RECOMMENDATION ITU-R M.1464-1*

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

(Question ITU-R 35/8)

(2000-2003)

Summary

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.

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 aeronautical radionavigation 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 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 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;

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[*] This Recommendation should be brought to the attention of the International Civil Aviation Organization (ICAO) and the World Meteorological Organization (WMO).

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);

j) that radars in this 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 and meteorological 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;

4 that the protection trigger level for meteorological radars be based upon Annex 3, in particular § 7, for assessing compatibility with interfering signal types from other services representative of those in Annex 3. 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 meteorological radars

1 Introduction

The 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 band on a basis of equality with stations in the aeronautical radionavigation service (see RR No. 5.423).

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 band for terminal approach/airport surveillance radars for civil air traffic worldwide. The meteorological radars are used for detection of severe weather elements such as tornadoes, hurricanes and violent thunderstorms. These weather radars also provide quantitative area precipitation measurements so important in hydrologic forecasting of potential flooding. This information is used to provide warnings to the public and it therefore provides a safety-of-life service.

2 Technical characteristics

The 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 band include ATC and weather observation. Radar operating frequencies can be assumed to be uniformly spread throughout the 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 and meteorological radars deployed in the 2 700-2 900 MHz band. 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 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 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 band 2 700-2 900 MHz

Characteristics	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)	1.4 MW	1.32 MW	25 kW	450 kW	22 kW	70 kW
Pulse width (µs)	0.6	1.03	1.0, 89	1.0	1.0, 55.0	0.4, 20 0.5, 27(3)
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	6 MHz	5 MHz	2.6 MHz (short impulse) 5.6 MHz (long impulse)			3 MHz (valeur type)
3 dB		600 kHz	1.9 MHz			2 MHz
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 (*end*)

Characteristics	**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[3]
Antenna horizontal scan type (continuous, random, 360°, sector, etc.)	360°					
Antenna vertical scan rate (degrees/s)	Not applicable					
Antenna vertical scan type (continuous, random, 360°, 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)		+7.3 dBi	+9.5 dBi 3.5°			+7.5 dBi 0 to –3 dBi
Antenna height (m)	8					8-24
Receiver IF 3 dB bandwidth	5 MHz	653 kHz	15 MHz		1.2 MHz	4 MHz
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)		–20				–10
Receiver on-tune saturation level (dBm)		–45				
Receiver RF 3 dB bandwidth (MHz)	2-2.3	10	280.6			400[1]
Receiver RF and IF saturation levels and recovery times						
Doppler filtering bandwidth (Hz)		95 per bin				
Interference-rejection features[4]	Feedback enhancer	[5]				
Geographical distribution	Worldwide					
Fraction of time in use (%)	100					

[1] 2.7 to 3.1 GHz.

[2] Fixed systems operate up to 750 kW or 1 MW.

[3] Depends on range.

[4] 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, saturating pulse removal.

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

TABLE 2

Characteristics of meteorological radars in the band 2 700-2 900 MHz

Characteristics	**Radar G**	**Radar H**
Platform type (airborne, shipborne, ground)	Ground, weather	Ground, weather
Tuning range (MHz)	2 700-3 000	2 700-2 900
Modulation	P0N	
Transmitter power into antenna (kW)	500	400 or 556
Pulse width (μs)	1.6 (short pulse) 4.7 (long pulse)	1.0 (short pulse) 4.0 (long pulse)
Pulse rise/fall time (μs)	0.12	
Pulse repetition rate (pps)	318-1 304 (short pulse) 318-452 (long pulse)	539 (short pulse) 162 (long pulse)
Duty cycle (%)	0.21 maximum	
Chirp bandwidth	Not applicable	Not applicable
Phase-coded sub-pulse width	Not applicable	Not applicable
Compression ratio	Not applicable	Not applicable
RF emission bandwidth:		
–20 dB	4.6 MHz	
3 dB	600 kHz	
Output device	Klystron	Coaxial magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil	Pencil
Antenna type (reflector, phased array, slotted array, etc.)	Parabolic reflector	Parabolic reflector
Antenna polarization	Linear: vertical and horizontal	Linear: horizontal
Antenna main beam gain (dBi)	45.7	38.0
Antenna elevation beamwidth (degrees)	0.92	2.0
Antenna azimuthal beamwidth (degrees)	0.92	2.0
Antenna horizontal scan rate (degrees/s)	18	18 and full manual slewing

TABLE 2 (*end*)

Characteristics	**Radar G**	**Radar H**
Antenna horizontal scan type (continuous, random, 360°, sector, etc.)	360° and sector	360° and sector
Antenna vertical scan rate (degrees/s)	14 steps in 5 min	
Antenna vertical scan type (continuous, random, 360°, sector, etc.) (degrees)	Fixed steps: 0.5-20	–2.0 to +60
Antenna side lobe (SL) levels (1st SLs and remote SLs) (dBi)	+20	+15 (estimated)
Antenna height (m)	30	30
Receiver IF 3 dB bandwidth	630 kHz	0.25 MHz (long pulse) 0.5 MHz (short pulse)
Receiver noise figure (dB)	2.1	9.0
Minimum discernible signal (dBm)	–115	–110
Receiver front-end 1 dB gain compression point (dBm)	–17	–32
Receiver on-tune saturation level (dBm)	–10	
Receiver RF 3 dB bandwidth (MHz)	1.6	0.5 (long pulse) 1.5 (short pulse)
Receiver RF and IF saturation levels and recovery times	–10 dBm, 1 μs	
Doppler filtering bandwidth (Hz)	Estimate 95(1)	
Interference-rejection features		
Geographical distribution	Worldwide	
Fraction of time in use (%)	100	

(1) Doppler filtering and saturating pulse removal.

TABLE 3

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

Characteristics	**Radar I**	**Radar J**	**Radar K**	**Radar L**
Platform type (airborne, shipborne, ground)	Ground, ATC gap-filler coastal	2D/3D naval surveillance ground air defence	Ground air defence	Multifunction various types
Tuning range (MHz)	2 700-3 100	2 700-3 100	2 700 to 3 100 2 900 to 3 400	Whole band up to 25% BW
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
Modulation	Non-linear FM P0N, Q3N	Non-linear FM P0N, Q3N	Non-linear FM Q3N	Mixed
Transmitter power into antenna	60 kW typical	60 to 200 kW	1 MW typical	30 to 100 kW
Pulse width (μs)	0.4[(1)] to 40	0.1[(1)] to 200	> 100	Up to 2
Pulse rise/fall time (μs)	10 to 30 typical	10 to 30 typical	Not given	Not given
Pulse repetition rate (pps)	550 to 1 100 Hz	300 Hz to 10 kHz	< 300 Hz	Up to 20 kHz
Duty cycle (%)	2.5 maximum	10 maximum	Up to 3	30 maximum
Chirp bandwidth (MHz)	2.5	Up to 10	> 100	Depends on modulation
Phase-coded sub-pulse width	Not applicable	Not applicable	Not applicable	Not given
Compression ratio	Up to 100	Up to 300	Not applicable	Not given
RF emission bandwidth (MHz): –20 dB –3 dB	3.5 2.5	15 10	> 100	Not given
Output device	TWT	TWT or solid state	Klystron CFA	Active elements
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Cosecant-squared	Pencil beam 3D or cosecant-squared 2D	Swept pencil beam	Pencil beam
Antenna type (reflector, phased array, slotted array, etc.)	Shaped reflector	Planar array or shaped reflector	Frequency scanned planar array or reflector	Active array
Antenna azimuth beamwidth (degrees)	1.5	1.1 to 2	Typically 1.2	Depends on number of elements
Antenna polarization	Linear or circular or switched	Linear or circular or switched	Fixed linear or circular	Fixed linear
Antenna main beam gain (dBi)	33.5 typical	Up to 40	> 40	Up to 43
Antenna elevation beamwidth (degrees)	4.8	1.5 to 30	Typical 1	Depends on number of elements

TABLE 3 (*end*)

Characteristics	Radar I	Radar J	Radar K	Radar L
Antenna horizontal scan rate (degrees/s)	45 to 90	30 to 180	Typical 36	Sector scan instantaneous rotation scan up 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
Antenna vertical scan rate (degrees/s)	Not applicable	Instantaneous	Instantaneous	Instantaneous
Antenna vertical scan type (continuous, random, 360°, sector, etc.) (degrees)	Not applicable	0 to 45	0 to 30	0 to 90
Antenna side lobe (SL) levels (1st SLs and remote SLs)	26 dB 35 dB	> 32 dB typical < –10 dBi	> 26 dB typical < 0 dBi	Not given
Antenna height above ground (m)	4 to 30	4 to 20	5	4 to 20
Receiver IF 3 dB bandwidth (MHz)	1.5 long 3.5 short	10	Not given	Not given
Receiver noise figure(2) (dB)	2.0 maximum	1.5 maximum	Not given	Not given
Minimum discernible signal (dBm)	–123 long pulse –104 short pulse	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
Receiver on-tune saturation level power density at antenna (W/m2)	4.0×10^{10}	1×10^{10}	Not given	Not given
RF receiver 3 dB bandwidth (MHz)	400	400	150 to 500	Up to whole band
Receiver RF and IF saturation levels and recovery times	Not given	Not given	Not given	Not given
Doppler filtering bandwidth	Not given	Not given	Not given	Not given
Interference-rejection features(3)	(4)	(4) and (5)	(4) and (5)	Adaptive beamforming (4) and (5)
Geographical distribution	Worldwide fixed site transportable	Worldwide fixed site naval transportable	Worldwide fixed site transportable	Worldwide fixed site naval transportable
Fraction of time in use (%)	100	Depends on mission	Depends on mission	Depends on mission

(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.

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%, that 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.

Meteorological radars, designed to track particles in the atmosphere and hydrometeors of sub millimetre size utilize extensive processing to extract signals from received noise. Testing conducted on one radar type used worldwide characterized this processing gain to be of the order of 6 to 9 dB. In addition, meteorological radars detect more than just the presence of a return pulse. The processing derives data on return pulse characteristics to determine factors such as wind velocity, wind shear, turbulence and precipitation type. The processing, combined with the fact that meteorological radars require more than just the detection of the presence of a return pulse at negative S/N ratios makes them very vulnerable to interference. Additional information is provided in Annex 3 of this Recommendation.

2.3 Antennas

Only parabolic reflector-type antennas are used on radars operating in the 2 700-2 900 MHz band. The ATC radars have a cosecant-squared elevation pattern, while the meteorological radars have a pencil beam antenna pattern. Since the radars in the 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.

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.

4 Operational characteristics

4.1 Meteorological radars

The technical characteristics of a representative weather radars, that predominately operate in the 2 700-2 900 MHz band, are depicted in Table 2 as radars G and H. However, radar G can operate up to 3 000 MHz. These are the primary weather radar systems used for flight planning activities and are often collocated at airports worldwide, to provide accurate weather conditions for aircraft. Therefore, these radars are also in operation 24 h per day.

Radar G utilizes Doppler radar technology to observe the presence and calculate the speed and direction of motion of severe weather elements such as tornadoes, hurricanes and violent thunderstorms. Radar G also provides quantitative area precipitation measurements so important in hydrologic forecasting of potential flooding. The severe weather and motion detection capabilities offered by this radar contributes toward an increase in the accuracy and timeliness of warning services. Radar G 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. Radar H is a non-Doppler radar used in many countries.

