ECC REPORT 112

Electronic Communications Committee (ECC)
within the European Conference of Postal and Telecommunications Administrations (CEPT)

IMPACT OF UNWANTED EMISSIONS OF IRIDIUM SATELLITES TO RADIOASTRONOMY STATIONS IN THE BAND 1610.6-1613.8 MHZ

Budapest, September 2007

0 EXECUTIVE SUMMARY

This report adresses the compatibility of the IRIDIUM MSS system using the band 1618.25 – 1626.5 MHz and the Radioastronomy service in the band 1610.6 - 1613.8 MHz.

CEPT adressed the issue of unwanted emissions of MSS systems (including IRIDIUM) falling into the RAS band 1610.6-1613.8 MHz in 1997. The results of studies are contained in ERC report 050 (carried out before the implementation of the satellite constellation), which concludes that unwanted emissions of the IRIDIUM MSS satellite constellation may exceed the threshold level of Recommendation ITU-R RA.769 by up to 26 dB (21 dB) at 1613.8 MHz (respectively 1610.6 MHz) for about 20 hours per day.

In 1998, a legal agreement was signed between IRIDIUM and the European Science Foundation (ESF) Committee for Radioastronomy Frequencies (CRAF). This agreement mentions that "From 1 January 2006, European radioastronomers shall be able to collect measurement data consistent with the recommendation ITU-R RA769-1". The compliance with the RA.769-1 levels is unconditional.

Measurements were performed by the monitoring station in Leeheim in November 2006 on the unwanted emissions of IRIDIUM satellites, while they were emitting in the band 1618.25 – 1626.5 MHz. The measurements results were used in a simulation tool to assess the epfd generated in the RAS band and compare it to the RAS protection criteria contained in the relevant ITU-R recommendations.

The measurements performed by Leeheim clearly show that IRIDIUM unwanted emissions in the band 1610.6-1613.8 MHz are highly time-variable, and cannot be directly compared to the protection levels contained in RA.769-2 because of the particular nature of the IRIDIUM system (non-GSO constellation) and signal (TDMA), and the particular mode of observations of RAS stations (integration of the signal received over a large period of time).

The epfd simulation shows that interference averaged over 2000 seconds exceeds the levels of recommendation ITU-R RA.769 at predominantly low elevations, resulting in a loss of data to the RAS. The epfd simulations show that the level of data loss produced in one single 20 kHz channel of the band 1610.6 – 1613.8 MHz at a RAS station located in Europe by the unwanted emissions measured by Leeheim would not exceed a percentage of 0.7%, against the 2% criterion contained in recommendation ITU-R RA.1513.

In radio astronomers view, whenever the epfd criterion is exceeded in one or more frequency channels of 20 kHz, the overall spectral analysis performed over the entire band 1610.6-1613.8 MHz has to be discarded and is therefore considered as data loss. This interpretation would lead to a much larger percentage of data loss than what has been shown in this report.

Another interpretation is that loss of discrete data samples within a channel may not result in a complete loss of the integration period, in cases where less than 2% of samples are corrupted. This would lead to a lower percentage of data loss than is shown in this study.

One of the objectives of the study was to assess the impact of the operations of the IRIDIUM system in the fully extended band 1618.25-1626.5 MHz on the interference generated in the RAS band 1610.6-1613.8 MHz, compared with operations in the core band 1621.35-1626.5 MHz. As the IRIDIUM system was operating over the fully extended band during the period of test, it was not possible to separately assess the unwanted emissions from operation within the core band only. However, while it is possible that additional intermodulation products would fall within the RAS band from the same level of traffic activity when contained within the core band, such operation may still comply with the 2% data loss criterion.

It has to be noted that these measurements addressed the traffic loading of the IRIDIUM system over Europe at the time the measurements were made. It is possible that a higher level of traffic activity may result in more intermodulation products falling within the RAS band, but this was not considered within the study.

Future impact of IRIDIUM operations on the RAS band will have to be monitored as the system develops and the traffic level grows.

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List of Abbreviations

Abbreviation	Explanation
CEPT	European Conference of Postal and Telecommunications Administrations
CRAF	Comitee for Radioastronomy Frequencies
ECC	Electronic Communications Committee
EPFD	Equivalent Power Flux Density
ERO	European Radiocommunication Office
ESF	European Science Foundation
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FSS	Fixed Satellite Service
GSO	Geostationnary Orbit
ITU	International Telecommunications Union
LEO	Low Earth Orbit
MRC	Milestone Review Comittee
MSS	Mobile Satellite Service
NORAD	North American Defense
OH	Hydroxyl
PFD	Power Flux Density
RAS	Radioastronomy Service
SEPFD	Spectral Equivalent Power Flux Density
SPFD	Spectral Power Flux Density
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
WGSE	Working Group Spectrum Engineering

Impact of unwanted emissions of IRIDIUM satellites to radioastronomy stations in the band 1610.6-1613.8 MHz

1 INTRODUCTION

This report adresses the compatibility of the IRIDIUM MSS system using the band 1618.25 – 1626.5 MHz and the Radioastronomy service (RAS) in the band 1610.6 - 1613.8 MHz.

CEPT (WGSE PT28) addressed the issue of unwanted emissions of MSS systems (including IRIDIUM) falling into the RAS band 1610.6-1613.8 MHz in 1997. The results of studies are contained in ERC report 050.

This reports concluded, before the launch of the IRIDIUM system, that:
"

- The unwanted emissions of the IRIDIUM MSS satellite constellation, operating at 1.6 GHz (estimated from simulation up to -215 dBW/(m².Hz) at peak time in the middle of the RAS band, source Motorola) will be 26 dB (21 dB) at 1613.8 MHz (respectively 1610.6 MHz) above the interference threshold (-238 dBW/(m².Hz) as defined by ITU-R Rec. RA.769 for spectrum line measurement) for about 20 hours per day.
- Motorola has indicated several mitigating factors and proposed one mitigation technique which they believe will allow RAS observations to proceed at the sensitivity assumed by ITU-R Rec. RA.769 assuming a total mitigation factor of up to 23.5 dB with only a small loss in observation time. This is disputed by radio astronomers who consider that Motorola's proposals will not apply to all radio telescopes and in all circumstances and could result in a total mitigation factor of less than 8 dB. Real measurements from orbiting IRIDIUM satellites are needed to confirm or deny the conflicting claims. Such tests should be carried out with fully loaded satellite transmitters simulating maximum to minimum traffic conditions."

In 1998, a legal agreement was signed between IRIDIUM and the European Science Foundation (ESF) Committee for Radioastronomy Frequencies (CRAF). This agreement mentions that "From 1 January 2006, European radio astronomers shall be able to collect measurement data consistent with the recommendation ITU-R RA.769-1.", and, in particular, "The interference from the IRIDIUM Satellite System shall not exceed for single dish spectral line observations in the band 1610.6-1613.8 MHz at any time an interference level of –238 dB ($Wm^{-2}\ Hz^{-1}$) in the absence of any alternative solution". The compliance with the RA.769-1 levels is unconditional.

In 2004, the monitoring station in Leeheim made measurements on the IRIDIUM satellite network, and further data and analysis from this campaign was also provided through the European Satellite Monitoring MoU. However, those measurements could not be directly compared to the levels contained in recommendation ITU-R RA.769-1 because of the particular nature of the IRIDIUM system (non-GSO constellation) and signal (TDMA), and the particular mode of observations of RAS stations (integration of the signal received over a large period of time).

In 2005, it was then agreed to use the latest version of recommendation ITU-R RA.769 (RA.769-2) which gives a methodology to adress the specific case of non-GSO constellations based upon the epfd concept. It was also agreed to use the criteria and methodology contained in RA.1513 and M.1583, which were not available when the IRIDIUM-CRAF Agreement was signed. Further measurements were performed by Leeheim in November 2006 on the unwanted emissions of IRIDIUM satellites, while they were emitting in the band 1618.25 – 1626.5 MHz. The measurements results were used in a simulation tool to assess the epfd generated in the RAS band and compare it to the RAS protection criteria contained in the relevant ITU-R recommendations.

This report gives the results of those simulations and assesses the impact of IRIDIUM unwanted emissions on the RAS operations in the band 1610.6-1613.8 MHz.

