REPORT ITU-R RS.2094

Studies related to the compatibility between Earth exploration-satellite service (active) and the radiodetermination service in the 9 300-9 500 MHz and 9 800-10 000 MHz bands and between Earth exploration-satellite service (active) and the fixed service in the 9 800-10 000 MHz band

(2007)

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1 Introduction

The purpose of this Report is to summarize the results of the studies related to the compatibility between Earth exploration-satellite service (EESS) (active) and the radiodetermination service in the 9 300-9 500 MHz and 9 800-10 000 MHz bands and between EESS (active) and the fixed service in the 9 800-10 000 MHz band.

2 EESS (active)

2.1 Applications

In 2007 there are five synthetic aperture radars (SAR) that are planned to operate in the band near 9.6 GHz. These include the SARs found on board the four satellites of a constellation as commissioned by the Italian Space Agency (ASI) but not yet launched; and one SAR labelled "SAR3" that is currently under consideration by the United States' National Aeronautics and Space Agency (NASA).

The SARs operating near 9.6 GHz would be controlled via ground command to turn on and off as required to view only specific areas on the earth due to power constraints of the spacecraft. This mode of operation results in the SAR transmitting for 10% to 20% of the time. Another mode of operation is the spotlight mode. In the spotlight mode, a look angle is selected between 20° and 44°, and data will typically be collected by taking 49 to 65 sub-swaths of 20 km in range by 0.35 km in azimuth. This data can then be put into a mosaic of the sub-swaths in azimuth to process a 20 km by 20 km image.

2.2 Parameters

Technical characteristics of spaceborne active sensors in the frequency band 9 300-10 000 MHz are given in Table 1, the SAR1 antenna gain pattern is given in Table 2, the SAR2 antenna gain pattern is given in Table 3 and the SAR3 antenna gain pattern is given in Table 4.

TABLE 1

Technical characteristics of proposed SAR

Parameter	SAR1	SAR2	SAR3
Orbital altitude (km)	400	619	506
Orbital inclination (degrees)	57	98	98
RF centre frequency (GHz)	9.6	9.6	9.6
Peak radiated power (W)	1 500	5 000	25 000
Pulse modulation	Linear FM chirp	Linear FM chirp	Linear FM chirp
Chirp bandwidth (MHz)	10	400	450
Pulse duration (μs)	33.8	10-80	1-10
Pulse repetition rate (pps)	1 736	2 000-4 500	410-515
Duty cycle (%)	5.9	2.0-28.0	0.04-0.5
Range compression ratio	338	< 12 000	450-4 500
Antenna type	Slotted waveguide	Planar array	Planar phased array
Antenna peak gain (dBi)	44.0	44.0-46.0	39.5-42.5
e.i.r.p. (dBW)	75.8	83.0	83.5-88.5

TABLE 1 (*end*)

Parameter	SAR1	SAR2	SAR3
Antenna orientation	20° to 55° from Nadir	34° from Nadir	20° to 44° from Nadir
Antenna beamwidth	5.5° (El) 0.14° (Az)	1.6-2.3° (El) 0.3° (Az)	1.1-2.3° (El) 1.15° (Az)
Antenna polarization	Linear vertical	Linear HH or VV	Linear horizontal/vertical
System noise temperature (K)	551	500	600

TABLE 2

SAR1 antenna gain pattern near 9.6 GHz

Pattern	Gain *G*(θ) (dBi) as a function of off-axis angle θ (degrees)	Angular range (degrees)
Vertical (elevation)	$G_v(\theta_v) = 44.0 - 0.397(\theta_v)^2$ $G_v(\theta_v) = 24.5$ $G_v(\theta_v) = 9.5$ $G_v(\theta_v) = 22.5$	$\theta_v < 7.1$ $7.1 \leq \theta_v \leq 30$ $30 < \theta_v \leq 60$ $\theta_v > 60$
Horizontal (azimuth)	$G_h(\theta_h) = 0 - 612.2(\theta_h)^2$ $G_h(\theta_h) = -12$ $G_h(\theta_h) = 0 - 27.0(\theta_h)$ $G_h(\theta_h) = -35$	$\theta_h \leq 0.14$ $0.14 < \theta_h \leq 0.44$ $0.44 < \theta_h \leq 1.3$ $\theta_h > 1.3$
Beam pattern	$G(\theta) = \{G_v(\theta_v) + G_h(\theta_h), -3\}$ max	

TABLE 3

SAR2 antenna gain pattern near 9.6 GHz

Pattern	Gain *G*(θ) (dBi) as a function of off-axis angle θ (degrees)	Angular range (degrees)
Vertical (elevation)	$G_v(\theta_v) = 46.0 - 0.835(\theta_v)^2$ $G_v(\theta_v) = 31.0$ $G_v(\theta_v) = 26.0$ $G_v(\theta_v) = 10.0$	$\theta_v < 3.8$ $3.8 \leq \theta_v \leq 15$ $15 < \theta_v \leq 30$ $\theta_v > 30$
Horizontal (azimuth)	$G_h(\theta_h) = 0 - 444.5(\theta_h)^2$ $G_h(\theta_h) = -16$ $G_h(\theta_h) = -20.0(\theta_h)$	$\theta_h \leq 0.3$ $0.3 < \theta_h \leq 0.7$ $\theta_h > 0.7$
Beam pattern	$G(\theta) = \{G_v(\theta_v) + G_h(\theta_h), -3\}$ max	

TABLE 4

SAR3 antenna gain pattern near 9.6 GHz

Pattern	Gain $G(\theta)$ (dBi) as a function of off-axis angle θ (degrees)	Angle range (degrees)
Vertical (elevation)	$G_V(\theta_V) = 42.5 - 9.92(\theta_V)^2$ $G_V(\theta_V) = 31.4 - 0.83\,\theta_V$ $G_V(\theta_V) = 10.5 - 0.133\,\theta_V$	$0 < \theta_V < 1.1$ $1.1 \leq \theta_V < 30$ $\theta_V \geq 30$
Horizontal (azimuth)	$G_h(\theta_h) = 0.0 - 9.07(\theta_h)^2$ $G_h(\theta_h) = +1.9 - 12.08\,\theta_h$ $G_h(\theta_h) = -48$	$0 < \theta_h < 1.15$ $1.15 \leq \theta_h < 4.13$ $\theta_h \geq 4.13$
Beam pattern	$G(\theta) = G_V(\theta_V) + G_h(\theta_h)$	

3 Radiodetermination services

3.1 Applications

The band 8 500-10 500 MHz is used by many different types of radars on ground-based, transportable, shipboard, and airborne platforms. Radiodetermination functions performed in this frequency range include airborne and surface search, ground-mapping, terrain-following, navigation (both aeronautical and maritime), and meteorological (both airborne and ground-based).

3.2 Parameters

The radiodetermination radar characteristics were provided in reference [1]. Characteristics were provided for ten airborne radar systems, nine shipborne radar systems, and eight beacon/ground-based radar systems that operate in the 8 500-10 500 MHz band. A set of representative radar systems that operate in the 9 300-10 000 MHz band were selected for the following studies and their characteristics are listed in Tables 5, 6, and 7.

TABLE 5

Characteristics of airborne radiodetermination radars in the 8 500-10 500 MHz band

Characteristics	System A1	System A2	System A3
Function	Search and track radar (multifunction)	Airborne search radar	Ground-mapping and terrain-following radar (multifunction)
Tuning range (MHz)	9 300-10 000	8 500-9 600	9 240, 9 360 and 9 480
Modulation	Pulse	Pulse	Non-coherent frequency-agile pulse-position modulation
Peak power into antenna (kW)	17	143 (min) 220 (max)	95
Pulse widths (μs) and Pulse repetition rates	0.285; 8 200 to 23 000 pps	2.5; 0.5 400 and 1 600 pps	0.3, 2.35, and 4 2 000, 425 and 250 pps, resp.
Maximum duty cycle	0.0132	0.001	0.001

TABLE 5 (*continued*)

Characteristics	System A1	System A2	System A3
Pulse rise/fall time (μs)	0.01/0.01	0.02/0.2	0.1/0.1
Output device	Travelling wave tube	Tunable magnetron	Cavity-tuned magnetron
Antenna pattern type	Pencil	Fan	Pencil
Antenna type	Planar array	Parabolic reflector	Flat-plate planar array
Antenna polarization	Linear	Linear	Circular
Antenna main beam gain (dBi)	32.5	34	28.3
Antenna elevation beamwidth (degrees)	4.6	3.8	5.75
Antenna azimuthal beamwidth (degrees)	3.3	2.5	5.75
Antenna horizontal scan rate	118 scans/min	6 or 12 rpm	Up to 53 scans/min
Antenna horizontal scan type (continuous, random, sector, etc.)	Sector: ±60° (mechanical)	360° (mechanical)	Sector: ±60° (mechanical)
Antenna vertical scan rate	59 scans/min	Not applicable	Up to 137 scans/min
Antenna vertical scan type	Sector: ±60° (mechanical)	Not applicable	Sector: +25/–40° (mechanical)
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	7.5 dBi at 15°	Not specified	5.3 dBi at 10°
Antenna height	Aircraft altitude	Aircraft altitude	Aircraft altitude
Receiver IF 3 dB bandwidth (MHz)	3.1; 0.11	5	5.0, 1.8 and 0.8
Receiver noise figure (dB)	Not specified	Not specified	6
Minimum discernible signal (dBm)	–103	–107; –101	–101
Total chirp width (MHz)	Not applicable	Not applicable	Not applicable
RF emission bandwidth (MHz) – 3 dB – 20 dB	 3.1; 0.11 22.2; 0.79	 0.480; 2.7 1.5; 6.6	(Frequency and pulsewidth dependent) 100 to 118 102 to 120

TABLE 5 (*end*)

Characteristics	System A7d	System A8	System A10
Function	Navigation	Search (radiolocation) weather	Weather avoidance, ground mapping, search
Tuning range (MHz)	Frequency agile pulse-to-pulse over 340 MHz	9 250-9 440, frequency-agile pulse-to-pulse, 20 MHz steps	Preheat pulse: 9 337 and 9 339 (precedes each oprtl pulse) Operational pulse: 9 344
Modulation	Linear FM pulse	FM pulse	Pulse
Peak power into antenna	50 kW	10 kW	26 W (14 dBW)
Pulse width (µs) and Pulse repetition rate	10 approx. 380 pps	5 and 17 2 500, 1 500, 750, and 400 pps (all pulse widths)	9 337 and 9 339 MHz: 1-29 µs at 2 200-220 pps (dithered) for all pulse widths; 9 344 MHz: 1.7-2.4, 2.4-4.8, 4.8-9.6, 17, 19, and 29 µs at 2 200-220 pps (dithered)
Maximum duty cycle	0.004	0.04	9 337 and 9 339 MHz: ≤ 0.064 9 344 MHz: ≤ 0.011 (with 17 µs pulses)
Pulse rise/fall time (µs)	0.1/0.1	0.1/0.1	9 337 and 9 339 MHz: 0.3/0.2 9 344 MHz: 0.5/0.5
Output device	Travelling wave tube	Travelling-wave tube	IMPATT diode
Antenna pattern type	Pencil/Fan	Fan	Pencil
Antenna type	Parabolic Reflector	Slotted array	Flat array
Antenna polarization	Horizontal	Vertical and horizontal	Horizontal
Antenna main beam gain (dBi)	34.5	32	29
Antenna elevation beamwidth (degrees)	4.0	9.0	<10
Antenna azimuthal beamwidth (degrees)	2.4	1.8	7
Antenna horizontal scan rate	36, 360, 1800°/s	15 or 60 rpm	30°/s
Antenna horizontal scan type (continuous, random, sector, etc.)	10° sector	360°	Sector 60 or 120°
Antenna vertical scan rate	Not applicable	Not applicable	Not applicable
Antenna vertical scan type (continuous, random, sector, etc.)	Selectable tilt 0°/–90°	Selectable tilt +15°/–15°	Operator-selected tilt: ±30°
Antenna sidelobe (SL) levels (1st SLs and remote SLs)	14.5 dBi at 12°	20 dBi	+13.9 dBi
Antenna height	Aircraft altitude	Aircraft altitude	Aircraft altitude
Receiver IF 3 dB bandwidth (MHz)	Not specified	16	2.0
Receiver noise figure (dB)	5	Not specified	2
Minimum discernible signal (dBm)	Depends on processing gain (17 dB for one return pulse)	–98	–128 (detection sensitivity after processing
Total chirp width (MHz)	5	10	Not applicable
RF emission bandwidth (MHz)			–3 dB: 9 337 and 9 339 MHz: 0.7
– 3 dB	4.5	9.3	9 344 MHz: 0.4, 0.25, 0.150, 075, 0.08, and 0.05
– 20 dB	7.3	12	–20 dB: 9 337 and 9 339 MHz: 3.6 9 344 MHz: 1.8, 1.5, 0.8, 0.375, 0.35, and 0.2

TABLE 6

Characteristics of shipborne radiodetermination radars in the 8 500-10 500 MHz band

Characteristics	**System S1**	**System S3**	**System S4**	
Function	Search and navigation radar	Low altitude and surface search radar (multifunction)	Maritime radionavigation radar	
Platform type	Shipborne, shore training sites	Shipborne	Shipborne	
Tuning range (MHz)	8 500-9 600	8 500-10 000	9 375 ± 30 and 9 445 ±30	
Modulation	Pulse	Frequency-agile pulse	Pulse	
Peak power into antenna (kW)	35	10	5 (min)	50 (max)
Pulse width (μs) and Pulse repetition rate	0.1; 0.5 1 500; 750 pps	0.56 to 1.0; 0.24 19 000 to 35 000 pps; 4 000 to 35 000 pps	0.03 (min) at 4 000 pps (max)	1.2 (max) at 375 pps (min)
Maximum duty cycle	0.00038	0.020	0.00045	
Pulse rise/fall time (μs)	0.08/0.08	0.028/0.03; 0.038/0.024	Not specified	
Output device	Magnetron	Travelling wave tube	magnetron	
Antenna pattern type	Fan	Pencil	Fan	
Antenna type)	Horn array	Slotted array	Slotted array	
Antenna polarization	Linear	Linear	Not specified	
Antenna main beam gain (dBi)	29	39	27 (min)	32 (max)
Antenna elevation beamwidth (degrees)	13	1	20.0 (min)	26.0 (max)
Antenna azimuthal beamwidth (degrees)	3	1.5	0.75 (min)	2.3 (max)
Antenna horizontal scan rate	9.5 rpm	180°/s	20 (min)	60 (max)
Antenna horizontal scan type (continuous, random, sector, etc.)	360° (mechanical)	360° or Sector Search/Track (mechanical)	360°	
Antenna vertical scan rate	Not applicable	Not applicable	Not applicable	
Antenna vertical scan type	Not applicable	Not applicable	Not applicable	
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	Not specified	23 dBi (1st SL)	–4 dBi at ≤ 10° (min) –13 dBi at ≥ 10° (max)	9 dBi at ≤ 10° (max) 2 dBi at ≥ 10° (max)
Antenna height	Mast/deck mount	Mast/deck mount	Mast/deck mount	
Receiver IF (MHz)	Not specified	Not specified	45 (min)	60 (max)
Receiver IF 3 dB bandwidth (MHz)	12	2.5; 4; 12	6; 2.5 (min) (short and long pulse, resp.)	28; 6 (max) (short and long pulse, resp.)
Receiver noise figure (dB)	Not specified	9	3.5 (min)	8.5 (max)
Minimum discernible signal (dBm)	–96	–102; –100; –95	–106 (min)	–91 (max)
Chirp bandwidth (MHz)	Not applicable	Not applicable	Not applicable	
RF emission bandwidth (MHz) – 3 dB – 20 dB	 10; 5 80; 16	 1.6; 4.2 10; 24	 Not specified Not specified	

TABLE 6 (*end*)

Characteristics	**System S6**	**System S7**	**System S9**	
Function	Maritime radionavigation radar	Navigation and search	Maritime radionavigation radar	
Platform type	Shipborne	Shipborne	Shipborne	
Tuning range (MHz)	9 380-9 440	9 300-9 500	9 410± 30	9 445 ± 30
Modulation	Pulse	Pulse	Pulse	
Peak power into antenna (kW)	25	1.5	1.5-10	
Pulse width (µs) and Pulse repetition rate)	0.08, 0.2, 0.4, 0.7, and 1.2 2 200 pps (0.08 µs); 1 800, 1 000, and 600 pps (1.2 µs)	0.08, 0.25, and 0.5 2 250, 1 500, and 750 pps	0.08 (min) at 3 600 pps	1.2 (max) at 375 pps
Maximum duty cycle	0.00072	0.000375	0.00045	
Pulse rise/fall time (µs)	0.010/0.010	0.01/0.05	Not specified	
Output device	Magnetron	Magnetron	Magnetron	
Antenna pattern type	Fan	Fan	Fan	
Antenna type)	End-fed slotted array	Center-fed slotted waveguide	Slotted/patch array or horn	
Antenna polarization	Horizontal	Horizontal	Horizontal	
Antenna main beam gain (dBi)	31	23.9	22-30	
Antenna elevation beamwidth (degrees)	20	25	24-28	
Antenna azimuthal beamwidth (degrees)	0.95	6	1.9-7	
Antenna horizontal scan rate	24 rpm	24 rpm	24 rpm	
Antenna horizontal scan type (continuous, random, sector, etc.)	360°	360°	360°	
Antenna vertical scan rate	Not applicable	Not applicable	Not applicable	
Antenna vertical scan type	Not applicable	Not applicable	Not applicable	
Antenna sidelobe (SL) levels (1st SLs and remote SLs)	Not specified	+2.9 dBi	22 dBi main beam: 3 to 4 dBi within 10°; 0 to 3 dBi outside 10° 30 dBi main beam: 7 to 10 dBi within 10°; –2 to +7 dBi outside 10°	
Antenna height	Mast	Mast	Mast	
Receiver IF (MHz)	Not specified	Not specified	45-60	
Receiver IF 3 dB bandwidth (MHz)	15	10 and 3	2.5-25	
Receiver noise figure (dB)	6	6	4 to 8	
Minimum discernible signal (dBm)	–97 (noise floor)	–102 (noise floor)	Not specified	
Total chirp width (MHz)	Not applicable	Not applicable	Not applicable	
RF emission bandwidth (MHz) – 3 dB – 20 dB	 14 43	 20 55	Not specified	

