International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Recommendation ITU-R M.1464-2
(02/2015)

Characteristics of non-meteorological radiolocation radars, and characteristics and protection criteria for sharing studies for aeronautical radionavigation and radars in the radiodetermination service operating in the frequency band 2 700-2 900 MHz

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150 1865-2015

International Telecommunication Union

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

Electronic Publication
Geneva, 2015

RECOMMENDATION ITU-R M.1464-2

Characteristics of non-meteorological radiolocation radars, and characteristics and protection criteria for sharing studies for aeronautical radionavigation and radars in the radiodetermination service operating in the frequency band 2 700-2 900 MHz

(2000-2003-2015)

Scope

This Recommendation should be used for performing analyses between systems operating in the radiodetermination service and systems operating in other services. It should not be used for radar to radar analyses.

Keywords

Aeronautical, Radionavigation, Protection Criteria, Characteristics

Abbreviations/Glossary

AESA	Active electronically scanned array
ATC	Air traffic control
CFAR	Constant false alarm rate
CPIs	coherent processing intervals
CW	Carrier wave
MLT	Mean level threshold
PESA	Passive electronically scanned array
PPS	Pulses per second
PRF	Pulse repetition frequency
QPSK	Quadrature phase shift keying
STC	Sensitivity time control
TDMA	Time division multiple access
TWT	Travelling wave tube

The ITU Radiocommunication Assembly,

considering

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

b) that the technical characteristics of aeronautical radionavigation and non-meteorological radars are determined by the mission of the system and vary widely even within a frequency band;

c) that the radionavigation service is a safety service as specified by No. **4.10** of the Radio Regulations (RR) 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 frequency bands between 420 MHz and 34 GHz used by radionavigation and meteorological radars;

f) that representative technical and operational characteristics of radionavigation and meteorological radars are required to determine the feasibility of introducing new types of systems into frequency bands in which the latter are operated;

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

h) that ground-based radars used for meteorological purposes are authorized to operate in this band on a basis of equality with stations in the aeronautical radionavigation service (see RR No. **5.423**);

i) that Recommendation ITU-R M.1849 contains technical and operational aspects of ground based meteorological radars and can be used as a guideline in analysing sharing and compatibility between ground based meteorological radars with systems in other services;

j) that radars in this frequency band are employed for airfield surveillance which is a critical safety service at airfields, providing collision avoidance guidance to aircraft during approach and landing. Aviation regulatory authorities ensure and preserve safety and impose mandatory standards for minimum performance and service degradation,

recognizing

1 that the protection criteria depend on the specific types of interfering signals such as those described in Annexes 2 and 3;

2 that the application of protection criteria requires consideration for inclusion of the statistical nature of the criteria and other elements of the methodology for performing compatibility studies (e.g. antenna scanning and propagation path loss). Further development of these statistical considerations may be incorporated into future revisions of this and other related Recommendations, as appropriate,

recommends

1 that the technical and operational characteristics of the aeronautical radionavigation radars described in Annex 1 be considered representative of those operating in the frequency band 2 700-2 900 MHz;

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

3 that the protection trigger level for aeronautical radionavigation radars be based on Annex 2, in particular § 4, for assessing compatibility with interfering signal types from other services representative of those in Annex 2. These protection criteria represent the aggregate protection level if multiple interferers are present.

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

Annex 1

Characteristics of aeronautical radionavigation and non-meteorological radiolocation radars

1 Introduction

The frequency band 2 700-2 900 MHz is allocated to the aeronautical radionavigation service on a primary basis and the radiolocation service on a secondary basis. Ground-based radars used for meteorological purposes are authorized to operate in this frequency band on a basis of equality with stations in the aeronautical radionavigation service (see RR No. **5.423**). The frequency band 2 900-3 100 MHz is allocated to the radionavigation and radiolocation services on a primary basis. The frequency band 3 100-3 400 MHz is allocated to the radiolocation service on a primary basis.

The aeronautical radionavigation radars are used for air traffic control (ATC) at airports, and perform a safety service (see RR No. **4.10**). Indications are that this is the dominant frequency band for terminal approach/airport surveillance radars for civil air traffic worldwide.

2 Technical characteristics

The frequency band 2 700-2 900 MHz is used by several different types of radars on land-based fixed and transportable platforms. Functions performed by radar systems in the frequency band include ATC and weather observation. Radar operating frequencies can be assumed to be uniformly spread throughout the frequency band 2 700-2 900 MHz. The majority of systems use more than one frequency to achieve the benefits of frequency diversity. Two frequencies are very common and the use of four is not unknown. Table 1 contains technical characteristics of representative aeronautical radionavigation radars deployed in the frequency band 2 700-2 900 MHz. This information is sufficient for general calculation to assess the compatibility between these radars and other systems.

2.1 Transmitters

The radars operating in the frequency band 2 700-2 900 MHz use continuous wave (CW) pulses and frequency modulated (chirped) pulses. Cross-field, linear beam and solid state output devices are used in the final stages of the transmitters. The trend in new radar systems is toward linear beam and solid state output devices due to the requirement of Doppler signal processing. Also, the radars deploying solid state output devices have lower transmitter peak output power and higher pulsed duty cycles approaching 10%. There is also a trend towards radionavigation radar systems that use frequency diversity.

Typical transmitter RF emission bandwidths of radars operating in the frequency band 2 700-2 900 MHz range from 66 kHz to 6 MHz. Transmitter peak output powers range from 22 kW (73.4 dBm) for solid state transmitters, 70 kW (78.5 dBm) for travelling wave tube (TWT) systems, to 1.4 MW (91.5 dBm) for high power radars using klystrons and magnetrons.

In the high peak power systems it is normal to have a single transmitter per frequency and these tend to have narrow-band output stages. The lower peak power systems using TWTs or solid state have single transmitters capable of multifrequency operation. They thus have wideband output stages capable of multifrequency use.

TABLE 1

Characteristics of aeronautical radionavigation radars in the frequency band 2 700-2 900 MHz

Characteristics	Units	Radar A	Radar B	Radar C	Radar D	Radar E	Radar F
Platform type (airborne, shipborne, ground)		Ground, ATC					
Tuning range	MHz	2 700-2 900(1)					
Modulation		P0N		P0N, Q3N	P0N	P0N, Q3N	P0N, Q3N
Transmitter power into antenna(2)	kW	1 400	1 320	25	450	22	70
Pulse width	µs	0.6	1.03	1.0, 89(3)	1.0	1.0, 55.0	0.4, 20 0.5, 27(4)
Pulse rise/fall time	µs	0.15-0.2		0.5/0.32 (short pulse) 0.7/1 (long pulse)			0.1 (typical)
Pulse repetition rate	pps	973-1 040 (selectable	1 059-1 172	722-935 (short impulse) 788-1 050 (long impulse)	1 050	8 sets, 1 031 to 1 080	1 100 840(3)
Duty cycle	%	0.07 maximum	0.14 maximum	9.34 maximum	0.1 maximum		2 (typical)
Chirp bandwidth	MHz	Not applicable		2	Not applicable	1.3 non-linear FM	2
Phase-coded sub-pulse width		Not applicable					
Compression ratio		Not applicable		89	Not applicable	55	40:1 55:1
RF emission bandwidth: –20 dB 3 dB	MHz	6	5 0.6	2.6 (short impulse) 5.6 (long impulse) 1.9			3 (valeur type) 2
Output device		Klystron		Solid state transistors, Class C	Magnetron	Solid state transistors, Class C	TWT
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	degrees	Cosecant-squared +30		Cosecant-squared 6 to +30			Cosecant-squared Enhanced to +40
Antenna type (reflector, phased array, slotted array, etc.)		Parabolic reflector					
Antenna polarization		Vertical or left hand circular polarization	Vertical or right hand circular polarization	Circular or linear	Vertical or left hand circular polarization	Vertical or right hand circular polarization	Left hand circular

