REPORT ITU-R M.2081

Test results illustrating compatibility between representative radionavigation systems and radiolocation and EESS systems in the band 8.5-10 GHz

(2006)

1 Background

There is a need for contiguous spectrum in the bands around 9 GHz for the radiolocation service, that is allocated on a primary basis worldwide, in order to provide adequate spectrum for new radar systems to function. Emerging requirements for increased image resolution and increased range accuracy necessitate wider contiguous emission bandwidths than are currently available. This fact was recognized at WRC-03 and agenda item 1.3 was developed to consider the upgrade of the frequency allocations of the radiolocation service in the frequency range 9 000-9 200 MHz and 9 300-9 500 MHz to co-primary status with the radionavigation service in order for existing and planned radar systems to satisfy their required missions.

The band 9 500-9 800 MHz is allocated on a primary basis to the Earth exploration-satellite (EESS) (active), space research (active), radiolocation and radionavigation services, taking into account the constraints of footnote 5.476A (EESS must protect systems in radionavigation and radiolocation services). It is desirable to increase by up to 200 MHz the bandwidth available to the EESS (active) and the space research service (active) to satisfy global environmental monitoring requirements for improved resolution. There are plans to enhance spaceborne synthetic aperture radars (SAR) that operate near 9.6 GHz to improve the spatial resolution to the order of 1 m, which would require up to 500 MHz bandwidth. This additional bandwidth would greatly improve the resolution of the features for global monitoring and for environmental and land-use purposes. To accommodate this desire for additional bandwidth, consideration is being given to both the 9 300-9 500 MHz band, and the 9 800-10 000 MHz band.

2 Representative radionavigation and weather radar systems

Five representative radionavigation systems operating in the 9 000-9 200 and 9 300-9 500 MHz bands were identified to be tested to assess their compatibility with radiolocation and EESS systems. They are: marine radionavigation, precision approach (PAR), airborne weather, and airport surface detection equipment (ASDE) radars. A general description of these systems and how they are used are given in the following paragraphs. The exact technical characteristics of the radionavigation systems that will be tested are also included.

3 Objectives

The objective of these measurements is to:

a) Collect a parametric set of radar performance data that demonstrated the compatibility of maritime radionavigation, aeronautical radionavigation, meteorological radars, and radiolocation services in the 8.5-10 GHz band. The compatibility of EESS systems with those representative radionavigation systems was also analysed through the testing.

b) Verify that the radar performance degradation is a function of the interference-to-noise (I/N) ratio at the receiver IF output (detector input) as well as the undesired signal pulse width and PRF (duty cycle), and perhaps modulation by observing the radar display for lost targets and/or an increase in false targets. Three types of radiolocation waveforms were used for these tests: chirped, phase coded, and un-modulated. Various subsets of each type of radiolocation waveform were tested.

c) Collect a parametric set of radar performance data that can be used to assess the compatibility of pulsed and digital communications type modulations with radionavigation systems operating in the 9 000-9 200 and 9 300-9-500 MHz bands.

4 Approach

To show that the EESS can have an extension and radiolocation service can be upgraded to a primary allocation status without causing unwanted interference to systems already operating in the radionavigation service, the five representative radionavigation systems that operate in the 9 000-9 200 and 9 300-9 500 MHz bands were tested to show their compatibility with various radiolocation and EESS systems. Since the band contains many types of radiolocation systems mounted on land, ship, and aircraft platforms as shown in the draft new Recommendation entitled "Characteristics of and protection criteria for radars operating in the radiodetermination service in the frequency band 8.5-10.5 GHz", it was impractical to make measurements using the actual radiolocation system themselves. Therefore, the radionavigation systems were tested with simulated waveforms of representative radiolocation systems contained in the 8.5-10 GHz Recommendation and waveforms of representative EESS systems from other ITU-R documents. For the tests, the radiolocation and EESS waveforms were calibrated at the radiolocation receivers IF to produce peak I/N values of I/N levels of –9, –6, –3, 0, 3, 6, 9, 12, 20, and 40 dB or greater.

The waveforms of the radiolocation and EESS systems were generated and injected into the receiver of the radionavigation systems at the RF level for calibrated levels in the IF bandwidth of the victim receiver, and their performance degradation, if any, was monitored and documented. This Report can be referenced in the WRC-07 Conference Preparatory working (CPM) text to support the upgrade and be available for all administrations for review. A similar method was used for the successful radiolocation upgrade in the 2.9-3.1 GHz band[1] for WRC-03.

5 Performance criteria

The maritime, PAR, and ASDE radars are used to observe point targets in space at some distance from the radar itself. Pilots of aircrafts use the airborne weather radar while in flight, to observe distributed targets such as rain, hail, windshear, and other atmospheric conditions. Therefore, the performance criteria of the weather radar are very different than the criteria of the other radars. The performance criteria of the marine, PAR and ASDE radars and the meteorological radars are discussed in the following paragraphs.

