International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Recommendation ITU-R M.1460-2
(02/2015)

Technical and operational characteristics and protection criteria of radiodetermination radars in the frequency band 2 900-3 100 MHz

M Series

Mobile, radiodetermination, amateur and related satellite services

150
1865 - 2015

International Telecommunication Union

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

Policy on Intellectual Property Right (IPR)

ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Annex 1 of Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from http://www.itu.int/ITU-R/go/patents/en where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

Series of ITU-R Recommendations

(Also available online at http://www.itu.int/publ/R-REC/en)

Series	Title
BO	Satellite delivery
BR	Recording for production, archival and play-out; film for television
BS	Broadcasting service (sound)
BT	Broadcasting service (television)
F	Fixed service
M	**Mobile, radiodetermination, amateur and related satellite services**
P	Radiowave propagation
RA	Radio astronomy
RS	Remote sensing systems
S	Fixed-satellite service
SA	Space applications and meteorology
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems
SM	Spectrum management
SNG	Satellite news gathering
TF	Time signals and frequency standards emissions
V	Vocabulary and related subjects

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

Electronic Publication
Geneva, 2015

RECOMMENDATION ITU-R M.1460-2*

Technical and operational characteristics and protection criteria of radiodetermination radars in the frequency band 2 900-3 100 MHz

(2000-2006-2015)

Scope

This Recommendation provides the technical and operational characteristics and protection criteria for radiodetermination systems operating in the frequency band 2 900-3 100 MHz which is allocated to the radiodetermination service on a primary basis. 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.

Keywords

Radar, shipborne, land-based, characteristics, protection

Abbreviations/Glossary

⇐⇒	correspondence (between carrier frequency and elevation angle)
AGC	automatic gain control
AIS	automatic identification system
Burn-thru	a mode in which power is concentrated in a narrow elevation sector to facilitate detection of targets under difficult conditions
BW	bandwidth or beamwidth, depending on context
CDMA	Code division multiple access
CFAR	Constant-false alarm rate
Chirp-thru	a type of burn-thru mode in which pulse compression is used to reduce return from extended clutter
Coincident video	pulse-to-pulse correlation
CSG	clean strobe generation. This is a technique for observing signals from active sources using the radar only as a receiver. It can be used with or without sidelobe blanking applied
Dicke fix	hard limiting of composite received signal (radar return plus interference) in a bandwidth substantially wider than that of the desired radar signal followed by filtering to a narrow bandwidth. This discriminates against wideband interference
ENG/OB	Electronic news gathering/outside broadcast

* This Recommendation should be brought to the attention of the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), the International Electrotechnical Commission (IEC) and the World Meteorological Organization (WMO).

f_{co}	cut-off frequency of filter
FTC	fast time constant
IF	Intermediate frequency
IMO	International Maritime Organization
INT	non-coherent (video) multiple-pulse integration
Jam strobe	similar to CSG
MTI	Moving-target indication
nm	Nautical miles
PRI	Pulse-repetition interval
PRF	Pulse-repetition frequency
PPI	Pulses per inch
PSD	Power spectral density
PW	Pulse width
QPSK	Quadrature phase shift keying
RCS	Radar cross section
STC	Sensitivity time control
WPB	Wide-pulse blanking

The ITU Radiocommunication Assembly,

considering

a) that antenna, signal propagation, target detection, and large necessary bandwidth characteristics of radar 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 frequency band;

c) 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 frequency band 2 900-3 100 MHz are to be found in Recommendation ITU-R M.824;

b) that technical and operational characteristics of aeronautical radionavigation radars operating in the frequency band 2 900-3 100 MHz are similar to those operating in the frequency band 2 700-2 900 MHz, which are found in Recommendation ITU-R M.1464 and ground-based meteorological radars which are found in Recommendation ITU-R M.1849;

c) some test results illustrating susceptibility of maritime radars are contained in Report ITU-R M.2050. Excerpts of this material have been reproduced in Annex 3, *recognizing*

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

b) that the required protection criteria depends upon the specific types of interfering signals such as those described in Annex 3, § 3;

c) that the application of protection criteria may require consideration for the inclusion of the statistical nature of the criteria and other elements of the methodology for performing compatibility studies (e.g. antenna scanning and motion of the transmitter and propagation path loss). Further development of these statistical considerations 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 2 900-3 100 MHz;

2 that this Recommendation along with Recommendation ITU-R M.1461 should be used as a guideline in analysing compatibility between radiodetermination radars with 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 the radiodetermination radars in the frequency band 2 900-3 100 MHz, even if multiple interferers are present. Further information is provided in Annex 2;

4 that the results of interference susceptibility trials performed on shipborne radionavigation radars operating in the frequency band 2 900-3 100 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 also Report ITU-R M.2050).

Annex 1

Technical and operational characteristics of radiodetermination radars in the frequency band 2 900-3 100 MHz

1 Introduction

Many transportable and shipborne radars operate in the frequency band 2 900-3 100 MHz. Shipborne radiolocation radars are discussed in § 2 through 4. Shipborne radionavigation radars are discussed briefly in § 5.

2 Technical characteristics of radiolocation radars other than meteorological radars

Characteristics of six representative shipborne radiolocation radars are presented in Table 1, and those of three representative land-based radiolocation radars are presented in Table 2.

All of the radiolocation systems identified are high-powered surveillance radars. The major radiolocation radars operating in this frequency 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 nm (approximately 545 km), so these radiolocation radars must have great sensitivity and must provide a high degree of suppression for all forms of clutter return, including that from sea, land and precipitation. The radiolocation radar emissions in this frequency band are not required to trigger radar beacons.

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

– they tend to have high transmitter peak and average power;
– they typically use master-oscillator-power-amplifier transmitters rather than power oscillators. They are usually tuneable, and some of them are frequency-agile. Some of them use linear-FM (chirp) or phase-coded intra-pulse modulation. The solid state technologies provide very stable wideband solutions;
– they can use frequency agility to mitigate some of the effects of interference;
– some of them have multiple or elevation-steerable beams using electronic beam steering. Active electronically steerable arrays embed the individual solid state transmitters in the antenna array and typically use higher duty cycles (typically 5 to 25%) to achieve the required average power levels with lower peak power levels than is achievable with vacuum tube technologies;
– some of them incorporate power-management features, i.e. capability for reducing transmitter power in some beams or for some functions while using full power for others;
– they typically employ versatile receiving and processing capabilities, such as use of auxiliary sidelobe-blanking receiving 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.

Some or all of the radiolocation radars whose characteristics are presented in Table 1 and 2 possess these properties, although they do not illustrate the full repertoire of attributes that might appear in future systems.