TABLE 1 *(continued)*

Characteristics	Units	Radar A	Radar B	Radar C	Radar D	Radar E	Radar F
Antenna main beam gain	dBi	33.5		34	32.8	34.3 low beam 33 high beam	33.5
Antenna elevation beamwidth	degrees	4.8			4	4.8	5.0
Antenna azimuthal beamwidth	degrees	1.35	1.3	1.45	1.6	1.4	1.5
Antenna horizontal scan rate	degrees/s	75			90	75	90 60(4)
Antenna horizontal scan type (continuous, random, 360^0, sector, etc.)		360^0					
Antenna vertical scan rate	degrees/s	Not applicable					
Antenna vertical scan type (continuous, random, 360^0, sector, etc.)	degrees	Not applicable		+2.5 to –2.5	Not applicable	Not applicable	Not applicable
Antenna side lobe (SL) levels (1st SLs and remote SLs)	dBi		+7.3	+9.5 3.5			+7.5 0 to –3 dBi
Antenna height	m	8					8-24
Receiver IF 3 dB bandwidth	MHz	13	0.7	1.1		1.2	4
Receiver noise figure	dB	4.0 maximum		3.3	2.7	2.1	2.0
Minimum discernible signal	dBm	–110	–108	–110	–112		–110 typical
Receiver front-end 1 dB gain compression point	dBm	–4	–6	–14			–10
Receiver on-tune saturation level	dBm		–45				
Receiver RF 3 dB bandwidth	MHz	13	12	345			400(1)
Receiver RF and IF saturation levels and recovery times							
Doppler filtering bandwidth	Hz		95 per bin				
Interference-rejection features(5)		Feedback enhancer	(6)				
Geographical distribution		Worldwide					
Fraction of time in use		100					

TABLE 1 (*continued*)

Characteristics	Units	Radar F1	Radar F2
Platform type (airborne, shipborne, ground)		Ground, ATC	Ground, ATC
Tuning range	MHz	2 700-2 900(7)	2 700-2 900(7)
Modulation		P0N, Q3N	P0N, Q3N
Transmitter power into antenna(2)		40 kW	160 kW
Pulse width	μs	1.0 (SP) 60.0 (LP)	1.0 (SP) ≤ 250.0 (LP)
Pulse rise/fall time	μs	0.2 (SP), 3 (LP)	0.2 (SP), 3 (LP)
Pulse repetition rate	pps	320-6 100 (SP) 320-1 300 (LP) (8)	320-4 300 (SP) 320-1 500 (LP) (8)
Duty cycle	%	0.2(9) -0.6 (SP) ≤ 12.0(10) (LP)	0.2(9) -0.4 (SP) ≤ 12.0(10) (LP)
Chirp bandwidth	MHz	3	3
Phase-coded sub-pulse width		Not applicable	Not applicable
Compression ratio		180	≤ 750
RF emission bandwidth: –20 dB –3 dB	MHz	3.2 (SP) / 5.0 (LP) 0.6 (SP) / 1.2(LP) (11)	3.2 (SP) / 5.0 (LP) 0.6 (SP) / 1.2 (LP) (11)
Output device		Solid state	Solid state
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	degrees	Pencil beam coverage to 70 000 feet	Pencil beam coverage to 100 000 feet
Antenna type (reflector, phased array, slotted array, etc.)		Phased array, 4 faces (4 meter diameter phased array per face)	Phased array, 4 faces (8 meter diameter phased array per face)
Antenna polarization		Linear horizontal and vertical; circular	Linear horizontal and vertical; circular
Antenna main beam gain	dBi	41	46
Antenna elevation beamwidth	degrees	1.6-2.7	0.9-1.5
Antenna azimuthal beamwidth	degrees	1.6-2.7	0.9-1.4
Antenna horizontal scan rate	degrees/s	Not applicable	Not applicable
Antenna horizontal scan type (continuous, random, 360°, sector, etc.)		Irregular to cover 360°	Irregular to cover 360°
Antenna vertical scan rate	degrees/s	Not applicable	Not applicable
Antenna vertical scan type (continuous, random, 360°, sector, etc.)	degrees	Irregular to cover required volume	Irregular to cover required volume
Antenna side lobe (SL) levels (1st SLs and remote SLs)	dB	17 on transmit, 25 on receive	17 on transmit, 25 on receive

TABLE 1 (*end*)

Characteristics	Units	Radar F1	Radar F2
Antenna height	m	Variable	Variable
Receiver IF 3 dB bandwidth	MHz	1.2 at –6 dB (SP) 1.8 at –6 dB (LP)	1.2 at –6 dB (SP) 1.6 at –6 dB (LP)
Receiver noise figure	dB	< 6	< 6
Minimum discernible signal	dBm/MHz	–110	–110
Receiver front-end 1 dB gain compression point	dBm	10	10
Receiver on-tune saturation level	dBm	N/A	N/A
Receiver RF 3 dB bandwidth	MHz	200	300
Receiver RF and IF saturation levels and recovery times		13 dBm, < 500 ns	13 dBm, < 500 ns
Doppler filtering bandwidth	Hz		
Fraction of time in use	%	100	100

(1) Some operate in the frequency range 2 700-3 100 MHz. Many of these systems require more than one carrier frequency in the tuning range to operate properly.

(2) Fixed systems operate up to 750 kW or 1 MW.

(3) This radar utilizes two fundamental carriers with a minimum separation of 30 MHz.

(4) Depends on range.

(5) The following represent features that are present in most radar systems as part of their normal function: sensitivity time control (STC), constant false alarm rate (CFAR), asynchronous pulse rejection and saturating pulse removal.

(6) The following represent features that are available in some radar systems: selectable pulse repetition frequencies (PRFs), Doppler filtering.

(7) Tuning range 2.7-3.0 GHz when replacing a meteorological radar with a multipurpose system that performs both the aeronautical radionavigation and meteorological functions. Characteristics and protection criteria of the meteorological operation are found in Recommendation ITU-R M.1849.

(8) Very high PRFs only used at high elevation angles.

(9) Duty cycle for short pulse is 0.2% at lowest elevation (horizon) scan.

(10) Combination of pulse width and PRF will be matched to keep duty cycle under 12%.

(11) RF emission bandwidth at –6/–40 dB: 1.3/ 10.4 MHz for SP; 2.0/ 6.2 MHz for LP.