5.1 Maritime, PAR, and ASDE radars performance criteria

The following radar performance criteria were monitored during the measurements to evaluate the effects of the radiolocation, and EESS, type of emissions on the maritime, PAR, and ASDE radar's system performance.

[1] Report ITU-R M.2032 – Tests illustrating the compatibility between maritime radionavigation radars and emissions from radiolocation radars in the band 2 900-3 100 MHz.

a) *Loss of desired target*. For the marine radar, the power level of the simulated target returns was set to obtain a probability of target detection of 90% without the undesired[2] signal being present, with the targets non-fluctuating[3]. This corresponds to a loss of one target per rotation. Twenty rotations were used to set the baseline probability of detection, P_d, without interference being present. With the undesired waveform being present, twenty rotations were also used for each data point with calibrated values of the radiolocation signal set to produce specific I/N levels in the IF of the radionavigation receiver. The number of lost targets per 20 rotations was counted and the P_d was calculated based on 200 total targets generated.

b) *False targets/strobes*. For the ASDE-X and PAR radars, the display was observed for evidence of false indications and false targets resulting from injection of the undesired signals. This was reflected in the test logs and this Report. The target power for both radars was non-fluctuating as in the case of the marine radar.

Note that these criteria are not based on any particular decrement of P_d. They are based on the increase of signal power required to recover the overall performance of the radar (P_d for a search radar, track precision for a track radar, image resolution for an imaging radar, rainfall rate and wind velocity accuracy for weather radars, etc.) to the values they would have in the absence of interference, *regardless of the size of decrement* in those measures of effectiveness that needs to be recovered. The increase of signal power could occur through decrease in maximum free-space range, loss of coverage in regions to/from which propagation is less favourable, or expensive increase of the radar's power-aperture product. We can show that irrespective of the more gradual falloff of P_d with I/N (to a degree that depends on the particular radar being tested) that attends fluctuating target return relative to steady target return.

5.2 Airborne weather radar performance criteria

The following radar performance criteria will be monitored during the measurements to evaluate the effects of the radiolocation and EESS emissions on the airborne weather radar system performance. ARINC has a performance standard identified as ARINC 708[4] for airborne weather radar systems. RTCA has also published a specification[5] for airborne weather radars. The RTCA requirement is that "Transmission from an identical-type radar, operating on an aircraft flying a parallel approach to an adjacent runway or following the equipped aircraft as closely as two nautical miles, shall not cause false alerts, missed detections or other observable interference". The display of the weather radar was observed for effects due to the interference, such as strobes, abrupt colour changes and variations.

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[2] The term undesired signals refers to both the radiolocation and EESS signals.

[3] The target power was held constant.

[4] Airborne Weather Radar with Forward Looking Windshear Detection Capability, ARINC Characteristic 708A-3, November 1999.

[5] RTCA/D0-220, Minimum Operational Performance Standard for Airborne Weather Radar with Forward-looking Windshear Capability. Section 2.2.2.15. September 1993.

6 Description of radionavigation radars

6.1 Maritime radionavigation radar

The maritime radionavigation radar used for these tests nominally operates at 9 410 MHz and was introduced into service in 2000. This type of radar is regularly updated with improved software and hardware. It was designed for commercial applications and is an International Maritime Organization (IMO) category radar. Nominal values for the principal parameters of this radar were obtained from regulatory type-approval documents, sales brochures, and technical manuals. This radar is designed for Coastguard and Navy ships and therefore has features not normally available to commercial and recreational radionavigation radars. This includes constant false alarm rate (CFAR) processing, synthetic/enhanced targets, and target tracking. Table 1 contains the pulse characteristics of the radar. The radar is an “upmast” design in that the transmitter and receiver are located directly below the antenna in a sealed housing. The plan position indicator (PPI) and associated radar controls are located away from the housing and connected to it via cabling.