TABLE 1

Characteristics of shipborne radiolocation radars operating in the frequency band 2 900-3 100 MHz

Characteristics	Units	Radar No. 1	Radar No. 2	Radar No. 3	Radar No 3A	Radar No. 3B	Radar No. 3C
Overall tuning range	MHz	2 910-3 100.5	Nominally 2 900-3 100	2 910-3 100.5	2 900-3 100	2 900- 3 100	2 900- 3 100
Tuning options and frequency/elevation relationship	MHz	Deterministic: High frequency ⇐⇒ low elevation angle				8 Channels 20 MHz each from 2 920 to 3 080 MHz	
Frequency at horizon	MHz	Smooth sea: 3 048-3 051	Smooth sea: 3 055	Smooth sea: 3 051	Not applicable	Not applicable	Not applicable
Coverage/ performance modes		Long-range Long-range/limited elevation Short-range Short-range/limited elevation (each with normal, coincident video, or moving target indication (MTI) beams/pulses)	Normal (≤ 45º elevation) 5º Burn-thru: 1 fixed 1.6º beam Chirp-thru: 1 beam with chirped waveform Long-range MTI, 3-pulse; 5º or 45° Short-range MTI, 4-pulse; 5º or 45º Passive	Long-range (≤ 12.8º elevation) Long-range/low-elevation (≤ 4.8º) High-angle (≤ 41.6º) Limited-elevation (≤ 12.8º) High-data-rate (≤ 41.6º) MTI (≤ 36.9º)		Short range to 45 km (24 nm) Long range to 90 km (48 nm)	

TABLE 1 (*continued*)

Characteristics	Units	Radar No. 1	Radar No. 2	Radar No. 3	Radar No 3A	Radar No. 3B	Radar No. 3C
Tx pulse waveform-type		Unmodulated	Normal, 5º, and MTI modes: 9 stepped-frequency sub-pulses (1.5 MHz between adjacent subpulses); Burn-thru mode: unmodulated Chirp-thru mode: linear FM	Unmodulated	Non Linear FM	Non-Linear FM	FM
Tx RF output device(s)		Klystron	Cross-field amplifier (amplitron)	Klystron	Solid state	Solid state	Solid state
Tx filter			High-pass; $f_{co} \geq$ 2 840 MHz			Not applicable	
Tx maximum peak power	kW	900-1 000 at horizon to 35º	2 200 at horizon to 5º	1 000-1 500 at horizon to 35º	200	170	4-90
Tx peak powers at higher elevations and/or reduced-range modes	kW	Power decreases smoothly from circa 1 000 at 35º to 300 at 41.6º	600 at 5.5º to 21º; 60 above 21º and at horizon in most MTI pulses	Power decreases smoothly from circa 1 000 at 35º to 300 at 41.6º		Power can be reduced to 0.033	
Tx pulse/subpulse width	µs	Early units: 4 and 3 or 2 Later units: 10, 4.6, and 2.5	Normal, 5º, and MTI: 27 (9 contiguous 3 µs sub-pulses); Burn-thru and chirp-thru: 27	Long-range and long-range/ low-elevation: 10 High-angle and limited-elevation: 4.6 High-data-rate and MTI: 2.5	0.1 to 1 000	0.1, 5 and 33	0.1 to 100 Duty cycle < 20%

TABLE 1 (*continued*)

Characteristics	**Units**	**Radar No. 1**	**Radar No. 2**	**Radar No. 3**	**Radar No 3A**	**Radar No. 3B**	**Radar No. 3C**
Pulse-compression ratio		Not applicable	Normal, MTI, and burn-thru: not applicable Chirp-thru: 9	Not applicable	Up to 20 000	100, 660	Up to 400
Tx 3 dB bandwidth	MHz	10 µs PW: approximately 0.1 4.6 µs PW: approximately 0.225 2.5 µs PW: approximately 0.7	Normal and MTI: 0.3/ sub-pulse Chirp-thru: 0.3 Burn-thru: 0.034	10 µs PW: approximately 0.1 4.6 µs PW: approximately 0.225 2.5 µs PW: approximately 0.7	25	15 for short range, 20 for long range	15 or 3
Tx 20 dB bandwidth	MHz		Normal and MTI: 2/ sub-pulse Chirp-thru: 0.7 Burn-thru: 0.24			18 for short range and 22 for long range	
PRI(1)	µs	Varied: 2 050 to 500 (2 050 at horizon) Fixed: 2 116	Normal: variable 2 830-732 (2 830 at horizon) Burn-thru, chirp-thru, and low-elevation: fixed at 2 830, 4 850, or 6 180	Varied: 3 106-426 (3 106 at horizon)	Varied: 3 000-100	12 for short range 64 for medium range and 365 for long range	2000-100

TABLE 1 (*continued*)

Characteristics	**Units**	**Radar No. 1**	**Radar No. 2**	**Radar No. 3**	**Radar No 3A**	**Radar No. 3B**	**Radar No. 3C**
Average PRI of full-power pulses containing horizon-level beams	µs		Normal mode: 5 120 5º mode: 4 977 Long-range 3-pulse MTI: 5º: 4 357 45º: 6 760 Short-range 4-pulse MTI: 5º: 10 534 45º: 19 695 (1 or 2 subpulses/ pulse reach horizon)	Long-range: 7 491 Long-range/low-elevation: 6 190 High-angle: 10 972 Limited-elevation: 7 383 High-data-rate: 14 020 MTI: 9 886 or 10 903 (on alternate azimuth scans)		Not applicable	Not applicable
Polarization		Horizontal					Vertical
Antenna gain	dBi	Early units: 33.5 Later units: 37	38.5	37	40	27.5	Up to 40
Antenna beamwidths	degrees	Azimuth: 1.9 Elevation: 2.25	Azimuth: 1.5 Elevation: 1.6	Azimuth: 1.9 Elevation: 2.25	Azimuth: 1.1 to 5.0	2 in Azimuth 26.5 in Elevation	Azimuth: 1.5 to 6 Elevation: 4 to 20
Frequency shift for 1/2 BW elevation change		2.25 MHz (0.5º per MHz)	4.1 MHz (0.39º per MHz)	2.25 MHz (0.5º per MHz)		Not applicable	Not applicable
1st side-lobe suppression	dB	Early units: Azimuth: 16 Elevation: 20 Later units: Azimuth: 25 Elevation: 25	Azimuth: 25 Elevation: 15	Azimuth: 25 Elevation: 25		At least 28 dB from peak	
Remote side-lobe suppression		Often limited by structure scattering				At least 28 dB from peak	
Antenna azimuth scan type	degrees	Continuous 360				Not applicable	Continuous 360

TABLE 1 (*continued*)

Characteristics	Units	Radar No. 1	Radar No. 2	Radar No. 3	Radar No 3A	Radar No. 3B	Radar No. 3C
Antenna frame (revisit) time	s	Early units: Normal: 4 MTI: 5.2 Coincident video: 12.5 Later units: 8, 6, 4	4 and 8	8, 6, and 4	1 to 12	5 or 2.5	
Antenna elevation scan	degrees	Early units: 0-48 Later units: 0.3-41.6	0-45	0.3-41.6	0-90	Not applicable	Not applicable
Formation of distinct elevation beams		Sequential Rx via single channel	Simultaneous Rx via 9 parallel channels, plus sequential stepping from pulse-to-pulse	Sequential Rx via single channel		Not applicable	Simultaneous Rx beams (digital beamforming)
Rx RF bandwidth(2)	MHz	200 (estimated)	≥ 200 MHz	200 MHz	400	200	≥ 200
Rx IF bandwidth(2)	MHz	0.5	0.35 per channel 12 overall	Long-range: 0.08 High-angle: 0.174 High-data-rate and MTI: 0.348	10-30	15, 0.3, and 0.045	15 or 3
Processing gain relative to noise	dB		Chirp mode: 9			0	
Desired-signal sensitivity or noise level (referred to antenna port)	dBm	Noise level: –109				–125	