TABLE 7

Characteristics of beacons and ground-based radiodetermination radar in the 8 500-10 500 MHz band

Characteristics	System G2	System G3	System G9
Function	Rendezvous beacon transponder	Tracking radar	Meteorological (radiolocation)
Platform type	Ground (manpack)	Ground (trailer)	Ground
Tuning range (MHz)	9 375 and 9 535 (Rx); 9 310 (Tx)	9 370-9 990	9 300-9 375 MHz
Modulation	Pulse	Frequency-agile pulse	Pulse
Peak power into antenna	20 to 40 W	31 kW	50 kW
Pulse width (μs) and Pulse repetition rate	0.3 to 0.4 Less than 20 000 pps	1 7 690 to 14 700 pps	0.1, 0.25 and 1.0 1 000 to 2 000 pps
Maximum duty cycle	0.008	0.015	0.002
Pulse rise/fall time (μs)	0.10/0.15	0.05/0.05	0.05
Output device	Solid State	Travelling wave tube	Klystron or magnetron
Antenna pattern type	Quadrant	Pencil	Pencil beam
Antenna type	Printed-circuit array	Phased array (linear slotted waveguide)	Parabolic reflector with Cassegrain feed
Antenna polarization	Circular	Linear	Linear (dual polarization)
Antenna main beam gain (dBi)	13	42.2	46
Antenna elevation beamwidth (degrees)	20; 3	0.81	0.9
Antenna azimuthal beamwidth (degrees)	65; 10	1.74	0.9
Antenna horizontal scan rate	Not applicable	Not specified	0 to 20°/s
Antenna horizontal scan type (continuous, random, sector, etc.)	Not applicable	Sector: ± 45° (phase-scanned)	Volume, sector volume, stationary and tracking
Antenna vertical scan rate	Not applicable	Not specified	0 to 20°
Antenna vertical scan type	Not applicable	Sector: 90° ± array tilt (frequency-scanned)	Steps to next elevation after horiz. rotation or elevation change at constant azimuth
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	0 dBi (1st SL)	Not specified	26 dBi
Antenna height	Ground level	Ground level	4 m
Receiver IF 3 dB bandwidth (MHz)	40	1	10, 4 or 1
Receiver noise figure (dB)	13	Not specified	–110
Minimum discernible signal (dBm)	–65	–107	Not specified
Chirp bandwidth (MHz)	Not applicable	Not applicable	Not applicable
RF emission bandwidth (MHz) – 3 dB – 20 dB	 4.7 11.2	 0.85 5.50	 Not Specified 6 to 60 MHz – dependent on pulse width

4 Fixed service

4.1 Applications

Recommendation ITU-R F.758-3 lists various parameters for fixed service (FS) systems being deployed in this general portion of the spectrum, but no FS system descriptions are provided for the 9 800 to 10 000 MHz band in particular. It is assumed that FS systems likely operate as point-to-point microwave relays in this band.

4.2 Parameters

Recommendation ITU-R F.758-3 lists various parameters for fixed service (FS) systems being deployed in this general portion of the spectrum, but no FS parameters are provided for the 9 800 to 10 000 MHz band in particular. The parameters listed for point-to-point fixed service (P-P FS) systems in the 10.6-10.68 GHz band were assumed to also apply within the 9 800 to 10 000 MHz frequency band for the studies in this Report. Such systems are predominantly deployed in urban and suburban areas, but no specific information was available on the number of such systems or channel plan that should be assumed for sharing studies. In the absence of more definitive information, it was assumed that each channel was used once. However, it should be noted that for an actual implementation of fixed service systems within this band, channels may be re-used multiple times within major urban areas.

The point-to-point fixed service parameters are given in Table 8.

TABLE 8

Point to-point fixed service system parameters

Parameter	Value
Modulation	FSK, QPSK
Capacity	16 Mbit/s
Channel spacing (MHz)	14
Antenna gain (maximum) (dBi)	49
Antenna Pattern	Recommendation ITU-R F.1245-1
Feeder/multiplexer loss (minimum) (dB)	0
Antenna type	Dish
Maximum transmit output power (dBW)	–2
e.i.r.p. (maximum) (dBW)	47
Receiver IF bandwidth (MHz)	14
Receiver noise figure (dB)	3
Receiver thermal noise (dBW)	−129.5
Nominal receiver input level (dBW)	−60
Receiver input level for 1×10^{-3} BER (dBW)	−114

5 Interference analysis

5.1 Analysis Study No. 1: Assessment of potential interference from the radiodetermination service to active spaceborne sensors operating in the 9 300-9 500 MHz band and 9 800-10 000 MHz band

5.1.1 Analysis approach

A computer simulation model was developed which calculates the time-dependent interference power level at the receiver of a spaceborne SAR active sensor from the radiodetermination systems. Using this simulation model, interference statistics were collected in the form of the probability that an interference power level was exceeded, and the maximum interference power level at the SAR receiver.

Recommendation ITU-R RS.1166 defines the performance and interference criteria for spaceborne active sensors. The criteria for unacceptable degradation in performance for imaging or topographical interferometric SARs operating in the 9 500 to 9 800 MHz band is a peak power level of -104 dB(W/20 MHz), or –89.9 dB(W/512 MHz) for the SAR3 radar. This criterion applies to non-FM pulsed interference sources with pulse duration of 2 μs or less. For pulse lengths greater than 2 μs, an interference threshold of –102 dB(W/20 MHz) is derived; however, for the purpose of this analysis, a worst case interference criterion of –104 dB(W/20 MHz) is used.

The availability criteria is also given in Recommendation ITU-R RS.1166 as follows: "In shared frequency bands, availability of SAR data shall exceed 99% of all geographical locations targeted as selected sites or for global coverage in topographical mapping."

Two sets of simulations were carried out. The first set of simulations assumed co-polar and co-channel frequency operation with a SAR centre frequency of 9 600 MHz and a SAR receiver IF bandwidth of 512 MHz. The second set of simulations employed frequency dependent rejection (FDR). For simulations, interference levels were calculated from a single source interferer as well as aggregate interference levels from 1 000 randomly distributed radar systems.

To determine the impact of multiple radar systems on the operation of SAR3, it was assumed that one hundred of each of the ten representative radar systems were deployed worldwide, resulting in a total deployment of 1000 radar systems.

A random deployment of the radar systems was used with a uniform distribution over the range of –60° to +70° in latitude and –180° to +180° in longitude. A slight modification was made to the random distribution of the radars so that all fixed radars were placed on land and all shipborne radars were placed in seas, lakes or rivers. Airborne radars were placed anywhere with a random height above sea level in the range of 1 to 10 km.

The radar transmit antenna elevation angles were selected initially as described below, and remained static for the duration of the simulations.

– Radar A1 − elevation angles were selected from a random value between ±60°
– Radar A2 − elevation angle for all A2 radars was 0°
– Radar A3 − elevation angles were selected from a random value between −40° to +25°
– Radar A7d − elevation angles were selected from a random value between −90° and 0°
– Radar A8 − elevation angles were selected from a random value between ±15°
– Radar G3 − elevation angles were selected from a random value between 0° to 90°
– Radar S1 − elevation angle for all S1 radars was 3°
– Radar S3 − elevation angle for all S3 radars was 0°

– Radar S6 − elevation angle for all S6 radars was 5°

– Radar S7 − elevation angle for all S7 radars was 8°

Each radar transmit antenna scanned in azimuth at the rates listed in Tables 5, 6, and 7 using a starting azimuth randomly selected from a value between ±180°. The heading for each airborne and shipborne radar was also selected from a random value between ±180°.

For the simulations employing FDR, the SAR receive frequency is set to 9 600 MHz and the transmit radar frequencies are varied randomly at each time sample within the radar tuning range listed in Tables 5, 6 and 7. The FDR values, in decibel, were derived using the approach described below, and applied to the interference calculations.

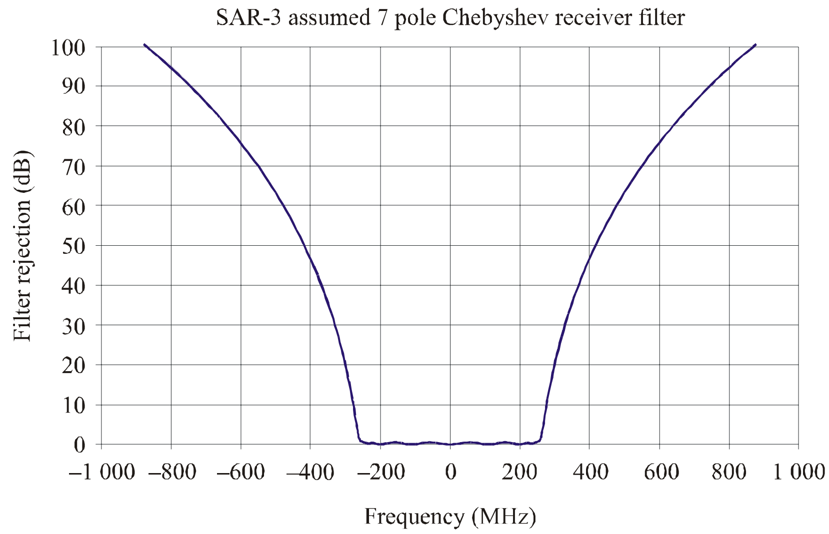
All simulations were performed for a period of 10 days with incremental time steps of three seconds. At each increment, the azimuth and elevation of each radar antenna were determined based on the antenna scan rate. The distance between the SAR receiver and the radar transmitters was calculated based on the SAR orbital parameters and radar station location. The radar stations interference power at the victim SAR was calculated using equations (15) and (16) in Annex 1 of Recommendation ITU-R M.1461-1.

The FDR used in this analysis is the amount of attenuation offered by the SAR3 receiver to the radar transmitted signals. This attenuation is composed of two parts: on-tune rejection (OTR) and off-frequency rejection (OFR). The FDR is calculated using Recommendation ITU-R SM.337-4 Frequency and distance separations.

As shown in Fig. 1, a 7-pole Chebyshev filter centred at 9.6 GHz with a 3 dB intermediate frequency (IF) bandwidth of 512 MHz was assumed for the SAR3 receiver.

FIGURE 1

SAR3 Chebyshev receiver filter



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In order to determine the power spectral-density for each radar transmitter, formulas were employed from Recommendation ITU-R SM.1541, Annex 8 (OoB domain emission limits for primary radar systems) to calculate the 40 dB bandwidth of the radar transmitter pulse. Table 9 lists the radar parameters used to calculate the radar emission spectrum mask. The one-sided radar spectrum plots, shown in Fig. 2, roll off at 20 dB per decade from the 40 dB bandwidth.

TABLE 9

Radar parameters for ITU-R SM.1541-1 RF spectrum calculation

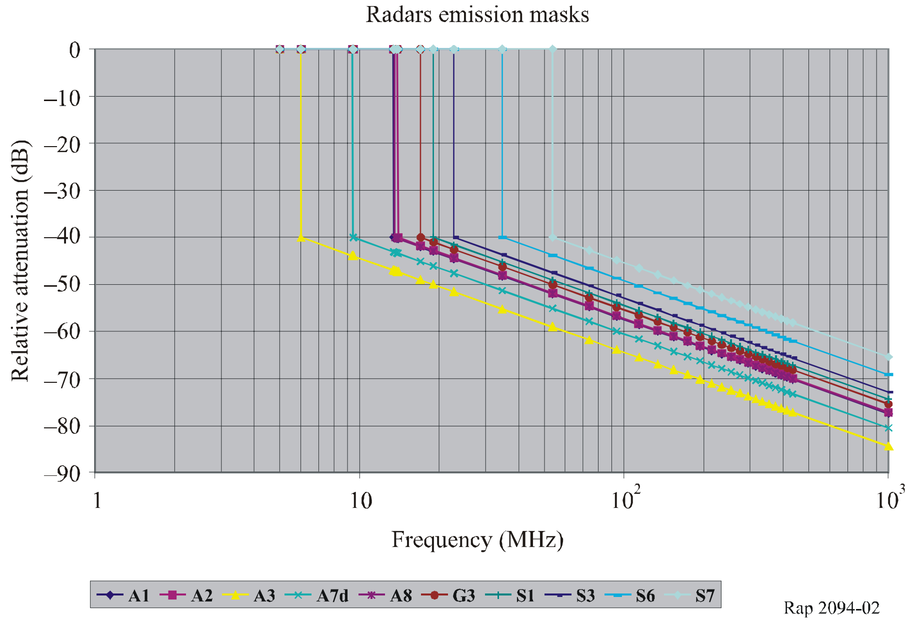
	Radar system									
	A1	**A2**	**A3**	**A7d**	**A8**	**G3**	**S1**	**S3**	**S6**	**S7**
Peak trans. power (kW)	17	143	95	50	10	31	35	10	25	1.5
Modulation type	Pulse	Pulse	Pulse	LFM	LFM	Pulse	Pulse	Pulse	Pulse	Pulse
Pulse length (µs)	8.00	2.50	4.0	10.0	17.0	1.0	0.5	1.0	1.2	0.5
Pulse rise time (µs)	0.010	0.020	0.100	0.100	0.100	0.050	0.080	0.028	0.010	0.010
Pulse fall time (µs)	0.010	0.020	0.100	0.100	0.100	0.050	0.080	0.030	0.010	0.050
Chirp bandwidth (MHz)	N/A	N/A	N/A	5	10	N/A	N/A	N/A	N/A	N/A

LFM: Linear frequency modulation

N/A: Not applicable

FIGURE 2

Radar transmit spectrum plots



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The resulting FDR plots, produced using the equations in Recommendation ITU-R SM.337-4, are shown in Fig. 3. Radars that have similar FDR results were combined together into one plot. The combined plots are for radars A1, A2 and A8; radars A3 and A7d; and radars G3 and S1. Radars S3, S6 and S7 were plotted individually.

As seen in the centre of Fig. 3, FDR values are negligible for frequency separations less than ±250 MHz. Because the SAR3 IF bandwidth is large with respect to the radar transmitter bandwidths, the on-tune rejection component of the FDR equation was negligible. The primary contributor was to the FDR calculation was the off-frequency rejection due to the offset between the SAR3 receive centre frequency and the radar transmit centre frequency. A look-up table that lists

FDR versus offset frequency was created based in the FDR results in Fig. 3 and was used in the simulation that randomly varies the radar transmit frequency at each simulation time step.

FIGURE 3

SAR3 frequency dependent rejection (FDR)

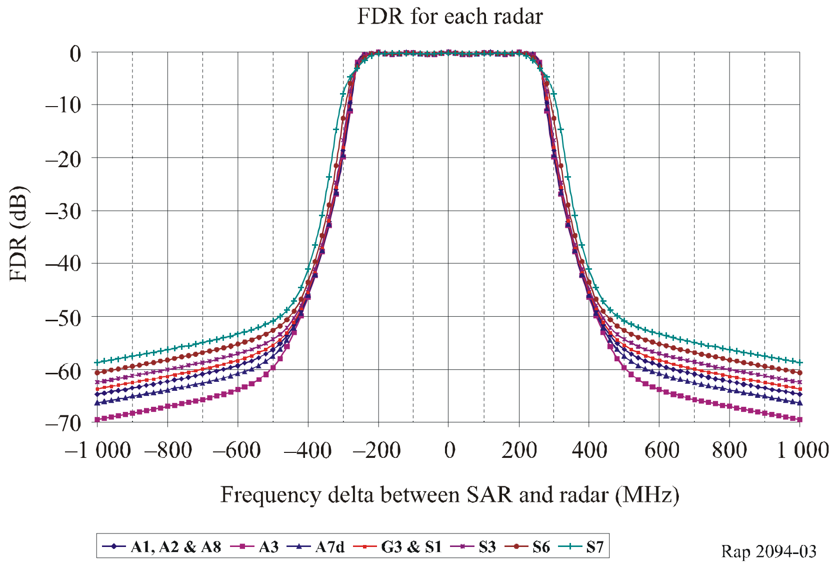
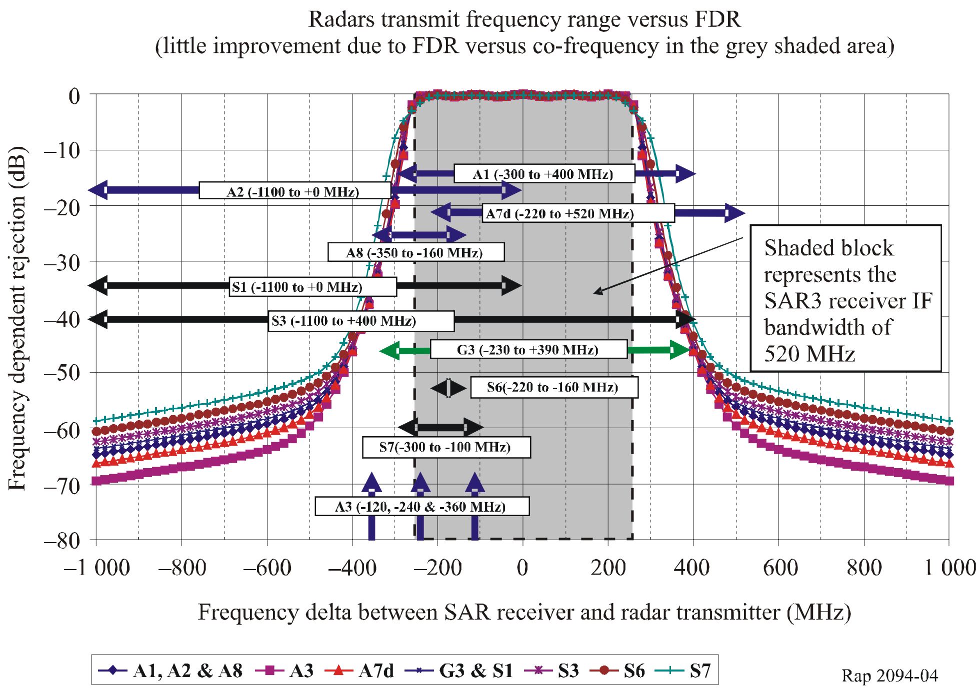


Figure 4 shows the frequency range that the radar centre frequencies will hop over. If a radar frequency is selected in the shaded area, then there will be no significant difference between the co-frequency and FDR analysis cases. Outside the grey region, the FDR increases resulting in a lower interference power levels at the SAR receiver.