TABLE 2

Characteristics of radiolocation radars in the frequency band 2 700-3 400 MHz

Characteristics	Units	Radar I	Radar J	Radar K	Radar L	Radar M
Platform type (airborne, shipborne, ground)		Ground, ATC gap-filler coastal	2D/3D naval surveillance ground air defence	Ground air defence	Multifunction various types	Shipborne, ground
Tuning range	MHz	2 700-3 400	2 700-3 100	2 700 to 3 100 2 900 to 3 400	Whole frequency band up to 25% BW	2 700-3 400
Operational frequencies minimum/ maximum		Minimum: 2 spaced at > 10 MHz Maximum: fully agile	Minimum: 2 spaced at > 10 MHz Maximum: fully agile	Minimum: fixed Maximum: fully agile	Minimum: 2 spaced at > 10 MHz Maximum: fully agile	Minimum: 2 spaced at > 10 MHz Maximum: fully agile
Modulation		Non-linear FM P0N, Q3N	Non-linear FM P0N, Q3N	Non-linear FM Q3N	Mixed	P0N, Q3N

TABLE 2 *(continued)*

Characteristics	Units	Radar I	Radar J	Radar K	Radar L	Radar M
Transmitter power into antenna	kW	60 typical	60 to 200	1 000 typical	30 to 100	60 to 1 000
Pulse width	µs	0.4[(1)] to 40	0.1[(1)] to 200	> 100	Up to 2	0.1 to 1 000
Pulse rise/fall time	µs	10 to 30 typical	10 to 30 typical	Not given	Not given	> 50 0.05-1.00[(6)]
Pulse repetition rate	pps	550 to 1 100 Hz	300 Hz to 10 kHz	< 300 Hz	Up to 20 kHz	300 Hz to 10 kHz
Duty cycle	%	2.5 maximum	10 maximum	Up to 3	30 maximum	20 maximum
Chirp bandwidth	MHz	2.5	Up to 10	> 100	Depends on modulation	Up to 20
Compression ratio		Up to 100	Up to 300	Not applicable	Not given	Up to 20 000
RF emission bandwidth: –20 dB –3 dB	MHz	3.5 2.5	15 10	> 100	Not given	25
Output device		TWT	TWT or solid state	Klystron CFA	Active elements	Solid state
Antenna pattern type (pencil, fan, cosecant-squared, etc.)		Cosecant-squared	Pencil beam 3D or cosecant-squared 2D	Swept pencil beam	Pencil beam	Pencil beam 3D or cosecant-squared 2D
Antenna type (reflector, phased array, slotted array, etc.)		Shaped reflector	Planar array or shaped reflector	Frequency scanned planar array or reflector	Active array	Active array
Antenna azimuth beamwidth	degrees	1.5	1.1 to 2	Typically 1.2	Depends on number of elements	Depends on number of elements Typically 1.1 to 5
Antenna polarization		Linear or circular or switched	Linear or circular or switched	Fixed linear or circular	Fixed linear	Mixed
Antenna main beam gain	dBi	33.5 typical	Up to 40	> 40	Up to 43	Up to 40
Antenna elevation beamwidth	degrees	4.8	1.5 to 30	Typical 1	Depends on number of elements	Depends on number of elements typically 1 to 30
Antenna horizontal scan rate	degrees/s	45 to 90	30 to 180	Typical 36	Sector scan instantaneous rotation scan up to 360	30 to 360
Antenna horizontal scan type (continuous, random, 360°, sector, etc.)	degrees	Continuous 360	Continuous 360 + sector scan	Continuous 360 + sector scan on	Random sector scan sector scan + rotation	Continuous 360+ Sector scan+ Random sector scan
Antenna vertical scan rate	degrees/s	Not applicable	Instantaneous	Instantaneous	Instantaneous	Instantaneous
Antenna vertical scan type (continuous, random, 360°, sector, etc.)	degrees	Not applicable	0 to 45	0 to 30	0 to 90	0 to 90
Antenna side lobe (SL) levels (1st SLs and remote SLs)	dB dBi	26 35	> 32 typical < –10	> 26 typical < 0	Not given	> 32 typical < –10

TABLE 2 *(end)*

Characteristics	Units	Radar I	Radar J	Radar K	Radar L	Radar M
Antenna height above ground	m	4 to 30	4 to 20	5	4 to 20	4 to 50
Receiver IF 3 dB bandwidth	MHz	1.5 long 3.5 short	10	Not given	Not given	10-30
Receiver noise figure(2)	dB	2.0 maximum	1.5 maximum	Not given	Not given	1.5 maximum
Minimum discernible signal	dBm	–123 long pulse –104 short pulse	Not given	Not given	Not given	Not given
Receiver front-end 1 dB gain compression point. Power density at antenna	W/m^2	1.5×10^{-5}	5×10^{-5}	1×10^{-6}	1×10^{-3}	5×10^{-5}
Receiver on-tune saturation level power density at antenna	W/m^2	4.0×10^{-10}	1×10^{-10}	Not given	Not given	1×10^{-10}
RF receiver 3 dB bandwidth	MHz	400	400	150 to 500	Up to whole frequency band	400
Receiver RF and IF saturation levels and recovery times		Not given	Not given	Not given	Not given	Not given
Doppler filtering bandwidth		Not given	Not given	Not given	Not given	Not given
Interference-rejection features(3)		(4)	(4) and (5)	(4) and (5)	Adaptive beamforming (4) and (5)	Not given
Geographical distribution		Worldwide fixed site transportable	Worldwide fixed site naval transportable	Worldwide fixed site transportable	Worldwide fixed site naval transportable	Littoral and offshore areas Worldwide fixed site Transportable
Fraction of time in use	%	100	Depends on mission	Depends on mission	Depends on mission	100

(1) Uncompressed pulse.

(2) Includes feeder losses.

(3) The following represent features that are present in most radar systems as part of their normal function: STC, CFAR, asynchronous pulse rejection, saturating pulse removal.

(4) The following represent features that are available in some radar systems: selectable PRFs, moving target filtering, frequency agility.

(5) Side lobe cancellation, side lobe blanking.

(6) This rise/fall time corresponds to short pulses with pulse width of 0.1 μs to 100 μs.

2.2 Receivers

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

Also, the signal processing in the newer generation of ATC radars use chirped pulses which produce a processing gain for the desired signal and may also provide suppression of undesired signals.

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

In general high peak power systems tend to use one receiver per frequency and thus have narrow-band RF front ends. The lower-power systems tend to have wideband RF front ends capable of receiving all frequencies without tuning followed by coherent superheterodyne receivers. Systems which use pulse compression have their IF bandwidth matched to the expanded pulse and act as matched filters for minimum S/N degradation.

2.3 Antennas

Parabolic reflector-type antennas are used on radars operating in the frequency band 2 700-2 900 MHz. The ATC radars have a cosecant-squared elevation pattern and/or a pencil beam antenna pattern. Since the radars in the frequency band 2 700-2 900 MHz band perform ATC and weather observation functions the antennas scan 360° in the horizontal plane. Horizontal, vertical and circular polarizations are used. Newer generation radars using reflector-type antennas have multiple horns. Dual horns are used for transmit and receive to improve detection in surface clutter. Also, multiple horns, stack beam, reflector antennas are used for three-dimensional radars. The multiple horn antennas will reduce the level of interference. Typical antenna heights for the aeronautical radionavigation and meteorological radars are 8 m and 30 m above ground level, respectively.

Two fundamental architectural forms of phased array antenna systems are being applied in terrestrial and maritime applications. The two technologies are the passive electronically scanned array (PESA) and the active electronically scanned array (AESA). PESA arrays use high power transmitter technologies to generate the transmitted signals and these are passed through or reflected from the PESA array. In this transmission and or reflection process the beams are steered and formed to meet the operational needs on a transmission by transmission basis.

