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Radio frequency compatibility of unwanted emissions from 9 GHz EESS synthetic aperture radars with the Earth exploration-satellite service (passive), space research service (passive), space research service and radio astronomy service operating in the frequency bands 8 400-8 500 MHz and 10.6-10.7 GHz, respectively

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***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R RS.2308-0

Radio frequency compatibility of unwanted emissions from 9 GHz EESS synthetic aperture radars with the Earth exploration-satellite service (passive), space research service (passive), space research service and radio astronomy service operating in the frequency bands 8 400-8 500 MHz and 10.6-10.7 GHz, respectively

(2014)

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1 Introduction

This Report comprises results from studies on unwanted emissions from Earth exploration-satellite service (EESS) (active) into the radio astronomy service (RAS) and the EESS (passive) in the frequency band 10.6-10.7 GHz, as well as the space research service (SRS) in the frequency band 8 400-8 500 MHz.

Section 2 provides the assumed characteristics of EESS synthetic aperture radars (SARs) operating around 9 600 MHz as defined by Recommendation ITU-R RS.2043.

Compatibility studies and results are provided in

– Section 3 on unwanted emissions of EESS SARs operating around 9 600 MHz into RAS

– Section 4 on compatibility studies of EESS (active) with EESS (passive)

– Section 5 on compatibility studies of EESS (active) with SRS

Summary and conclusions for each of the studies are provided in § 6 and referenced documents in § 7.

Annex A: Pulse shaping methods and their performance

Annex B: Abbreviations used in this Report

2 Characteristics of EESS SAR used in the studies

Table 1 provides the characteristics of the currently operated SAR-1, SAR-2 and SAR-3 systems as well as SAR-4 which were taken from Recommendation ITU-R RS.2043. SAR-4 represents a new generation of SAR systems intending to provide high resolution performance of less than 25 cm while using transmission chirp bandwidth of up to 1 200 MHz. Figure 1 shows the typical operating modes of SAR systems in Table 1.

TABLE 1

Technical characteristics of EESS SAR systems

Parameter	**SAR-1**	**SAR-2**	**SAR-3**	**SAR-4**
Orbital altitude (km)	400	619	506	510
Orbital inclination (degrees)	57	98	98	98
RF centre frequency (GHz)	9.6	9.6	9.6	9.3-9.9*
Peak radiated power (W)	1 500	5 000	25 000	7 000
Pulse modulation	Linear FM chirp	Linear FM chirp	Linear FM chirp	Linear FM chirp
Chirp bandwidth (MHz)	10	400	450	1 200
Pulse duration (μs)	33.8	10-80	1-10	50
Pulse repetition rate (pps)	1 736	2 000-4 500	410-515	6 000
Duty cycle (%)	5.9	2.0-28.0	0.04-0.5	30
Range compression ratio	338	< 12 000	450-4 500	60 000
Antenna type	Slotted waveguide	Planar array	Planar phased array	Planar array
Antenna peak gain (dBi)	44.0	44.0-46.0	39.5-42.5	47.0
e.i.r.p. (dBW)	75.8	83.0	83.5-88.5	85.5
Antenna orientation from Nadir	20° to 55°	34°	20° to 44°	18.5° to 49.3°
Antenna beamwidth	5.5° (El) 0.14° (Az)	1.6-2.3° (El) 0.3° (Az)	1.1-2.3° (El) 1.15° (Az)	1.13° (El) 0.53° (Az)
Antenna polarization	Linear vertical	Linear HH or VV	Linear horizontal/ vertical	Linear horizontal/ vertical
System noise temperature (K)	551	500	600	500

* Final value depends on the decision eventually taken under WRC-15 agenda item 1.12.

It should be noted that only the technical characteristics of a SAR-4 system have been taken for the studies since only SAR-4 systems are assumed to transmit with the full bandwidth of up to 1 200 MHz.

Table 2 provides the pattern of a SAR-4 antenna. The antenna patterns of SAR-1 to SAR-3 systems are defined in Recommendation ITU-R RS.2043.

TABLE 2

SAR-4 average antenna gain pattern near 9 600 MHz

Pattern	Gain $G(\theta)$ (dBi) as function of off-axis angle θ (degrees)	Angular range (degrees)
Vertical (elevation)	$G_v(\theta_v) = 47.0 - 9.91 (\theta_v)^2$ $G_v(\theta_v) = 35.189 - 1.944\theta_v$ $G_v(\theta_v) = 21.043 - 0.468\theta_v$ $G_v(\theta_v) = 12.562 - 0.185\theta_v$ $G_v(\theta_v) = 3.291$	$\theta_v < 1.149$ $1.149 \le \theta_v \le 9.587$ $9.587 \le \theta_v \le 29.976$ $29.976 \le \theta_v \le 50$ $50.0 \le \theta_v$
Horizontal (azimuth)	$G_h(\theta_h) = 0 - 45.53(\theta_h)^2$ $G_h(\theta_h) = -11.210 - 4.022\theta_h$ $G_h(\theta_h) = -26.720 - 0.953\theta_h$ $G_h(\theta_h) = -35.031 - 0.388\theta_h$ $G_h(\theta_h) = -41.936 - 0.158\theta_h$ $G_h(\theta_h) = -51.387$	$\theta_h \le 0.542$ $0.542 < \theta_h \le 5.053$ $5.053 < \theta_h \le 14.708$ $14.708 < \theta_h \le 30.00$ $30.00 < \theta_h \le 59.915$ $59.915 < \theta_h$
Beam pattern	$G(\theta) = G_v(\theta_v) + G_h(\theta_h)$	

FIGURE 1

Modes of operations for SAR system in the 9 GHz EESS allocation

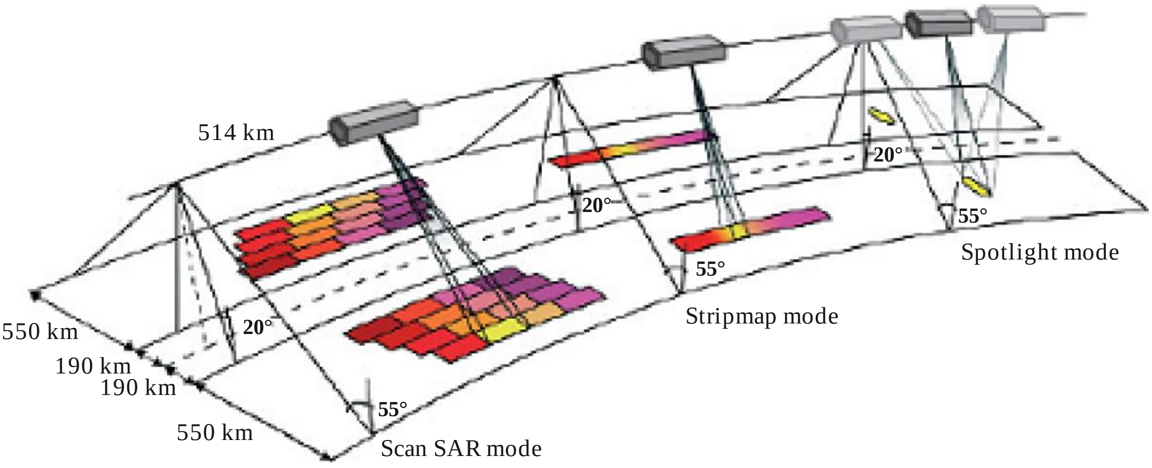

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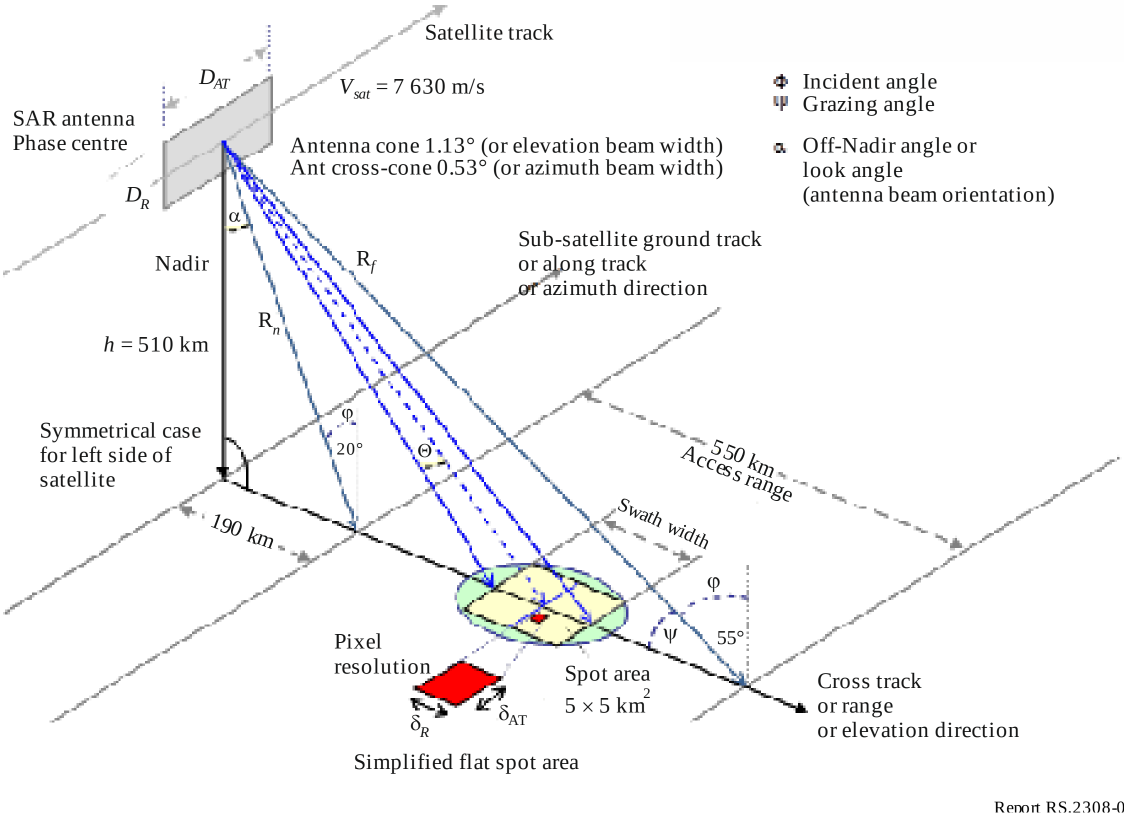
Figure 1 illustrates the different operating modes that can be provided by typical SAR systems. Figure 2 provides definitions and terminologies of a SAR-4 type instrument operating in the wideband spotlight mode.

The maximum chirp bandwidth of up to 1 200 MHz is assumed for the spotlight mode of the SAR-4 system, when highest radar picture resolution is required as described in Report ITU-R RS.2274. This mode is estimated to occur for less than 30% of all images (“snapshots”) taken by the SAR. For the other SAR modes, the bandwidth will be either 600 MHz or less, thus in full compliance with the existing allocation.

FIGURE 2

EESS SAR imaging geometry for high resolution spotlight mode (wideband with 1 200 MHz chirp bandwidth)



As shown in Fig. 2, in spotlight mode, the spot area can be tracked with incident angles of between 20° and 55° selectable on either or both sides of the satellite. When taking snapshots the azimuth angle (cross track) is within 90° ± 2.5°, thus reducing the effective exposure time of a spot to five seconds as described in Recommendation ITU-R RS.2043.

3 Analysis of the impact of unwanted emissions of EESS SAR operating around 9 600 MHz on radio astronomy stations operating in the band 10.6-10.7 GHz

3.1 Introduction

WRC-15 agenda item 1.12 deals with a possible extension of the EESS (active) allocation in the band 9 300-9 900 MHz by up to 600 MHz. This section analyses the potential impact and protection measures of stations operating in RAS from out-of-band (OoB) emissions from satellite-based SAR operating in EESS (active) as described in Recommendation ITU-R RS.2043 and § 2 above.

3.2 Characteristics of stations operating in RAS

The band 10.6-10.68 GHz is allocated to the EESS (passive), RAS and SRS (passive) and also terrestrial services (fixed and mobile). The band 10.68-10.7 GHz has a provision, RR No. **5.340**, relevant for passive services (see Table 3).

TABLE 3

Adjacent band allocations

Services in lower allocated bands		Passive band	Service in upper allocated band
10.55-10.6 GHz	**10.6-10.68 GHz**	**10.68-10.7 GHz**	**10.7-11.7 GHz**
FIXED MOBILE except aeronautical mobile radiolocation	EARTH EXPLORATION-SATELLITE (Passive) FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY SPACE RESEARCH (Passive) Radiolocation 5.149 5.482 5.482A	EARTH EXPLORATION-SATELLITE (Passive) RADIO ASTRONOMY SPACE RESEARCH (Passive) 5.340 5.483	FIXED FIXED-SATELLITE (space-to-Earth in all Regions) 5.441 5.484A (Earth-to-space in Region 1) MOBILE except aeronautical mobile

A number of radio telescopes use the 10.6-10.7 GHz band for radio astronomical observations. This study is based on the characteristics of the radio astronomy station located at Effelsberg (Germany) with a 100 m diameter antenna with an assumed 81 dBi maximum gain at 10.6 GHz.

In the band 10.6-10.7 GHz, Recommendation ITU-R RA.769 provides with a pfd level of −160 dBW/m²/100 MHz only a protection criterion for continuum observations. This may be converted into an epfd criterion of –241 dBW/m²/100 MHz taking into account a maximum antenna gain of 81 dBi.

The antenna pattern used is based on Recommendation ITU-R RA.1631.

3.3 Methodology

3.3.1 Static analysis

Column 9 of Table 1 in Recommendation ITU-R RA.769 provides a limit for the spectral pfd of –240 dBW/m² Hz as the threshold for harmful interference in the band 10.6-10.7 GHz based on an integration time of 2 000 s and receivable from any direction. For SAR-4 in spot mode we find that the average spectral pfd on the Earth's surface is given by

$$S_{pfd}(\Phi) = 10 \cdot \log(P_{rad} \cdot \eta) + G_{SAR} - 10 \cdot \log(B) - 10 \cdot \log\left(4\pi \cdot h_{alt}{}^{2}\right) + 20 \cdot \log(\cos(\Phi))$$

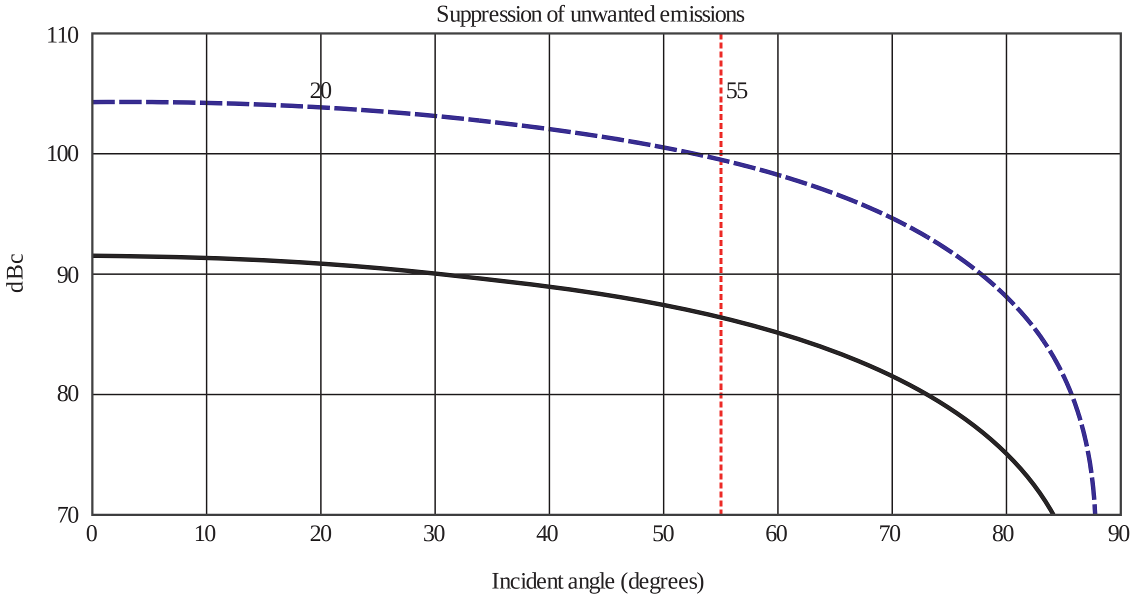
as a function of the incident angle Φ (see also § 3.5.1), where values for the radiated power P_{rad} (W), bandwidth B (Hz), duty cycle η, altitude h_{alt} (m) and the antenna gain G_{SAR} (dBi) are listed in Table 4. As a worst case, we assume that the area of the radio astronomical station will be illuminated once during a 2 000-second integration interval and that the illumination lasts for a maximum of five seconds and travels through the boresight gain axis of the RAS antenna. We thus increase the interference threshold by $5 \cdot \log\left(\frac{2000 \cdot s}{5 \cdot s}\right) = 13\,\text{dB}$ according to Recommendation ITU-R RA.769 and obtain an effective interference threshold of S_{5s} = –227 dBW/m² Hz per exposure event ("snapshot"). The required suppression of unwanted emissions A_{OOB} is then the difference given by

$$A_{OOB}(\Phi) = S_{pfd}(\Phi) - S_{5s}$$

which is shown as a function of incident angle in Fig. 3.