TABLE 1 (*end*)

Characteristics	**Units**	**Radar No. 1**	**Radar No. 2**	**Radar No. 3**	**Radar No. 3A**	**Radar No. 3B**	**Radar No. 3C**
Interference-suppression features		Coincident video MTI Later units: sidelobe blanking	STC FTC AGC INT CSG WPB Sidelobe blanking Single-beam blanking Pulse-to-pulse correlation Noise clipping (Dicke fix)	Sidelobe blanking Log video Dicke Fix Jam strobe[(3)]		STC CFAR	CFAR
Years in use		1960 – ... (superseded by radars No. 2 and No. 3)	1965 to present	1966 to present	2000 to present	2007 to present	2012 to present

(1) In most modes of radars Nos. 1, 2, and 3, the interpulse interval, along with the peak power, decreases as the beam scans upward.

(2) Rx RF and IF saturation levels are referred to antenna port.

(3) The jam strobe displays a visible radial line identifying the direction of sources of certain kinds of interference.

TABLE 2

Characteristics of land-based radiolocation radars operating in the frequency band 2 900-3 100 MHz

Characteristics	Units	Radar No. 4	Radar No. 5	Radar No. 6
Overall tuning range	MHz	2 905-3 080	2 901.5-3 098.4	2 900-3 100
Tuning options and frequency/elevation relationship		Deterministic: Low frequency ⇐⇒ low elevation angle 0.1°-0.15º per MHz	a) fixed frequency b) pulse-pulse frequency agile (≤ 16 frequencies): – environment-sensed – random c) MTI (12-pulse bursts): frequency agile (environment-sensed or random)	a) fixed frequency b) pulse-pulse frequency agile (16 frequencies from among 4 sets of 16 each): – environment-sensed – random c) MTI (4-pulse bursts): frequency agile (environment-sensed or random)
Frequency at horizon	MHz	2 924-2 935	Independent of elevation angle	
Coverage/performance modes		Normal (0º–18º) Coded-pulse (pulse compression at 0º-2.24º, normal above 2.24º) MTI (≤ 18º) Burn-thru (one selected 0.8º elevation beam)	Pulse-compression (0º-20º) MTI with pulse-compression (0º-20º)	240 nm (≈436 km) instrumented range Pulse-compression (0º-20º) MTI with pulse-compression (0º-20º)
Tx pulse waveform type		Normal and MTI: stepped-frequency subpulses (frequency/elevation-scanned within pulse) Low-elevation/high-power pulses have 6 subpulses; high-elevation pulses and low-power MTI pulses have 9 subpulses. Both have approximately 2.8 MHz step between adjacent subpulses Coded-pulse: three contiguous 9.9 μs subpulses, each comprised of 13 coded chips Burn-thru: unmodulated	Bi-phase coded (Barker 13)	
Tx RF output device(s)		Cross-field amplifier	Twystron	

TABLE 2 (*continued*)

Characteristics	Units	Radar No. 4	Radar No. 5	Radar No. 6
Tx filter		High-pass		None 2nd harmonic suppressed 60 dB 3rd harmonic suppressed 50 dB
Tx maximum peak power	MW	2.2 from 0º to 7.2º elevation except 0.06 in MTI beams from 0º to 3º	2.8	3.0
Tx peak powers at higher elevations and/or reduced-range modes	kW	665 from 7.2º to 12.6º elevation 60 at 12.6º elevation	Tx power is distributed among multiple beams so as to form approximately cosec2 pattern	Tx power is distributed among multiple beams over 0º to 20º elevation
Tx pulse/subpulse width	µs	Normal: 6 contiguous 5 subpulses at low elevation and high power; 9 contiguous 3 subpulses at high elevation MTI: 9 contiguous 3.3 subpulses Coded-pulse: 3 contiguous 9.9 pulses, each with 13 subpulses (0.76 chips)	6.5	6.5 coded pulse
Pulse-compression ratio		Coded-pulse: 13	13	
Tx 3 dB bandwidth	MHz	Normal and MTI: 0.35 per subpulse Coded-pulse: 1.3 for beams with pulse compression	Approximately	1.4
Tx 20 dB bandwidth			9.5 MHz	2.7 MHz (5.9 MHz at 40 dB, 40 MHz at 60 dB)
PRI[(1)]	µs	Varied: 3 772 at horizon to 1 090 at 18º, except 1 090 for MTI	Fixed: 4 082, 4 000, or 3 876 Deterministically staggered: 3 597→3 788→4 255→4 405→ 3 876 →4 082→repeat	Fixed PRFs include 245, 250, and 258 pps (4.082, 4.0 or 3.876 ms) Pulse-to-pulse jittered interval sequence is typically 4.08→ 3.59→3.79→4.25→4.40→ 3.87 ms→repeat Two other interpulse-interval jitter patterns may be used

TABLE 2 (*continued*)

Characteristics	**Units**	**Radar No. 4**	**Radar No. 5**	**Radar No. 6**
Average PRI of full-power pulses containing horizon-level beams		Normal: approximately 9 670 μs (1 or 2 subpulses/pulse reach the horizon)	All pulses cover 0º-20º	272.5 pps
Polarization		Horizontal	Vertical	Horizontal
Antenna gain	dBi	41	Tx: 34.5 Rx: 38 (Tx power is divided among 13 beams; returns are combined into only 6 Rx channels.)	Tx: 35 (Tx energy is spread over 0.5º-20º) Rx: 36.7, 35.7, 35.3, 35.5, 32.1, and 31.9, from low beam to high beam
Antenna beamwidths	degrees	Azimuth: 2.15 Elevation: 0.84	Azimuth: 1.1 Elevation: 20 cosec2	Azimuth: 1.6 Elevation: 20 on transmit; 2.3 to 6.0 on receive
Frequency shift for 1/2 BW elevation change				Frequency independent
1st side-lobe suppression	dB	Azimuth: 25 Elevation: 25	18.5 (azimuth presumed)	Tx: 20 in vertical plane Rx: at least 35 in azimuth; at least 49 in elevation
Remote side-lobe suppression				Ultra-low sidelobes
Antenna azimuth scan type	degrees	Continuous 360		
Antenna frame (revisit) time	s	10		9.4 (6.4 rpm)
Antenna elevation scan	degrees	–1 to 18	Not scanned. Tx beam spans 0º-20º elevation	
Formation of distinct elevation beams		Sequential Rx via single channel	20º Tx beam is subdivided into 6 Rx beams and processed simultaneously in 6 parallel channels	6 stacked Rx beams are processed simultaneously in 6 parallel channels
Rx RF bandwidth	MHz	200	> 200 (uses image-reject mixer in each channel)	
Rx RF and IF saturation levels, referred to antenna port			–35 dBm	Dynamic ranges: 90 dB, using up to 46.5 dB of STC