Typical beam dwell times are tens to hundreds of milliseconds. AESA technologies incorporate large numbers of lower peak power transmitters at each radiating element of the array. This technology relies on solid state devices generally at individual power levels of a few watts to hundreds of watts. The overall result is high levels of radiated power with the individual elements coherently contributing to the formation of beams. Most mobile ESA arrays have apertures ranging from less than 1 square meter to 20 square meters. Fixed site arrays tend to be larger. Most ESA antennas use electronic steering in both azimuth and elevation. A sub-class of ESA arrays use mechanical scanning in the azimuth plane and electronic steering in elevation. These systems are widespread in maritime and terrestrial applications.

3 Protection criteria

The desensitizing effect on aeronautical radionavigation and meteorological radars from other services of a CW, BPSK, QPSK or noise-like type modulation is predictably related to its intensity. In any azimuth sectors in which such interference arrives, its power spectral density can simply be added to the power spectral density of the radar receiver thermal noise, to within a reasonable approximation. If power spectral density 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 power spectral density becomes simply $I_0 + N_0$.

The aggregation factor can be very substantial in the case of certain communication systems, in which a great number of stations can be deployed. An aggregation analysis has to consider cumulative contributions from all directions, received via the radar antenna's main and/or side lobes in order to arrive at the overall I/N ratio.

The effect of pulsed interference is more difficult to quantify and is strongly dependent on receivers/processor design and mode of operation. In particular, the differential processing gains for valid-target return, which is synchronously pulsed, and interference pulses, which are usually asynchronous, often have important effects on the impact of given levels of pulsed interference. Several different forms of performance degradation can be inflicted by such desensitization. Assessing it will be an objective for analyses of interactions between specific radar types. In general, numerous features of radiodetermination radars can be expected to help suppress low-duty cycle pulsed interference, especially from a few isolated sources. Techniques for suppression of low-duty cycle pulsed interference are contained in Recommendation ITU-R M.1372 – Efficient use of the radio spectrum by radar stations in the radionavigation service.

Systems which use pulse compression have their IF bandwidth matched to the compressed pulse and act as a matched filter for minimum *S/N* degradation. Pulse compression filters may be partially matched to and hence increase the effect of noise-like interference. In that case, further studies or compatibility measurements may be necessary to assess the interference in terms of the operational impact on the radar's performance.

4 Operational characteristics

4.1 Aeronautical radionavigation radars

Airport surveillance radars operate throughout the world in the frequency band 2 700-2 900 MHz. Eight representative types of ATC radars are depicted in Table 1, as radars A through radar F including F1 and F2. These radars perform airport surveillance for terminal approach control and normally require surveillance of a full 360° sector use on a round-the-clock schedule. Radars A, C, E and F are typically located at airports and every major airport is usually equipped with one or more similar radar systems. Radars A, through F including F1 and F2 are the current generation of radars deployed. Radars C and E are representative of the next generation systems, although many have now been deployed and are representative of some currently used technology and these should augment and/or replace radars A, B and eventually F after the year 2010. Radar D is a transportable system used for ATC at airfields where there are no existing facilities. There are also, however, still significant numbers of this type of non-coherent magnetron radar on fixed sites around the world. These generally operate with peak powers of approximately 1 MW. When in use, radar D is operated 24 h per day. Some of these radars operate in a frequency diversity mode, which requires two and, in some cases, four frequency assignments per radar. Radars F1 and F2 are the airport surveillance and weather radars. These radars are designed to meet aeronautical surveillance requirements to mitigate wind turbine clutter, provide unmanned aircraft system surveillance, and provide enhanced aviation weather products.

Annex 2

Results of tests with aeronautical radionavigation radars

1 Introduction

This Annex describes the results of two administrations' tests on aeronautical radionavigation radars and concludes that a –10 dB *I*/*N* protection criteria will fully protect those types of radars in the frequency band 2 700-2 900 MHz band. The results of one administration's tests are based upon measurements of a pulsed Doppler aeronautical radionavigation radar that has technical characteristics similar to that of radar B in Table 1 of Annex 1. The other administration's tests are based upon measurements of radars that operate with characteristics similar to that of radars D and E in Table 1 of Annex 1.

2 Radar B tests

Tests were performed to determine the effects that emissions from digital communication systems would have on an air search radionavigation radar (identified as radar B in Table 1 of Annex 1) operating with the primary allocation for the aeronautical radionavigation service in the frequency band 2 700-2 900 MHz. The results of those tests have been used to determine the *I*/*N* protection criteria that should be used in studies that assess the compatibility of radionavigation radars and the mobile service or outside broadcast/electronic news gathering systems in the frequency band 2 700-2 900 MHz. This radar employs interference mitigation techniques/processing methods identified in Recommendation ITU-R M.1372, which allows it to operate in the presence of other radionavigation, radiolocation, and meteorological radars. As shown in Report ITU-R M.2032, techniques of that kind are very effective in reducing or eliminating pulsed interference between radars.

These tests investigated the effectiveness of the radar's interference suppression circuitry/software to reduce or eliminate interference due to the emissions from a communications system employing a digital modulation scheme.

2.1 Radar B test objectives

The objectives of the testing for radar B was:

– To quantify the capability of radar B's interference-rejection processing to mitigate unwanted emissions from digital communication systems as a function of their power level.

– To develop *I*/*N* protection criteria for unwanted digital communication systems emissions received by the radionavigation radar.

– To observe and quantify the effectiveness of the radionavigation radar's interference rejection techniques to reduce the number of false targets, radial streaks (strobes), and background noise.

– To observe and quantify the effectiveness of the radionavigation radar's interference rejection techniques to mitigate the loss of desired targets.

2.2 Radar B technical and operational characteristics

Radar B is used by administrations for monitoring air traffic in and around airports within a range of 60 NM (approximately 111 km). Nominal values for the principal parameters of this radar were obtained from regulatory approval documents, sales brochures, and technical manuals. These are presented in Table 1 of Annex 1.

The radar divides its 60 NM operational range into 1/16 NM intervals (approximately 116 m) and the azimuth into 256 approximately 1.4° intervals, for a total of 249 088 range-azimuth cells. In each 1.4° azimuth interval the transmitter sends ten pulses at one constant PRF and then sends eight pulses at another lower PRF. The receiver processes each set of 18 pulses to form 18 Doppler filters. Alternating PRFs within every 1.4° helps eliminate blind speeds, unmasks moving targets hidden by weather, and eliminates second-time clutter returns and divides the radar output into approximately 4 483 584 range-azimuth-Doppler cells.

