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ITU-R

Radiocommunication Sector of ITU

Recommendation ITU-R M.1796
(03/2007)

Characteristics of and protection criteria for terrestrial radars operating in the radiodetermination service in the frequency band 8 500-10 500 MHz

M Series

Mobile, radiodetermination, amateur and related satellite services

International Telecommunication Union

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Note: *This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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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

(Question ITU-R 226/5)

(2007)

Scope

This Recommendation provides the technical and operational characteristics and protection criteria for radiodetermination systems operating in the band 8 500-10 500 MHz. It was developed with the intention to support sharing studies in conjunction with Recommendation ITU-R M.1461 addressing analysis procedures for determining compatibility between radars operating in the radiodetermination service and other services.

The ITU Radiocommunication Assembly,

considering

a) that antenna, signal propagation, target detection, and large necessary bandwidth characteristics of radars to achieve their functions are optimum in certain frequency bands;

b) that the technical characteristics of radiodetermination radars are determined by the mission of the system and vary widely even within a band;

c) that ITU-R is considering the potential for the introduction of new types of systems or services in bands between 420 MHz and 34 GHz used by radars in the radiodetermination service;

d) that representative technical and operational characteristics of radars operating in the radiodetermination service are required to determine, if necessary, the feasibility of introducing new types of systems into frequency bands allocated to the radiodetermination service,

noting

a) that technical and operational characteristics of maritime radar beacons operating in the 9 300-9 500 MHz band are to be found in Recommendation ITU-R M.824;

b) that technical parameters of radar target enhancers operating in the 9 300-9 500 MHz band are to be found in Recommendation ITU-R M.1176;

c) that technical and operational characteristics of search and rescue radar transponders (SART) operating in the 9 300-9 500 MHz band are to be found in Recommendation ITU-R M.628,

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* Radiocommunication Study Group 5 made editorial amendments to this Recommendation in 2009 in accordance with Resolution ITU-R 1.

recognizing

a) that the radionavigation service is a safety service as delineated in No. 4.10 of the Radio Regulations;

b) that the required protection criteria depend upon the specific types of interfering signals;

c) that the application of protection criteria may require consideration for the inclusion of the statistical nature of the application of those criteria and other elements of the methodology for performing compatibility studies (e.g. propagation loss). Further development of these statistical considerations, together with the required probability of detection for various maritime operational scenarios may be incorporated into future revisions of this Recommendation, as appropriate,

recommends

1 that the technical and operational characteristics of the radiodetermination radars described in Annex 1 should be considered representative of those operating in the frequency band 8 500-10 500 MHz;

2 that this Recommendation, along with Recommendation ITU-R M.1461, should be used as a guideline in analysing compatibility between radiodetermination radars and systems in other services;

3 that the criterion of interfering signal power to radar receiver noise power level, an I/N ratio of −6 dB, should be used as the required protection level for radiodetermination radars in the band 8 500-10 500 MHz, even if multiple interferers are present (see Note 1);

4 that the results of interference susceptibility trials performed on shipborne radionavigation radars operating in the band 9 300-9 500 MHz, which are contained in Annex 3, should be used in assessing interference into shipborne radionavigation radars, noting that the results are for non-fluctuating targets and that radar cross-section (RCS) fluctuations should be taken into account (see Note 2).

NOTE 1 – Further information is provided in Annex 2. In particular, the coverage degradation due to the proposed criterion for meteorological radars (21%) is higher than for other radiolocation systems. Application of this criterion to meteorological radars would need further study.

NOTE 2 – The subject of fluctuating RCS is under study within ITU-R.

Annex 1

Technical and operational characteristics of radars in the radiodetermination service in the frequency band 8 500-10 500 MHz

1 Introduction

The characteristics of radiodetermination radars operating worldwide in the frequency band 8 500-10 500 MHz are presented in Tables 1, 2 and 3, and described further in the following paragraphs.

2 Technical characteristics

The band 8 500-10 500 MHz is used by many different types of radars on land-based, transportable, shipboard, and airborne platforms. Radiodetermination functions performed in the band include airborne and surface search, ground-mapping, terrain-following, navigation (both aeronautical and maritime), target-identification, and meteorological (both airborne and ground-based). Other major differences among the radars include transmit duty cycles, emission bandwidths, presence and types of intrapulse modulation, frequency-agile capabilities of some, transmitter peak and average powers, and types of transmitter RF power devices. These characteristics, individually and in combination, all have major bearing on the compatibility of the radars with other systems in their environment, while other characteristics affect that compatibility to lesser degrees. Radar operating frequencies can be assumed to be uniformly spread throughout each radar's tuning band. Tables 1, 2 and 3 contain technical characteristics of representative radiolocation and radionavigation radars deployed in the 8 500-10 500 MHz band.

The major radiolocation radars operating in this band are primarily used for detection of airborne objects. They are required to measure target altitude as well as range and bearing. Some of the airborne targets are small and some are at ranges as great as 300 nautical miles (~ 556 km), so these radiolocation radars must have great sensitivity and must provide a high degree of suppression to all forms of clutter return, including that from sea, land, and precipitation. In some cases, the radar emissions in this band are required to trigger radar beacons.

Largely because of these mission requirements, the radars using this band tend to possess the following general characteristics:

– they tend to have low to medium (from 1 W to 250 000 W) transmitter peak and average power, with notable exceptions;
– they typically use master-oscillator power-amplifier transmitters rather than power oscillators. They are usually tunable, and some of them are frequency-agile. Some of them use linear – or non-linear – FM (chirp) or phase-coded intra-pulse modulation;
– some of them have antenna main beams that are steerable in one or both angular dimensions using electronic beam steering;
– they typically employ versatile receiving and processing capabilities, such as auxiliary sidelobe-blanking receive antennas, processing of coherent-carrier pulse trains to suppress clutter return by means of moving-target-indication (MTI), constant-false-alarm-rate (CFAR) techniques, and, in some cases, adaptive selection of operating frequencies based on sensing of interference on various frequencies;
– individual radars often have numerous different pulse widths and pulse repetition frequencies; some chirp radars have a choice of chirp bandwidths; and some frequency-agile radars have a variety of agile- or fixed-frequency modes. This flexibility can provide useful tools for maintaining compatibility with other radars in the environment.

Some or all of the radars whose characteristics are presented in Tables 1, 2 and 3 possess these properties. Those Tables are extensive to exemplify the wide variety of radar missions, platforms, waveforms, bandwidths, duty cycles, power levels, transmitter devices, etc. found in radars using this band, although they do not illustrate the full repertoire of attributes that might appear in future systems.

TABLE 1

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

Characteristics	System A1	System A2	System A3	System A4
Function	Search and track radar (multifunction)	Airborne search radar	Ground-mapping and terrain-following radar (multifunction)	Track radar
Tuning range (MHz)	9 300-10 000	8 500-9 600	9 240, 9 360 and 9 480	10 000-10 500
Modulation	Pulse	Pulse	Non-coherent frequency-agile pulse-position modulation	CW, FMCW
Peak power into antenna	17 kW	143 kW (min) 220 kW (max)	95 kW	1.5 kW
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.	Not applicable
Maximum duty cycle	0.0132	0.001	0.001	1
Pulse rise/fall time (µs)	0.01/0.01	0.02/0.2	0.1/0.1	Not applicable
Output device	Travelling wave tube	Tunable magnetron	Cavity-tuned magnetron	Travelling wave tube
Antenna pattern type	Pencil	Fan	Pencil	Pencil
Antenna type	Planar array	Parabolic reflector	Flat-plate planar array	Planar array
Antenna polarization	Linear	Linear	Circular	Linear
Antenna main beam gain (dBi)	32.5	34	28.3	35.5
Antenna elevation beamwidth (degrees)	4.6	3.8	5.75	2.5
Antenna azimuthal beamwidth (degrees)	3.3	2.5	5.75	2.5
Antenna horizontal scan rate	118 scans/min	6 or 12 rpm	Up to 53 scans/min	90 °/s
Antenna horizontal scan type (continuous, random, sector, etc.)	Sector: ±60° (mechanical)	360° (mechanical)	Sector: ±60° (mechanical)	Sector: ±60° (mechanical)

TABLE 1 (*continued*)

