RECOMMENDATION ITU-R M.1460*

TECHNICAL AND OPERATIONAL CHARACTERISTICS AND PROTECTION CRITERIA OF RADIODETERMINATION AND METEOROLOGICAL RADARS IN THE 2 900-3 100 MHz BAND

(Questions ITU-R 226/8 and ITU-R 216/8)

(2000)

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 and meteorological radars are determined by the mission of the system and vary widely even within a band;

c) that the radionavigation service is a safety service as specified by RR No. S4.10 and harmful interference to it cannot be accepted;

d) that considerable radiolocation and radionavigation spectrum allocations (amounting to about 1 GHz) have been removed or downgraded since WARC-79;

e) that some ITU-R technical groups are considering the potential for the introduction of new types of systems (e.g. fixed wireless access and high density fixed and mobile systems) or services in bands between 420 MHz and 34 GHz used by radiodetermination and meteorological radars;

f) that representative technical and operational characteristics of radiodetermination and meteorological radars are required to determine the feasibility of introducing new types of systems into bands used by the radars;

g) that procedures and methodologies are needed to analyse compatibility between radiodetermination and meteorological radars and systems in other services;

h) Question ITU-R 216/8 calling for studies of compatibility between the two radiodetermination services in the bands 2 900-3 300 MHz and 5 350-5 650 MHz;

j) that radar stations operating in the radionavigation, radiolocation, and meteorological aids services are operated in the 2 900-3 100 MHz band,

noting

a) that technical and operational characteristics of maritime radionavigation radars operating in the 2 900-3 100 MHz band are to be found in Recommendation ITU-R M.1313;

b) that technical and operational characteristics of maritime radar beacons operating in the 2 900-3 100 MHz band are to be found in Recommendation ITU-R M.824;

c) that technical and operational characteristics of aeronautical radionavigation radars operating in the 2 900-3 100 MHz band are expected to be similar to those operating in the 2 700-2 900 MHz band, which are to be found in Recommendation ITU-R M.1464,

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[*] This Recommendation should be brought to the attention of the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the International Association of Lighthouse Authorities (IALA), and the World Meteorological Organization (WMO).

recommends

1 that the technical and operational characteristics of the radiodetermination and meteorological radars described in Annex 1 and in the Recommendations in *noting* a), b), and c) be considered representative of those operating in the frequency band 2 900-3 100 MHz;

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

3 that the criterion of interfering signal power to radar receiver noise power level, I/N, of –6 dB be used as the required protection level for the radiodetermination and meteorological radars, and that this represents the net protection level if multiple interferers are present.

NOTE 1 – This Recommendation should be revised as more detailed information becomes available.

ANNEX 1

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

1 Introduction

Many transportable and shipborne radars operate in the 2 900-3 100 MHz band. Radiolocation radars are discussed in § 2 through 4. Radionavigation radars are discussed briefly in § 5, and meteorological radars are discussed in § 6. Interference or protection criteria for radars are discussed in § 7.

2 Technical characteristics of radiolocation radars

Characteristics of three 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 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, 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 band are not required to trigger radar beacons.

Largely because of those mission requirements, the radiolocation radars using this 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 tunable, and some of them are frequency-agile. Some of them use linear-FM (chirp) or phase-coded intra-pulse modulation;
- some of them have multiple or elevation-steerable beams using electronic beam steering;
- 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 Table 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 in the 2 900-3 100 MHz band

