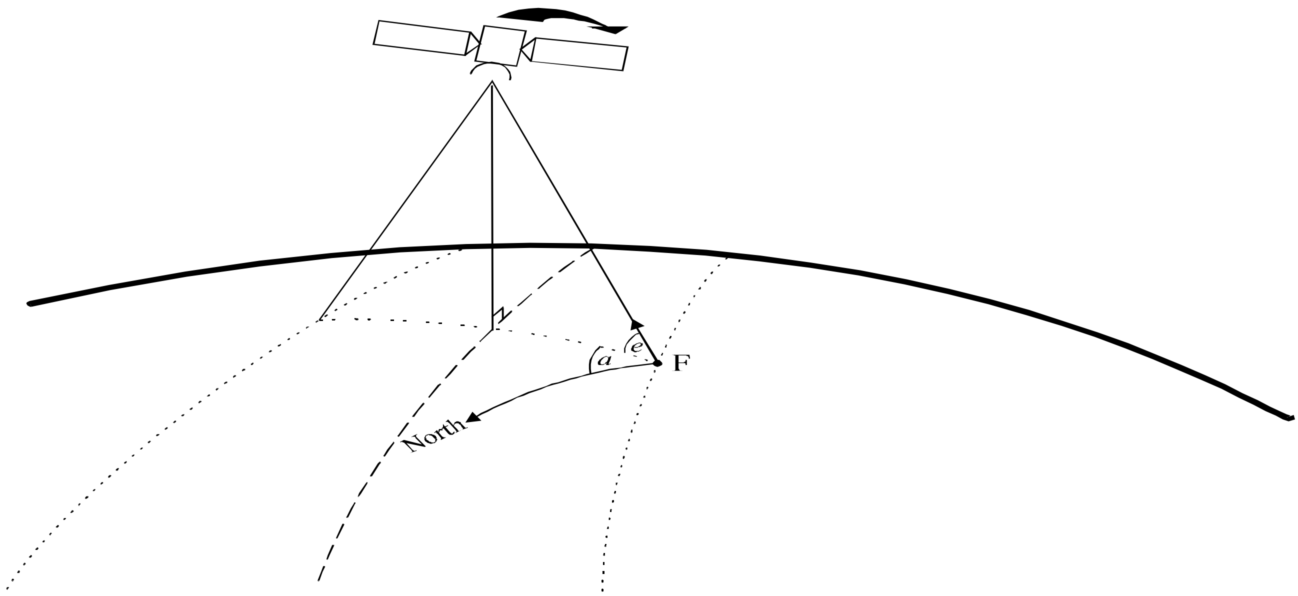

Figure 2: Relationship between satellite sensor and Fixed Service transmitter

Consider a fixed link transmitter at point F. The transmitting antenna is raised to elevation angle *e*° and is aligned on azimuth *a*° east of north. As the satellite passes and the sensor scans to its limit, the sensor antenna and the fixed link antenna are aligned boresight-to-boresight and a high level of interference can be received. If the fixed link was aligned to a different azimuth *or* a lower elevation, boresight-boresight alignment could not occur. When planning a fixed link it may be necessary to avoid the combination of this "critical azimuth" and "critical elevation".

This section describes a method to determine the critical elevation.

The geometry is shown in Figure 3.

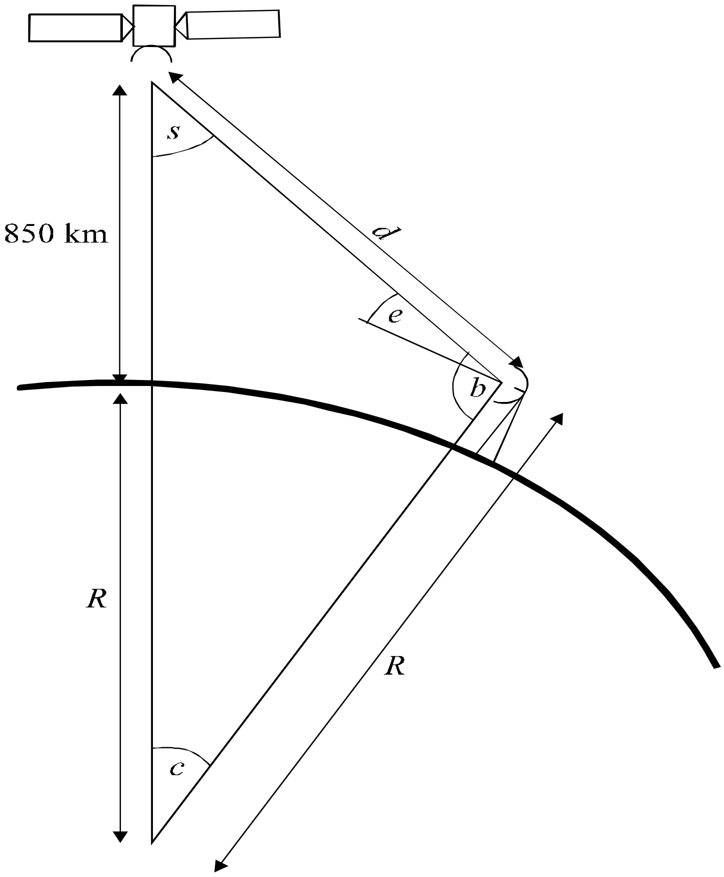

Figure 3: Geometrical relationship between satellite and Fixed Service transmitter