Characteristics	System A1	System A2	System A3	System A4
Antenna vertical scan rate	59 scans/min	Not applicable	Up to 137 scans/min	90°/s
Antenna vertical scan type	Sector: ±60° (mechanical)	Not applicable	Sector: +25/–40° (mechanical)	Sector: ±60° (mechanical)
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	7.5 dBi at 15°	Not specified	5.3 dBi at 10°	Not specified
Antenna height	Aircraft altitude	Aircraft altitude	Aircraft altitude	Aircraft altitude
Receiver IF 3 dB bandwidth (MHz)	3.1; 0.11	5	5.0, 1.8 and 0.8	0.48
Receiver noise figure (dB)	Not specified	Not specified	6	3.6
Minimum discernible signal (dBm)	–103	–107; –101	–101	
Total chirp width (MHz)	Not applicable	Not applicable	Not applicable	Not specified
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 pulse width dependent) 100 to 118 102 to 120	Not specified Not specified

TABLE 1 (*continued*)

Characteristics	System A5	System A6a[(1)]	System A6b[(1)]
Function	Weather avoidance including wind-shear detection (navigation)	Weather avoidance (WA), including wind-shear detection (WS) (navigation)	Ground-mapping, including: Monopulse ground mapping (MGM) and Doppler beam sharpening (DBS)
Tuning range (MHz)	9 330	9 305-9 410 WA: frequency agile pulse-to-pulse (≤ 2 000 hops/s); WS: adaptive single frequency	9 360 and 9 305-9 410 MGM: frequency agile pulse-to-pulse (≤ 600 hops/s); DBS: single frequency (9 360)
Modulation	Pulse	WA: unmodulated and Barker-coded (5:1 and 13:1) pulses; WS: unmodulated pulses	MGM and DBS: Barker-coded (13:1) pulses
Peak power into antenna	150 W	≤ 150 W	≤ 150 W
Pulse width (µs) and Pulse repetition rate	1 to 20 180 to 9 000 pps	WA: 0.2-230; WS: 2 WA: 2 000 pps for 0.2-6 µs pulses, decreasing to 230 pps for 230 µs pulses; WS: 3 600-3 940 pps	MGM: 1.3-260; DBS: 0.64-20 MGM: 600 pps for 1.3-60 µs pulses, decreasing to 220 pps for 260 µs pulses; DBS: 700-1 600 pps for all pulse widths
Maximum duty cycle	Not specified	WA: 0.054; WS: 0.0076	MGM: 0.057; DBS: 0.033 (0.024 long term)
Pulse rise/fall time (µs)	Not specified	WA: 0.02-0.05/0.01; WS: 0.02/0.01	MGM: 0.01-0.02/0.01-0.02; DBS: 0.02-0.04/0.01
Output device	Solid state	FET	FET
Antenna pattern type	Pencil	Pencil	Fan
Antenna type	Planar array	Planar array	Planar array
Antenna polarization	Not specified	Linear	Linear
Antenna main beam gain (dBi)	34.4	32	28.7
Antenna elevation beamwidth (degrees)	3.5	4	42
Antenna azimuthal beamwidth (degrees)	3.5	2.7	2.7
Antenna horizontal scan rate	Not specified	≤ 40 scans/min	≤ 40 scans/min

TABLE 1 (*continued*)

Characteristics	System A5	System A6a(1)	System A6b(1)
Antenna horizontal scan type (continuous, random, sector, etc.)	Sector: ±30°	Sector: ±15 to ±135° (mechanical)	Sector: ±15 to ±135° (mechanical)
Antenna vertical scan rate	Not specified	≤ 20 scans/min	Not applicable
Antenna vertical scan type (continuous, random, sector, etc.)	Not specified	1 or 2 horizontal bars (mechanical)	Not applicable
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	+3.4 dBi	8 dBi at 4.2°	3.7 dBi at 4.5°
Antenna height	Aircraft altitude	Aircraft altitude (wind-shear at low altitude)	Aircraft altitude
Receiver IF 3 dB bandwidth (MHz)	Not specified	WA: ≤ 16 for narrow pulses/subpulses, decreasing to 0.8 for wide pulses/subpulses; WS: ≥ 0.8	
Receiver noise figure (dB)	4.0	5	5
Minimum discernible signal (dBm)	−125	≥ −110	≥ −110
Chirp bandwidth (MHz)	Not applicable	Not applicable	Not applicable
RF emission bandwidth (MHz)	Not specified	For shortest plain pulse to longest subpulse: WA: 3 dB: 5 to 0.052; 20 dB: 40.5 to 0.37; WS: 3 dB: 0.46 20 dB: 3.28	For shortest to longest subpulses: MGM: 3 dB: 7.68 to 0.045; 20 dB: 59 to 0.31 DBS: 3 dB: 18 to 0.6; 20 dB: 150 to 4.1

TABLE 1 (*continued*)

Characteristics	System A7a, A7b, and A7c(2)	System A7d(2)	System A7e and A7f(2)	System A8
Function	Surface search and SAR imaging	Navigation	Inverse SAR imaging	Search (radiolocation) Weather
Tuning range (MHz)	9 380-10 120	Frequency agile pulse-to-pulse over 340 MHz	9 380-10 120	9 250-9 440, frequency-agile pulse-to-pulse, 20 MHz steps
Modulation	Linear FM pulse	Linear FM pulse	Linear FM pulse	FM pulse
Peak power into antenna	50 kW	50 kW	50 kW	10 kW
Pulse width (μs) and pulse repetition rate (pps)	Search: 5 μs @ 1 600-2 000 or 10 μs @ approx. 380 SAR: 13.5 μs @ 250-750	10 Approx. 380	10 470, 530, 800 and 1 000	5 and 17 2 500, 1 500, 750 and 400 (all pulse widths)
Maximum duty cycle	0.010 (5 μs & 13.5 μs); 0.004 (10 μs)	0.004	0.010	0.04
Pulse rise/fall time (μs)	0.1/0.1	0.1/0.1	0.1/0.1	0.1/0.1
Output device	Travelling wave tube	Travelling wave tube	Travelling wave tube	Travelling wave tube
Antenna pattern type	Pencil/fan	Pencil/fan	Pencil/fan	Fan
Antenna type	Parabolic reflector	Parabolic reflector	Parabolic reflector	Slotted array
Antenna polarization	Horizontal	Horizontal	Horizontal	Vertical and horizontal
Antenna main beam gain (dBi)	34.5	34.5	34.5	32
Antenna elevation beamwidth (degrees)	4.0	4.0	4.0	9.0
Antenna azimuthal beamwidth (degrees)	2.4	2.4	2.4	1.8
Antenna horizontal scan rate	36, 360, and 1 800°/s	36, 360, 1 800°/s	36, 360, and 1 800°/s	15 or 60 rpm

TABLE 1 (*continued*)

Characteristics	**System A7a, A7b, and A7c**[2]	**System A7d**[2]	**System A7e and A7f**[2]	**System A8**
Antenna horizontal scan type (continuous, random, sector, etc.)	10° sector	10° sector	10° sector	360°
Antenna vertical scan rate	Not applicable	Not applicable	Not applicable	Not applicable
Antenna vertical scan type (continuous, random, sector, etc.)	Selectable tilt 0°/–90°	Selectable tilt 0°/–90°	Selectable tilt 0°/–90°	Selectable tilt +15°/–15°
Antenna sidelobe (SL) levels (1st SLs and remote SLs)	14.5 dBi at 12°	14.5 dBi at 12°	14.5 dBi at 12°	20 dBi
Antenna height	Aircraft altitude	Aircraft altitude	Aircraft altitude	Aircraft altitude
Receiver IF 3 dB bandwidth (MHz)	Not specified	Not specified	Not specified	16
Receiver noise figure (dB)	5	5	5	Not specified
Minimum discernible signal (dBm)	Depends on processing gain (34 dB (5 µs), 30 dB (10 µs) and 39.5 dB (13.5 µs) for one return pulse)	Depends on processing gain (17 dB for one return pulse)	Depends on processing gain (30 dB (100 MHz) or 33 dB (200 MHz) for one return pulse)	–98
Total chirp width (MHz)	Search: 500 (5 µs) or 100 (10 µs) SAR: 660	5	100 or 200	10
RF emission bandwidth (MHz) – 3 dB – 20 dB	Search (5 µs) Search (10 µs) 470 95 640 540 110 730	 4.5 7.3	100 MHz chirp 200 MHz chirp 95 190 110 220	 9.3 12

TABLE 1 (*continued*)