2 MSS AND RAS FREQUENCY ALLOCATIONS

Allocation to services		
Region 1	**Region 2**	**Region 3**
1 610.6-1 613.8 MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION 5.149 5.341 5.355 5.359 5.363 5.364 5.366 5.367 5.368 5.369 5.371 5.372	**1 610.6-1 613.8** MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION RADIODETERMINATION-SATELLITE (Earth-to-space) 5.149 5.341 5.364 5.366 5.367 5.368 5.370 5.372	**1 610.6-1 613.8** MOBILE-SATELLITE (Earth-to-space) 5.351A RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION Radiodetermination-satellite (Earth-to-space) 5.149 5.341 5.355 5.359 5.364 5.366 5.367 5.368 5.369 5.372
1 613.8-1 626.5 MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION Mobile-satellite (space-to-Earth) 5.347A 5.341 5.355 5.359 5.363 5.364 5.365 5.366 5.367 5.368 5.369 5.371 5.372	**1 613.8-1 626.5** MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION RADIODETERMINATION-SATELLITE (Earth-to-space) Mobile-satellite (space-to-Earth) 5.347A 5.341 5.364 5.365 5.366 5.367 5.368 5.370 5.372	**1 613.8-1 626.5** MOBILE-SATELLITE (Earth-to-space) 5.351A AERONAUTICAL RADIONAVIGATION Mobile-satellite (space-to-Earth) 5.347A Radiodetermination-satellite (Earth-to-space) 5.341 5.355 5.359 5.364 5.365 5.366 5.367 5.368 5.369 5.372

Table 1: Frequency allocations in the band 1 610-1 626.5 MHz

RAS has a **primary** allocation in the band **1610,6-1613,8 MHz**. To this band two footnotes are applicable:

- **5.149** :"….administrations are urged to take all practicable steps to protect the radio astronomy service from harmful interference"
- **5.372** :"Harmful interference shall not be caused to stations of the radio astronomy service using the band 1610.6 - 1613.8 MHz by stations of the radiodetermination-satellite and mobile-satellite services (No.2904/29.13 applies").

IRIDIUM is designed to operate over 10.5 MHz of spectrum in the band between 1616 MHz and 1626.5 MHz.

In the band **1613.8 – 1626.5 MHz**, Mobile-Satellite (Space-to-Earth) has a **secondary** allocation. Resolution 739 (WRC-03) applies to future systems planned for this band.

The IRIDIUM system utilises time division multiple access (TDMA) technology for satellite access, with service link transmission in both directions (i.e. bi-directional TDMA where both the satellite uplink and downlink occupy the same frequency assignment). At launch in 1998, the IRIDIUM system was initially authorised to operate within the band 1621.35 – 1626.5 MHz, but additionally has been authorised in the USA and a number of other countries worldwide to use an extension of 3.1 MHz of spectrum, shared with the GLOBALSTAR system as shown in Figure 1.

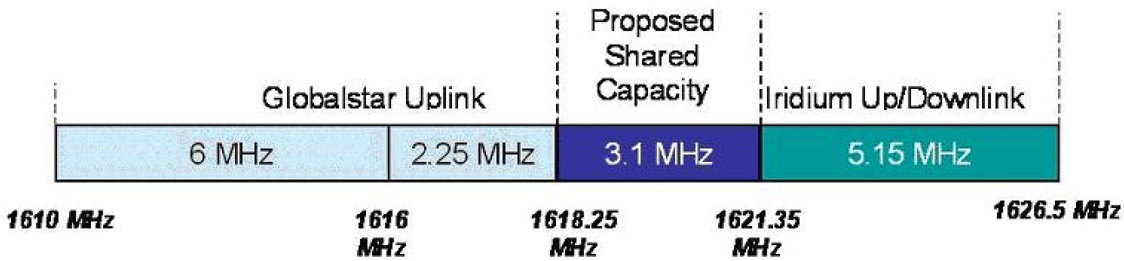

Figure 1: Proposed usage of the MSS allocation between 1610 and 1626.5 MHz

3 RADIOASTRONOMY CHARACTERISTICS AND PROTECTION CRITERIA

3.1 RAS operations in the band 1610.6-1613.8 MHz

The 1 610.6-1 613.8 MHz band is used for spectral line observations of the hydroxyl radical (OH). The OH line, which has a rest frequency of 1 612 MHz, is one of the most important spectral lines for RAS, and is listed as such in Recommendation ITU-R RA.314. OH was the first cosmic radical to be detected at radio frequencies (1963), and continues to be a powerful research tool. OH produces four spectral lines, at frequencies of approximately 1 612, 1 665, 1 667 and 1 720 MHz, all of which have been observed in our own galaxy, as well as in external galaxies. The study of OH lines provides information on a wide range of astronomical phenomena, e.g. the formation of protostars and the evolution of stars. To interpret most observations made in the OH lines, it is necessary to measure the relative strength of several of these lines. Loss of the ability to observe any one of these lines may prevent the study of some classes of physical phenomena.

Spectral line observations are made using spectrometers that can simultaneously integrate the power in each of a large number of frequency channels (typically 256-4 096) distributed across the frequency band used. The width and number of channels has to be large enough to accurately reproduce the spectrum of the emission received by the radio telescope. Instantaneous bandwidths of typically ~0.2-20 kHz per frequency channel are used, depending on the scientific program.

Observations in the 1 612 MHz band are carried out at a number of RAS sites in numerous countries, worldwide. Observations in the 1 612 MHz band are sometimes conducted on targets of opportunity, e.g. on objects such as comets, which have been observed to produce transient emissions in this line.

3.2 Protection criteria of RAS

Recommendation ITU-R RA.769 specifies the protection criteria for radio astronomical observations and gives threshold levels of detrimental interference for primary RAS bands. In the 1 610.6-1 613.8 MHz band, for single-dish spectral line observations made using a channel bandwidth (one of the spectrometer channels) of 20 kHz, the threshold pfd limit is –194 dB(W/m^2) per 20 kHz. This assumes a 0 dBi antenna gain and an integration time of 2000 seconds for the RAS station. This band is used only for spectral line observations, not for continuum observations.

For detrimental interference from non-GSO systems, the protection criteria and the relevant methodologies are described in Recommendations ITU-R RA.769-2 and ITU-R RA.1513-1, as well as in Recommendation ITU-R S.1586 for FSS systems and in Recommendation ITU-R M.1583 for MSS and RNSS systems. In particular, an epfd threshold of -258 dB(W/m^2) per 20 kHz may be derived from the threshold pfd level considering a maximum antenna gain of 64 dBi and an integration time of 2000 seconds.

Data loss is defined in recommendation ITU-R RA.1513 as “data that have to be discarded because they are contaminated by the aggregate interference, from one or more sources that exceeds the levels of Recommendation ITU-R RA.769”.

Recommendation RA.1513 includes a percentage of data loss criterion of 2% for any single MSS network. This percentage of data loss has to be considered as an average value calculated over all the possible pointing directions of the RAS station. For the purpose of this study, data loss has been defined as the number of integration periods where the epfd exceeds -258 dB(W/m^2) in one chosen channel of 20 kHz over the total number of observations (integration periods) performed in this channel.

However, alternative interpretations for assessing data loss have been proposed. For radio astronomers, whenever the epfd criterion is exceeded in one or more frequency channels of 20 kHz the overall spectral analysis performed over the entire band 1610.6-1613.8 MHz has to be discarded and is therefore considered as data loss. This interpretation would lead to a much larger percentage of data loss than what has been shown in this report.

Another interpretation is that loss of discrete data samples within a channel may not result in a complete loss of the integration period, in cases where less than 2% of samples are corrupted. This would lead to a lower percentage of data loss than is shown in this study.

4 IRIDIUM SYSTEM CHARACTERISTICS

4.1 IRIDIUM constellation description

The IRIDIUM system employs 66 Low Earth Orbit (LEO) satellites that support user-to-user, user-to-gateway, and gateway-to-gateway communications. The 66 satellites are evenly distributed in six orbital planes with a 86.4° inclination, with one in-orbit spare for each orbital plane. Except for planes 1 and 6, the orbital planes are co-rotating planes spaced 31.6° apart. The first and last orbital planes are spaced 22° apart and form a seam where the satellites are counter-rotating. The IRIDIUM satellite constellation is depicted in Figure 2. The satellites orbit at an altitude of 780 km and have an orbital period of approximately 100 min 28 s.