The maximum scan angle *s* is 50° and the satellite is at an altitude of 850 km. The Earth radius *R* is taken as 6376 km.

$$c = 180 - 50 - b = 10.2°$$
$$d = \frac{R \sin c}{\sin s} = 1474 \text{ km}$$

The critical elevation angle *e* is thus *b* - 90° = 29.8°.

Any elevation angle below this value will not allow boresight to boresight alignment. Any elevation angle equal to or above this value will allow boresight to boresight coupling only if the transmitting antenna is also on a critical azimuth.

Figure 4 shows a fixed link at 0° elevation causing interference by the zenith/nadir path (a). The same fixed link antenna is then repointed x° from the boresight-to-boresight path (b). Referring to Figure 4, one can ask the question:- Let I_a be the level of interference created on the zenith/nadir path (a). Now referring to the boresight-to-boresight path (b), at how many degrees off boresight-to-boresight alignment (angle x) does the level of interference equal I_a?

One can then conclude that an offset from the boresight-to-boresight path of *greater than* x° means that path (a) is the worst case. Conversely, an offset of *less than* x° means that path (b) is the worst case.

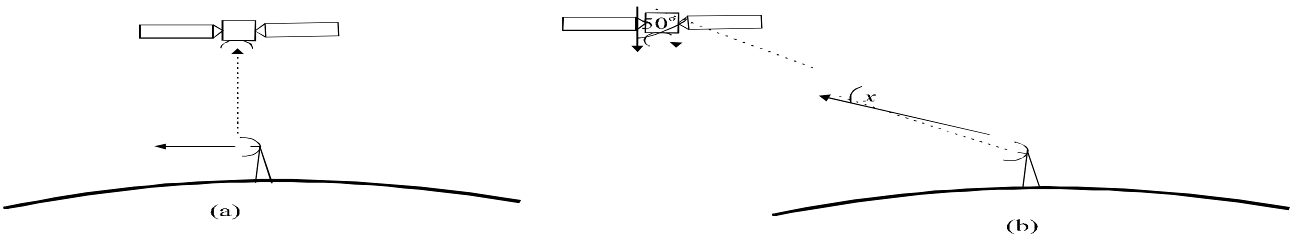

Figure 4: Interference paths between a fixed link and a satellite

The answer to this question depends on: The level of absorption on each path (and hence the frequency) and the fixed link antenna gain off-boresight. Two examples are considered below.

Example 1: 54.25 GHz, High Performance Antenna
In this example the frequency is 54.25 GHz, and the antenna pattern is assumed to conform to Draft prETS 300 407 mask 2B - the high performance mask. The fixed link is assumed to be at sea level and the transmitter power of 0 dBW is assumed. The antenna gain 90° off-boresight is -10 dBi. The free-space-loss for the zenith path is 185.7 dB and the absorption is 15.3 dB. For interference path (b) the figures are 190.3 dB and 30.5 dB respectively.

Thus, the received level of interference for alignments (a) and (b) are

$$I_a = 0 - 10 - 185.7 - 15.3 + 45$$
$$I_a = -166.0 \text{ dBW}$$

and

$$I_b = 0 + G - 190.3 - 30.5 + 45$$
$$I_b = -175.8 + G \text{ dBW}$$

For I_b to exceed I_a, G must exceed (-166.0 - (-175.8) =) 9.8 dBi. Referring to the high performance antenna mask, a gain of 9.8 dBi occurs at approximately 10° off-boresight. Thus we can conclude that such a fixed link with high performance antenna, *if aligned within approximately 10° of a boresight-to-boresight path*, will cause greater interference than the level resulting from the zenith/nadir path.

Thus, at this frequency, a limit of the fixed link elevation angle of (29.8 - 10) ≈ 20° will ensure that the greater interference is always on the zenith/nadir path.

Example 2: 56 GHz, High Performance Antenna
This frequency is again within the band covered by Draft prETS 300 407 and again the high performance antenna is considered. On path (a), free-space-loss is 186.0 dB and absorption is 59 dB. On path (b), free-space loss is 190.6 dB and the absorption is 117.7 dB.