FIGURE 3

EESS SAR required suppression of unwanted emissions in the band 10.68-10.7 GHz



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The dotted curve provides the required suppression for a continuous transmission and the solid curve gives the required average suppression of unwanted emissions in the band 10.68-10.7 GHz for five seconds during the transit of the satellite. Within the operating range of the incidence angle, the suppression ranges from $A_{OOB}(20°) = 90.736\,\text{dBc}$ to about $A_{OOB}(55°) = 86.448\,\text{dBc}$.

3.3.2 Dynamic analysis

An epfd simulation (Monte Carlo method) using the methodology described in Recommendation ITU-R M.1583 was used to assess the impact of a SAR system on radio astronomy. 100 runs were performed in a total of 2 334 cells of equal solid angles distributed over the sky. The initial time of RAS integration was chosen randomly for each cell and each run. The EESS satellite orbit propagated over this integration time and the epfd generated at the RAS station were calculated, and the epfd was compared with the criterion. Whenever the epfd exceeds the threshold given by the criterion, there would be a loss of data in the observation performed by the radio astronomy station. The overall percentage of assumed tolerable data loss is 2%.

Since the RAS protection criterion is defined for a period of 2 000 s, the pfd needs to be averaged using the duty cycle, and converted into 100 MHz which is the reference bandwidth for RAS continuum measurements in this band.

In order to assess the potential interference conditions produced by a SAR-4 system in spotlight mode, a simulation model was developed, based on a combination of Satellite Tool Kit® and MATLAB®.

The track period of the SAR-4 sub-satellite point repeats every 11 days. The full satellite orbit (interference) scenario has been calculated for this period at time intervals of one second. The satellite illuminates the area around the RAS station when the angular conditions are met as shown in Fig. 4. The entire illumination period of the station occurs during typically 5 s under varying incident angles.

FIGURE 4

Applied simulation scenario modelling the spotlight mode

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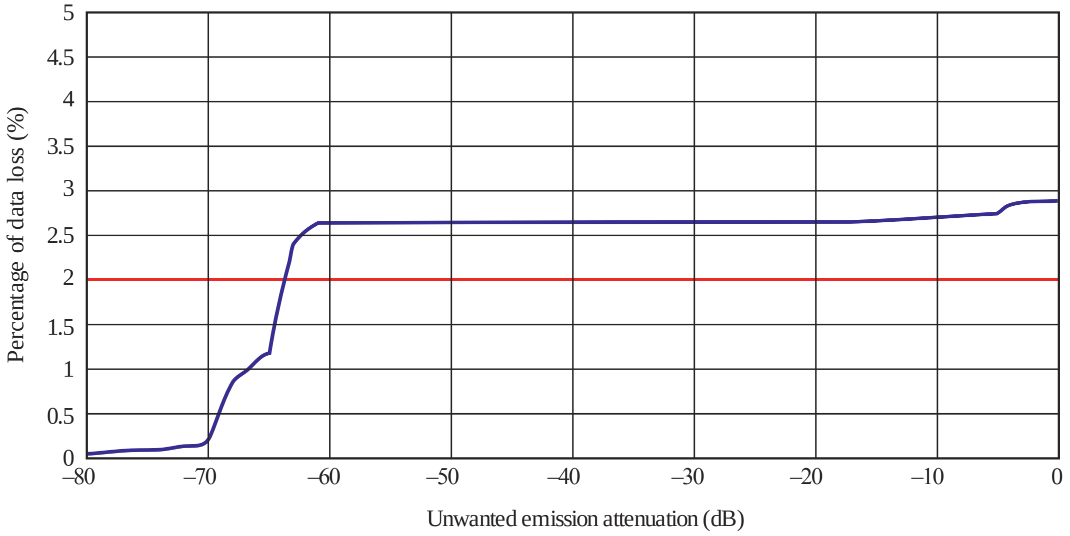
3.4 Simulation results and discussion

Figure 5 provides the percentage of data loss vs. the unwanted emission attenuation on the peak RF transmission power when the SAR system illuminates the RAS station area during all passages where it is within the radio range of the satellite.

FIGURE 5

Data loss vs. attenuation for spotlight mode above RAS station



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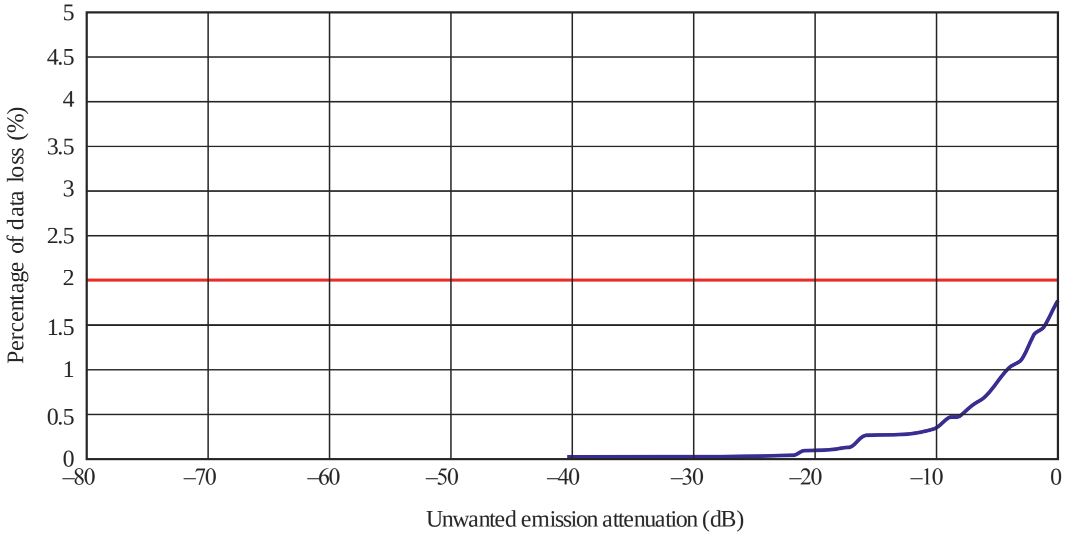
In such cases, an attenuation of 63 dB would be required to meet the 2% protection criterion.

FIGURE 6

Data loss vs. attenuation for spotlight mode avoiding RAS station



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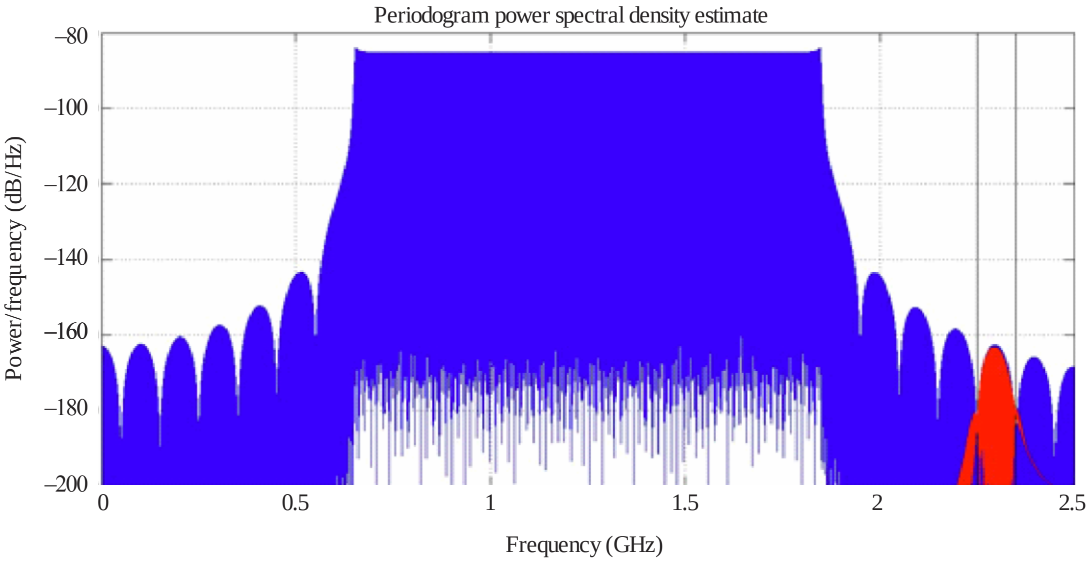
As shown in Fig. 6, if the RAS station location is not within a spotlight mode acquisition area, no specific attenuation would be required to meet the 2% criterion, as the SAR antenna provides the required isolation.

A 63 dB attenuation might be difficult to implement in practice, also somewhat dependent on where the EESS (active) extension will actually be allocated (below 9 300 MHz or above 9 900 MHz). Figures 7 and 8 show the theoretical average power spectral density (PSD) of a 1 200 MHz chirp transmission with a 50 µs pulse length, 10 ns rise and fall times, and a 0 dBW peak power centered on 9 600 or 9 900 MHz, respectively.

The blue line is the original SAR spectrum, while the red one would be the result of filtering applying a 100 MHz Butterworth type pass-band filter.

FIGURE 7

Average PSD of the SAR signal centered at 9 600 MHz



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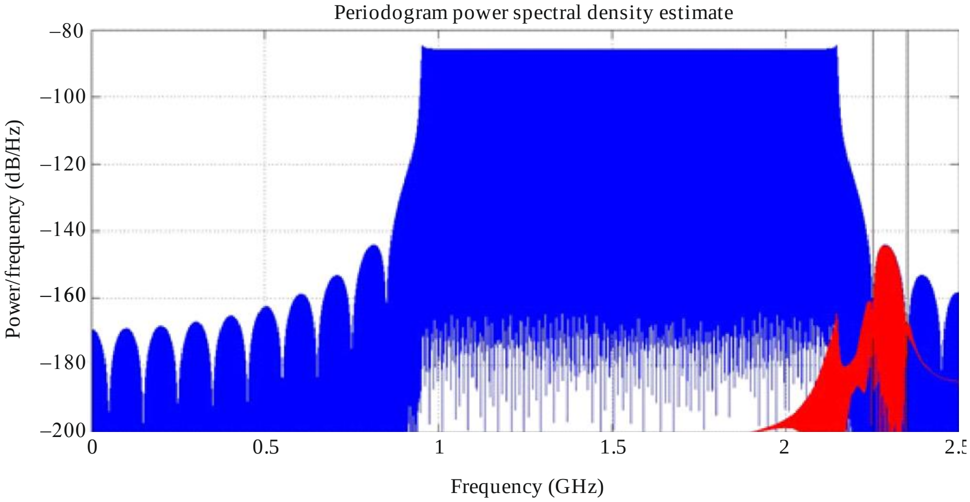
The average power produced in the RAS band is –96 dBW.

FIGURE 8

Average PSD of the SAR signal centered at 9 900 MHz



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The average power produced in the RAS band is –77 dBW.

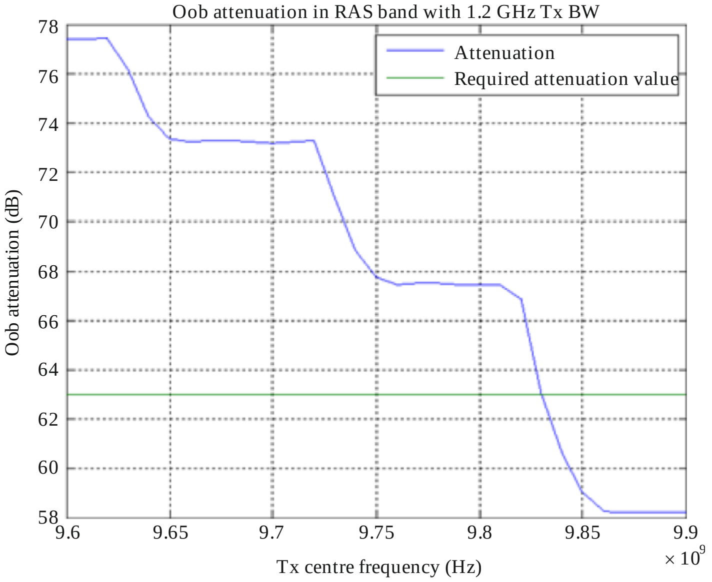
It is important to note that the levels shown in Figs 7 and 8 are theoretical values. Power amplifiers in the transmitter modules of active SAR antennas might generate additional OoB or spurious emissions that could increase these levels.

Should such an attenuation not be achievable in practice, additional mitigation techniques would be required. One simple mitigation technique would consist in limiting the recurrence of image acquisition of the area where a RAS observatory performing observations in this band is located. In the simulation above, an acquisition is systematically done as soon as the RAS is under the specific angular conditions as specified in Fig. 2, which happens up to 12 times over the 11 days for the latitude considered. In normal operation, such a number of pictures of one single remote area would not be requested. Dividing by 2 the number of acquisitions would, as a consequence, also divide by 2 the percentage of data loss, allowing the 2% criterion to be met.

In case 63 dB attenuation is needed, Fig. 9 shows the actual PSD OoB emission attenuation in the RAS observation bandwidth as a function of the SAR transmitted centre frequency in the range of 9 600-9 900 MHz assuming a bandwidth of 1 200 MHz.

FIGURE 9

OoB attenuation in RAS band vs. SAR transmission centre frequency (BW=1 200 MHz)



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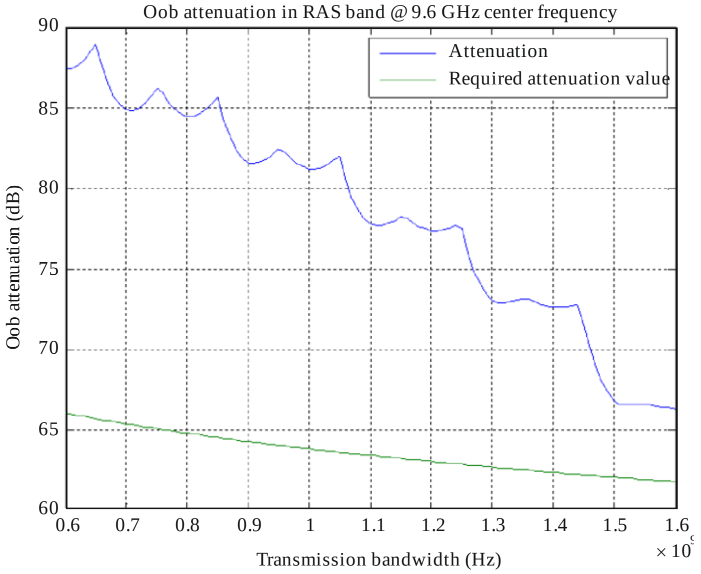
The highest centre frequency that meets the 63 dB attenuation, without margin, is 9 820 MHz as shown in Fig. 9.