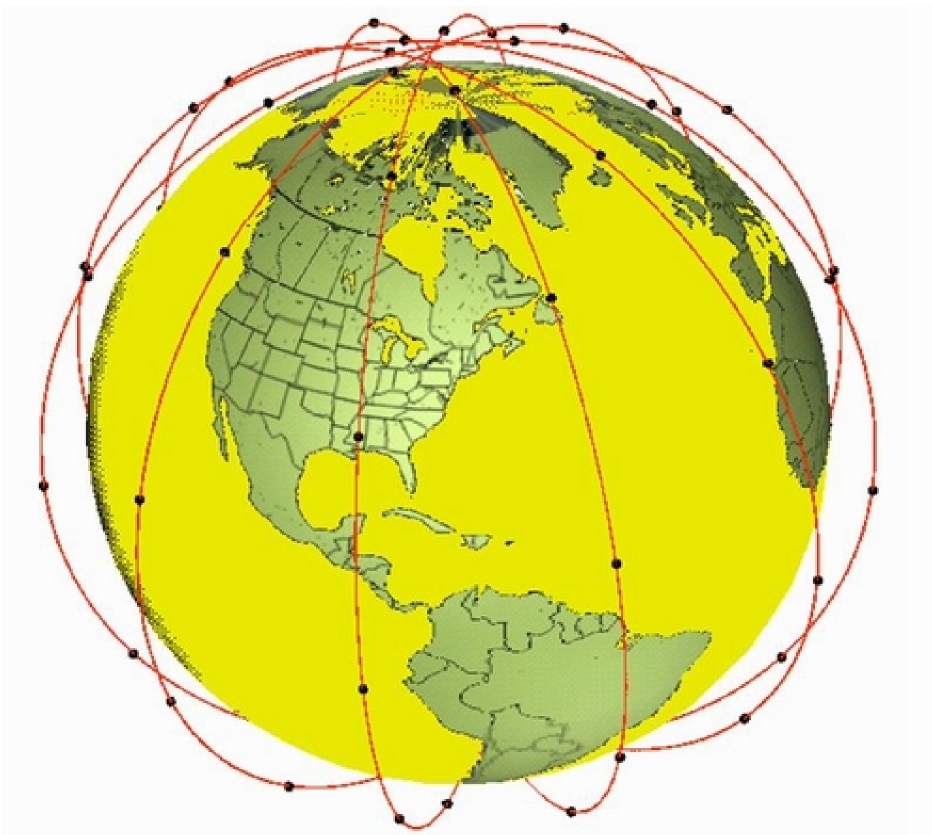

Figure 2: IRIDIUM Satellite Constellation

4.2 Particularities of the IRIDIUM signal

IRIDIUM user terminals employ a time division duplex (TDD) approach wherein they transmit and receive in an allotted time window within the frame structure. The TDD structure is built on a 90 ms frame and is composed of a 20.32 ms downlink simplex time slot, followed by four 8.28 ms up-link time slots and four 8.28 ms down-link time slots, with some guard times interspersed as is depicted in Figure 3. Since the system is using TDD, the subscriber units transmit and receive in the same frequency band. The access technology is a Frequency Division Multiple Access/ Time Division Multiple Access

(FDMA/ TDMA) method whereby a subscriber is assigned a channel composed of a frequency and time slot in any particular beam. Channel assignments may be changed across cell/ beam boundaries and are controlled by the satellite.

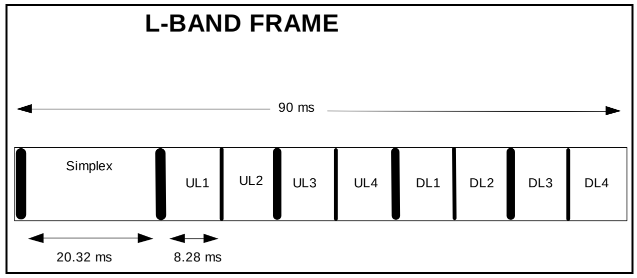

Figure 3: IRIDIUM Frame Structure

5 MEASUREMENTS OF IRIDIUM SATELLITES

5.1 Description of Leeheim monitoring station

The Leeheim monitoring earth station is located approximately 35 km south-west of Frankfurt/Main.

Leeheim has a number of satellite antennas including a 12 m parabolic reflector antenna designed to cover the 1 - 13 GHz frequency range (Antenna 1). Optimised characteristics at 1.5 - 1.8 GHz (as well as other frequency sub-bands) together with a high angular accuracy allow monopulse tracking for high precision antenna pointing.

Leeheim also has an array of radio measurement equipment including a high-speed frequency registration device, for the collection of data on a large number of simultaneous radio channels, spectrum analyser and data recording equipment.

For this measurement campaign, the frequency registration device was used to record the power of emissions across the whole band 1610.6 – 1613.8 MHz, and in detail across two bandwidth of 100 kHz each. Separately, a calibrated spectrum analyser was used to measure the peak power in some of the signals, to permit verification of the absolute accuracy of the data in the frequency registration device. Direct calibration of the frequency registration device was not possible.

The measurements were made in direct mode without any re-calculation (e.g. measurement under the noise floor). The absolute noise level of the spectra is at - 188.2 dBW/m²/20kHz.

Monitoring was done by means of Antenna 1. Its relevant parameters are:

- Antenna type: cassegrain
- Dish diameter: 12 m
- Polarization: linear
- Antenna gain: 44 dBi (1.5 – 1.8 GHz band)
- Figure of merit: 17 dB/K (1.5 – 1.8 GHz band)
- Antenna tracking: program track
- Frequency stability: 10-12
- Measurement uncertainty: 1.6 dB r.s.s. error (95% confidence level)

Due to the restriction of either linear or horizontal polarisation an correction of 3 dB for the praticular receiving mode of the measurement antenna may be needed.

Recording is done by the frequency registration device. Its relevant parameters are:

- System: FBS-3000 v1.02 (Schönhofer)
- Serial number 97115/sh-01
- Resolution: 1000 – 10 000 lines
- Measurement interval: 6 seconds (minimum)
- Input frequency range: 20 – 3000 MHz
- Dynamic resolution 0.5 dB

For all observations a Band Reject Filter is used. Its relevant parameters are:

- Type: Wainwright Instruments GmbH
- Model Number: WRCD 1616/1627-1614/1630-70/16EE
- Reject Attenuation: 1 616.0 to 1 627.0 MHz / 70 dB minimum

Spectral monitoring is done by signal analyser. Its relevant parameters are:

- System: R&S, FSIQ 40
- Serial number 1119.6001.

5.2 Leeheim measurements

5.2.1 General setup

Emissions from 4 different IRIDIUM satellites have been measured at different times of the day. The antenna was program-tracked according to the ephemeris (NORAD two line elements) of a selection of IRIDIUM satellites. Signals were parallel-recorded at wide band IF by means of a power splitter with a spectrum analyser and the frequency registration device. The measurement results are contained in the report[1] which is available from the ERO website.

Unwanted emissions in the band 1610.6-1613.8 MHz appear with different durations and amplitudes from all 4 satellites. An example of the observed emissions, shown as a plot of “maximum hold”, is given in Figure 4.

[1] “Leeheim report - IRIDIUM (November 2006)”