Characteristics	**System A9**	**System A10**	**System A11**
Function	Weather avoidance, search and rescue, ground mapping	Weather avoidance, ground mapping, search	Weather avoidance, ground mapping, search and rescue
Tuning range (MHz)	Radar: 9 375 ± 10; Beacon: 9 310	Preheat pulse: 9 337 and 9 339 (precedes each operational pulse) Operational pulse: 9 344	9 375 ± 30 MHz
Modulation	Pulse	Pulse	Pulse
Peak power into antenna	25 kW	26 W (14 dBW)	2.5-6.0 kW
Pulse width (µs) and Pulse repetition rate (pps)	4.5, 2.4, 0.8 and 0.2 µs at 180, 350, 350 and 1 000 pps, resp.	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)	Fixed at 4 µs 106.5 pps
Maximum duty cycle	0.00082	9 337 and 9 339 MHz: ≤ 0.064 9 344 MHz: ≤ 0.011 (with 17 µs pulses)	0.00043
Pulse rise/fall time (µs)	Not specified	9 337 and 9 339 MHz: 0.3/0.2 9 344 MHz: 0.5/0.5	Rise time: 0.3 µs Fall time: 0.4 µs
Output device	High-reliability magnetron	IMPATT diode	Magnetron
Antenna pattern type	Pencil and fan	Pencil	Pencil
Antenna type	Flat-plate array	Flat array	Flat array
Antenna polarization	Horizontal and vertical	Horizontal	Horizontal
Antenna main beam gain (dBi)	Pencil: 30; fan: 29	29	26.7
Antenna elevation beamwidth (degrees)	Pencil: 3; fan: 6	< 10	8.1
Antenna azimuthal beamwidth (degrees)	Pencil: 3; fan: 3	7	8.1

TABLE 1 (*end*)

Characteristics	System A9	System A10	System A11
Antenna horizontal scan rate	360°: 12 rpm (long-range), 45 rpm (short-range) Sector: not specified	30°/s	25°/s
Antenna horizontal scan type (continuous, random, sector, etc.)	Continuous (360°) Sector (90°)	Sector 60° or 120°	Sector volume (90° or 120°)
Antenna vertical scan rate	Not applicable	Not applicable	Not applicable
Antenna vertical scan type (continuous, random, sector, etc.)	Not applicable	Operator-selected tilt: ±30°	Sector volume: ±30°
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	Not specified	+13.9 dBi	+4.7 dBi
Antenna height	Aircraft altitude	Aircraft altitude	Aircraft altitude
Receiver IF 3 dB bandwidth (MHz)	Not specified	2.0	1.0
Receiver noise figure (dB)	6.5	2	5
Minimum discernible signal (dBm)	Not specified	–128 (detection sensitivity after processing)	–110
Total chirp width (MHz)	Not applicable	Not applicable	Not applicable
RF emission bandwidth (MHz)			
– 3 dB	Not specified	–3 dB: 9 337 and 9 339 MHz: 0.7 9 344 MHz: 0.4, 0.25, 0.150, 075, 0.08, and 0.05	–3 dB: 0.5 MHz
– 20 dB	Not specified	–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	–20 dB: 1.5 MHz

(1) Multimode radar; also has a beacon-interrogator mode at 9 375 MHz, not described herein.

(2) Multimode radar.

TABLE 2

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

Characteristics	System S1	System S2	System S3	System S4		System S5
Function	Search and navigation radar	Track radar	Low altitude and surface search radar (multifunction)	Maritime radionavigation radar(3)		Surface surveillance and navigation radar
Platform type	Shipborne, shore training sites	Shipborne	Shipborne	Shipborne		Shipborne
Tuning range (MHz)	8 500-9 600	10 000-10 500	8 500-10 000	9 375 ± 30 and 9 445 ± 30		9 300-9 500
Modulation	Pulse	CW, FMCW	Frequency-agile pulse(4)	Pulse		FMCW
Peak power into antenna	35 kW	13.3 kW	10 kW	5 kW (min)	50 kW (max)	1 mW to 1 W
Pulse width (µs) and pulse repetition rate (pps)	0.1; 0.5 1 500; 750	Not applicable Not applicable	0.56 to 1.0; 0.24 19 000 to 35 000; 4 000 to 35 000	0.03 (min) at 4 000 (max)	1.2 (max) at 375 (min)	Not applicable 1 000(5)
Maximum duty cycle	0.00038	1	0.020	0.00045		1
Pulse rise/fall time (µs)	0.08/0.08	Not applicable	0.028/0.03; 0.038/0.024	Not specified		Not applicable
Output device	Magnetron	Travelling wave tube	Travelling wave tube	Magnetron		Solid state
Antenna pattern type	Fan	Pencil	Pencil	Fan		Fan
Antenna type)	Horn array	Planar array	Slotted array	Slotted array		Slotted waveguide
Antenna polarization	Linear	Linear	Linear	Not specified		Linear
Antenna main beam gain (dBi)	29	43	39	27 (min)	32 (max)	30

TABLE 2 *(continued)*

Characteristics	System S1	System S2	System S3	System S4		System S5
Antenna elevation beamwidth (degrees)	13	1	1	20.0 (min)	26.0 (max)	20
Antenna azimuthal beamwidth (degrees)	3	1	1.5	0.75 (min)	2.3 (max)	1.4
Antenna horizontal scan rate	9.5 rpm	90°/s	180°/s	20 (min)	60 (max)	24 rpm
Antenna horizontal scan type (continuous, random, sector, etc.)	360° (mechanical)	360° (mechanical)	360° or sector search/track (mechanical)	360°		360°
Antenna vertical scan rate	Not applicable	90°/s	Not applicable	Not applicable		Not applicable
Antenna vertical scan type	Not applicable	Sector: +83/–30° (mechanical)	Not applicable	Not applicable		Not applicable
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	Not specified	23 dBi (1st SL)	23 dBi (1st SL)	4 dBi at ≤ 10° (min) 3 dBi at ≥ 10° (max)	9 dBi at ≤ 10° (max) 2 dBi at ≥ 10° (max)	5 dBi (1st SL)
Antenna height	Mast/deck mount	Mast/deck mount	Mast/deck mount	Mast/deck mount		Mast/deck mount
Receiver IF (MHz)	Not specified	Not specified	Not specified	45 (min)	60 (max)	
Receiver IF 3 dB bandwidth (MHz)	12	0.5	2.5; 4; 12	6; 2.5 (min) (short and long pulse, resp.)	28; 6 (max) (short and long pulse, resp.)	0.5
Receiver noise figure (dB)	Not specified	3.5	9	3.5 (min)	8.5 (max)	3.5
Minimum discernible signal (dBm)	–96	–113	–102; –100; –95	–106 (min)	–91 (max)	–113
Chirp bandwidth (MHz)	Not applicable	Not specified	Not applicable	Not applicable		1.7 to 54
RF emission bandwidth (MHz) – 3 dB – 20 dB	 10; 5 80; 16	 Not specified Not specified	 1.6; 4.2 10; 24	 Not specified Not specified		 Not specified Not specified

TABLE 2 (*continued*)

Characteristics	System S6	System S7	System S8	System S9	
Function	Maritime radionavigation radar	Navigation and search	Maritime radionavigation radar(6)	Maritime radionavigation radar(7)	
Platform type	Shipborne	Shipborne	Shipborne	Shipborne	
Tuning range (MHz)	9 380-9 440	9 300-9 500	9 410 ± 30	9 410 ± 30	9 445 ± 30
Modulation	Pulse	Pulse	Pulse	Pulse	
Peak power into antenna	25 kW	1.5 kW	5 kW	1.5-10 kW	
Pulse width (μs) and Pulse repetition rate (pps)	0.08, 0.2, 0.4, 0.7, and 1.2 2 200 (0.08 μs); 1 800, 1 000 and 600 (1.2 μs)	0.08, 0.25, and 0.5 2 250, 1 500 and 750	0.05, 0.18, and 0.5 3 000 pps at 0.05 μs to 1 000 pps at 0.5 μs	0.08 (min) at 3 600 pps	1.2 (max) at 375 pps
Maximum duty cycle	0.00072	0.000375	0.0005	0.00045	
Pulse rise/fall time (μs)	0.010/0.010	0.01/0.05	Not specified	Not specified	
Output device	Magnetron	Magnetron	Magnetron	Magnetron	
Antenna pattern type	Fan	Fan	Fan	Fan	
Antenna type)	End-fed slotted array	Centre-fed slotted waveguide	Slotted array	Slotted/patch array or horn	
Antenna polarization	Horizontal	Horizontal	Horizontal	Horizontal	
Antenna main beam gain (dBi)	31	23.9	30	22-30	
Antenna elevation beamwidth (degrees)	20	25	26	24-28	
Antenna azimuthal beamwidth (degrees)	0.95	6	0.95	1.9-7	
Antenna horizontal scan rate	24 rpm	24 rpm	30 rpm	24 rpm	
Antenna horizontal scan type (continuous, random, sector, etc.)	360°	360°	360°	360°	