Figure 10 shows the SAR-4 PSD OoB attenuation in the RAS observation bandwidth when a chirp signal is transmitted at a central frequency of 9 600 MHz and its bandwidth is a parameter. Since the required OoB attenuation of 63 dB has been computed above for a 1 200 MHz signal bandwidth, this limit has been updated on the basis of the effective BW according to the following equation:

$$\text{Required OoB attenuation (dB)} = 63 + 10 * \log_{10}\left(\frac{B_{TX}\ (\text{MHz})}{1200}\right)$$

FIGURE 10

OoB attenuation in RAS band vs. SAR transmission bandwidth (at 9 600 MHz centre frequency)



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The result of this analysis is that the required SAR OoB emission attenuation limit to meet the RAS protection threshold is always met when the signal carrier is at 9 600 MHz.

Finally, Figs 11 and 12 show the trend of the integrated interference mean power within the RAS bandwidth in the same hypothesis of simulations when 0 dBW peak power is transmitted by the SAR-4 system. These results are consistent with those reported in § 3.

FIGURE 11

Mean interference power in RAS band vs. SAR transmission centre frequency (TX_BW = 1 200 MHz)

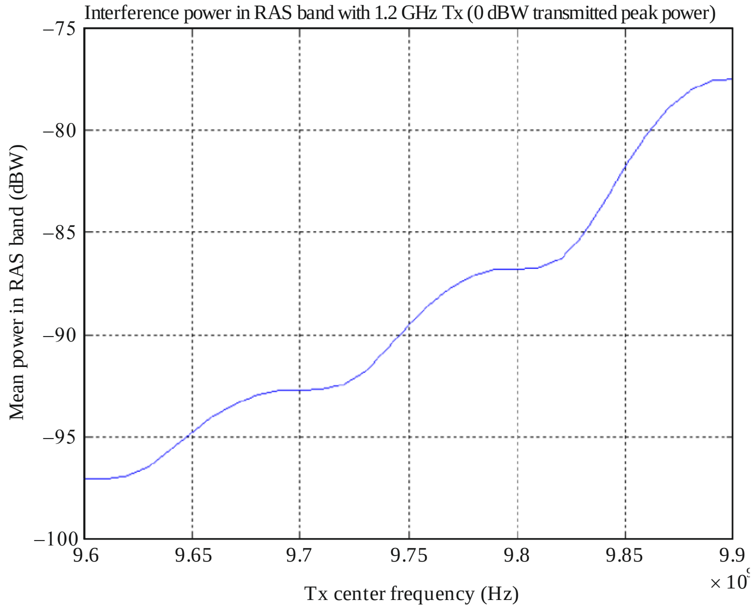

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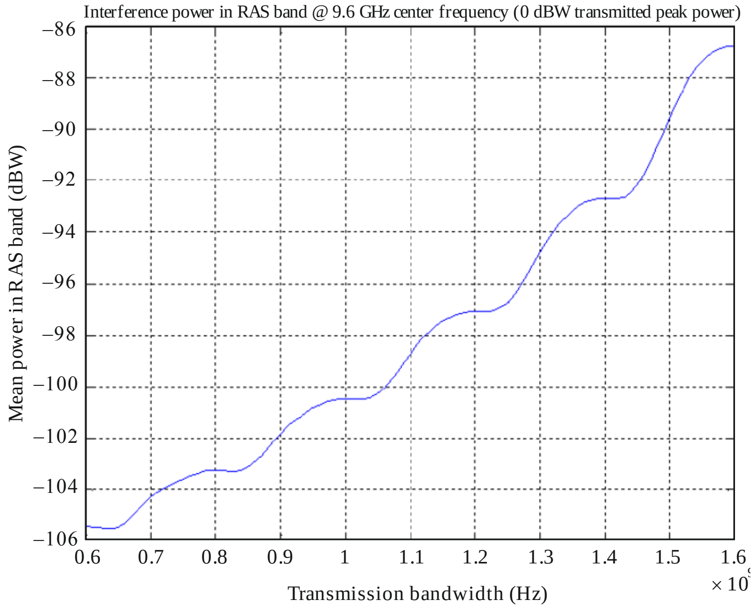
FIGURE 12

Mean interference power in RAS band vs. SAR transmission bandwidth (centre frequency 9 600 MHz)



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3.5 Additional potential impairments of RAS operations

3.5.1 Basic assumptions

The pfd level of the SAR is calculated as:

$$pfd = \frac{P \cdot G}{4\pi}\left(\frac{\cos\Phi}{h}\right)^2$$

with:

pfd: power flux-density level at Earth's surface (W/m²)
P: SAR transmit power (W)
G: SAR antenna gain
h: orbit altitude (m)
Φ : incident angle (degrees).

3.5.2 Detection and blocking by strong ambient signals from outside the receiver IF bandwidth

Radio astronomical receivers suppress strong local signals mainly by the directivity of the antenna and in addition to that with an IF selectivity that suppresses OoB signals entering the feed by typically 60 dB. This number also corresponds in the order of magnitude to the compression point of the receiver chain (or system). Using the values for the typical receiver and antenna temperatures for 10.6 GHz given in columns 3 and 4 of Table 1 of Recommendation ITU-R RA.769 and adding 60 dB headroom to it, we obtain a critical ambient pfd of

$$10 \cdot \log\left[(22K) \cdot k \cdot 10^8\,\mathrm{Hz}\right] - 10 \cdot \log\left[\frac{c^2}{4\pi \cdot (10.6 \cdot 10^9\,\mathrm{Hz})^2}\right] + 60 = -33.213\,\mathrm{dBW/m}^2$$

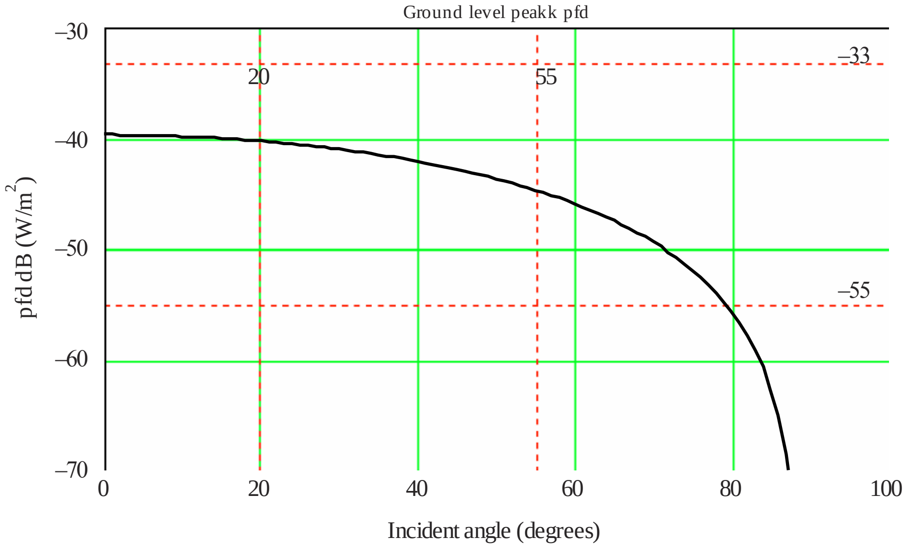
with:

k: Boltzmann Constant (Ws/K)
c: speed of light (m/s).

Figure 13, based on the calculations given in § 3.5.1, shows that this is unlikely to happen in cases where SAR and the RAS antennas are not aligned, as for typical operations there is still a margin of about 7 dB.

FIGURE 13

Ground level peak pfd from EESS SAR-4



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However, it must also be noted that in order to avoid blocking and overloading of the receiver, the RAS antenna must avoid the direction of the satellite emissions[1] by $10^{\frac{32-7}{25}} = 10$ degrees.

3.5.3 Non-linear response of RAS receivers to strong signals

Front-ends (low noise amplifier (LNA)) of a typical radio astronomical receiver have a third order input intercept point of about –25 dBm or IIP_3 = –55 dBW. For isotropic reception, this corresponds to a pfd of

$$IIP_3 = -55 - 10 \cdot \log\left[\frac{c^2}{4 \cdot \pi \cdot (10.6 \cdot \text{GHz})^2 \cdot \text{m}^2}\right]$$

resulting in $IIP_3 = -13.038$ dBW/m^2.

The strength of third order harmonics and intermodulation products is estimated by

$$S_{IM}(\Phi) = 3S_{peak}(\Phi) - 2 \cdot IIP_3 \ \text{dBW/m}^2$$

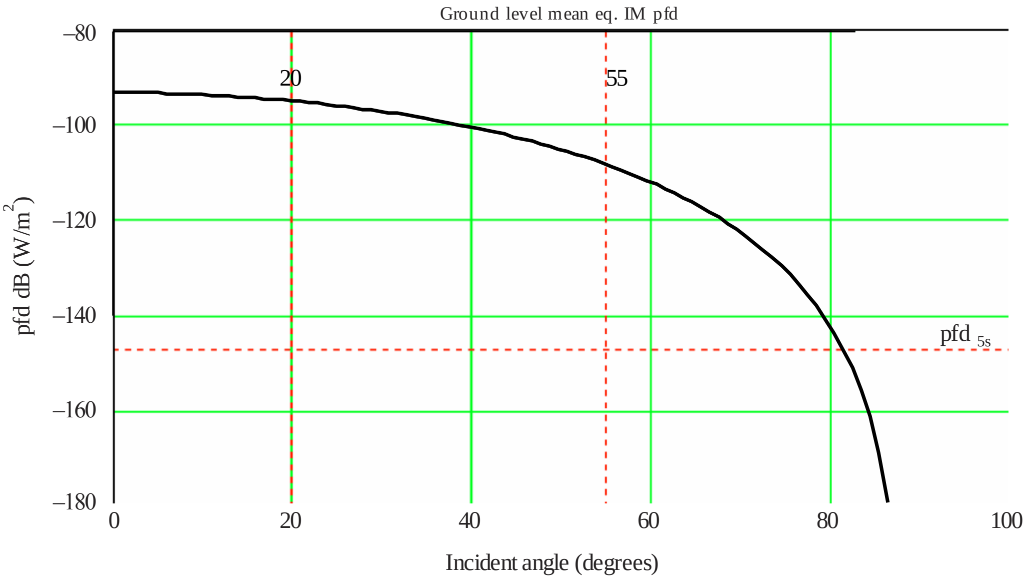
and shown in Fig. 14 below.

---

[1] This figure is based on the G = 32−25*log10(φ) gain approximation as given by Recommendation ITU-R S.1428.

FIGURE 14

Non-linear response of the RAS receiver to strong ambient signals



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The pfd limit for five second integration time of –147 dBW/m^2 is also indicated. For the range of operating incidence angles we find a margin of –52 dB for 20° incidence and –39 dB for 55°.

There would therefore be a potential problem since the second order intermodulation products generated by a signal starting for instance at 9 GHz and finishing at 10.2 GHz could fall within the 10.6-10.7 GHz band[2]. However this supposes that during the pulse duration the full bandwidth is transmitted simultaneously, which is not at all the case. The pulse is in fact a ramp in frequency, a chirp, where a single tone moves from one side of the bandwidth to the other side during the pulse duration, which is 50 µs for SAR-4.

In the example given here the frequency 9 820 MHz is not transmitted at the same time as the frequency 9 000 MHz, but 34 µs later. Therefore, there is no possibility of intermodulation products falling into the RAS receiver bandwidth.

3.5.4 Risk of damage to the RAS receiver

To determine the worst case, it is assumed that the main transmission boresight beam of the SAR is directly boresight coupled with the RAS stations receive antenna.

Following Report ITU-R RA.2188, the possibility of damaging a receiver operating in the RAS is investigated. Table 1 of that Report indicates that the pfd level of a SAR system must be less than –55 dBW/m^2 over the frequency range 1-20 GHz to protect RAS receivers.

It should be noted that this level is defined in all frequency bands, including outside, and far away from, RAS allocated bands, whereas similar levels defined for the space research service are limited within or close to the SRS allocations.

For the Effelsberg 100 m deep-space antenna with an effective receiving area of 7 840 m^2, the –55 dBW/m^2 damage limit corresponds to an input power of about 25 mW.

Different incident angles were used for the calculations. The results are presented in Table 4 and Fig. 14 gives a graphic illustration of the pfd as a function of incident angle.

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[2] For example: 2 × 9 820 MHz – 9 000 MHz would result in 10.64 GHz.

TABLE 4

Power flux density level at Earth's surface

Parameter	**SAR-1**		**SAR-2**	**SAR-3**		**SAR-4**	
Radiated power (W)	1 500		5 000	25 000		7 000	
SAR antenna gain (dBi)	44		46	42.5		47	
Orbital altitude (km)	400		619	506		510	
Incidence angle (°)	21	60	38	22	50	20	55
Slant range (km)	426	758	765	542	737	540	830
pfd (dB(W/m^2))	–47.8	–52.8	–45.7	–39.2	–41.9	–40.2	–43.9
Criterion (dB(W/m^2))	–55	–55	–55	–55	–55	–55	–55
Margin (dB(W/m^2))	–7.2	–2.2	–9.3	–15.8	–13.1	–14.8	–11.1

Table 4 indicates that there would be a margin of –14.8 dB which corresponds to a maximum input power of 750 mW which clearly is destructive for any sensitive input stage (LNA). However, it should be noted that the pfd levels radiated by SAR-4 with the extended bandwidth are similar to other SAR systems that operate or are planned to operate around 9 600 MHz. These results are also very similar to the results obtained for other EESS (active) systems such as SAR, scatterometers and precipitation radars in other frequency bands of which information can be found on the website of the Space Frequency Coordination Group (SFCG) (www.sfcgonline.org).

Appropriate measures may need to be developed to completely avoid even a low risk of receiver damage. These measures may include a coordination between operators of SAR systems and potentially affected RAS stations.

For the SAR system

The emission beam contour corresponding to the margin defines the damage zone for a potential boresight-to-boresight coupling of both antenna beams. These contours have the form of an ellipse with a major axis $\delta\theta_h$ in the horizontal beam direction and the minor axis $\delta\theta_v$ in the vertical beam direction, thus defining an area where the pfd level at the RAS station would exceed –55 dBW/m^2. The telescope should not be exposed to SAR emissions within a range of $\Phi \pm \delta\theta_h$ in the horizontal and $\Phi \pm \delta\theta_v$ in the vertical direction of the SAR beam when transmitting with an incident angle Φ.

The projection onto the ground provides the size of an area with an extension of $\pm\delta_h$ in the horizontal direction and $\pm\delta_v$ in the vertical direction around the RA station which should not be illuminated. Table 5 lists the parameter range for the avoidance of accidental damage to a RA station[3].

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[3] In the vertical direction, there is an asymmetry of 5.6% for $\delta\theta_v$ and δ_h between inner and outer exclusion angles and distances which has been neglected. Only the larger outer value has been listed. The ground projections of the margin contours which are distorted ellipses were approximated by rectangles.

TABLE 5

Parameters for the avoidance of accidental damage to RA receivers

Incident angle Φ	Horizontal exclusion angle $\delta\theta_h$	Vertical exclusion angle $\delta\theta_v$	Horizontal separation δ_h (km)	Vertical separation δ_v (km)
20°	1.9°	4.4°	19.4	45.9
55°	0.5°	1.1°	13.1	28.6

For the RAS stations

The new SAR missions using the extended band might need to be added to the list of EESS (active) missions on the SFCG website.

The SAR is only able to make an acquisition of any location on the Earth in an area limited in azimuth and elevation on both sides of the satellite orbit as shown in blue in Fig. 15. It is possible to determine four sectors in azimuth and elevation where the RAS station could have to avoid pointing towards the SAR satellite when it is in visibility, in order to avoid main-beam to main-beam coupling situations. These sectors are derived from the portions of orbits where the antenna is in visibility of the RAS station, shown in white color in Fig. 15.