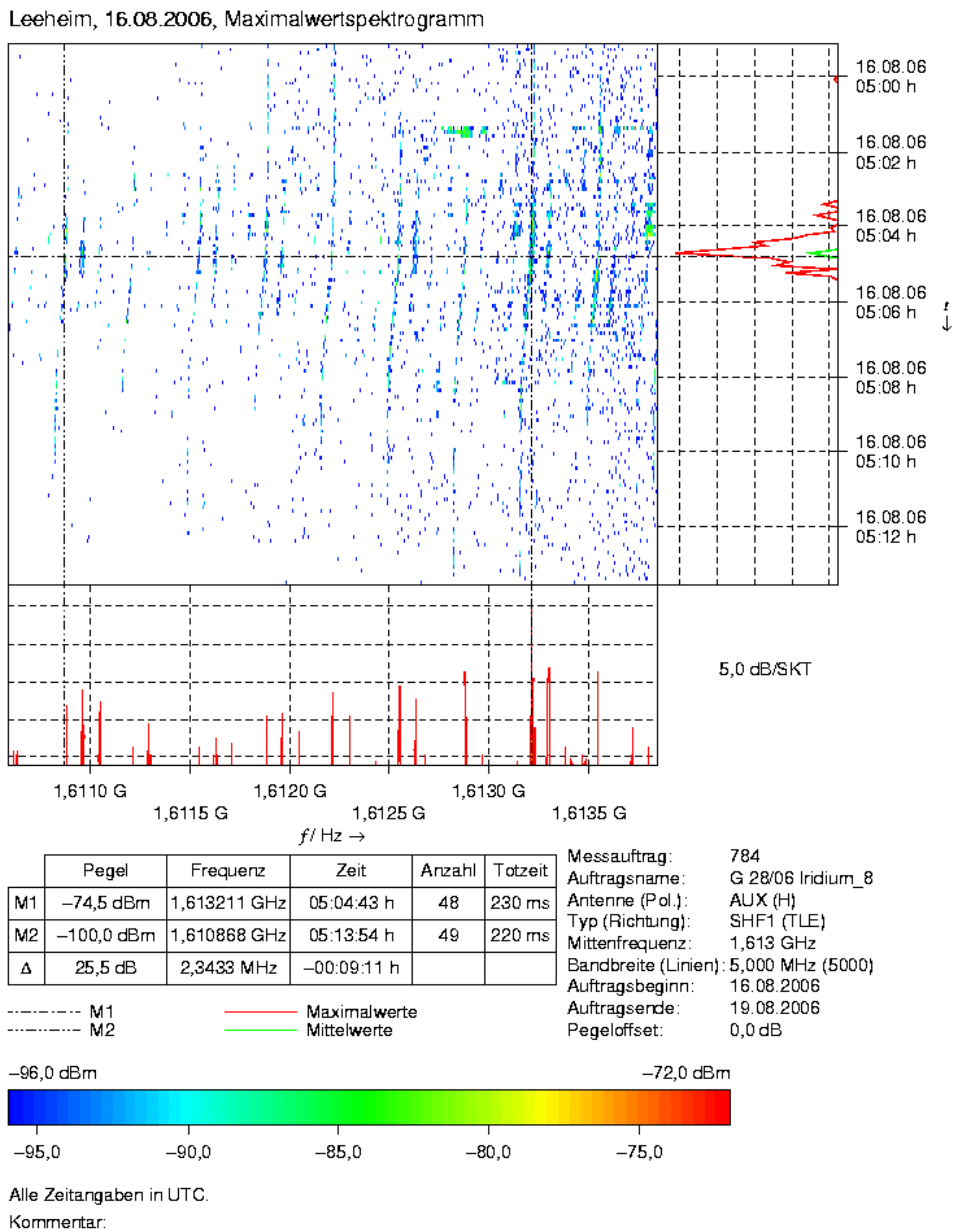

Figure 4: Unwanted emissions from IRIDIUM 77 in the RAS band

The origin of the unwanted emissions is clearly from the IRIDIUM satellites because:

- The Leeheim station antenna has been following one particular IRIDIUM satellite during its passage, therefore the other emissions are attenuated by the antenna pattern.
- No GLONASS satellite is crossing the antenna main beam as shown in Annex 36 of the Leeheim report.
- The records of signal vs time made by Leeheim show a pattern similar to the TDMA pattern used by IRIDIUM.

Detailed measurements are available in 10 spectral line channels around 2 particular frequencies: 1612.6 MHz and 1613.2 MHz. The activity in the RAS band at the two chosen frequencies varies a lot from one satellite to the other. However, it has to be noted that some unwanted emissions were measured on all satellites in the frequency channels centred on 1613.17, 1613.19 and 1613.21 MHz, whatever the time of the day. These particular channels are analysed in more detail in the following sections.

5.2.2 Doppler effect

The effect of Doppler shift may be observed in Figure 5, where the frequency decreases as the satellite moves across the sky.

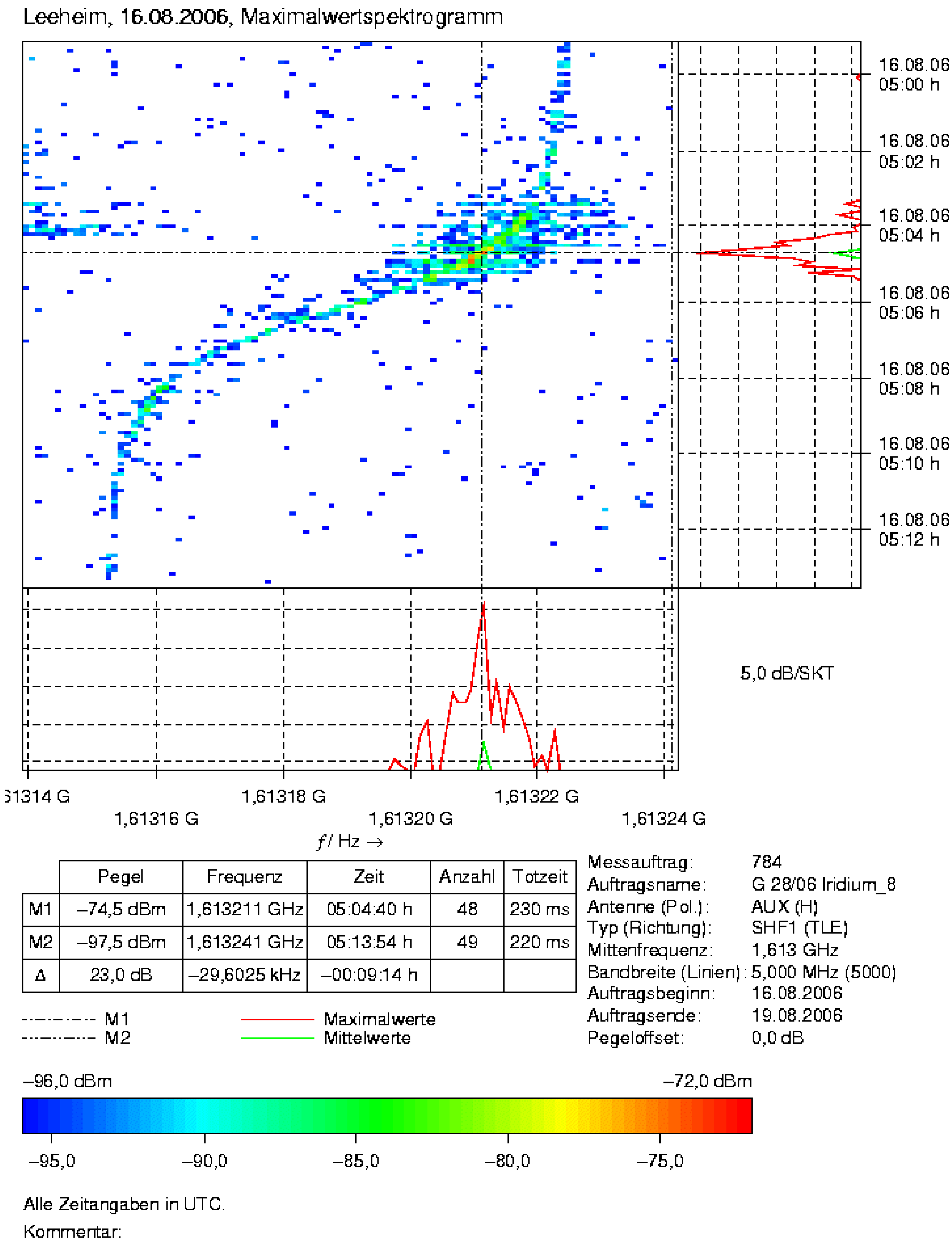

Figure 5: Unwanted emissions from IRIDIUM 77 around 1613.2 MHz

The centre frequency of the signal producing this Doppler shift is estimated at 1613.183 MHz on the curve. It is similar on all 4 satellites. The duration of interference in one given frequency channel of the RAS station is thus mainly driven by the frequency shift due to doppler effect.

5.2.3 Avoidance of GLONASS emissions

Unwanted emissions in the band 1610.6 – 1613.8 MHz may come from a number of sources, including terrestrial devices and other satellites. In particular, it has been noted that GLONASS satellites cause unwanted emissions in this band, and GLONASS measurements taken by Leeheim are documented in a separate report [2].

In the measurement of IRIDIUM emissions, Leeheim took measures to avoid corruption of measurement of IRIDIUM emissions due to other signal sources, notably by avoiding making measurements during coincidences of the GLONASS and IRIDIUM orbits. However, it is theoretically possible that aggregate emissions from multiple GLONASS satellites, received through the sidelobes of the Leeheim antenna, may have had an impact on the measurements if they approached or exceeded the noise floor of the receiver.

To assess this possibility, the earlier GLONASS measurements were reviewed. It was noted that GLONASS emissions fell across the whole RAS band at levels of about -166 to -174 dBW/m^2/20 kHz, with little variance during a visible orbit. Assuming that Leeheim sidelobe gain is 0 dBi beyond 3 degrees from boresight, then aggregate emissions from five visible GLONASS satellites (the maximum number visible from Europe) would be approximately -211 dBW/m^2/20 kHz: {-174 (*per satellite*) + 7 (*5 visible satellites*) – 44 (*antenna discrimination*)}. The noise floor of the Leeheim measurements was at least –205 dBW/m^2/20 kHz, and so the impact of any GLONASS emissions could not have affected the results.

5.2.4 Peak power level of unwanted emissions

The power level recorded by the analyser (the calibrated device), according to the figures contained in Annexes 27 to 34 of the Leeheim report, is measured in a reference bandwidth of 20 kHz. For example in Annex 27 it is -74.9 dBm for IRIDIUM 77. In Annex 35 (pfd calculation), a conversion factor is then applied (-98.2 dB), which takes into account the maximum antenna gain and frequency dependant rejection factor. The result for the example of IRIDIUM 77 is a maximum pfd of -173.1 dBW/m² in 20 kHz.

The noise level of the analyser is estimated to be around -92 dBm for IRIDIUM 77, -93 dBm for IRIDIUM 86, -94 dBm for IRIDIUM 30 and -93 to -91 dBm for IRIDIUM 33, according to Annexes 27 to 34. Applying the conversion factor of – 98.2 dB, it gives a noise pfd varying from -192.2 to -189.2 dBW/m²/20 kHz. This may be compared to the value of -178 dBW/m²/20 kHz, which was measured by Leeheim for GLONASS using the same resolution bandwidth, 11 to 14 dB above.