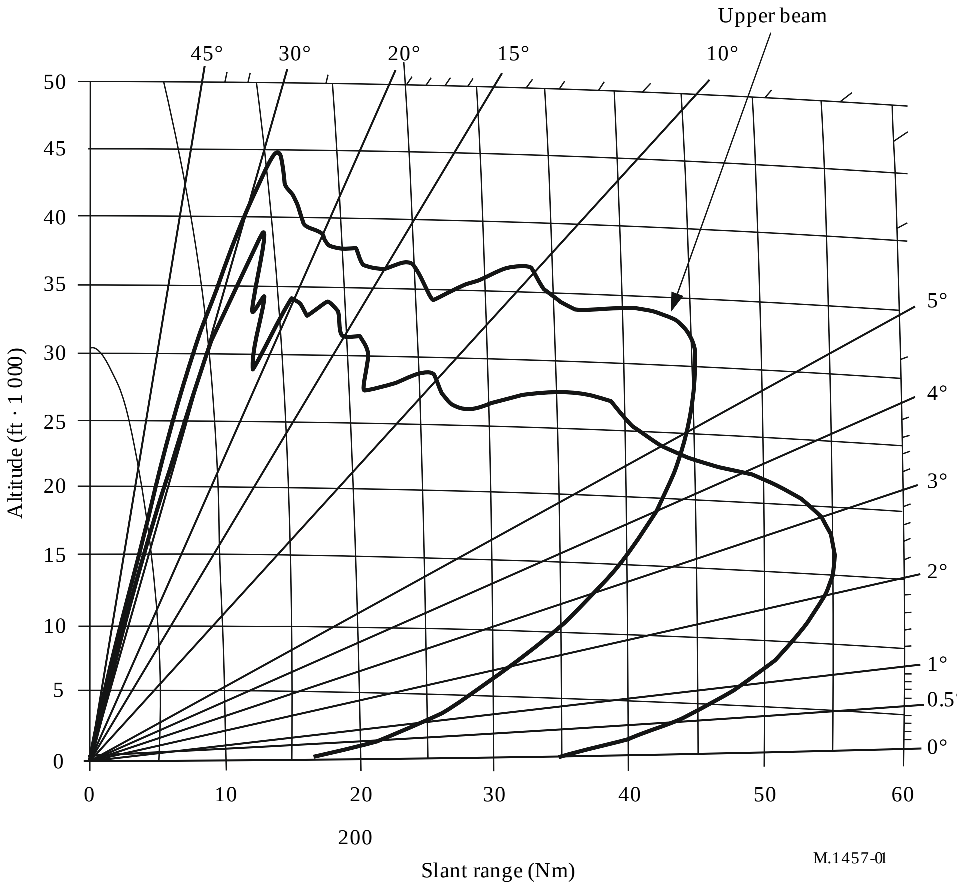
2.3 Radar B signal processing characteristics

2.3.1 Antenna

Radar B employs high- and low-beam horns in the antenna feed array. The reflected pulses are received by the high- and low-beam horns in the antenna array and are switched, attenuated, and amplified by microwave components and sent to their respective receivers. The high-beam horn receives returns from high-altitude targets close to the antenna, while the low-beam horn receives returns from low-altitude targets at greater distances. The high-beam path reduces clutter strength at short ranges in order to improve sub-clutter visibility. For these tests, the low-beam receiver was selected because the radar would most likely receive interference from local ground-based emitters through this path. The low beam is used for observation of targets at ranges exceeding about 15-20 NM (approximately 28-37 km). The beams are not used simultaneously; the radar receiver toggles between them. The coverage patterns for the high and low beams for a 1 m^2 target cross-section with a probability of detection equal to 0.80 are shown in Fig. 1.

FIGURE 1

High and low beams coverage patterns



2.3.2 Radar B target receiver

The target receiver/processor in radar B employs STC and moving target detection, which includes Doppler filtering and CFAR processing, to detect and separate target returns from noise, ground clutter and weather. The target receiver/processor sorts the target returns according to range, detects their Doppler shift, and sends them to the radar system post processor.

2.3.2.1 Radar B IF circuitry

The IF receiver amplifies the outputs of the RF receiver and detects their phase shifts. The IF circuitry consists of a three-stage logarithmic video detector/amplifier with a wide dynamic range and an I and Q phase detector. The output of the IF amplifier receiver is at 31.07 MHz. A CW signal swept in frequency was applied as input stimuli to the radar receiver to obtain the receiver's 3 dB bandwidth, which was measured to be about 680 kHz at the input to the phase detectors. The receiver's response to the swept CW signal is shown in Fig. 2. The dynamic range of the radar receiver was measured by varying the power level of a fixed frequency CW signal and monitoring the output of the IF circuitry at the same test point. Figure 3 shows the gain characteristics of the radar receiver. The compression point occurs with an input signal that has a power level of about –43 dBm.

FIGURE 2

Radar B IF selectivity curve

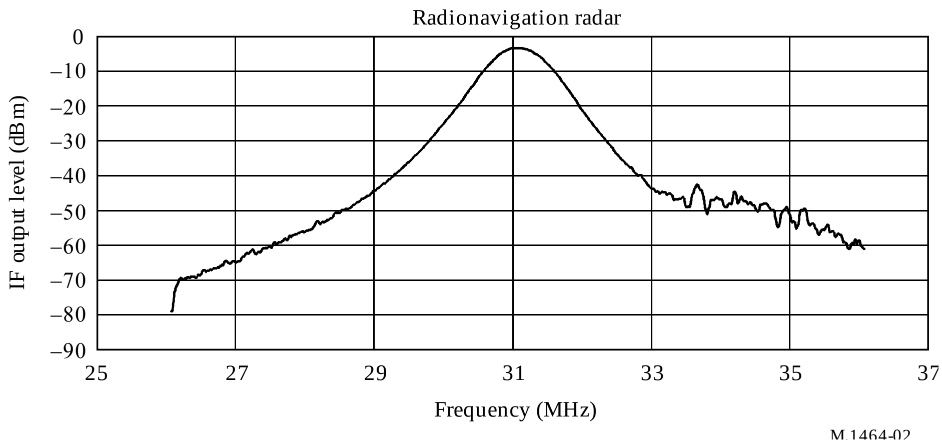
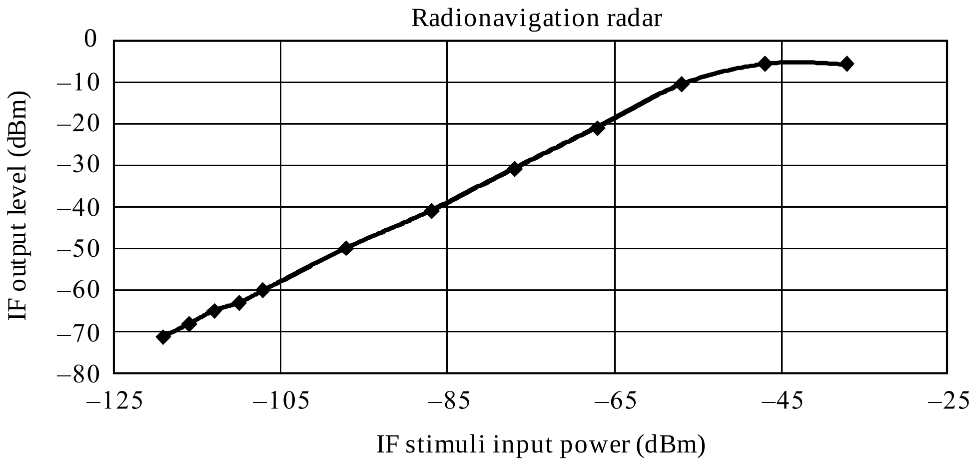


FIGURE 3

Radar B input/output gain curve



The phase detectors at the output of the IF amplifier determine the change in phase between the returns and the transmit pulses that produced them, using the coherent oscillator (COHO) from the frequency generator as a transmit pulse phase reference. The phase detectors each have sinusoidal responses, and produce in-phase (I) and quadrature (Q) outputs with a sine-cosine (90°) phase relationship to each other. Because the I and Q phase detector responses are sine and cosine functions, their outputs can be added vectorially to determine the actual magnitude of the target returns. Software-implemented servo loops set the DC offsets, gain balance, and phase balance of the I and Q outputs from the phase detectors. They also set the automatic gain control level of the RF and IF amplifiers to limit the noise level within one quanta (the change in RF level represented by the least significant bit output of the analogue-to-digital (A/D) converter) of the noise itself.