Radar G is used in an integrated network spanning the entire United States of America, Guam, Puerto Rico, Japan, South Korea, China and Portugal. The 2 700-2 900 MHz band 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. The WMO reports that more than 320 meteorological radars operate in this band in at least 52 countries throughout the world.

4.2 Aeronautical radionavigation radars

Airport surveillance radars operate throughout the world in the band 2 700-2 900 MHz. Six representative types of ATC radars are depicted in Table 1, as radars A through radar F. 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, B and F 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.

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 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 (ARNS) in the 2 700-2 900 MHz band. 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 OB/ENG systems in the 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.

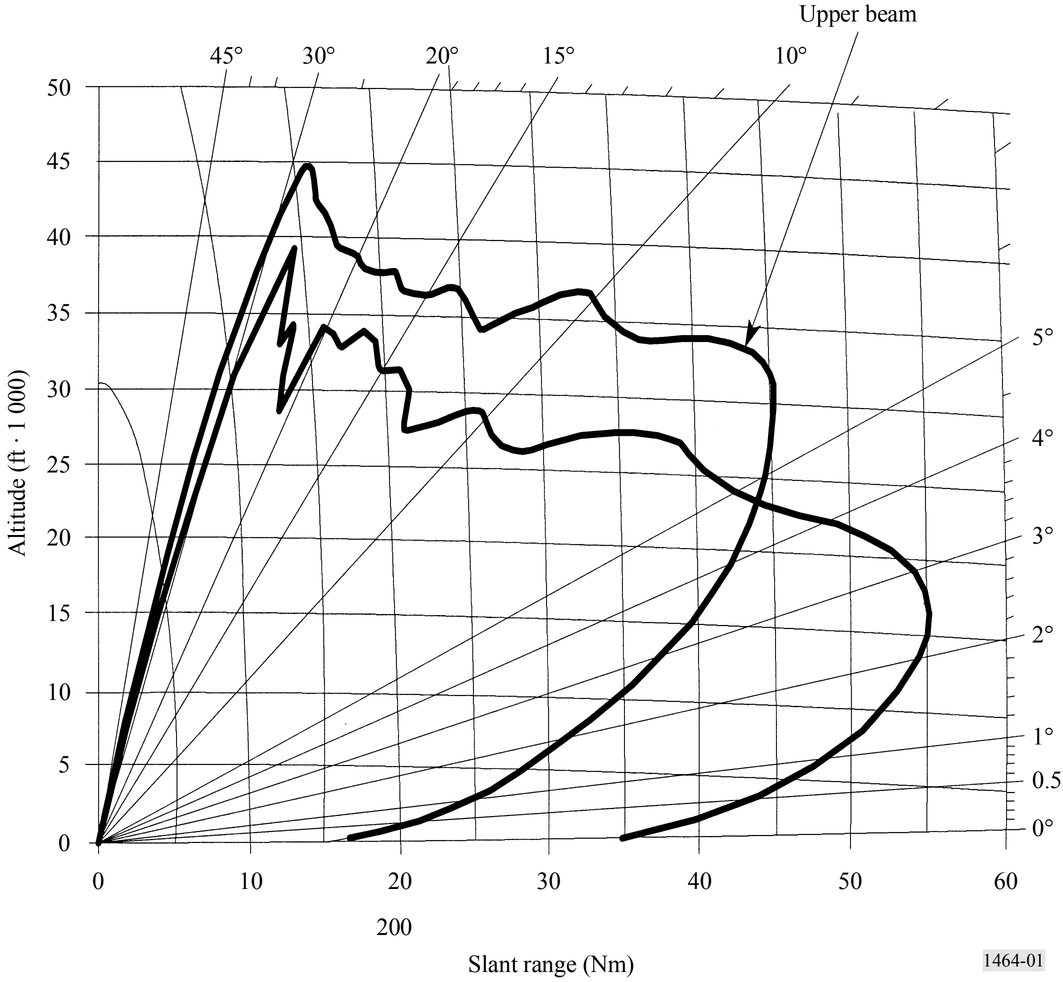
2.3 Radar B signal processing characteristics

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

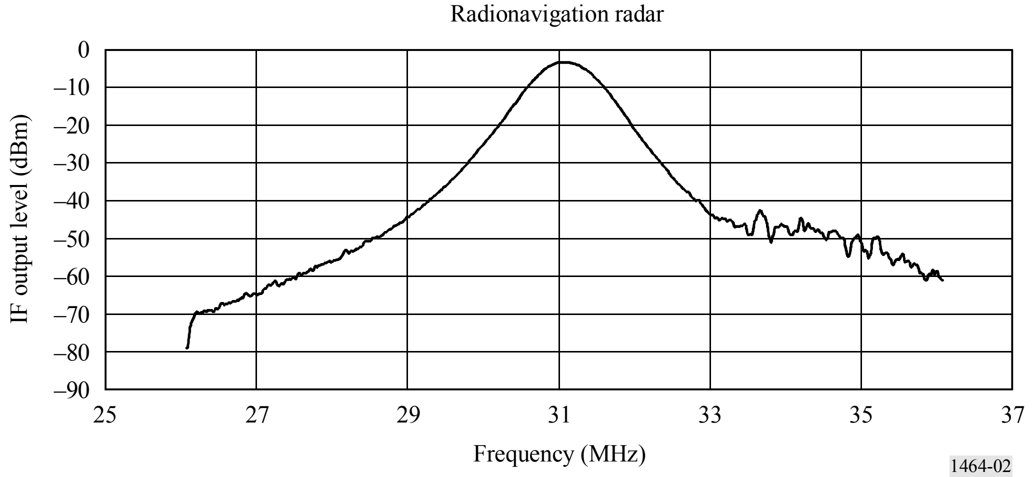
The target receiver/processor in radar B employs STC and moving target detection, which includes Doppler filtering and CFAR processing, to detect and separate target returns from noise, ground clutter and weather. The target receiver/processor sorts the target returns according to range, detects their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

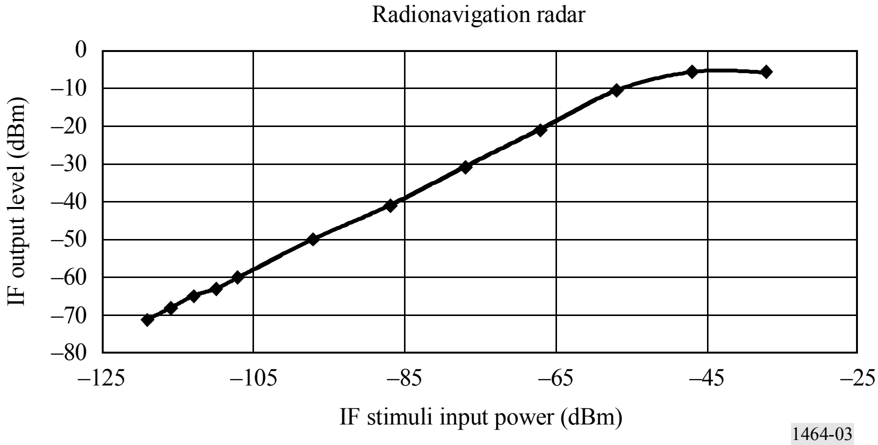
Radar B IF selectivity curve



1464-02

FIGURE 3

Radar B input/output gain curve



1464-03

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 CFAR 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.

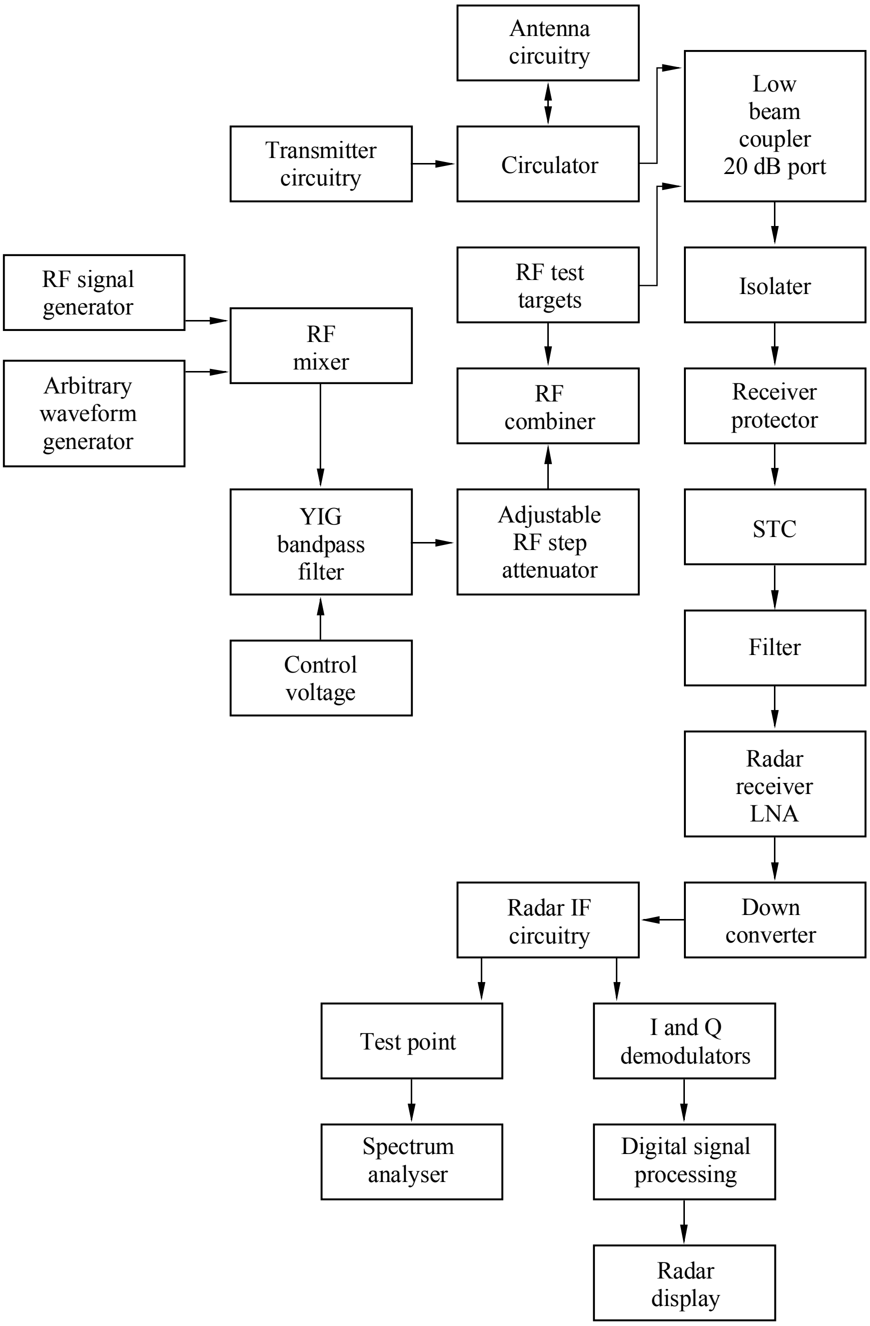
Random noise will occasionally exceed the MLT and the detector will falsely indicate that a target is present. The higher the detection threshold to the mean level of the noise energy the lower the probability of a false alarm will be, and vice versa. If the detection threshold is too high, valid targets 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 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



1464-04

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 4.

