

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 EEES (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 $G(\theta)$ (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 $G(\theta)$ (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 (μ s) 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 (μ s)	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: $\pm 60^\circ$ (mechanical)	360° (mechanical)	Sector: $\pm 60^\circ$ (mechanical)
Antenna vertical scan rate	59 scans/min	Not applicable	Up to 137 scans/min
Antenna vertical scan type	Sector: $\pm 60^\circ$ (mechanical)	Not applicable	Sector: $+25/-40^\circ$ (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)			(Frequency and pulsewidth dependent)
– 3 dB	3.1; 0.11	0.480; 2.7	100 to 118
– 20 dB	22.2; 0.79	1.5; 6.6	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	4.5	9.3	-3 dB: 9 337 and 9 339 MHz: 0.7 9 344 MHz: 0.4, 0.25, 0.150, 0.075, 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	10; 5	1.6; 4.2	Not specified	
– 20 dB	80; 16	10; 24	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 (1 st 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)			Not specified	
– 3 dB	14	20		
– 20 dB	43	55		

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 radio-determination 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 $-104 \text{ dB(W/20 MHz)}$, or $-89.9 \text{ dB(W/512 MHz)}$ for the SAR3 radar. This criterion applies to non-FM pulsed interference sources with pulse duration of $2 \mu\text{s}$ or less. For pulse lengths greater than $2 \mu\text{s}$, an interference threshold of $-102 \text{ dB(W/20 MHz)}$ is derived; however, for the purpose of this analysis, a worst case interference criterion of $-104 \text{ dB(W/20 MHz)}$ 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 $+70^\circ$ in latitude and -180° to $+180^\circ$ 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 $\pm 60^\circ$
- Radar A2 – elevation angle for all A2 radars was 0°
- Radar A3 – elevation angles were selected from a random value between -40° to $+25^\circ$
- 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 $\pm 15^\circ$
- 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°

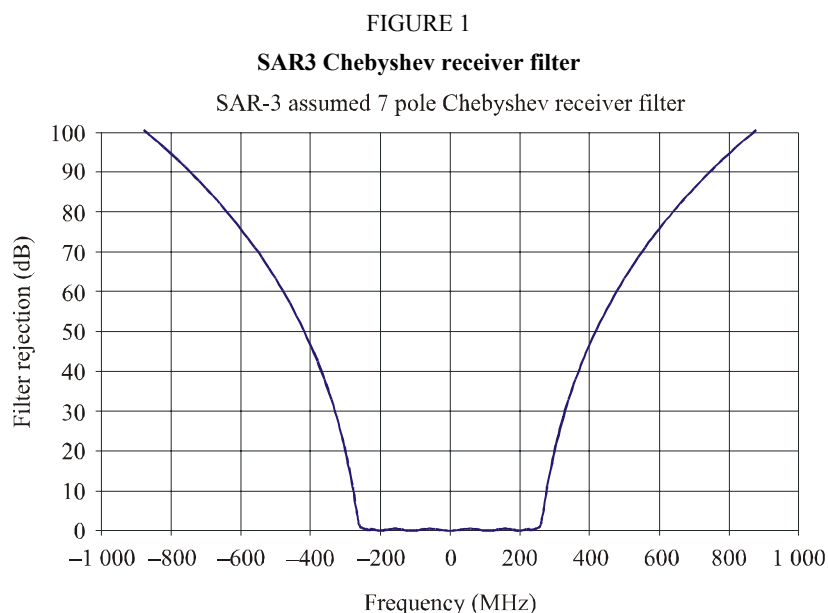
Each radar transmit antenna scanned in azimuth at the rates listed in Tables 5, 6, and 7 using a starting azimuth randomly selected from a value between $\pm 180^\circ$. The heading for each airborne and shipborne radar was also selected from a random value between $\pm 180^\circ$.

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.