FIGURE 15

SAR-4 acquisition geometry

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These sectors are as shown in Table 6.

TABLE 6

Sectors to be avoided by the RAS station in order to avoid main beam to main beam coupling with the SAR

Sector	Elevation	Azimuth
1	35-70°	70-83°
2		95-108°
3		253-265°
4		277-289°

In those cases, in order to avoid main-beam-to-main-beam coupling, the RAS station would have to avoid pointing into a cone with a half angle limited to 0.03° around the SAR satellite location. For a 100 m antenna, this corresponds to a reduction of more than 25 dB in the power received.

4 Compatibility between EESS (active) around 9 600 MHz and EESS (passive) in the frequency band 10.6-10.7 GHz

4.1 Introduction

Under WRC-15 agenda item 1.12, an extension of the EESS (active) allocation in the frequency band 9 300-9 900 MHz by up to 600 MHz is sought in the frequency range 8.7 to 10.5 GHz.

Concerns were expressed about the protection of EESS passive sensors operating in the band 10.6-10.7 GHz from harmful interference due to the unwanted emission levels of such wide bandwidth EESS (active) systems. This document analyses the impact of SAR systems planned to operate with the possible expansion into passive sensors.

4.2 Characteristics of EESS (passive)

4.2.1 Provisions of the EESS (passive) allocation

The band 10.6-10.68 GHz is allocated to the EESS (passive), RAS and SRS (passive) and also terrestrial services (fixed and mobile). The band 10.68-10.7 GHz has a provision, RR No. **5.340**, relevant for passive services (see Table 3).

The band 10.6-10.7 GHz is of primary interest for passive EESS systems to measure rain, snow, sea state and ocean wind.

4.2.2 Required protection criteria

Recommendations ITU-R RS.515 and RS.2017 establish the interference criteria for passive sensors.

The first criterion is the permissible interference power received by the EESS (passive) sensor which is −166 dBW in the reference bandwidth of 100 MHz. This is a maximum aggregate interference level from all sources.

The second criterion is the maximum number of occurrences that the threshold is exceeded. These interference levels should not be exceeded for more than 0.1% of sensor viewing area (data availability of 99.9%) for measurement area defined as a square on the Earth of 10 000 000 km^2.

4.2.3 Operational characteristics

According to Recommendation ITU-R RS.1861, Table 7 shows specifications for five microwave radiometric systems.

TABLE 7

EESS (passive) sensor characteristics in the 10.6-10.7 GHz band

	Sensor C1	**Sensor C2**	**Sensor C3**	**Sensor C4**	**Sensor C5**
Sensor type	Conical scan				
Orbit parameters					
Altitude	817 km	705 km	833 km	835 km	699.6 km
Inclination	98°	98.2°	98.7°	98.85°	98.186°
Eccentricity	0	0.0015	0	0	0.002
Repeat period	N/A	16 days	17 days	N/A	16 days
Sensor antenna parameters					
Number of beams	1		2	1	
Reflector diameter	0.9 m	1.6 m	2.2 m	0.6 m	2.0 m
Maximum beam gain	36 dBi	42.3 dBi	45 dBi	36 dBi	44.1 dBi
Polarization	H, V		H, V, R, L	H, V	
−3 dB beamwidth	2.66°	1.4°	1.02°	3.28°	1.2°
Instantaneous field of view	56 km × 30 km	51 km × 29 km	48 km × 28 km	76 km × 177 km	41 km × 21 km
Main beam efficiency		94.8%	95%		93%
Off-nadir pointing angle	44.3°	47.5°	47°	55.4°	47.5°
Beam dynamics	20 rpm	40 rpm	31.6 rpm	2.88 s scan period	40 rpm
Incidence angle at Earth	52°	55°	58.16°	65°	55°
−3 dB beam dimensions	56.7 km (cross-track)	27.5 km (cross-track)	42.9 km (cross-track)	N/A	23 km (cross-track)
Swath width	1 594 km	1 450 km	1 600 km	2 000 km	1 450 km
Sensor antenna pattern	See Rec. ITU-R RS.1813	Fig. 8a (Rec. ITU-R RS.1861) [See note]	Fig. 8b (Rec. ITU-R RS.1861) [See note]	See Rec. ITU-R RS.1813	
Cold calibration ant. gain	N/A	29.1 dBi	N/A		29.6 dBi
Cold calibration angle (degrees re. satellite track)	N/A	115.5°	N/A		115.5°
Cold calibration angle (degrees re. nadir direction)	N/A	97.0°	N/A		97.0°
Sensor receiver parameters					
Sensor integration time	1 ms	2.5 ms	2.47 ms	N/A	2.5 ms
Channel bandwidth	100 MHz	100 MHz centered at 10.65 GHz			
Measurement spatial resolution					
Horizontal resolution	38 km	27 km	15 km	38 km	23 km
Vertical resolution	38 km	47 km	15 km	38 km	41 km

Under Recommendation ITU-R RS.1861, the title of Fig. 8a is “Sensor C1 antenna pattern envelope for the 10.6-10.7 GHz band”, and the title of Fig. 8b is “Sensor C2 antenna pattern envelope for the 10.6-10.7 GHz band”. Therefore, Sensor C2 and C3 of this Table 7 do not match with these Figures.

4.3 Static analysis of the impact of SAR-4 on EESS (passive)

It should be noted that only single entry interference from proposed SAR should be taken into account in the interference analyses. Aggregate interference of proposed SAR does not need to be considered. This is because it is very unlikely that multiple SAR observes the same area (otherwise there may be mutual impact among proposed SARs).

The orbital characteristics of all SAR systems are quite similar, as well as the antenna orientation of the satellites.

Table 8 provides a comparison of the mean pfd spectral density created on the Earth's surface by EESS (active) SAR systems. The mean pfd is considered appropriate here because EESS (passive) sensors perform some post-integration in order to be able to retrieve the very low power signal of interest, over a few ms or tens of ms, which in any case is larger than the pulse repetition interval of the SAR system.

TABLE 8

Comparison of the pfd spectral density with other SAR systems

	SAR-1	**SAR-2**	**SAR-3**	**SAR-4**
e.i.r.p. (dBW)	76	83	86	85.5
Bandwidth (MHz)	10	400	450	1 200
Pulse length (µs)	34	80	10	50
PRF (pps)	1 736	4 500	515	6 000
Mean e.i.r.p. spectral density (dBW/MHz)	54	53	37	50
Minimum slant range (km)	424	654	536	540
Mean pfd spectral density (dBW/m²/MHz)	–70	–75	–89	–75

It can be seen that SAR-4 will radiate a mean pfd spectral density similar to SAR-2 and even lower than SAR-1.

There may be two different worst-case situations of possible interference to EESS (passive) satellites:

- Scenario 1: Interference due to the back lobes of the EESS (active) satellite antenna and received in the passive sensor main beam.
- Scenario 2: Interference due to scattering of the SAR signal by the Earth surface.

Scenario 1 occurs when the EESS (passive) sensor receives part of the SAR energy through the main lobe. The results of the analysis are provided in Table 9, assuming that the sensors operate in the same frequency band. Therefore, no unwanted emission attenuation is considered.

It should be noted that the theoretical SAR antenna pattern given in Table 2 does not give a representative value for the back lobes, which should rather be in the order of –9 dB. While this would not have any impact on sharing or compatibility studies dealing with terrestrial stations, this would have a major impact in compatibility studies involving satellites at higher altitudes than SAR, including EESS (passive) satellites. The value of –9 dBi was taken into account in Table 9, but not in the dynamic analyses.

TABLE 9

Interference to EESS (passive) sensor through the main lobe by SAR-4

EESS (passive) sensor	Sensor-1	Sensor-2	Sensor-3	Sensor-4	Sensor-5
SAR mean e.i.r.p. (dBW/MHz)	50.0				
SAR backlobe gain (dBi)	–9.0				
SAR antenna gain discrimination (dB)	56.0				
EESS (passive) off-nadir pointing angle (°)	44.3	47.5	58.2	55.4	47.5
EESS passive satellite altitude (km)	817.0	705.0	833.0	835.0	700.0
Main lobe passive sensor antenna gain (dBi)	36.0	42.3	45.0	36.0	44.1
Distance SAR− Satellite EESS passive (km)	438.5	293.7	655.8	604.0	286.0
Space attenuation (dB)	165.8	162.3	169.3	168.6	162.1
Power received in the EESS sensor (dBW/100 MHz)	–115.8	–106.0	–110.3	–118.6	–104.0
Protection criterion (dBW/100 MHz)	–166				
Margin (dB)	–50.2	–60.0	–55.7	–47.4	–62.0

Scenario 2 occurs when the EESS (passive) sensor receives part of the SAR energy reflected by the Earth surface through the main lobe. Table 10 shows the results of the analysis without attenuation due to OoB emissions, as a typical case. Table 11 shows the worst-case static analysis results using the worst-case backscatter coefficient without attenuation due to unwanted emissions.

It should be noted that backscatter coefficient is one of the key parameters in this interference scenario. Since the 10% (–10 dB) value for the backscatter coefficient appears generally applicable, 10% value is used for the typical case analysis. On the other hand, since the assumption of 10% backscatter is not always applicable, the worst-case analysis with the worst-case backscatter coefficient should also be conducted.

TABLE 10

Interference to EESS (passive) sensor from SAR-4 backscattered energy (typical case)

EESS (passive) sensor	Sensor-1	Sensor-2	Sensor-3	Sensor-4	Sensor-5
SAR in-band mean ground pfd (dB(W/m²/MHz))	–76.2				
Reflected area (km^2)	41.8				
Backscatter coefficient (%)	10.0				
Reflected SAR power (dBW/100 MHz)	10.0				
EESS (passive) off-nadir pointing angle (degrees)	44.3	47.5	58.2	55.4	47.5
EESS passive satellite altitude (km)	817.0	705.0	833.0	835.0	700.0

TABLE 10 (*end*)

EESS (passive) sensor	**Sensor-1**	**Sensor-2**	**Sensor-3**	**Sensor-4**	**Sensor-5**
Distance ground − Satellite EESS passive (km)	1 221.7	1 123.5	2 033.7	1 766.1	1 114.9
Space attenuation (dB)	174.7	174.0	179.2	177.9	173.9
Passive sensor satellite antenna gain (dBi)	36.0	42.3	45.0	36.0	44.1
Received power at the passive sensor (dBW/100 MHz)	–128.7	–121.7	–124.2	–131.9	–119.9
Protection criterion (dBW/100 MHz)	–166				
Margin (dB)	–37.3	–44.3	–41.8	–34.1	–46.1

TABLE 11

Worst-case interference to EESS (passive) sensors from SAR backscattered energy

EESS (passive) sensor	**Sensor-1**	**Sensor-2**	**Sensor-3**	**Sensor-4**	**Sensor-5**
SAR in-band mean ground pfd (dB(W/m²/MHz))	–76.2 (Note 1)				
Reflected area (km²)	41.8 (Note 2)				
Backscatter coefficient (%)	120 (worst-case value)				
Reflected SAR power (dBW/100 MHz)	20.8 (Note 3)				
EESS (passive) off-nadir pointing angle (°)	44.3	47.5	58.2	55.4	47.5
EESS passive satellite altitude (km)	817.0	705.0	833.0	835.0	700.0
Distance ground − Satellite EESS passive (km)	1 221.7	1 123.5	2 033.7	1 766.1	1 114.9
Space attenuation (dB)	174.7	174.0	179.2	177.9	173.9
Passive sensor satellite antenna gain (dBi)	36.0	42.3	45.0	36.0	44.1
Received power at the passive sensor (dBW/100 MHz)	–107.5	–100.5	–103.0	–110.7	–98.7
Protection criterion (dBW/100 MHz)	–166				
Margin (dB)	–49.1	–54.5	–52.6	–44.9	–56.9

NOTE 1 – The pfd value is derived from the technical characteristics of SAR-4 in Table 8.

NOTE 2 – The reflected area is derived from the beam-width (azimuth and elevation) of SAR-4 in Table 8.

NOTE 3 – It should be noted that “Reflected area” is smaller than the observation area of EESS (passive) sensors derived from “–3 dB beam width in” Table 7 (529 km^2 to 3136 km^2). Thus, all of “Reflected SAR Power” can be considered to fall into the main beams of EESS (passive) sensors.

The negative margins which have been derived in Table 10 will be compensated by the OoB attenuation which is expected to be greater than 40 dB in the band 10.6-10.7 GHz. This is based on Recommendation ITU-R SM.1541 which gives a –40 dB bandwidth of 1 868 MHz for a chirp 1 200 MHz wide, a pulse duration of 50 µs, and rise and fall times of 10 ns. Assuming a centre frequency at 9 600 MHz, this means that the power will drop by 40 dB at 10 534 MHz. This is not true when considering a centre frequency at 9 900 MHz. However, it is expected that radar sensors will perform much better than the mask given in Recommendation ITU-R SM.1541.

It should also be noted that the situations described above are very unlikely to happen in practice.

Indeed, the risk that the SAR satellite is within the main lobe of the passive sensor is already a rare situation which last only for a very small amount of time. A SAR is not always transmitting, as the transmission time per orbit for SAR-4 is in average 200 s. The conjunction of a SAR transmitting while in the main beam of a passive sensor is an event unlikely to happen.

The same should be true for the scattering scenario. The conjunction of a passive sensor pointing to a pixel while a SAR-4 system is taking a high resolution picture of exactly the same pixel at the same time is very unlikely.

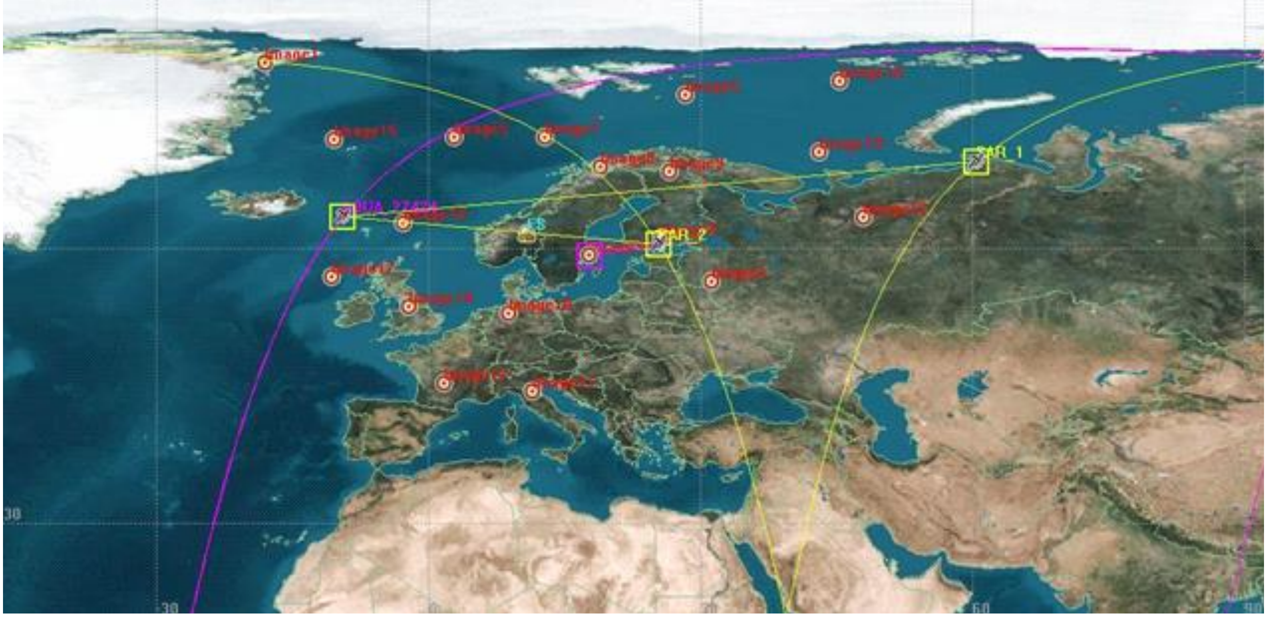
4.4 Dynamic analysis of the impact of SAR-4 on EESS (passive)

In order to assess the potential interference conditions produced by a SAR-4 system in spotlight mode, a simulation model was developed, based on a combination of Satellite Tool Kit® and MATLAB® as shown in Fig. 16. The difficulty of this kind of simulation is that the time and location of SAR acquisitions are variable and largely unknown. In this simulation a number of 20 areas have been deployed, concentrated over Europe. Each time the SAR is in visibility of these areas with the conditions given in the previous paragraph, a picture in high resolution is taken.