TABLE 2 (*end*)

Characteristics	System S6	System S7	System S8	System S9
Antenna vertical scan rate	Not applicable	Not applicable	Not applicable	Not applicable
Antenna vertical scan type	Not applicable	Not applicable	Not applicable	Not applicable
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	Not specified	+2.9 dBi	< 5 dBi within 10°; ≤ 2 dBi outside 10°	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	Mast
Receiver IF (MHz)	Not specified	Not specified	50	45-60
Receiver IF 3 dB bandwidth (MHz)	15	10 and 3	15-25	2.5-25
Receiver noise figure (dB)	6	6	6	4 to 8
Minimum discernible signal (dBm)	–97 (noise floor)	–102 (noise floor)	Not specified	Not specified
Total chirp width (MHz)	Not applicable	Not applicable	Not applicable	Not applicable
RF emission bandwidth (MHz) – 3 dB – 20 dB	 14 43	 20 55	Not specified	Not specified

(3) IMO category – including fishing.

(4) Uncompressed pulse, pseudo-random frequency-agile.

(5) Frequency sweep rate (sweep/s).

(6) River category.

(7) Pleasure craft category.

TABLE 3

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

Characteristics	System G1	System G2	System G3	System G4	System G5
Function	Rendezvous beacon transponder	Rendezvous beacon transponder	Tracking radar	Tracking radar	Precision approach and landing radar
Platform type	Airborne	Ground (manpack)	Ground (trailer)	Ground (trailer)	Ground (trailer)
Tuning range (MHz)	8 800-9 500	9 375 and 9 535 (Rx); 9 310 (Tx)	9 370-9 990	10 000-10 500	9 000-9 200
Modulation	Single or double pulse	Pulse	Frequency-agile pulse	CW, FMCW	Frequency-agile pulse
Peak power into antenna	300 W	20 to 40 W	31 kW	14 kW	120 kW
Pulse width (μs) and pulse repetition rate (pps)	0.3 10 to 2 600	0.3 to 0.4 Less than 20 000	1 7 690 to 14 700	Not applicable Not applicable	0.25 6 000
Maximum duty cycle	0.00078	0.008	0.015	1	0.0015
Pulse rise/fall time (μs)	0.1/0.2	0.10/0.15	0.05/0.05	Not applicable	0.02/0.04
Output device	Magnetron	Solid state	Travelling wave tube	Travelling wave tube	Travelling wave tube
Antenna pattern type	Omnidirectional	Quadrant	Pencil	Pencil	Pencil/fan
Antenna type	Open-ended waveguide	Printed-circuit array	Phased array (linear slotted waveguide)	Planar array	Planar array of dipoles
Antenna polarization	Linear	Circular	Linear	Linear	Circular
Antenna main beam gain (dBi)	8	13	42.2	42.2	40

TABLE 3 *(continued)*

Characteristics	System G1	System G2	System G3	System G4	System G5
Antenna elevation beamwidth (degrees)	18	20; 3	0.81	1	0.7
Antenna azimuthal beamwidth (degrees)	360	65; 10	1.74	1	1.1
Antenna horizontal scan rate	Not applicable	Not applicable	Not specified	90°/s	5-30°/s
Antenna horizontal scan type (continuous, random, sector, etc.)	Not applicable	Not applicable	Sector: ± 45° (phase-scanned)	360° (mechanical)	Sector: +23/+15° (phase-scanned)
Antenna vertical scan rate	Not applicable	Not applicable	Not specified	90°/s	5-30°/s
Antenna vertical scan type	Not applicable	Not applicable	Sector: 90° ± array tilt (frequency-scanned)	Sector: 90° ± array tilt (mechanical)	Sector: +7/–1° (frequency-scanned)
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	Not specified	0 dBi (1st SL)	Not specified	Not specified	Not specified
Antenna height	Aircraft altitude	Ground level	Ground level	Ground level	Ground level
Receiver IF 3 dB bandwidth (MHz)	24	40	1	0.52	2.5
Receiver noise figure (dB)	Not specified	13	Not specified	3.4	Not specified
Minimum discernible signal (dBm)	–99	–65	–107	–113	–98
Chirp bandwidth (MHz)	Not applicable	Not applicable	Not applicable	Not specified	Not applicable
RF emission bandwidth (MHz) – 3 dB – 20 dB	 2.4 13.3	 4.7 11.2	 0.85 5.50	 Not specified Not specified	 3.6 25.0

TABLE 3 (*continued*)

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

Characteristics	System G6	System G7	System G8
Function	Airport surveillance/GCA	Precision approach radar	Airport surface detection equipment (ASDE)
Platform type	Ground (mobile)	Ground (fixed or transportable)	Ground
Tuning range (MHz)	9 025	9 000-9 200 (4 frequencies/system)	9 000-9 200; pulse-to-pulse agile over 4 frequencies
Modulation	Plain and NLFM pulses	Plain and NLFM pulse pairs	Plain and LFM pulse pairs
Peak power into antenna	310.5 W	500 W	60 W
Pulse width (μs) and pulse repetition rate (pps)	1.2, 30, and 96 12 800, 3 200-6 300 and 2 120, resp.	0.65 and 25 pulse-pair 3 470, 3 500, 5 200 and 5 300	0.04 and 3.7 (compressed to 0.040) 4 000
Maximum duty cycle	0.203	0.11	0.015
Pulse rise/fall time (μs)	Not specified	0.15/0.15 and 0.15/0.15	Short pulse: 0.02/0.12; Long pulse: 0.11/0.12
Output device	Solid state	Transistors	Solid state with combiner
Antenna pattern type	Fan (csc^2)	Vertical fan and horizontal fan	Inverse csc^2
Antenna type	Active array + reflector	Two phased arrays	Passive array
Antenna polarization	Vertical	Right-hand circular	Circular
Antenna main beam gain (dBi)	37.5 Tx, 37 Rx	Vertical fan: 36 Horizontal fan: 36	35
Antenna elevation beamwidth (degrees)	3.5 + csc^2 to 20	Vertical fan: 9.0 Horizontal fan: 0.63	17
Antenna azimuthal beamwidth (degrees)	1.05	Vertical fan: 1.04 Horizontal fan: 15	0.35

TABLE 3 (*continued*)

Characteristics	System G6	System G7	System G8
Antenna horizontal scan rate	12°/s	Vertical fan: 60°/s, half time (60 scans/min)	60 rpm
Antenna horizontal scan type (continuous, random, sector, etc.)	360°	30° sector	Continuous
Antenna vertical scan rate	Not applicable	Horizontal fan: 20°/s, half time (60 scans/min)	Not applicable
Antenna vertical scan type	Not applicable	10° sector	Not applicable
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	7.5 average on Tx, 2.9 average on Rx	Vertical fan: 17 dBi Horizontal fan: 18.5 dBi	Az plane: ≤ +10 El plane: ≤ +20
Antenna height	Ground level	Ground level	30 to 100 m above ground level
Receiver IF 3 dB bandwidth (MHz)	Not specified 0.8 (estimated)	40	28
Receiver noise figure (dB)	5 to 6.5	7.5	3.5
Minimum discernible signal (dBm)	Not specified	–90 (S/N = 13.5 dB)	Not specified
Dynamic range (dB)	65 from noise to 1 dB compression	Not specified	Not specified
Minimum number of processed pulses per CPI	7	6	4-pulse noncoherent integration
Total chirp width (MHz)	Not specified 0.8 (estimated)	2	Short pulse: none; Long pulse: 50
RF emission bandwidth (MHz) – 3 dB – 20 dB	Not specified 0.8 (estimated) Unknown	 1.1 (plain pulse),1.8 (NLFM) 5.8 (plain pulse), 3.15 (NLFM)	Not specified Approx. 50 Approx. 100
Interference rejection features	Not specified	Not specified	Local CFAR; Clutter map; 2-D spatial filter

TABLE 3 (*continued*)