Thus,

$$I_a = 0 - 10 - 186.0 - 59.0 + 45$$
$$I_a = -210 \text{ dBW}$$

and

$$I_b = 0 + G - 190.6 - 117.7 + 45$$
$$I_b = -263.3 + G \text{ dBW}$$

For I_b to exceed I_a, G must exceed (-210 - -263.3 =) 53.3 dBi. To achieve an antenna of this gain would require an unrealistically large antenna (approximately 1m diameter). For frequencies above 56 GHz the oxygen absorption is much greater and the calculated value of G would thus be even greater. Thus, we can conclude that for the band 56 - 58.2 GHz, the worst case interference alignment is *always* the zenith/nadir path and that the boresight-to-boresight path is irrelevant.

We can thus conclude that, for frequencies between 54.25 - 56 GHz, the zenith path will dominate if the elevation angle of the fixed link is below 20°. For frequencies greater than 56 GHz, the zenith path is always the worst case.

5.1.2 Link budget calculations

The interference threshold of §4.1.3 can be converted into maximum acceptable EIRP in the zenith direction. The following formula is used:

$$P_h = \left(\frac{l}{4pR}\right)^2 G_r (EIRP)(Att)$$

Where:

* P_h(w) is the interference threshold at radiometer's input.
* l(m) is the wavelength.
* R(m) is the distance, which is the altitude of the satellite in the "zenith" case.
* G_r is the gain of the radiometer antenna.
* *EIRP*(w) is the total interferer power radiated in the zenith direction.
* *Att* is the total oxygen and water vapour attenuation at the frequency considered.

The maximum acceptable EIRP spectral density (dBW/Hz) is also a useful parameter, because it takes into account possible differences of channel bandwidths.

Calculations are carried out using the parameters given in §4 and the assumptions that the fixed links are at an altitude of 0 km and are using high performance antennas.
The results of the calculations are shown in Tables 5 and 6.

In Tables 5 and 6, the propagation loss is the free space loss. The O_2 absorption ("Att" above) is equal to $-10\log(e^{\tau})$, where τ is the atmospheric opacity.

In order to meet the derived maximum EIRP limit, different combinations of output power and density of links can be used. Some examples are given in Tables 5 and 6.

Since the results in Tables 5 and 6 assume that all fixed terminals are at 0 km altitude, some correction is needed for terminals at significantly higher altitudes. A simple way to account for this would be to allow 3 dB less output power for fixed terminals at altitudes above 500 m. This procedure is expected to ensure that the interference limit is not exceeded for the same maximum density of fixed links at altitudes above 0 km.

It should be noted that fixed links operating in slot 9 may use standard antennas.

5.2 Interference by indirect propagation mechanisms

A number of indirect coupling mechanisms have been identified and listed in §4.3. Peliminary analysis has indicated that the following mechanisms *may* be significant:

- reflection from roof tops,
- reflection from vertical walls,
- rain scatter.

Details are given in Annex 1.

More detailed analysis, involving measurements at around 50 GHz, has yet to be performed. It is anticipated that results of these measurements will enable an estimate of the level and probability of indirect coupling to be made. It is assumed that both the level and probability of indirect interference will be sufficiently low as to be acceptable to the remote sensors. In the meantime, analysis is restricted to direct coupling.

It will be necessary to return to this topic when analysis is complete and when ITU-R SG 7 has re-investigated the interference criteria for passive remote sensors.

6 OTHER CONSIDERATIONS

6.1 Percentages of time and location

Interference thresholds are typically associatied with time and location percentages. The protection criteria of Recommendation ITU-R SA.1029 include a provision that the specified interference threshold could be exceeded for 5% of measurement cells. SE20 discussed the meaning of this provision, in particular the definition of "measurement cells", but were unable to interpret it. Several reservations were expressed by the EESS experts, who find this provision unacceptable but irrelevant to the work of SE20.

The methodology used by SE20 is based on simple link budget calculations. The compatibility criterion has been that the interfering power must not exceed the interference threshold, ie. there is no statistical analysis, and the concept of time/location percentages does not need to be addressed.

This issue should urgently be studied by ITU Study Group 7.

6.2 Fulfilment of the mandate

This report has dealt with most of the issues in the SE20 mandate. However, the questions of cost implications of changing the frequencies for FS and EESS and satellite visibility statistics have not been addressed.

The reason satellite visibility statistics have not been studied is explained by §6.1. The question of cost implications was only to be studied "if required". The group did not feel this was the case.