FIGURE 4

Comparison of SAR3 FDR and radar transmitter tuning range



5.1.2 Analysis results

This section presents the analysis results for the following:

a) Co-frequency analysis to determine:
   – Individual interference levels at SAR3 from each radar system
   – Aggregate interference levels at SAR3 from 1000 randomly distributed radar systems

b) Frequency Dependent Rejection (FDR) analysis to determine:
   – Individual interference levels at SAR3 from each radar system
   – Aggregate interference levels at SAR3 from 1000 randomly distributed radar systems

5.1.2.1 Co-frequency analysis – Single interferer case

Figure 5 shows the cumulative distribution function plots of the resulting interference at the spaceborne SAR from the airborne, shipborne and ground-based radar transmitters. Table 10 provides a summary of the interference statistics in terms of the 1% exceedance levels and the maximum interference levels. The maximum interference levels for the radars simulated are well below the spaceborne SAR interference criteria of –89.9 dB(W/512 MHz), except for the A1 radar system which exceeds the criteria for less than 0.01% of the time. In these simulations, all interference values greater than –300 dBW were included in the collected statistics. It is assumed that at values below –300 dBW there was no visibility between the SAR3 and the radars.

For each of the simulation runs, the radar was continuously transmitting from a fixed location of 40° N latitude and 97° W longitude.

FIGURE 5

Interference results for single interfering radar

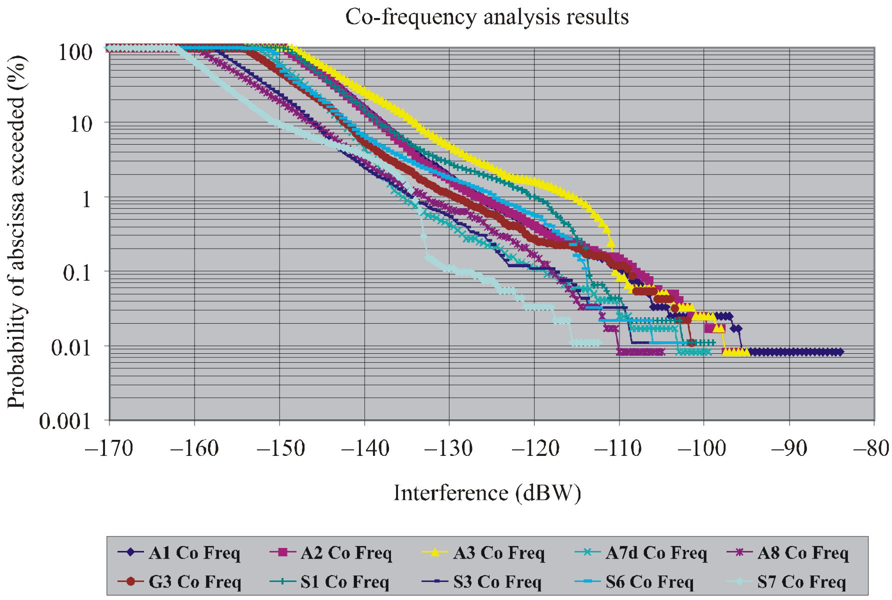


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TABLE 10

Summary of single radar interference into SAR3 for co-frequency analysis

Radar	Interference value at 1.0% threshold (dBW)	Maximum interference value (dBW)
Airborne radars		
A1	−126.5	−84.0
A2	−127.0	−96.0
A3	−115.5	−95.5
A7d	−135.5	−99.5
A8	−133.0	−105.0
Shipborne radars		
S1	−120.0	−99.5
S3	−135.0	−106.0
S6	−125.0	−102.5
S7	−133.5	−113.0
Ground based radar		
G3	−129.5	−102.0

5.1.2.2 Co-frequency analysis – Multiple interferer case

Figure 6 shows the cumulative distribution function plot of the resulting aggregate interference at the spaceborne SAR from a total of 1000 airborne, shipborne, and ground-based radar transmitters. Table 11 provides a summary of the interference statistics in terms of the maximum interference levels and the 1% exceedance level. From Fig. 6, it is seen that the spaceborne SAR interference criterion was exceeded 0.018% of the time.

FIGURE 6

Aggregate interference results for 1 000 radars using co-frequency analysis

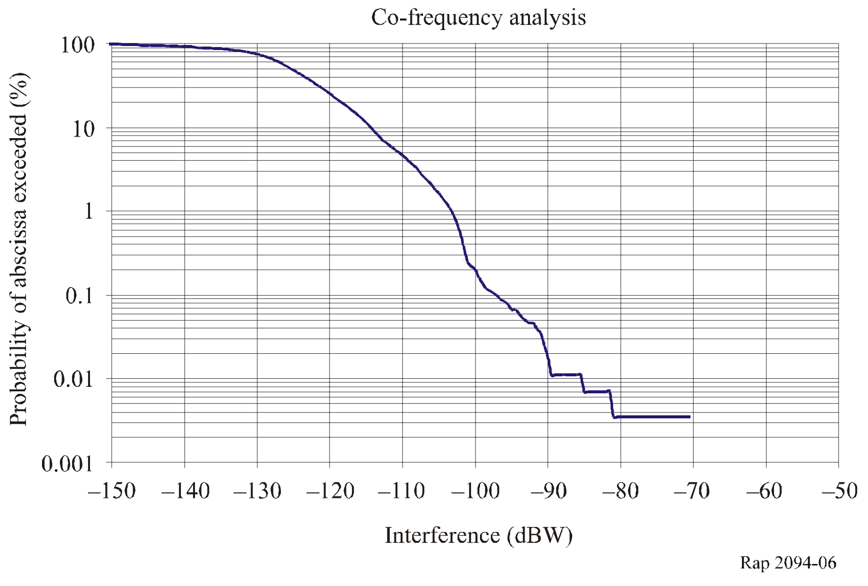

TABLE 11

Summary of aggregate radar interference into SAR3

Interference value at 1.0% threshold (dBW)	Maximum interference value (dBW)	Percent time maximum level received
−103.5	−70.5	0.0035%

5.1.2.3 FDR analysis – Single interferer analysis

The same radar deployment configuration and assumptions used for the co-frequency analysis were used in the FDR analysis. Figure 7 shows the cumulative distribution function plots of the resulting interference at the spaceborne SAR from the airborne, shipborne and ground-based radar transmitters. Table 12 provides a summary of the interference statistics in terms of the maximum interference levels and the 1% probability levels. The maximum interference levels for all the radars simulated are well below the spaceborne SAR interference criteria of −9.9 dB(W/512 MHz).

When comparing Fig. 7 with the co-channel simulation results at the 1% probability point, the interference power level at the SAR is less in most cases for the FDR simulation than the co-channel simulation. The reduction in interference power when considering FDR ranges from 0 dB for the S6 radar system to 15 dB for the S1 radar system. The amount of FDR is a function of the radar transmitter tuning range and its offset from the SAR receiver centre frequency as illustrated in Fig. 4.

FIGURE 7

Interference results for single interfering radar

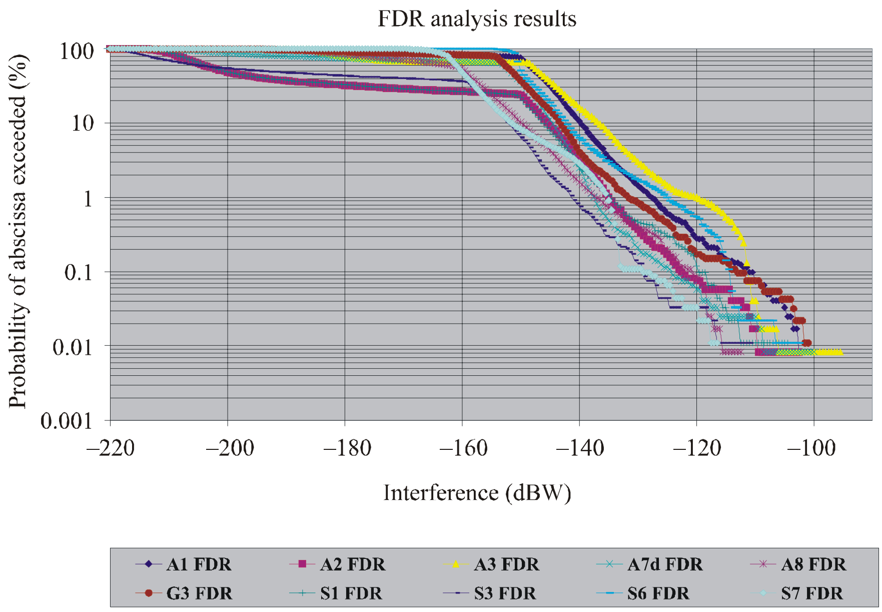

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TABLE 12

Summary of single radar interference into SAR3 employing FDR

Radar	interference value at 1.0% threshold (dBW)	Maximum interference value (dBW)
Airborne radars		
A1	−128.0	−100.5
A2	−135.0	−102.5
A3	−120.0	−95.5
A7d	−137.5	−100.0
A8	−137.5	−112.5
Shipborne radars		
S1	−135.0	−104.5
S3	−141.5	−111.0
S6	−125.0	−103.0
S7	−135.0	−116.5
Ground based radar		
G3	−132.0	−101.0

5.1.2.4 FDR analysis – Multiple interferer analysis

The same radar deployment configuration and assumptions used for the co-frequency analysis were used in the FDR analysis. Figure 8 shows the cumulative distribution function plot of the resulting aggregate interference at the spaceborne SAR from a total of 1000 airborne, shipborne, and ground-based radar transmitters. Table 13 provides a summary of the interference statistics in terms of the maximum interference levels and the 1% exceedance level. From Fig. 8, it is seen that the spaceborne SAR interference criterion was exceeded 0.0035% of the time. When FDR is accounted for by randomly hopping the radar transmit frequency, the aggregate interference level at SAR3 is approximately 4.5 dB lower at the 1% exceedance point than when co-frequency operation is assumed.

5.1.3 SAR interference mitigation techniques

Although the results of this study indicated that SAR interference mitigation techniques would not be necessary with respect to the radiodetermination service, SAR processing techniques offer appreciable interference suppression for certain types of waveforms. Raw data from a SAR receiver are processed in range and azimuth to produce a radar image. A point target return is spread linearly in frequency both in the range and azimuth dimensions. The SAR processor correlates the data in both dimensions and the processing gain is typically 20 to 40 dB for the return echo. These processing gains are accounted for in determining the interference criteria for a spaceborne SAR as given in Recommendation ITU-R RS.1166.

FIGURE 8

Frequency dependent rejection (FDR) analysis

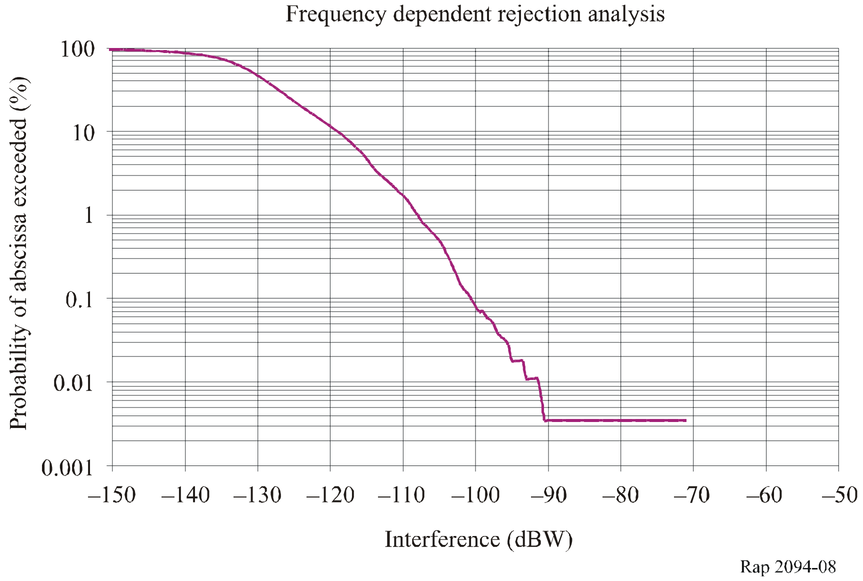


TABLE 13

Summary of aggregate radar interference into SAR3 using FDR

Interference value at 1.0% threshold (dBW)	Maximum interference value (dBW)	Percent time maximum level received
−108.0	−71.0	0.0035%

5.1.4 Analysis conclusion

This study evaluated the interference power levels at a spaceborne SAR receiver from airborne, shipborne, and ground based radiodetermination transmitters operating in the 9 300 to 10 000 MHz band. Simulation results indicate the following:

– Maximum interference levels from the individual radar systems considered in this study for the co-channel simulation are well below the spaceborne SAR interference criteria of -89.9 dB(W/512 MHz), except for the A1 radar system which exceeds the criteria for less than 0.01% of the time

– Maximum interference levels from the individual radar systems considered in this study are well below the spaceborne SAR interference criteria of –89.9 dB(W/512 MHz) for the frequency dependent rejection simulation

– The spaceborne SAR interference criteria was exceed 0.018% of the time for a worldwide random deployment of 1000 radar systems operating co-channel with SAR3.

– The spaceborne SAR interference criteria was exceed 0.0035% of the time for a worldwide random deployment of 1000 radar systems when assuming that the radar transmitters randomly frequency hop over their specified tuning range.

5.2 Analysis Study No. 2: Assessment of the potential for interference from ground based meteorological radars into the EESS (active) in the band 9 300-9 500 MHz

The potential for interference from ground-based meteorological radars was analyzed using dynamic simulations. The operational parameters of the EESS (active) systems are well defined, as are the characteristics of the meteorological radars. However, the deployment (number of systems, density, locations) of the ground-based meteorological radars operating in 9 300-9 500 MHz is not well documented. Assumptions were required on deployment locations, density and the total number of systems operating worldwide. Simulations were run for a period of 20 days for 30, 60 and 120 randomly placed ground-based meteorological radars operating around the world. The radars are assumed to operate within 9 300-9 500 MHz, all falling completely within the operational bandwidth of the SAR.

5.2.1 EESS (active) simulated parameters

A single SAR operating at the orbital parameters defined under SAR 3 in Table 1 was used for this analysis. The criterion of –95.9 dB(W/512 MHz) for no greater than 1% of the time was used to determine compatibility. Statistics of the aggregate interference to the SAR receiver from the ground-based meteorological radars were collected.

5.2.2 Meteorological radar simulated parameters

A spreadsheet was used to generate random locations falling on landmasses for the meteorological radar locations. The antenna rotation speed and starting elevation were also randomly selected for each radar. While it is not possible to identify the actual number of ground-based meteorological radars operating in the band 9 300-9 500 MHz, the total number appears to fall in the range of 30 to 60 radars worldwide. To account for possible expansion in meteorological radar operations in the band 9 300-9 500 MHz, the simulation containing 120 radars was also performed.

While meteorological radars may use a variety of antenna scanning strategies, all radars in the simulation were configured to perform volume scans. In performing a volume scan, the radar starts at a low elevation (typically on the order of 0.5°), conducts a full rotation in elevation, increases its elevation by several degrees, performs another rotation in azimuth, repeating this process until a maximum elevation of 20° to 30° is reached. The antenna then returns to the minimum elevation to begin the process again. Figure 9 is a plot of antenna elevation for the volume scan process used in the simulations.

5.2.3 Results

The simulation results show the current deployment of meteorological radars (30 to 60 radars worldwide) will exceed the SAR interference criterion of -95.9 dBW in a 512 MHz bandwidth for no more than 0.015% to 0.025% of the time, as given in Fig. 10, which is well below the 1% non-availability requirement. The 120 radar simulation resulted in only a slight increase in interference to the SAR, with the criterion exceeded for 0.04% of the time.

