REPORT ITU-R M.2136*

Theoretical analysis and testing results pertaining to the determination of relevant interference protection criteria of ground-based meteorological radars

(2008)

The present Report provides theoretical analysis and testing results pertaining to the determination of relevant interference protection criteria of ground based meteorological radars with the key objective to establish the maximum interference level that meteorological radar systems can withstand before their forecasting capability is compromised.

The analysis and related test results as in Annex 1 are related to meteorological radars operating in the frequency band 2 700-2 900 MHz and support the requirement for a protection value that could be as low as –9 dB I/N for the base reflectivity data. Calculations show that the I/N value at which the spectrum width performance is degraded beyond the system requirements (bias ≥ 1 m/s) is even lower (–14.4 dB) but measurements only support an I/N of –10 dB for spectrum width.

The test results performed with a meteorological radar operating in the frequency band 5 600-5 650 MHz as in Annex 2 confirm the analysis described in Annex 1 for meteorological radar operating in the frequency band 2 700-2 900 MHz and support the requirement for a protection value that could be as low as –12.75 dB I/N for the base reflectivity, i.e. for products that are related to signal power. For meteorological products not related to signal power (such as Doppler of differential phase modes) lower sensitivity thresholds would likely be necessary.

As an overall conclusion, this Report provides elements that confirm that, in order that most meteorological radars and their corresponding products be protected, a minimum I/N = –10 dB should be used.

---

* This Report should be brought to the attention of the World Meteorological Organization (WMO).

Annex 1

Results of tests with a meteorological radar operating in the frequency band 2 700-2 900 MHz

Executive summary

The key objective of the work contained in this Annex 1 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 Introduction

Tests were run on a modern meteorological radar (noted as radar 1 in Annex 2 of Recommendation ITU-R M.1849) to determine the appropriate criteria necessary for protection from continuous wave (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 maximum *I*/*N*

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 the system specifications[1]. Given the radar systems dB bias and *S*/*N*, the following equations can be used to calculate the *I*/*N* that is required in order to protect the integrity of the reflectivity product.

Bias in terms of *I*/*S* is given by:

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

Solving for *I*/*S* yields:

$$I/S = \left[10\hat{}\left(\frac{\text{dB bias}}{10}\right)\right] - 1$$

I/*N* is then equal to:

$$I/N = 10 \log (I/S) + S/N$$

Example calculation for a 1 dB bias and an *S*/*N* of –3 dB:

$$I/S = \left[10\hat{}\left(\frac{1}{10}\right)\right] - 1$$

$$I/S = 0.26$$

$$10 \log I/S = -5.8 \text{ dB}$$

Therefore, reflectivity is biased 1 dB at an interference level 5.8 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 −5.8 dB, the maximum *I*/*N* is:

$$(-3 \text{ dB}) + (-5.8 \text{ dB}) = -8.8 \text{ dB } I/N$$

---

[1] The dB bias is a function of the radars calibration accuracy and equal to the standard deviation of the reflectivity estimate as specified in the radar technical requirements.

2.3 Mean radial velocity maximum *I*/*N*

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:

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

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 *I*/*N* as a function of a percentage variance increase of a given radars benchmark parameters and *S*/*N* is given by:

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

where[2]:

W: standard deviation of frequency spectrum (Hz)

T: sampling interval (s)

M: number of samples in estimate

N: noise power

S: signal power

β: signal correlation at lag T.

Example calculation for a 50% variance increase of the technical requirements benchmark parameters and an $S/N = -3$ 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:

$$W = 80 \text{ Hz}$$

$$T = 10^{-3} \text{ s}$$

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

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

$$S = 0.5 \text{ N.}$$

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 maximum *I/N*

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

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

---

2 The standard deviation of frequency spectrum (Hz), the sampling interval (s) the number of samples in the estimate and the S/N are governed by the radars technical specifications and performance benchmarks.

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. The I/N at which this bias level occurs can be calculated by solving for the covariance that is defined by the radars performance metric and signal power of $N/2$, then solving for the $S + I$ level that produces a spectrum width that is equal to spectrum width base value as defined in the radars technical specifications plus value of the spectrum width accuracy requirement.

An example calculation follows for radar with a width accuracy requirement of less than 1 m/s at a spectrum width of 4 m/s follows. To calculate I/N, the equation above is solved for the 4 m/s and 5 m/s cases ($S/N = –3$ dB).

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

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

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

$$I/N = 0.0366$$

$$10 \log (I/N) = -14.4 \text{ dB}$$

Table 1 shows the results of several I/N calculations that were based upon varying SNR and spectrum width accuracies. The results show that the theoretical I/N requirements of meteorological radars varies as a function of the radars technical specifications and base data accuracy requirements.

TABLE 1

Comparison of *I*/*N* for several hypothetical meteorological radars

	Radar A	**SNR = –3 dB**	**Radar B**	**SNR = 0 dB**	**Radar C**	**SNR = 0 dB**
	Base data accuracy requirement	**Theoretical *I*/*N***	**Base data accuracy requirement**	**Theoretical *I*/*N***	**Base data accuracy requirement**	**Theoretical *I*/*N***
Reflectivity	<1 dB	–9 dB	<1 dB	–6 dB	<1 dB	–6 dB
Radial velocity	<1 m/s	–3 dB	<1 m/s	0 dB	<1 m/s	0 dB
Spectrum width	<1 m/s	–14.4 dB	<1 m/s	–14.4 dB	***< 2 m/s***	–10.6 dB

From this observation one can conclude that the defining of an "average" *I*/*N* for meteorological radars would provide some degree of overall meteorological radar protection but could not be applicable to all meteorological radars. As a result, *I*/*N* would have to be computed for various meteorological radars based upon their specifications and base data accuracy requirements.

In the absence of test data to determine protection criteria for specific radar, the formulas may be used to derive the protection criteria for studies where more detail is required.

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 PRF. 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 2 provides the characteristics of the mode used in testing.

TABLE 2

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 3 shows which interference induced errors, bias and variance affect the base products.

TABLE 3

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.

The interference signals used in the testing are shown in Table 4.

TABLE 4

Interference signals

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

WCDMA: Wideband CDMA.