This simulation is intended to verify the likelihood of scenario 1 and does not account for the SAR backscattered energy.

FIGURE 16

Applied simulation scenario modeling the spotlight mode



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The interference received by EESS (passive) Sensor 2 (on board the AQUA satellite) was calculated and is shown in Fig. 17. Two types of SAR orbits are considered: A SAR-1 orbit (e.g. TerraSAR-X) and a SAR-2 orbit (e.g. COSMO SKYMED).

FIGURE 17

Interference cumulative distribution function (CDF) on Sensor 2 on board AQUA

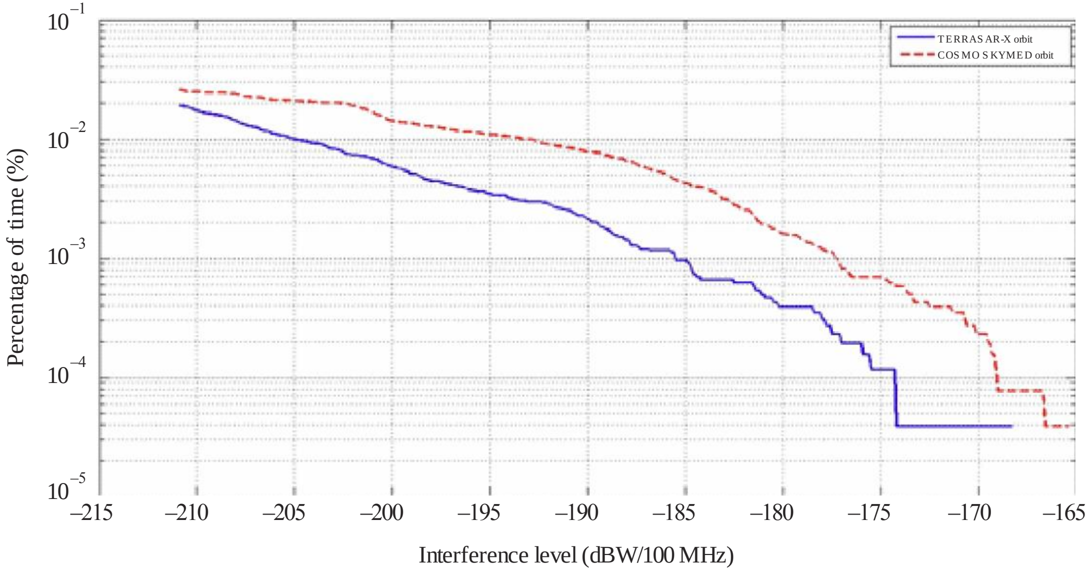

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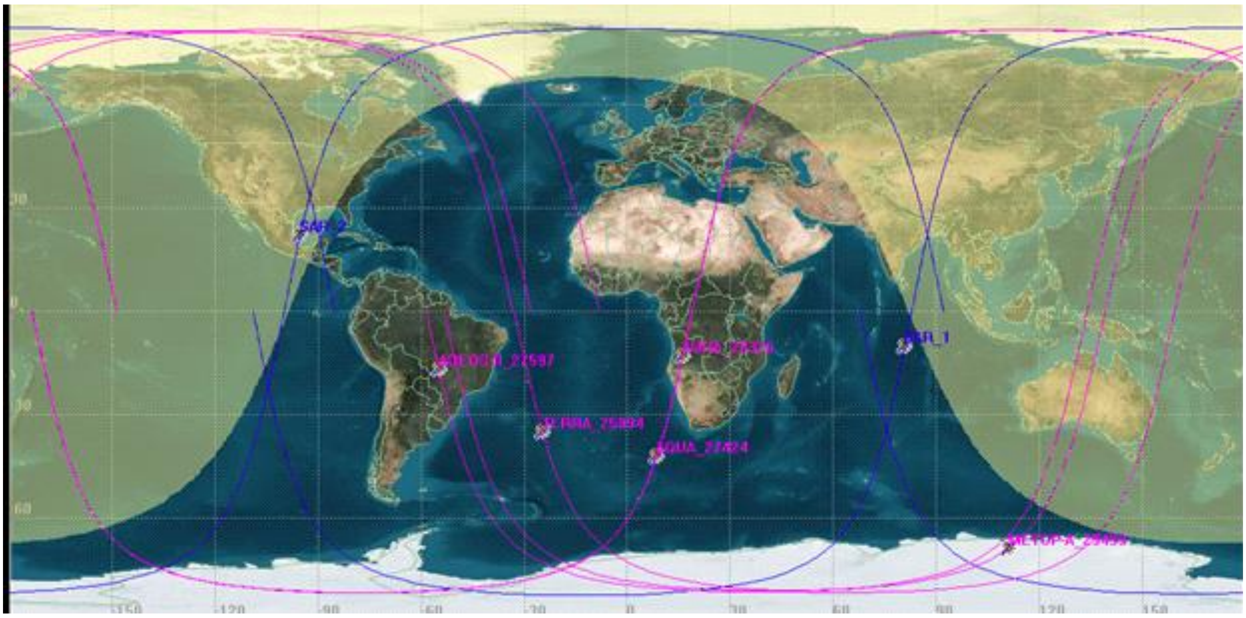
Figure 17 shows that the level of interference does not exceed –166 dBW/100 MHz for 0.00004% of the time which is to be compared with the maximum possible level of –119 dBW/100 MHz in Table 10. This means that over the entire simulation period, the worst-case scenario 1 never occurred.

It should be noted that all orbits of SAR system are phased to achieve acquisition over an intended observation area either at dawn or sunset, when the atmospheric conditions are at best for SAR systems. Other Earth observation systems use different times for ascending nodes of their orbits. It is therefore unlikely in practice that either scenarios 1 or 2 described in § 4 occur. Figure 18 illustrates this situation with two different SAR orbits (terraSAR-X and COSMO SKYMED) in blue and several other EESS satellites in pink.

FIGURE 18

Phasing of orbits of two different SAR systems and other EESS (passive) satellites



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5 Compatibility between EESS (active) and SRS in the frequency band 8 400-8 500 MHz

5.1 Introduction

Under WRC-15 agenda item 1.12, an extension of the EESS (active) allocation in the frequency band 9 300-9 900 MHz by up to 600 MHz is to be studied in the frequency range 8.7 to 10.5 GHz.

This section provides an analysis of the compatibility of space borne SAR that intend to use the full extended bandwidth of 1 200 MHz with space research systems operating in the SRS (space-to-Earth) allocated in the band 8 400-8 500 MHz. Both, deep-space SRS in the band 8 400-8 450 MHz and near-Earth SRS in the band 8 450-8 500 MHz, are analysed.

5.2 Characteristics of stations operating in the space research service

A total of 15 earth stations operate in the SRS (deep-space) worldwide, some of them using different antenna diameters. Their locations from Recommendation ITU-R SA.1014 are listed in Table 12.

TABLE 12

Location of SRS deep-space earth stations

Administration	Location	Antenna diameter (m)	Latitude	Longitude
China	Kashi Jiamusi	35 64	38° 55' N 46° 28' N	75° 52' E 130° 26' E
European Space Agency	Cebreros (Spain) Malargüe (Argentina)	35 35	40° 27' N 35° 46' S	4° 22' W 69° 22' W
	New Norcia (Australia)	35	31° 20' S	116° 11' E
Germany	Weilheim	30	47° 53' N	11° 04' E
	Effelsberg	100	50° 31' N	6° 53' E
	Wettzell	25	49° 10' N	12° 50' E
Ukraine	Evpatoriya	70	45° 11' N	33° 11' E
Russia	Medvezhi ozera	64	55° 52' N	37° 57' E
	Ussuriisk	70	44° 01' N	131° 45' E
Japan	Usuda, Nagano	64	36° 08' N	138° 22' E
United States of America	Canberra (Australia)	70	35° 28' S	148° 59' E
	Goldstone, California (United States of America)	70	35° 22' N	115° 51' W
	Madrid (Spain)	70	40° 26' N	4° 17' W

One of the largest antennas listed in Table 12 has a diameter of 70 m with a corresponding maximum antenna gain of 74 dBi at 8 400 MHz. However, most of them have an antenna diameter in the order of 35 m. For this analysis, an antenna diameter of 35 m has been considered which is representative for an earth station antenna of the European Space Agency (ESA).

The 35 m antenna is also used for Lagrange missions. Other near-Earth earth stations may use smaller antennas for missions in high elliptical orbits or to the Moon. However, the same antenna diameter of 35 m was also used for these missions in the analysis.

Recommendation ITU-R SA.1157 gives the protection criteria of SRS deep-space Earth stations as –221 dB(W/Hz) for the SRS frequency band 8 400-8 450 MHz. The calculation of non-line-of-sight interference due to trans-horizon propagation should be based on weather statistics that apply for 0.001% of the time. Recommendation ITU-R SA.1157 provides the protection criteria for receivers in SRS deep-space systems. These protection criteria are set up to protect operations of SRS deep-space earth stations and spacecraft.

Compliance to the protection criteria for these assets determines the mission success of SRS deep-space missions. Harmful interference during mission critical events, e.g. orbit insertions, planetary fly-bys, and entry-decent-and-landing (EDL) phases, can cause potential loss of a spacecraft or loss of invaluable data. There are also one-time scientific observations where a spacecraft penetrates the atmosphere of a planet or a moon, or it impacts a moon, a planet, an asteroid, or a comet. The spacecraft may be destroyed in the process, and therefore, the data transmitted during the approach or the moments before and during the impacts define the success of the missions.

In addition to the provisioning of communications and navigation needs for SRS deep-space spacecraft, the 8 400-8 450 MHz frequency band is also used for radio science experiments. For these experiments, it can be difficult to distinguish between interference events and valid observations. Therefore, the protection of SRS deep-space spacecraft and earth stations, to the extent demanded by Recommendation ITU-R SA.1157, is crucial for the success of SRS deep-space missions.

It has to be recognized that the SRS deep-space bands are not shared with any space or aeronautical radio services. For the analyses it was assumed, that the value of –221 dBW/Hz is essential to be met for 100% of the time.

Recommendation ITU-R SA.609 recommends a protection criterion for near-Earth SRS earth stations of –216 dBW/Hz in frequency bands below 20 GHz. Similar to Recommendation ITU-R SA.1157, Recommendation ITU-R SA.609 leaves ambiguities when dealing with non-terrestrial interference sources. However, similar to other studies performed in the past and at 37-38 GHz, a percentage of time of 0.1% was considered for unmanned missions and 0.001% for manned missions.

5.3 Static analysis with SRS deep-space earth stations

Table 13 provides the results of a static analysis using the characteristics of SAR-1, SAR-2 and SAR-3 systems which were taken into account in the studies prior to WRC-07 leading to the extension of the EESS allocation from 300 to 600 MHz. SAR-4 represents a new SAR system generation that intends to provide high resolution performance using a 1 200 MHz chirp bandwidth, preferably with a centered frequency at 9 600 MHz.

Four cases were defined for SAR-4 transmissions:

- a chirp bandwidth of 1 200 MHz centered on 9 300 MHz;
- a chirp bandwidth of 600 MHz centered on 9 600 MHz;
- a chirp bandwidth of 1 200 MHz centered on 9 600 MHz;
- a chirp bandwidth of 1 200 MHz centered on 9 900 MHz.

The spectral roll-off was determined using a pulse with a 10 ns rise and fall time in all cases. Some examples of spectra are given in Fig. 19. These spectra were computed based on theoretical roll-off of chirp signals used by the 600 MHz and 1 200 MHz SAR systems. However, higher OoB emission is possible if EESS (active) systems include high-efficiency power amplifiers operating in saturation mode. Further analysis of the effects of EESS (active) power amplifiers in saturation mode on EESS (active) OoB emission is needed.

In Fig. 19 below, the frequency-axis origin corresponds to a frequency of 8 350 MHz.

FIGURE 19

Shape of spectra considered to derive the spectral roll off used in Table 13

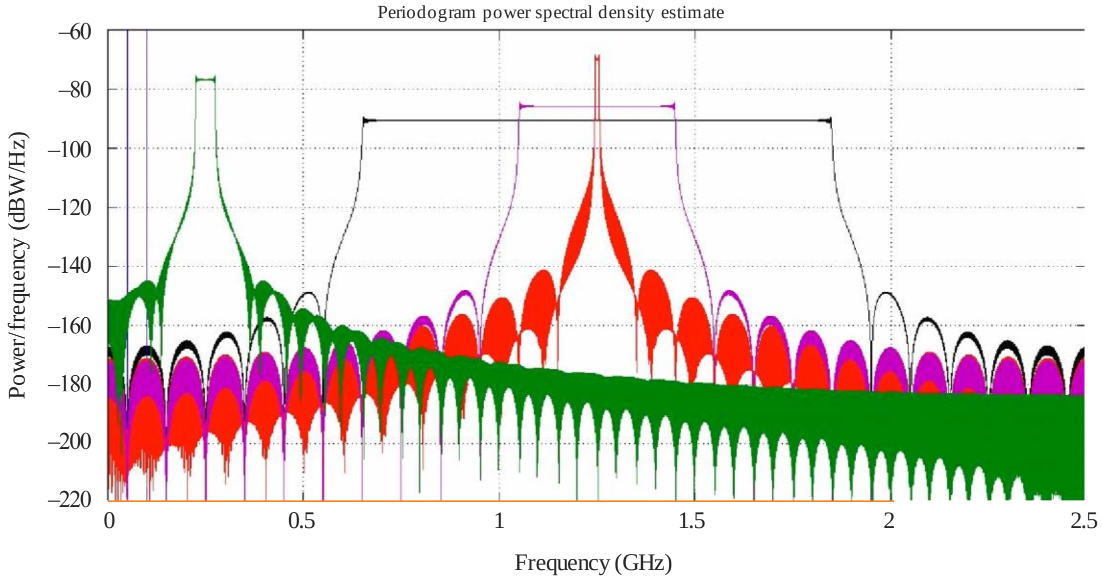

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TABLE 13

Worst-case interference power spectral densities (PSD) from five typical SARs operating on neighboring bands of SRS (deep space)

	SAR-1	**SAR-2**	**SAR-3**	**SAR-4 (9 300 MHz)**	**SAR-4 (9 600 MHz)**	**SAR-4 (9 600 MHz)**	**SAR-4 (9 900 MHz)**
e.i.r.p. (dBW)	76	83	86	85.5	85.5	85.5	85.5
Bandwidth (MHz)	10	400	450	1 200	1 200	600	1 200
Minimum slant range (km)	424	654	536	540	540	540	540
Space loss (dB)	–164	–167	–166	–166	–166	–166	–166
Rx antenna peak gain (dBi)	74	74	74	74	74	74	74
Polarization loss (dB)	–3	–3	–3	–3	–3	–3	–3
Rx PSD in SAR Bands (dBW/Hz)	−87	−99	−95	−100	−100	−97	−100
Deep-space protection criterion (dBW/Hz)	–221	–221	–221	–221	–221	–221	–221

TABLE 13 (*end*)

	SAR-1	**SAR-2**	**SAR-3**	**SAR-4 (9 300 MHz)**	**SAR-4 (9 600 MHz)**	**SAR-4 (9 600 MHz)**	**SAR-4 (9 900 MHz)**
Req. OoB attenuation for SRS (deep-space)	134	122	126	121	121	124	121
Theoretical spectral roll-off (dB)	–102	–87	–84	–65	–75	–80	–81
Rx interference PSD (dBW/Hz) in 8 400-8 450 MHz	–189	–186	–179	–165	–175	–177	–181
Exceedance of protection threshold (dB)	32	35	42	56	46	44	40

It can be seen that, using a pure static analysis, with the theoretical spectral roll-off shown in Fig. 19, all systems would exceed the SRS (deep-space) protection criteria by 32 to 56 dB. For SAR-4 with bandwidth of 1 200 MHz, 121 dB of OoB attenuation at 8 400-8 450 MHz band is needed to protect SRS (deep space) missions.