TABLE 2 (*end*)

Characteristics	Units	Radar No. 4	Radar No. 5	Radar No. 6
Rx IF bandwidth	MHz	Normal and MTI: 0.35 Coded-pulse: 1.3	1.6	1.1 at 3 dB 3.4 at 20 dB 12.1 at 60 dB
Processing gain relative to noise	dB	Normal/non-MTI: 3 (2-pulse video integration) Coded-pulse: 11	10 (pulse compression) + 9 (pulse integration) = 19	11 (pulse compression) 4-pulse MTI used
Desired-signal sensitivity or noise level (referred to antenna port)	dBm	Normal mode: noise level: –116 Coded-pulse: noise level: –110	–105	
Interference-suppression features		2-pulse video integration Log FTC Coded-pulse (pulse-compression) mode Pulse-pulse correlation Stationary-target censor	Frequency agility Pulse compression Sidelobe blanking Staggered PRIs with post detect integration Hard-limiting CFAR (without MTI) or STC (with MTI) Raw signal monitor channel	Extremely low receive antenna sidelobes Others similar to radar No. 5
Years in use		1975 to present	1975 to present	Late 1980s to present

(1) In most modes of radar No. 4, the interpulse interval, along with the peak power, decreases as the beam scans upward.

All references in Tables 1 and 2 to angles in degrees pertain to elevation angles unless otherwise specified.

2.1 Specific characteristics

Radars No. 1, No. 2, No. 3 and No. 4 are mechanically scanned in azimuth but frequency-scanned in elevation. Of these, radars No. 2 and No. 4 normally step-scan in elevation within each pulse, since each pulse is often divided into as many as 9 contiguous subpulses with carrier-frequency steps from each subpulse to the next. Radars No. 2 and No. 4 also contain 9 parallel receiver/processor channels (apart from a sidelobe-blanker channel). Each receiver channel processes return from a different elevation beam, corresponding to a different subpulse, within the same pulse-repetition interval. In that way, these radars can observe about 5º (radar No. 2) or about 3º (radar No. 4) of elevation within a single pulse-repetition interval, or radar-return round-trip time, with a resolution of about 1.6º (radar No. 2) or 0.84º (radar No. 4). These radars observe different 5º (radar No. 2) or 3º (radar No. 4) elevation sectors during different inter-pulse intervals.

Radars No. 1 and No. 3 transmit on only one beam in each pulse and contain only one receiver channel (apart from a sidelobe-blanker channel). They observe a different elevation sector during each pulse-repetition interval.

The required instrumented range, which determines the pulse-repetition interval, is usually large at low elevation angles but is reduced at higher elevations because long ranges there correspond to altitudes above the atmosphere. At the higher elevation angles, peak transmitted power can be reduced because the shorter ranges require less average power to detect targets and because the transmit duty ratio is increased due to the shorter pulse-repetition intervals. In radar No. 2, the transmitter peak-power reduction is accomplished by de-energizing the final and intermediate power amplifier devices, thereby reducing high-voltage stresses and achieving cleaner emission spectra. In radars No. 1 and No. 3, transmit power remains high at elevation angles up to about 35º and decreases at higher angles as a natural consequence of the gain-vs.-frequency characteristic of the final power amplifier device.

The pulse/frequency-sequences of radars No. 2 and No. 4 are quite diverse and complex. For example, in the normal mode of radar No. 2, each complete elevation scan contains 18 transmit pulses, each comprised of 9 frequency-stepped subpulses. The base frequency of each of the 18 pulses differs from that of the others to contribute to the elevation-scanning effect, except for three pulses whose frequencies are identical to those of another three. In the 5º MTI modes, groups of 3 or 4 identical pulses separated by constant inter-pulse intervals are radiated at elevation angles up to 5º and are intermingled with 15 non-periodic (non-MTI) pulses radiated at all elevation angles up to 45º within each complete elevation scan. In most modes, the beams associated with the subpulses of each pulse overlap the adjacent beams in elevation. The beams associated with all the subpulses in the 18 or more pulses that comprise an elevation scan overlap in azimuth as well because the antenna assembly rotates by less than the antenna's azimuth beamwidth (1.5º) during transmission and reception of all of them. Thus, target return from any one subpulse is overlapped in both azimuth and elevation by returns from several other subpulses. Beam-to-beam and pulse-to-pulse correlation among those overlapping returns helps to lower the false-alarm rate with respect to noise and to distinguish valid-target returns from asynchronously pulsed interference.

The Tables contain calculated values for the average intervals between complete pulses emitted by radars No. 2, No. 3 and No. 4 that are radiated at the horizon (radar No. 3) or contain at least one horizon-level subpulse (radars No. 2 and No. 4) of 3 µs or 3.3 µs duration. The calculations account for the fact that, in some modes, short-range MTI operation is intermingled with long-range non-MTI operation. At any one base frequency, only one of the subpulses is likely to be within the passband of other systems, since the frequency is stepped between subpulses. In any event, two contiguous subpulses are likely to have roughly the same effect on another receiver as one subpulse.

Radars No. 5 and No. 6 do not frequency-scan. However, they do form multiple simultaneous receive beams and have 6 parallel (simultaneous) receive channels, each covering a distinct elevation region. Since they do not frequency-scan, they are able to observe any region in space on any of a large number of frequencies distributed throughout their 200 MHz operating range. In fact, they can do so in a frequency-agile manner. In non-MTI modes, they can jump to any of those frequencies before each pulse. In MTI modes, they can jump to a new frequency after each 12 pulses (in the case of radar No. 5) or after every 4 pulses (in the case of radar No. 6). To aid in exploiting that capability, they incorporate a look-through feature by which they sample a measure of the signal occupancy in the environment at each frequency that they visit and record that activity in a memory. An algorithm accessing that memory permits them to choose little-used frequencies for future transmissions.

The specific form of pulse-compression waveform used by radar No. 4 could not be determined with certainty. However, from the fact that the compression ratio is stated to be 13 and that the waveform is coded, it is reasonable to assume that the waveform uses a bi-phase Barker code. There is only one such code of length 13.

The stationary-target censoring or removal feature of radar No. 4, also known as a clutter map, is a post-processing algorithm that maintains a count of detections that have occurred within each of many azimuth/range/elevations cells within the recent past. The count is incremented with each detection; it is decremented, according to judiciously-chosen rules, when the same cell is revisited but no detections occur. When detections occur while the count exceeds certain threshold numbers, they are not displayed to the operator or used for other purposes, since they are likely to be caused by stationary clutter.

Because of the multitude of operating modes, it is difficult to specify detection sensitivity level quantitatively and unambiguously for these radars. Detection sensitivity might be estimated by calculations that assume a noise figure on the order of 4 to 5 dB for contemporary radars, although early radars such as those of type 1 probably had higher noise figures. For radar No. 6, detection sensitivity is stated explicitly.