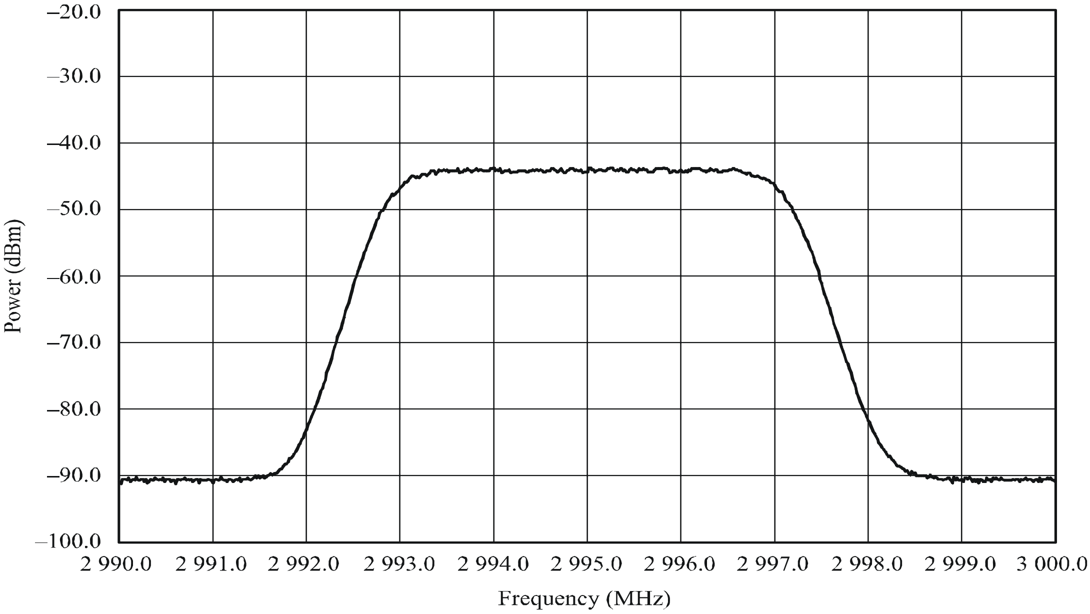
MSK: Gaussian filtered minimum shift keying

ECT: Digital enhanced cordless telecommunication.

The spectrum for the WCDMA and CDMA-2000 3X signals are shown in Figs. 1 and 2.

FIGURE 1

Spectrum plot for WCDMA signal

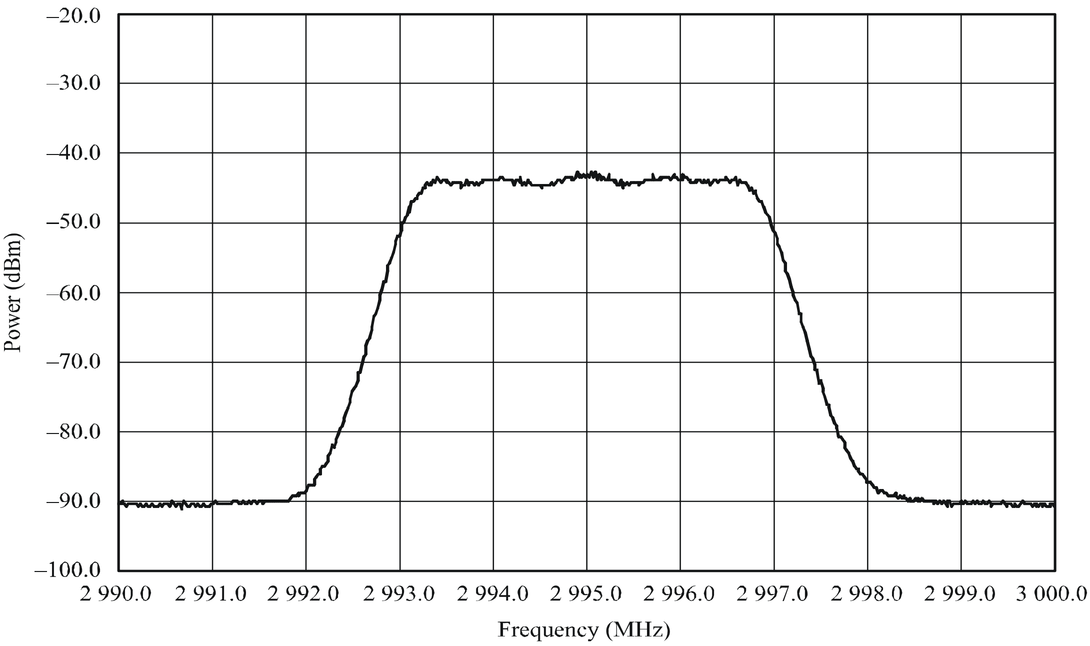


Spectrum analyser settings:
Resolution bandwidth: 300 kHz
Sweep time: 5 s

Rep 2136-01

FIGURE 2

Spectrum plot for CDMA-2000 3X signal



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

Rep 2136-02

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 3 provides example results of the receiver noise measurements with and without the presence of interference for the WCDMA signal tests.

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 3

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

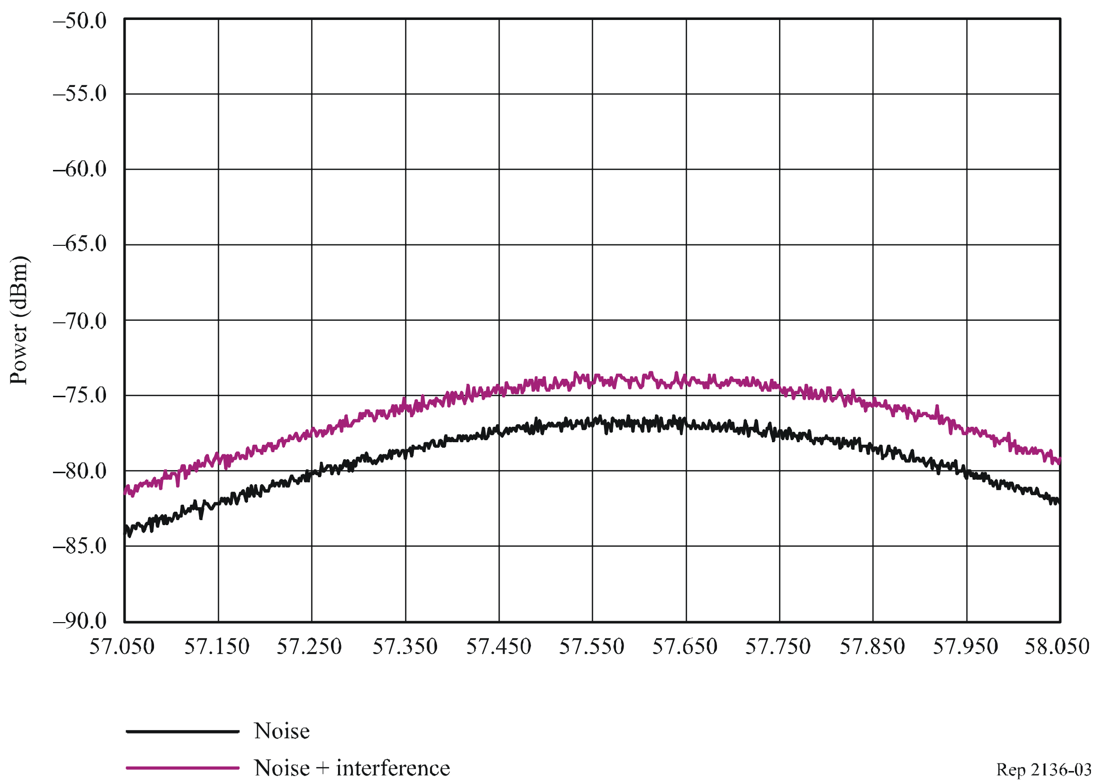
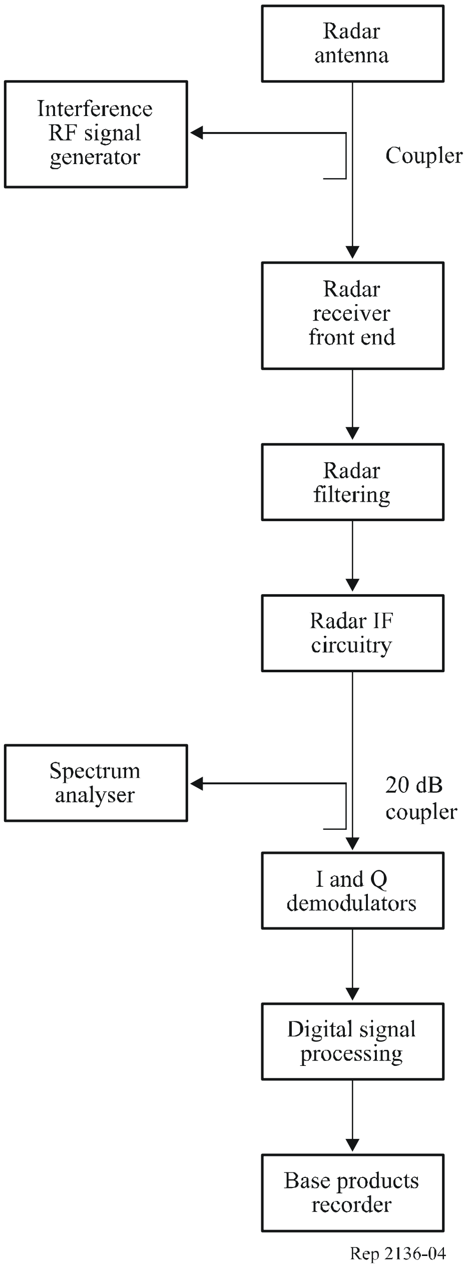