Characteristics	Radar No. 1	Radar No. 2	Radar No. 3
Overall tuning range (MHz)	2 910-3 100.5	Nominally 2 900-3 100	2 910-3 100.5
Tuning options and frequency/elevation relationship	Deterministic: High frequency ⇐⇒ low elevation angle		
Frequency at horizon (MHz)	Smooth sea: 3 048-3 051	Smooth sea: 3 055	Smooth sea: 3 051
Coverage/performance modes	Long-range Long-range/limited elevation Short-range Short-range/limited elevation (each with normal, coincident video, or MTI beams/pulses)	Normal (≤ 45° elevation) 5° Burn-thru: 1 fixed 1.6° beam Chirp-thru: 1 beam with chirped waveform Long-range MTI, 3-pulse; 5° or 45° Short-range MTI, 4-pulse; 5° or 45° Passive	Long-range (≤ 12.8° elevation) Long-range/low-elevation (≤ 4.8°) High-angle (≤ 41.6°) Limited-elevation (≤ 12.8°) High-data-rate (≤ 41.6°) MTI (≤ 36.9°)
Tx pulse waveform-type	Unmodulated	Normal, 5°, and MTI modes: 9 stepped-frequency sub-pulses (1.5 MHz between adjacent subpulses); Burn-thru mode: unmodulated Chirp-thru mode: linear FM	Unmodulated
Tx RF output device(s)	Klystron	Cross-field amplifier (amplitron)	Klystron
Tx filter		High-pass; f_{co} ≥ 2 840 MHz	
Tx maximum peak power	0.9-1 MW at horizon to 35°	2.2 MW at horizon to 5°	1.0-1.5 MW at horizon to 35°
Tx peak powers at higher elevations and/or reduced-range modes	Power decreases smoothly from circa 1 MW at 35° to 300 kW at 41.6°	600 kW at 5.5° to 21°; 60 kW above 21° and at horizon in most MTI pulses	Power decreases smoothly from circa 1 MW at 35° to 300 kW at 41.6°
Tx pulse/subpulse width (μs)	Early units: 4 and 3 or 2 Later units: 10, 4.6, and 2.5	Normal, 5°, 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
Pulse-compression ratio	Not applicable	Normal, MTI, and burn-thru: not applicable Chirp-thru: 9	Not applicable

TABLE 1 *(continued)*

Characteristics	Radar No. 1	Radar No. 2	Radar No. 3
Tx 3 dB bandwidth	10 µs PW: approximately 100 kHz 4.6 µs PW: approximately 225 kHz 2.5 µs PW: approximately 700 kHz	Normal and MTI: 300 kHz/ sub-pulse Chirp-thru: 300 kHz Burn-thru: 34 kHz	10 µs PW: approximately 100 kHz 4.6 µs PW: approximately 225 kHz 2.5 µs PW: approximately 700 kHz
Tx 20 dB bandwidth		Normal and MTI: 2 MHz/ sub-pulse Chirp-thru: 700 kHz Burn-thru: 240 kHz	
PRI (µs)(1)	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)
Average PRI of full-power pulses containing horizon-level beams (µs)		Normal mode: 5 120 5° mode: 4 977 Long-range 3-pulse MTI: 5°: 4 357 45°: 6 760 Short-range 4-pulse MTI: 5°: 10 534 45°: 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)
Polarization	Horizontal		
Antenna gain (dBi)	Early units: 33.5 Later units: 37	38.5	37
Antenna beamwidths (degrees)	Azimuth: 1.9 Elevation: 2.25	Azimuth: 1.5 Elevation: 1.6	Azimuth: 1.9 Elevation: 2.25
Frequency shift for 1/2 BW elevation change	2.25 MHz (0.5° per MHz)	4.1 MHz (0.39° per MHz)	2.25 MHz (0.5° per MHz)
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
Remote side-lobe suppression	Often limited by structure scattering		
Antenna azimuth scan type (degrees)	Continuous 360		
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

TABLE 1 *(end)*

Characteristics	Radar No. 1	Radar No. 2	Radar No. 3
Antenna elevation scan (degrees)	Early units: 0-48 Later units: 0.3-41.6	0-45	0.3-41.6
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
Rx RF bandwidth(2)	200 MHz (estimated)	≥ 200 MHz	200 MHz
Rx IF bandwidth(2)	500 kHz	350 kHz per channel 12 MHz overall	Long-range: 80 kHz High-angle: 174 kHz High-data-rate and MTI: 348 kHz
Processing gain relative to noise (dB)		Chirp mode: 9	
Desired-signal sensitivity or noise level (dBm) (referred to antenna port)	Noise level: –109		
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)
Years in use	1960 – ... (superseded by radars No. 2 and No. 3)	1965 – present	1966 – 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 in the 2 900-3 100 MHz band

Characteristics	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°-0.15° 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 (0°-18°) Coded-pulse (pulse compression at 0°-2.24°, normal above 2.24°) MTI (≤ 18°) Burn-thru (one selected 0.8° elevation beam)	Pulse-compression (0°-20°) MTI with pulse-compression (0°-20°)	240 nautical miles instrumented range Pulse-compression (0°-20°) MTI with pulse-compression (0°-20°)
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	
Tx filter	High-pass		None 2nd harmonic suppressed 60 dB 3rd harmonic suppressed 50 dB
Tx maximum peak power	2.2 MW from 0° to 7.2° elevation except 60 kW in MTI beams from 0° to 3°	2.8 MW	3.0 MW