7 CONCLUSIONS

The analysis in §5 has shown that sharing between the Fixed and Earth Exploration-Satellite (passive) Services is possible in most of the bands allocated on a co-primary basis in the Radio Regulations. However, in some of the sub-bands sharing is not possible or subject to constraints on the part of the Fixed Service. The conclusions are based on the following assumptions:

- protection is given to future cross-track push-broom sensors, which are expected to come into operation around 2005,
- since scanning sensors require less stringent restrictions on the FS (see Table 5), the current and next generation of sensors, eg. AMSU-A, would also be protected,
- high performance antennas are used by the fixed links,
- elevation angles are kept below 20° for fixed links operating below 56 GHz,
- the direct propagation mechanism dominates over the indirect mechanism,.
- interference by indirect mechanisms is acceptable to the passive sensor community.

Fixed services can use the shared bands as long as the EIRP limits derived in Table 5 are met. These limits are expressed as maximum EIRP/pixel. It should be noted that a trade-off can be made between the output power and the density of links. The conclusions slot by slot can be derived by considering likely operational scenarios of the fixed links, eg. it is highly unlikely that more than 50 links within one pixel area (16 km diameter) would be possible.

In slots 1 and 2 (50.2 - 50.4 GHz and 54.25 - 54.67 GHz) sharing is not practicable within the 15 MHz bandwidth of a push-broom sensor channel; the necessary power limitations for fixed links are too severe.

In slot 3 (54.67 - 55.22 GHz) sharing may be possible if a very limited number of fixed link terminals are used; low output powers (around -16 dBW) would probably have to be used.

The necessary restrictions on fixed links in slot 4 (55.22 - 55.78 GHz) would allow the band to be used by the fixed service, especially if low output powers were used. It would also be possible to use higher powers if a trade-off were made with the number of links.

In slots 5 and above the Fixed Service can operate without any risk of causing interference to passive sensors.

Since the push-broom channel bandwidth is only 15 MHz, and a limited number of channels will be used, large parts of the shared bands will not be used by temperature sounders. However, the meteorological community is not able today to commit to specific measurement frequencies. WG FM should consider seeking information from the meteorological community about the specific measurement frequencies needed for temperature sounding. If this information becomes available, fixed links may be so assigned as to avoid use at or near these frequencies.

Only in the event that such a possibility is found after detailed investigation to be unsustainable should WG FM consider possible reallocations of bands to compensate the Fixed Service for the unusable parts of the primary bands specified above. One option might be to allocate parts of the now exclusively passive bands 51.4 - 54.25 GHz, 58.2 - 59 GHz and 64 - 65 GHz to the fixed service. It should be noted, however, that these bands may not be as attractive for the Fixed Service as the now allocated bands, eg. the high oxygen absorption in the band 58.2 - 59 GHz would make this band difficult to use.

It is also recommended that ITU Study Group 7 study the interpretation and implementation of recommends 3 of Rec. SA.1029 which states "that, in shared frequency bands, the interference levels given above can be exceeded for less than 5% of measurement cells, within a sensor's service area in the case where the interference occurs randomly and for less than 1% of measurement cells in the case the interference occurs systematically at same locations".

Fixed terminal max.EIRP to zenith (dBW)								
Output power 0 dBW		-10	-10	-10	-10	-10	-10	-10
Output power -16 dBW		-26	-26	-26	-26	-26	-26	-26
Frequency slots (GHz)	50.2-50.4	54.25-54.67	54.67-55.22	55.22-55.78	55.78-56.26	56.26-56.36	56.36-56.96	56.96-57.2
Slot n°	1	2	3	4	5	6	7	8
Center frequency (GHz)	50.3	54.25	54.74	55.31	55.89	56.29	56.57	57.19
Wavelength (cm)	0.596	0.553	0.548	0.542	0.537	0.533	0.530	0.525
Altitude (km)	850	850	850	850	850	850	850	850
Propagation loss (dB)	-185.1	-185.7	-185.8	-185.9	-186.0	-186.0	-186.1	-186.2
System noise temp. (K)	550	550	550	550	550	550	550	550
O2 absorp.0 km init. (dB)	-1.6	-15.3	-23.7	-37.0	-57.4	-86.4	-80.2	-98.8
Nadir pixel diameter (km)	16	16	16	16	16	16	16	16
Integration time (s)	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45
Antenna gain (dBi)	45	45	45	45	45	45	45	45
Channel bandwidth (MHz)	15	15	15	15	15	15	15	15
Radiation sensitivity (K)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Radiation threshold (dBW)	-167.3	-167.3	-167.3	-167.3	-167.3	-167.3	-167.3	-167.3
Interference threshold in Channel bw (dBW)	-174.3	-174.3	-174.3	-174.3	-174.3	-174.3	-174.3	-174.3
Interference threshold in 100 MHz ref bw (dBW)	-166.0	-166.0	-166.0	-166.0	-166.0	-166.0	-166.0	-166.0
Interference spectral density (dBW/Hz)	-246.0	-246.0	-246.0	-246.0	-246.0	-246.0	-246.0	-246.0
Max EIRP in EES channel bw (dBW/pxl)	-33.0	-18.7	-10.2	3.2	23.7	52.7	46.6	65.3
Max EIRP spectral density (dBW/Hz)	-104.8	-90.5	-82.0	-68.6	-48.1	-19.1	-25.2	-6.5
Max number of terminals/pixel								
Output power 0 dBW, 14 MHz channel bw		0	1	19	2187	1737979	426928	31392236
Output power 0 dBW, 140 MHz channel bw		1	9	194	21870	17379791	4269278	313922363
Output power -16 dBW, 14 MHz channel bw		5	35	772	87066	69190196	16996301	1249747437
Output power -16 dBW, 140 MHz channel bw		50	353	7723	870663	691901957	169963012	12497474371