Figure 4 shows the test set-up which consists of the signal generator feeding an RF coupler where the interference signal is combined with the received radar return signal at input to the receiver. The receiver amplifies and down-converts the signal to IF where it is monitored on a spectrum analyser. 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 4

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 5 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.

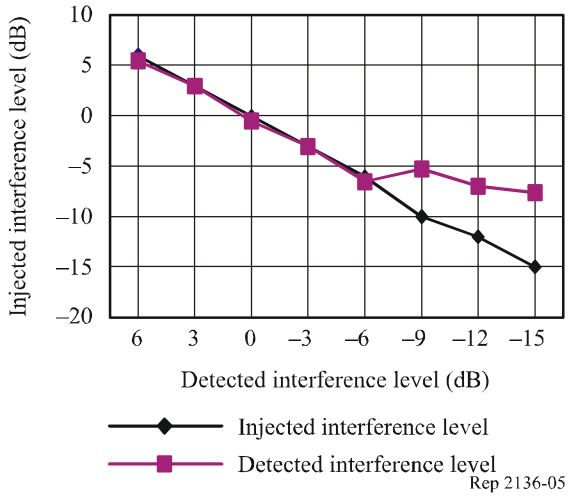
The impact of this residual effect impacts our analysis in the following way:

– *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.

FIGURE 5

Injected vs. detected interference level



We can use the data from Fig. 5 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 5 lists the correction values that are applied to the spectrum width analysis. The data is not required for the reflectivity analysis.

TABLE 5

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

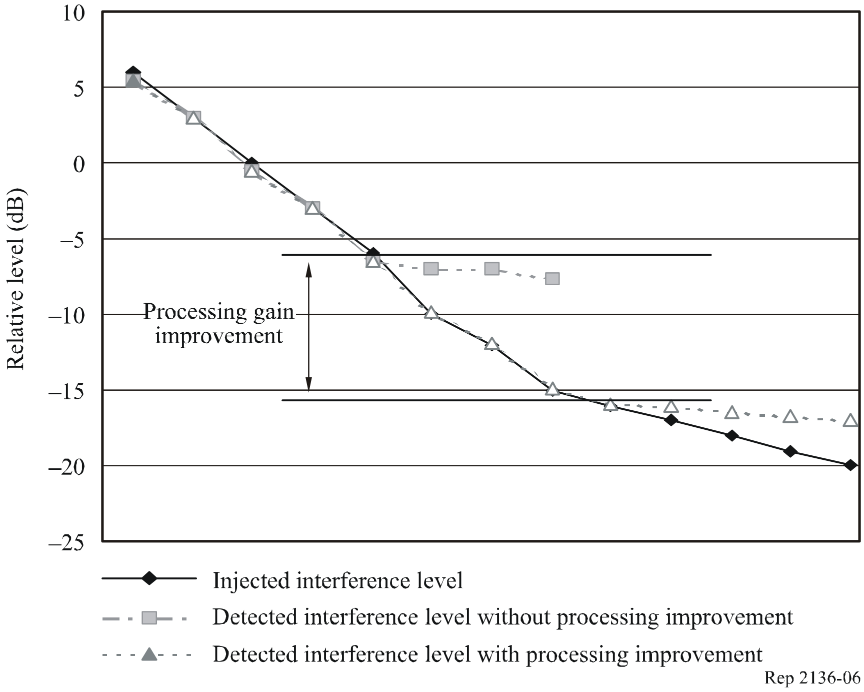
Additional variability that adds to the data analysis errors comes into play as a function of graphically estimating the mean and associated data points.

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. 6 will decrease by the amount equal to the processing power. Figure 5 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. 6 are theoretical and are not based upon actual measurements.