TABLE 1

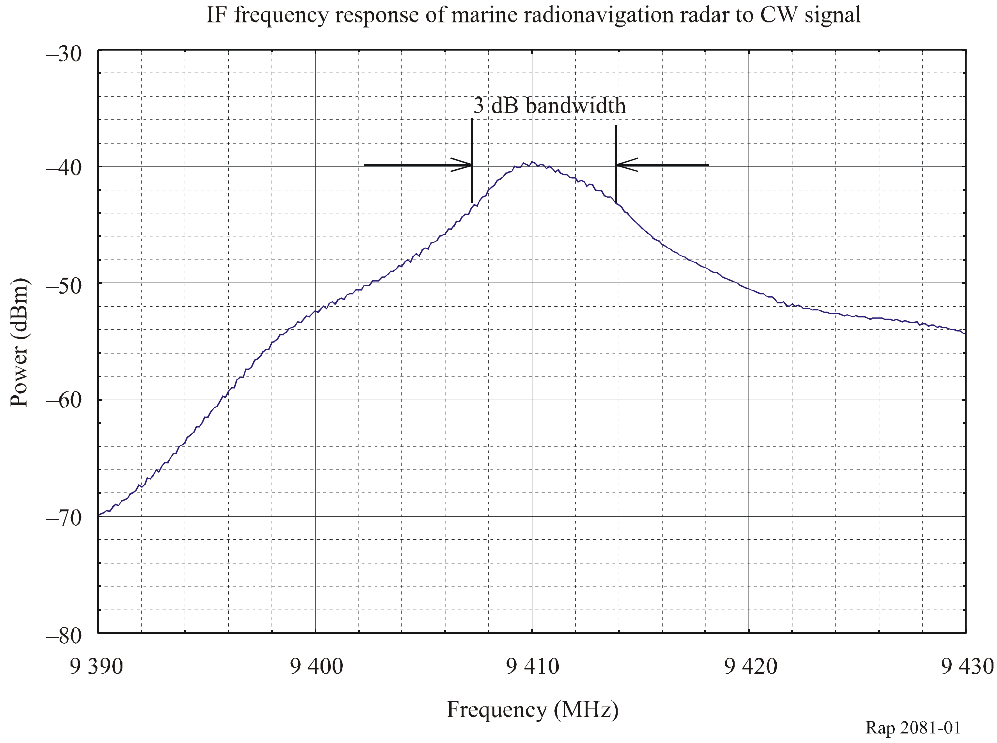
Marine radionavigation radar characteristics

Frequency	Short pulse 1	Short pulse 2	Medium pulse 1	Medium pulse 2	Long pulse
9 410 MHz	80 ns	200 ns	400 ns	700 ns	1.2 µs
	Range				
	0.125-1.5 NM (2-8 km)	0.5-3 NM (0.9-5.6 km)	1.5-6 NM (2.8-11.2 km)	3-24 NM (5.6-44.4 km)	6-72 NM (11.2-133.3 km)
	Pulse repetition rate				
	2 200 Hz		1 000 Hz		600 Hz
IF bandwidth	27 MHz	4.5 MHz	3 MHz		

The radar uses a summing multistage logarithmic amplifier with the IF bandwidths given in Table 1 for each pulse width and associated range. A test point was provided that is located at the output of the 3rd amplifier. A CW signal was swept in frequency to determine the response of the receiver and measure the IF bandwidth. The result is shown in Fig. 1. The 3 dB IF bandwidth of the radar when set to short pulse mode 1, which uses a pulse width of 200 ns for a maximum range of three nautical miles, was measured to be about 6 MHz. This mode was used for all of the tests.

FIGURE 1

Marine radar IF response curve



6.1.1 Marine radar video displays

The marine radar has the ability to display various types of targets in different combinations. The radar is able to display amorphous "blips" (known as image display and what people typically see when looking at a ppi display) and synthetic targets that are processed "blips". For these types of targets, the radar itself has declared the "blips" as targets and they appear as an "o" on the PPI overlaid onto the "blip". Targets that are tracked by the radar appear as an "x" on the PPI. The brightness of the video image targets corresponds to the level of the target return. Targets that have a brighter "blip" have a greater return echo. The synthetic targets required about 2-3 dB of additional desired power than the video targets to obtain the same P_d when operating at MDS level, but do not change their brightness in correspondence to the reflected signal strength. That is to say that if the target power for the 90% P_d for image or "blip" display was –90 dBm, then the power level to achieve the P_d of 90% for the synthetic targets would be about –88 dBm. Adding signal power does not change the intensity of the display of the synthetic targets. For synthetic targets the radar has a built in target counter that counts the number of targets per scan and display that value on the PPI.

6.1.2 Marine radar test target characteristics

The targets for these tests were generated using a variety of test equipment including RF signal generators, arbitrary waveform generators, and pulse generators. Ten equally spaced targets at the same azimuth were generated for each scan[6] with the farthest target being located at the maximum range of 3-nmi. Each target was comprised of 18-19 pulses with the characteristics of the short pulse 2 mode setting. Each target on the radial had the same power level. That power level was held

[6] A scan is a 360° rotation of the antenna.

constant. When the radiolocation and EESS signals were injected into the radar, they were at the same azimuth of the targets for a duration time equal to the antenna beam sweeping across a stationary object.