TABLE 4

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 2 700-2 900 MHz band 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.

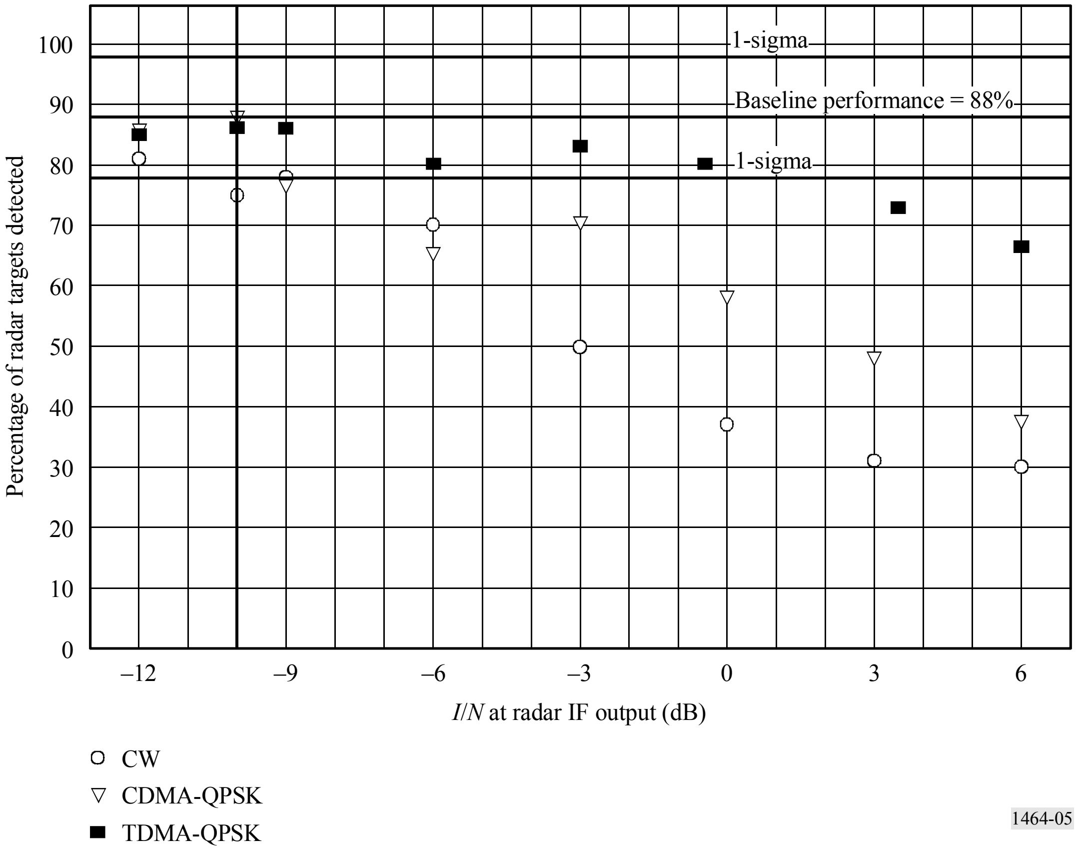
For the baseline tests (no interference injected into the radar) the radar had a mean value of 8.8 targets observed per rotation, out of ten targets injected per rotation. Twenty rotations were observed per trial. The actual baseline target P_d was then 175/200, or 88%. Although nine out of ten targets 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).

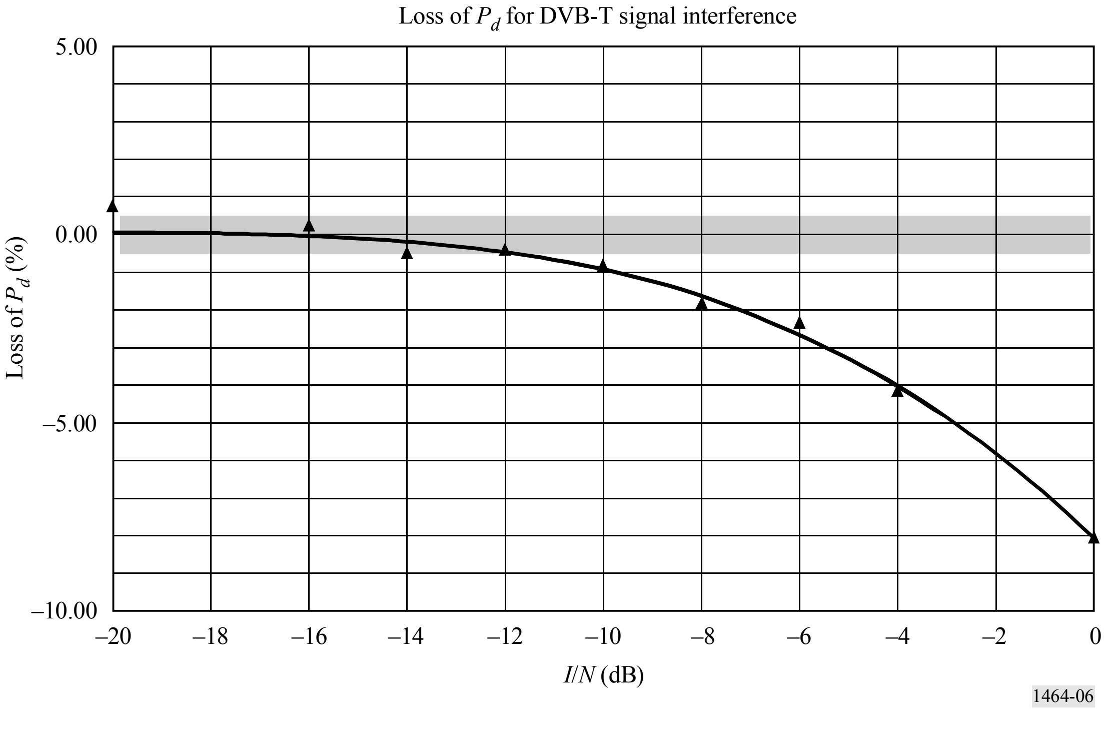
It must be mentioned that although this is a scenario where the loss of performance is of course more severe than for the vicinity of the radar, there are other circumstances where the effects would be even worse:

- 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

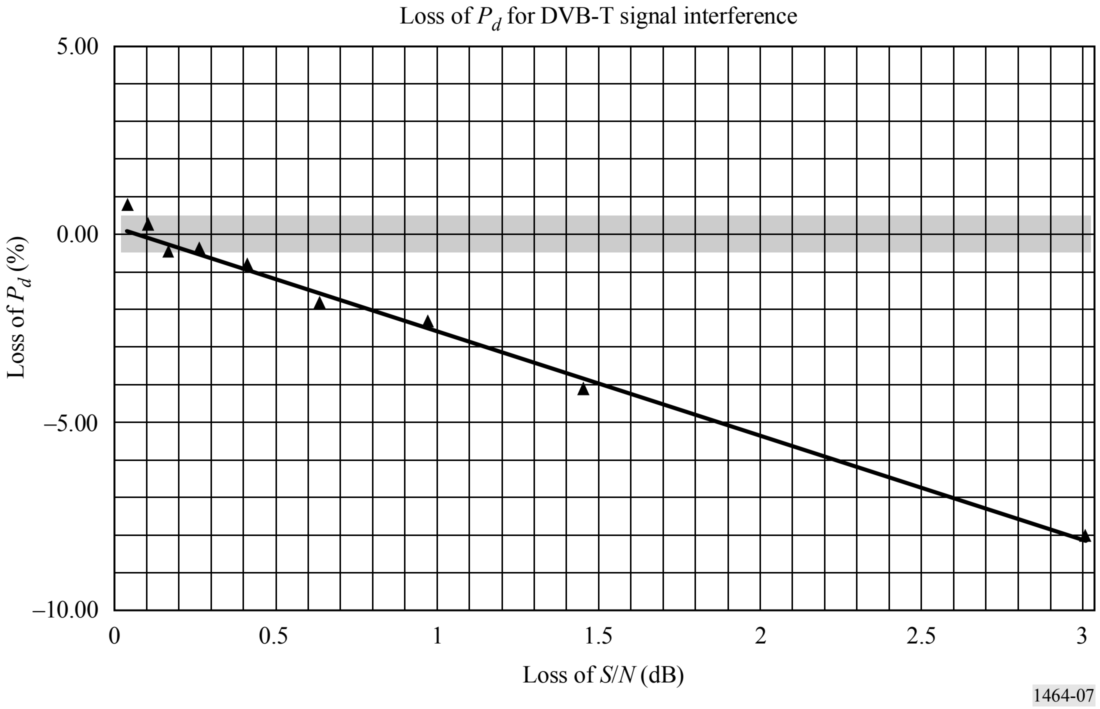


At $I/N = -6$ dB there is already a loss of about 2.5% detection probability and at –10 dB it is 0.8% which is still outside the error margin. The interpolation curve shows that the drop of P_d starts about –14 dB and becomes significant above –10 dB. Figure 7 shows the same data but as a function of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

$\Delta S/N$ 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 2 700-2 900 MHz band 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 2 700-2 900 MHz band to detect and track targets with a smaller cross-sections may lead to more stringent protection criteria.

Annex 3

Results of tests with a meteorological radar

1 Executive summary

The key objective of the work contained in this Annex was to establish the maximum interference level that meteorological radar systems can withstand before their forecasting capability is compromised.

Based upon the radar's technical specifications, mathematical models have been derived for key products (base reflectivity, mean radial velocity and spectrum width) that indicate what these expected levels should be. In order to physically validate this analysis, a test and data analysis methodology has been defined through which data were collected and analysed.

The analysis of the data supports the calculated value required for protection of the reflectivity measurements. Current limitations in the radar calibration and noise removal process performed by the low-level data processor limit the measurement of the necessary protection criteria for the spectrum width measurements. However, correction of the data for the limitations of this processing results in values that support the calculated protection values.

1.1 Introduction

Tests were run on a modern meteorological radar (noted as radar G in Annex 1, Table 2) to determine the appropriate criteria necessary for protection from CW and interference signals in the 2 700-2 900 MHz band. The tests were comprised of injecting a CW signal and six different digital modulation schemes into the radar receiver while it was scanning the atmosphere. Low-level or base meteorological products (base reflectivity, mean radial velocity and spectrum width) were recorded while conducting a series of antenna rotations at a single antenna elevation. Interference signals were injected with I/N ratios ranging from +6 dB to −15 dB.

2 Theoretical calculation of necessary protection criteria

The radar generates three base products that are used by the signal processing system to derive the meteorological products that are used by the meteorologist. These base products are:

- volume reflectivity, Z (mm^6/m^3) which for rain is a measure of total water in the radar sample volume;
- mean radial velocity, V (m/s) which is the power weighted mean radial motion of the targets in the sample volume;
- spectrum width, W (m/s) which is a measure of the radial velocity dispersion of the targets in the sample volume.

2.1 Minimum signal level

Signal processing removes the radar system noise effects from the reflectivity and spectrum width products so that the system can provide these products when the signal level is below the receiver noise level. The S/N threshold, i.e. the lowest level for which the return signal is processed, is selectable by the radar operator between the limits of −12 dB S/N and +6 dB S/N. With the present signal processing, the lower values are generally not used due to limitations with noise removal but the system provides useful products down to −3 dB S/N. The interference level that compromises the system is related to the minimum signal level of −3 dB S/N and the product characteristics themselves, as described below. Excessive interference will impact data quality, degrade the meteorological products, and compromise the system's ability to accomplish its mission of providing data necessary for public weather forecasting, severe weather warning, and rainfall measurement for flash flood prediction and water management.