It should be noted that there are systems in orbit for many years, such as the Italian Cosmo SkyMed system similar to SAR-2, operating four satellites, where no harmful interference has been reported to the ITU-R Radio Bureau, although brief interference events, not necessarily attributable to Cosmo SkyMed system, have been observed by SRS (deep-space) stations.

It is also important to note that SAR-4, when using a bandwidth limited to 600 MHz at 9 600 MHz, would generate a worst-case interference PSD which is only 2 dB below SAR-4 using the 1 200 MHz extended bandwidth. Currently, neither specific regulatory provisions nor an ITU-R Recommendation exist to specify the protection of SRS systems from unwanted emissions of EESS systems using the 9 600 MHz allocation.

A purely static approach seems to indicate that harmful interference may occur under rare conditions. The significant difference between the results of this analysis and the reality may be explained when considering a dynamic simulation as shown in § 5.4 below.

5.4 Dynamic analysis with both deep-space and near-Earth SRS

The victim SRS station in the sharing scenario is located in Robledo in Spain. The satellite illuminates the area around the SRS station when the angular constraints are met as shown in Fig. 20. The entire illumination period of the station occurs during five seconds under varying incident angles. In addition to the SRS station, nineteen targets have been deployed around the SRS earth station in order to account for additional interference due to the side lobes of the SAR system. The locations of the targets are shown in Table 14 and Fig. 20 where the victim SRS station in Robledo, Spain is listed as Target 1.

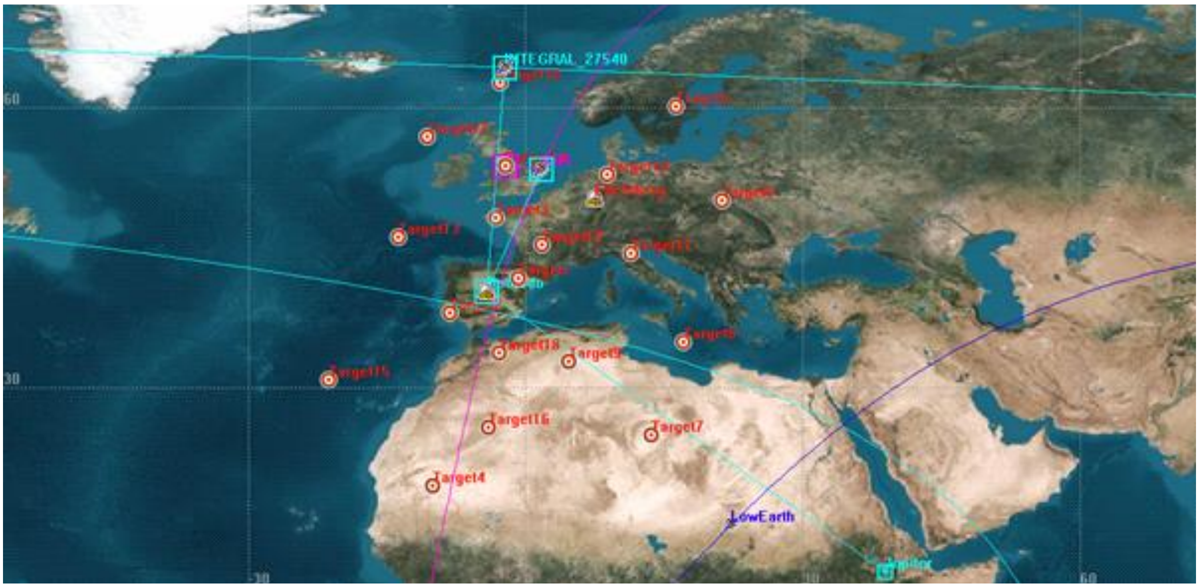
TABLE 14

Targets used in dynamic simulations of OoB interference to SRS

	Lat (degrees)	Lon (degrees)		Lat (degrees)	Lon (degrees)
Target 1	40.260	–4.170	Target 11	62.730	–2.708
Target 2	41.648	–0.805	Target 12	33.645	–2.802
Target 3	52.840	8.828	Target 13	37.978	–8.145
Target 4	44.354	11.442	Target 14	48.161	–3.191
Target 5	45.226	1.809	Target 15	19.463	–10.006
Target 6	46.097	–13.741	Target 16	50.035	21.268
Target 7	53.712	–2.136	Target 17	60.159	16.357
Target 8	30.730	–21.310	Target 18	24.876	13.650
Target 9	25.687	–3.939	Target 19	34.799	17.058
Target 10	56.856	–10.571	Target 20	32.749	4.653

FIGURE 20

Applied simulation scenario modeling the spotlight mode



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Simulations were conducted for a mission around Jupiter (SRS Earth station tracking Jupiter), a mission around Mars, a low Earth orbit (600 km altitude, 30° inclination), and the ESA Integral mission (high elliptical orbit). As mentioned in § 3, a 34 m dish was considered for all three missions, with a pattern defined in Annex III of RR Appendix **8**.

FIGURE 21

Cumulative distribution functions of the interference received for different types of SRS missions

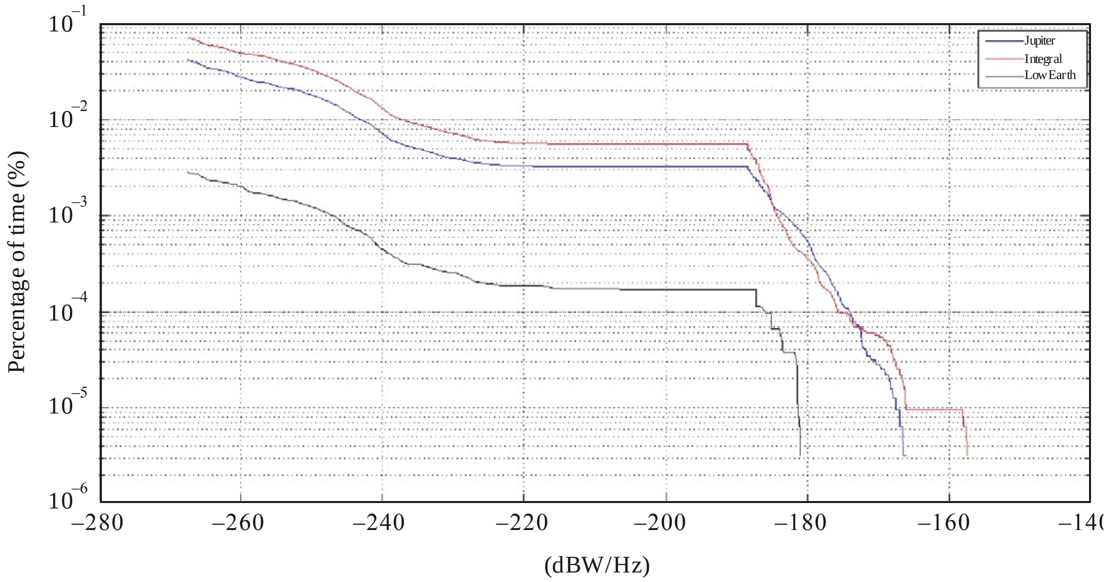

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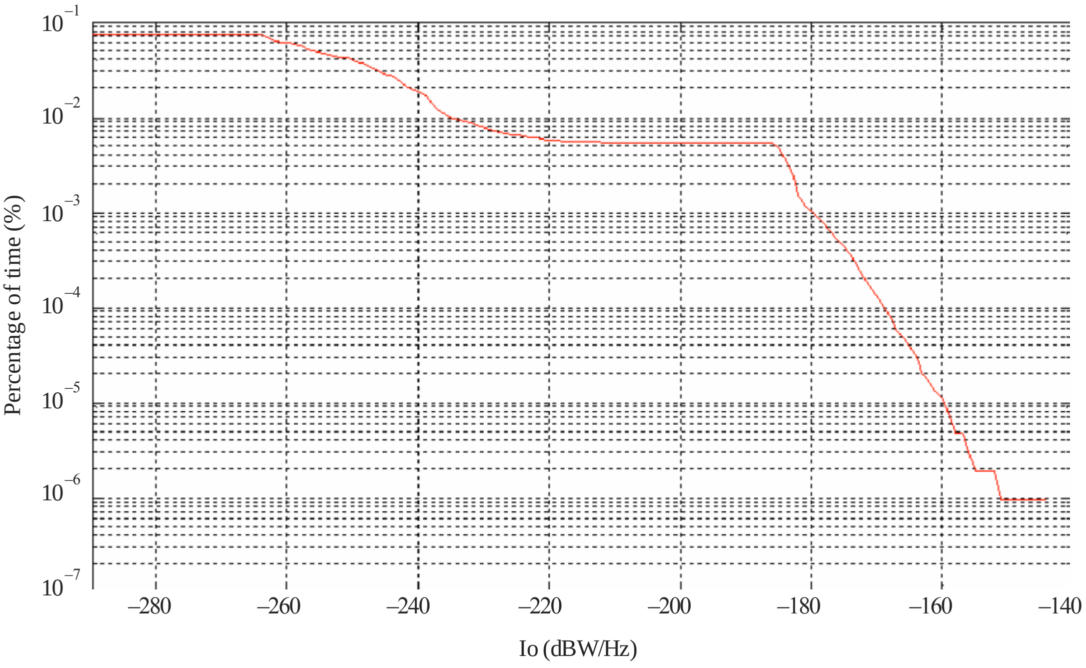
FIGURE 22

Cumulative distribution function of the interference received for an SRS spacecraft around Mars



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The analysis is done for a representative SRS near-Earth satellite. The worst-case results are obtained for the Integral mission, which is the satellite with higher visibility time from Spain (apogee in the northern hemisphere). To the contrary, an SRS earth station tracking a spacecraft at low orbits (sample return for instance) will face lower interference levels.

Without concluding on a specific percentage of time, the CDF shows that a total interference power density level of −166 dBW/Hz was never exceeded during one year when simulating a transmitting SAR within the SRS bandwidth to an SRS earth station tracking Saturn (deep-space) or –157.5 dBW/Hz when tracking a satellite on a high elliptical orbit such as Integral (near-Earth).

Simulations also showed that the interference power density level of –144 dBW/Hz was never exceeded for an SRS earth station tracking Mars over a five-year period. There was no main-beam to main-beam (boresight) coupling observed during all simulations. Nevertheless, even if such a main-beam to main-beam coupling would in theory occur, its duration would be very short. Although the probability of main-beam coupling is very small during the critical events of SRS missions, such risk cannot be ignored.

The OoB emission attenuation required to protect SRS (deep space) earth stations may be expressed as:

Attenuation = –144 – (–221) = 77 dB

This attenuation is 44 dB less than computed using static analysis shown in Table 13. With regard to unmanned near-Earth missions, the percentage of time associated with unmanned missions is 0.1%, and it is never exceeded, whatever the interference level. The EESS (active) could in principle even share the band with this kind of missions. However, for manned missions the percentage of time is 0.001%, which would lead to a required OoB attenuation of:

Attenuation = –185 – (–216) = 31 dB

However, near-Earth satellites planned with orbital parameters similar to SAR-4 may be exposed with higher level of interference.

The –216 dBW/Hz protection level to the SRS near-Earth does not account of apportionment of the level of interference among different potential in-band and OoB interference sources.

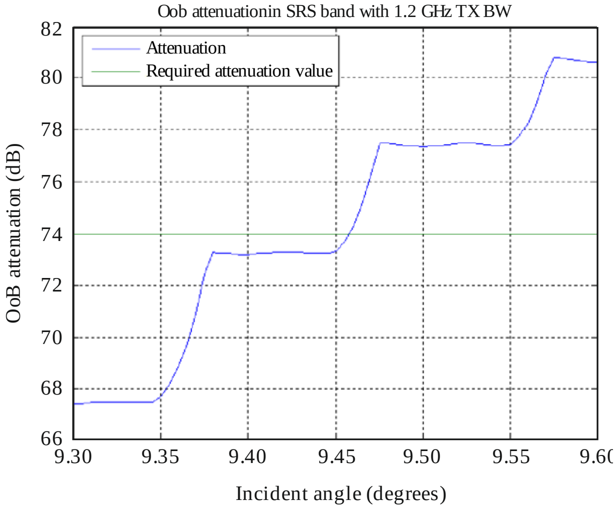
The feasibility of these attenuation levels will depend on the OoB performance of the SAR instrument.

In the following numerical analysis, the value of 77 dB is used as the minimum OoB emission attenuation needed in the 8 400-8 450 MHz band for a SAR-4 system to protect the SRS (deep space) systems. The threshold represents the worst-case interference scenario captured in the dynamic simulations presented earlier. Higher OoB attenuation may be needed to protect SRS (deep space) systems during the critical events of deep space missions.

Figure 23 shows the SAR-4 theoretical OoB emission attenuation in the SRS (deep space) band when 1 200 MHz bandwidth is transmitted around a variable centre frequency in the range 9 300-9 600 MHz.

FIGURE 23

OoB attenuation in DSN SRS band vs. SAR-4 Tx centre frequency (BW=1 200 MHz)



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The lowest centre frequency that meets the 77 dB attenuation without margin is 9 470 MHz as shown in Fig. 23.

5.5 Proposed interference mitigation techniques

Several interference mitigation techniques are described in this section. Potential interference from the unwanted emissions of 1 200 MHz EESS (active) systems can be reduced using these techniques.

Generally, the first three techniques, pulse shaping, antenna pointing, and filtering, can significantly reduce the unwanted emission of EESS (active) systems. The effectiveness of Techniques 4 and 5 depends on the roll-off characteristics of the linear frequency modulation (LFM) pulses and the frequency separation between the LFM signals and the 8 400-8 450 MHz band. Each of these techniques may reduce the unwanted emission by a few decibels for rectangular pulses or tens of decibels for trapezoid and raised-cosine pulses. Through the use of one or more techniques described in this section, it appears that the unwanted emission of the expanded 1 200 MHz EESS (active) system may be able to meet the deep-space protection criteria.

5.5.1 Pulse shaping

Pulse shaping changes the envelope of the LFM chirp pulses to reduce the OoB emission of the radar. The technique and the effectiveness of pulse shaping are described in detail in the Annex. Compared to a LFM system with zero rise-time and zero fall-time, pulse shaping with trapezoid waveform and raised-cosine waveform can theoretically reduce the unwanted emission of LFM radars by more than 59 dB and 119 dB, respectively. It should be noted that imperfections and non linearities of various components in the EESS (active) transmit chain will likely increase the OoB emission.

5.5.2 Antenna pointing

EESS (active) systems operate in the expanded 1 200 MHz band around 9 600 MHz are expected to have highly directional antennas like SAR-2 and SAR-3 systems in Report ITU-R RS.2094. The antenna peak gain of SAR-4 is 46 dBi. The antenna pattern rolls-off quickly in horizontal (or azimuth) direction. If SAR-4 can point the antenna away from the SRS (deep-space) earth stations, in particular during critical events or when the SRS main-beam comes close to the SAR location, such that the antenna gain towards the SRS (deep-space) earth stations is limited, the unwanted emission of SAR-4 would be drastically reduced, thus reducing the likelihood of harmful interference or saturation of SRS receivers.