However, the frequency registration device performs FFTs with a resolution bandwidth 521 Hz and has in 796 Hz a peak noise level around -99.5 dBm. This corresponds to -99.5+14 = -85.5 dBm in 20 kHz. Applying the same conversion factor of -98.2 dB, this would correspond to a pfd level of -183.7 dBW/m² in 20 kHz, 4.5 dB above the noise level of -188.2 dBW/m²/20 kHz mentioned in the main body of the report and 5.5 to 8.5 dB above the noise level determined from the curves in Annexes 27 to 34 of the Leeheim report.

Assuming that the noise level is the same in the frequency registration device and in the analyser, there would therefore be a difference of 5.5 to 8.5 dB between the power level measured in the frequency registration device and the power level measured in the analyser.

In the frequency registration device, the power measured in 20 kHz should be the linear sum (or integral) of the power measured in 20 adjacent bins of 1 kHz contained in the 20 kHz bandwidth. However, from the figures contained in Annexes 9 to 24 and the tables contained in Annexes 25 and 26 of the Leeheim report, it seems that it is not the case since the noise level is around -99 dBm in 1 kHz in the figures and around -99.5 dBm in the tables (instead of -86.5 dBm). It seems that the scaling has not been done.

Figure 6 below gives the spectrum of one signal taken from the figure in Annex 21 of the Leeheim report for IRIDIUM 77. The 20 kHz frequency channel is centred on 1613.21 MHz. The first dotted line corresponds to the frequency 1613.20 MHz and the second one to the frequency 1613.22 MHz. This range has been divided into 20 “1 kHz” bins. The following Table 2 gives the relative power in dBm in each bin as well as the sum of all bins.

[2] SE21(06)05, “Report on Monitoring Glonass Emissions in the Radio Astronomy Band 1610.6-1613.8 MHz and in the Useful Band at 1.6 GHz”.

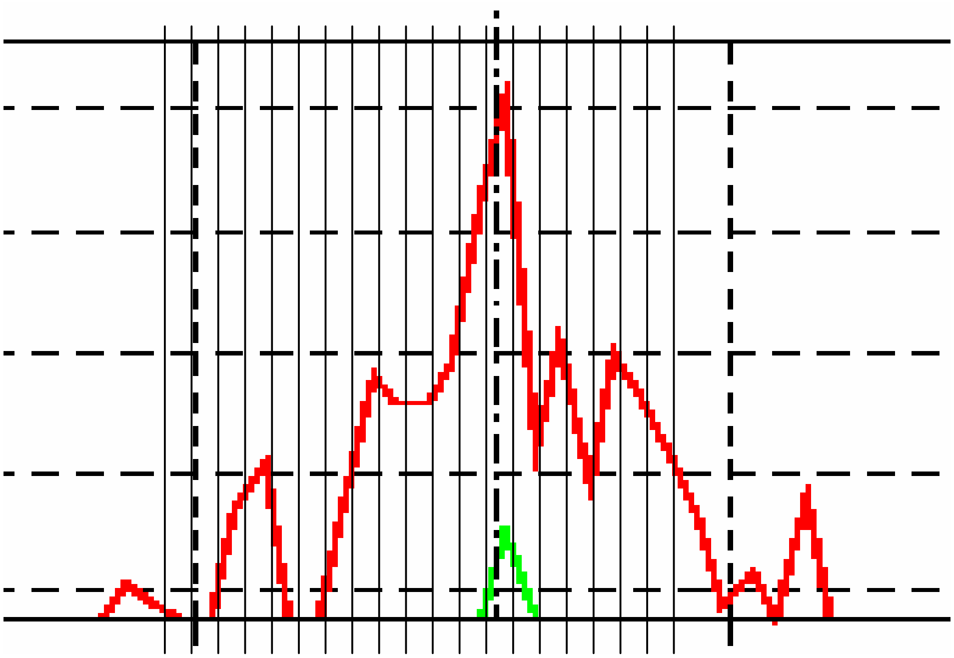

Figure 6: Unwanted emissions spectrum

Frequency (MHz)	Received power (dBm)	Comment
1613.2005	-96	
1613.2015	-93	
1613.2025	-89	
1613.2035	-96	
1613.2045	-96	
1613.2055	-91	
1613.2065	-86	
1613.2075	-87	
1613.2085	-87	
1613.2095	-86	
1613.2105	-80	
1613.2115	**-74.5**	**Maximum power in 1 kHz**
1613.2125	-90	
1613.2135	-84	
1613.2145	-89	
1613.2155	-86	
1613.2165	-87	
1613.2175	-88	
1613.2185	-92	
1613.2195	-95	
1613.2100	**-71.5**	**Total power in 20 kHz**

Table 2: Determination of the unwanted emission power level in 20 kHz at 1613.21 MHz

There is a difference of 3 dB between the power received in 1 kHz and the power received in 20 kHz in this case. Another example is given in the following Table 3 for IRIDIUM 86 as reported in Annex 23 of the Leeheim measurements report.

Frequency (MHz)	Received power (dBm)	Comment
1613.1605	-99.5	
1613.1615	-96	
1613.1625	-95	
1613.1635	-97	
1613.1645	-96	
1613.1655	-93	
1613.1665	-90	
1613.1675	-88	
1613.1685	-88	
1613.1695	-92	
1613.1705	-92	
1613.1715	-90	
1613.1725	-90	
1613.1735	-90	
1613.1745	-87	
1613.1755	-88	
1613.1765	-91	
1613.1775	-90	
1613.1785	-86	
1613.1795	**-80**	**Maximum power in 1 kHz**
1613.1700	**-76.4**	**Total power in 20 kHz**

Table 3: Determination of the unwanted emission power level in 20 kHz at 1613.17 MHz

There is in this case an error of 3.6 dB between the maximum power and the total power.

Another example is given in the following Table 4 for IRIDIUM 30 as reported in Annex 22 of the Leeheim report.

Frequency (MHz)	Received power (dBm)	Comment
1613.1805	-85	
1613.1815	-94	
1613.1825	-85	
1613.1835	**-80**	**Maximum power**
1613.1845	-84	
1613.1855	-85	
1613.1865	-84	
1613.1875	-83	
1613.1885	-84	
1613.1895	-89	
1613.1905	-93	
1613.1915	-94	
1613.1925	-92	
1613.1935	-94	
1613.1945	-94	
1613.1955	-92	
1613.1965	-96	
1613.1975	-95	
1613.1985	-97	
1613.1995	-99.5	
1613.1900	**-74**	**Total power in 20 kHz**

Table 4: Determination of the unwanted emission power level in 20 kHz at 1613.19 MHz

This time the difference is of 6 dB.

This difference of +3 to +6 dB more or less compensates for the difference of -5.5 to -8.5 dB between the analyser and the frequency registration device. That would explain why the power measured by both devices appears to be similar in Annex

35 of the Leeheim report. The formula to get the pfd in 20 kHz from the power levels measured in 1 kHz in the frequency registration device is therefore:

P (Annex 26) – 8.5 + 3 < unwanted emission power received in 20 kHz < P (Annex 26) - 5.5 + 6

5.2.5 Average power level of unwanted emissions

It is necessary to model the signal level during the duration of observations. To do so, the average power measurements (averaged over 6 s) are not sufficient, since the events for which these measurements apply are limited. It would be better to evaluate the average power directly from the peak power, for which there are more measurements. As shown in the Figure 7 below, there seems to be some correlation between both values. The average power may be approximated by the peak power minus 16 dB. This correction factor is more important at low power levels, which are closer to the noise floor of the measurement device.