The I and Q outputs of the IF circuitry are sampled and digitized by A/D converters during each 0.77 μs (equal to 0.75% of the transmit pulsewidth), covering a 1/16 NM (approximately 116 m) range cell, at a 2.6 MHz clock rate. The results are then interleaved. The A/D converter outputs 12-bit digital words that represent the samples of the I and Q signals to the filter and magnitude processor.

2.3.2.2 Doppler filtering

In each 1/16 NM range cell, coherent processing intervals (CPIs), consisting of returns from alternately 10 and 8 successive pulse repetition intervals, are formed. In the 10-pulse case, the batches associated with each successive 1/16 NM range increment are sequentially applied to the same set of ten Doppler filters. The random access memory stores digital representations of the returns over several pulse-repetition trains and the Doppler filters process them together so that pulse-to-pulse changes in target-return amplitudes (representing apparent Doppler frequencies) can be calculated. For the 10-pulse CPI, five of the filters are used to detect targets moving towards the radar antenna and the other five are used to detect receding targets. A similar process is used for the 8-pulse CPI, except that eight filters are used. The Doppler filters improve the receiver's S/N because the Doppler filters add or integrate a series of target returns at their frequency. This causes return signals to progressively accumulate at the output of the filter, while random-frequency noise accumulates at the filter outputs at a much slower rate.

2.3.2.3 Constant false alarm rate process

Radar B uses a 27-cell sliding-window averaging (or range averaging) CFAR technique to calculate the mean level threshold (MLT). CFAR processing automatically varies a detection threshold to maintain false target declarations, based on the return signal plus noise outputs of the Doppler filters at a constant rate. Each Doppler filter sums the energy contained in the stream of returns received as the antenna sweeps over a target. The energy combines with the noise energy that accumulates in the filter during the same time interval. If the integrated signal plus noise at the output of a filter exceeds the MLT, the detector concludes that a target is present.

Thresholds for the non-zero velocity resolution cells are established by summing the detected outputs of the signals in the same velocity filter in a 27-cell window centred about the cell of interest. Thus, each filter output is averaged to establish the mean level of non-zero velocity clutter. Filter thresholds are determined by multiplying the mean levels by an appropriate constant to obtain the desired false-alarm probability.

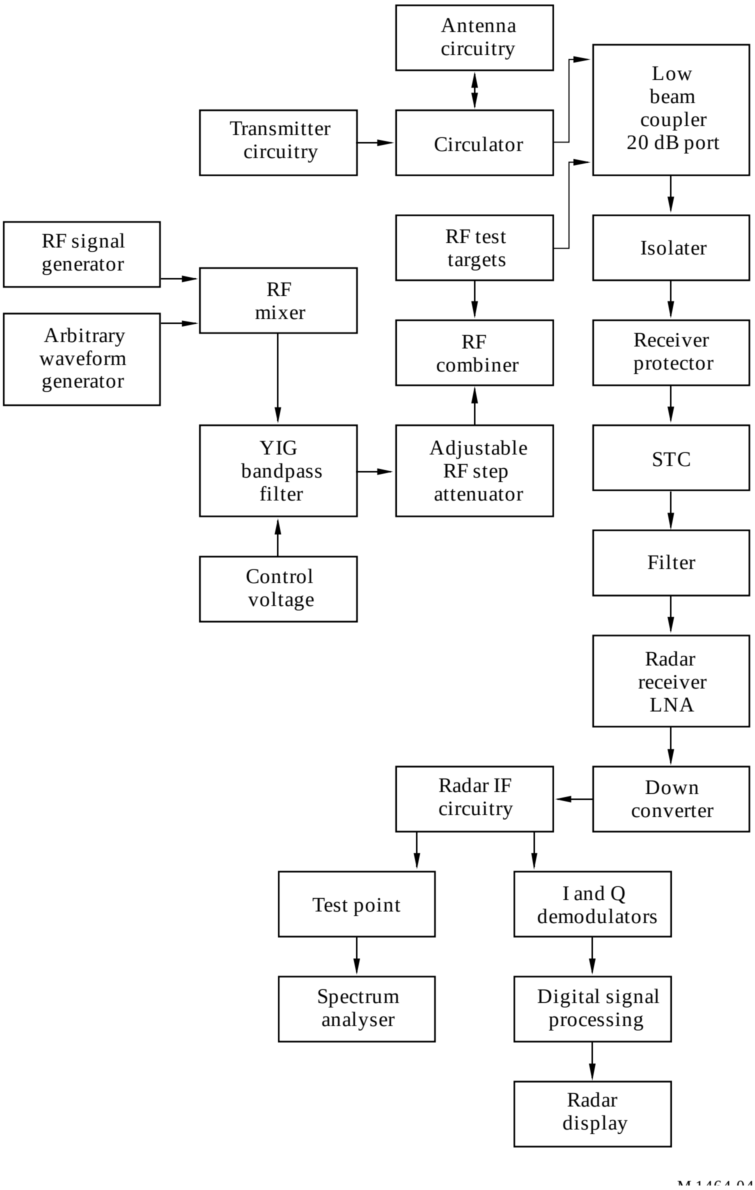
Random noise will occasionally exceed the MLT and the detector will falsely indicate that a target is present. The higher the detection threshold to the mean level of the noise energy the lower the probability of a false alarm will be, and vice versa. If the detection threshold is too high, valid targets may go undetected. The outputs of the Doppler filters are continuously monitored to maintain an optimum threshold setting. The CFAR sets the detection thresholds to maintain the false alarm rate for each Doppler filter at an optimum value. A quadrature phase shift keying (QPSK)-type waveform covering the band of the radar receiver will appear simultaneously in all the Doppler filters as noise and cause the CFAR to raise the detection threshold, causing all targets to have a correspondingly lower probability of detection.

2.4 Unwanted signals

Three types of signals were injected into the radar as unwanted emissions through a 20 dB coupled port in the receiver's waveguide path (see Fig. 4). The signals were an unmodulated CW, a 2 Mbit/s QPSK waveform, and a 2 Mbit/s QPSK waveform with a 1/8 time slot duty factor. All three signals were on-tune with the radar's operating frequency and occurred within the full 360° of the antenna's rotation.

FIGURE 4

Test set-up with QPSK signal generator



The continuous and pulsed QPSK waveforms represent the type of signals that are expected to be used by digital communication systems.

The QPSK signal was generated and injected into the radionavigation radar receiver using the test set-up shown in Fig. 4.

The CW signal was simulated using an RF signal generator. For the code division multiple access (CDMA) type QPSK waveform, an arbitrary waveform generator was programmed to output a QPSK waveform at a data rate of 2 Mbit/s. For the time division multiple access (TDMA) type QPSK waveform, another AWG was used to pulse the QPSK waveform for a 1/8 time slot duty factor. The on-time of the pulse was 577 μs and the period was 4.6 ms.