FIGURE 9

Antenna elevation movement for a volume scan strategy used in the simulations

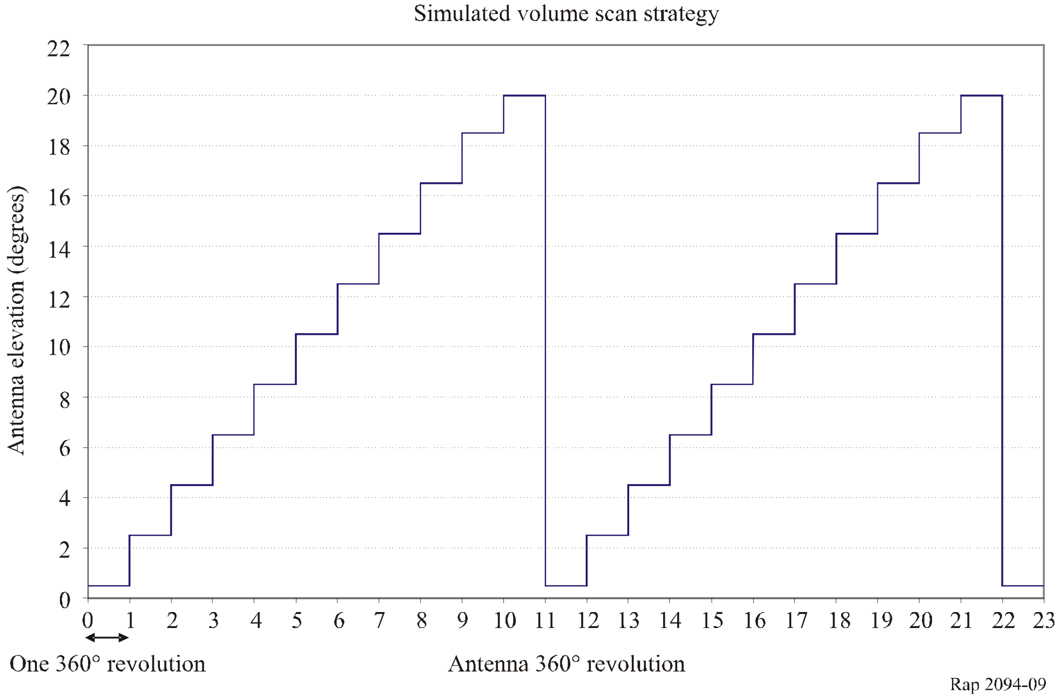
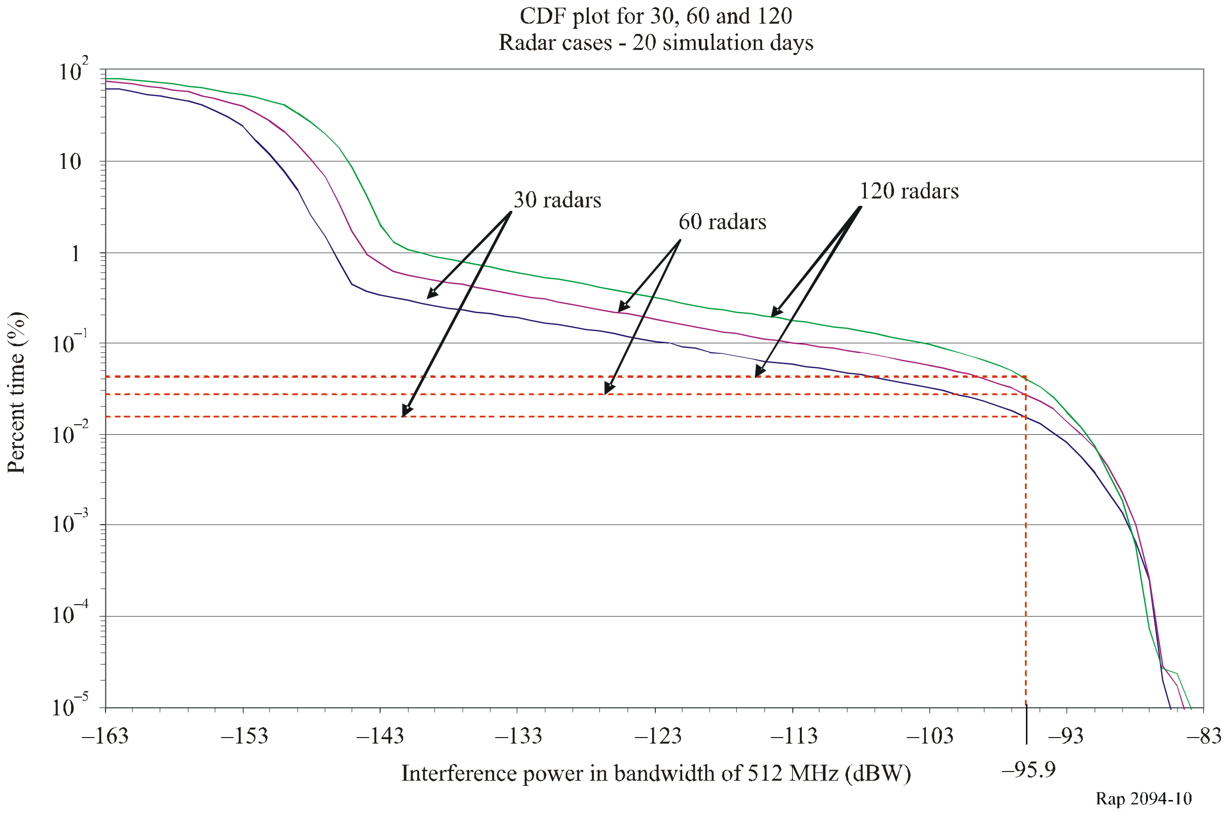


FIGURE 10

Cumulative distribution function (CDF) plot for 30, 60 and 120 radar cases



5.2.4 Conclusion

Simulations show interference levels to the EESS (active) for 30 and 60 radars operating worldwide will exceed –95.9 dBW for 0.015% and 0.025% of the time respectively. A simulation was also performed with 120 radars randomly deployed worldwide to provide insight on how an increase in radars could affect EESS (active) operations in the future. A random deployment of 120 radars produced aggregate interference levels of –95.9 dBW for 0.04% of the time. Based on these results, the aggregate interference caused by current and future ground-based meteorological radars is well below the interference criteria for the EESS (active). With respect to the interference path from the ground-based meteorological radars to the EESS (active), the operations are compatible.

5.3 Analysis Study No. 3: Assessment of maximum interference levels from the EESS (active) into the radiolocation service in the bands 9 300-9 500 MHz and 9 800-10 000 MHz

5.3.1 Analysis approach

A computer simulation model was developed which calculates the maximum interference-to-noise level in the receiver of the radiodetermination systems on or just above the Earth from a spaceborne SAR active sensor in the 9 300-9 500 MHz band. While the analysis was performed using frequencies within the frequency range 9300-9500 MHz, many of the radiolocation systems used in the analysis also operate in the 9800 -10 000 MHz range. Therefore the characteristics of radars operating in 9800-10 000 MHz were considered and the results of this study apply to the 9800-10 000 MHz range as well.

The simulation places the airborne radars (Systems A1, A2, A8, and A10) on a single aircraft at an altitude of 9.1 km, and flying the aircraft in a square pattern with each leg of the square measuring approximately 500 km. Simulations were performed with the aircraft flying at latitudes between 30° N and 35° N and longitudes between 90° W and 95° W. Similarly, the shipborne radars (Systems S1, S3, S4, and S9) were simulated by placing the four systems on a single ship cruising in a square pattern with each leg of the square measuring approximately 500 km. Simulations were performed with the ship cruising at latitudes between 30° N and 35° N and longitudes between 30° W and 35° W. The ground-based radars (Systems G2 and G3) were placed at fixed point on the earth (30° N latitude, 115° W longitude). Antenna scanning was simulated for all radars in accordance with the parameters in Tables 5, 6, and 7. For radar systems that have selectable antenna vertical tilt (elevation) angles, the antenna was set at the highest tilt angle.

The simulations assumed co-polar and co-channel frequency operation. The simulations were performed for a period of 10 days with incremental time steps of 10 ms in order to determine the maximum I/N level at a radar receiver. At each increment, the azimuth and elevation of the radar antenna was determined based on its scan rate. The distance between each SAR transmitter and radar receiver was calculated based on the SAR orbital parameters and radar station location. The SAR interference power at the victim radar station was calculated using equations (15) and (16) in Annex 1 of Recommendation ITU-R M.1461-1, including peak OTR.

5.3.2 Analysis results

The peak SAR transmitter power levels at a radiolocation receiver were determined in the form of maximum I/N power ratio levels. The radar receiver system noise level was calculated using the receiver IF bandwidth and noise figure values given in the radar characteristics tables. If the noise figure was not specified, a value of 5 dB was assumed when calculating the receiver noise power.

To account for the bandwidth difference of the SAR transmitter and the radar receivers, the on-tune rejection (OTR) was calculated. The calculated OTR values shown in Table 14 were applied to calculate the *I*/*N* values in the simulation. A 1 μs SAR pulse duration was used in the calculation to provide a worst case OTR value.

TABLE 14

Calculated on-tune rejection (dB)

	Airborne radar systems				**Shipborne radar systems**				**Ground-based radar systems**	
	A1	**A2**	**A8**	**A10**	**S1**	**S3**	**S4**	**S9**	**G2**	**G3**
SAR3	6.7	2.6	0.0	10.5	0.0	0.0	0.0	0.0	0.0	16.5

Table 15, 16, and 17 lists the maximum *I*/*N* levels for the airborne, shipborne, and ground based radars, respectively.

TABLE 15

Summary of SAR interference into airborne radars

Radar system	**Maximum *I*/*N* level (dB)**
A1	32
A2	38
A8	42
A10	45

TABLE 16

Summary of SAR interference into shipborne radars

Radar system	**Maximum *I*/*N* level (dB)**
S1	32
S3	37
S4	52
S9	28

TABLE 17

Summary of SAR interference into ground radars

Radar system	**Maximum *I*/*N* level (dB)**
G2	11
G3	23

5.3.3 Discussion of interference mitigation

When assessing the degradation to radiodetermination radar systems from pulsed type waveforms, other factors such as interference suppression circuitry and processing gain in the radiodetermination systems should be considered to determine the effects of the *I*/*N* levels. For example, according to Recommendation ITU-R M.1372, a pulse amplitude discriminator can be used to suppress asynchronous pulsed interference at a radar receiver, and under certain conditions, a peak *I*/*N* of 14 dB or greater can be eliminated from further processing in the radar receiver. A constant false alarm rate (CFAR) process can also be used in a radar receiver to mitigate low-duty cycle asynchronous pulse interference. A CFAR process is performed to provide a detection threshold that adapts to clutter and interference levels, and as stated in Recommendation ITU-R M.1372, pulsed interference will not affect the threshold until *I*/*N* ratios are on the order of 30 dB or greater.

Also, radars that perform a Doppler processing on the received signal will "smear" the dissimilar pulsed signal across a number of Doppler bins, resulting in an averaged interfering signal level. The use of average SAR power rather than peak power in this study would lower the potential interference levels by approximately 23 dB.

Interference suppression levels will vary for each radar system and the actual suppression levels can only be determined by performing tests with the proposed SAR waveform. EESS waveforms are planned to be tested with several types of radar systems including marine radionavigation, airport surface detection equipment (ASDE), and airborne and ground based weather radars. The testing will use EESS waveforms that produce *I*/*N* levels given in Tables 15, 16, and 17.

Previous studies and testing with an air surveillance radar that had CFAR processing and a specific SAR waveform determined that an *I*/*N* of approximately +35 dB was required to significantly degrade the radars performance. Interference mitigation techniques and processing gain in the radar receiver was the primary factor in it being able to withstand an *I*/*N* of 35 dB due to the SAR waveform.

5.3.4 Analysis conclusion

This study evaluated the *I*/*N* levels at a radar receiver input due to a spaceborne SAR operating co-channel in the 9 300 to 9 500 MHz band. Since many of the radiolocation systems used in this study also operate in the 9800-10 000 MHz range, the results can be applied to the 9800-10 000 MHz band as well. Recommendation ITU-R M.1461 states that the effect of pulsed interference is more difficult to quantify and is strongly dependent on receivers/processor design and mode of operation. In particular, the differential processing gains for valid-target return, which is synchronously pulsed, and interference pulses, which are usually asynchronous, often have important effects on the impact of given levels of pulsed interference.

Several different forms of performance degradation can be inflicted by such desensitization. Assessing it will be an objective for analysis of interactions between specific radar types. In general, numerous features of radiodetermination radars can be expected to help suppress low-duty cycle pulsed interference, especially from a few isolated sources. Techniques for suppression of low-duty cycle pulsed interference are contained in Recommendation ITU-R M.1372.

5.4 Analysis Study No. 4: Analysis of potential interference from the EESS (active) into ground-based meteorological radars operating in the radiolocation service in the band 9 300-9 500 MHz

The analysis results of compatibility between the ground-based meteorological radar and the EESS were obtained through the use of dynamic simulations using a commercial software package. Only interference to the ground-based meteorological radar from the EESS was considered for this study. The simulations were run to cover a period of approximately 23 days for each scenario. This analysis contains two parts. The first part, a preliminary analysis, used assumed *I*/*N* protection values of –6 dB and +10 dB in order to provide a quick determination of whether a compatibility problem could exist. Based on the results showing the –6 dB and +10 dB *I*/*N* thresholds could be exceeded for significant amounts of time, additional analysis was performed in the second part to determine the ability of the meteorological radars to mitigate higher levels of interference.

5.4.1 Preliminary analysis

This portion analysis makes some basic assumption that the victim radar is not able to mitigate high levels of pulsed interference.

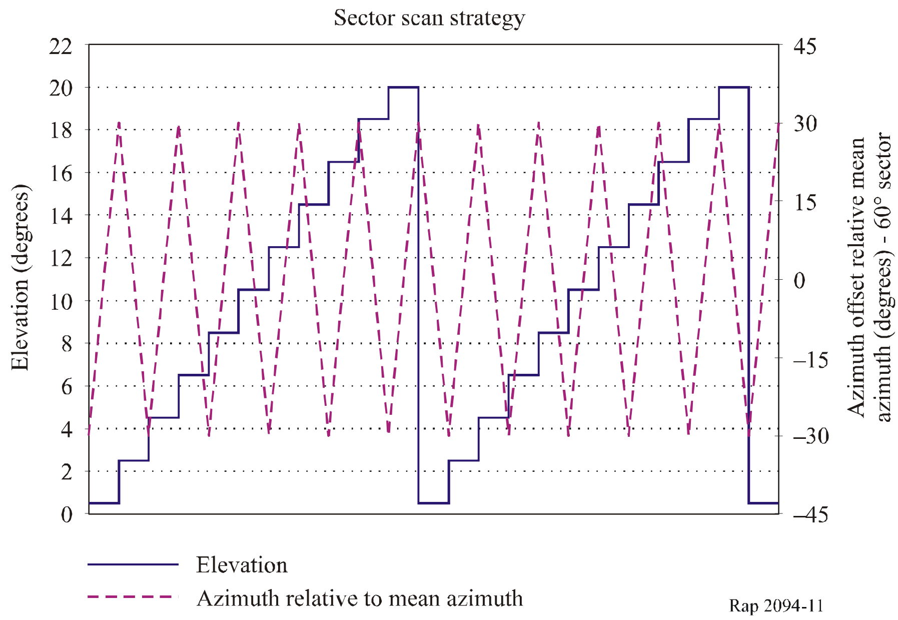
5.4.1.1 Ground-based meteorological radar parameters

Ground-based meteorological radars can be operated in a variety of modes resulting in different antenna rotation speeds and antenna movement strategies. The most common scanning strategy is a volume scan, where the radar performs a series of antenna full rotations at elevation angle increments ranging from near 0° to a maximum of 20° to 30°. Figure 9, in § 5.2.2, is a plot of antenna volume scan strategy used in the simulations involving volume scans.

Ground-based meteorological radars can also perform other scanning strategies to meet specific operational requirements. To closely monitor a specific area of the atmosphere, the radar can perform sector scans or operate in a spotlight mode. In the sector volume scan mode, the antenna concentrates on an azimuth sector while progressing through a series of elevation steps. In spotlight mode, the antenna azimuth and elevation are held constant to illuminate a small area of atmosphere for an extended period of time. For this study, the sector volume scan was simulated by scanning an azimuth range of 60°, ±30° about a mean azimuth value. Simulations were run with median azimuth values of 0°, 90° and 135°. Figure 11 shows a plot of the sector volume scanning strategy used in the simulations.

FIGURE 11

Sector scan antenna movement used in simulation (60° wide sector)



As can be seen from Table 7, the radar system G9 uses a range of antenna rotation speeds. The volume scan and sector scan strategies are simulated at antenna rotation speeds of 5°/s and 20°/s. The ground-based meteorological radar is assumed to remain in a fixed location. Three radar locations were used in the simulations since latitude of the radar may affect the length of time the SAR will be in sight of the radar. Simulations were run with the radar placed at low, mid and high latitude locations (0°, 45° N and 60° N) respectively. Since the IF bandwidth is adjustable, a large number of simulations would be required to cover all the possible combinations. To obtain results indicating the worst potential for interference, a radar IF bandwidth of 10 MHz was used.

5.4.1.2 SAR parameters

The orbital characteristics of the SAR were also simulated. The simulations use four SARs separated by 90° in longitude. The SAR uses linear FM chirp where the pulse duration is variable from 1 to 10 μs. To limit the number of simulations, the pulse width of 10 μs was used, corresponding to the lowest FDR and the worst sharing case. Co-frequency operation with the meteorological radar was assumed. Tests were performed that showed that the effective pulse width of a chirped waveform is with a bandwidth that is much wider than the receive bandwidth was reduced due to the response of the receiver's IF circuitry. Therefore, the chirped 10 μs pulse width of SAR 3 within the met radar's receiver will be considerably reduced. This may aid in the compatibility between the systems.

5.4.1.3 Frequency dependent rejection

Frequency dependent rejection (FDR) between an interference source and a victim receiver is a combination two factors, off-frequency rejection (OFR) and on-tune rejection (OTR):

$$FDR = OFR + OTR$$

In this case where the SAR and radar are operating co frequency, the OFR is zero.

The OTR of chirped signals is calculated in the following manner:

$$OTR = 10 \log (B_c/(B_R^2\, T)) \qquad \text{for } B_c/(B_R^2\, T) > 1$$

where:

T: chirped pulse width (s)

B_c: transmitter chirped bandwidth during the pulse width, T (Hz)

B_R: receiver 3 dB bandwidth.

For the selected meteorological radar bandwidth of 10 MHz, and the selected SAR chirp pulse width of 10 μs, the OTR is zero. The simulations used a value of 0 dB for the FDR.

5.4.1.4 Analysis results

Since the ability of the ground-based meteorological radar to mitigate the SAR interference is unknown at the time the initial results were obtained, the generic I/N of –6 dB was used as a reference. The generic –6 dB I/N is associated with a continuous wave (CW) or noise-like interference signal and it may not be applicable to a space borne SAR signal due to its chirped pulsed nature. It should be noted that the radar used in this analysis and other types of ground-based meteorological radars that are operating in this band may not contain interference mitigation techniques that are described in Recommendation ITU-R M.1372 for eliminating the effects of pulsed interference. The initial results, as presented, should not be used to determine compatibility based on signal processing.