A number of trials were performed to determine the target signal power that would result in a P_d of 90% *without* the radiolocation or EESS waveforms being present. This value was found to be about –70 dBm at the panel display of the target generator. The target power supplied to the low noise amplifier (LNA) input of the radar receiver due to RF losses from the test set-up was –88 dBm. The noise figure was measured to be about 9 dB. This results in a calculated noise power of about –97 dBm in the 6 MHz IF bandwidth of the radar receiver. Therefore, the signal-to-noise value to achieve the P_d of 90% was about 8-10 dB. Note that the accuracy of this measurement is probably within ±2 dB.

The receiver's noise power measured at the IF test point using the spectrum analyser in zero span mode without any targets, radiolocation, or EESS waveforms present in the bandwidth was about –57 dBm. This shows a nominal gain of about 40-42 dB. The gain compression point[7] using an on-tune CW signal was found to be –25 dBm on the panel display or –43 dBm at the LNA input. It should be noted that the interference suppression circuitry and/or software of the radar can not mitigate the effects of receiver saturation.

6.1.3 Marine radar interference suppression circuitry/software

The radar uses the following features to minimize clutter breakthrough and electromagnetic RF interference: sensitivity time control (STC), fast time constant (FTC), order statistic constant false alarm rate (CFAR), spike suppression, clutter mapping, and scan-to-scan correlation. The STC and FTC were disabled for the tests, since they are used to discriminate sea clutter returns from target returns and to offset the effects of rain, respectively. Obviously, sea clutter and rain did not affect these measurements as they were performed on a test bench. A brief description of the other interference mitigation features follows.

The spike suppression circuitry provides a means of instantaneously filtering interference from other transmitters by detecting and eliminating spikes that occur at a given range over three adjacent sweeps based on a maximum rise and fall criteria. The circuit substitutes the spike value with the average of the amplitudes on the previous and subsequent sweeps.

The CFAR uses an ordered statistic (OS) technique. This adaptive technique minimizes clutter breakthrough in large homogeneous clutter areas. It permits target returns near or above the peak noise plus clutter level to be detected while eliminating the bulk of the noise and clutter. The OS CFAR operates by automatically adjusting the detection threshold based on an instantaneously derived estimate of the predominant noise plus clutter level in the vicinity of the test cell. A programmable guard cell region allows the OS CFAR to accommodate targets of extended range run length, like a super tanker, without loss of sensitivity while still discriminating against clutter.

The clutter mapping compensates for unique spatially distributed clutter situations, such as ones that might be caused by multi-path, grazing angle versus sea state, or a combination of such conditions. The radar operator is provided a means of biasing the OS CFAR derived threshold on an area-by-area basis through the use of the threshold bias map (TBM). The threshold offset stored in the TBM for a particular area is added to the OS CFAR computed threshold for all detections occurring in that area. There are 16 TBM areas centred around the antenna's position which permit the specification of an annulus clutter filter area, which may be used to counter the effects that are

[7] The gain compression point is the value where the LNA is saturated by the input signal and will no longer give a linear relationship between the input and output signals.

range dependent but bearing independent. The TBM area may be defined to negatively bias the OS CFAR generated threshold to increase sensitivity or completely mask returns such as those from land mass. The TBM is organized as a table of 1 024 range cells by 1 024 azimuth cells.

The scan-to-scan correlator takes advantage of the fact that sea clutter is correlated on a pulse-by-pulse basis, but decorrelated on a scan-by-scan basis. Clutter that is permitted to pass through all previous clutter suppression stages is processed through a temporal-spatial decorrelation filter, the retrospective processor. This processor performs scan-to-scan correlation, maintaining as many as nine scans of data.

6.1.4 Marine radar test methods

The tests were performed in a conducted manner, using RF cables, RF combiners, and waveguide-to-cable adapters to join the RF signals containing the targets and radiolocation and EESS waveforms, and then send them into the RF front end of the radar receiver at the LNA input. The radar was tested in the laboratory on a workbench so that monitoring the IF card test points and connecting to the LNA were easier to accomplish. The antenna was not used for the tests, however the appropriate signals from the antenna position resolver circuitry was supplied to the radar receiver so that its normal operation was mimicked.

A more complete description of the test methods is contained in Annex 1.

6.2 Precision approach radars

The PAR is used by a ground controlled approach (GCA) operator to provide accurate navigational information for guiding an aircraft to a GCA landing during both clear weather and instrument flight rules (IFR) weather conditions. The PAR detects and tracks aircraft approaching a runway for landing. The system consists of a Beta scan display, transmitter, receiver, signal processing equipment and antenna assembly. The radar set generates data that displays the position of the aircraft relative to the glide path (angle and distance) of a selected airport runway. The displayed data includes real time video of aircraft in the sector scanned by the radar antenna, synthetically generated symbols designating the locations of aircraft during final approach, glideslope, decision height, and safety zone specified for the selected runway. The antenna and RF equipment is located in a shelter at the end of the runways. There is display equipment located in the shelter, or a display can be located away from the shelter, connected via a coaxial cable or fibre optic link.