Radar transmitters using cross-field devices, such as those of radars No. 2 and No. 4, emit wideband noise at relatively high levels, much as is done by radars using cross-field power oscillators (magnetrons). Quantification of those levels is beyond the scope of this Recommendation.

2.2 Characteristics of particular interest

Interactions involving emissions from radiolocation radars and reception by radionavigation radars are of greater interest than interactions of the reverse type. This is because radiolocation radars operating in this frequency band typically have a wide array of capabilities for avoiding interference of the type that might arise from maritime navigation radars. It has been determined that the carrier frequencies of maritime navigation radars operating in this frequency band have for the past several decades been concentrated almost completely in the region between 3 020 and 3 080 MHz. It is therefore of interest that radiolocation radars No. 1, No. 2 and No. 3, which have also operated in the marine environment, have emitted their horizon-level beams almost entirely within that spectral region. All three of those radiolocation radars have used antennas that are frequency-steered in elevation. Since they are shipborne, they need to compensate for ship’s attitude (roll and pitch) changes by means of adaptive changes in frequency. As a consequence, the exact frequency at which their horizon beam is energized varies somewhat as the ship rolls and pitches and as the radar antenna rotates mechanically to provide azimuth scanning. Nevertheless, the centroid of the frequency distribution corresponding to the horizon beam is very close to 3 050 MHz, which also happens to be the centroid of the distribution of navigation-radar frequencies. Thus, the horizon beams of the shipborne radars described in Table 1 have been concentrated at and near the frequencies of the navigation radars.

Very significantly, all three of those shipborne radiolocation radars have used horizontal polarization, which has been the predominant polarization used by navigation radars for the past several decades.

It is also noteworthy that the radiolocation radars No. 1, No. 2, No. 3 and No. 4 have normally radiated some of their pulses at their maximum transmitter peak power when their beam is on the horizon, as quantified in Tables 1 and 2.

Thus, conditions that have prevailed for the past several decades have tended to maximize the opportunities for coupling of interference from shipborne radiolocation radars of the types identified here into typical marine navigation radars. If there have been any observations of interference to radionavigation radars attributed to these radiolocation radars during the past several decades, their import should be assessed in this context.

Radar No. 6 is distinguished from radar No. 5 principally by its use of an ultra-low-sidelobe planar array antenna instead of the reflector antenna used by radar No. 5. The achievement of very low sidelobes in this case might be due in part to the fact that, although the antenna has multiple beams on receive, those beams are not electronically steered. The excitation of the array is therefore not influenced by the quantization of phase shifters or by the deterioration that occurs when beams are steered far away from the array's geometric boresight or normal.

3 Operational characteristics of radiolocation systems other than meteorological systems

The radiolocation radars in this frequency band are much less numerous than the maritime navigation radars in the frequency band. Almost every ship exceeding 3 000 gross tons carries a navigation radar operating in this frequency band.

It is believed that the shipborne radiolocation radars described herein are operated a high percentage of the time when their ships are underway. The most commonly used modes are understood to be those providing a large-volume (high-angle) search capability. Thus, use of the normal mode of radars No. 2 and No. 4 is self-evident, while the primary mode of radar No. 3 is their high-angle mode. Modes that cover limited spans of elevation, such as burn-through and chirp-through, are typically reserved for special circumstances, and even then those modes might be used only in narrow azimuth sectors while full elevation coverage is maintained in the remaining azimuth sectors. MTI modes are expected to be used only when required by conditions such as high sea state or nearby land masses.

The land-based radiolocation radars are likely to operate only a small percentage of time except in a few fixed areas. An exception occurs if they are used in navigation roles. Radars No. 5 normally operate on fixed frequencies except under special circumstances.

4 Future radiolocation systems other than meteorological systems

In broad outline, radiolocation radars that might be developed in the future to operate in the frequency band 2 900-3 100 MHz are likely to resemble the existing radars described here.

Future radiolocation radars are likely to have at least as much flexibility as the radars already described, including the ability to operate differently in different azimuth and elevation sectors.

It is reasonable to expect some future designs to strive for a capability to operate in a wide band extending well above 3 100 MHz.

They are likely to have electronically-steerable arrays as do the existing radars Nos. 1-4. However, current technology makes phase steering a practical and attractive alternative to frequency steering, and numerous radiolocation radars developed in recent years for use in other frequency bands have employed phase steering in both azimuth and elevation. Unlike frequency steering, phase-steered radars would be free to steer their beams independently of frequency. Among other advantages, that would facilitate maintenance of compatibility in varying circumstances.

Some future radiolocation 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 design of future radars to operate in this frequency band would strive to reduce wideband noise emissions below those of the existing radars that employ cross-field vacuum-tube devices. Such noise reduction will be achieved in some future radars by the use of solid-state transmitter/antenna systems. In that case, the transmit duty ratios would be higher than those of current tube-type radar transmitters and the pulses would be longer.

5 Technical and operational characteristics of shipborne radionavigation systems in the frequency band 2 900-3 100 MHz[1]

Characteristics of representative shipborne radionavigation radars are presented in Tables 3 and 4.

Characteristics of maritime radionavigation beacons, some of which operate in the frequency band 2 900-3 100 MHz, are contained in Recommendation ITU-R M.824.

Transmitter power and numbers of radars for International Maritime Organization (IMO) type shipborne radars, are presented in Table 3.

TABLE 3

Shipborne radionavigation radars

Radar category	Peak power (kW)	Global total
IMO and fishing	≤ 75	> 300 000

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 IMO type radars use slotted array antennas.

The technical characteristics for the IMO category radar are summarized in Table 4. The range for each characteristic is expressed in the form of a maximum and minimum value.

[1] The characteristics of maritime fixed civil radars used for, e.g. vessel traffic services are not included as they are dependent upon location and function, i.e. surveillance of coastal and harbour shipping.

TABLE 4

Maritime radionavigation radars (IMO category – including fishing)
Transmitter/receiver – typical characteristics

Characteristics	Units	2 900-3 100 MHz	
		Maximum	**Minimum**
Antenna (for transmission/reception):			
		Slotted waveguide array	
Antenna height		Typically 10-50 m depending on ship's installation	
Antenna pattern type		Fan beam	
Antenna polarization		Horizontal	
Beamwidth (to –3 dB)			
Horizontal	degrees	4.0	1.0
Vertical	degrees	30.0	24.0
Sidelobe attenuation	dB		
Within ±10º	degrees	28	23
Outside ±10º	degrees	32	31
Gain	dB	28	26
Rotation rate	rpm	60	20
Transmitter:			
Output device		Magnetron	
Modulation		Pulsed	
Maximum duty cycle		7.5×10^{-4}	
Pulse rise/fall time	µs	0.015/0.067	
Peak power	kW	75	30
Frequency	MHz	3 080	3 020
Pulse duration(1)	µs	1.2	0.05
Pulse repetition frequency(1)	Hz	4 000	375
RF emission bandwidth – 3 dB – 20 dB	MHz	For shortest pulse 8 43	
Receiver:			
Intermediate frequency (IF)	MHz	60	45
IF bandwidth	MHz		
Short pulse		28	6
Medium/long pulse		6	2.5
Minimum discernible signal	dBm	–126	
Noise figure	dB	8.5	3