TABLE 2 *(continued)*

Characteristics	Radar No. 4	Radar No. 5	Radar No. 6
Tx peak powers at higher elevations and/or reduced-range modes	665 kW from 7.2° to 12.6° elevation 60 kW at 12.6° elevation	Tx power is distributed among multiple beams so as to form approximately cosec^2 pattern	Tx power is distributed among multiple beams over 0° to 20° elevation
Tx pulse/subpulse width	Normal: 6 contiguous 5 µs subpulses at low elevation and high power; 9 contiguous 3 µs subpulses at high elevation MTI: 9 contiguous 3.3 µs subpulses Coded-pulse: 3 contiguous 9.9 µs pulses, each with 13 subpulses (0.76 µs chips)	6.5 µs	6.5 µs coded pulse
Pulse-compression ratio	Coded-pulse: 13	13	
Tx 3 dB bandwidth	Normal and MTI: 350 kHz per subpulse Coded-pulse: 1.3 MHz for beams with pulse compression	Approximately 2 MHz	1.4 MHz
Tx 20 dB bandwidth		9.5 MHz	2.7 MHz (5.9 MHz at 40 dB, 40 MHz at 60 dB)
PRI(1)	Varied: 3 772 µs at horizon to 1 090 µs at 18°, except 1 090 µs for MTI	Fixed: 4 082, 4 000, or 3 876 µs Deterministically staggered: 3 597→3 788→4 255→4 405→ 3 876 →4 082 µs→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→ 3.87ms→repeat Two other interpulse-interval jitter patterns may be used
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 0°-20°	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 0.5°-20°) 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 cosec^2	Azimuth: 1.6 Elevation: 20 on transmit; 2.3 to 6.0 on receive
Frequency shift for 1/2 BW elevation change			Frequency independent

TABLE 2 *(end)*

Characteristics	Radar No. 4	Radar No. 5	Radar No. 6
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 0°-20° elevation	
Formation of distinct elevation beams	Sequential Rx via single channel	20° 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
Rx IF bandwidth	Normal and MTI: 350 kHz Coded-pulse: 1.3 MHz	1.6 MHz	1.1 MHz at 3 dB 3.4 MHz at 20 dB 12.1 MHz at 60 dB
Processing gain relative to noise	Normal/non-MTI: 3 dB (2-pulse video integration) Coded-pulse: 11 dB	10 dB (pulse compression) + 9 dB (pulse integration) = 19 dB	11 dB (pulse compression) 4-pulse MTI used
Desired-signal sensitivity or noise level (dBm) (referred to antenna port)	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 postdetect 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 – present	1975 – present	Late 1980s – present

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

In the Tables, the following terms and abbreviations are used:

⇐⇒:	correspondence (between carrier frequency and elevation angle)
AGC:	automatic gain control
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
Chirp-thru:	a type of burn-thru mode in which pulse compression is used to reduce return from extended clutter
Coincident video:	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
f_{co}:	cut-off frequency of filter
FTC:	fast time constant
INT:	non-coherent (video) multiple-pulse integration
Jam strobe:	similar to CSG
PRI:	pulse-repetition interval
PRF:	pulse-repetition frequency
PW:	pulse width
STC:	sensitivity time control
WPB:	wide-pulse blanking.

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 5° (radar No. 2) or about 3° (radar No. 4) of elevation within a single pulse-repetition interval, or radar-return round-trip time, with a resolution of about 1.6° (radar No. 2) or 0.84° (radar No. 4). These radars observe different 5° (radar No. 2) or 3° (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 35° 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 5° MTI modes, groups of 3 or 4 identical pulses separated by constant inter-pulse intervals are radiated at elevation angles up to 5° and are intermingled with 15 non-periodic (non-MTI) pulses radiated at all elevation angles up to 45° 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 (1.5°) 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 so because the radiolocation service is currently allocated in this band on a secondary basis while the radionavigation service is allocated on a primary basis, and also because radiolocation radars operating in this 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 band have for the past several decades been concentrated almost completely in the region between 3 020 and 3 080 MHz. (See Recommendation ITU-R M.1313.) 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

The radiolocation radars in this band are much less numerous than the maritime navigation radars in the band. Almost every ship exceeding 10 000 gross tons carries a navigation radar operating in this 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

In broad outline, radiolocation radars that might be developed in the future to operate in the 2 900-3 100 MHz band 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 antennas 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 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 band would strive to reduce wideband noise emissions below those of the existing radars that employ cross-field vacuum-tube devices. That 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 radionavigation systems in the 2 900-3 100 MHz band

Characteristics of maritime radionavigation radars are presented in Recommendation ITU-R M.1313.