2.2 Reflectivity

Reflectivity is used in multiple applications; the most important of which is rainfall rate estimation. Reflectivity is calculated from a linear average of return power and is subject to contamination by interference as an unknown increase in the measured reflectivity. Reflectivity is seriously contaminated if the bias exceeds 1 dB. A 1 dB bias is twice the radar calibration accuracy and equal to the standard deviation of the reflectivity estimate specified in the radar technical requirements.

Bias in terms of I/S is given by:

$$\text{dB bias} = 10 \log \frac{S+I}{S}$$

And a 1 dB bias occurs at:

$$I/S = 0.26$$

$$10 \log I/S = -6 \text{ dB}$$

Therefore, reflectivity is biased 1 dB at an interference level 6 dB below the signal.

Since the minimum signal level has an S/N of −3 dB and the maximum I/S level for the reflectivity product is −6 dB, the maximum I/N is:

$$(-3 \text{ dB}) + (-6 \text{ dB}) = -9 \text{ dB } I/N$$

2.3 Mean radial velocity

Mean radial velocity is calculated from the argument of the single lag complex covariance. The complex covariance argument provides an estimate of the Doppler signal vector angular displacement from radar pulse to radar pulse. The displacement divided by the time interval between the pulses is the Doppler vector angular velocity.

As a broadband noise, the interference signal vector has uniform probability over the complex plane and thus does not introduce a systematic rotation of the Doppler vector and does not introduce a bias in the estimate. However, the "randomness" of the composite signals plus interference vector due to the interference increases the variance of the Doppler signal estimate.

The Doppler frequency variance, retaining all terms except those inversely proportional to the number of samples squared can be calculated as:

$$\operatorname{var}(\hat{f}) = \frac{2\pi^{3/2}WT}{8\pi^2 M \beta^2(T)T^2} + \frac{\left(\frac{N}{S}\right)^2 + 2\left(\frac{N}{S}\right)[1-\beta(2T)]}{8\pi^2 M \beta^2(T)T^2}$$

where:

$\hat{f}$: frequency estimate (Hz)

W: standard deviation of frequency spectrum (Hz)
= 80 Hz with 4 m/s for N/T benchmark at $f_c = 2\,995$ MHz

T: sampling interval (s)
= 10^{-3} s for N/T benchmark

M: number of samples in estimate

N: noise power

S: signal power

β: signal correlation at lag T
= $\exp(-2\pi^2 W^2 T^2)$ for the assumed Gaussian spectra.

The first term is the variance contribution due to the signal characteristics and the second term is the variance contribution due to the noise.

The frequency variances are severely compromised if the interference increases the variance by more than 50%. The uncertainty in the data degrades all velocity-based products and the velocity shear measurements in particular. (Velocity shear is a velocity difference over some distance.) A 50% increase in variance increases the reliably detected shear value approximately 25% above the severe weather event formative stage value.

An expression for the I/N resulting in a 50% variance increase of the technical requirements benchmark parameters and $S/N = -3$ dB is given by:

$$2\pi^{3/2}WT + \left(\frac{N+I}{S}\right)^2 + 2\left(\frac{N+I}{S}\right)[1-\beta(2T)] = 3/2(2\pi^{3/2}WT) + 3/2\left(\frac{N}{S}\right)^2 + 3/2(2)\left(\frac{N}{S}\right)[1-\beta(2T)]$$

where:

$W = 80$ Hz

$T = 10^{-3}$ s

$2\pi^{3/2}WT = 0.89$

$1 - \beta(2T) = 0.4$

$S = 0.5$ N

Substituting and solving for *I/N* yields the quadratic expression:

$$(I/N)^2 + 2\,(I/N) - 1.21 = 0$$

$$I/N = 0.49$$

$$10 \log I/N = –3 \text{ dB}$$

Therefore, the interference can be no greater than the minimum signal value.

2.4 Spectrum width

The spectrum width is calculated from the single lag correlation assuming a Gaussian spectral density. The algorithm is expressed as:

$$W = \frac{Va}{\pi} \left| \ln \frac{R^2}{S^2} \right|^{1/2}$$

where:

W: spectrum width (standard deviation)

Va: Nyquist velocity, 25 m/s from the radar technical requirements

R: single lag covariance power

S: signal power.

The interference signal causes both a bias and a variance increase in spectrum width estimation but the bias is more detrimental. Spectrum width is compromised when the interference induced bias exceeds the radar technical requirement width accuracy of 1 m/s. The *I/N* at which this bias level occurs can be calculated by solving for the covariance at 4 m/s and signal power of *N*/2, then solving for the *S* + *I* level producing a 5 m/s spectrum width. 4 m/s is the base value given in the technical requirements. To calculate *I/N*, the equation above is solved for the 4 m/s and 5 m/s cases.

For $W = 4$ m/s:

$$25/\pi \left| \ln (R^2/S^2) \right|^{1/2} = 4$$

$$\text{In } (R^2/S^2) = –0.25$$

$$R/S = 0.88$$

$$R = 0.88\, S$$

$$R = 0.88\,(N/2)$$

For $W = 5\; m/s$:

$$25/\pi \left| \ln (R^2 + I)^2) \right|^{1/2} = 5$$

$$\text{In } R^2/(S + I)^2) = –0.39$$

$$R/(S + I) = 0.82$$

Substitute: $R = 0.88\,(N/2)$, $S = N/2$:

$$0.88\,(N/2) \,/\, (N/2) + I = 0.82$$

$$0.82\,((N/2) + I) = 0.88\,(N/2)$$

$$I/N = 0.0366$$

$$10 \log (I/N) = –14.4 \text{ dB}$$

3 System operation, output products and interference sensitivity

3.1 System operation mode for testing

The radar has multiple modes of operation that utilize different antenna rotation rates, antenna elevations and PRFs. The operation mode selected for the tests is one of the more commonly used modes, and is optimized for system sensitivity leading to high susceptibility of interference. Table 5 provides the characteristics of the mode used in testing.

TABLE 5

Characteristics of the meteorological radar system used in testing

Radar characteristics	
Frequency	2 995 MHz
Pulse power	750 kW
Pulse width	4.7 μs
PRF	322 Hz (first cut) 446 Hz (second cut)
Maximum coverage range	290 miles (approximately 467 km)
RF bandwidth (at 3 dB points)	13 MHz
IF bandwidth	630 kHz
System noise figure	4.9 dB
Antenna pattern type	Pencil
Antenna scan rate	0.84 r.p.m.
Antenna scan time	71.4 s
Antenna height	30 m
Antenna beamwidth	0.90°
Polarization	Linear horizontal

In the mode used, the antenna rotation starts at an elevation of 0.5°, the radar transmits a 4.7 μs pulse every 3.1 ms for the first rotation, then transmits a pulse every 2.24 ms for the second rotation. These correspond to PRFs of 322 Hz and 446 Hz respectively. Each revolution covers 360° in azimuth. Under normal operation, the radar also performs antenna rotations at several higher elevation angles before returning to 0.5°. For the purposes of this test, the two elevation cuts at the single antenna elevation provided sufficient data for analysis and the cuts at higher elevations were not performed. The first antenna rotation is used to measure reflectivity and the second rotation is used to measure mean radial velocity and spectrum width (see further). For each location in the atmosphere, multiple pulses are transmitted and received. Due to the duration of the transmit pulses compared to the time between pulses, the system is in receive mode more than 99.5% of the time. Magnitude of the received pulses are approximately 200 dB lower than the transmitted pulses because the pulses are scattered by small airborne objects (on the order of millimetres in diameter or smaller) at distances up to hundreds of kilometres from the radar. The received signal is down-converted from 2 995 MHz to the IF frequency of 57 MHz where it is then applied to the synchronous detector. The detected I and Q baseband signals are digitized to a 16-bit level for use in the processing subsystems.

3.2 Output products

The returned pulses from each location are used by the processing subsystems to derive the three meteorological base moments of base reflectivity, mean radial velocity, and spectrum width. The base moments are displayed as products to users and are used to develop other meteorological products representing rainfall accumulation, tornadoes, wind shear, etc. Reflectivity is derived from the amplitude (or power) of the received signal. Mean radial velocity is the mean radial speed and is derived from the differences in the I and Q vectors caused by the Doppler shift. Spectrum width is the variance between pulses of the velocities received from the same location.

3.3 Interference sensitivity

Base products are affected by interference in two different ways. First, values can be biased which decreases the accuracy of the system, and second, the variance of the outputs can be affected. In the presence of interference, reflectivity is sensitive to bias, mean radial velocity is sensitive to variance errors, and spectrum width is affected by both bias and variance errors. For spectrum width, the errors due to biasing are more significant than the errors due to variance because the bias, or offset, represents a velocity measurement error while the variance represents the uncertainty of the velocities measured. Table 6 shows which interference induced errors, bias and variance affect the base products.

TABLE 6

Sensitivity of base meteorological products from interference induced error

	Interference induced errors	
Base product	**Bias**	**Variance**
Reflectivity	X	
Velocity		X
Spectrum width	X	X

The radar was designed with specific performance criteria to achieve the highest level of weather forecasting possible. The radar technical requirements specify the reflectivity calibration must be accurate too less than 1 dB (0.5 dB is achieved in practice). Reflectivity is seriously contaminated if the bias in the estimate exceeds 1 dB. A 1 dB bias is twice the radar calibration accuracy and is equal to the standard deviation of the reflectivity estimate specified in the meteorological radar technical requirements. Velocity and spectrum width must be accurate to 1 m/s as specified by the technical requirements. The velocity measurements are severely compromised if the interference increases the estimated variance by more than 50%. The uncertainty in the data degrades the mean radial velocity-based products. When these levels are exceeded due to interference, use of the radar system as a forecasting tool is severely compromised and harmful interference has occurred.

Of the three base products, spectrum width is the most sensitive because it is derived from an autocorrelation function that is highly sensitive to noise. Interference levels that affect the accuracy by more than 1 m/s will compromise system performance. Mean radial velocity and spectrum width are used jointly to distinguish wind, which has a low spectrum width, from tornadoes and other violent weather phenomena that have high values of spectrum width. The radar threshold for interference is limited to the 1 m/s spectrum width bias.

4 Measurement approach

The measurements were conducted by injecting the interference signal into the radar receiver, using a coupler to combine the interference with the signal received by the radar. The operating frequency of the particular radar tested and the simulated interference signal frequency was 2 995 MHz.

NOTE 1 – Recommendation ITU-R M.1464 recognizes that meteorological radar systems can operate up to 3 000 MHz.

The interference signals used in the testing are shown in Table 7.