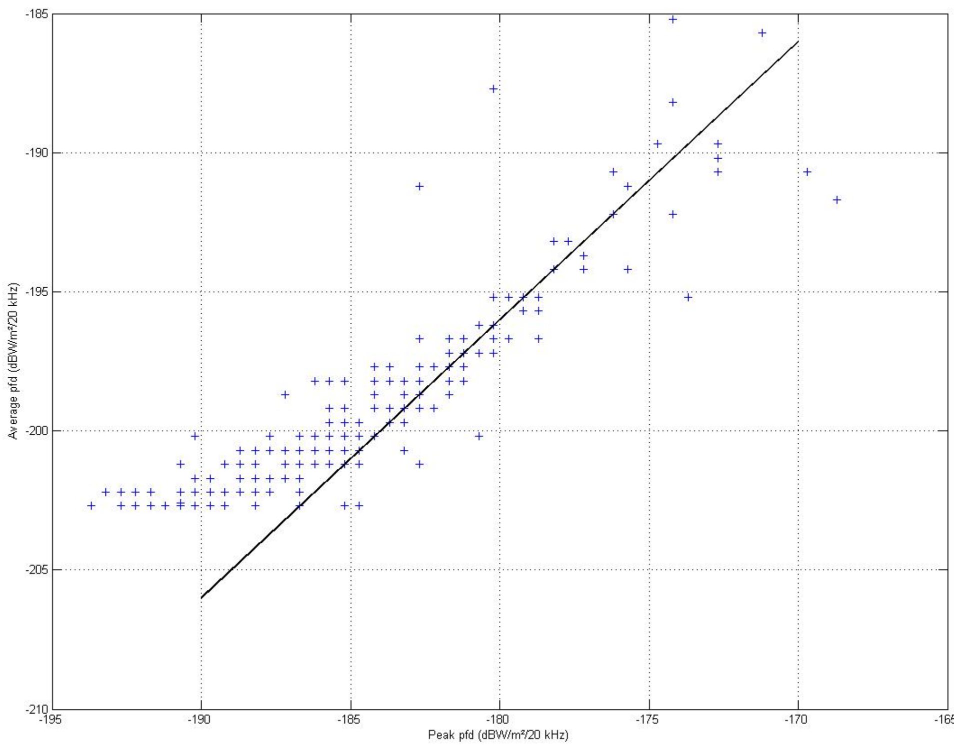

Figure 7: Correlation of Power$_{max}$ – Power$_{avg}$

5.2.6 Determination of the pfd levels

The pfd measured in 20 kHz may be derived from the power levels measured in 20 kHz using a conversion factor of -98.2 dB, taking into account the Leeheim antenna gain as well as other frequency dependant rejection factors. Figure 8 gives the distribution of the (peak pfd – 16 dB), calculated over all satellites in frequency channels around the frequency 1613.2 MHz.

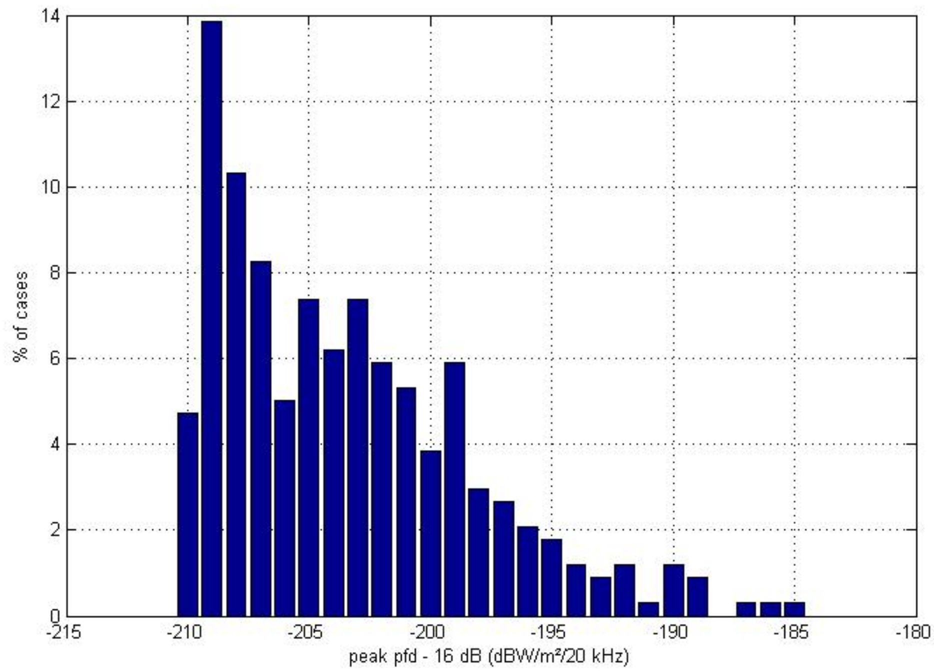

Figure 8: Distribution of pfd values

5.3 Impact of current traffic and operational configuration of IRIDIUM

One of the objectives of the study was to assess the impact of the operations of the IRIDIUM system in the fully extended band 1618.25-1626.5 MHz on the interference generated in the RAS band 1610.6-1613.8 MHz, compared with operations in the core band 1621.35-1626.5 MHz. As the IRIDIUM system was operating over the fully extended band during the period of test, it was not possible to separately assess the unwanted emissions from operation within the core band only. However, while it is possible that additional intermodulation products would fall within the RAS band from the same level of traffic activity when contained within the core band, such operation may still comply with the 2% data loss criterion.

It has to be noted that these measurements address the current traffic loading of the IRIDIUM system over Europe at the time the measurements were made. It is possible that a higher level of traffic activity may result in more intermodulation products falling within the RAS band, but this was not considered within the study.

Future impact of IRIDIUM operations on the RAS band will have to be monitored as the system develops and the traffic level grows.

6 ASSESSMENT OF IRIDIUM IMPACT TO RAS

6.1 Methodology

The methodology is based on a modified version of the methodology contained in Recommendation ITU-R M.1583 to take into account the Doppler effect and pfd difference from one satellite to the other. The algorithm flow is summarized below:

For each trial:

For each cell over the sky:

- determine a random pointing of the telescope within the cell
- determine a random initial time of simulation T_0

For each satellite:

- o Calculate the position of the satellite for each second of the integration time, starting at T_0
- o Calculate the Doppler shift and determine when the unwanted signal enters and goes out of the considered frequency channel, assuming the signal frequency is centred at 1613.19 MHz (best evaluation of the centre frequency from measurements)
- o determine for each time step a pfd value within the previously determined Doppler window following the distribution law in Figure 8
- o Calculate the RAS antenna gain in the direction of the satellite
- o Calculate the sum of RAS gain and pfd

- Calculate the epfd at the RAS station by linearly summing the contribution of each satellite, then divide by the maximum antenna gain to get an epfd instead of an aggregate pfd, then determine the mean value over the integration time.
- Compare the epfd value in dB to the (RA.769 limit – maximum antenna gain) to determine whether there is a data loss or not

Calculate the % of data loss for each cell and for the whole sky (average of all cells).

Figure 10 shows the Doppler shift in the time domain of unwanted emissions from all visible satellites over an integration period of 2000 s. This illustrates the fact that aggregation of unwanted emissions rarely occurs in a given 20 kHz channel.

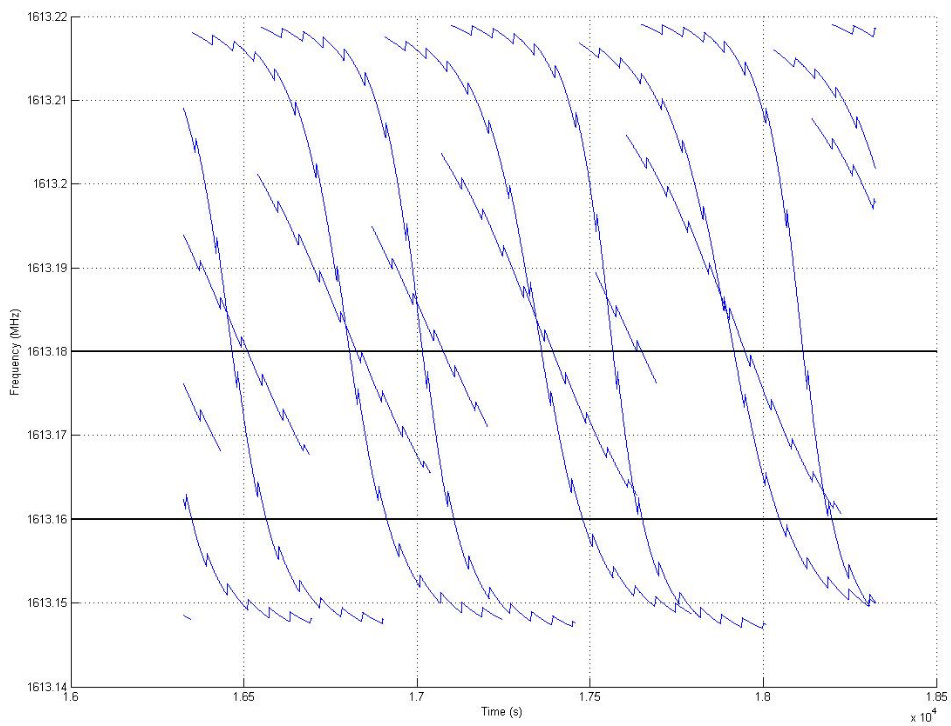

Figure 9: Simulation of the Doppler shift of the unwanted signal

6.2 Results

6.2.1 Integration time of 2000 s – RAS channel at 1613.17 MHz

The threshold levels contained in the tables in Annex to recommendation ITU-R RA.769 are given for an integration time of 2000 s. The first simulation has been run with this integration time. The percentage of data loss has been determined for a RAS frequency channel of 20 kHz centred on 1613.17 MHz. The following Figure 10 gives the results obtained for 100 trials.