Table 5: Interference link budgets for push-broom microwave sounders

Fixed terminal max.EIRP to zenith (dBW)								
Output power 0 dBW		-10	-10	-10	-10	-10	-10	-10
Output power -16 dBW		-26	-26	-26	-26	-26	-26	-26
Frequency slots (GHz)	50.2-50.4	54.25-54.67	54.67-55.22	55.22-55.78	55.78-56.26	56.26-56.36	56.36-56.96	56.96-57.2
Slot n°	1	2	3	4	5	6	7	8
Center frequency (GHz)	50.3	54.25	54.74	55.31	55.89	56.29	56.57	57,19
Wavelength (cm)	0.596	0.553	0.548	0.542	0.537	0.533	0.530	0.525
Altitude (km)	850	850	850	850	850	850	850	850
Propagation loss (dB)	-185.1	-185.7	-185.8	-185.9	-186.0	-186.0	-186.1	-186.2
System noise temp. (K)	2300	2300	2300	2300	2300	2300	2300	2300
O2 absorp.0 km init. (dB)	-1.6	-15.3	-23.7	-37.0	-57.4	-86.4	-80.2	-98.8
Nadir pixel diameter (km)	49	49	49	49	49	49	49	49
Integration time (s)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Antenna gain (dBi)	36	36	36	36	36	36	36	36
Channel bandwidth (MHz)	400	400	400	400	400	400	400	400
Radiation sensitivity (K)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Radiation threshold (dBW)	-148.5	-148.5	-148.5	-148.5	-148.5	-148.5	-148.5	-148.5
Interference threshold in channel bw (dBW)	-155.5	-155.5	-155.5	-155.5	-155.5	-155.5	-155.5	-155.5
Interference threshold in 100 MHz ref bw (dBW)	-161.5	-161.5	-161.5	-161.5	-161.5	-161.5	-161.5	-161.5
Interference spectral density (dBW/Hz)	-241.5	-241.5	-241.5	-241.5	-241.5	-241.5	-241.5	-241.5
Max EIRP in EES channel bw (dBW/pxl):	-4.5	9.8	18.3	31.7	52.2	81.2	75.1	93.8
Max EIRP spectral density (dBW/Hz):	-90.5	-76.3	-67.8	-54.4	-33.8	-4.8	-10.9	7.7
Max number of terminals/pixel								
Output power 0 dBW, 14 MHz channel bw		3	23	514	57927	46033758	11308013	831484445
Output power 0 dBW, 140 MHz channel bw		33	235	5138	579271	460337583	113080129	8314844450
Output power -16 dBW, 14 MHz channel bw		132	935	20456	2306121	1832636927	450180100	33101991976
Output power -16 dBW, 140 MHz channel bw		1321	9350	204560	23061213	18326369274	4501801001	331019919756

Table 6: Interference link budgets for scanning microwave sounders

Annex 1

Preliminary analysis of indirect propagation mechanisms

A.1 Interference through reflections from roof tops

Although terrestrial link inclinations greater than say 25° can be viewed as unlikely, reflection by surfaces illuminated by a link transmitter is a more probable hazard. The most obvious scenario is reflection from pitched roofs from radiation which spills beyond a link terminal, as illustrated below.