TABLE 7

Interference signals

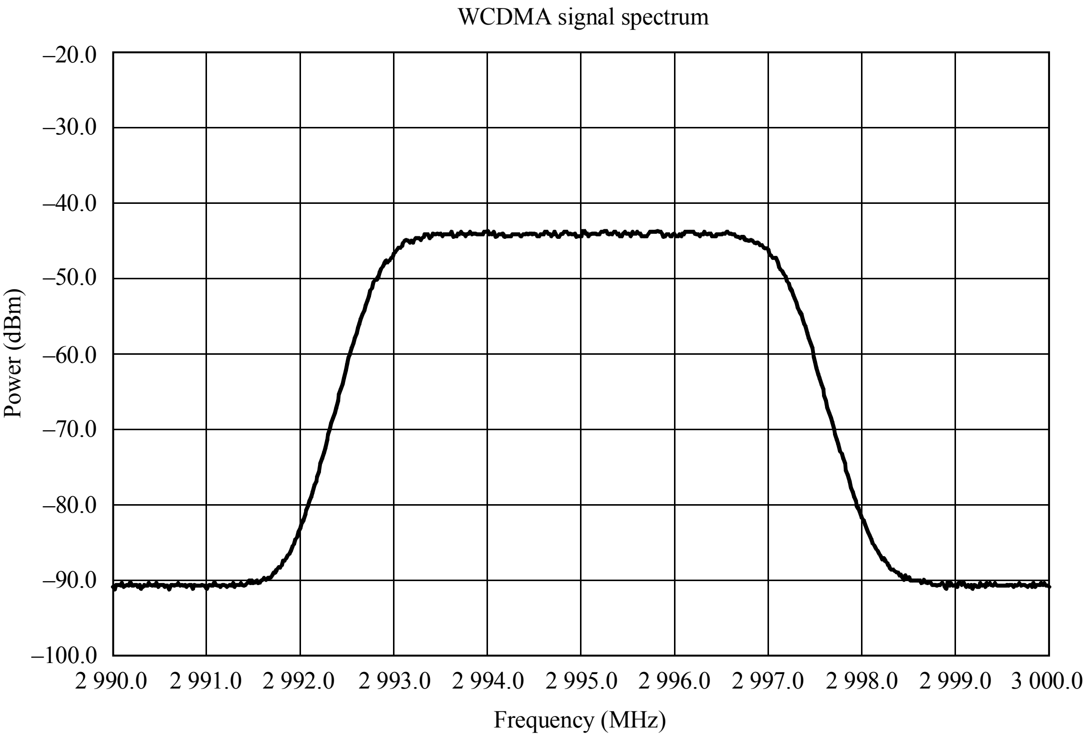
Interference signal source Centre frequency = 2 995 MHz	
CW	
WCDMA	4.096 Msamples/s
CDMA-2000-3X	3.686 Msamples/s
EDGE-GMSK	384 ksamples/s
EDGE-8-PSK	384 ksamples/s
DECT	1.152 Msamples/s

WCDMA:	wideband CDMA
GMSK:	Gaussian filtered minimum shift keying
DECT:	digital enhanced cordless telecommunication

The spectrum for the WCDMA and CDMA-2000 3X signals are shown in Figs. 8 and 9.

FIGURE 8

Spectrum plot for WCDMA signal

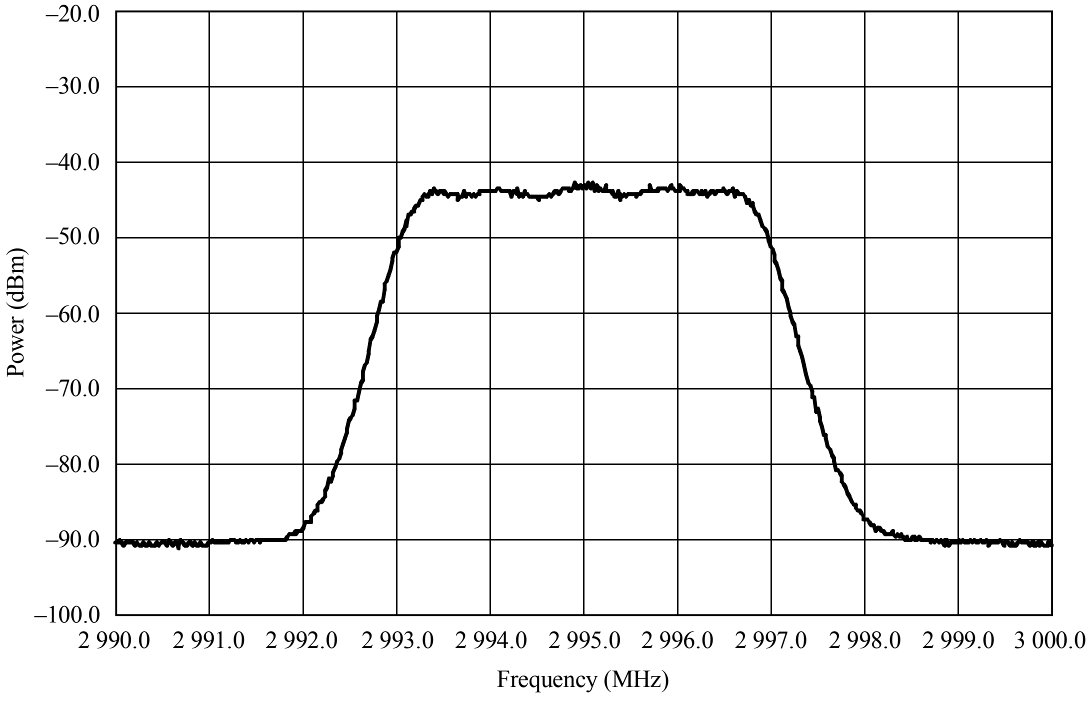


Spectrum analyser settings:
Resolution bandwidth: 300 kHz
Sweep time: 5 s

1464-08

FIGURE 9

Spectrum plot for CDMA-2000 3X signal



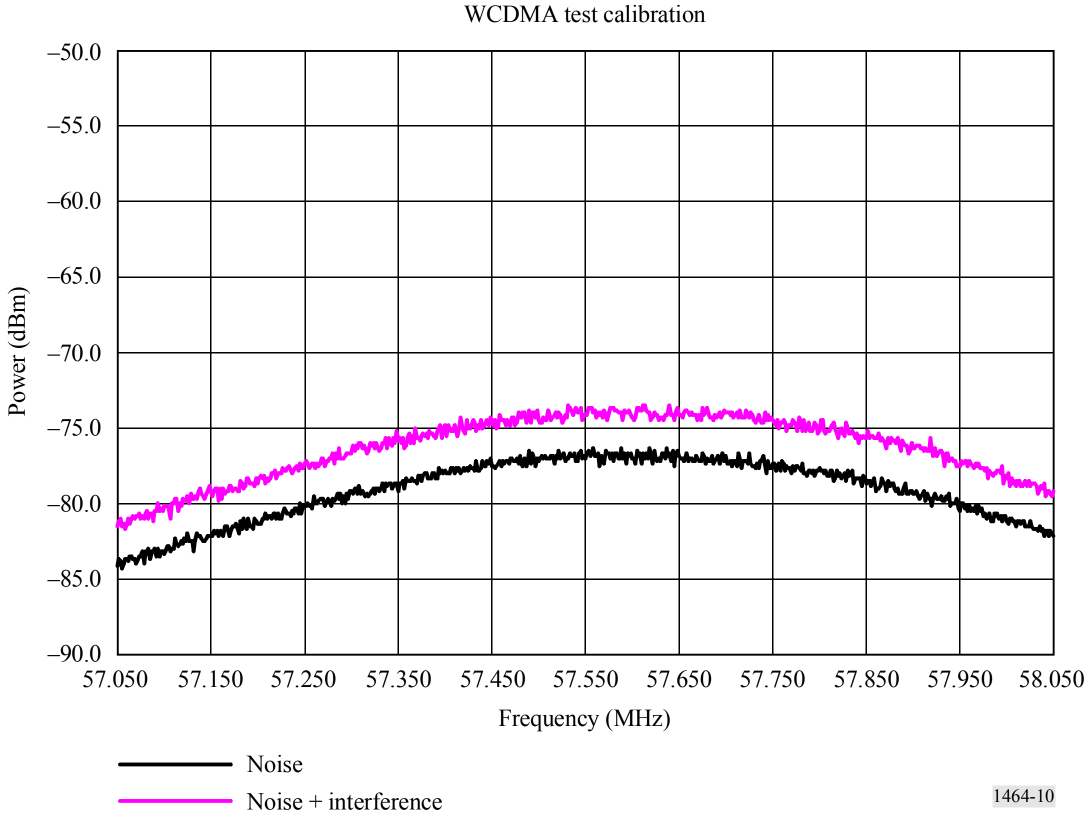
Spectrum analyser settings:
Resolution bandwidth: 300 kHz
Sweep time: 5 s

1464-09

To calibrate the test set-up for a known interference level at the radar receiver input, the receiver noise floor was measured, without presence of interference, at the 57.55 MHz IF output of the receiver. Once the noise floor was recorded at the IF output, the interference signal level was activated and increased until the radar IF output noise floor increased by 3 dB. The point at which the noise increased by 3 dB corresponded to the interference level within the radar passband being equal to the radar receiver noise within the passband, and an *I*/*N* ratio of 0 dB. The signal source output was recorded for the 0 dB *I*/*N* and the actual level being injected into the radar receive path was also measured and recorded. Knowing the signal source setting for the 0 dB *I*/*N*, the signal source could be set for any other desired *I*/*N* by adjusting the signal source output level. Testing was conducted at interference level points corresponding to *I*/*N* levels of –15 dB, −12 dB, −10 dB, −6 dB, −3 dB, 0 dB, +3 dB and +6 dB. Figure 10 provides example results of the receiver noise measurements with and without the presence of interference for the WCDMA signal tests.

FIGURE 10

0 dB *I*/*N* calibration noise spectrum (57.55 MHz IF centre frequency) for WCDMA

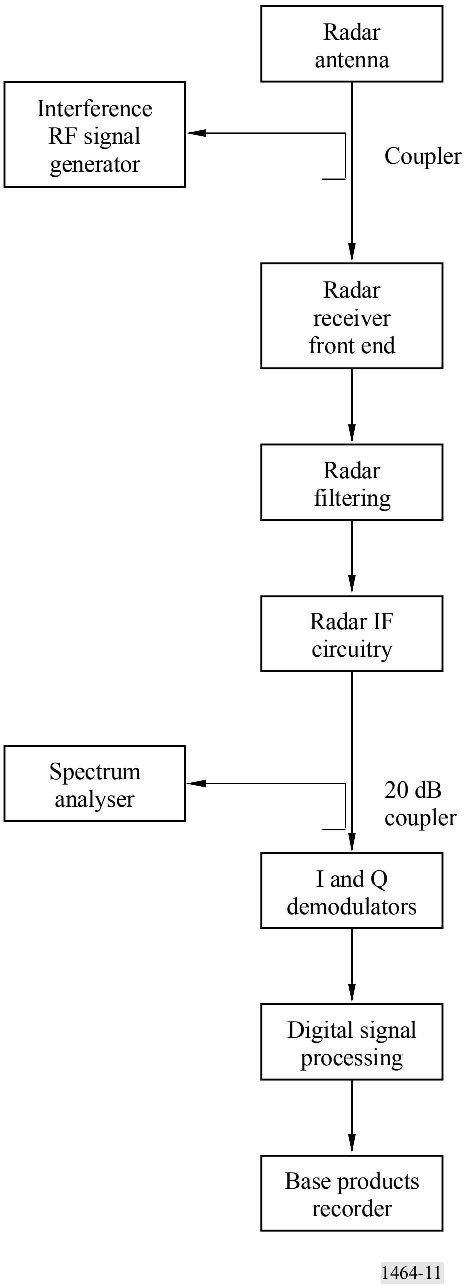


The radar was set to scan the atmosphere, hereafter called a "volume scan", at one antenna elevation without interference followed by a volume scan with interference. For each volume scan, with or without interference, the antenna made two complete rotations allowing elevation cuts at the same elevation using two different PRF. The PRF used on the first rotation is a low PRF optimized for collecting the base reflectivity product. The PRF used on the second rotation is high and is used for collecting the mean radial velocity and spectrum width data. This alternating pattern of volume scans, with and without interference, was continued for the interference levels ranging from –15 dB to +6 dB. This test approach provided a volume scan immediately before and after each interference volume scan that could be used as baseline references for determining the statistical effects of the interference. During the entire test, base product radar data was recorded for analysis.