FIGURE 6

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



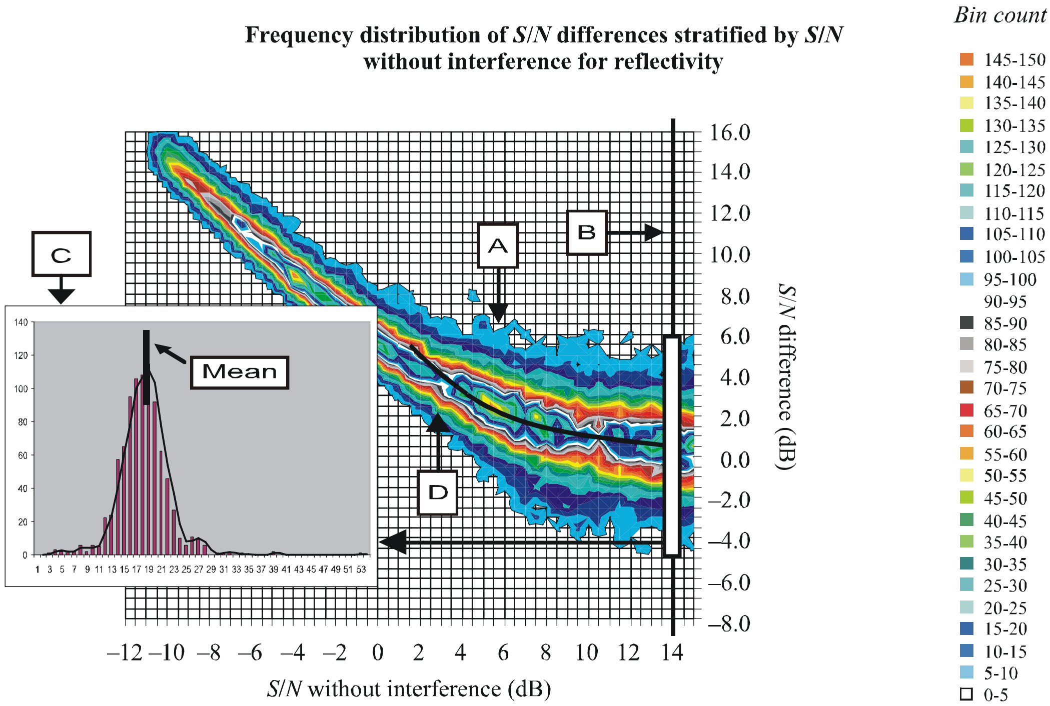
5.2 Data analysis methodology

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. 7, (A) where it is displayed as a colour-coded contour diagram.

Slicing this contour diagram at a specific S/N without interference level (Fig. 7, (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. 7, (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. 7, (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 7

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



Rep 2136-07

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. 7, (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: lowest usable signal level in the presence of noise

I: interference level

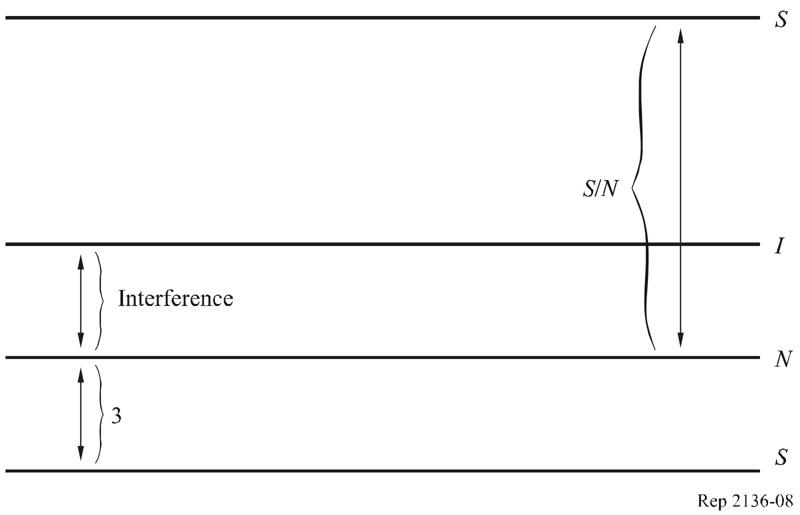
N: noise floor of the receiver

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

The relationship between the factors is illustrated in Fig. 8.

FIGURE 8

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:

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

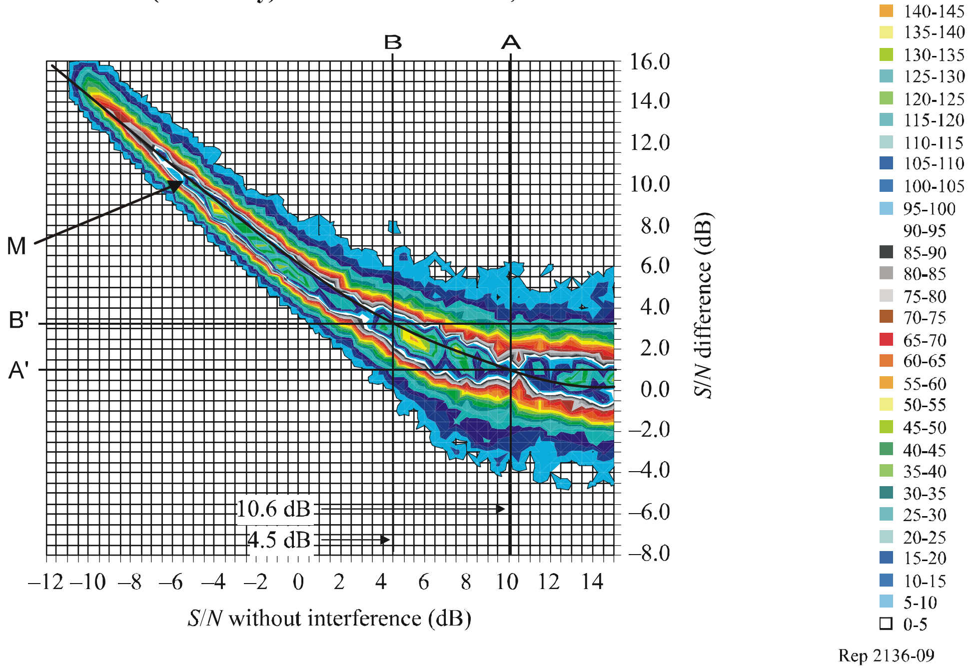
* The equivalent I/N could be increased to –7.6 dB if the calculation assumes that the correct I/N is +6 dB instead of 4.5 dB.

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 9

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



What we want to determine from Fig. 9 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. 9).

The next step is to identify the point where I/S = 0 dB. This corresponds to an S/N difference of 3 dB (Fig. 9, line B′). The reflectivity data becomes compromised at an S/N difference of 1 dB (Fig. 9, 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 6.