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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

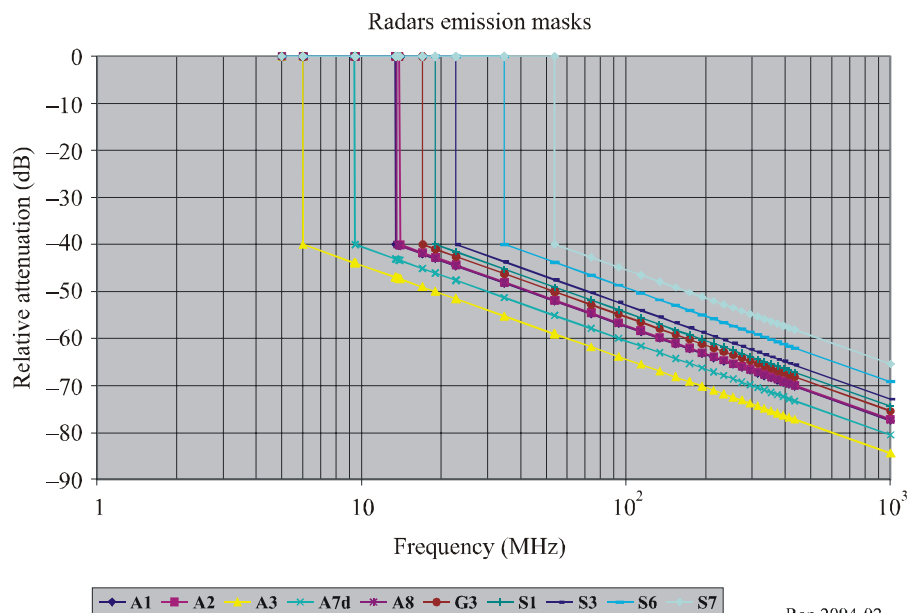
Radar parameters for ITU-R SM.1541-1 RF spectrum calculation

	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 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.

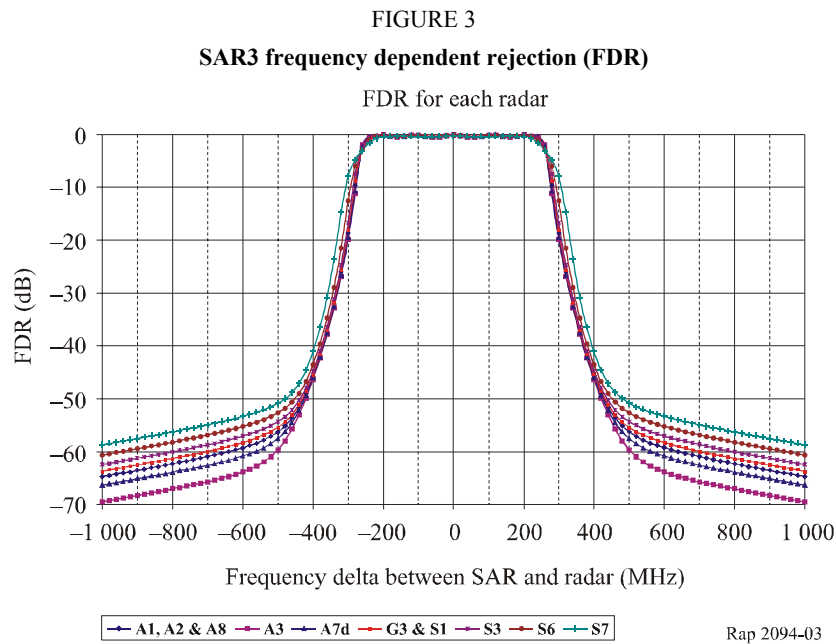
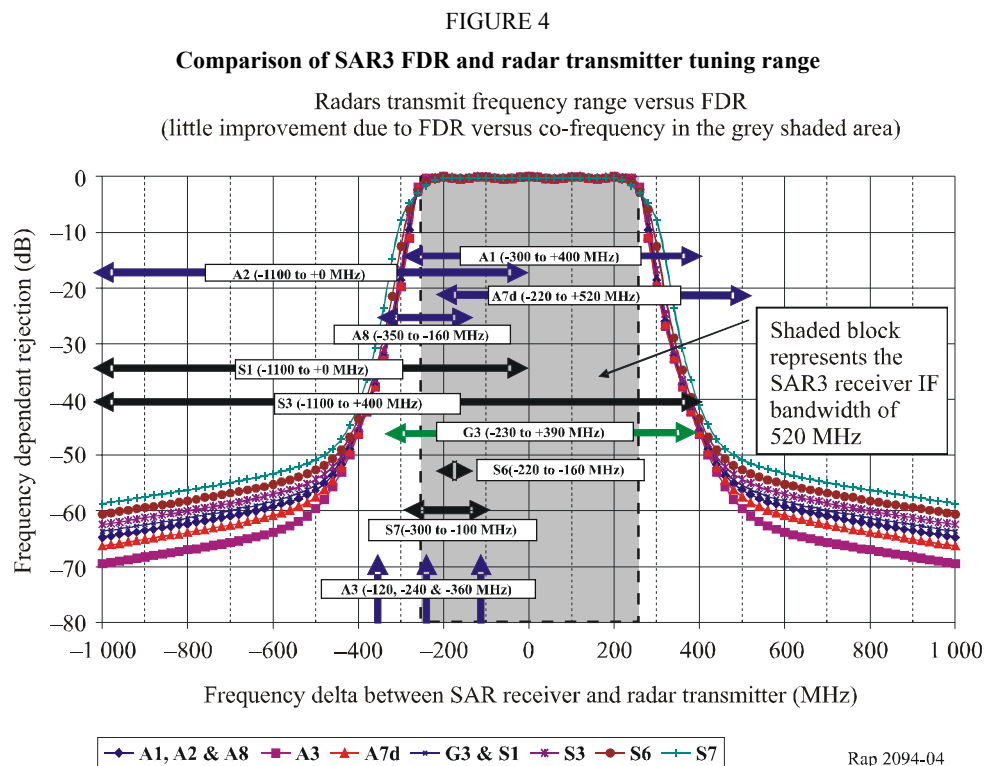


