

## 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  $\geq 1$  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.

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\* 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,  $Z$  ( $\text{mm}^6/\text{m}^3$ ) 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<sup>1</sup>. 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:

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

$I/N$  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:

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

$$I/S = 0.26$$

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

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:

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

<sup>1</sup> 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:

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

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
- $\beta$ : 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<sup>2</sup>:

$W$ : standard deviation of frequency spectrum (Hz)

$T$ : sampling interval (s)

$M$ : number of samples in estimate

$N$ : noise power

$S$ : signal power

$\beta$ : 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:

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

<sup>2</sup> 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)
- $V_a$ : 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:

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

$$\ln(R^2/S^2) = -0.25$$

$$R/S = 0.88$$

$$R = 0.88 S$$

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

For  $W = 5$  m/s:

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

$$\ln R^2/(S + I)^2 = -0.39$$

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

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**

|                 | <b>Radar A</b>                        | <b>SNR = -3 dB</b>                  | <b>Radar B</b>                        | <b>SNR = 0 dB</b>                   | <b>Radar C</b>                        | <b>SNR = 0 dB</b>                   |
|-----------------|---------------------------------------|-------------------------------------|---------------------------------------|-------------------------------------|---------------------------------------|-------------------------------------|
|                 | <b>Base data accuracy requirement</b> | <b>Theoretical <math>I/N</math></b> | <b>Base data accuracy requirement</b> | <b>Theoretical <math>I/N</math></b> | <b>Base data accuracy requirement</b> | <b>Theoretical <math>I/N</math></b> |
| 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**

| <b>Radar characteristics</b>  |                                           |
|-------------------------------|-------------------------------------------|
| Frequency                     | 2 995 MHz                                 |
| Pulse power                   | 750 kW                                    |
| Pulse width                   | 4.7 $\mu$ s                               |
| PRF                           | 322 Hz (first cut)<br>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  $0.5^\circ$ , the radar transmits a  $4.7 \mu\text{s}$  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  $360^\circ$  in azimuth. Under normal operation, the radar also performs antenna rotations at several higher elevation angles before returning to  $0.5^\circ$ . 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

| Base product   | Interference induced errors |          |
|----------------|-----------------------------|----------|
|                | 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<br>Centre frequency = 2 995 MHz |                 |
|------------------------------------------------------------|-----------------|
| CW                                                         |                 |
| WCDMA                                                      | 4.096 Msample/s |
| CDMA-2000-3X                                               | 3.686 Msample/s |
| EDGE-GMSK                                                  | 384 ksampling/s |
| EDGE-8-PSK                                                 | 384 ksampling/s |
| DECT                                                       | 1.152 Msample/s |

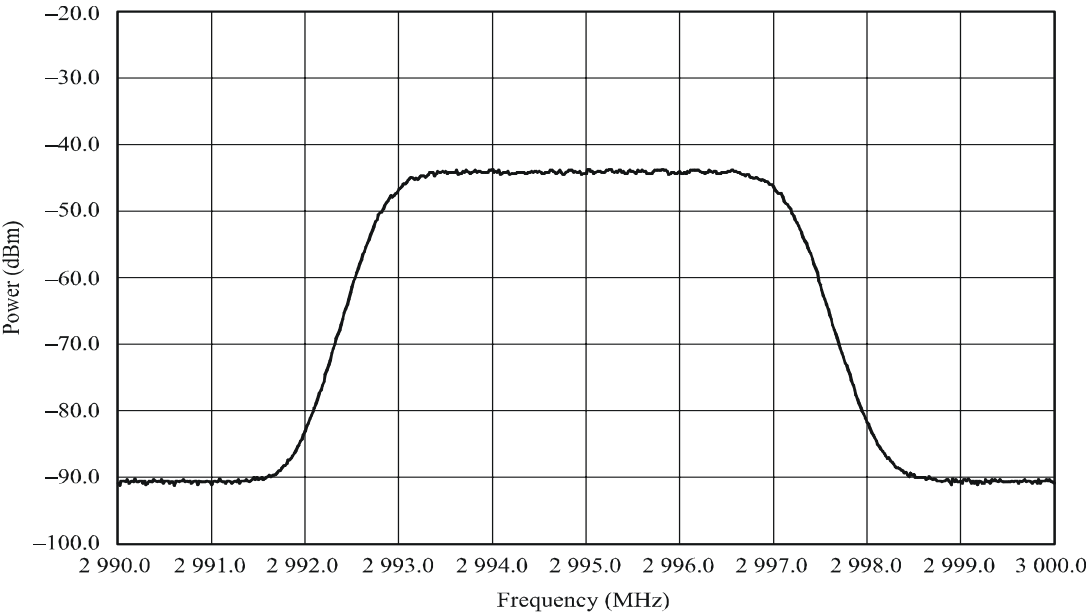
WCDMA: Wideband CDMA.

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.