The technical characteristics of the PAR are shown in Table 2.

TABLE 2

PAR characteristics

Operating frequency	9.0 to 9.2 GHz
Pulse repetition rate	Multiple PRFs (see Appendix C)
Pulse width	1 µs
IF bandwidth	2.0 MHz
Noise figure	3.25 dB
Antenna type	Limited scan, hyperbolic section reflector with an offset, phased array steered monopulse feed
Antenna gain	42 dB
Antenna polarization	Circular
Antenna beamwidth	Elevation 0.75° Azimuth 1.3°
Receiver types	Normal Coherent MTI Non-coherent MTI Range track Angle track

The PAR includes several features to improve its ability to detect targets . These include the use of: frequency diversity techniques, use of coherent and non-coherent MTI processing techniques, enhancement of weak target echoes, second return rejection, STC, and FTC.

In the normal receiver, the radar can operate in the limiting mode. This mode provides hard limiting on noise followed by narrow band pass filtering which is effective in obtaining good distinction between aircraft and wideband noise. This method is also known as a "dickie fix" circuit and functions as a type of CFAR processing.

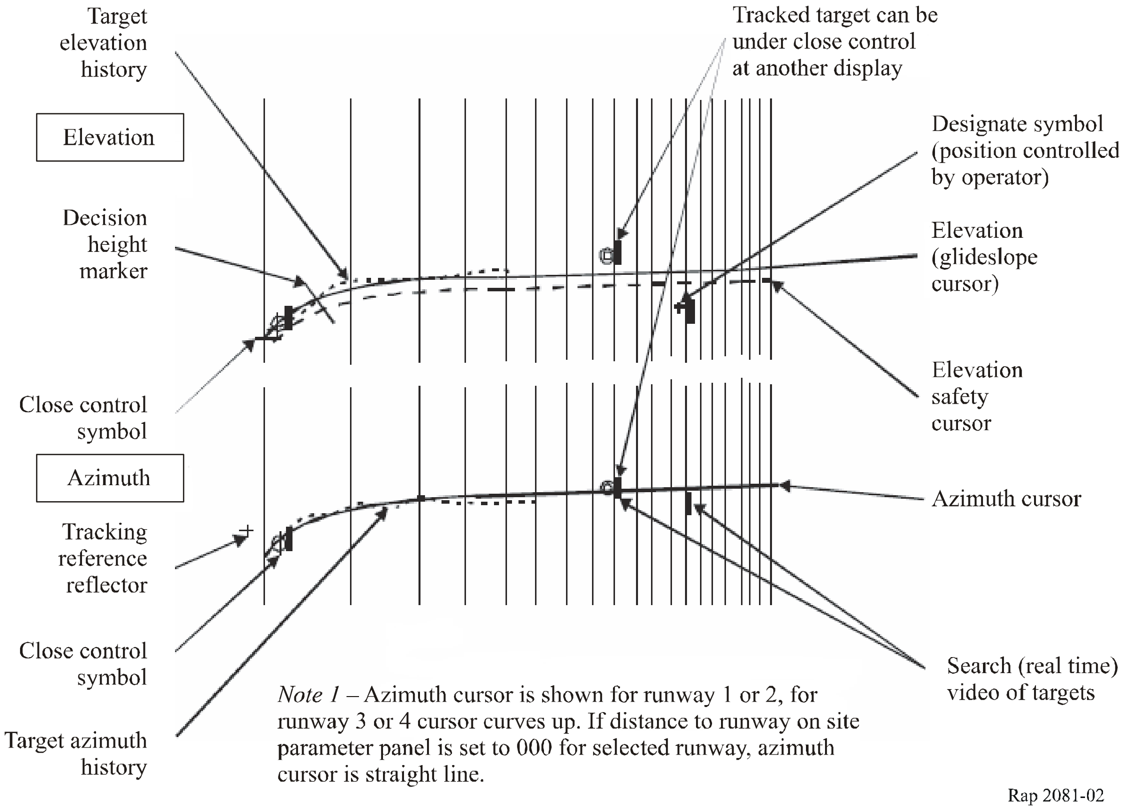
The radar steps in the –10 to +10 degree azimuth and –1 to +7 degree elevation volume, in 439 discrete steps utilizing a two dimensional raster scan. The entire volume is scanned in approximately 0.5 s (20 NM range) and 0.4 s (8-15 NM (15-28 km) range mode). In scan mode, the PAR operates on two sets of two distinct frequencies, called (A1, A2) and (B1, B2). These frequencies are A1 = 9.02 GHz, A2 = 9.057 GHz, B1 = 9.143 GHz, and B2 = 9.180 GHz. From the RF, the radar has dual first IF frequencies, 592 MHz and 629 MHz, leading to two separate IF channels, labelled in the radar as Scan 1 and Scan 2. Pulses A1 and B1 are taken to 592 MHz, while A2 and B2 are taken to 629 MHz. The frequency separation is sufficient to not allow any effects of one frequency into the other channel. The second IF of each channel is 74 MHz. The 74 MHz IF signal is then converted to video (baseband) with a detector. After conversion to baseband video, the signal is then processed according to the radar operating mode: coherent MTI, non-coherent MTI, or normal. In this test, only normal mode will be considered. In this mode, the radar pulses are non-coherently integrated and the results are displayed on the radar display.