5.4.1.5 Radar volume scan results

Table 18 presents the results for the volume scan simulations. The time durations are independent of the maximum *I*/*N* value. The durations provide some insight into how long a radar operator may experience interference from a SAR before any processing gain or mitigation techniques are applied to the analysis results. Table 18 also presents the data for an *I*/*N* threshold of = +10 dB, to provide insight into how the results will be affected by the radar's potential ability to mitigate the effects of interference at levels greater than an *I*/*N* of –6 dB. As with the *I*/*N* = –6 dB level, the +10 dB level has no significance and was just selected to illustrate the point that as the radar can withstand a higher interference level, the number of interference occurrences and the interference durations change.

Within the United States of America, ground-based meteorological radars operating in this band are generally used for atmospheric research and other applications that can and do withstand some periods of pulsed interference. Other administrations may have more stringent protection requirements for radars operating in 9 300-9 500 MHz.

TABLE 18

Volume scan simulation results

5°/s rotation							
Radar location	**Max *I*/*N* (dB)**	**Longest duration above *I*/*N* = –6 dB (s)**	**Average duration above *I*/*N* = –6 dB (s)**	**Number of *I*/*N* > –6 dB occurrences over 23 day period**	**Longest duration above *I*/*N* = +10 dB (s)**	**Average duration above *I*/*N* = +10 dB (s)**	**Number of *I*/*N*>+10 dB occurrences over 23 day period**
Low latitude	23.8	0.55	0.34	225	0.40	0.22	139
Mid latitude	27.3	2.50	0.38	366	0.35	0.22	231
High latitude	24.6	0.55	0.34	488	0.40	0.22	371
20°/s rotation							
Low latitude	23.9	0.15	0.09	853	0.10	0.06	523
Mid latitude	24.2	2.5	0.10	1321	0.10	0.06	836
High latitude	24.2	0.15	0.09	2205	0.01	0.06	1330

The results presented in Table 18 indicate that the ground-based meteorological radar may experience maximum *I*/*N* values on the order of 24 to 27 dB when operating in a typical volume scan mode. A limited number of simulations were also run to confirm the number of interference occurrences was directly proportional to the number of SARs used in the simulation. The results showed the number of occurrences was reduced by a factor of 4 when a single SAR was used, but the peak levels and durations remained approximately the same.

5.4.1.6 Radar sector volume scan results

Table 19 present the results with the radar simulated operating in a sector volume scan mode. In the sector scan mode none of the radar receiver characteristics change. The antenna is moved in a pattern as shown in Fig. 11. The simulations were run for only the 45° latitude location.

TABLE 19

Sector scan simulation results (45° latitude)

60° sector start/end azimuth	5°/s rotation			20°/s rotation		
	Max *I/N* (dB)	Longest duration above *I/N* = –6 dB (s)	Average duration above *I/N* = –6 dB (s)	Max *I/N* (dB)	Longest duration above *I/N* = –6 dB (s)	Average duration above *I/N* = –6 dB (s)
North sector (330° to 60°)	24.0	2.50	0.36	28.3	2.50	0.10
East sector (60° to 120°)	23.6	2.50	0.37	24.3	2.50	0.10
Southeast sector (105° to 165°)	24.1	2.50	0.38	23.0	2.50	0.10

5.4.1.7 Radar spotlight mode results

Table 20 present the results with the radar simulated operating in a spotlight mode. Ground-based meteorological radars operated in the band 9 300-9 500 MHz for atmospheric research will periodically be used in a spotlight mode, where a point in the atmosphere is illuminated for a long period of time. During this operation, the antenna elevation and azimuth do not change. Simulations were run with the radar placed at the 45 degree latitude location, and the antenna held at a fixed azimuth and elevation. Azimuths of 0° N and 90° E, and antenna elevations of 0.5, 20 and 45° were used.

TABLE 20

Spotlight mode simulation results (45° latitude only)

	0° azimuth (N)			90° azimuth (E)		
	Max *I/N* (dB)	Longest duration above *I/N* = –6 dB (s)	Average duration above *I/N* = –6 dB (s)	Max *I/N* (dB)	Longest duration above *I/N* = –6 dB (s)	Average duration above *I/N* = –6 dB (s)
0.5° antenna elevation	17.0	23.0	14.0	18.0	13.55	7.14
20° antenna elevation	24.6	11.75	6.98	15.6	5.65	2.83
45° antenna elevation	24.5	4.75	3.36	3.3	2.5	1.86

5.4.1.8 Preliminary analysis conclusion

Concluding on whether compatibility exists between the EESS and ground-based meteorological radars is difficult without a better understanding of the ability of meteorological radar to mitigate the effects of the SAR interference. For purposes of this study, a generic thresholds of *I*/*N* = –6 dB and +10 dB were used to develop data on time durations that the SAR could potentially impact the radar's operations. This is most likely not the appropriate threshold, and the threshold could potentially fall somewhere in the I/N = 0 dB to +40 dB range. The maximum I/N shown to occur in the simulations for this study was I/N = +28.3 dB, with most of the peak levels falling near I/N = +24 dB. These results are for pulsed interference and the typical –6 dB or –10 dB I/N thresholds used with meteorological radars do not apply as they are applicable only for noise-like and CW interference. The difference in duration of interference between use of a –6 dB and a +10 dB protection criterion is marginally significant. Use of the +10 dB criterion reduces the interference durations by approximately 30-36 %. The effect of the higher protection criterion is more significant on the number of occurrences of interference. To significantly reduce the durations and number of interference occurrences, the meteorological radars will need to be capable of withstanding I/N levels greater than +10 dB.

5.4.2 Additional factors to mitigate interference to meteorological radars

The preliminary analysis results indicate, in the absence of the ability of meteorological radars to mitigate pulsed interference, compatibility between the EESS and ground based meteorological radars may be problematic. This section further evaluates the ability of meteorological radars to operate in the presence of the pulsed EESS (active) interfering signals. Interference mitigation of pulsed interference resulting from normal meteorological radar data processing as well as the EESS operational characteristics were not considered in the initial analysis. This section addresses those factors in detail. Intentional mitigation techniques which could be implemented are not considered since they generally are not used in meteorological radars due to degradation in performance.

5.4.2.1 EESS (active) operational periods

Due to the amount of power required for SAR operation, the EESS is only intended to operate for a maximum of 20% of the time. This operational duty cycle is different than the pulse duty cycle; it is the percentage of time the SAR would be operating to collect data. Within a one year period (8 766 h) the SAR would only operate a maximum of 1 753 h, greatly reducing the number of interference occurrences. While it is operating, the maximum interference levels could occur for the durations shown in Tables 18, 19 and 20. The preliminary simulations assumed the SAR operated continuously over the simulation period, therefore the number of interference occurrences can be reduced by a factor of 5.

5.4.2.2 On-tune rejection considerations

In order to quickly obtain a preliminary analysis, only the worst case sharing situation was previously considered. The meteorological radar IF bandwidth was selected to be 10 MHz resulting in an on-tune rejection value of 0 dB. (Further investigation has shown the IF bandwidth of 10 MHz to be larger than is typically used on most meteorological radars.) Most meteorological radars have an IF bandwidth in the 1 to 4 MHz range, yielding an improvement in the sharing situation. Given a SAR pulse width variation of 1 to 10 μs, an IF bandwidth of 4 MHz will provide 14.5 to 4.5 dB of on-tune rejection. However, the narrower IF bandwidth will increase radar sensitivity by reducing the radar noise floor by 4 dB. A resulting 10.5 to 0.5 dB improvement in comparison to the previously analyzed sharing situation is possible due to OTR. For a 1 MHz meteorological radar IF bandwidth, the sharing improvement, taking into account OTR and a reduction in radar noise floor, is from 6.5 to 15.5 dB. Table 21 provides a summary of IF bandwidths, receiver noise levels, and the associated OTR values.

TABLE 21

On-tune rejection values

SAR chirp bandwidth (MHz)	SAR pulse width (µs)	Met radar IF bandwidth (MHz)	OTR (dB)	Radar noise floor (dBm)
450 MHz	1.0	1 MHz	25.5	–110
	5.0		19.5	
	10.0		16.5	
	1.0	4 MHz	14.5	–104
	5.0		7.5	
	10.0		4.5	
	1.0	10 MHz	6.5	–100
	5.0		0.0	
	10.0		0.0	

5.4.2.3 Derivation of *I*/*N* levels for pulsed interference

Meteorological radars process signal returns to measure precipitation and wind patterns. The processing involves collecting and processing base products; reflectivity, mean radial velocity, and spectrum width. In simplest terms, the radar averages a sample of signal returns to derive the estimates needed for production of meteorological products. The averaging function will provide the meteorological radar the ability to process higher pulsed interference levels relative to CW or noise-like interference signals.

Meteorological radars process multiple pulse returns falling within a range bin to form a sample of a size defined by the user. The multiple pulse returns forming a range bin sample are averaged to derive the range bin estimate. The proposed EESS systems and meteorological radars operate on significantly different pulse repetition frequencies, so the likelihood of more than one interfering pulse falling within a single meteorological radar range bin sample set is small, given a small sample size. The approach is to determine the maximum level of a single pulse that will not corrupt the average of the sample size beyond the base data product performance objectives of the radar.

Determination of a protection criterion requires an understanding of the radar's receiver noise level, the minimum *S*/*N* used for processing, and the radar's base products (reflectivity, man radial velocity and spectrum width) accuracy requirements. Since a variety of meteorological radars are operated in the band, some assumptions must be made. The radar used in the analysis has a receiver noise floor of –110 dBm at the narrowest IF bandwidth. The base products accuracy requirements for radars operated in this band are not readily available, but it can be assumed the accuracies defined in Annex 3 of Recommendation ITU-R M.1464 would be applicable. The minimum *S*/*N* is probably the most difficult value to establish without reference to specific radars. For radars operated in the band 2 700-2 900 MHz *S*/*N* ratios of 0 to –3 dB are used since the lower

Frequency radars generally are operated for detection at long ranges. Meteorological radars operated in the band 9 300-9 500 MHz are generally used for shorter range, higher resolution detection, and may operate at higher minimum *S*/*N* ratios. For this analysis, an *S*/*N* of +3 dB will be assumed.

As shown in Annex 3 of Recommendation ITU-R M.1464, the maximum reflectivity bias limit for a meteorological radar is assumed to be 1 dB, which translates to an interference to minimum signal ratio (I/S) of 0.26, or a power ratio of 1.26. A reflectivity sample size of 25 will be assumed. A sample size larger than 25 is possible, further reducing the effects of a single pulse, but a larger sample size also increases the probability of a second interfering pulse occurring in the same sample:

$$\frac{25 * S_{min} + P_i}{25 * S_{min}} = 1.26 \qquad \text{or} \qquad P_i = 6.5\, S_{min} \tag{1}$$

where:

S_{min}: minimum receive signal level

P_i: pulsed interference signal peak power.

Therefore:

$$P_i = S_{min} + 8.2 \text{ dB} \tag{2}$$

As stated above, a minimum signal-to-noise ratio of 3 dB is assumed for radars operating in the 9 300-9 500 MHz band, leading to maximum interference-to-noise ratio of 11.2 dB for the pulsed EESS signals.

5.4.2.4 Chirped EESS pulse duty cycle reduction in victim radar IF filter

The results of tests showed the ability of a victim receiver's IF filtering stage to effectively reduce the pulse width of a chirped signal. The preliminary test results show that, depending on the chirp rate of the interfering signal, the interfering signal pulse width can be reduced as follows:

For low chirp rates (~ <5 MHz/μs) the pulse width reduction factor is:

$$C \approx \frac{B_{IF}}{B_c} \tag{3}$$

where:

B_{IF}: IF bandwidth of the victim receiver

B_c: chirp bandwidth of the interfering signal.

For high chirp rates (~ > 40 MHz/μs) the width reduction factor is:

$$C \approx \frac{2 * B_{IF}}{B_c} \tag{4}$$

Therefore, based on SAR 3 (B_c = 450 MHz) used in the previous simulations, a minimum duty cycle reduction can be predicted. The duty cycle reduction factors for low and high chip rates are given in Table 22.

TABLE 22

Duty cycle reduction factor (for B_c = 450 MHz)

B_{IF} (MHz)	Low chirp rate	High chirp rate
1.0	0.0022	0.0044
4.0	0.0089	0.018
10.0	0.022	0.044

Section 5.4.2.3 discussed the fact meteorological radars average a sample set of pulses within a range bin to derive the based product estimates. It is unclear what effect the duty cycle reduction will have as the range bin sample sets are averaged. A reduction in interference duty cycle could translate directly to a reduction in interference susceptibility due the range bin seeing less power. In that case the duty cycle reduction factors ranging from 0.0022 to 0.044 would result in interference mitigation processing gain of 26.6 to 13.6 dB, respectively. However, these values are probably overly optimistic, and further study is needed.

5.4.2.5 Summary – Sharing between EESS and meteorological radars

The second part of the analysis contained in § 5.4.2.1 to 5.4.2.4 presents several mechanisms that will improve the results of sharing between the EESS (active) transmitting pulsed signals and meteorological radars as presented in previous studies. Improvement in the sharing results are obtained from a higher applicable *I*/*N* protection criterion for pulsed interference from the EESS into the meteorological radar, on-tune rejection for a more representative meteorological radar IF bandwidth, and EESS duty cycle reduction due to the narrower IF bandwidth of the meteorological radar. Table 23 presents a summary of the improvements.

TABLE 23

Summary of additional interference mitigation values

Description	Original value used in previous studies	Updated value	Comments
I/*N* protection criterion (dB)	–6 and +10	At least +11.2	Dependent on number of pulses averaged per range-bin sample
On-tune rejection (dB)	0	0.5 to 15.5	Dependent on radar IF bandwidth and SAR pulse width
Duty cycle reduction due to IF filter narrower than chirp bandwidth	Not considered	Actual value unknown- potential improvement in 13.6 to 26.6 dB range	Further study required before an actual value can be applied to results

Using the information presented in Table 23, the results of the previously submitted simulations can be reprocessed to determine more representative durations of interference that may occur to meteorological radars. Unfortunately, due to the variability of some of the values in Table 23 caused by variable SAR and meteorological radar parameters, a single interference threshold cannot be determined. At a minimum, the meteorological radar should be able to operate in the presence of pulsed EESS (active) interference at a level of I/N = 11.2 dB. Introducing the updated OTR values, the interference mitigation could increase so that radar could withstand I/N levels another 0.5 to 15.5 dB above the 11.2 dB level. That would bring the maximum acceptable I/N levels to a range of 11.7 to 26.7 dB. Due to the uncertainty of effect of the duty cycle reduction (discussed in § 5.4.2.5) on the meteorological radar's ability to mitigate interference, specific values will not be applied to the results of this document It will only be recognized that the duty cycle reduction should further improve the sharing situation.

5.4.3 Conclusion – Re-evaluating data from the preliminary analysis

The preliminary analysis resulted in periods of time where interference exceeded the thresholds of I/N = –6 dB and +10 dB. However, when considering the additional analysis and information on signal processing and operational characteristics, the maximum I/N levels meteorological radars operating in 9 300-9 500 MHz may be able to withstand from the pulsed signals of the EESS (active) fall in the range of 11.7 to 26.7 dB, and potentially greater. The simulation results were reprocessed using thresholds of +19.2 dB and +26.7 dB, representing a median threshold between 11.7 and 26.7 dB, and a high threshold, respectively. The results for the 11.7 dB level are close to the previously presented results for I/N = +10 dB. The reader should recognize these results will not contain the effects of duty cycle reduction discussed in § 3.5, or other interference mitigation techniques implemented in the radar.

The results, summarized in Table 24, show that even if typical ground-based meteorological radars experience EESS (active) pulsed interference levels on the order of 24 to 28 dB relative to the radar noise floor, the degradation of performance will be insignificant. The factors of on-tune rejection and radar data processing were not considered in the preliminary analysis. These additional factors make sharing feasible between ground-based meteorological radars operating in the radiodetermination service and the EESS (active). These results apply only to sharing between the EESS (active) and ground-based meteorological radars in 9 300-9 500 MHz, and cannot be extended to other cases involving other interfering systems or other bands. Other factors discussed in this document, but not taken into account may also further improve the sharing situation.

TABLE 24

Simulation results taking into account interference mitigation

5°/s rotation									
		***I/N* threshold = +19.2 dB**				***I/N* threshold = +26.7 dB**			
Radar location	**Max *I/N* (dB)**	**Longest duration above threshold (s)**	**Average duration above threshold (s)**	**Number of threshold violations over 23 days(1)**	**Average corrupted azimuth sector (degrees)**	**Longest duration above threshold (s)**	**Average duration above threshold (s)**	**Number of threshold violations over 23 days(1)**	**Average corrupted azimuth sector(3) (degrees)**
Low latitude	23.8	0.20	0.12	8	0.6	0	0	0	0
Mid latitude	27.3	0.25	0.13	13	0.65	0.05	0.05	1	0.25
High latitude	24.6	0.25	0.12	19	0.6	0	0	0	0
20°/s rotation									
		***I/N* threshold = +19.2 dB**				***I/N* threshold = +26.7 dB**			
Low latitude	23.9	0.10	0.05(2)	97	1	0	0	0	0
Mid latitude	24.2	0.05	0.05(2)	31	1	0	0	0	0
High latitude	24.2	0.05	0.05(2)	42	1	0	0	0	0

(1) Takes into account the fact the SAR has a maximum operational duty cycle of 20%.

(2) The simulation step size was 0.05 s. Therefore, the durations shown as 0.05 s in Table 24 may actually be shorter time durations.