The output of the AWG was inputted to a mixer whose other input was connected to an RF signal generator. The RF signal generator functioned as a local oscillator and its frequency was adjusted so that the carrier of the QPSK waveform was co-tuned with the radar receiver. The Yttrium-iron-garnet (YIG) bandpass filter was used to suppress any spurious emissions that resulted from the mixing process. The RF step attenuator immediately after YIG filter was used to control the power level of the QPSK emissions.

2.5 Target generation and counting

Ten simulated equally-spaced targets were generated along a radial using the radar's built-in test target generator hardware/software. The targets on the radial have a constant power envelope. The target count was made with 20 rotations of the radar. In 20 rotations, 200 targets were generated. If 200 targets were counted then the probability of detection, P_d, was 100%, and if 180 targets were counted the P_d was 0.90, and so on. Therefore, the P_d was calculated by dividing the number of counted targets by the number of expected targets (or targets generated). The targets were counted manually by observing the correlated video output on the radar's ppi.

2.6 Test conditions

The tests were performed with the following parameters set on the aeronautical radionavigation radar as shown in Table 3.

TABLE 3

Radar control settings

Parameter	Setting
STC	Off
Interference rejection (IR)	On
Automatic gain control	On
Image selected	Processed video
Range	60 NM (approximately 111 km)
Desired baseline target P_d	0.90 (software controlled)

Although the automatic gain control was enabled, the interfering signals were not at a high enough power level to affect its operations.

The manufacturer's performance specification for radar B is a target P_d of 80% for a 1 m^2 target cross-section at 55 NM with a probability of false alarm, P_{fa}, of 1×10^{-6}. The desired baseline target P_d of 0.90 that was chosen for the tests represents a performance level that radars operating in the frequency band 2 700-2 900 MHz will achieve in the near future as additional processing gain allows them to detect targets at or below the noise floor of the radar receiver.

2.7 Test procedures

The RF power output of the target generator system was adjusted so that the target P_d was as close as possible (given that the target levels could only be adjusted in 1 dB increments) to the baseline target P_d of 90% without interference being present (for correlated video targets). Targets were counted in twenty scans to set the baseline P_d. Due to the CFAR processing, the radar took 8-10 scans before it would reach a steady state after the target power was adjusted.

After the radar was set to its baseline condition, the CW and QPSK interference was injected into the radar receiver. The power of the CW and QPSK signals that were injected into the radar receiver was set to different levels while the power level of the targets was held constant. The power levels of the

CW and QPSK signals were set to values that produced I/N levels of –12, –10, –9, –6, –3, 0, +3, and +6 dB in the IF circuitry of the radar receiver. To account for the radar's CFAR processing, the targets were not counted until ten scans had occurred after the interference had been enabled. After 20 scans with the interference enabled and the targets counted, the interference was disabled and an additional ten scans were allowed to occur before the next I/N level was tested. Waiting ten scans to occur ensured that the present measurement was not affected by the previous one.

As the CW and QPSK power levels were varied, the display of the radar was observed for an increase in the number of false targets, radial streaks ("strobes"), and an increase in background "speckle".

2.8 Test results

Curves showing the target P_d versus the I/N levels were produced for the CW, CDMA-QPSK, and TDMA-QPSK unwanted emissions. The results are shown in Fig. 5.

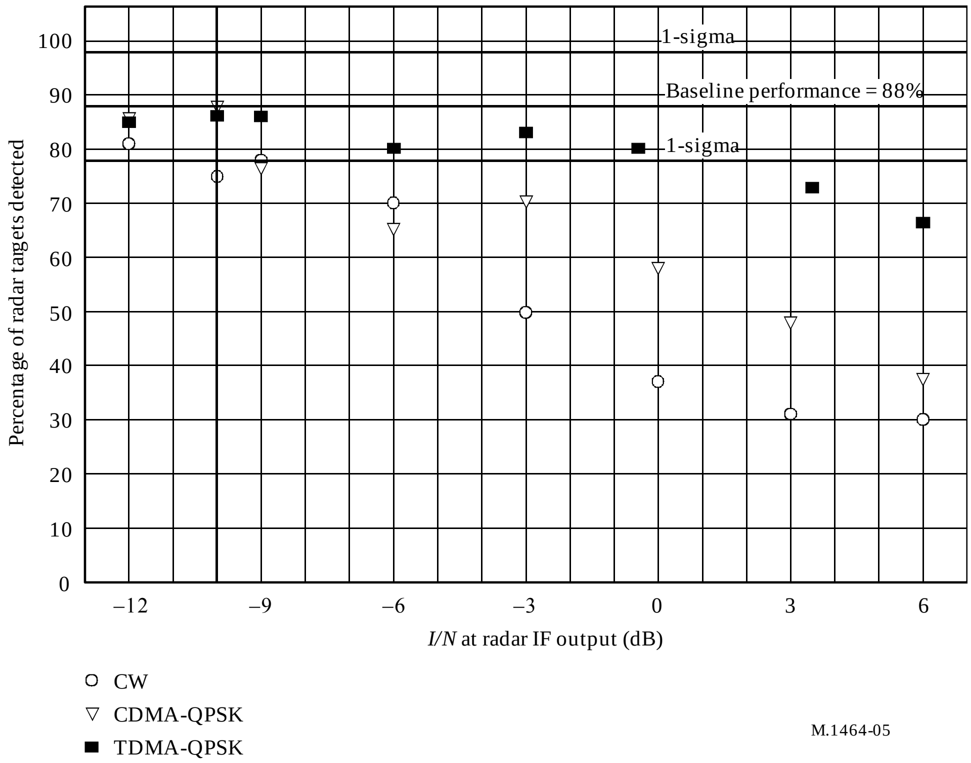
For the baseline tests (no interference injected into the radar) the radar had a mean value of 8.8 targets observed per rotation, out of ten targets injected per rotation. Twenty rotations were observed per trial. The actual baseline target P_d was then 175/200, or 88%. Although nine out of ten targets per rotation was specified as the desired baseline target P_d for these tests, the ability to control the RF output power of the target generator was limited to 1 dB steps which made obtaining an exact P_d of 0.90 extremely difficult. At the target power setting which was used in the tests, 1 dB more of target power resulted in a P_d above 0.95 and 1 dB less target power resulted in a P_d approximately equal to 0.75.

The variance in any given baseline target count was 1.1 targets per rotation. The 1-sigma value is equal to the square root of the variance, or 1.05. This size of the allowable error from the baseline P_d is the mean target value minus the 1-sigma value, divided by 10. This value is (8.8 – 1.05)/10, or ±10%. Figure 5 shows the baseline P_d of 88% and also shows the upper and lower bounds of the allowable error in the P_d based on the 1-sigma values. The upper bound is a P_d of 98% and the lower bound is a P_d of 78%. The acceptable I/N level with the interference introduced into the radar receiver is the I/N value where the interference does not cause the P_d to drop below the lower limit of 78%. For a higher P_d the 1-sigma value would be smaller, which would make the I/N protection more stringent.