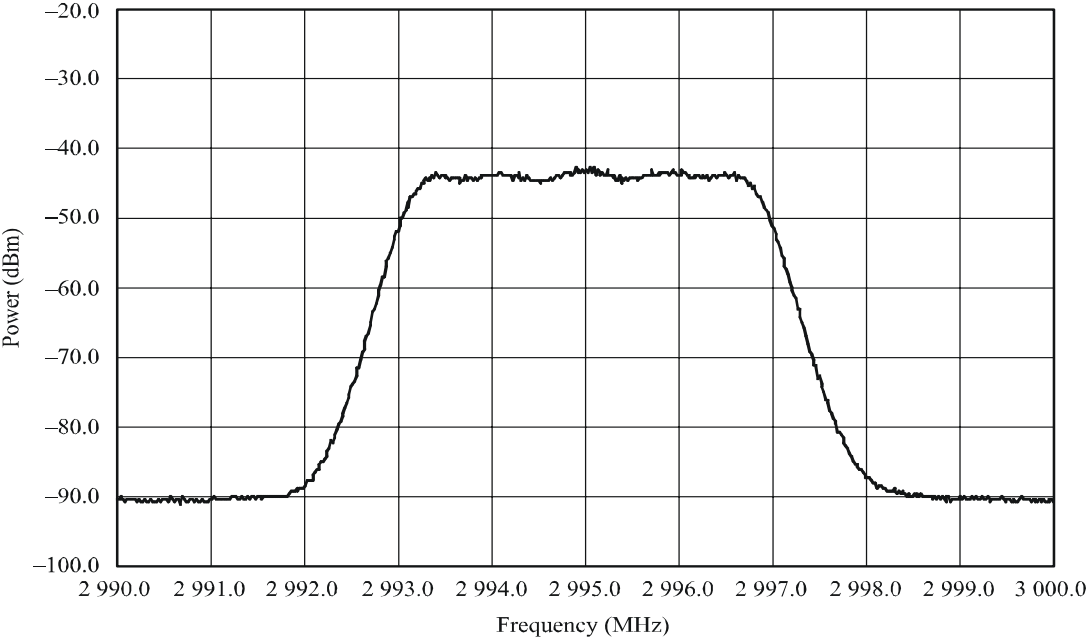
FIGURE 1  
Spectrum plot for WCDMA signal



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

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FIGURE 2  
Spectrum plot for CDMA-2000 3X signal



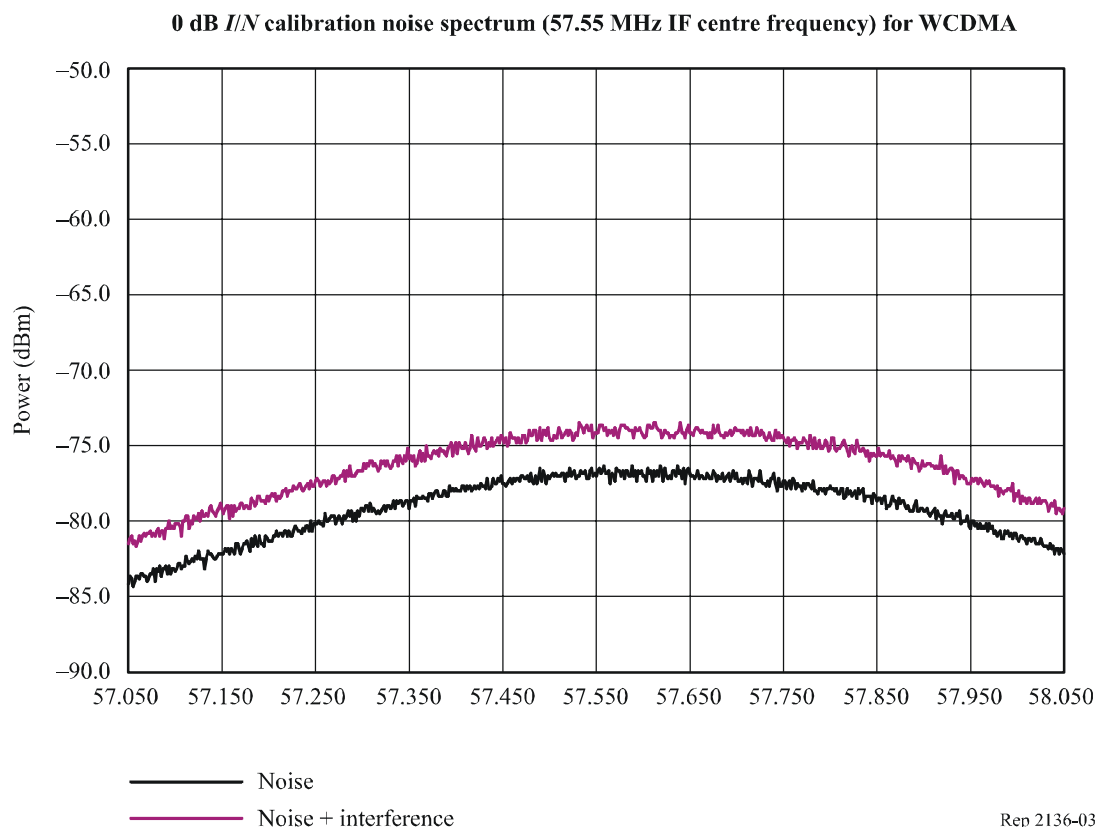
*Spectrum analyser settings:*  
Resolution bandwidth: 300 kHz  
Sweep time: 5 s

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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



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