6.2.1 PAR radar beta-scan display

The radar utilizes a beta-scan display type, and a typical display is shown in Fig. 2. The top portion of the display shows the aircraft's elevation relative to the glide slope cursor (optimal approach path), represented by the solid curved line on the display. The line is curved even though the path is straight in space because the antenna is placed beyond the runway and offset in azimuth. The vertical bars are mark range, in a logarithmic scale.

FIGURE 2

Typical parameters of PAR beta-scan display



The vertical axis represents elevation angle relative to the antenna, and is plotted linearly. The bottom portion of the display shows aircraft azimuth relative to the glide path (or azimuth cursor, representing an extension of the runway's centre line). Again, the line is curved because of the azimuth offset of the antenna from the runway. The vertical bars here also mark range in a logarithmic scale. Other things the display shows include: elevation and azimuth history data from the tracker, an elevation safety cursor, and a decision height marker.

A target that has been detected shows up on the display as a rectangular "blip", labelled as "Search (Real Time) Video of Targets". Once the target has been selected for tracking and has been acquired, it is shown with two concentric circles. A circle with a vertical line represents a target being tracked under close approach, meaning the aircraft is about to land. Blinking track symbols indicate that the track was lost and that the radar has begun to predict the future location of the aircraft, and will attempt to re-acquire the track if possible. Up to six targets can be tracked at once. The tracking reference reflector is used by the tracker as a reference to allow calibration of the elevation and azimuth error calculations.

6.3 Airborne weather radar

The airborne weather radar that was tested is typical of those operated on transport aircraft and may also be used on some commercial aircraft. It has been in production for a number of years and is still in production with updates and is still being installed on aircraft. The radar's antenna is placed in the nose of the aircraft and the receiver/transmitter unit is located directly behind it. The radar has a colour display and control unit located in the cockpit of the aircraft. The colour display shows the weather phenomena on the display as variations of colours. The control unit allows the pilot to change some of the operational parameters of the system such as range and scanning angle. Table 3 lists the technical parameters of the radar.

TABLE 3

Airborne weather radar characteristics

Operating frequency	9 310 MHz to 9 410 MHz
Pulse repetition frequency	230 to 2 000 pps
Pulse width	0.19 μs to 234 μs
3 dB IF bandwidth	400 kHz (short pulse)
Sensitivity	–110 dBm typical
Antenna scan angle	±15° to ±135°
Antenna scan rate	60°/s
Antenna gain	32.0 dBi
Antenna beamwidth	2.7° Horizontal 4.0° Vertical

The airborne weather radar tested was designed to randomly (uniform distribution) hop every pulse in its operating band, in 5 MHz increments. This hopping was done for interference rejection and to reduce frequency dependent effects of the weather targets. For the interference tests, the radar was placed in an operator-defined single frequency mode (9 335 MHz was arbitrarily chosen). The single frequency mode was tested rather than the hopping mode because in that mode, the radar would automatically delete a given channel from the hopset if it detected interference on that channel. Another reason for choosing the single frequency mode is that most weather radars operate on a single frequency.

The radar utilizes a triple down-conversion heterodyne receiver, with a 5 dB noise figure. The RF is mixed down to 870 MHz, and the first IF filter is matched to the narrowest sub-pulse bandwidth. The second IF, at 90 MHz, is filtered with either an 800 kHz or 120 MHz filter (depending on the selected range scale), and then down-converted to the third IF stage, which is baseband video, in the 0 to 50 MHz range. The baseband video is then detected and sampled with either an 8 or 11 bit A/D converter that is dependent on the selected radar range scale. This radar utilizes a CFAR processor to reduce the effects of noise and clutter.