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

An informal report indicates that the 2 900-3 100 MHz band is also used by aeronautical radionavigation systems in at least eight countries in and near Europe. This is partially corroborated by the fact that aeronautical radionavigation radars are registered with the ITU at twenty locations in France and one location in the Netherlands. Those entries are evidently primary radars, since they all have peak powers in the range of 0.6 MW to 2.0 MW and most of them have identical coordinates for transmit and receive locations, although the entries contain numerous anomalies such as indications that the antennas have 0 dBi of gain and/or do not rotate.

It has not yet been possible to determine, however, whether the air-traffic-control use of this band is very extensive and whether it is solely for airport surveillance (terminal approach control), air-route surveillance, or a mixture of the two roles. Because most air-route surveillance radars have longer range than airport surveillance radars and usually operate in the 1 215-1 400 MHz band, it is likely that any aeronautical radionavigation use of the 2 900-3 100 MHz band is mainly for airport surveillance or terminal approach control. It appears that the 2 900-3 100 MHz band is used for civil air traffic control only where the 2 700-2 900 MHz band is already saturated with such radars. In particular, almost all manufacturers' marketing information for civil air traffic control radars in the band 2.3-3.4 GHz found to date indicates that their tuning capability is confined to 2 700-2 900 MHz. The radars used for aeronautical radionavigation in the 2 900-3 100 MHz band are tentatively expected to be similar to the radiolocation radars described herein. That is, they are expected to be 3-dimensional radars rather than the 2-dimensional radars used for civil air-traffic control in the 2 700-2 900 MHz band. To the extent that some of them might resemble the 2 700-2 900 MHz radars, their characteristics are described in Recommendation ITU-R M.1464. Specific usage of the 2 900-3 100 MHz band for aeronautical radionavigation is being assessed on an ongoing basis.

6 Technical and operational characteristics of meteorological radars in the 2 900-3 100 MHz band

Technical and operational characteristics of representative weather radars in the 2.3-3.4 GHz band are presented in Recommendation ITU-R M.1464. Those radars are operated predominantly in the 2 700-2 900 MHz band. The 2 700-2 900 MHz stations operate compatibly with other radars in that band, but due to spectrum saturation there, some of those radars are also operated in the 2 900-3 100 MHz band in some countries.

This radar uses Doppler radar technology to observe the presence and calculate the speed and direction of motion of severe weather elements such as tornadoes and violent thunderstorms. It also provides quantitative area precipitation measurements that are important in hydrologic forecasting of potential flooding. The severe weather and motion detection capabilities of this radar contributes toward an increase in the accuracy and timeliness of warning services. The radar excels in detecting the severe weather events that threaten life and property, from early detection of damaging winds to estimating rainfall amounts for use in river and flood forecasting.

These radars form an integrated network spanning the entire United States of America, Guam, Puerto Rico, Japan, South Korea, China, and Portugal. The 2 700-3 100 MHz range offers excellent meteorological and propagation characteristics for weather forecast and warning capabilities. Planned enhancements to the radar should extend its service life to the year 2040.

7 Protection criteria

The desensitizing effect on radiodetermination and meteorological radars of wideband continuous-wave interference of a noiselike type is predictably related to its intensity. In any azimuth sectors in which such interference arrives, its power spectral density can, to within a reasonable approximation, simply be added to the power spectral density of the radar receiver thermal noise. If power spectral density of radar-receiver noise in the absence of interference is denoted by N_0 and that of noiselike interference by I_0, the resultant effective noise power spectral density 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 $(I + N)/N$ ratio of 1.26, or an I/N ratio of about -6 dB. This represents the tolerable aggregate effect of multiple interferers in the main beam; 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. If continuous-wave interference of that intensity were received from most directions, it would cause a surveillance area reduction of about 12% for a surface-search radar or a surveillance volume reduction of about 19% for an air-search radar; a lower I/N ratio would then need to be maintained.

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.