Figure 11 shows the test set-up which consists of the signal generator feeding an RF coupler where the interference signal is combined with the received radar return signal at input to the receiver. The receiver amplifies and down-converts the signal to IF where it is monitored on a spectrum analyser. The I and Q outputs are digitized and processed to provide the meteorological base products of base reflectivity, mean velocity and spectrum width. The base products were recorded for statistical analysis. Testing with each of the interference signal types, at all data rates and modulation schemes was not feasible due to the large number of combinations. The test signals were selected to cover CDMA and TDMA signals as well as several modulation schemes and a range of data rates.

FIGURE 11

Test set-up block diagram



5 Data analysis assumptions, methodology and results

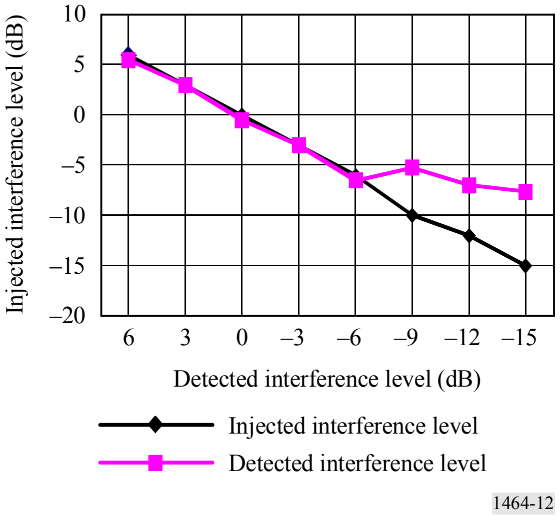
Radars tested in the past have been used for navigational purposes where point targets are detected. Meteorological radar collects a much different type of data in that they perform a volume scan of the atmosphere and a present data on the atmosphere for a full 360° in azimuth and up to elevations on the order of 60°. For previous reports, where the radars tracked point targets, analysis of the effects of interference on the probability of detection often was sufficient. Interference on those types of systems often masked desired targets or created false targets. In meteorological radar, where data is collected and analysed for a volume of the atmosphere, the radars performance is not characterized with the use of probability of detection. The data analysis must take a much different approach in order to provide meaningful results. Rather than studying the effects on probability of detection, statistical analysis is performed on the low level meteorological data for each range gate response received. Studying visual responses displayed on the radar display does show some effects on the interference, but does not provide a scientific analysis of the results on the meteorological products generated such as rain fall estimates, wind speed measurement or shear detection.

5.1 Assumptions

- As stated earlier, the test procedure used to inject interference signals into the radar receiver called for injecting a known interference level at the radar receiver's input. The data analysis process for graphically determining the *I*/*N* level at which a 1 dB bias will take advantage of this known interference level.
- For this particular radar, the minimum usable signal, with current technology, is 3 dB below the noise floor.
- For the reflectivity product, the required maximum *I*/*N* ratio is equal to the interference level below the signal that results in a 1 dB bias plus the minimum signal level that needs to be retrieved (–9 dB from § 2.2).
- For the spectrum width product the maximum *I*/*N* ratio is equal to the interference level below the signal that results in a 1 m/s difference in the spectrum width (–14.4 dB from § 2.4).
- The system uses processing to remove the effects of noise, allowing the radar to process signals below the noise floor. In a system that contains no residual noise effects, one would expect the interference that was injected at the receiver input to linearly track the interference level that was detected through the data analysis. Figure 12 compares the relative levels of the interference that was injected at the receiver input to the interference level that was detected through the data analysis. A divergence can be seen at approximately –6 dB.

FIGURE 12

Injected vs. detected interference level



The impact of this residual effect impacts our analysis in the following way:

- *Reflectivity:* No effect as the graphical technique that was used to determine the level at which a 1 dB bias in the reflectivity occurs is relative and is not impacted by this residual effect.
- *Spectrum width:* Residual noise, which is present as a result of the uncertainties associated with the setting of the absolute interference levels and the uncertainties associated with the noise removal process, impacts our ability to graphically determine the level at which the spectrum width difference exceeds 1 m/s.

We can use the data from Fig. 12 to compensate for errors that were introduced by using a graphical technique to determine the level at which the spectrum width difference is 1 m/s. Table 8 lists the correction values that are applied to the spectrum width analysis. The data is not required for the reflectivity analysis.

TABLE 8

Level correction values

Injected interference level *I*/*N* (dB) – A	**Detected interference level *I*/*N* (dB) – B**	**Correction values (B – A)**
6	5.5	–0.5
3	3	0
0	–0.5	–0.5
–3	–3.0	–0.0
–6	–6.5	–0.5
–10	–5.25	4>75
–12	–7	5
–15	–7.6	7.4

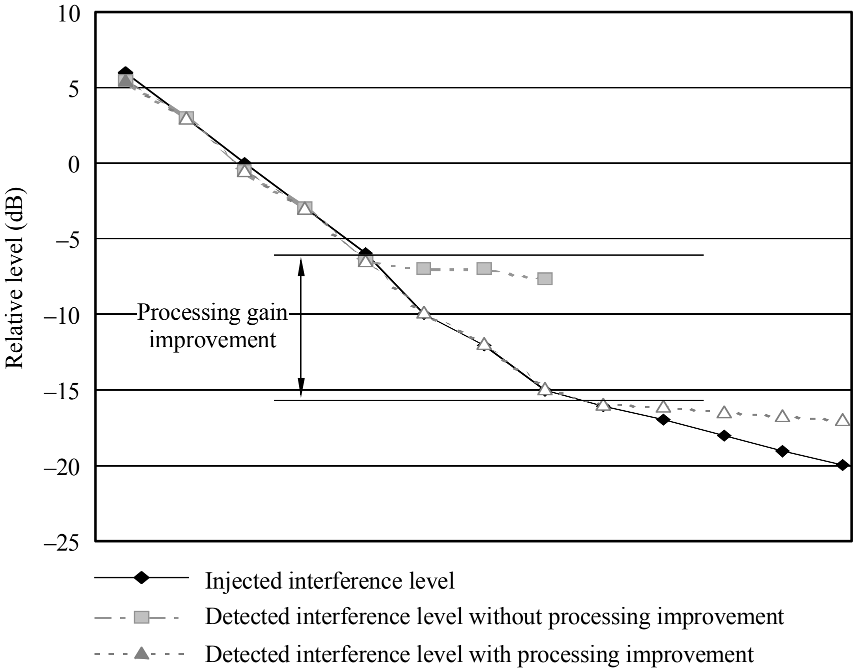
Additional variability that adds to the data analysis errors comes into play as a function of graphically estimating the mean and associated data points.

Introduction of the radar improvements discussed in § 6 will provide about 10 dB of processing power, resulting in a reduction in the effective noise floor by a value equivalent to the detection improvement. The end result is that the point where the radar's actual sensitivity to interference deviates from the theoretical curve in Fig. 13 will decrease by the amount equal to the processing power. Figure 12 shows the test results deviate from theory at an I/N = –6 dB. Introducing improvements providing 10 dB of processing power will move that point to an I/N = –16 dB. However, the value at which the performance is degraded beyond the system requirements due to interference (bias of 1m/s) dictates the I/N should be equal to –14.4 dB as demonstrated through earlier calculations and measurements.

NOTE 1 – The effects of the proposed receiver improvements that are illustrated in Fig. 13 are theoretical and are not based upon actual measurements.

FIGURE 13

Impact of processing gain improvement on *I*/*N*



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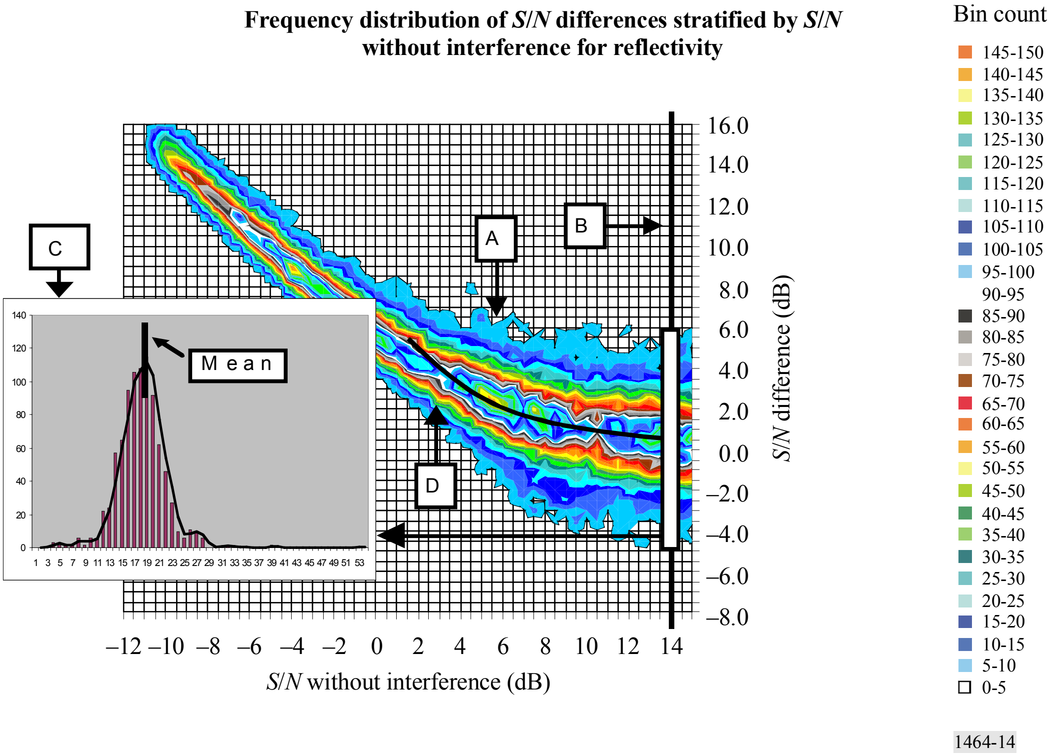
5.2 Data analysis methodology

Data from a number of volume scans (see § 4) were collected and processed using the radar product generation algorithms. The data that was collected represented thousands of data points that, as a function of the volume scan, were segmented into 920 bins across 360 radials. A C program was developed to analyse the data. At a high level, this program sorted the overall data into two arrays, S/N without interference (S/N) and S/N with interference $(S+I+N)/N$. A third array, S/N difference, was calculated that contained the difference between the S/N without interference (S/N) and the S/N with interference arrays $(S + I + N)/N$. The contents of this array were stratified by bin count (S/N without interference). The numbers of entries that have the same value were collected in these bins, colour-coded and then plotted. The regression can be seen in Fig. 14-A where it is displayed as a colour-coded contour diagram.