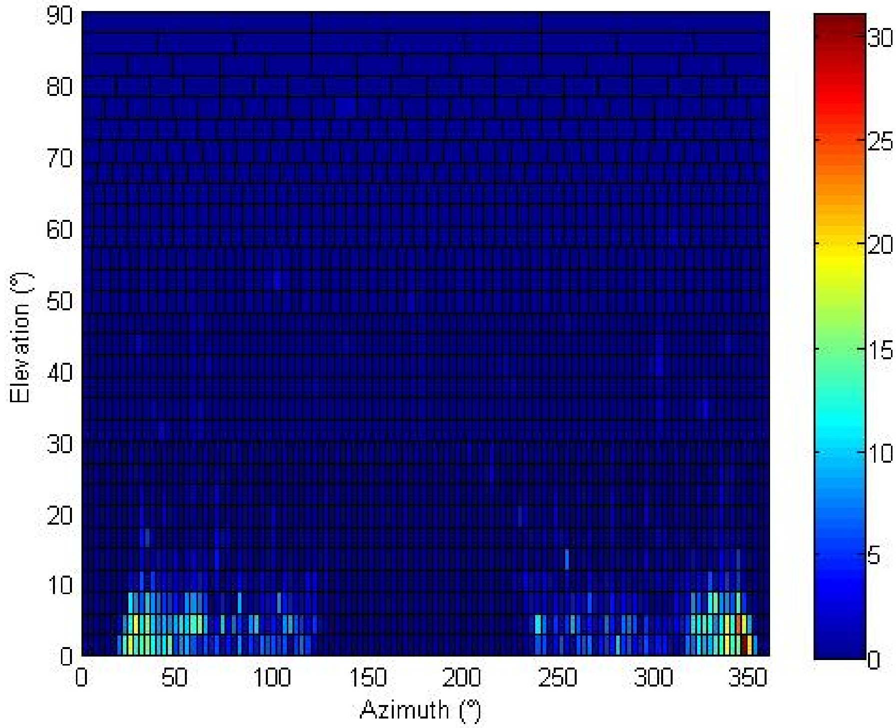

Figure 10: Percentage of data loss over entire sky for an integration time 2000 s – 1613.17 MHz

The overall percentage of data loss is 0.7%. The pfd per satellite could be increased by 3 dB, the percentage of data loss would remain below the 2% criterion specified in RA.1513. Therefore, any possible error in the determination of pfd levels from Annexes 25 and 26 of the Leeheim report, using a simple shift of -98.2 dB, would have no consequence on the conclusions.

6.2.2 Integration time of 2000 s – RAS channel at 1613.23 MHz

In this simulation the percentage of data loss has been determined for a RAS frequency channel of 20 kHz centred on 1613.23 MHz. The following Figure 11 gives the results obtained for 100 trials.

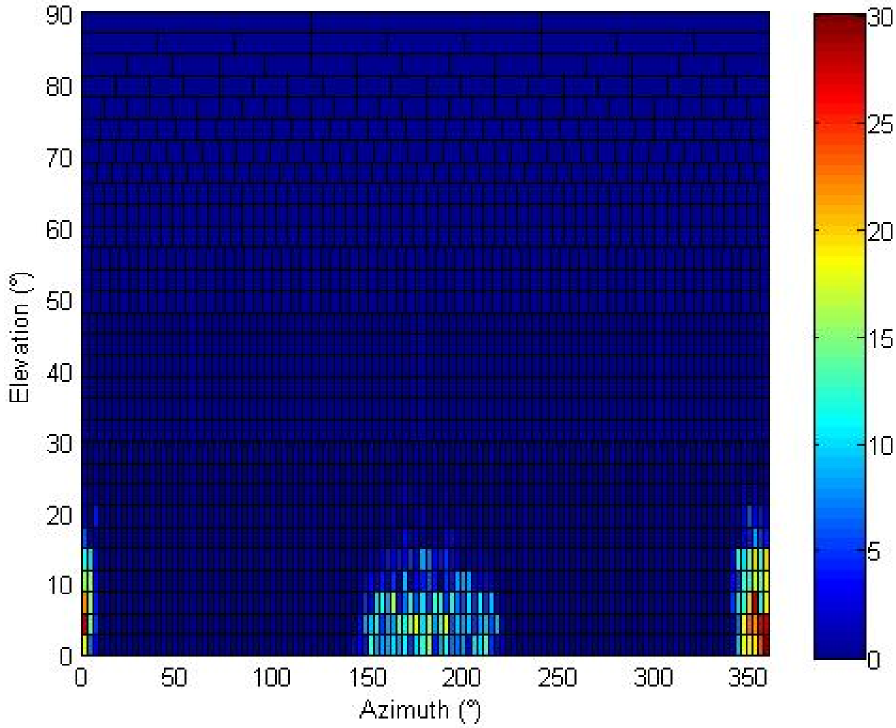

Figure 11: Percentage of data loss over entire sky for an integration time 2000 s – 1613.23 MHz

In this case the overall percentage of data loss is still 0.7 %. However the worst cases have shifted on the sky picture. This is explained by the fact that the difference between the RAS frequency channel and the frequency of the fundamental of the unwanted emission corresponds to a maximum Doppler shift which is only observed when the satellite is in the North or South directions.

6.2.3 Integration time of 30 s – RAS channel at 1613.23 MHz

In this simulation the percentage of data loss has been determined for a RAS frequency channel of 20 kHz centred on 1613.23 MHz. The integration time has been reduced to 30 s. In this case the epfd detrimental threshold level needs to be corrected by a factor of $10\log(\sqrt{\frac{2000}{30}})$ and becomes -249 dBW/m² in 20 kHz.

The following Figure 12 gives the results obtained for 200 trials.

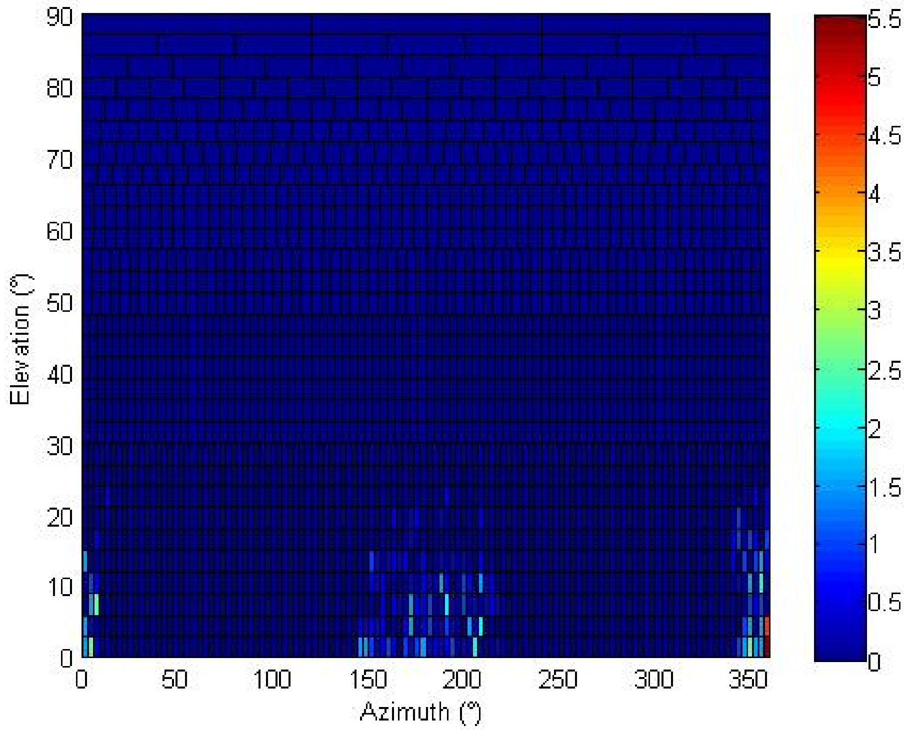

Figure 12: Percentage of data loss over entire sky for an integration time 30 s – 1613.23 MHz

In this case the overall percentage of data loss is 0.04 %. The value obtained for the particular azimuth angle 210° and elevation angle 8° is around 1%.

7 MEASUREMENTS PERFORMED AT RADIOASTRONOMY STATIONS

Separately from aforementioned Leeheim measurements, the Effelsberg radotelescope located in Germany was used to record unwanted signal power falling in the band 1610.6 – 1613.8 MHz over a period of approximately four hours. The measurement process was less comprehensive than the Leeheim measurements in some respects, for example:

- the test method used a fixed antenna and so could not distinguish or identify different sources of unwanted emissions (e.g. terrestrial emissions, GLONASS satellites, etc),
- the test set-up used measurement equipment with a noise floor that was less sensitive than at the Leeheim, and
- measurements were taken using a time resolution of 60 s and an integration time of 30 s.