Characteristics	System G9	System G10	System G11	System G12
Function	Meteorological (radiolocation)	Meteorological (radiolocation)	Meteorological (radiolocation)	Tracking radar
Platform type	Ground	Ground	Ground	Ground
Tuning range (MHz)	9 300-9 375 MHz	9 200-9 500 MHz	9 375 MHz	8 700-9 500 MHz
Modulation	Pulse	Pulse	Pulse	Linear FM pulse
Peak power into antenna	50 kW	250 kW	35 kW per polarization	150 kW
Pulse width (μs) and Pulse repetition rate (pps)	0.1, 0.25 and 1.0 1 000 to 2 000	0.5, 1.0, 0.8 and 2.0 1 500 to 250	1 and 2 500	1-15 500-15 000
Maximum duty cycle	0.002	Not specified	Not specified	Not specified
Pulse rise/fall time (μs)	0.05	Not specified	Not specified	0.05
Output device	Klystron or magnetron	Magnetron	Magnetron	TWT
Antenna pattern type	Pencil beam	Pencil beam	Pencil beam	Pencil
Antenna type	Parabolic reflector with Cassegrain feed	Parabolic reflector	Parabolic reflector	Planar array
Antenna polarization	Linear (dual polarization)	Linear	Linear (dual polarization)	Linear
Antenna main beam gain (dBi)	46	45	40	38
Antenna elevation beamwidth (degrees)	0.9	< 1.0	1.5	5
Antenna azimuthal beamwidth (degrees)	0.9	< 1.0	1.5	5
Antenna horizontal scan rate	0° to 20°/s	0 to 36°/s	6°/s	300°/s
Antenna horizontal scan type (continuous, random, sector, etc.)	Volume, sector volume, stationary and tracking	Volume	Volume	Continuous
Antenna vertical scan	0° to 20°	Not specified	0° to 90°	Not applicable

TABLE 3 (*end*)

Characteristics	System G9	System G10	System G11	System G12
Antenna vertical scan type	Steps to next elevation after horizontal rotation or elevation change at constant azimuth	Steps to next elevation after horizontal rotation	Not specified	Random
Antenna side-lobe (SL) levels (1st SLs and remote SLs)	26 dBi	16 dBi	10 dBi (1st SL) 0 dBi (remote SL)	Not specified
Antenna height	4 m	2 to 30 m	5 to 15 m	Ground level
Receiver IF 3 dB bandwidth (MHz)	10, 4 or 1	Not specified	Not specified	3 MHz
Receiver noise floor (dBm)	–110	–114	–113	–105
Receive loss, dB	Not specified	Not specified	Not specified	Not specified
Chirp bandwidth (MHz)	Not applicable	Not applicable	Not applicable	3
RF emission bandwidth (MHz) – 3 dB – 20 dB	 Not specified 6 to 60 MHz – dependent on pulse width	 Not specified Not specified	 1 MHz 6 MHz	 3 MHz

* Radar systems with characteristics similar to those given in Table 2 for maritime radionavigation systems may also be used for ground based aeronautical radars at airports.

2.1 Transmitters

The radars operating in the 8 500-10 500 MHz band use a variety of modulations including unmodulated pulses, continuous wave (CW), frequency-modulated (chirped) pulses, and phase-coded pulses. Crossed-field, linear-beam, and solid-state output devices are used in the final stages of the transmitters. The trend in new radar systems is toward linear-beam and solid-state output devices due to the requirements of Doppler signal processing. Also, the radars deploying solid-state output devices have lower transmitter peak output power and higher pulse duty cycles. In four cases (Systems A4, S2, S5, and G4), the duty cycle is 100%, with the high-power CW radiolocation radars all operating only above 10 GHz. There is also a trend towards frequency-agile type radar systems that will suppress or reduce interference, much as is done in some communications systems. Frequency agility is also sometimes used to avoid range-ambiguous clutter return. The random (or pseudo-random) transmissions on a single carrier frequency can occur throughout a coherent processing interval or even a full antenna-beam position or dwell, during which many pulses are transmitted, or for only a single pulse. These alternatives are similar to “slow frequency hopping” and “fast frequency hopping” in a communication system. These important aspects of radar systems should be taken into account in compatibility studies.

Typical transmitter RF emission (3 dB) bandwidths of radars operating in the band 8 500-10 500 MHz range from 45 kHz to 637 MHz. Transmitter peak output powers range from 1 mW (0 dBm) for solid-state transmitters to 220 kW (83.4 dBm) for high-power radars using crossed-field devices (magnetron).

The characteristics of unwanted emissions are not addressed in this Recommendation.

2.2 Receivers

The newer-generation radar systems use digital signal processing after detection for range, azimuth and Doppler processing. Generally, the signal processing includes techniques that are used to enhance the detection of desired targets and to produce target symbols on the display. The signal-processing techniques used for the enhancement and identification of desired targets also provide some suppression of low-duty-cycle (less than 5%) pulsed interference that is asynchronous with the desired signal.

The signal processing in the newer generation of radars uses chirped and phase-coded pulses to produce a processing gain for the desired signal and may also provide suppression of undesired signals.

Some of the newer low-power solid-state radars use high-duty-cycle multichannel signal processing to enhance the desired signal returns. Some radar receivers have the capability to identify RF channels that have low levels of undesired signals and command the transmitter to transmit on those RF channels.

2.3 Antennas

A variety of types of antennas are used on radars operating in the 8 500-10 500 MHz band. Antennas in this band are generally of convenient size and thus are of interest for applications where mobility and light weight are important and long range is not. Many radars in the 8 500-10 500 MHz band operate in a variety of modes, including search and navigation (weather observation) modes. The antennas for such radars usually scan through 360° in the horizontal plane.

Other radars in the band are more specialized and limit scanning to a fixed sector. Most radars in 8 500-10 500 MHz use mechanical scanning, however newer-generation radars use electronically scanned array antennas. Horizontal, vertical, and circular polarizations are used. Typical antenna heights for ground-based and shipborne radars are 8 m and 30 m above surface level, respectively, although many maritime radionavigation radars are lower than 30 m.

3 Additional technical and operational characteristics of shipborne radionavigation systems in the 9 300-9 500 MHz band

In global terms a clear distinction can be made between radars that conform to the requirements of the International Maritime Organization (IMO) (including those used on fishing vessels), those that are used for inland navigation (rivers) and those fitted on a voluntary basis in pleasure crafts, for safety purposes.

In Table 4 are the comparisons of transmitter power and numbers of radars for the three categories above.

TABLE 4

Categories of shipborne radionavigation radars

Radar category	Peak power (kW)	Global total
IMO and fishing	≤ 75	> 300 000
River	< 10	< 20 000
Pleasure	< 5	> 2 000 000

Almost all the radars used aboard river and pleasure craft operate in the 9 300-9 500 MHz band. Most of the IMO and fishing-craft radars also operate in the same band, although substantial numbers of IMO radars operate in the 2 900-3 100 MHz band.

The radar characteristics that affect the efficient use of the spectrum, including protection criteria, are those associated with the radar antenna and transmitter/receiver. Most of the maritime radars use slotted array antennas, however, some of the pleasure craft radars use patch arrays or horns.

4 Additional information relevant to maritime radionavigation radars

4.1 Performance requirements and interference effects

Radionavigation systems may fail to meet their performance requirements if undesired signals inflict excessive amounts of various types of interference degradation. Dependent upon the specific interacting systems and the operational scenarios, those types may include:

– diffuse effects, e.g. desensitization or reduction of detection range, target drop-outs and reduction of update rate;

– discrete effects, e.g. detected interference, increase of false-alarm rate.

Associated with these types of degradation, the protection criteria are associated with threshold values of parameters, e.g. for a collision avoidance system:

– tolerable reduction of detection range and associated desensitization;

– tolerable missed-scan rate;

– tolerable maximum false-alarm rate;

– tolerable loss of real targets;

– tolerable errors in estimation of target position.

The operational requirement for maritime radars is a function of the operational scenario. This is related to the distance from shore and sea obstacles. In simplistic terms this can be described as oceanic, coastal or harbour/port scenarios.

The IMO has adopted a revision to the operational performance standards for maritime radar[2]. The IMO revision, for the first time, gives recognition to the possibility of interference from other radio services.

Most importantly, the international maritime authorities have stated, without reservation, in their recent update of the IMO Safety of Life at Sea Convention (SOLAS), that radar remains a primary sensor for the avoidance of collisions.

This statement should be viewed in the context of the mandatory fitting of Automatic Identification Systems (AIS) to some classes of ships. These systems rely upon external references, e.g. GPS, for the verification of relative position indication in terms of collision avoidance scenarios.