(3) Typical meteorological radars use a radial resolution on the order of approximately 1°. A corrupted azimuth of less than 1° will result in at least one full radial corrupted, and possibly two if the interference occurs over the boundary between radials. A small number of meteorological radars use radial resolution in the tenths of degrees.

5.5 Analysis Study No. 5: Compatibility studies between the EESS (active) and the fixed service in the 9 800-10 000 MHz band

5.5.1 Analysis approach

A computer simulation model was used to determine interference statistics at fixed service receivers from a proposed spaceborne SAR transmitter, and interference statistics at a proposed spaceborne SAR receiver from fixed service transmitters.

5.5.1.1 Interference from the P-P FS into SAR3 receiver

A computer simulation model was developed which calculates the time-dependent interference power level at the receiver of a spaceborne SAR active sensor from fixed service transmitters. Using this simulation model, interference statistics were collected in the form of the probability that an interference power level was exceeded, and the maximum interference power level at the SAR receiver.

All simulations were performed for a period of 10 days with incremental time steps of one second. At each time increment, the distance between the SAR receiver and the fixed service transmitters was calculated based on the SAR orbital parameters and the fixed service station location. For this study, the SAR antenna was pointed 44° off-nadir in the cross-track direction. The interference power at the SAR receiver was calculated based on transmitter power, path loss, and antenna discrimination. Co-antenna polarization and co-channel frequency operation were assumed in this study, and insertion losses were not considered. The P-P FS stations are assumed to continuously transmit using average power.

Parameters for the EESS (active) and the P-P FS stations used in this study are given in § 2 and 4 of this Report, respectively.

Simulations were performed for two fixed service station deployment models:

– Worldwide random distribution of 1 536 P-P FS stations

– 1 536 P-P FS stations distributed within the administrations listed in RR No. 5.477

The SAR protection criteria used for this analysis is $I/N = -6$ dB. The mean noise power in the SAR receiver is:

$$P_N = k\, T_0\, B \qquad \text{(W)}$$

where:

k: Boltzmann's constant ($1.38 \cdot 10^{-23}$ Joule/°K)

T_0: SAR3 receiver noise temperature (600 K)

B: SAR3 receiver IF bandwidth ($512 \cdot 10^{6}$ Hz)

therefore:

P_N: –113.73 dBW

To meet the SAR protection criteria, the interference power at the input to the SAR receiver must be lower than –119.73 dB(W/512 MHz), 99% of the time.

5.5.1.1.1 Random worldwide deployment simulation

A total of 1 536 P-P FS stations were randomly distributed within –55 to +70° in latitude and ±180° in longitude. Some random locations were modified to ensure that all stations were located on land. The following FS station parameters were selected initially as described below, and remained static for the duration of the simulation:

– latitude of each station is selected from a random value between –55° to 70°
– longitude of each station is selected from a random value between ±180°
– station antenna height is selected from a random value between 10 to 100 m
– station antenna transmit beam elevation angle is selected from a random value between ±5°
– station antenna azimuth is selected from a random value between ±180°

A representation of the P-P FS station distribution is shown in Fig. 12.

FIGURE 12

Fixed service station locations used in simulation

Rap 2094-12

5.5.1.1.2 Deployment simulation based on RR No. 5.477

P-P FS stations were located within the administrations defined in RR No. 5.477. The footnote states:

> **5.477** *Different category of service:* in Algeria, Saudi Arabia, Bahrain, Bangladesh, Brunei Darussalam, Cameroon, Egypt, the United Arab Emirates, Eritrea, Ethiopia, Guyana, India, Indonesia, Iran (Islamic Republic of), Iraq, Jamaica, Japan, Jordan, Kuwait, Lebanon, Liberia, Malaysia, Nigeria, Oman, Pakistan, Qatar, the Dem. People's Rep. of Korea, Singapore, Somalia, Sudan, Trinidad and Tobago, and Yemen, the allocation of the band 9 800-10 000 MHz to the fixed service is on a primary basis (see No. **5.33**). (WRC-03)

Figure 13 shows the territories of these administrations in black.

FS systems are predominantly deployed in urban and sub-urban areas, with few if any systems in rural areas. Within each major urban area of the administrations listed in RR No. 5.477, 12 P-P FS stations were randomly located. Pairs of P-P FS stations were pointed towards each other to simulate a realistic case. A total of 128 urban areas were used resulting in 1 536 P-P FS stations.

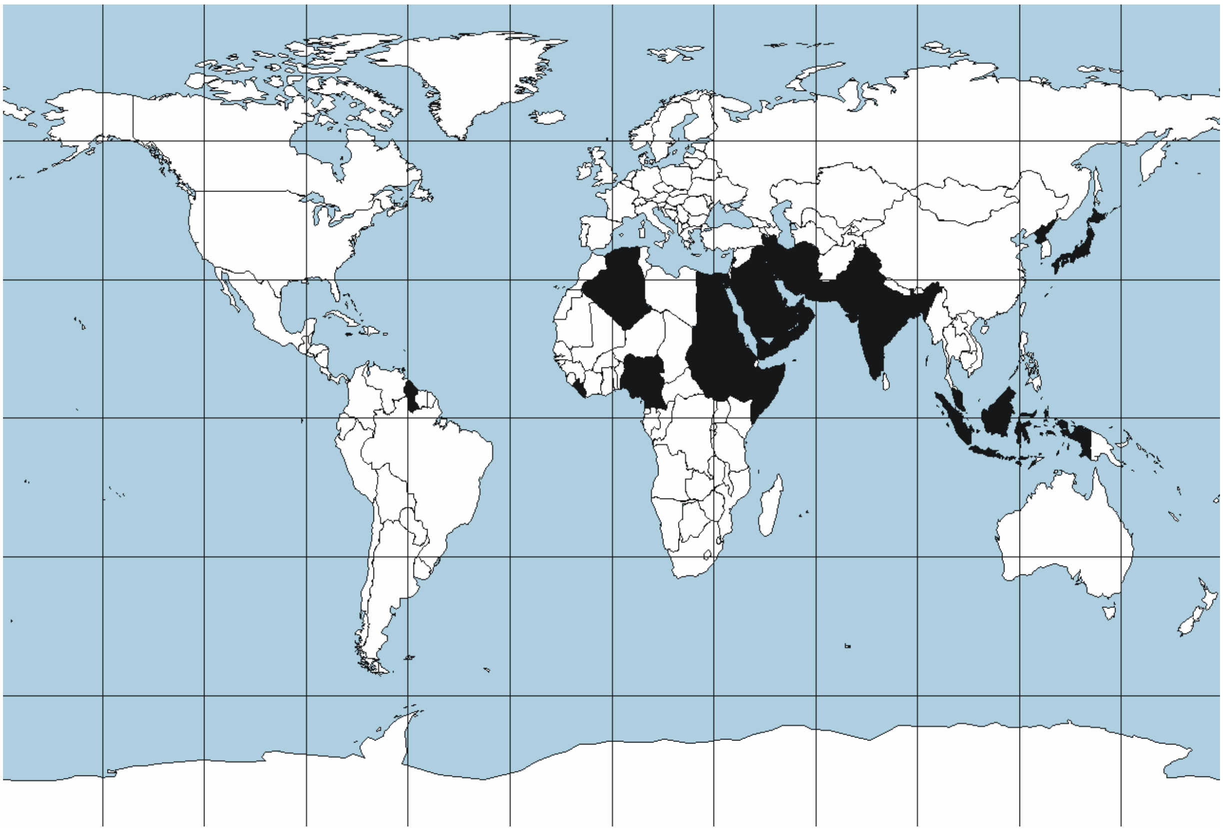
The following FS station parameters were selected initially as described below, and remained static for the duration of the simulation:

– Station antenna height is selected from a random value between 10 to 100 m

– Station antenna transmit beam elevation angle is selected from a random value between ±5°.

FIGURE 13

Countries listed RR No. 5.477



Rap 2094-13

5.5.1.2 Interference from SAR3 into the P-P FS receivers

A computer simulation model was developed which calculates the time-dependent interference power level at a fixed service receiver from the SAR3 spaceborne active sensor. Using this simulation model, interference statistics were collected in the form of the probability that an interference power level was exceeded, and the maximum interference power level at a fixed service receiver.

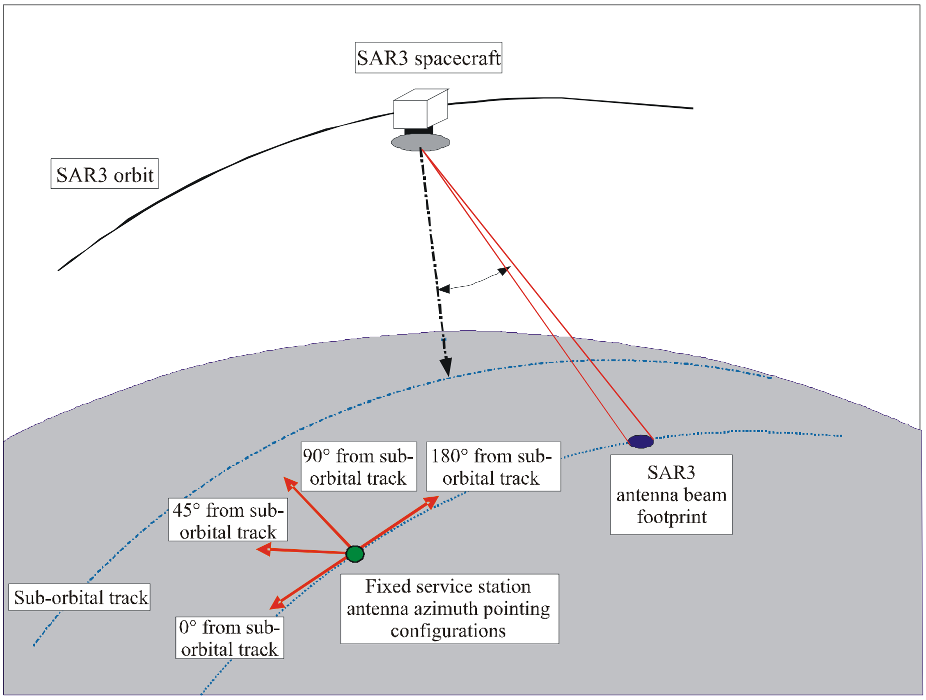
All simulations were performed for a period of 60 days with incremental time steps of 0.5 s. At each time increment, the distance between the SAR transmitter and the fixed service receiver was calculated based on the SAR orbital parameters and the fixed service station location. The interference power at the fixed service receiver was calculated, based on transmitter power, path loss, and antenna discrimination. Antenna co-polarization and co-channel frequency operation were assumed in this study, and insertion losses were not considered. It was assumed that the SAR3 continuously transmits using average power which the derived from the peak power and the pulse duty cycle. The results presented below do not take into account a factor for the SAR being operational for only 10% to 20% of a typical orbit.

Administrations listed in RR No. 5.477 are located within the range of approximately 15° S latitude and 45° N latitude. For this study, the deployment scenarios and antenna pointing configurations that were considered are listed in Table 25 and the FS station antenna azimuth angles were set relative to the azimuth corresponding to SAR3 inclination angle as illustrated in Fig. 14. The station antenna height was set at 20 m.

Interference statistics were collected for the five P-P FS stations at the various elevation and azimuth antenna angles, resulting in a total of 60 cases.

FIGURE 14

P-P FS antenna azimuth pointing configurations



Rap 2094-14

TABLE 25

P-P FS stations setup parameters (60 total cases)

Station latitude (degrees)	Station longitude (degrees)	Azimuth direction of antenna relative to SAR3 inclination angle (degrees)	Antenna elevation angle (degrees)
45	0	0, 45, 90, 180	–5, 0, 5
30	0	0, 45, 90, 180	–5, 0, 5
15	0	0, 45, 90, 180	–5, 0, 5
0	0	0, 45, 90, 180	–5, 0, 5
–15	0	0, 45, 90, 180	–5, 0, 5

5.5.2 Analysis results

5.5.2.1 Interference from the P-P FS into SAR3 receiver

Analysis results are provided for the two fixed service station deployment models:

– Worldwide random distribution of 1 536 P-P FS stations

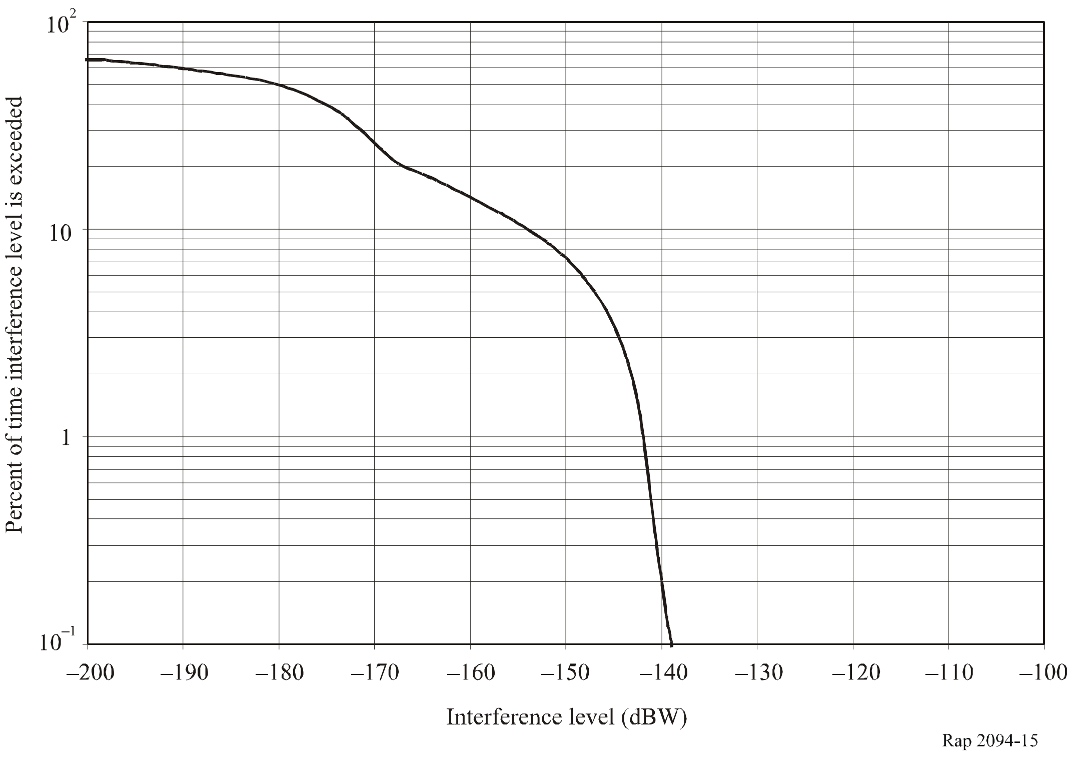
– 1 536 P-P FS stations distributed within the administrations listed in RR No. 5.477

5.5.2.1.1 Random worldwide deployment

Figure 15 shows the cumulative distribution function (CDF) plot of interference from 1 536 P-P FS stations at the SAR3 receiver. The results are presented as the interfering signal power received at the spaceborne sensor receiver IF bandwidth of 512 MHz as a percentage of time. As seen in the figure, the interfering signal power was approximately –142 dBW for the 99% data availability criteria (1% point). The maximum interference level received at the SAR3 receiver was –125.0 dBW, which is 5.3 dB below the SAR protection criteria.

FIGURE 15

CDF of interference from 1 536 P-P FS stations randomly distributed worldwide

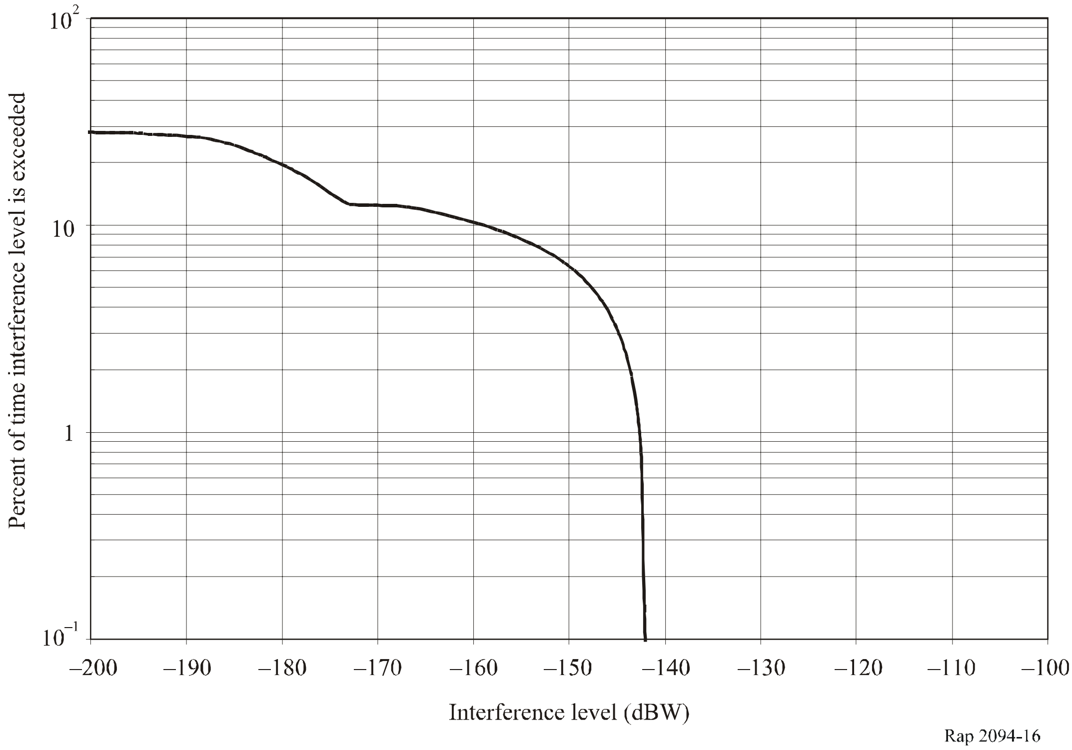


5.5.2.1.2 Deployment based on RR No. 5.477

Figure 16 shows the CDF plot of interference at the SAR3 receiver from 1 536 P-P FS stations, distributed within 128 urban centres of the administrations defined in RR No. 5.477. The results are presented as the interfering signal power received at the spaceborne sensor receiver IF bandwidth of 512 MHz as a percentage of time. As seen in the figure, the interfering signal power was approximately –143 dBW for the 99% data availability criteria (1% point). The maximum interference level at the SAR3 receiver was –125.17 dBW, which is 5.4 dB below the SAR protection criteria.