(1) When using this Table to calculate mean power it should be noted that the maximum pulse repetition frequency is associated with the minimum pulse duration and vice versa

Brief description of functions for maritime radar No. 3B

Radar No. 3B is a solid state output device radar that conforms to the design requirements of IMO minimum performance requirements and IEC 62388 (Shipborne Radar)Some of the important features of this radar are:

– controlled RF Spectrum that is ITU compliant and has frequency diversity of 8 different transmit RF frequencies each with 20 MHz non-linear chirp modulated pulses;

– non-Linear frequency modulation and Pulse compression are used to recover range resolution;

– the radar waveform are digitally generated;

– solid state transmitter that use transistors instead of a magnetron;

– coherent transmitter and receiver;

– target presence is determined using digital signal processing employing Doppler processing and variable threshold CFAR;

– antenna width is 3.9 m long with a horizontal beamwidth of less than 2 degrees;

– employs pulse repetition frequency discrimination;

– utilizes Doppler processing techniques;

– peak power is 200 watts with 170 watts minimum power at a 13% duty cycle;

– the radar uses 3 pulse transmission frames with short pulses that enable 30 m minimum range, medium and long pulses provide detection performance. The radar utilizes multiple frames on Target per antenna beamwidth;

– the radar signal processing provides protection from multiple time around echoes, that are generated by weather inversion phenomenon, making sure that the correct target distance is recorded;

– provides improved detection and rain and sea clutter rejection performance;

– the radar range cell size is maintained over the entire instrumented range;

– the radar is capable of a low power mode.

Annex 2

Protection criteria for radars

The desensitizing effect on radiodetermination radars from wideband continuous-wave interference of a noise-like type is predictably related to its intensity. In any azimuth sector in which such interference arrives, its power spectral-density (PSD) can, to within a reasonable approximation, simply be added to the psd of the radar receiver thermal noise. If PSD of radar-receiver noise in the absence of interference is denoted by N_0 and that of noise-like interference by I_0, the resultant effective noise PSD becomes simply $I_0 + N_0$. An increase of that effective noise level by about 1 dB would constitute significant degradation, equivalent to a detection-range reduction of about 6%. Such an increase corresponds to an $(I + N)/N$ of 1.26, or an I/N of about –6 dB. This represents the tolerable aggregate effect of multiple interferers; the tolerable I/N ratio for an individual interferer depends on the number of interferers and their geometry, and needs to be assessed in the analysis of a given scenario.

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 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-ratio 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.

It should be noted that studies are being undertaken on the feasibility of the use of statistical and operational aspects on the protection criteria for radiodetermination radar systems. This statistical approach may be relevant in the case of non-continuous signals.

1 Shipborne radionavigation radars protection criteria

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 should be based on a threshold of 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.

These protection criteria and the thresholds used to derive them, for shipborne radionavigation systems need to be developed further.

The operational requirement for shipborne 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.

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 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 IMO International Convention for the Safety of Life at Sea, states 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 *I/N* as a function of probability of detection (see Annex 3).

Annex 3

Results of interference susceptibility tests

Radar trials have been carried out in the United States and the United Kingdom to determine the vulnerability of current shipborne radionavigation radars to various forms of interference. Three marine radionavigation radars that operate in the frequency band 2 900-3 100 MHz with characteristics similar to those in Table 4 were tested for susceptibility to interference from a variety of signal types including: quadrature phase shift keying (QPSK), code division multiple access (CDMA), wideband CDMA, orthogonal frequency division multiplexing and pulsed signals.

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 international 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 trial 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 based on a 90% probability of detection (within a single scan).

Such differences are real and exist in current operational radars.

1 Test radar characteristics

Each of the test radars is an IMO category type of radar. The characteristics for each of the radars (identified as Radars A, B and C) are presented below in Tables 5 to 7. Nominal values for the principal parameters of the radars were obtained from regulatory type-approval documents, sales brochures, and technical manuals. No pleasure craft radars were tested. Radars A and C use a logarithmic amplifier/detector in their receiver designs, while Radar B uses 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.

2 Radar receiver interference suppression features

All of the radars employed circuitry and signal processing to mitigate interference from other co-located radars. Radar A has extensive signal processing and target tracking capabilities, including an adaptive local CFAR feature and a scan-to-scan correlation feature. Both Radars B and C use pulse-to-pulse and scan-to-scan correlators to mitigate interference from other radars. Radars B and C do not have CFAR processing. A description of these mitigation techniques is described in Recommendation ITU-R M.1372.

3 Emission spectra of interfering signals

The emission spectra of the interfering signals are shown below in Figs. 1 to 3. With the exception of the QPSK signal that was injected into Radar A and the QAM signal that was injected into the other radars, the other interfering signals were gated to coincide at the same azimuth with the target generation. In all cases, the emissions were on-tune with the operating frequency of the radars.

TABLE 5

Radar A transmitter and receiver parameters

Parameter	Units	Value			
Antenna horizontal beamwidth	degrees	1.9			
Frequency	MHz	3 050 ± 30			
Pulse power	kW	30			
Range	nm	0.375-1.5	3-6	12	24-96
Pulse width	μs	0.08	0.30	0.60	1.2
PRF	Hz	2 200		1 028	600
IF bandwidth	MHz	28	3	3	3
Spurious response rejection	dB	60			
System noise figure	dB	4			
RF bandwidth	MHz	N.A.			
Antenna scan rate	rpm	26			
Antenna scan time	s	2.31			
Antenna vertical beamwidth	degrees	22			
Polarization		Horizontal			

N.A.: Not available

TABLE 6

Radar B transmitter and receiver parameters

Parameter	Units	Value			
Frequency	MHz	3 050 ± 10			
Pulse power	kW	30			
Range	nm	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	N.A.			
System noise figure	dB	5.5			
RF bandwidth	MHz	N.A.			
Antenna scan rate	rpm	24/48			
Antenna horizontal beamwidth	degrees	2.8			
Antenna vertical beamwidth	degrees	28			
Polarization		Horizontal			

N.A.: Not available

TABLE 7

Radar C transmitter and receiver parameters

Parameter	Units	Value		
Frequency	MHz	3 050 ± 10		
Pulse power	kW	30		
Range	nm	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	N.A.		
System noise figure	dB	4		
RF bandwidth	MHz	N.A.		
Antenna scan rate	rpm	25/48		
Antenna horizontal beamwidth	s	2.31		
Antenna vertical beamwidth	degrees	2.0		