Figure 5 shows the I/N thresholds for each interference signal type where the target P_d drops below the 1-sigma threshold. For the continuous CW and the CDMA-QPSK interference signal types, this occurs at I/N values greater than –10 dB. For the TDMA-QPSK interference signal, the P_d did not drop below the 1-sigma line until the I/N was greater than 0 dB.

FIGURE 5

Target probability of detection curves



3 Radar D and E tests

Measurements were carried out by one administration with radars D and E using narrow-band white noise and orthogonal frequency division multiplexing signals as interference sources to determine the effect on the radars target P_d. Aircraft were used as targets of opportunity.

Besides P_d, the false alarm rate P_{fa} and accuracy are important radar performance parameters which may be affected by additional interference, although the false alarm rate should theoretically be constant since the video processor uses a CFAR algorithm to adjust the detection threshold. In these tests only the P_d results are presented.

The following figures show the effect of interference of DVB-T signals on the probability of detection at one radar for all aircraft in the volume:

– 40-60 NM (approximately 74-111 km) (60 NM is the maximum detection range of the radar); and

– above flight level 250 (25 000 ft, or approximately 7 620 m above sea level).

It must be mentioned that although this is a scenario where the loss of performance is of course more severe than for the vicinity of the radar, there are other circumstances where the effects would be even worse:

– only small aircraft (general aviation or military jets) instead of all;

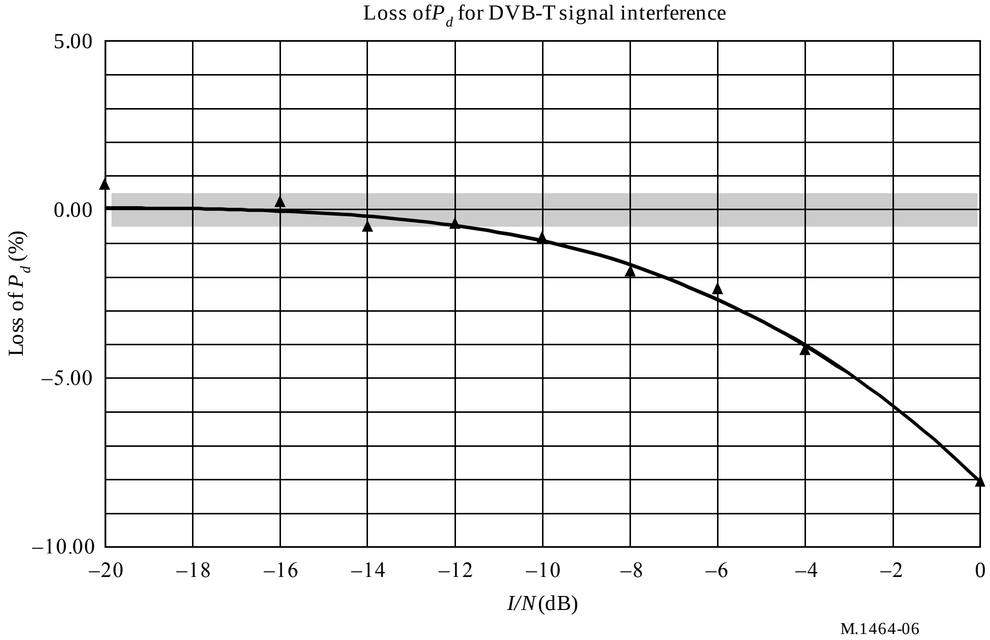
– low flight levels (especially large distances);

– focus only on the maximum range (e.g. 50-60 NM, or approximately 92-111 km).

The above example has been chosen because it provides enough samples for a stable statistical analysis. The reference value – for which the loss of P_d is 0% – is the average P_d of seven measurements without any interference signal. These values have a standard deviation of 0.5% which is composed of measurement errors and the impact of fluctuations in the opportunity traffic data set and indicated by the shaded horizontal bar in the following diagrams.

FIGURE 6

Interference level, *I*/*N* versus loss of P_d for aircraft above flight level 250 and beyond 40 nmi for Salzburg airport surveillance radar

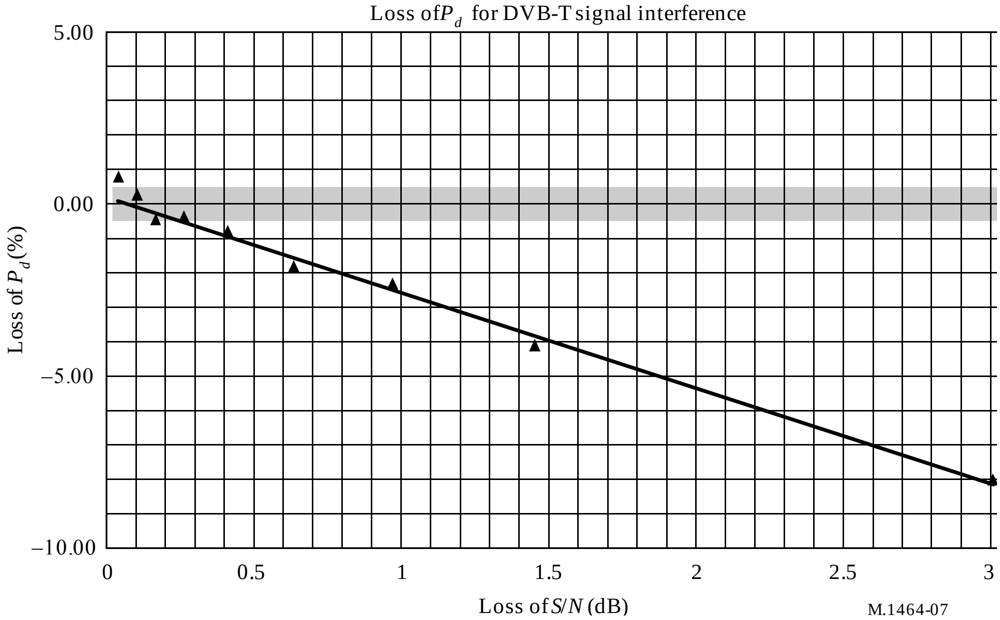


At I/N = –6 dB there is already a loss of about 2.5% detection probability and at –10 dB it is 0.8% which is still outside the error margin. The interpolation curve shows that the drop of P_d starts about –14 dB and becomes significant above –10 dB. Figure 7 shows the same data but as a function of $\Delta S/N$ instead of I/N. The sensitivity of the P_d on the loss of S/N is about 3%/dB between 1% and 7% loss of P_d.

The results of the measurements at the other radar are generally the same with the exception that the absolute P_d of the older radar system (especially when only one frequency channel is used) is generally lower than the value of the modern system with its different data processing.

FIGURE 7

Δ*S*/*N* loss versus loss of P_d for aircraft above flight level 250 and beyond 40 nm



4 Conclusions

The test results in this Annex show that radars B, D, and E's ability to detect targets is already impacted at an *I*/*N* level of –6 dB. In order to fully protect radar types B, D, E and other aeronautical radionavigation radars that operate in the frequency band 2 700-2 900 MHz from emissions of communication systems that use the tested digital modulation schemes, the *I*/*N* protection criterion should be –10 dB. This value represents the aggregate interference threshold if multiple interferers are present. Future requirements on radars that operate in the frequency band 2 700-2 900 MHz to detect and track targets with a smaller cross-sections may lead to more stringent protection criteria.