Slicing this contour diagram at a specific S/N without interference level (Fig. 14-B) gives us some insight into the distribution of the S/N differences. The values associated with the various S/N differences that are contained within the S/N without interference bin that is defined by any given S/N without interference level of 14 dB are plotted as a bar chart in Fig. 14-C. The item of interest is the mean of this distribution as it provides the average S/N difference due to interference for a specific S/N without interference value. We can determine the average S/N difference for each S/N without interference level and from that plot a single line (Fig. 14-D) that represents the average S/N difference as a function of S/N without interference. This forms the basis of the data that will be used for a graphical analysis that enables estimation of the measured bias of the signal plus interference in the presence of interference.

FIGURE 14

Frequency distribution of *S*/*N* differences stratified by *S*/*N* without interference for reflectivity



The regression of the difference in power with and without interference (*S*/*N* difference) of the signal without interference (*S*/*N* without interference) is the bias as a function of signal level since this is the difference between the true signal level and the signal plus interference, which is interpreted as the signal in the presence of interference.

At an *S*/*N* difference of 3 dB, i.e. a factor of two, the interference level is equal to the signal level. Since the processing removes the effects of noise, noise power can be disregarded. This enables estimation of the interference level and serves as a convenient reference point. The bias in the signal plus interference measurement can be specified as signal level relative to interference level or *S*/*I* ratio. Since the system noise is a know signal level and the interference level can be expressed as *S*/*N* and *I*/*N* ratios.

The expected behaviour of the regression is:

– As the signal becomes large relative to the interference the difference becomes small.

– When the signal and the interference are equal the *S*/*N* difference is 3 dB.

– As the signal becomes small relative to the *S*/*N* interference the difference becomes the interference ratio.

This behaviour can be seen in the regression/contour diagram of Fig. 14-A. Having the 3 dB point as a reference allows us to graphically determine the *I*/*S* ratio for any *S*/*N* difference by simply taking the difference between the *S*/*N* without interference level that is associated with an *S*/*N* difference level of 3 dB and the *S*/*N* without interference level that is associated with the *S*/*N* difference of interest. Since the *I*/*S* ratio at an *S*/*N* difference of 3 dB equals zero, this difference will be the *I*/*S* ratio that is associated with the S/N difference of interest. Since the radar receiver has the capability of pulling signals out of the noise to a level of –3 dB the I/N ratio that is required to protect to a given S/N difference level is then equal to:

$$I/N = I/S + (-3\text{ dB})$$

where:

I/S = (S/N without interference level (S/N) at S/N difference level = 3 dB ((where $S = I$) – (S/N without interference level (S/N) at S/N difference of interest (1 dB for reflectivity))

The factors that need to be taken into account when working through the graphical analysis technique include:

S_u: the lowest usable signal level in the presence of noise

I: the interference level

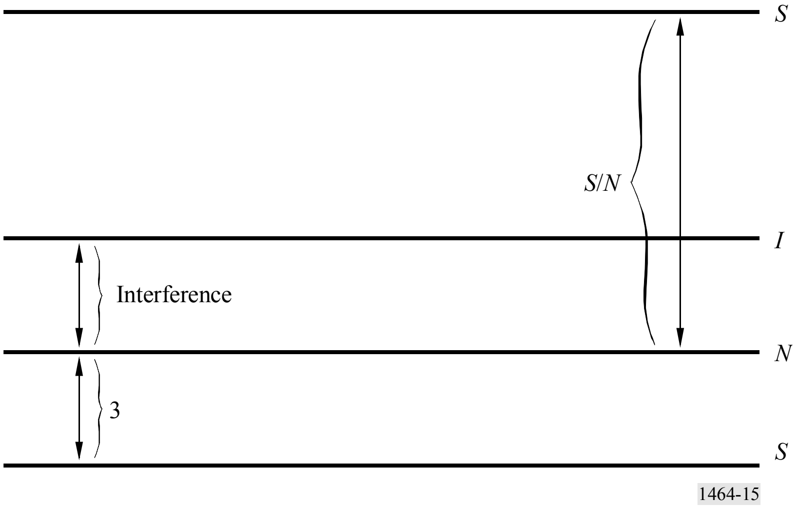
N: the noise floor of the receiver

S_m: the minimum signal that is recoverable if interference is not present and S/N without interference.

The relationship between the factors is illustrated in Fig. 15.

FIGURE 15

Factors involved in the determination of *I/N*
(for a 1 dB bias in reflectivity)



For analysis purposes let us assume that we have a relative interference level, I, of 6 dB above the noise floor and that we have determined, from the contour diagram, that the level at which a 1 dB bias occurs, S/N with interference is equal to 10.6 dB. In addition we know that $S_m = -3$ dB and that our measurements are made relative to the noise floor, N.

In this case a S/N without interference level of 10.6 dB or more is required to ensure that the reflectivity bias does not exceed 1 dB for a given interference level of 6 dB. The actual interference level can be obtained from the contour diagram at the point where $S = I$. For this data set the actual injected interference value is 4.5 dB relative to the noise floor. The 1.5 dB difference between the actual (I/N = 4.5 dB) and the injected relative interference level (I/N = 6 dB) occurs as a result of uncertainties in the setting of the injected interference level and uncertainties in the graphical analysis. In particular, the regression function is varying slowly in the part which is used for assessment of the injected interference level I and of the S/N for which the 1 dB bias occurs, hence, making results particularly sensitive to any variation of the measurement and graphical analysis conditions.

We need to bring S_u down to S_m in order to meet the 1 dB bias criteria at the radar's minimum used sensitivity. To do this we must decrease S_u by an amount that is equivalent to:

$$I - (S/N + S_m)$$

This gives us the equivalent I/N that is needed in order to assure that a 1 dB bias is not exceeded at the minimum sensitivity level.

S_m is S/N with interference (S/N) + 3 dB lower than S_u. So S_u must be lowered to S_m. This is a drop of 10.6 + 3 dB, a total of 13.6 dB in this case.

Therefore the interference level, I must be lowered by 13.6 dB. It is now 4.5 dB relative to N. So, for this example the equivalent I/N that is required to accomplish this is equal to:

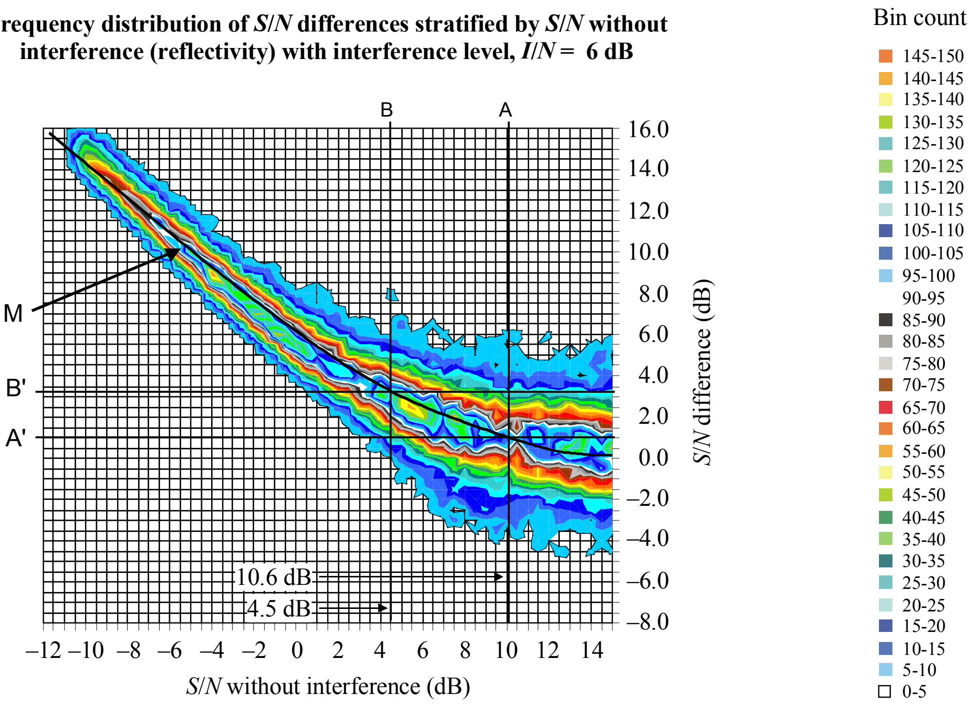
$$\text{Equivalent } I/N = 4.5 - (10.6 + 3) = -9.1 \qquad \text{dB}^{*}$$

These factors form the basis of the graphical analysis technique that is described in § 5.3 which compensates for the uncertainty that is associated with the setting of the absolute interference level.

5.3 Reflectivity analysis methodology

FIGURE 16

Frequency distribution of *S/N* differences stratified by *S/N* without interference (reflectivity) with interference level, *I/N* = 6 dB



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[*] The equivalent I/N could be increased to –7.6 dB if the calculation assumes that the correct I/N is +6 dB instead of 4.5 dB.

What we want to determine from Fig. 16 without is the *I*/*S* ratio that results in a 1 dB difference in the *S*/*N* relative to the level at which the *S*/*N* difference is 3 dB (*I*/*S* = 0). From this we can then determine the appropriate *I*/*N* protection ratio for the reflectivity product. We can determine the *I*/*S* ratio given the information that we have; the mean of the regression, the *S*/*N* difference level at which the *I*/*S* = 0 and the *S*/*N* difference level that corresponds to a difference or bias of 1 dB. The first step in the graphical analysis is to determine the mean of the regression (M on Fig. 16).

The next step is to identify the point where *I*/*S* = 0 dB. This corresponds to an *S*/*N* difference of 3 dB (Fig. 16, line B'). The reflectivity data becomes compromised at an *S*/*N* difference of 1 dB (Fig. 16, line A'). The next step is to identify the point of intersection between the mean, M, and the 3 dB *S*/*N* difference that corresponds to an *I*/*S* of 0 dB (B'). This yields an *S*/*N* without interference of 4.5 dB. This is the relative level at which the *I*/*S* ratio = 0 dB. The next step is to identify the point at which the *S*/*N* difference is equal to 1 dB (line segment A'). Line segment A' intersects with the mean M at a point where the *S*/*N* without interference equals 10.6 dB. The difference between the two points that are identified by the intersection of line segments A and B with the x axis corresponds to the *I*/*S* level that results in a 1 dB bias relative to an *I*/*S* value of 0 dB. This value can be determined by simply taking the difference between the point at which line segment A intersects the x axis and the point at which line segment B intersects the x axis. This results in an *I*/*S* ratio of (4.5 – 10.6 = –6.1 dB). This is the *I*/*S* below the minimum signal recovered, which has an *S*/*N* of –3 dB.

$$\text{Equivalent } I/N = (I/S) + (-3 \text{ dB})$$

The data taken from this graphical analysis yields the following result:

$$\text{Equivalent } I/N = -6.1 \text{ dB} + (-3 \text{ dB}) = -9.1 \text{ dB}$$

It has to be noted that, assuming that the correct *I*/*N* is 6 dB instead of 4.5 dB, the *I*/*N* could increase up to –7.6 dB.