TABLE 6

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

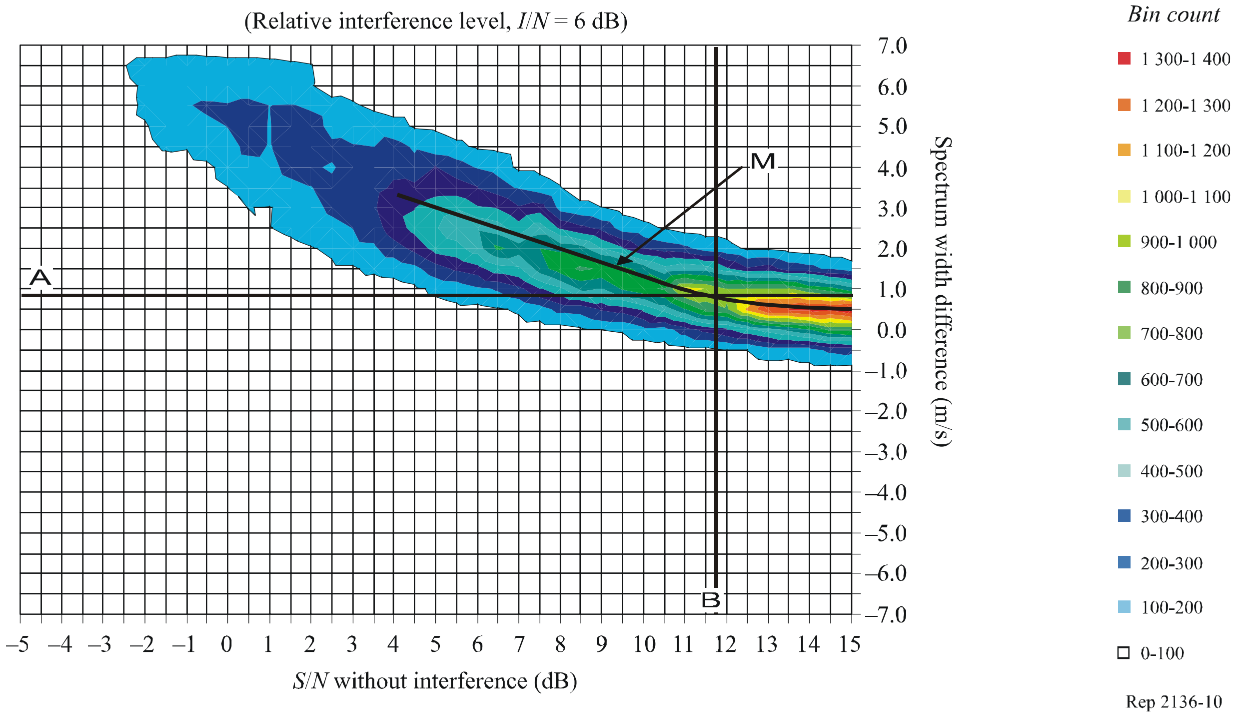
These results are consistent with and support the theoretical result that was derived in § 2.2. However there is inherent uncertainty in these measurements.

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. 10. (This is the same data set that was used in Fig. 9.)

FIGURE 10

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. 10 (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. 10 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. 9. *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:

Equivalent *I*/*N* (spectrum width) = –(11.75 – 4.5) – 3 – 0.5 = –10.75 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 7.

TABLE 7

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 8. 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 8

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 Msample/s	–9.5	–8.75
CDMA-2000-3X (fwd link)	3.686 Msample/s	–7.0	–10
CDMA-2000-3X (rev link)	3.686 Msample/s	–9.5	–10.5
EDGE-GMSK	384 ksample/s	–8.75	–10.75
EDGE-8PSK	384 ksample/s	–8.75	–9.75
DECT	1.152 Msample/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 8 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. Section 6 addresses those improvements in more detail.

5.6 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 ranges 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.

6 Overall summary

These analysis and related 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 ≥ 1 m/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.

Annex 2

Interference testing of meteorological radar operating in the band 5 600-5 650 MHz)

1 Testing configuration

1.1 Radar characteristics

Testing was performed on a meteorological radar operating at 5 625 MHz at the Météo France premises in Trappes.

FIGURE 11
Trappes meteorological radar

Rep 2136-11

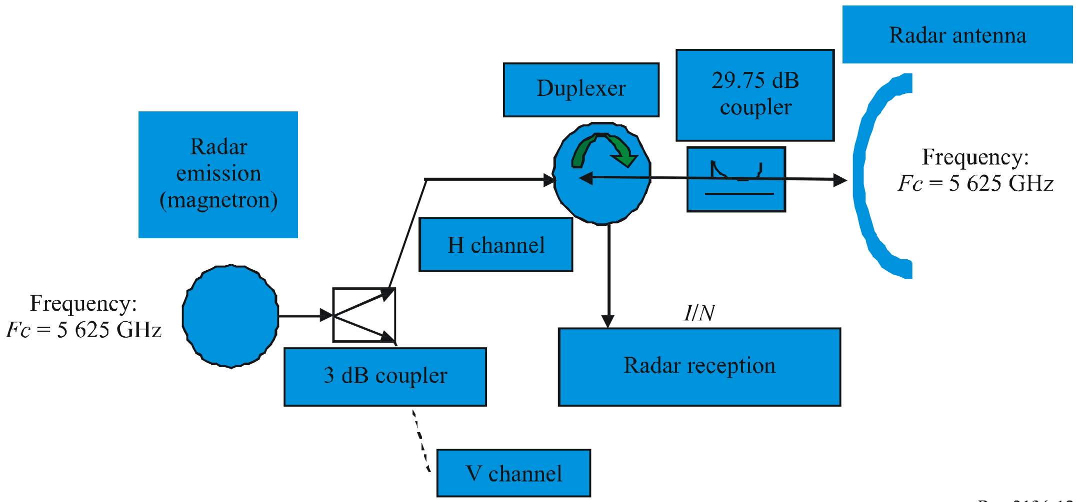
The main emission characteristics of the radar are the following (corresponding to radar 12 in Annex 2 of Recommendation ITU-R M.1849):

– Power = 125 kW on each polarization H and V
– Antenna gain = 45 dBi
– Pulse width = 2 µs
– PRF = Interleaved triple PRT 379 Hz, 325 Hz and 303 Hz, average 330 Hz
– Rotation speed = 6°/s.

Figure 12 presents the radar RF principle.

FIGURE 12

Radar RF principle



Rep 2136-12

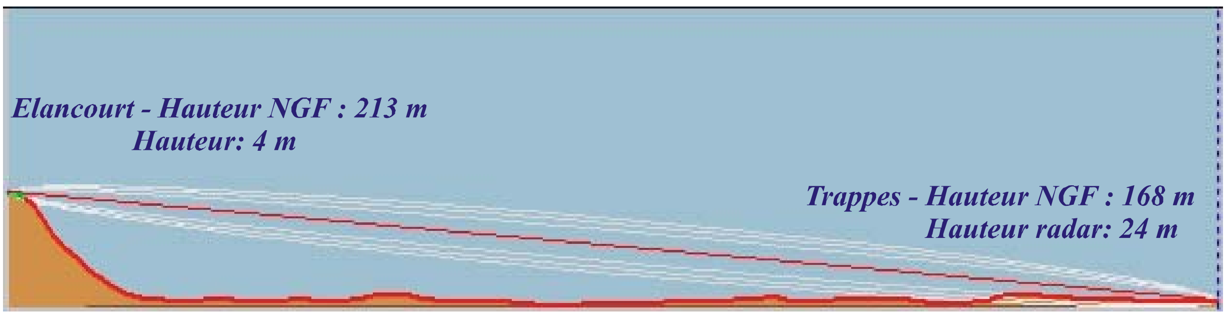
1.2 Interfering signal generation

The interference to the radar was produced using 2 different modes:

Mode 1: Free space propagation. The interference source is located at 3.3 km from the radar, as shown in Fig. 13:

FIGURE 13

Path profile between the interference source and the radar



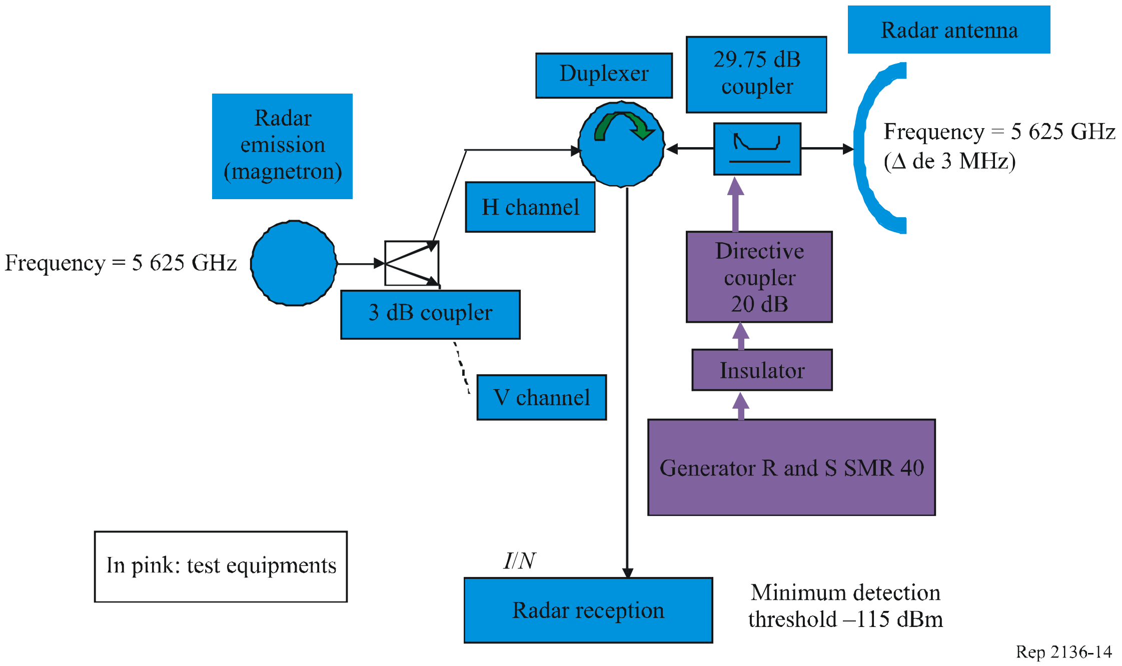
Rep 2136-13

This mode is representative of a "real life" situation, but since interference will only be seen for limited azimuths, it may not allow for precise analysis of interference impact.

Mode 2: Direct injection. The interference source is directly connected at the radar receiver as shown in Fig. 14:

FIGURE 14

Interference injonction principle

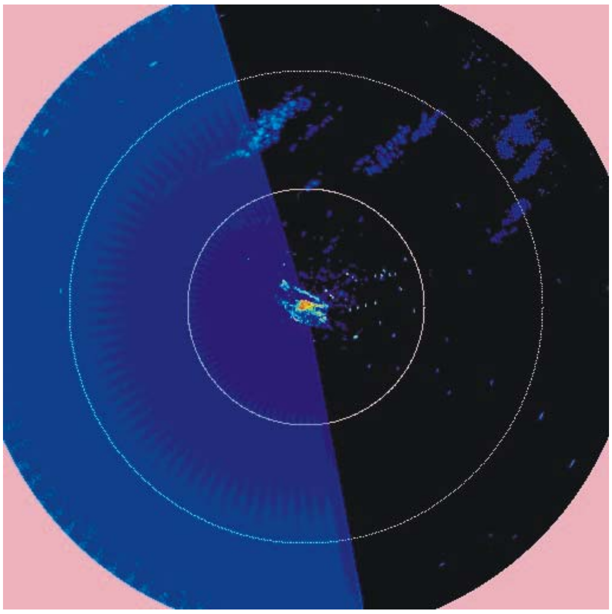


NOTE 1 – The overall attenuation between the generator and the radar receiver, including coupling losses, cable and other attenuation was estimated at 55.55 dB.

In this case, large azimuths will be impacted, as on Fig. 15, and hence will ease the analysis of interference impact.

FIGURE 15

Example of interference visualization under mode 2



Rep 2136-15

1.3 Interfering signals

Different interfering signals have been tested:

– CW,

– FM,

– pulsed, including linear chirp,

– varying signals such as SAR satellites.

These signal types were generated at the radar frequency (5 625 MHz).

Some testing was also conducted at the image frequency of the radar (120 MHz shift, i.e. 5 500 MHz).

The general objective of these tests was to determine the interference sensitivity thresholds of the radar for each type of interference.

The following type of meteorological visualizations were used in the visual determination of the sensitivity thresholds:

– Zh80niv1km (reflectivity)

– Sigma1km (standard deviation of reflectivity over the gates corresponding to a pixel)

– VitVrai1km (Doppler wind velocity)

– RoHV1km (reflectivity difference between H and V polarization)

– Phidp1km (differential phase between H and V polarization).

1.3.1 CW signals

The CW signals were tested in modes 1 and 2, at the radar frequency and radar image frequencies as well as different margin filters.

1.3.2 FM signals

The FM signals were tested at the radar frequency in both modes 1 and 2.

The following FM signals were generated:

TABLE 9

FM signals characteristics

Frequency excursion, Δf	Frequency of modulating signal, f_m	Power density correction in the radar bandwidth (dB)
±100 kHz	100 Hz	0
	1 kHz	0
	50 kHz	0
±500 kHz	100 Hz	−3.9
	1 kHz	−3.9
	100 kHz	−2.9
±1 MHz	100 Hz	−7.2
	1 kHz	−7.2
	100 kHz	−7
±2 MHz	100 Hz	−10.2
	1 kHz	−10.2
	100 kHz	−9.7
	1 MHz	−13

1.3.3 Pulsed signal

The pulsed signals were tested at the radar frequency in both modes 1 and 2.

The following pulsed signals were generated:

TABLE 10

Pulsed signals characteristics

Pulse width (µs)	Pulse repetition frequency (PRF)
1 µs	200 Hz
	3 kHz
20 µs	200 Hz
	3 kHz
600 ns	1 kHz

1.3.4 Linear FM chirp signals

The pulsed signals were tested at the radar frequency in both modes 1 and 2.