N.A.: Not available

FIGURE 1

Emission spectra of QPSK waveform

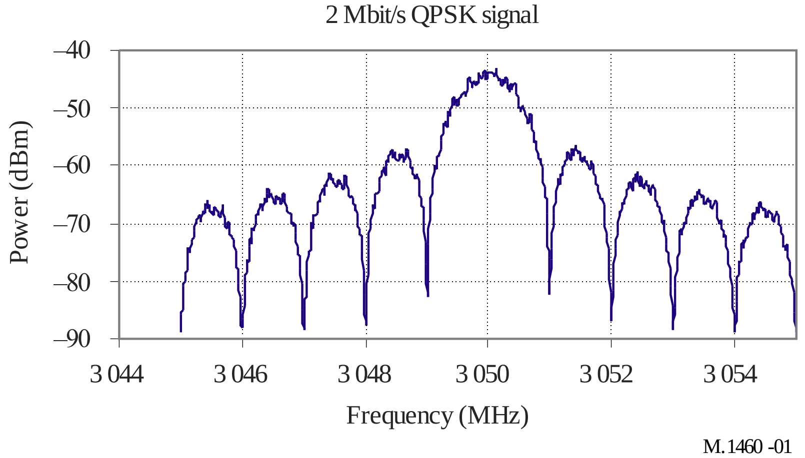


FIGURE 2

Electronic news gathering (ENG)/outside broadcast (OB) source with data carrier modes of 16-and 64-QAM (ETSI 300 744)

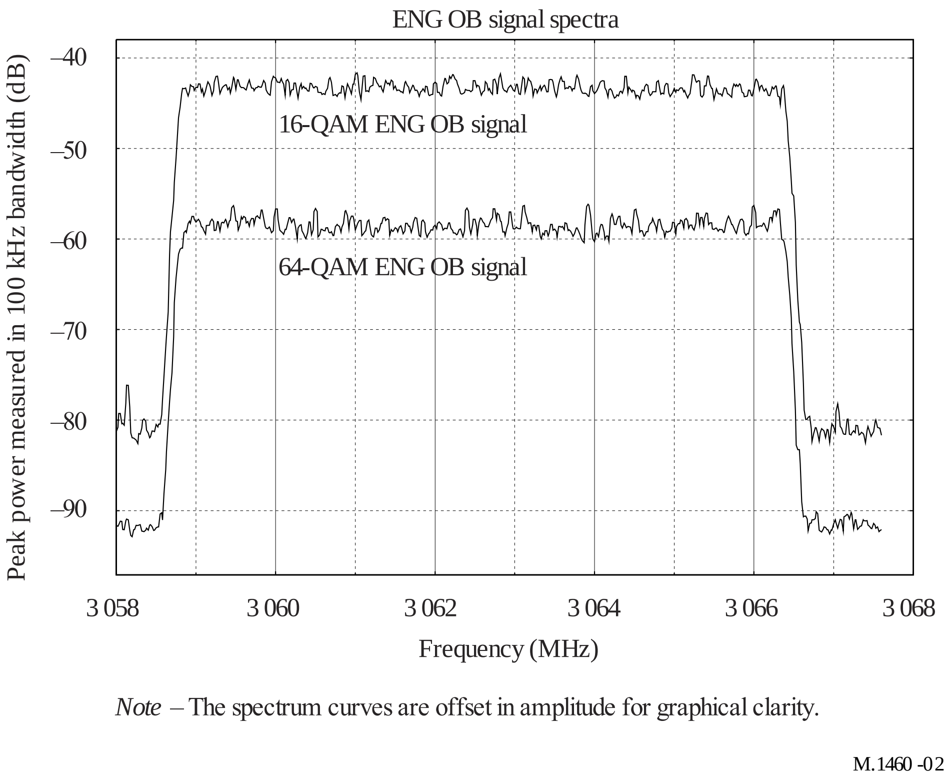
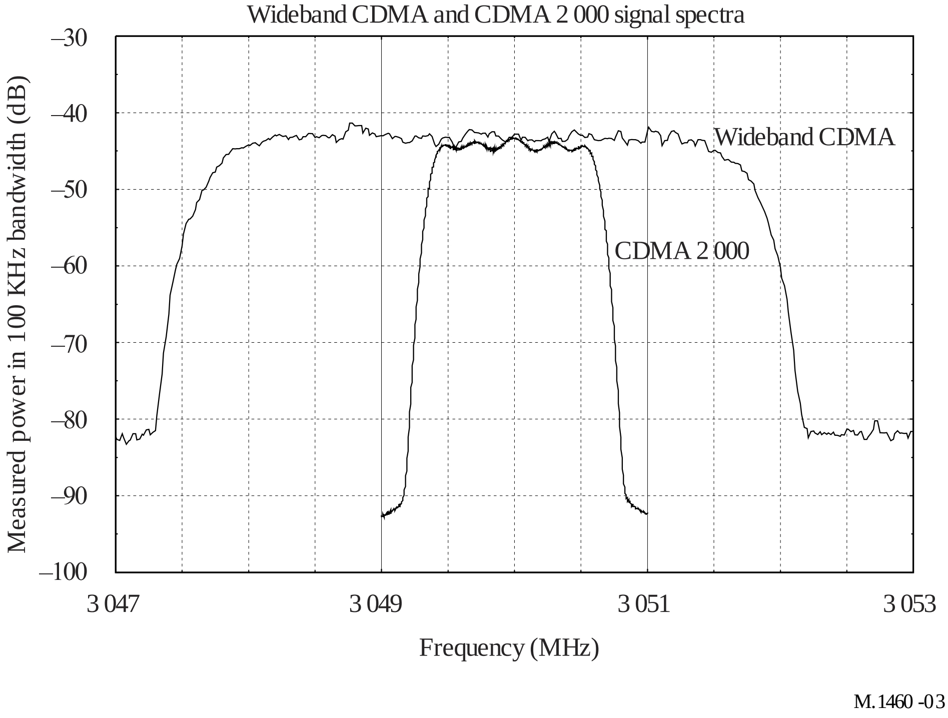


FIGURE 3

Europe wideband CDMA and for the United States/JAPAN CDMA-2000 signals (reverse link)



4 Non-fluctuating target generation

A combination of arbitrary waveform signal generators, 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 three-nmi 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 pixels per inch (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 manufactures and with professional mariners that 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.

The target generation system provides non-fluctuating targets: at each distance the RCS is constant.

5 Test results

5.1 Radar A

Observations of video image targets on the radar's ppi display were made with emissions from the QPSK generator applied to its receiver. The power level of the QPSK emission was adjusted till the appearance of the radar's ppi was in a baseline condition.

The power level of the QPSK waveform was adjusted within a range of values to find the level where the QPSK emissions did not adversely affect the performance of the radar in displaying video targets.

The results show that the effects of the QPSK waveform were negligible on the radar's ppi at a power level of about –112 dBm (measured within a 3 MHz bandwidth). The radar's receiver noise power is about –104 dBm. The resulting *I/N* ratio is about –8 dB.