The very low thresholds applicable in the band 1610.6-1613.8 MHz require specific techniques in order to achieve the required sensitivity. The operation of IRIDIUM and other systems in bands above and below the RAS band necessitates filtering to prevent non-linear effects being generated in the measurement equipment itself. In order to measure the interference levels, and given the sensitivity and limited dynamic range of RAS receivers, it is essential to filter out such unwanted signals before amplification, otherwise intermodulation products are very likely to be created in the receiver itself. These would be indistinguishable from unwanted emissions created by systems operating outside of the RAS band, and would result in avoidable data loss. Such filtering has not been implemented for these measurements, but would need to be done in future measurements.

However, these results gave some indication of the likely impact on the RAS band 1610.6 – 1613.8 MHz from <u>all</u> sources of interference, not just fromIRIDIUM satellites.

The Effelsberg antenna was pointed to a fixed direction of 8° elevation and 210° azimuth in the sky. The flux received at individual frequencies was measured and recorded during that time. The flux was expressed in Jansky (10^{-26} W/m²/Hz) and can be directly converted to spectral epfd, using the following formula:

$$epfd(dBW/m^2) = 10\log(Flux(Jy)) - 260$$

Time (Hour minute)	observation frequency (MHz)	Flux (Jansky)	Spectral epfd integrated over 60s (dBW/m²/Hz)
9:02	1610.61	1.47	-258
9:02	1611.27	0.67	-262
9:03	1610.93	0.33	-265
9:04	1611.11	5.33	-253
9:04	1611.81	4.67	-253
9:12	1612.72	3.00	-255
9:16	1611.75	0.80	-261
9:20	1612.41	1.00	-260
9:29	1612.63	6.67	-252
9:30	1613.39	1.13	-259
9:31	1613.39	4.33	-254
10:03	1612.50	0.67	-262
10:24	1613.39	0.80	-261
10:25	1612.73	1.07	-260
10:26	1612.73	0.67	-262
10:43	1610.93	1.00	-260
10:44	1610.93	1.07	-260
10:53	1611.24	1.47	-258
12:02	1612.72	1.00	-260
12:22	1613.67	1.33	-259
13:06	1611.56	3.33	-255
13:06	1613.42	0.67	-262
13:07	1612.16	0.80	-261
13:07	1612.73	0.53	-263
13:08	1612.98	1.00	-260
13:08	1612.57	0.67	-262
13:09	1613.07	0.53	-263
13:09	1612.60	2.67	-256
13:09	1613.13	2.00	-257
13:20	1611.90	1.07	-260
13:33	1613.23	2.00	-257
13:34	1613.64	1.00	-260
13:34	1613.23	0.67	-262
13:35	1612.06	0.67	-262
13:35	1613.04	0.67	-262
13:35	1613.27	1.67	-258
13:35	1613.73	1.33	-259
13:36	1612.06	1.13	-259
13:37	1612.06	0.67	-262

Table 5: Observation of unwanted emissions in the band 1610.6 – 1613.8 MHz

As an example, for the frequency of 1613.39 MHz there are 3 observation periods of 60 s which are lost. For the frequency of 1612.06 there are also 3 observation periods of 60 s which are lost. From the Effelsberg results, these represent the worst case channels detected. It is mentioned in the Effelsberg report that 240 observations were made; the percentage of data loss per channel for this pointing direction is therefore, at maximum, 1.25% (3/240). However, the measurement noise floor of the Effelsberg set-up was higher than the RA.769 threshold (approx. –269 dBWm^{-2}Hz^{-1}, instead of –-293 dBWm^{-2}Hz^{-1} from RA.769 for spfd measurements over a 60s period and an antenna of 63 dBi gain), and so absolute data loss per channel may be higher.

It is interesting to note that, from the frequencies 1613.15 to 1613.23 MHz as studied in the epfd simulation, only the frequency 1613.23 MHz appears in the Effelsberg measurements. This is because the radiotelescope is pointing at 210° azimuth. Interference at the frequency 1613.183 MHz as detected in the measurements from Leeheim only appears at the azimuth 210° in the RAS channels centred on 1613.23 MHz or 1613.15 MHz (at the extremity of the Doppler curve). This confirms the simulations above.

For the azimuth angle 210° and the elevation angle 8° the percentage of data loss calculated in the epfd simulation for the 20 kHz channel centred on 1613.23 MHz is around 1% (see Figure 12). Since the number of trials was limited to 200, the percentage of data loss per cell is given with a resolution of 0.5% only. The simulation result is therefore consistent with the percentage of data loss observed by Effelsberg per frequency channel for this pointing direction.

The maximum epfd value given by the simulation is around -228 dBW/m². The corresponding spectral epfd is -271 dBW/m²/Hz. There seems to be an inconsistency when compared to the maximum spectral epfd measured by Effelsberg which is -257 dBW/m²/Hz for the 20 kHz channel centred on 1613.23 MHz. The difference is in the order of 14 dB. However, it has to be noted that Effelsberg's antenna pattern may differ from the one described in recommendation ITU-R RA.1631.

The Effelsberg measurements have been confirmed during a second campaign, which has shown the same levels of interference for the same pointing direction. A further set of measurements at higher elevation (60°) recorded no discernable interference, in line with the simulation results.

Other RAS stations in Europe (Italy, Portugal, Switzerland, United Kingdom) have also provided information on high levels of interference received in the band 1610.6-1613.8 MHz, but corresponding data loss could not be assessed.

8 CONCLUSIONS

The measurements performed by the Leeheim monitoring station clearly show that IRIDIUM unwanted emissions in the band 1610.6-1613.8 MHz are highly time-variable, and can not be directly compared to the protection levels contained in Recommendation ITU-R RA.769-2 because of the particular nature of the IRIDIUM system (non-GSO constellation) and signal (TDMA), and the particular mode of observations of RAS stations (integration of the signal received over a large period of time).

The epfd simulation shows that interference averaged over 2000 s exceeds the levels of recommendation ITU-R RA.769 at predominantly low elevations, resulting in a loss of data to the RAS. The epfd simulations show that the level of data loss produced in one single 20 kHz channel of the band 1610.6 – 1613.8 MHz at a RAS station located in Europe by the unwanted emissions measured by Leeheim would not exceed a percentage of 0.7%, against the 2% criterion contained in recommendation ITU-R RA.1513.

In radio astronomers view, whenever the epfd criterion is exceeded in one or more frequency channels of 20 kHz, the overall spectral analysis performed over the entire band 1610.6-1613.8 MHz has to be discarded and is therefore considered as data loss. This interpretation would lead to a much larger percentage of data loss than what has been shown in this report.

Another interpretation is that loss of discrete data samples within a channel may not result in a complete loss of the integration period, in cases where less than 2% of samples are corrupted. This would lead to a lower percentage of data loss than is shown in this report.

One of the objectives of this report was to assess the impact of the operations of IRIDIUM system in the fully extended band 1618.25-1626.5 MHz on the interference generated in the RAS band 1610.6-1613.8 MHz, compared with operations in the core band 1621.35-1626.5 MHz. As the IRIDIUM system was operating over the fully extended band during the period of test, it was not possible to separately assess the unwanted emissions from operation within the core band only. However, while it is possible that additional intermodulation products would fall within the RAS band from the same level of traffic activity when contained within the core band, such operation may still comply with the 2% data loss criterion.

It has to be noted that these measurements address the traffic loading of the IRIDIUM system over Europe at the time the measurements were made. It is possible that a higher level of traffic activity may result in more intermodulation products falling within the RAS band, but this was not considered within the study.

Future impact of IRIDIUM operations on the RAS band will have to be monitored as the system develops and the traffic level grows.

9 REFERENCES

- Measurement report of Leeheim Satellite Monitoring Facility: “IRIDIUM (November 2006)”, available at www.ero.dk/sat_monitoring_results
- Recommendation ITU-R RA.769-2, “Protection criteria used for radio astronomical measurements”
- Recommendation ITU-R RA.1513-1, “Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy on a primary basis”
- Recommendation ITU-R RA.1631, “Reference radio astronomy antenna pattern to be used for compatibility analyses between non-GSO systems and radio astronomy service stations based on the epfd concept”
- Recommendation ITU-R M.1583, “Interference calculations between non-geostationary mobile-satellite service or radionavigation-satellite service systems and radio astronomy telescope sites”
- Agreement CRAF/IRIDIUM: “Framework Agreement between IRIDIUM LLC and the European Science Foundation”, August 1998 and the CEPT Milestone Review Committee (MRC) recommendation n^{o}4 of 27 March 1998 referenced in this document;
- Report ERC 050 : “Interference calculations from MSS satellites into radio astronomy observations”