This could be achieved through operational coordination between the SRS (deep space) operator and the EESS (active) operator.

5.5.3 Filtering

Depending on the implementations of EESS (active) systems, transmit filters and waveguides with steep cut-off below the EESS (active) band can be implemented to limit the unwanted emission of the systems. Filtering techniques have been successfully implemented by EESS space-to-Earth links in the 8 025-8 400 MHz band to reduce the unwanted emission of EESS downlinks by 40 dB and more in the 8 400-8 450 MHz band.

The phased array antennas are composed of several hundreds of transmission and receive (TR) modules including high-power amplifiers. Any output filtering would have to be applied to the high power stages of these modules and, thus, unduly increases the system complexity, costs, and performance losses of the radar. As an example, the specifications for radar systems in Europe in terms of spurious emission levels are 100 dB PEP, with the exception of phased array radars for which it is 60 dB PEP, for the reasons given above. It should be noted that the filtering capability of each TR module radiating element is also limited, contrary to other types of antennas where their gain decreases rapidly with frequency.

However, if needed, an appropriate notch filter may be added in the transmission chain in order to attenuate to the best possible extent the unwanted emissions of the SAR, in a limited bandwidth.

5.5.4 Selection of frequency sweep and pulse duration

The unwanted emission of LFM radars is a function of both the frequency sweep range and duration of the chirp signal. The unwanted emission increases as the chirp sweep range increases, and also as the time duration of the chirp signal decreases. It may be possible for an EESS (active) operator to vary the radar sweep range and pulse duration to reduce the unwanted emission, especially when the EESS (active) antenna is pointing near as SRS deep-space earth station. For example, the EESS satellite will use only 600 MHz of spectrum instead of the full 1 200 MHz bandwidth when operating in scan mode. The full 1200 MHz spectrum will only be used in the spotlight mode, when highest resolution is required. This can be assumed to occur for less than 30% of all images taken by the radar.

A different pulse width would allow for only a slight variation in terms of average PSD in the SRS (deep-space) bandwidth, and would not be sufficient by itself.

The area acquisition in spotlight-mode is performed by telecommand of the desired beam geometry (size, pointing) followed by a beam steering controlled through orbit tracking. Therefore, no scan or other acquisition pattern precedes a high-resolution spot measurement.

5.5.5 Location of the 600 MHz extension

As Figures A-1, A-2, and A-3 in Annex A show, unwanted emission of LFM systems decreases as the frequency separation from the EESS (active) band increases. Tables A-1, A-2, and A-3 in Annex A show that among the three expansion options examined, unwanted interference to the 8 400-8 450 MHz band is the lowest when the additional 600 MHz is added above the current 9 300-9 900 MHz allocation. The interference to the 8 400-8 450 MHz is the highest if the additional 600 MHz is added below the current allocation, closer to the 8 400-8 450 MHz band.

This would be feasible in practice, although the best performance would be obtained if the same centre frequency as with legacy modes is retained. It is also important to mention that it would not be possible to use different centre frequencies between different Regions.

5.5.6 Geographic separation

It is also possible to reduce the interference from EESS (active) systems through geographic separation. EESS (active) systems may keep a minimum slant range from an SRS deep-space earth station to maintain a minimum free space loss resulting in an exclusion zone. Taken to extreme, EESS (active) systems may refrain from transmission whenever there is line-of-sight between the EESS (active) systems and a SRS deep-space earth station.

Preventing the spotlight mode over an area of several thousands of square-kilometers around an SRS earth station is however assumed to be too constraining and not necessary.

5.6 Potential saturation and damage of the SRS earth station front end

NASA and ESA have provided characteristics of potential damage level if their earth stations would be exposed to SAR radiation under most unfavourable geometry, i.e. near boresight coupling of antennas. These levels are –107 dBW in the band of 8 400-8 500 MHz for the ESA earth stations and –105 dBW in the band of 8 200-8 700 MHz for the NASA earth stations as measured at the direct input terminal of the receiver front-ends (LNA). NASA’s SRS receivers in Table 12 are designed to also support NASA’s solar system radar operating in the frequency range 8 500-8 700 MHz which is allocated to radiolocation service. These damage levels should not be exceeded for any amount of time.

The saturation level for the NASA earth station is –115 dBW. The OoB emission from the EESS (active) should be below this level especially during the critical events of SRS missions.

There are usually no particular filter inserted between the termination of an SRS earth station antenna and the LNA.

Tables 15 and 16 provide the results of calculation for potential damage of SRS deep space receivers as specified by NASA and ESA, respectively, taking into account main-beam to main-beam (boresight) coupling. The theoretical receiver interference PSD was derived by using the roll-off factor displayed in Fig. 19.

TABLE 15

Worst-case calculation of damage potential to NASA SRS receivers

NASA	SAR-1	SAR-2	SAR-3	SAR-4 (9 300 MHz)	SAR-4 (9 600 MHz)	SAR-4 (9 600 MHz)	SAR-4 (9 900 MHz)
e.i.r.p. (dBW)	76	83	86	85.5	85.5	85.5	85.5
Bandwidth (MHz)	10	400	450	1 200	1 200	600	1 200
Minimum slant range (km)	424	654	536	540	540	540	540
Space loss (dB)	–164	–167	–166	–166	–166	–166	–166
Rx antenna peak gain (dBi)	74	74	74	74	74	74	74
Polarization loss (dB)	–3	–3	–3	–3	–3	–3	–3
Rx interference PSD (dB(W/500 MHz))	–108	–101	–90	–34	–96	–103	–103
SRS deep-space receiver damage threshold (dB(W/500 MHz))	–105	–105	–105	–105	–105	–105	–105
Exceedance of damage threshold (dB)	–3	4	15	71	9	2	2

It can be seen that, apart from SAR-1, all SAR systems previously studied have the potential to damage the SRS deep space receiver on NASA DSN. SAR-4, with the extension in the lower part of the band, would actually transmit within the band specified by NASA with the damage criterion.

TABLE 16

Worst-case calculation of damage potential to ESA SRS receivers

ESA	**SAR-1**	**SAR-2**	**SAR-3**	**SAR-4 (9 300 MHz)**	**SAR-4 (9 600 MHz)**	**SAR-4 (9 600 MHz)**	**SAR-4 (9 900 MHz)**
e.i.r.p. (dBW)	76	83	86	85.5	85.5	85.5	85.5
Bandwidth (MHz)	10	400	450	1 200	1 200	600	1 200
Minimum slant range (km)	424	654	536	540	540	540	540
Space loss (dB)	–164	–167	–166	–166	–166	–166	–166
Rx antenna peak gain (dBi)	68	68	68	68	68	68	68
Polarization loss (dB)	–3	–3	–3	–3	–3	–3	–3
Rx interference PSD (dB(W/100 MHz))	–123	–114	–104	–98	–112	–117	–118
Deep-space protection threshold (dB(W/100 MHz))	–107	–107	–107	–107	–107	–107	–107
Exceedance of damage threshold (dB)	–16	–7	3	9	–5	–10	–11

With regard to the protection of ESA stations, only SAR-3 and SAR-4 with the extension in the lower part would exceed the protection threshold.

The results above were computed using the theoretical roll-off of the EESS (active) systems. However, higher OoB emission is possible if EESS (active) systems include high-efficiency power amplifiers operating in saturation mode. It should be noted that the probability of main-beam to main-beam coupling is extremely low. However, in order to completely alleviate this risk, operational coordination between the SRS (deep space) operator and the EESS (active) operator may be needed if the unwanted emission performance of the SAR system is not sufficient to meet the damage protection criterion.

6 Summary and conclusions

6.1 Conclusions regarding the radioastronomy service (RAS)

Compatibility studies between EESS (active) and the RAS conducted prior to WRC-12 have been updated, leading to similar results in terms of simulation of the data loss. Data loss conditions were revisited for cases when a SAR-4 system illuminates a RAS observatory whenever a satellite is in visibility of the RAS station. Although the percentage of data loss, under technically feasible attenuation conditions rejecting unwanted emissions in the order of 30 to 40 dB, may exceed the 2% criterion in the first worst-case situation, but it would never and under any circumstances exceed 2.7%.

Reducing the data loss to 2%, as required by Recommendation ITU-R RA.1513, would make it necessary to attenuate the unwanted emissions by 63 dB with regard to the peak envelope power of the SAR pulse. If this would be impossible, particularly in the case of an extension into frequencies above the current allocation, additional mitigation techniques would become necessary. One of these possible mitigation techniques would consist in limiting the number of image acquisitions of areas where RAS observatories performing observations in the 10.6-10.7 GHz range are located.

Accidental damage to the RAS receiver can be avoided, if an area of up to 46 km (vertical) by 19.4 km (horizontal) centered on the RAS station is excluded from illumination, or if the RAS station avoids pointing towards the satellite, or to four angular sectors while the satellite is visible.

6.2 Conclusions regarding the EESS (passive)

The sharing conditions of a new generation of very wide band SAR-4 system using chirp bandwidth of up to 1 200 MHz around 9 600 MHz has been analysed. Although the worst-case analyses suggest a potential necessity of high attenuation levels for OOB emissions, the more realistic cases show that such worst-case scenarios are very unlikely to occur. Considering realistic SAR systems which are only transmitting in the high resolution mode for very short fractions of time, the protection criterion of EESS (passive) sensors will not be exceeded for more than 0.00004% of time over 11 days.

It is expected that EESS (active) unwanted emissions would not cause difficulties to the protection of EESS (passive) operating in the frequency band 10.6-10.7 GHz.

6.3 Conclusions regarding the space research service (SRS)

Studies have provided assessments of the unwanted emission of the bandwidth-expanded EESS (active) systems and the impacts on the SRS deep-space and near-Earth downlinks in the bands 8 400-8 450 MHz and 8 450-8 500 MHz, respectively. Without any mitigating techniques, 1 200 MHz EESS (active) SAR systems pose a potential significant threat to the SRS deep-space and near-Earth downlinks depending on the location of the new 600 MHz spectrum.

This Report provides some interference-mitigating techniques, such as waveform shaping, antenna pointing, filtering, selection of sweep range and pulse duration, location of additional 600 MHz spectrum, and geographical separation. With one or more of these techniques, it appears that the unwanted emission of EESS (active) systems can potentially be suppressed to levels to protect the SRS downlinks in the frequency band 8 400-8 500 MHz.

Many results in this Report were computed based on theoretical roll-off of the proposed 1 200 MHz EESS (active) systems. However, higher OoB emissions might occur if EESS (active) systems include non linear components such as high-efficiency power amplifiers operating in saturation mode. The attenuation needed to protect SRS (deep space) operations and to protect the SRS receivers from damages should be computed based on the OoB characteristics of actual EESS (active) hardware and not on theoretical OoB characteristics.

Further analysis of the effects of EESS (active) power amplifiers in saturation mode on EESS (active) OoB emission is needed. EESS (active) systems should implement the mitigation techniques described in this Report to reduce their OoB emissions as much as possible. Operational coordination shall be used as a last resort to completely alleviate any risk of interference during SRS (deep space) critical events, as well as SRS receiver damage at all time, if mitigation techniques and improvements in unwanted emission still are insufficient to address these issues. With multiple EESS (active) systems operating around 9 600 MHz, 66 dB attenuation from the peak of SAR-4 spectrum in the 8 400-8 450 MHz band has been shown to be sufficient to protect the routine operations of SRS (deep space) systems.

Saturation and permanent damage of the RF front-end of SRS receivers in Table 11 due to EESS (active) systems are major concerns. Analysis using theoretical OoB characteristics of EESS (active) systems has been performed. The results show that the OoB emissions of EESS (active) systems can exceed the SRS receiver damage threshold by

a) 71 dB if the extension is in the frequency range 8 700-9 300 MHz;

b) 9 dB if the extension is in the frequency ranges 9 000-9 300 MHz and the 9.9-10.2 GHz; and

c) 2 dB if the extension is in frequency range 9.9-10.5 GHz.

A 600 MHz allocation to the EESS (active) entirely in the frequency range of 8 700-9 300 MHz would pose a significant risk of damaging some SRS receivers.

7 Supporting documents

ITU-R Recommendations

ITU-R M.1583	Interference calculations between non-geostationary mobile-satellite service or radionavigation-satellite service systems and radio astronomy telescope sites
ITU-R RA.769	Protection criteria used for radio astronomical measurements
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
ITU-R RS.515	Frequency bands and bandwidths used for satellite passive remote sensing
ITU-R RS.2017	Performance and interference criteria for satellite passive remote sensing
ITU-R RS.2043	Characteristics of synthetic aperture radars operating in the Earth exploration-satellite service (active) around 9 600 MHz
ITU-R S.1428	Reference FSS earth-station radiation patterns for use in interference assessment involving non-GSO satellites in frequency bands between 10.7 GHz and 30 GHz

ITU-R SA.609	Protection criteria for radiocommunication links for manned and unmanned near-Earth research satellites
ITU-R SA.1014	Telecommunication requirements for manned and unmanned deep-space research
ITU-R SA.1157	Protection criteria for deep-space research

ITU-R Reports

ITU-R RA.2188	Power flux-density and e.i.r.p. levels potentially damaging to radio astronomy receivers
ITU-R RS.2274	Spectrum requirements for spaceborne synthetic aperture radar applications planned in an extended allocation to the Earth exploration-satellite service around 9 600 MHz

Annex A

Pulse shaping methods and their performance

The technique of pulse shaping and their performance is described in this Annex. The time-domain waveform and the theoretical spectral density of LFM (linear FM) signals with rectangular, trapezoid, and raised-cosine waveform-shaping are presented here. The 20 dB chirp bandwidth is set to be 1 200 MHz. The duration of each LFM chirp pulse is 10 μs. Pulse duration is measured from the 50% amplitude of the chirp at the start and the end of the pulse. Rise-time and fall-time are defined as the time the amplitude of the chirp rises and falls between 10% and 90% of the peak amplitude. The rise-time and the fall time are set to be 1 μs, except for the rectangular waveform.