However, the fitting of such systems can never take account of many maritime objects, e.g. icebergs, floating debris, wrecks, etc. that are not fitted with AIS. These objects are potential causes of collision with ships, and need to be detected by ship radars. Radar will therefore remain the primary system for collision avoidance for the foreseeable future.

Among other radar targets, the IMO standards mention the need for radar to detect small floating and fixed hazards and fixed aids to navigation. They require that various specified targets be detected on at least eight out of ten scans, with a false-alarm rate of 10^{-4}. The specified targets include small vessels with a radar reflector meeting IMO performance standards, as well as navigation buoys and small vessels with no radar reflector, each at particular ranges[3]. The standards also require range and bearing accuracy to be within 30 m and 1°, respectively. They call for means to be provided for adequate reduction of interference from other radars. They require capability for displaying resolution of two point targets on the same bearing but separated by 40 m in range and resolution of two point targets separated in bearing by 2.5°. They call further for minimizing the possibility of tracking one target in place of another ("target swap") and an alarm when a tracked target is lost, all of which also bears on target resolution and position errors that can be exacerbated by interference.

5 Future radiodetermination systems

In broad outline, radiodetermination radars that might be developed in the future to operate in the 8 500-10 500 MHz band are likely to resemble the existing radars described here. For example, the deployment of short-range, ground-based meteorological radars in the 9 300-9 500 MHz band is planned for one administration. In addition to providing the potential for high-resolution volume sampling throughout the entire troposphere, the network of distributed Doppler weather radars will be designed for efficient utilization by employing low-power solid-state operation. Other technical parameters, such as a 1 metre antenna diameter and low duty cycle modes of operation are consistent with current radiodetermination radars operating in the 8 500-10 500 MHz band. Future radiodetermination radars are also likely to have at least as much flexibility as the radars already described, including the capacity to operate differently in different azimuth and elevation sectors.

It is reasonable to expect that some future designs may strive for a capability to operate in a wide band extending at least to the band limits used in this consideration.

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[2] IMO Resolution MSC.192 (79), Adoption of the revised performance standards for radar equipment, adopted on 10 December 2004.

[3] IMO revised performance standards for radar reflectors (Resolution MSC.164(78)).

Future radiodetermination radars are likely to have electronically steerable beam antennas. Current technology makes phase steering a practical and attractive alternative to frequency steering, and numerous radiodetermination radars developed in recent years for use in other bands have employed phase steering in both azimuth and elevation. Unlike frequency-steered radars (e.g. Systems 15 and 17), new phased-array radars can steer any fundamental frequency in the radar's operating band to any arbitrary azimuth and elevation within its angular coverage area. Among other advantages, this would facilitate electromagnetic compatibility in many circumstances.

Some future radiodetermination radars are expected to have average-power capabilities at least as high as those of the radars described herein. However, it is reasonable to expect that designers of future radars will strive to reduce wideband noise emissions below those of the existing radars that employ magnetrons or crossed-field amplifiers. Such noise reduction is expected to be achieved by the use of solid-state transmitter/antenna systems. In that case, the transmitted pulses would be longer in duration and the transmit duty cycles would be substantially higher than those of current tube-type radar transmitters.

Annex 2

Protection criteria for radars

1 Protection criteria

1.1 Continuous noise-like interference

Radars are affected in fundamentally different ways by unwanted signals of different forms, and an especially sharp difference prevails between the effects of continuous noise-like energy and those of pulses. Continuous-wave interference of a noise-like type inflicts a desensitizing effect on radiodetermination radars, and that effect is predictably related to its intensity. Within any azimuth sectors in which such interference arrives, its power-spectral density can, to a reasonable approximation, simply be added to the power-spectral density of the radar-system thermal noise. If the power of radar-system noise in the absence of interference is denoted by N and that of noise-like interference by I, the resultant effective-noise power becomes simply $I + N$.

Given that, the radar protection criteria traditionally established within ITU-R are based on the penalties incurred to maintain the target-return signal-to-noise ratio in the presence of the interference, requiring that the target-return power be raised in proportion to the increase of noise power from N to $I + N$. That can only be done by accepting shorter maximum ranges on given targets, sacrificing observation of small targets, or modifying the radar to give it a higher transmitter power or power-aperture product. (In modern radars, receiving-system noise is usually already near an irreducible minimum and nearly optimum signal processing is becoming commonplace.)

These penalties vary depending on the radar's function and the nature of its targets. For most radars, an increase in the effective noise level of about 1 dB would inflict the maximum tolerable degradation on performance. In the case of a discrete target having a given average or median radar cross section (RCS), that increase would reduce the detection range by about 6% regardless of any RCS fluctuation characteristics that target might have. This effect results from the fact that the achievable free-space range is proportional to the 4th root of the resultant signal-to-noise power ratio (SNR), from the most familiar form of the radar range equation. A 1 dB increase of effective noise power is a factor of 1.26 in power, so it would, if uncompensated, require the free-space range from a given discrete target to be reduced by a factor of $1/(1.26^{1/4})$, or 1/1.06; i.e. a range capability reduction of about 6%. In the range equation, the SNR is also directly proportional to transmitter power, to power-aperture product (for a surveillance radar), and to target radar cross section. Alternatively, therefore, the 1 dB increase of effective noise power could be compensated by forgoing detection of targets except those having an average radar cross section 1.26 times as large as the minimum-size target that could be detected in the interference-free regime or by increasing the radar transmitter power or its power-aperture product by 26%. Any of these alternatives is at the limit of acceptability in most radar missions, and the system modifications would be costly, impractical, or impossible, especially in mobile radars. For discrete targets, those performance penalties hold for any given probability of detection and false-alarm rate and any target fluctuation characteristics.

Weather-avoidance and weather-observation radars differ from discrete-target radars in having extended targets, typically precipitation, that often fills the entire radar beam (which is typically quite narrow). In the corresponding form of the radar range equation, SNR is inversely proportional to the inverse square of range rather than to its inverse 4th power. For a weather radar observing beam-filling rain, the range reduction for a given precision of rainfall-rate estimation would be the square root of the 1 dB factor; i.e. $(1.26)^{1/2}$, which equals 1.12. Thus there is a 12% loss of range capability in the presence of such interference, that also corresponds to a 21% loss of area coverage. Alternatively, for a given range, the interference would raise (i.e. degrade) the minimum measurable weather reflectivity by about 26%, again without regard to weather reflectivity fluctuation characteristics.

For meteorological radars, an increase of about 0.5 dB would constitute a range and area coverage degradation of respectively 5 and 11%. Such an increase corresponds to an $(I + N)/N$ ratio of about −10 dB. However, further study is required regarding this issue.

Synthetic-aperture imaging radars (SARs) perform coherent integration of return pulses over the time required for the antenna beam RF traverse each pixel in the observed scene by virtue of the radar platform's motion. Since the width of the beam's illumination on the ground is directly proportional to the range (typically proportional to the altitude of the radar platform and also increasing with the swath angle), the number of pulses available for integration, and hence the integration processing gain relative to noise, is also proportional to the range. To the extent that design flexibility permits, the output (processed) SNR is therefore modified from the proportionality to the inverse-4th-power of range that prevails with a discrete target observed by a real-aperture radar to a proportionality to the inverse 3rd power of range. Consequently, a 1 dB increase of effective noise power; i.e. the increase by a factor of 1.26 in power, would require that the range of a SAR from given terrain to be imaged be reduced by a factor of $1/(1.26^{1/3})$, or 1/1.077; i.e. a loss of 7.7%. Provided that operational restrictions permit such a range reduction, that would in turn inflict a corresponding reduction in the rate at which imaging data can be gathered. This again is at the limit of acceptability. Another option would be to raise the average power of the SAR transmitter by 26%, which is likewise at the limit of acceptability.

1.1.1 Aggregation of interference contributions

The 1 dB increase referred to throughout the above discussions corresponds to an $(I + N)/N$ ratio of 1.26, or an I/N ratio of about −6 dB. This represents the tolerable aggregate effect of all interferers. It applies for reception via the radar's main beam as well as for simultaneous reception via side lobes. The tolerable I/N ratio for an individual noise-like interferer therefore depends on the number of interferers and their geometry and should be assessed in the analysis of a given scenario. This is a consequence of the fact that almost all the radars in this band serve event-driven missions, observe non-cooperative targets, and do not have the benefit of redundancy, including the re-transmission of packets that is becoming used more and more in communications technologies. Basically, sensing, including radar, is a fundamentally different use of the RF spectrum than is communications, and the same interference-protection rules are not appropriate for both.