The airborne weather radar uses three range dependent waveform modulations, depending on the user-defined range setting. For short range, unmodulated pulses are used. For medium range, a 5-chip binary Barker coded waveform is employed, leading to a pulse compression ratio (linear) of 5. For the longer ranges, a 13-chip binary Barker coded waveform is used, and the pulse compression ratio (linear) becomes 13. As shown in Table 4, the pulse bandwidth is also a function of the user-selected range.

6.4 Airport surface detection radars (ASDE-X)

The ASDE-X is a primary radar system that provides a comprehensive view of the airport movement as well as other areas on interest on the airport surface and approach corridors. The radar monitors targets of interest in the coverage volume (typically airport movement area, the airport surface, and approach corridors) and generates target plots for tracking, data fusion, and display to an operator. The targets are overlaid onto an electronic map of the runway for the operator allowing them to assist in avoidance of ground traffic incidents by clarifying the relative positions of aircraft and other vehicles under difficult viewing conditions.

The ASDE-X consists of an antenna, transceiver assembly, and radar data processor. The technical characteristics of the radar are shown in Table 4.

TABLE 4

ASDE-X characteristics

Detection specification	0.90 P_d for target of > 3.2 RCS with a pfa of 10^{-6}
Frequency	9.0-9.2 GHz with frequency diversity (4 channels) Channel separation – 39 MHz
Pulse width	40 ns for short range (608-4 050 ft.) (0.2-1.4 km) 4 µs with LFM 50 MHz chirp for ranges from (4 050-14 500 ft) (1.4-5 km)
Pulse repetition frequency	4 kHz (4 096 pps)
Range	24 000 ft. (8.4 km)
Scan rate	60 rpm (adjustable to trim out vibrations)
Azimuth beamwidth	0.36°
Elevation beamwidth	18°/fan beam
Polarization	Circular

6.4.1 ASDE-X signal processing

The radar receiver is a standard dual down conversion receiver with a limiter, filter, and low-noise amplifier along with a receiver blanking switch that protects the receiver during transmitter pulse time. The radar uses a 4 pulse non-coherent integration with STC in the short pulse coverage region (608-4 050 ft).

The radar has both a target detector and a static reflector. The ASDE-X target detector uses a variety of signal processing techniques to reduce or eliminate the effects of interference. This includes a primary and secondary CFAR. The primary CFAR provides an adaptive threshold for the airport movement areas and the secondary CFAR provides an adaptive threshold for areas on interest that are not part of the movement areas. Both primary and secondary CFAR contain:

– *Fixed CFAR* – A fixed threshold that is a function of range

– *Adaptive CFAR* – A dynamic threshold used to reduce the effects of changing airport clutter conditions

– *Clutter thresholds* – Thresholds used to reduce clutter from persistent sources of clutter.

The static reflector function requires the following thresholds:

– *Adaptive threshold* – Used to compute the static reflector threshold from a spatial average of the clutter map

– *Fixed threshold* – The threshold regions designed to balance static reflector declarations to enable effective multi-path target elimination.

The radar video amplitude is compared with the thresholds. If the amplitude is greater, then a potential target is declared out of the threshold function. The target detector and static reflector are internally similar, but the output is different. The target detector provides the tracker with plots for use in target decision/tracking. The static reflector provides the multi-path logic with potential static reflectors for use in multi-path target elimination.

7 Representative radiolocation systems

The tests were performed with radiolocation waveforms that are representative of the radiolocation systems that operate in the 9 000-9 200 and 9 300-9 500 MHz bands. The technical characteristics of these systems are contained in the Recommendation identified in § 4. Due to time constraints not all of the systems identified in the Recommendation could be tested.

Three types of radiolocation waveforms were used for the tests. They are chirped, phase coded, and un-modulated waveforms. The waveforms were gated on for the duration of the mainbeam dwell time for the radionavigation receiver as it would scan past a stationary object. They were also on-tune with the radar. The exact parameters of each waveform are given as follows.

7.1 Chirped waveform

Table 5 shows the parameters of the Chirped waveform. They were developed based on the characteristics of Radars A7 and A3 from the ITU-R Recommendation referenced in § 4. The number of pulses per beam dwell is dependent on the type of radiolocation system being tested.

TABLE 5

Chirped waveforms

Waveform No.	**Pulse width (µs)**	**prf (Hz)**	**pri interval (ms)**	**Duty cycle (%)**	**Chirp (MHz)**	**Chirp rate (MHz/µs)**
Chirp 1	10	750	1.3	0.8	10	1
Chirp 2	10	750	1.3	0.8	50	5
Chirp 3	13.6/1.65	5 000	0.20	0.8	660/80	48.5

prf: pulse repetition frequency

pri: pulse repetition interval

The victim's receiver IF output response (amplitude and pulse width) to interference from chirped pulses is a function of the rate at which the chirped frequency sweeps through the victim radar receiver pass-band. This rate, called chirp rate, R_c, is given by:

$$R_c = (B_c/t)$$

where:

R_c: sweep rate (MHz/µs)

B_c: chirp frequency range (MHz)

t: pulse duration (µs)

Victim radar receivers should not respond to interference on frequencies outside the –20 dB points pass-band of their IF circuitry, assuming that the amplitude of the interference is below the front-end overload threshold of the radar receiver RF front end.