FIGURE 16

CDF of interference from 1 536 P-P FS stations placed in administrations listed in RR No. 5.477



5.5.2.2 Interference from SAR3 into the P-P FS

5.5.2.2.1 Analysis results – Effect of FS station antenna elevation angle

FS antenna elevation angles of –5°, 0°, and 5° were used in the simulation for each of the various FS station azimuth angles and station latitudes. In order to determine the impact of elevation angle on *I*/*N* levels at a FS station, a comparison was performed using the simulation results illustrated in Fig. 16.

Figure 17 provides the analysis results in terms of a cumulative distribution function (CDF) of the *I*/*N* values at a FS receiver located at 0° latitude. As seen in the Figure, *I*/*N* levels at –5° elevation are approximately 5 dB less than at 5° elevation for the 0.1% point. Similarly, *I*/*N* levels at 0° elevation are approximately 3 dB less than at 5° elevation for the 0.1% point. At the 1% point, the CDF curves converge for the three FS antenna elevation angles. Similar results were obtained at the other FS station latitudes considered in this study.

5.5.2.2.2 Analysis results – Effect of FS station antenna azimuth angle

FS antenna azimuth angles of 0°, 45°, 90°, and 180° relative to the SAR3 inclination angle were used in the simulation for each of the various FS station latitudes. In order to determine the impact of azimuth angle on *I*/*N* levels at a FS station, a comparison was performed using simulation results at two representative latitudes as illustrated in Figs 18 and 19.

Figure 18 provides the results in terms of a CDF of the *I*/*N* values at a FS receiver located at 0° latitude, and similar results are provided for 30° latitude in Fig. 18. As seen in the Fig. 18 (0° latitude), the effect of variations in the FS antenna azimuth angle is small in terms of *I*/*N* levels, with all values within approximately 0.5 dB of each other at the 0.1% point.

FIGURE 17

CDF of *I*/*N* levels into a FS receiver at 0° latitude

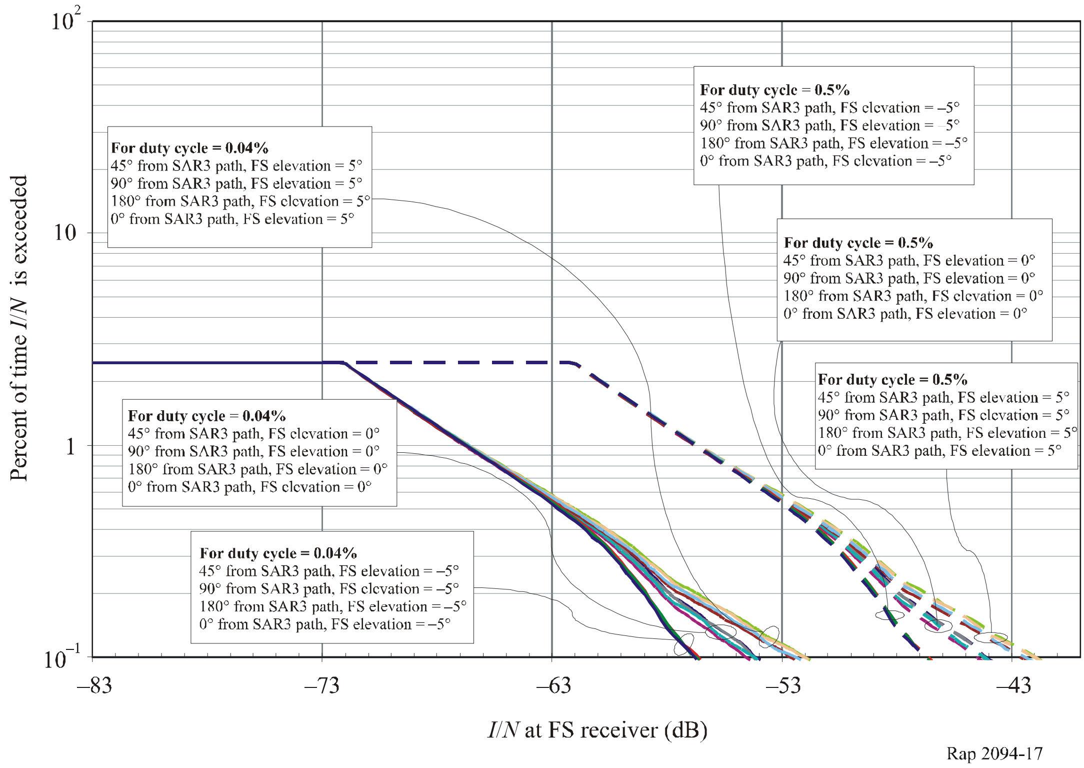


FIGURE 18

CDF of *I*/*N* levels into a FS receiver at 0° latitude and 5° antenna elevation

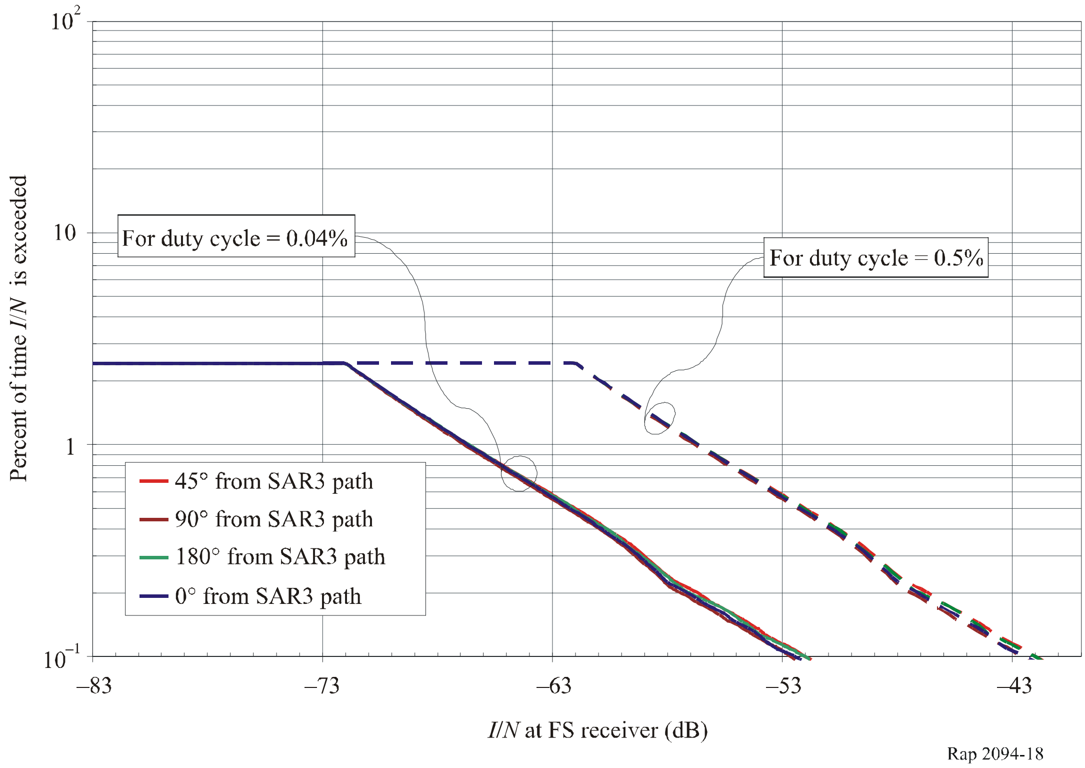
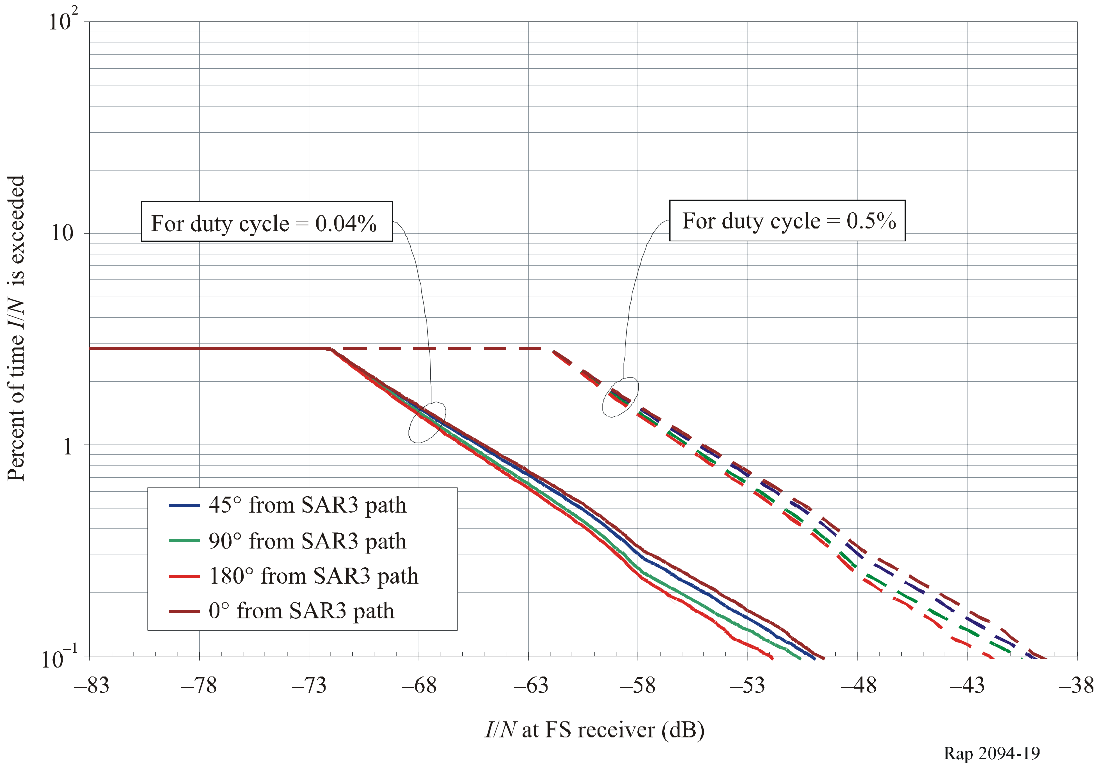


FIGURE 19

CDF of *I*/*N* levels into a FS receiver at 30° latitude and 5° antenna elevation



Similarly, in Fig. 19 (30° latitude), the *I*/*N* levels are within approximately 2 dB of each other at the 0.1% point. At the 1% point, the CDF curves begin to converge for the four FS antenna azimuth angles.

Similar results were obtained at the other FS station latitudes considered in this study.

5.5.2.2.3 Analysis results – Effect of FS station latitude

The previous sections of this document presented results indicating that the worst case FS antenna elevation angle was 5° and the worst case FS station azimuth antenna angle was either 0° or 180° with respect the spaceborne SAR inclination angle. This section presents the impact of FS station latitude on the *I*/*N* levels at the FS receiver. FS station latitudes of –15°, 0°, 15°, 30°, and 45° were used in the simulation and the worst case results are illustrated in Fig. 20. Table 26 summarizes the results.

FIGURE 20

CDF of worst case *I*/*N* levels into a FS receiver at EL = 5° with various latitudes

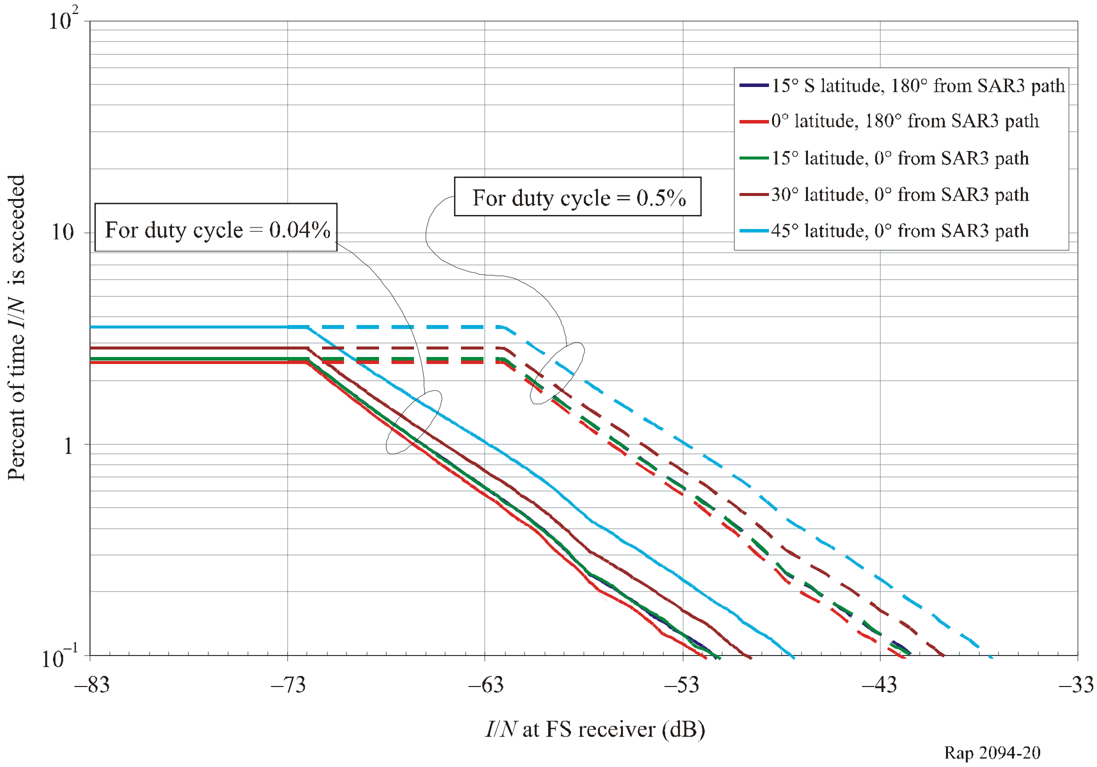


TABLE 26

Summary of worst case interference results

FS station latitude (degrees)	Azimuth direction of FS antenna relative to SAR3 inclination angle (degrees)	FS antenna elevation angle (degrees)	*I/N* level at FS Receiver (dB)		Max *I/N* level at FS receiver (dB) (0.04% duty cycle/ 0.5% duty cycle)	Percent of time maximum *I/N* level is received (%)
			I/N exceeded 1% of time (0.04% duty cycle/ 0.5% duty cycle)	*I/N* exceeded 0.1% of time (0.04% duty cycle/ 0.5% duty cycle)		
–15	180	5	–66.0/–56.0	–51.5/–41.5	–11.5/–1.5	0.04
0	180	5	–66.5/–56.5	–52.0/–42.0	–12.0/–2.0	0.04
15	0	5	–66.0/–56.0	–51.5/–41.5	–12.0/–2.0	0.06
30	0	5	–65.0/–55.0	–49.8/–39.8	–11.2/–1.2	0.07
45	0	5	–63.0/–53.0	–47.5/–37.5	–11.2/–1.2	0.03

5.5.3 Analysis conclusion

This study evaluated the compatibility between an EESS (active) spaceborne SAR and P-P FS stations operating in the 9 800 to 10 000 MHz band. Simulation results indicated the following:

– Maximum interference levels into the spaceborne SAR were approximately 5.3 dB below the SAR interference criteria for both a worldwide random distribution of 1 536 P-P FS stations, and 1 536 P-P FS stations distributed within the administrations listed in RR No. 5.477.

– The worst case *I*/*N* levels at P-P fixed service receivers from a spaceborne SAR occurred when the FS antenna was pointed at a 5° elevation angle and a 0° or 180° azimuth angle relative to the SAR3 inclination angle. The *I*/*N* levels varied based on the FS station latitude with a worst case value of –53.0 dB with a pulse duty cycle of 0.5% exceeded 1% of the time for an FS station located at a 45° latitude.

6 Examples of spaceborne SAR interference mitigation techniques

6.1 Example 1: Selection of emission characteristics for interference mitigation of active spaceborne sensors in EESS (active) for use in the 500 MHz bandwidth near 9.6 GHz

6.1.1 Selection of EESS (active) characteristics for interference mitigation

Using the procedure given in Recommendation ITU-R RS.1280, the average interfering signal power level was calculated.

Table 1, compares the key parameters for interference calculations for the SARs in question.

The most striking difference among SAR1, SAR2, and SAR3 is the range found in both pulse width and repetition frequency. With regards the pulse width, SAR2 and SAR3 have a difference between minimum and maximum as a factor of 8 and 10, respectively. With regard to the pulse repetition frequency, SAR2 has a maximum value approximately 250% that of the minimum.

To this end, it was deemed appropriate that separate calculations were performed for SAR2 for the two extremes of range. In Tables 27 and 28, SAR2 is divided into:

– SAR2a with pulse width of 10 μs and PRF of 2 000 Hz and antenna gain of 44.0 dBi.

– SAR2b with pulse width of 80 μs and PRF of 4 500 Hz and antenna gain of 46.0 dBi.

In so doing, the complete range from minimum to maximum interference is presented.

TABLE 27

Example of reduction in received unwanted sensor power, via changes in sensor pulse width and chirp bandwidth for SAR2a

	New parameter values for SAR2a			ΔOTR (dB)	ΔP_{avg} (dB)	Δ*I* (dB)
	τ (μs)	PRF (Hz)	B_c (MHz)			
Radar 1 (tracking)	10	2 000	400	–16.0	1.4[(1)]	–14.6
Radar 2 (search)	10	2 000	400	–19.0	–3.2	–22.3

(1) It has been deemed appropriate to use average interference signal power for the airborne radar, and peak interference signal power for the tracking radar.