The following Chirp signals were generated (with a 20 MHz frequency excursion):

TABLE 11

Chirp signals characteristics

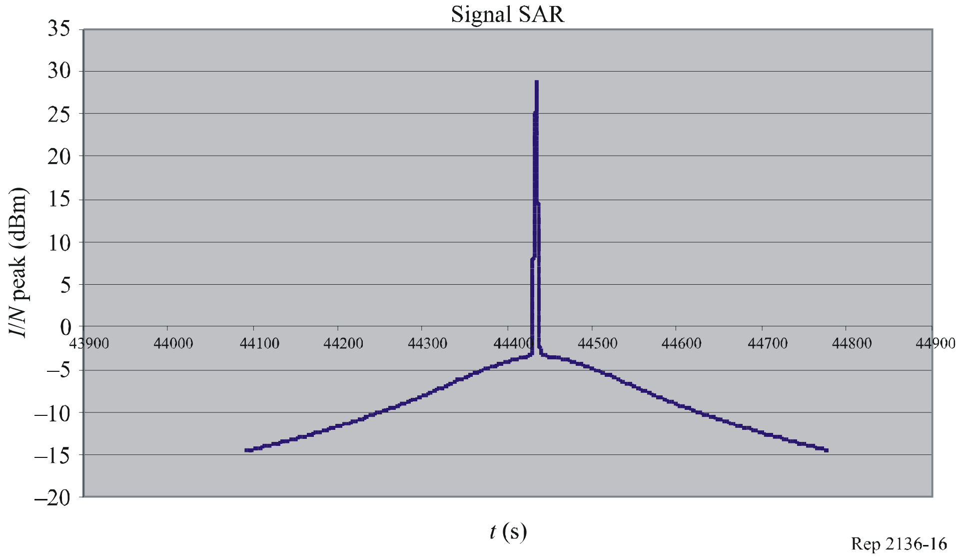
Pulse width (μs)	PRF
50	100 Hz
	5 000 Hz
100	500 Hz
	1 kHz

1.3.5 SAR satellite

The objective of this test was to determine the impact of satellite SAR type interference on the meteorological radar. The test signal which was used in described in Fig. 16.

FIGURE 16

Time varying interference level for SAR satellite interference



1.4 Radar measurement principle

Noting:

N: noise level

I: Interfering signal

S: useful signal (i.e. meteorological signal return).

The following process is performed at the radar:

1 At each gate, the radar measures global signal corresponding to the useful signal, S, and the noise, N, i.e. $N + S$.

2 To get the S, the radar extract from $N + S$, the noise level N, measured at each rotation of the radar. Then, from the S, the radar is able to determine all meteorological products, such as the Precipitation (dBz) or Wind velocity by Doppler analysis.

3 In order to avoid measurements errors due to the noise variation, a filter is applied, comparing the $N + S$ level to a threshold equal to "Noise + margin", the value of the margin being configurable (positive, typically in the range 0.7 to 2 dB). When the $N + S$ is below the threshold, the meteorological measurements and products are not validated.

Considering an interferer, I, together with the above described process, the radar will measure global signals corresponding to $N + S + I$, and then, extracting the noise, will consider a $S + I$ level to generate the meteorological products. For example, for precipitation products, this will lead to a rain intensity overestimation.

When there is no representative meteorological signal, S, then the I level is the only signal processed by the radar, that, for the precipitation mode example, will be transfer in reflectivity under the following formula:

$$\text{dBm} = \text{dBz} + C - 20 \log I$$

with:

dBm: radio power measured by the radar

C: met radar constant (–71 dB)

dBz: reflectivity

r: distance (km).

This principle was in particular used during the testing to calibrate the generated signal.

Noise variation

The average noise of the radar ($kTBF$) is roughly –113.8 dBm.

Considering the filtering threshold described above, it means that with a 2 dB margin, the theoretical maximum interference signal considered by the radar is 2.3 dB below the noise (i.e. −116.1 dBm) whereas for a 0.7 dB margin, the theoretical maximum interference signal considered by the radar is 7.6 dB below the noise (i.e. –121.4 dBm).

However, due to the rather short measurement time at each gate of the radar, the noise is not constant and presents a quite high dynamic range with a typical standard deviation of about 0.5 to 1 dB and extreme values between 3 dB and 10 dB.

The radar is not able to measure this dynamic noise, the N used in the above described process being an average figure, hence close to the $kTBF$.

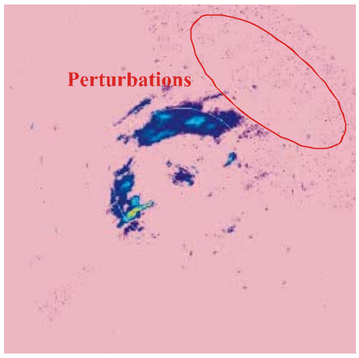
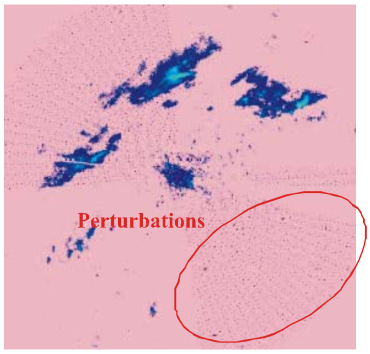
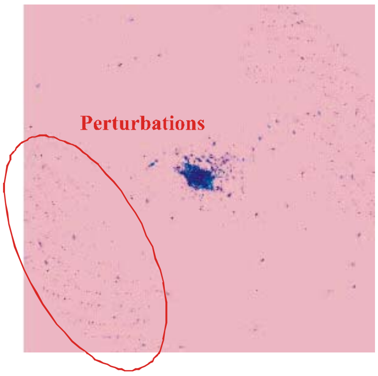
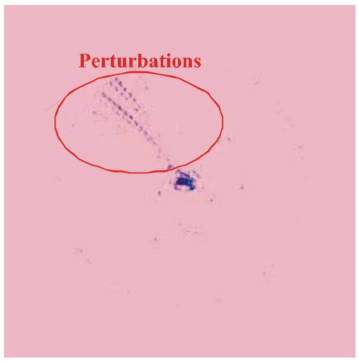
In this case, when the instantaneous noise is above the average figure, a potential interference below the theoretical interference signal above can still have an impact on the meteorological products. This effect was confirmed during the testing.

2 Testing results

2.1 Typical representation of interference impact at the threshold

FIGURE 17

Typical visualization of interference for different interference type

Signal type	Typical representation
CW and FM	
Pulsed	
Linear FM Chirp	
SAR satellite	

Rep 2136-17

These figures correspond to impact on the precipitation mode, at the interference threshold. Other representations are available for higher interference levels, presenting obvious higher impact but due to their bulky sizes are not given in this Report.

In all cases, similar, and consistent impacts were seen on the other meteorological products visualizations that are, for the radar considered, correlated with the precipitation measurements.