1.2 Pulsed interference

The effect of pulsed interference is more difficult to quantify and is strongly dependent on receiver-processor design and mode of system 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 interference. Assessing it will be an objective for analyses and/or testing of interactions between specific radar types. In general, numerous features of radars of the types described herein 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 – Efficient use of the radio spectrum by radar stations in the radiodetermination service.

2 Shipborne radionavigation radars protection criteria

There is as yet no international agreement on the protection criteria required for radars currently installed on ships for the scenarios identified above. However, Recommendation ITU-R M.1461 provides a generic interference/noise level of −6 dB.

The IMO has developed a revision to the operational performance standards for shipborne radar and this revision takes account of the recent ITU requirements for unwanted emissions. The IMO revision, for the first time, gives recognition to the possibility of interference from other radio services, and includes new requirements with respect to the detection of specific targets in terms of radar cross section (RCS) (fluctuating) and required range, as a function of radar frequency band. The detection of a target is based upon an indication of it in at least eight out of ten scans and a probability of false alarm of 10^{-4}. These detection requirements are specified in the absence of sea clutter, precipitation and evaporation duct, with an antenna height of 15 m above sea level.

Most importantly, the international maritime authorities have stated, without reservation, in their recent update of the IMO Safety of Life at Sea Convention (SOLAS), that radar remains a primary sensor for the avoidance of collisions.

This statement should be viewed in the context of the mandatory fitting of automatic identification systems (AIS) only to those vessels listed under IMO carriage requirements. These systems rely upon external references, e.g. GPS, for the verification of relative position indication in terms of collision avoidance scenarios.

However, the fitting of such systems can never take account of many maritime objects, e.g. icebergs, floating debris, wrecks, and other vessels, that are not fitted with AIS. These objects are potential causes of collision with ships, and need to be detected by ship radars. Radar will therefore remain the primary system for collision avoidance for the foreseeable future.

Intensive discussion with maritime authorities, including users, has resulted in an operational requirement that during all maritime voyages no interference that can be controlled by regulation is acceptable.

In the meantime, the approach has been to carry out trials and determine what current shipborne radars can accept in terms of interference to noise ratios (I/N) as a function of probability of detection (see Annex 3).

Annex 3

Results of interference trials

1 Interference to noise (*I/N*) radar trials

Prior to adoption of the revised IMO standards, radar trials were carried out in the United States of America and the United Kingdom to determine the vulnerability of current maritime radars to various forms of interference.

The trials used radars operating in the S and X frequency bands. Only the X-band (9 300-9 500 MHz) trials are discussed herein. The results of the trials are presented as probability of detection as a function of *I*/*N* with respect to each type of interference source.

It should be noted that there are no ITU or other internationally agreed receiver specifications for maritime radars, and therefore it is not surprising that there is a wide range of receiver characteristics operating in this operational environment. The trials results reflect this range, and indicate both the continuous degradation of probability of detection as the level of interference increases and also a "cut off" at which the receiver is no longer able to accept the specific level of interference.

Such differences are real and exist in current operational radars.

1.1 Characteristics of specific radars under test

Both of the radars, referred to as radars D and E, are IMO category radars. No pleasure-craft radars were tested. Nominal values for the principal parameters of the radars were obtained from regulatory type-approval documents, sales brochures, and technical manuals. Radar E uses a logarithmic amplifier/detector in its receiver design, while Radar D use a logarithmic amplifier followed by a separate video detector. For all of the radars, the sensitivity-time-control (STC) and fast-time-constant (FTC) were not activated for the tests.

The characteristics of radars D and E are presented below in Tables 5 and 6.

TABLE 5

Radar D parameters

Parameter	Value			
Frequency (MHz)	9 410 ± 10			
Pulse power (kW)	30			
Range (nmi)	0.125-1.5	3-24	48	96
Pulse width (μs)	0.070	0.175	0.85	1.0
PRF (Hz)	3 100	1 550	775	390
IF bandwidth (MHz)	22	22	6	6
Spurious response rejection (dB)	Unknown			
System noise figure (dB)	5.5			
RF bandwidth (MHz)	Unknown			
Antenna scan rate (rpm)	24/48			
Antenna horizontal beamwidth (degrees)	1.2			
Antenna vertical beamwidth (degrees)	25			
Polarization	Horizontal			

TABLE 6

Radar E parameters

Parameter	Value		
Frequency (MHz)	9 410 ± 10		
Pulse power (kW)	30		
Range (nmi)	0.125-3	6-24	48-96
Pulse width (μs)	0.050	0.25	0.80
PRF (Hz)	1 800		785
IF bandwidth (MHz)	20	20	3
Spurious response rejection (dB)	Unknown		
System noise figure (dB)	4		
RF bandwidth (MHz)	Unknown		
Antenna scan rate (rpm)	25/48		
Antenna scan time (s)	2.4/1.25		
Antenna horizontal beamwidth (degrees)	2.0		
Antenna vertical beamwidth (degrees)	30.0		
Polarization	Horizontal		

1.2 Radar receiver interference suppression features

Both of the radars employed circuitry and signal processing to mitigate interference from other co-located radars. Radars D and E use pulse-to-pulse and scan-to-scan correlators to mitigate interference from other radars. However, they do not have CFAR processing. A description of these mitigation techniques is described in Recommendation ITU-R M.1372.

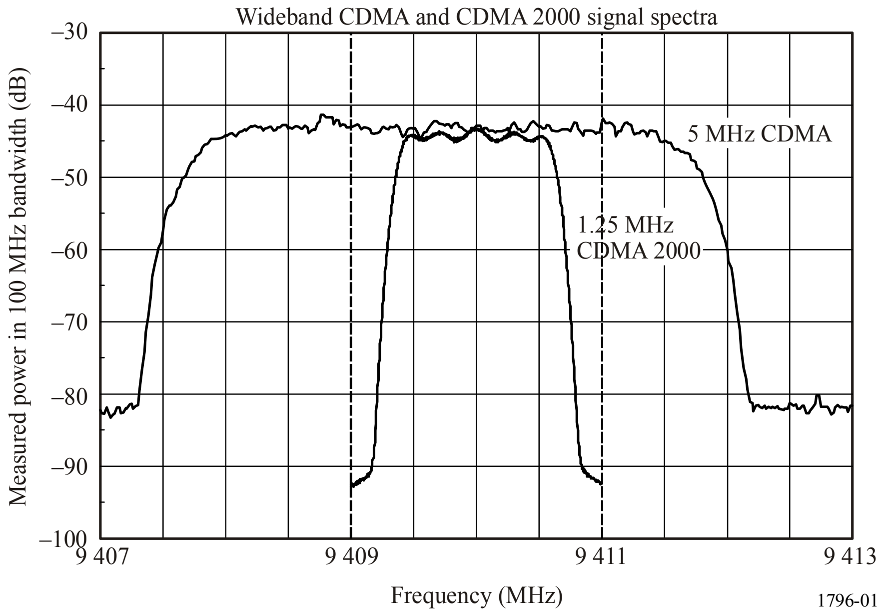
1.3 Interfering signals and targets

The interfering signals included pulses and digital mobile telephony. The pulse source simulated a radiolocation input. Pulse widths of 1 μs and 2 μs were used, with PRFs equivalent to duty cycles of 0.1% and 1%. The digital mobile telephony source simulated two generic CDMA signals one with a bandwidth of 5 MHz and one with a bandwidth of 1.25 MHz.

The emissions were on-tuned with the operating frequency and gated to occur with the simulated targets. The emission spectra of the CDMA interfering signals are shown below in Fig. 1.

FIGURE 1

Generic CDMA signals



1.4 Non-fluctuating target generation

A combination of arbitrary waveform signal generators (AWG), RF signal generators, discrete circuitry, a laptop PC and other RF components (cables, couplers, combiners, etc.) were used to generate ten equally spaced targets along a 3 nautical mile (~ 5.6 km) radial that had the same RF power level. The power level of the simulated targets was adjusted till the target probability of detection was about 90%. The ten target pulses triggered by each radar trigger all occur within the return time of one of the radar's short-range scales, i.e. "one sweep". Consequently, the pulses simulate ten targets along a radial; i.e. a single bearing. For adjustment of the display settings, the RF power of the target generator was set to a level so that all ten targets were visible along the radial on the PPI display with the radar's video controls set to positions representative of normal operation. Baseline values for the software functions that controlled the target and background brilliance, hue, and contrast settings were found through experimentation by test personnel and with the assistance of the manufacturers and with professional mariners who were experienced with operating these types of radars on ships of various sizes. Once these values were determined, they were used throughout the test program for that radar.