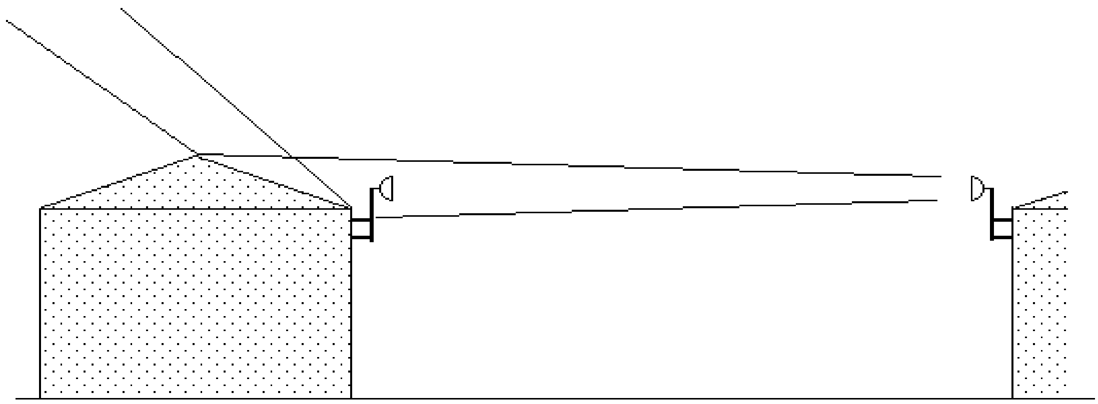

Figure 1: Reflections of fixed link transmissions from a pitched roof

It should be noted that at 50 GHz, even a modest-sized roof will provide an ample Fresnel zone for reflection. The question of reflection coefficient is more variable. A metal roof will in general have a reflection coefficient close to unity, but fortunately such roofs are normally corrugated, reducing the area available for reflection in a given direction. Also, no roof will be truly flat compared with the millimetric wavelength.

Dielectric surfaces also reflect, and glass roofs in particular are likely to be smooth enough to provide good specular reflection. Although it is not clear how representative such figures are for non-metal roofs, calculations of reflection coefficient were run for $\varepsilon = 30$ and $\sigma = 0.001$ S/m:

$i := 1 .. 200 \qquad e := 30 \qquad s := 0.001 \qquad f := 50000$

$d_i := 0.1 \cdot i \qquad a_i := d_i \cdot \frac{\pi}{180} \qquad j := \sqrt{-1} \qquad b := e - j \cdot 18 \cdot 10^9 \cdot \frac{s}{f}$

$sina_i := \sin(a_i) \qquad cosa_i := \cos(a_i) \qquad cos2a_i := cosa_i \cdot cosa_i$

$$Rh_i := \frac{sina_i - \sqrt{b - cos2a_i}}{sina_i + \sqrt{b - cos2a_i}} \qquad RealRh_i := \mathrm{Re}(Rh_i) \qquad ImagRh_i := \mathrm{Im}(Rh_i)$$

$$AmplRh_i := \sqrt{RealRh_i \cdot RealRh_i + ImagRh_i \cdot ImagRh_i}$$

$$Rv_i := \frac{b \cdot sina_i - \sqrt{b - cos2a_i}}{b \cdot sina_i + \sqrt{b - cos2a_i}} \qquad RealRv_i := \mathrm{Re}(Rv_i) \qquad ImagRv_i := \mathrm{Im}(Rv_i)$$

$$AmplRv_i := \sqrt{RealRv_i \cdot RealRv_i + ImagRv_i \cdot ImagRv_i}$$

with the following results for the amplitude of the vertical and horizontally-polarised reflection coefficients:

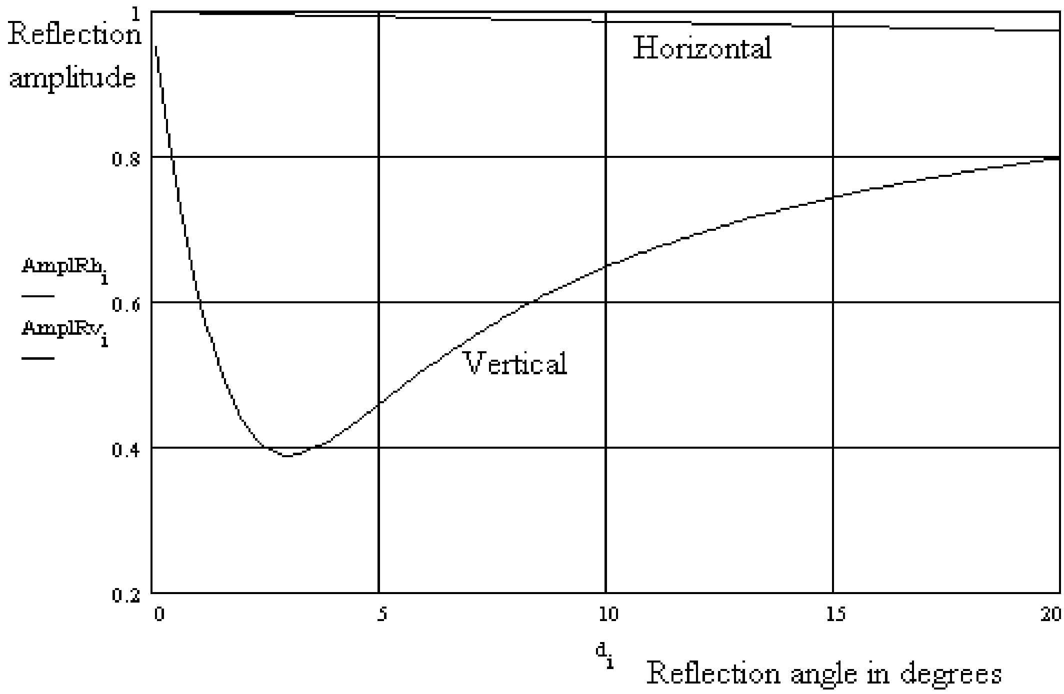

Figure 2: Reflection amplitudes for vertical and horizontally polarised signals

This shows that horizontally-polarised terrestrial links represent a more serious hazard than vertically polarised installations. However, the position of the Bragg-angle minimum for vertical polarisation changes significantly for different values of conductivity, σ, and dielectric roofs will reflect well over certain ranges of small reflection angles.

Not all 50 GHz links will illuminate a suitable surface for reflecting energy upwards at more than 30°, and of those that do, not all will point in the aximuthal direction of the satellite. The following is an attempt to estimate the probabilities involved:

	Probability
Illumination of suitable surface for reflection to a vertical angle of 30° or more. Say 1 link in 20	0.05
Any given azimuthal angle alignment: for terrestrial source with a 2° beamwidth, probability is 2 / 360°	0.005
Thus probability of unfavourable combination: or 1 case in 3,600 links.	0.00025

The overall estimate of risk now depends on the orbital and scanning characteristics of the satellite:

a) The satellite looks at every point of the earth's surface for a particular azimuthal angle and a low vertical angle: in time it will see interference from 1 link in 3,600.

b) The satellite looks at every point for a given azimuth but not necessarily at a low vertical angle: the risk will be less than a), since some links will not have beams reflected to high enough angles to be seen by the satellite;

c) The satellite looks at every point of the earth's surface at a low vertical angle for more than one azimuthal direction: the risk will be greater than a). In particular, if the satellite looks at every point on the ground at reciprocal directions, as seems probable, then the risk is 4 times a), ie., 1 in 900 links.

Many of the offending terrestrial links will illuminate a reflecting roof with only part of the beamwidth. This results in a reflected beam occupying a smaller solid-angle than the original, reducing the probability of intersection with the satellite. The above probabilistic assessment suggests that 1 link in 20 illuminates a roof with its full beam, in practice there would be a spectrum of more or less partial illuminations.

Although in theory both metal and non-metal roofs can provide reflection coefficients close to unity, implying a loss of only a few dB or less, the presence of corrugations and non-flatness will result in substantially less perfect reflections. An estimate is that where the geometry otherwise favours reflection, a net loss due to the reflection process of 5 dB for horizontal polarisation and 10 dB for vertical could be taken as working assumptions. However, since a proportion of this loss will be due to the reflected beam being broken into several near-parallel beams by non-flatness, in practice the beam dispersions due to reflection will make interference more probable, but at a lower level than for perfect reflection. Thus as a broad estimate, based on option c) above, the reflection hazard is estimated as:

Horizontal polarisation: 1 link in 1,000 at 10 dB below main-main coupling;

Vertical polarisation: 1 link in 1,000 at 15 dB below main-main coupling.

The general effect of such reflections will be to produce point-source of interference with pronounced directivity.

A.2 Interference through scattering from vertical surfaces

If one terminal of a 50 GHz fixed link is installed on the vertical wall of a building, or similar structure, diffuse scattering is very likely to occur where the incident energy illuminates it. The surface will approximate to a Lambert surface,