2.2 Sensitivity threshold for modes 1 and 2 (with a filter margin = 2 dB)

TABLE 12

Sensitivity thresholds

		Sensitivity mode 2	Sensitivity mode 1
CW	5 624.77 MHz	−115.80 dBm	−117.01 dBm
Image CW	5 504.77 MHz	−80.80 dBm	−85.01 dBm
Signals FM	± 100 kHz/100 Hz	−115.80 dBm	−114.01 dBm
	± 100 kHz/1 kHz	−115.80 dBm	−116.01 dBm
	± 100 kHz/50 kHz	−115.80 dBm	−116.01 dBm
	± 500 kHz/100 Hz	−113.80 dBm	−117.01 dBm
	± 500 kHz/1 kHz	−115.80 dBm	−118.01 dBm
	± 500 kHz/100 kHz	−113.80 dBm	−118.01 dBm
	± 1 MHz/100 Hz	−109.80 dBm	−112.01 dBm
	± 1 MHz/1 kHz	−112.80 dBm	−113.01 dBm
	± 1 MHz/100 kHz	−110.80 dBm	−113.01 dBm
	± 2 MHz/100 Hz	−109.80 dBm	−112.01 dBm
	± 2 MHz/1 kHz	−109.80 dBm	−110.01 dBm
	± 2 MHz/100 kHz	−109.80 dBm	−109.01 dBm
	± 2 MHz/1 MHz	−105.80 dBm	−106.01 dBm
Pulses	1µs/200 Hz	−92.80 dBm	−84.01 dBm
	1 µs/3 kHz	−92.80 dBm	−93.01 dBm
	20 µs/200 Hz	−103.80 dBm	−94.01 dBm
	20 µs/3 kHz	−107.00 dBm	−103.01 dBm
	600 ns/1 kHz	−93.80 dBm	−89.01 dBm
Chirp	50 µs/20 MHz/100 Hz	−93.75 dBm	−87.01 dBm
	50 µs/20 MHz/5 000 Hz	−96.75 dBm	−99.01 dBm
	100 µs/20 MHz/500 Hz	−96.75 dBm	−97.01 dBm
	100 µs/20 MHz/1 000 Hz	−96.75 dBm	−96.01 dBm
SAR satellite		−96.75 dBm	–

For the FM signals with frequency excursion higher than the radar bandwidth (600 kHz), the power density correction in the radar bandwidth (dB) (see § 1.3.2) needs to be taken into account and leads to the following threshold (for mode 2).

TABLE 13

Sensitivity thresholds for FM signals

Frequency excursion, Δf	Frequency of modulating signal, f_m	Threshold (dBm)	Threshold in the radar bandwidth (dBm/600 kHz)
±500 kHz	100 Hz	−113.8	−117.7
	1 kHz	−115.8	−119.7
	100 kHz	−113.8	−116.7
±1 MHz	100 Hz	−109.8	−117.0
	1 kHz	−112.8	−120.0
	100 kHz	−110.8	−117.8
±2 MHz	100 Hz	−109.8	−120.0
	1 kHz	−109.8	−120.0
	100 kHz	−109.8	−119.5
	1 MHz	−105.8	−118.8

Under mode 2, a certain uncertainty was seen on the injected signal. A detailed analysis on the precipitation levels given by the radar showed that the thresholds were most likely overestimated by 1 to 2 dB. This could explain the differences that were seen between mode 1 and mode 2.

The following information can be drawn from these results:

– It confirms that meteorological radars sensitivity level to interference can be even below the theoretical level corresponding to the 2 dB filter margin (−116. 1 dB). In this case, the interference visualization is not constant, presenting disparate impact (quite similar to pulse interference), hence also confirming the impact of the noise dynamic.

– In the case of pulsed or chirp signals, it confirms the theoretical approach that higher level of interference can be tolerated. However, the threshold difference differs from the theoretically calculated value. This can be explained by the fact that the radar pulses do not present a constant PRF. However, this effect could need additional analysis.

– Even though not presented, the threshold observed for other meteorological products is the same. This is due to the fact that, on the considered radar, for practical reasons, all products are currently correlated with reflectivity measurements. This means that these thresholds represent the reflectivity sensitivity to interference. This situation is likely not general for all meteorological radars. Indeed, if not correlated, meteorological products not related to signal power (such as Doppler of differential phase) would likely present much lower sensitivity thresholds.

2.3 Impact of the filter margin on the threshold

The filter margin has an obvious impact on the potential interference threshold. Further testing was performed with margin values that varied from 0.7 to 3 dB using CW signals in mode 2.

Table 14 provides the interference thresholds noted for 0.7 and 2 dB margins.

TABLE 14

Sensitivity threshold for different filter margin

Signal	Interference threshold (dBm) Reflectivity	Wind velocity	RhoHV	Phidp
CW (margin = 2 dB)	−115.55	−115.55	−115.55	−115.55
CW (margin = 0.7 dB)	−126.55	−126.55	−126.55	−126.55

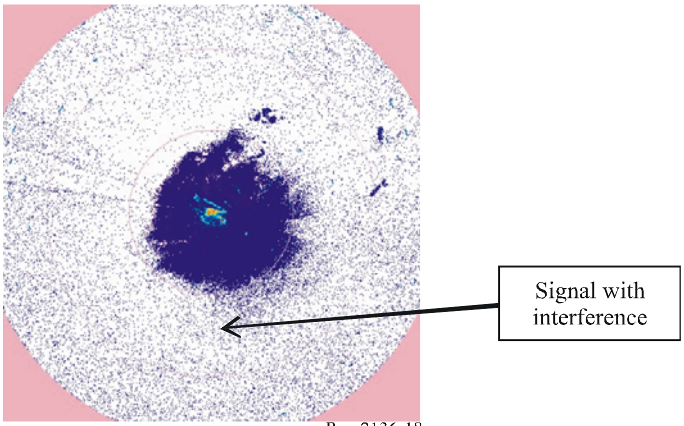
It shows that, when using a lower margin of 0.7 dB, the interference threshold is about 11 dB below the one noted with a margin of 2 dB (see § 2.3).

For a margin of 0.7 dB, it confirms that the threshold is below the theoretical threshold (−126.55 vs. −121.4 dBm) and corresponds to an $I/N = -12.75$ dB.

With a 0.7 dB margin, the difference between the noise impact (without interference and interference at such low level) is weak, as shown in Fig. 18.

FIGURE 18

Visualization of CW interference with a filter margin of 0.7 dB



Rep 2136-18

On the other hand, even though obviously limiting the impact of interference, this filter margin is primarily dedicated to limit the effect of noise variation on the radar products. Indeed, the determination of the adequate margin value is made on a compromise between such noise impact suppression and the degradation of radar performance when weak meteorological signals are measured (mainly degradation of the coverage capacity of the radar in Doppler and differential phase modes).

The margin value determination may depend on the radar characteristics, on the season, or other operational constraints.

3 Overall summary

These test results performed with a meteorological radar operating in the frequency band 5 600-5 650 MHz confirm the analysis described in Annex 1 for meteorological radar operating in the frequency band (2 700-2 900 MHz) and support the requirement for a protection value that could be as low as –12.75 dB *I*/*N* for the base reflectivity, i.e. for products that are related to signal power. For meteorological products not related to signal power (such as Doppler of differential phase modes) lower sensitivity thresholds would likely be necessary. It should be noted that the determination of such sensitivity thresholds was made on a visual basis and that, a more detailed analysis of the meteorological products degradation on a pixel per pixel basis would have obviously led to even lower sensitivity thresholds.