Figure 4 shows the frequency range that the radar centre frequencies will hop over. If a radar frequency is selected in the shaded area, then there will be no significant difference between the co-frequency and FDR analysis cases. Outside the grey region, the FDR increases resulting in a lower interference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



5.1.2 Analysis results

This section presents the analysis results for the following:

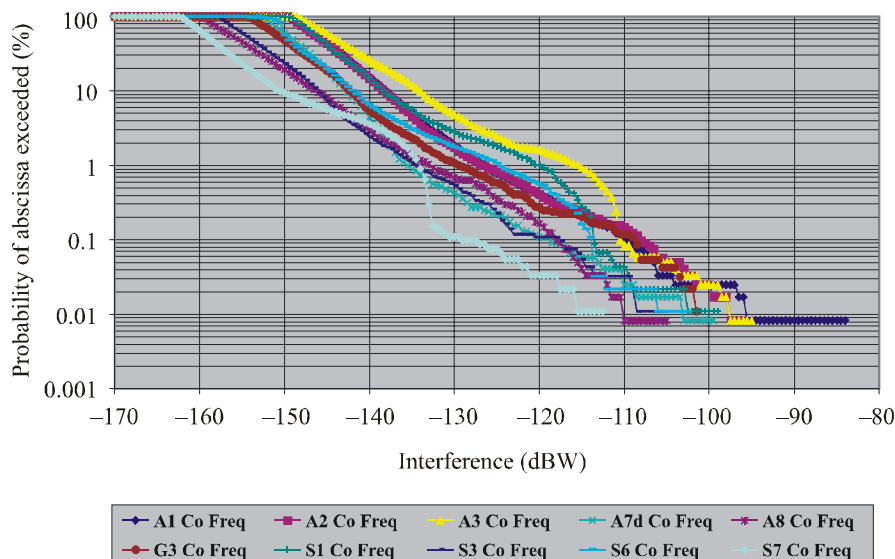
- a) Co-frequency analysis to determine:
 - Individual interference levels at SAR3 from each radar system
 - Aggregate interference levels at SAR3 from 1000 randomly distributed radar systems
- b) Frequency Dependent Rejection (FDR) analysis to determine:
 - Individual interference levels at SAR3 from 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 $-89.9 \text{ dB(W/512 MHz)}$, 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
Co-frequency analysis results



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