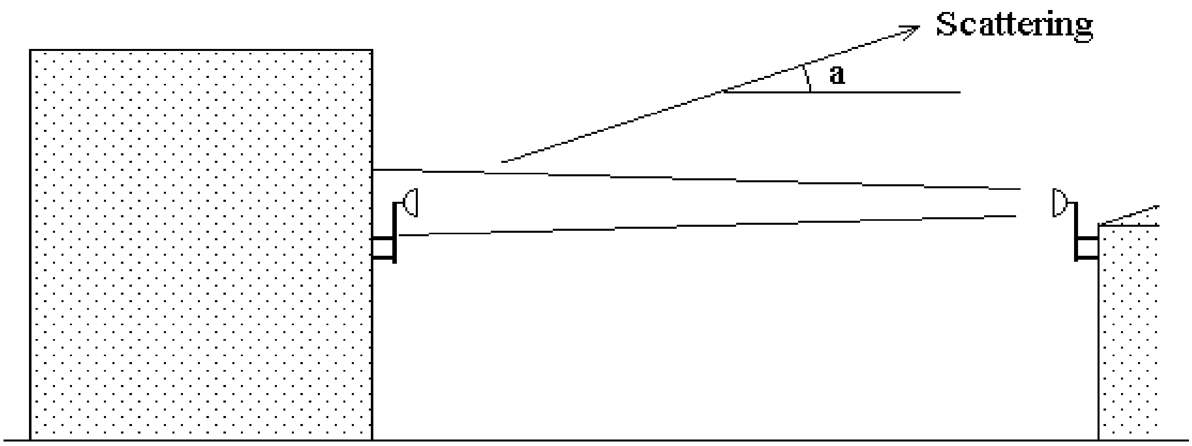

Figure 3: Scattering from vertical surfaces

with a directional component in the scattering proportional to cos (a), as illustrated in Figure 3.

The equivalent EIRP in the direction of the satellite is theoretically given by:

$$\text{EIRP} = 6.0 + W_r + 10.\log(\sigma) + 10.\log\{\cos(a)\} \qquad \text{dB(W)}$$

where:

W_r	=	Total power illuminating the surface in dB(W)
σ	=	Fraction of incident energy scattered

Recent measurements at 38 GHz show a distribution which does not match the above equation.

Little data is available on the proportion of energy scattered by typical building surfaces. Estimating the value as 0.25 for illustration, at an elevation of 30° the equivalent EIRP will be given by:

$$\text{EIRP}_{30} = W_r - 0.6 \text{ dB(W)}$$

Calculations show that an individual link with 1W radiated power can exceed the EIRP limit by about 2 dB, if a suitable vertical surface is illuminated, this surface is not screened by other buildings, and if the azimuthal orientation is appropriate. The nature of the source will be physically small and without pronounced directivity, although the hazard will be greater for more slanting paths, and will reduce for satellite scanning angles approaching the vertical. On the other hand, scattering surfaces are more likely to be screened by other buildings for more slanting paths.

A.3 Interference through rain scattering

To a first order of approximation, rain scattering is isotropic. In fact a minimum occurs at 90° to the original direction, with more scattering at smaller angles, both forwards and backwards. Little data is available at 50 GHz, but the principal rain attenuation mechanism for a fixed link is scattering rather than absorption.

At 50 MHz links will suffer severe rain fades, with fade margins up to 10 dB for 99.9% availability and more for higher-reliability links. At a fade of 10 dB, 90% of the radiated power has been taken out of the main beam, and at 50 GHz, well over half of this will be scattered rather than absorbed, the scattering predominately occuring within 1 km of the transmitter.

Thus the effect of rain scatter will be to turn a 50 GHz horizontal terrestrial link transmitter into an approximately isotropic source, with an absorption loss of perhaps 2 dB. If the radiated power is 1 W, the EIRP becomes approximately -2 dB(W). Calculations show that a single link will be at approximately the level likely to cause interference, particularly for low values of angle A.

However, the scattered energy will suffer further rain absorption. The extent of this depends upon the position of the link in relation to cloud structure. Heavy rain normally falls from a "melting layer", which is a relatively thin horizontal formation of melting ice near the top of the cloud. The melting layer height can vary from almost ground level to several km. Energy scattered from a link just below the melting layer would suffer little further absorption over the slant path to the satellite, although a minimum of several dB would be a safe assumption. For a link several km below the melting layer, significantly more rain absorption will occur.

There will thus be a time variability in this mechanism, varying as the height of the melting layer during rainy weather. In general in temperate climates the melting layer is lowest during the winter. Rain scatter will transform each link into a diffuse source of energy, with a horizontal extent of the order of 1 km, and without pronounced directional effects. For 1W link transmitters each individual link is likely to be from about 4 to about 20 dB below the level necessary to cause interference.

A.4 Interference through tropospheric scattering

Variations in the refractive index of the atmosphere cause scattering which can be exploited to provide communication via transhorizon links. In a deliberate troposcatter link, a relatively large common volume is illuminated, as defined by the beams of the transmitting and receiving antennas.

The mechanism has most effect at small scattering angles. The current ITU-R model for the basic transmission loss for a tropo path, Rec.PN.452-5 Equation (10a), has a term 0.573θ, where θ is the total scattering angle in milliradians. This is equivalent to about 10 dB per degree. To scatter through 30° will thus cause a large excess loss. The effective common volume for a 50 GHz terrestrial link will also be comparatively small. For these reasons it is thought that the mechanism can be neglected.

A.5 Interference through re-radiation

Energy absorbed by the oxygen near the fixed link transmitter is re-radiated. The sensor receives an artificially high level of energy and interprets this as a higher than actual temperature.

This mechanism is difficult to analyse but information received from NOAA suggests that this "should not be a problem".