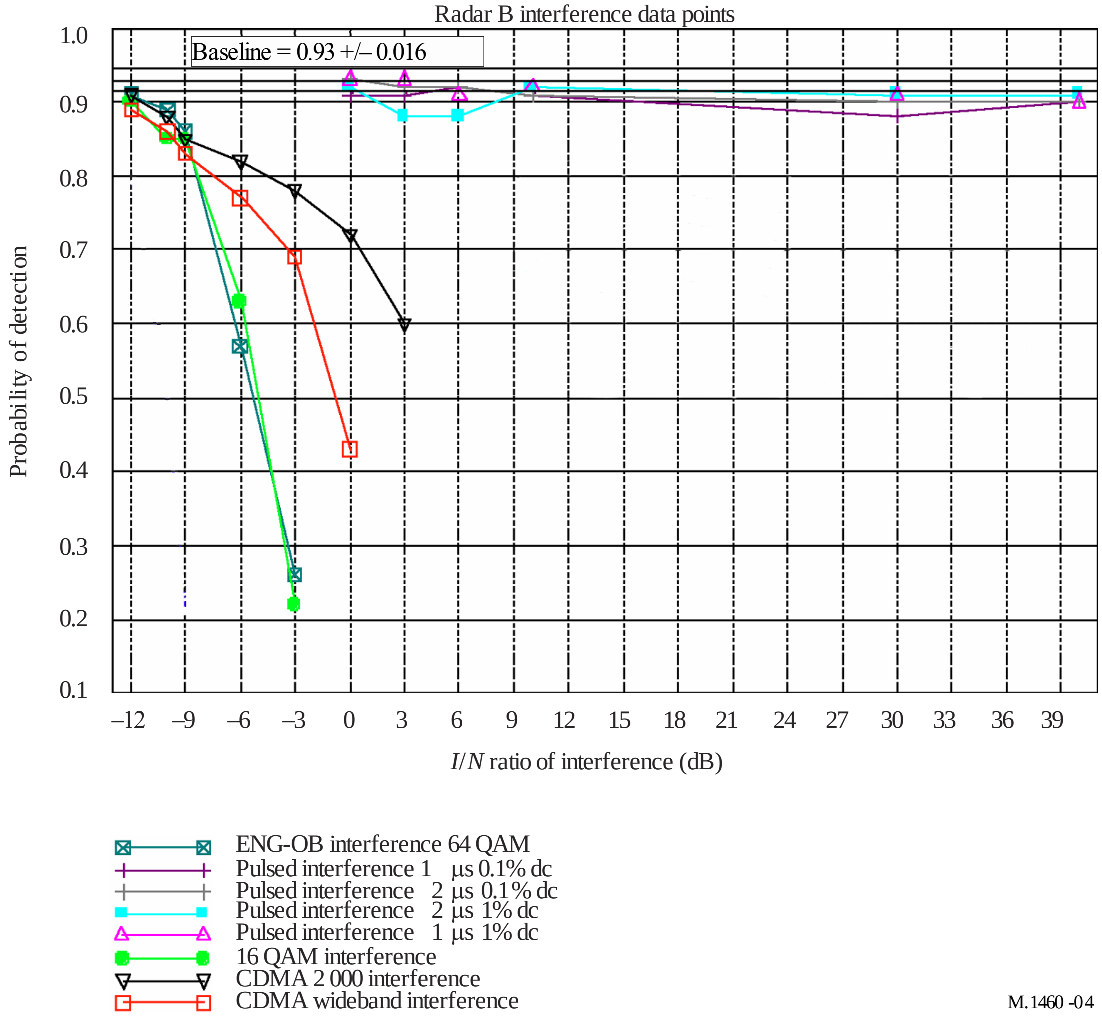
5.2 Radar B

For Radar B 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 (Pd) count was performed before the beginning of each test. The results of the tests on Radar B are shown below in Fig. 4, which shows the target Pd versus the *I/N* level for each type of interference. The baseline Pd in Fig. 4 is 0.93 with the 1-sigma error bars 0.016 above and below that value. Note that each point in Fig. 4 represents a total of 500 desired targets.

Figure 4 shows that, except for the case of the pulsed interference, the target Pd was reduced below the baseline Pd used in these tests minus the standard deviation for *I/N* values above –12 dB for all of the unwanted signals that used a digital modulation.

FIGURE 4

Radar B probability of detection curve



5.3 Radar C

For Radar C it was difficult to count the decrease in target Pd 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 located 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 Pd. Therefore, the data taken for Radar C 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 C is summarized below in Tables 8 and 9.

The data in Table 8 shows that the unwanted QAM signals affected the visibility of the targets for Radar C on its ppi at an *I/N* level of –9 dB. At that level the brightness of the targets on the ppi was slightly dimmed from their baseline state. At *I/N* levels of –6 dB they were dimmed more and for *I/N* levels above –3 dB the targets had dimmed so much that they were no longer visible on the ppi.

The data in Table 9 shows that the unwanted CDMA signals affected the visibility of the targets for Radar C 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 –3 dB and above, the targets had dimmed so much that they were no longer visible on the ppi.

For Radar C, 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.

TABLE 8

Radar C with continuous ENG/OB interference

***I/N* (dB)**	**64-QAM**	**16-QAM**
–12	No effect	No effect
–10	No effect	No effect
–9	Targets slightly dimmed	Targets slightly dimmed
–6	Targets dimmed	Targets dimmed
–3	Targets not visible	Targets not visible
0	Targets not visible	Targets not visible
3	Targets not visible	Targets not visible
6	Targets not visible	Targets not visible

TABLE 9

Radar C with gated CDMA interference

***I/N* (dB)**	**Wideband CDMA**	**CDMA2000**
–12	No effect	No effect
–10	No effect	No effect
–9	No effect	No effect
–6	Targets dimmed	Targets dimmed
–3	Targets not visible	Targets not visible
0	Targets not visible	Targets not visible
3	Targets not visible	Targets not visible
6	Targets not visible	Targets not visible

6 Summary of trials results

Radar trials were performed to determine for specific radars using non-fluctuating targets 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 detection and is summarized below in terms of *I/N* for each radar and interference source. The results are summarized in Table 10. 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 10

Summary results for non-fluctuating targets

Interference source	Radar A	Radar B	Radar C
QPSK	–8	–	–
64-QAM	–	–10	–10
16-QAM	–	–12	–10
Pulsed 0.1	–	+40	+30
Pulsed 1.0	–	+40	+30
CDMA2000	–	–10	–9
Wideband CDMA WB	–	–10	–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 shipborne radars tested do not generally contain CFAR processing. Only Radar A, which is used for additional regulatory duties, contained more sophisticated CFAR processing and had the ability to display processed/synthetic targets.

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). Pleasure craft category radars do not have the interference suppression circuitry/processing features that are contained in Radars A, B and C, or the other interference mitigation techniques found in Recommendation ITU-R M.1372, 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 been 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 frequency band 2 900-3 100 MHz 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 frequency band 2 900-3 100 MHz as well.

Authorities wishing to carry out sharing studies, with a view to possible sharing in the designated frequency bands, should use these results as guidance in their studies knowing that the test results presented in § 5 and 6 and in particular in Table 10 were based on non-fluctuating targets and wideband communications signals that were modelled as being noise-like. If tests were performed with fluctuating targets they are likely to bring different results.