1.5 Test results

1.5.1 Radar D

For Radar D it was possible to observe the effect that the unwanted signals had on individual targets. For each unwanted signal, it was possible to count the decrease in the number of targets that were visible on the PPI as the I/N level was increased. Target counts were made at each I/N level for each type of interference. A baseline target probability of detection, P_d, count was performed before the beginning of each test. The results of the tests on Radar D are shown below in Fig. 2, which shows the target P_d versus the *I*/*N* level for each type of interference. The baseline P_d in Fig. 2 is 0.92 with the 1-sigma error bars 0.016 above and below that value. Note that each point in Fig. 2 represents a total of 500 desired targets.

FIGURE 2

Radar D P_d curves

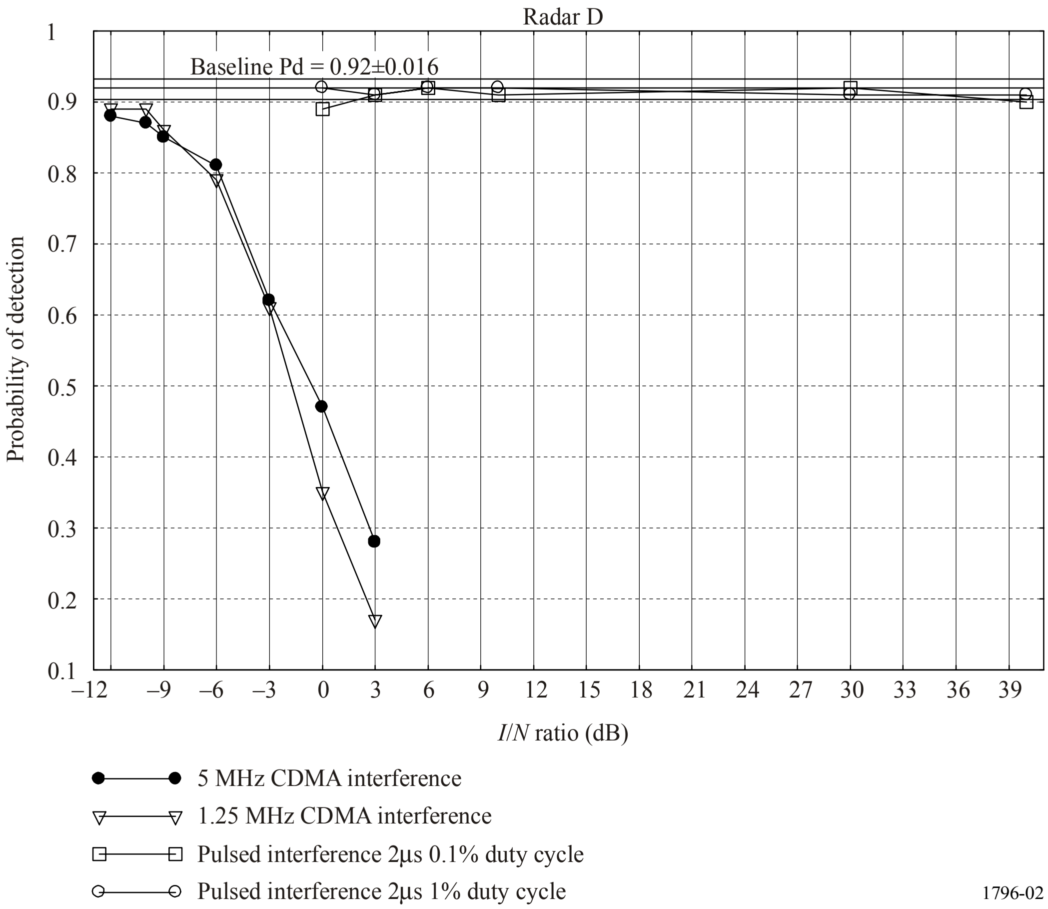


Figure 2 shows that, except for the case of the pulsed interference, the target P_d was reduced below the baseline P_d used in these tests minus the standard deviation for *I*/*N* values above −12 dB for the unwanted CDMA signal.

1.5.2 Radar E

For Radar E it was difficult to count the decrease in target P_d as the interference was injected into the radar's receiver. The interference caused all of the targets to fade at the same rate no matter where they were in the string of targets. It was not possible to make individual targets "disappear" as the interference power was increased and count the number of lost targets in order to calculate the P_d. Therefore, the data taken for Radar E reflects whether or not the appearance of all the targets was affected at each *I*/*N* level for each type of interference. The data for Radar E is summarized below in Table 7.

TABLE 7

Radar E with gated CDMA interference

I/*N* ratio (dB)	5 MHz CDMA	1.25 MHz CDMA 2000
–12	No effect	No effect
–10	No effect	No effect
–9	No effect	No effect
–6	Targets dimmed	Targets dimmed
–3	Targets dimmed	Targets dimmed
0	Targets not visible	Targets not visible
3	Targets not visible	Targets not visible
6	Targets not visible	Targets not visible

The data in Table 7 show that the unwanted CDMA signals affected the visibility of the targets for Radar E on its PPI at an *I*/*N* level of −6 dB. At that level the brightness of the targets on the PPI was noticeably dimmed from their baseline state. At *I*/*N* levels of 0 dB and above, the targets had dimmed so much that they were no longer visible on the PPI.

For Radar E, the gated 2.0 and 1.0 μs pulsed interference with duty cycles of 0.1 and 1.0% did not affect the visibility of the targets on the PPI at the highest *I*/*N* level, which was 40 dB.

1.6 Summary of trials results

Radar trials were performed to determine for specific radars and interference sources an *I*/*N* level for which there is "no effect" from the interference (i.e. the radar is operating at its baseline condition). Unprocessed radar returns commonly known as "blips" or "raw video" were observed and/or counted as targets in these tests.

This "no effect" level is qualified as relative to a 90% probability of a single-scan detection and is summarized below in terms of *I*/*N* for each radar and interference source. The results are summarized in Table 8. Determining the acceptable amount of interference for these types of radars can be somewhat subjective due to the eyesight and experience of the radar operator looking at the PPI counting targets and grading the brightness of the targets themselves. However, due to the radar's design, there is no other way for these tests to be performed other than for the operator/tester to observe the targets on the radar's PPI.

TABLE 8

Summary of results

Interference source	Radar D	Radar E
Pulsed 0.1	+40	+40
Pulsed 1.0	+40	+40
1.25 MHz CDMA 2000	–10	–9
5 MHz CDMA	–12	–9

It should be noted that there are other effects from interference that reduce the operational effectiveness of a radar. An example is the creation of "false targets". The maritime radars tested do not generally contain "constant false alarm rate" (CFAR) processing.

The results of these tests show that when the emissions of devices using digital modulations are directed towards a radar of the type tested herein exceed an I/N ratio of −6 dB, some of the radars started to have dimmed targets, lost targets, or generate false targets. For other radars at this I/N level, these effects had already manifested. No recommendation is made, at this time, on what I/N is required in any specific scenario different from what is already specified ($I/N = -6$ dB).

None of the radars tested are within the pleasure-craft category. Such radars represent the single largest radar population (currently > 2 000 000 units worldwide). Such radars do not have all the anti-interference facilities contained in Radars D and E and may require more protection to achieve their anti-collision requirements.

The tests show that the radars can withstand low duty cycle pulsed-interference at high I/N levels due to the inclusion of radar-to-radar interference mitigating circuitry and/or signal processing. The radar-to-radar interference mitigation techniques of scan-to-scan and pulse-to-pulse correlators and CFAR processing, described in Recommendation ITU-R M.1372, have shown to work quite well. However, the same techniques do not work for mitigating continuous or high duty cycle emissions that appear noise-like within the radar receiver.

As most marine radars in the 9 300-9 500 MHz band are very similar in design and operation, one does not expect a great variation from the protection criteria that was derived from the radars that were used for these tests. Therefore, these test results should apply to other similar radars that operate in the 9 300-9 500 MHz band as well.

Authorities wishing to carry out sharing studies, with a view to possible sharing in the designated band, should use these results as guidance in their studies knowing that the test results presented in § 1.5 and § 1.6, and in particular in Table 8, were based on non-fluctuating targets. If tests were performed with fluctuating targets they are likely to bring different results.