The results of using this analysis technique for a single interference type across the full range of relative interference levels that were tested (*I*/*N* of +6 to –15 dB) is detailed in Table 9.

TABLE 9

Relative interference test level	**Equivalent *I*/*N* level at which a 1 dB bias occurs**
6	–9.1
3	–9.5
0	–9.5
–3	–10
–6	–7.5
–10	–9
–12	–7.5
–15	–8

The mean and the standard deviation of this data set are:

Mean = –8.8

Standard deviation = 0.9

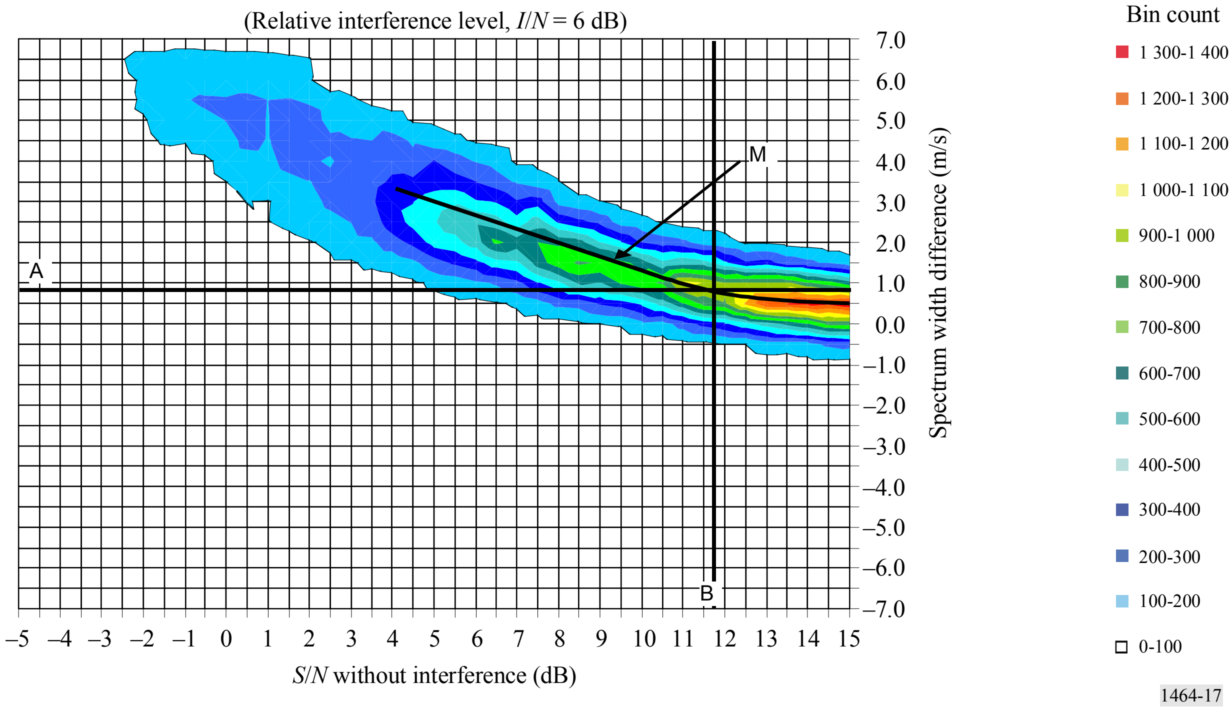
These results are consistent with and support the theoretical result that was derived in § 2.2. However there is inherent uncertainty in these measurements.

5.4 Spectrum width analysis methodology

A similar analysis approach can be taken for determining the level at which a 1 m/s bias occurs in the spectrum width. In this case the regression used for graphically determining this value is shown in Fig. 17. (This is the same data set that was used in Fig. 16.)

FIGURE 17

Frequency distribution of spectrum width stratified by *S*/*N* without interference



The process is very similar to the method used to determine the *I*/*N* level for the reflectivity product. We know that the point at which the spectrum width data is degraded beyond acceptable limits is the point at which the bias in the estimate of the spectrum width is equal to 1 m/s. This corresponds to a spectrum width difference of 1 m/s in Fig. 17 (line segment A). Once again we fit a mean to the regression and identify the point at which line segment A intersects with the mean (line segment B). This corresponds to an *S*/*N* without interference level of 11.75 dB. The actual *I*/*N* ratio that results in a difference in spectrum width that compromises the spectrum width data is defined by the following equation:

I/*N* (spectrum width) = –((*S*/*N* without interference level at which the spectrum width difference is 1 m/s) – (relative level at which the *I*/*S* ratio equals 1 dB) – (level correction factor))

In this example the *S*/*N* without interference level at which the spectrum width difference is 1 m/s can be derived from Fig. 17 and is equal to 11.75 dB.

The level at which the *I*/*S* ratio for this data set equals one can be derived from the reflectivity analysis is Fig. 16. *I*/*S* equals one where the *S*/*N* difference is equal to 3 dB. In this example the level (*S*/*N* without interference level) at which the *S*/*N* difference is equal to 3 dB is equal to 4.5 dB.

Given this data, the *I*/*N* ratio that is required to meet the spectrum width specification corresponds to the following:

$$\text{Equivalent } I/N \text{ (spectrum width)} = -(11.75 - 4.5) - 3 - 0.5 = -10.75 \quad \text{dB}$$

It has to be noted that, assuming that the correct *I*/*N* is 6 dB instead of 4.5 dB, the equivalent *I*/*N* (spectrum width) could increase up to –9.25 dB.

The results of using this analysis technique for a single interference type across the range of relative interference levels that were not heavily impacted by the residual noise effects (*I*/*N* of 6 to –6 dB) are detailed in Table 10.

TABLE 10

Interference level (dB)	**Equivalent *I*/*N* level at which a 1 m/s difference occurs (dB)**
6	–10.75
3	–10.9
0	–12.3
–3	–9.75
–6	–12.25

The mean and the standard deviation of this data set are:

Mean = –11.2

Standard deviation = 0.97

For this particular radar, the *I*/*N* ratio that was derived from the actual spectrum width measurement data is consistent with § 2.4 and 5.1. However, there is inherent uncertainty in these measurements.

5.5 Summary of actual measurement results

Overall test results using various IMT-2000 modulation techniques as interference signals are shown in Table 11. These values were derived using the graphical analysis technique that was described in § 5.2, 5.3 and 5.4 where the relative interference level was set to an *I*/*N* of 6 dB.

TABLE 11

Measured interference thresholds (*I*/*N*) necessary for protection of the radar from harmful interference

Interference signal		Reflectivity *I*/*N*	Spectrum width *I*/*N*
CW		–7.5	–10.5
WCDMA	4.096 Msamples/s	–9.5	–8.75
CDMA-2000-3X (fwd link)	3.686 Msamples/s	–7.0	–10
CDMA-2000-3X (rev link)	3.686 Msamples/s	–9.5	–10.5
EDGE-GMSK	384 ksamples/s	–8.75	–10.75
EDGE-8PSK	384 ksamples/s	–8.75	–9.75
DECT	1.152 Msamples/s	–9.5	–10
Mean		–8.6	–10.04
Standard deviation		0.94	0.62

These results support the calculated value required for protection of the reflectivity product. It should be noted that figures in Table 11 are based on an indirect determination of the injected *I*/*N* level for which the test was run in comparison to nominal value that was intended to be injected. Using the values of the nominal intended *I*/*N* value, rather than the indirectly determined value, may modify these values.

As noted earlier, the measurements and analysis of the mean velocity were difficult to perform, however, because the mean radial velocity is the least sensitive to interference, the results do not affect the overall interference levels that the radar can tolerate.

The results suggest that the measured value of the *I*/*N* ratio that is required to protect the spectrum width product is slightly lower that the values that were calculated in § 2.4. As discussed above, current limitations in the radar calibration and noise removal process performed by the low level data processor limit the measurement of the necessary protection criteria for the spectrum width measurements. Improvements to the radar receiver and processor are currently underway which will allow the system to approach or exceed its originally intended design criteria. § 6 addresses those improvements in more detail.

6 Radar improvements

The radar system that was used for testing is one that has been operating in one administration for approximately 11 years. Upgrades to these systems that incorporate advances in signal-processing systems are currently under way. These upgrades will enable signal detection at a level that is about 10 dB lower than the current level.

The need for these improvements are driven by several requirements:

– improved measurement performance above the planetary boundary layer;

– detection of small water drops and fine mist precipitation that can result in aircraft icing;

– with the event of dual polarization measurements, improved monitoring of meteorological growth process.

All of these requirements call for a detection performance that is about 10 dB better than what is achievable today with current weather radar systems.

To meet these requirements the radar’s performance can be improved by increasing the transmitter power, reducing the receiver’s noise floor or increasing the radar’s computational power.

Increasing the transmitter power is not cost effective. Noise floor reduction could be accomplished by extending the pulse width. Extending the pulse width reduces the required bandwidth of the matched filter thereby reducing the noise power within the receiver IF. Increasing the pulse width by a factor of 2 increases the sample volume by a factor of 3 dB. Matching the receiver bandwidth results in a reduction of the receiver noise by 3 dB. This leads to an overall detection improvement of 6 dB. Unfortunately, design limitations on the transmitter duty cycle will not allow extension of the pulse width for the system used in these tests. The noise temperature of the receiver could also be reduced but a reduction of 1 to 2 dB in noise is all that can be achieved. Therefore, the most cost-effective way to achieve these improvements is through enhanced signal processing.

Implementing dual polarization requires dividing the transmit signal power between horizontally and vertically polarized antenna feeds, resulting in a 3 dB reduction in transmit power on a single polarization. This reduction in transmit power must be offset elsewhere so performance will not be degraded.

The reductions in transmit power for each polarization combined with the increased detection capability results in a minimum requirement of about 10 dB of improvement in the radar’s performance. Increasing the radar processing power with upgraded hardware will enable implementation of data processing algorithms that were not previously available. This additional processing will utilize coherent integration and frequency domain detection. The radar currently collects all the parameters necessary for performing these functions, but the limited processing power has prevented its implementation. The planned improvements that are currently under way will eliminate the processing power limitation. Coherent integration, as implemented on this radar, has demonstrated a 10 dB improvement in detection. Frequency domain detection, the upgrade that is presently under way, will provide about 10 dB of improved performance. With frequency domain detection, the spectrum is broken into discrete coefficients, where the actual number of coefficients is determined by antenna rotation rate and operating mode. In the present storm modes the number of samples range from 41 to 111. Processing in the frequency (spectral density calculation) domain results in the desired signal being confined to a few spectral coefficients while the noise is spread over all the coefficients at a much lower level.

The improvements to the radar performance enabled by greater processing power do not reduce the actual noise floor of the receiver, but the effect is a reduction in the effective noise floor by providing the ability to recover signals of interest at much lower signal levels. The difference between the actual noise floor and the effective noise floor is the processing detection improvement.

7 Overall summary

The test results support the requirement for a protection value that could be as low as –9 dB *I*/*N* for the base reflectivity data in the conditions given in the previous sections. Calculations show that the *I*/*N* value at which the spectrum width performance is degraded beyond the system requirements (bias ≥ 1m/s) is even lower (–14.4 dB) but measurements only support an *I*/*N* of –10 dB for spectrum width.

In order that the most sensitive meteorological product be protected, the *I*/*N* = –10 dB should be used.