TABLE 28

Example of reduction in received unwanted sensor power, via changes in sensor pulse width and chirp bandwidth for SAR2b

	New parameter values for SAR2b			ΔOTR (dB)	ΔP_{avg} (dB)	ΔI (dB)
	τ (µs)	PRF (Hz)	B_c (MHz)			
Radar 1 (tracking)	80	4 500	400	–7.0	3.4[(1)]	–3.6
Radar 2 (search)	80	4 500	400	–19.0	11.3	–7.7

(1) It has been deemed appropriate to use average interference signal power for the airborne radar, and peak interference signal power for the tracking radar.

SAR3 has pulse width of 1-10 µs and PRF of 410-515 Hz and antenna gain of 39.5-42.5 dB and the reduction of received unwanted sensor power for PRF of 410 Hz and antenna gain of 39.5 dB is shown in Tables 29 and 30. Separate calculations were performed for SAR3 for the two extremes of range of pulse width and PRF. In Tables 29 and 30, SAR3 is divided into:

– SAR3a with pulse width of 1 µs and PRF of 410 Hz and antenna gain of 39.5 dBi.

– SAR3b with pulse width of 10 µs and PRF of 515 Hz and antenna gain of 42.5 dBi.

If the spaceborne sensors of Table 1 can be operated with a different pulse width and chirp bandwidth such as in Tables 27 and 28, then a significant reduction in the unwanted signal power level can be achieved. For example, there are two radars assumed operating in 9 500-9 800 MHz in Recommendation ITU-R RS.1280:

– a tracking radar with a 1 MHz IF bandwidth (radar 1);

– a search radar with a 5 MHz IF bandwidth (radar 2).

TABLE 29

Example of reduction in received unwanted sensor power, via changes in sensor pulse width and chirp bandwidth for SAR3a

	New parameter values for SAR3a			ΔOTR (dB)	ΔP_{avg} (dB)	ΔI (dB)
	τ (µs)	PRF (Hz)	B_c (MHz)			
Radar 1 (tracking)	1	410	450	–26.5	5.7[(1)]	–20.9
Radar 2 (search)	1	410	450	–19.5	–15.9	–35.4

(1) It has been deemed appropriate to use average interference signal power for the airborne radar, and peak interference signal power for the tracking radar.

TABLE 30

Example of reduction in received unwanted sensor power, via changes in sensor pulse width and chirp bandwidth for SAR3b

	New parameter values for SAR3b			ΔOTR (dB)	ΔP_{avg} (dB)	ΔI (dB)
	τ (μs)	PRF (Hz)	B_c (MHz)			
Radar 1 (tracking)	10	515	450	–16.5	8.7[(1)]	–7.9
Radar 2 (search)	10	515	450	–19.5	–1.9	–21.4

(1) It has been deemed appropriate to use average interference signal power for the airborne radar, and peak interference signal power for the tracking radar.

6.1.2 Analysis conclusion

The technical and operational characteristics of several wideband SARs are presented in this annex. The extent to which certain characteristics can be chosen to mitigate the potential interference effects to terrestrial and airborne radars is also calculated and demonstrated. All cases for radar 1 and radar 2 bandwidths of 1 MHz and 5 MHz, respectively, show that there is actually a reduction with regard to the interference caused by SAR1.

6.2 Example 2: Interference mitigation technique using active spaceborne sensor SAR3 antenna in EESS (Active) for use in 500 MHz bandwidth near 9.6 GHz

This section presents an interference mitigation technique of the SAR3 antenna for use in compatibility and sharing studies.

6.2.1 Technical characteristics of wideband active spaceborne sensor SAR3 antenna

Table 1 presents technical characteristics of active spaceborne sensor SAR3. The SAR3 antenna has a different antenna gain pattern in azimuth on transmit than on receive. In azimuth, the resolution for subarray processing can be improved to one metre. In subarray processing, the array length in azimuth is subdivided into subarrays, whereby individual subarrays receive the return signals simultaneously. The effective receive array length in azimuth is the subarray length, such that the antenna beam width in azimuth is broader, corresponding to the shorter subarray length. The transmit antenna pattern uses all the subarrays and applies a phase spoiling across the array such that the 3 dB width of the azimuth gain pattern is approximately the same as each subarray receive azimuth gain pattern. Two benefits of phase weighting across the entire array is that the peak transmit power of 25 kW can be applied, versus, 1/32 of that power for one of the subarrays. Another benefit is that with the phase spoiling on transmit, the antenna gain pattern in azimuth falls off faster with angle from boresight, thus providing interference mitigation as the side lobe levels decrease with angle from boresight.

6.2.1.1 Design parameters

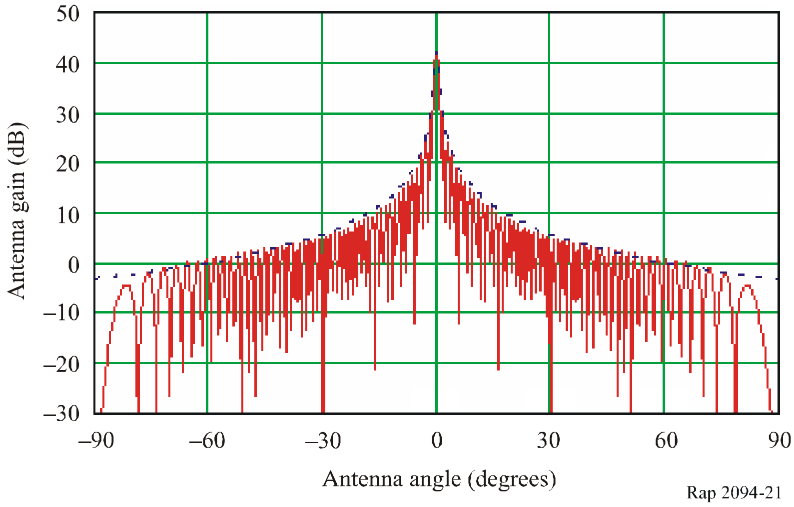
SAR3 would transmit linear FM pulses centered near 9.6 GHz, with a pulse repetition rate between 410 and 515 Hz as shown in Table 1. The signal is either vertically or horizontally polarized at transmission and reception, to give one polarization, selectable between HH, or VV. The pulse width is 1-10 μs and the range bandwidth is 450 MHz.

6.2.1.2 Antenna gain pattern

The antenna gain pattern for the uniform weighting across an individual panel and the curve fit to the envelope for angles between –90° to +90° in azimuth is shown in Fig. 21.

FIGURE 21

Spaceborne SAR3 uniform transmit (solid line for uniform weighting of panel), uniform weighting envelope curve fit (short dashed line) at 9 600 MHz (–4.5° to +4.5°)



For both uniform weighting and phase weighting, the “knife-edge” effect of the antenna pattern of linear phased arrays also offers interference mitigation in that the antenna gain falls significantly off the principal axes.

Table 31 shows the revised antenna gain equations. The revised equations retain the –48 dB floor along the azimuth principal axis but eliminate the overall –5 dBi floor off-axis. Figure 22 shows the antenna gain pattern over ranges of the elevation and azimuth angles of $-90° < \theta_v < 90°$ and $-90° < \theta_h < -90°$. The “knife-edge” effect along the principal axes in elevation and azimuth is evident with these equations, with the antenna gain falling below –40 dBi in the off-axis areas of the plot.

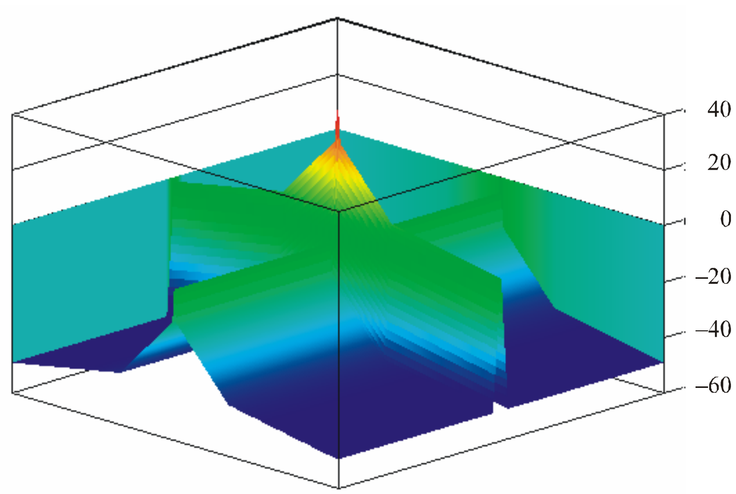
TABLE 31

Revised spaceborne SAR3 antenna gain equations at 9 600 MHz

Pattern	Gain $G(\theta)$ (dBi) as a function of off-axis angle θ (degrees)	Angle range (degrees)
Vertical (elevation)	$G_v(\theta_v) = 42.5 - 9.92(\theta_v)^2$ $G_v(\theta_v) = 31.4 - 0.83\,\theta_v$ $G_v(\theta_v) = 10.5 - 0.133\,\theta_v$	$0 < \theta_v < 1.1$ $1.1 \leq \theta_v < 30$ $\theta_v \geq 30$
Horizontal (azimuth)	$G_h(\theta_h) = 0.0 - 9.07(\theta_h)^2$ $G_h(\theta_h) = +1.9 - 12.08\,\theta_h$ $G_h(\theta_h) = -48$	$0 < \theta_h < 1.15$ $1.15 \leq \theta_h < 4.13$ $\theta_h \geq 4.13$
Beam pattern	$G(\theta) = G_v(\theta_v) + G_h(\theta_h)$	

FIGURE 22

Spaceborne SAR3 3D antenna pattern at 9 600 MHz
(–90° <θ_h < +90° and –90° <θ_v < +90°) using equations of Table 32



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6.2.2 Technical characteristics of terrestrial radar system

The system G3 in Table 7 is fixed at 0° elevation with a beamwidth of 0.81° in elevation so that as SAR3 looks down at 50° inclination angle, the system G3 would see SAR3 about 40° in the elevation side lobes, which would be approximately in the 48th side lobe for a 0.81° beamwidth, at an antenna gain of –4 dBi in the side lobes, for uniform illumination, whereas, the actual illumination probably has amplitude weighting in elevation to give a faster rate of side-lobe decrease.

6.2.3 Receive power profiles at terrestrial stations

The SAR3 interference power profiles into G3 will be calculated as the satellite flies past a given terrestrial station G3. The first profile will be that obtained by using the phase weighting across the entire 50 m length of the antenna, and the second profile will be obtained by transmitting from a single subarray with the same peak e.i.r.p.

The SAR interference power at the terrestrial radar station was calculated using equations (15) and (16) in Annex 1 of Recommendation ITU-R M.1461.

The SAR3 characteristics are shown in Table 1. For this example of interference from SAR3 into G3, the pulse width is 10μs, and the peak antenna gain is 42.5 dBi.

The interference levels from SAR3 into G3 as the SAR3 orbits over the fixed location of system G3 at 44° look angle from the SAR3 is show in Fig. 23 over 2 min of orbit time.

The interference threshold assumes an *I*/*N* of –10 dB. Using uniform weighting across an individual panel, the SAR is above the threshold about 118 s; whereas, using phase weighting across the array, the SAR is above the threshold about 14 s. For this example, the phase weighting technique provides interference mitigation and reduces the amount of time the SAR interference is above the terrestrial radar's threshold by a factor of over 8.

If the revised antenna gain equations from Table 31 are used, there is no longer a –5 dBi floor for the SAR3 antenna gain. Suppose that the terrestrial radar is 23° further in the range side-lobes of SAR3 as the spacecraft passes by. The interference levels from SAR3 into G3 as the SAR3 orbits over the fixed location of system G3 while 23° into the range side-lobes of SAR3, is shown in Fig. 4 over 2 min of orbit time. The profile with the higher receive power represents the SAR3 gain equations with the 5 dBi floor and shows the received interference power as the SAR3 main-lobe passes through the terrestrial radar. The profile with the lower receiver power represents the revised SAR3 gain equations from Table 31 and shows the received interference power as the SAR3 main lobe is 23° out in the range side-lobes.

FIGURE 23

Interference levels at terrestrial radar G3 from SAR3 (using either phased weighting across array or uniform weighting across panel) at 506 km orbital altitude

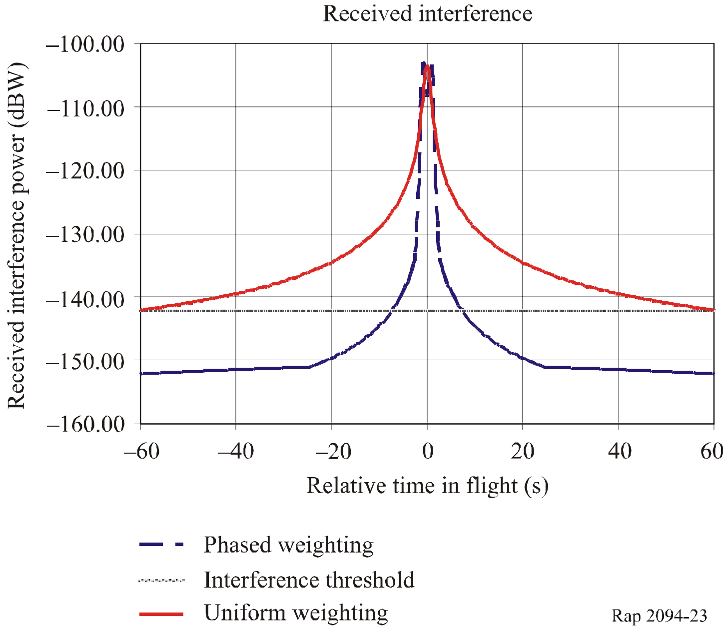
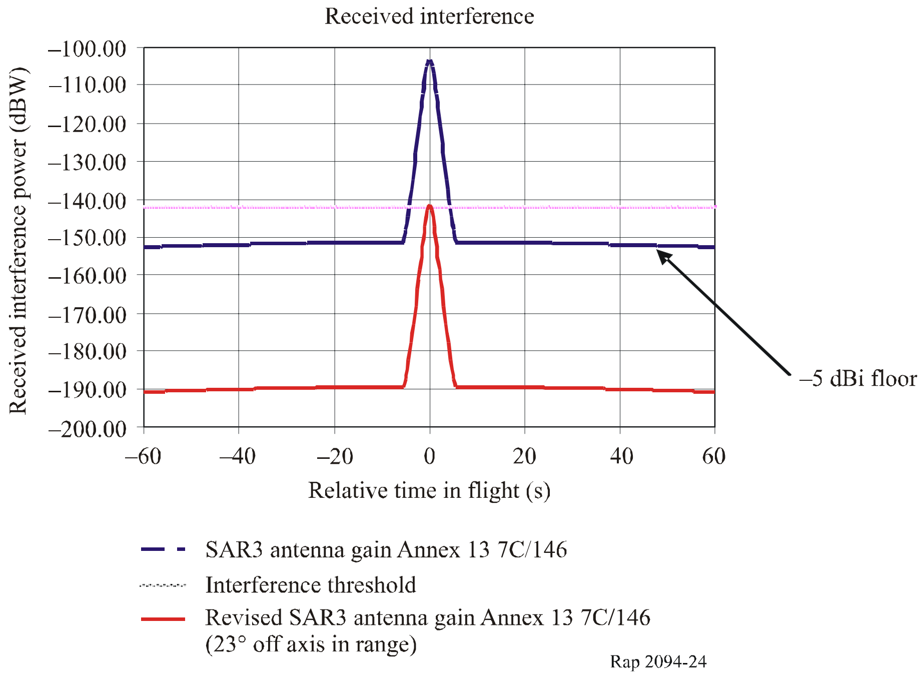


FIGURE 24

Interference levels at terrestrial radar G3 from SAR3 (using original antenna gain equations for SAR3 and revised equations from Table 31) at 506 km orbital altitude



6.2.4 Analysis conclusion

The interference mitigation technique using phase weighting across the wideband SAR3 antenna array is presented in this document. It has been shown that use of the phase weighting approach can significantly reduce interference into terrestrial radars from the SAR antenna side lobes. This interference mitigation technique may improve the sharing conditions between a SAR and terrestrial radars.

7 Summary and conclusion

This Report presents details on the studies related to the compatibility between EESS (active) and the radiodetermination service in the 9 300-9 500 MHz and 9 800-10 000 MHz bands and between EESS (active) and the fixed service in the 9 800-10 000 MHz band. In addition to these compatibility and interference studies, the Report also presents information on EESS (active) interference mitigation techniques.

8 Supporting documents

ITU-R texts

Recommendation ITU-R M.1796 – Characteristics of and protection criteria for terrestrial radars operating in the radiodetermination service in the frequency band 8 500-10 500 MHz.

Report ITU-R M.2081 – Test results illustrating compatibility between representative radionavigation systems and radiolocation and EESS systems in the band 8.5-10 GHz.

Recommendation ITU-R F.758-4 – Considerations in the development of criteria for sharing between the terrestrial fixed service and other services (January 2005).

Recommendation ITU-R SM.337-4 – Frequency and distance separation (October 1997).

Recommendation ITU-R SM.1541-1 – Unwanted emissions in the out-of-band domain (November 2002).

Recommendation ITU-R RS.1166-2 – Performance and interference criteria for spaceborne active sensors (October 1999) (Replaces ITU-R SA.1166-2).

Recommendation ITU-R M.1461-1 – Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services (June 2003).

Recommendation ITU-R M.1372-1 – Efficient use of the radio spectrum by radar stations in the radiodetermination service (June 2003).

Recommendation ITU-R RS.1280 – Selection of active spaceborne sensor emission characteristics to mitigate the potential for interference to terrestrial radars operating in frequency bands 1-10 GHz (October 1997).