FIGURE A-1

Waveform and normalized PSD of a 1 200 MHz LFM system with a rectangular waveform

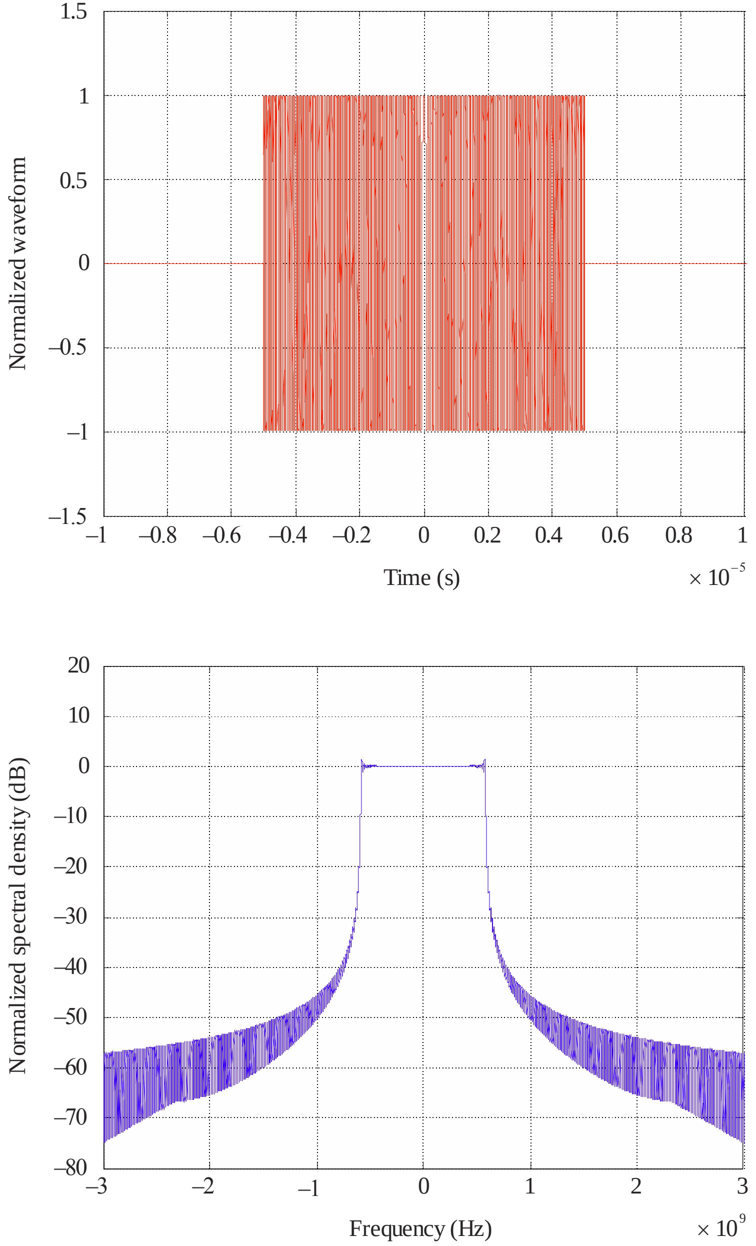

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FIGURE A-2

Waveform and normalized PSD of a 1 200 MHz LFM system with a trapezoid waveform

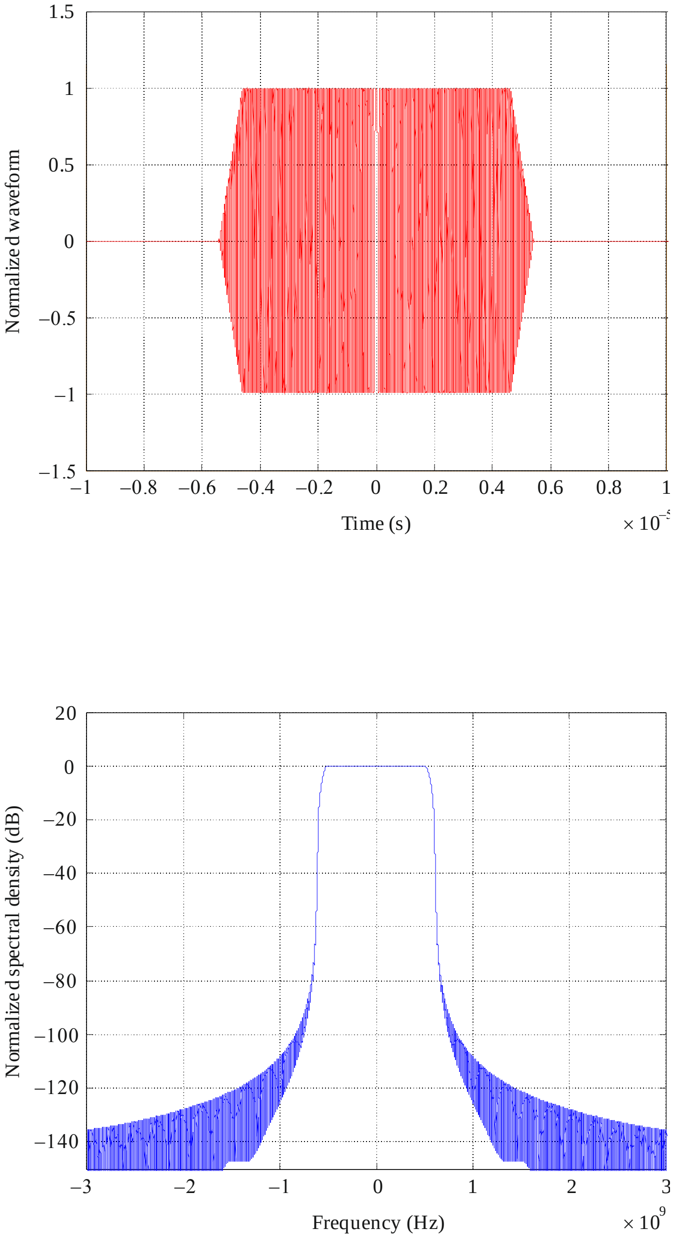

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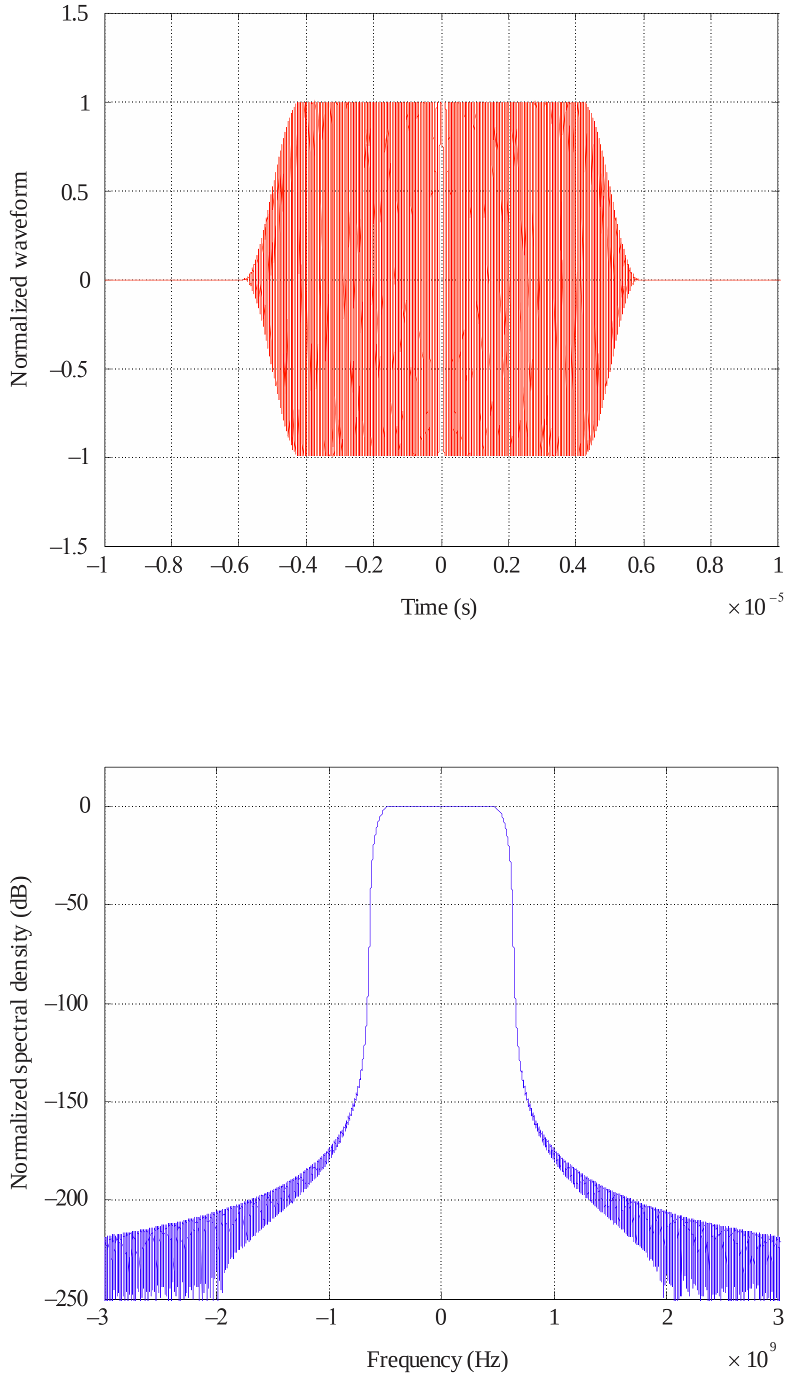
FIGURE A-3

Waveform and normalized PSD of a 1 200 MHz LFM system with a raised-cosine waveform



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Two sample SAR systems, SAR-2 and SAR-3, with parameters shown in Table A-1, are used to demonstrate the effectiveness of pulse shaping.

TABLE A-1

Technical characteristics of SAR-2 and SAR-3 systems used in this study

Parameter	**SAR-2**	**SAR-3**	**Unit**
Orbital altitude	619	506	km
Orbital inclination	98	98	degrees
RF centre frequency	9 600	9 600	MHz
Pulse modulation	Linear FM chirp	Linear FM chirp	
Antenna type	Planar array	Planar phased array	
Antenna peak gain	44.0-46.0	39.5-42.5	dBi
e.i.r.p.	83.0	83.5-88.5	dBW
Antenna orientation	34° from Nadir	20° to 44° from Nadir	
Chirp bandwidth	1 200	1 200	MHz
Pulse duration	10-80	1-10	μs
Pulse repetition rate	2 000-4 500	410-515	pps
Antenna polarization	Linear HH or VV	Linear horizontal/vertical	

We consider three possible options for expanding the EESS (active) band around the frequency band 9 300-9 900 MHz.

- Option 1) 300 MHz above and 300 MHz below the current allocation keeping the centre frequency at 9 600 MHz.
- Option 2) the entire 600 MHz above the current allocation moving the centre frequency to 9 900MHz.
- Option 3) the entire 600 MHz below the current allocation moving the centre frequency to 9 300 MHz.

Table A-2 below shows the interference from SAR-2 and SAR-3 systems with the three bandwidth expansion options when the antennas of SAR-2 and SAR-3 systems are at the boresight of an SRS deep-space earth station with peak antenna gain of 74 dBi, the directive antennas of SAR-2 and SAR-3 systems are pointed directly at the SRS earth station, and SAR-2 and SAR-3 systems have 20 dB bandwidth of 1 200 MHz.

As the baseline, SAR-2 and SAR-3 are assumed to have zero rise-time and zero fall-time. In other words, the systems have a rectangular pulse waveform. The chirp duration is assumed to be 10 μs. Table A-2 shows that the worst-case interference PSD exceeds the SRS deep-space protection criteria for the 8 400-8 450 MHz band by at least 65 dB. This analysis uses the theoretical unwanted characteristics of rectangular waveforms. The actual LFM signals are likely to be filtered and should have lower unwanted emission. Without any interference mitigating techniques, the interference from EESS (active) systems can cause severe degradations to the SRS deep-space downlinks.

TABLE A-2

Worst-case interference PSD from two representative EESS (active) systems with rectangular waveform to the deep-space downlinks in the 8 400-8 450 MHz band

	Option 1 (f_c = 9 600 MHz)		**Option 2 (f_c = 9 900 MHz)**		**Option 3 (f_c = 9 300 MHz)**	
	SAR-2	**SAR-3**	**SAR-2**	**SAR-3**	**SAR-2**	**SAR-3**
e.i.r.p. (dBW)	83	88.5	83	88.5	83	88.5
Bandwidth (MHz)	1 200	1 200	1 200	1 200	1 200	1 200
Minimum slant range (km)	764	541	764	541	764	541
Space loss (dB)	–169	–166	–169	–166	–169	–166
Rx antenna peak gain (dBi)	74	74	74	74	74	74
Polarization loss (dB)	–3	–3	–3	–3	–3	–3
Spectral roll-off (dB)	–48	–48	–51	–51	–42	–42
Rx interference PSD (dB(W/Hz))	–153	–145	–156	–148	–148	–139
Deep-space protection criterion (dB(W/Hz))	–221	–221	–221	–221	–221	–221
Exceedance of protection criterion (dB)	68	76	65	73	73	82

Tables A-3 and A-4 show the worst-case interference PSD from SAR-2 and SAR-3 for the three expansion options using trapezoid and raised-cosine waveform shaping. Table A-3 shows the worst-case unwanted emission from EESS (active) systems when the waveforms are shaped by a trapezoid. The spectral roll-off is at least 101 dB below the peak at 8 400-8 450 MHz. That is an improvement of 59 dB or more compared to SAR-2 and SAR-3 systems without waveform shaping, i.e. with rectangular waveforms.

Table A-3 shows that, except in one case, the worst-case unwanted interference in the 8 400-8 450 MHz band still exceeds the SRS deep-space protection criteria, although the exceedance is greatly reduced compared to the LFM systems with rectangular waveforms shown in Table A-2.

In Table A-4, the waveforms of SAR-2 and SAR-3 systems are shaped by a raised-cosine function. For these cases, the spectral roll-off in the 8 400-8 450 MHz band is theoretically at least 161 dB below the peak in the 8 400-8 450 MHz band, and the unwanted emission of SAR-2 and SAR-3 meets the SRS deep-space protection criteria by large margins.

Waveform shaping of LFM systems can be achieved through the use of low-pass filters or digital synthesizers depending on the transmitter implementations. It is, however, arguable whether an EESS (active) system can suppress the unwanted emission by 161 dB and more from the peak as in the case of raised-cosine waveform shaping. It should also be noted that imperfections and non linearities of various components in the EESS (active) transmit chain are likely to increase the side-lobe PSDs. However, the use of waveform shaping is expected to be a useful technique in mitigating the unwanted emission of EESS (active) systems. If an EESS (active) system operator plans to implement waveform shaping to suppress the unwanted emissions, it may be necessary to verify the effectiveness of their waveform shaping technique by measuring the PSDs of the unwanted emissions in the 8 400-8 450 MHz band.

TABLE A-3

Worst-case interference PSD from two representative EESS (active) systems with trapezoid waveform to the deep-space downlinks in the 8 400-8 450 MHz band

	Option 1 (f_c = 9 600 MHz)		**Option 2 (f_c = 9 900 MHz)**		**Option 3 (f_c = 9 300 MHz)**	
	SAR-2	**SAR-3**	**SAR-2**	**SAR-3**	**SAR-2**	**SAR-3**
e.i.r.p. (dBW)	83	88.5	83	88.5	83	88.5
Bandwidth (MHz)	1 200	1 200	1 200	1 200	1 200	1 200
Minimum slant range (km)	764	541	764	541	764	541
Space loss (dB)	–169	–166	–169	–166	–169	–166
Rx antenna peak gain (dBi)	74	74	74	74	74	74
Polarization loss (dB)	–3	–3	–3	–3	–3	–3
Spectral roll-off (dB)	–113	–113	–120	–120	–101	–101
Rx interference PSD (dB(W/Hz))	–219	–210	–226	–217	–206	–198
Deep-space protection criterion (dB(W/Hz))	–221	–221	–221	–221	–221	–221
Exceedance of protection criterion (dB)	2	11	–5	4	15	23

TABLE A-4

Worst-case interference PSD from two representative EESS (active) systems with raised-cosine waveform to the deep-space downlinks in the 8 400-8 450 MHz band

	Option 1 (f_c = 9 600 MHz)		**Option 2 (f_c = 9 900 MHz)**		**Option 3 (f_c = 9 300 MHz)**	
	SAR-2	**SAR-3**	**SAR-2**	**SAR-3**	**SAR-2**	**SAR-3**
e.i.r.p. (dBW)	83	88.5	83	88.5	83	88.5
Bandwidth (MHz)	1 200	1 200	1 200	1 200	1 200	1 200
Minimum slant range (km)	764	541	764	541	764	541
Space loss (dB)	–169	–166	–169	–166	–169	–166
Rx antenna peak gain (dBi)	74	74	74	74	74	74
Polarization loss (dB)	–3	–3	–3	–3	–3	–3
Spectral roll-off (dB)	–183	–183	–194	–194	–161	–161
Rx interference PSD (dB(W/Hz))	–288	–279	–299	–290	–267	–258
Deep-space protection criterion (dB(W/Hz))	–221	–221	–221	–221	–221	–221
Exceedance of protection criterion (dB)	–67	–58	–78	–69	–46	–37

Annex B

Abbreviations

CDF	Cumulative distribution function
DSN	Deep space network
LFM	Linear frequency modulation
LNA	Low noise amplifier
PEP	Peak envelope power