In some cases, the frequency sweep range of the chirp-pulse generation system used in these tests was limited by hardware to less than the full chirp range of the corresponding radar emission specified in the Recommendation identified in § 4. In such cases, the tests were still performed to fully and accurately replicate the response of radar receivers to the specified chirp parameters. To accomplish this goal, the chirped pulses used in the tests were swept across at least twice the –20 dB frequency response range of the victim radar receivers, at the same rate as the sometimes wider-bandwidth chirp pulses from potentially interfering sources.

For example in Table 5, the 660 MHz chirp in a 13.6 µs pulse (R_c = (660 MHz/13.6 µs) = 48.5 MHz/µs) is not possible to generate with the ITS test equipment. An equivalent interference effect can be generated with an 80 MHz chirp pulse in an interval of 1.65 µs

(R_c = (80 MHz/1.65 µs) = 48.5 MHz/µs), provided that the –20 dB radar IF pass-band of the victim is equal to or less than 50 MHz wide.

In the tests described in this Report, the value of R_c was always preserved and the victim radar receivers always saw the chirped interference across their full receiver IF pass-bands in exactly the same way as they would have if the chirped interference had been generated across wider bandwidths. That is the key element in accessing the effects of the interference.

7.2 Phase coded waveform

Table 6 shows the parameters of the phase coded waveform. They are based on radar A6 from the Recommendation identified in § 4. The waveforms in Table 3 represent a 13-bit Barker code.

TABLE 6

Phase coded waveforms

Waveform No.	Pulse width (µs)	prf (Hz)	Sub-pulse width (µs)
Phase 1	0.64	1 600	0.049
Phase 2	20	1 600	1.54

7.3 Un-modulated pulsed waveform

Table 7 shows the parameters of the un-modulated waveforms. They are based on the characteristics of various radars in the Recommendation identified in § 4 along with higher duty cycles that may be used in future systems.

TABLE 7

Un-modulated waveforms

Waveform No.	Pulse width (µs)	prf (kHz)	pri (µs)	Duty cycle (%)
Ummod1	1	19	52.63	1.9
Unmod2	1	35	28.57	3.5
Unmod3	1	8	125	0.8
Unmod4(1)	1	50	20.0	5.0
Unmod5(1)	1	75	13.3	7.5
Unmod6(1)	1	100	10	10
Unmod7(1)	1	200	5	20

(1) Note that waveforms with these duty cycles ARE NOT contained in the Recommendation. They were used merely to empirically determine the effectiveness of the radar's signal processing abilities at high duty cycles.

7.4 EESS waveforms

The radionavigation systems were tested with waveforms representative of EESS systems. These waveforms primarily use a chirped modulation scheme. As in the case of the chirped waveforms from Table 5, the values are scaled to the maximum 80 MHz chirp bandwidth of the test equipment. The values are shown in Table 8. The duty cycles are calculated using the scaled pulse widths.

TABLE 8

EESS waveforms

Waveform No.	Pulse width (μs)	Scaled width (μs)	Prf (Hz)	Pri (ms)	Duty cycle (%)	Chirp (MHz)	Chirp rate (MHz/μs)
EESS1	10	2	2 000	0.5	0.4	400/80	40
EESS2	80	16	4 500	0.22	7.2	400/80	5
EESS3	10	17.7	515	1.94	0.91	45/80	4.5
EESS4	10	1.7	5 150	1.94	0.88	460/80	46

8 Test procedures

The test procedures for each of the radars are unique to each system. The test procedures for them are contained in the Annexes as follows: maritime radars, Annex 1; PAR radar, Annex 2; airborne weather radar, Annex 3; and ASDE radar, Annex 4.

9 Test results

The results for each of the representative systems are discussed in the following paragraphs. In some cases the P_d was not directly observable because the interference caused an increase in the number of false targets, which obscured the desired targets rather than decreasing the P_d. In that case a table indicates what effect was visible on the PPI. For the weather radar, the metric was not a change in P_d but a change in the colour and intensity of the interference strobe. For the PAR, the metric was also not a change in P_d, but observations of effects of the interference on the radar display, such as loss of targets, false targets, or target drifting. In the case of the ASDE-X the P_d was not directly observable. The criterion that was used as a performance metric was either a loss of, or the drifting of targets.

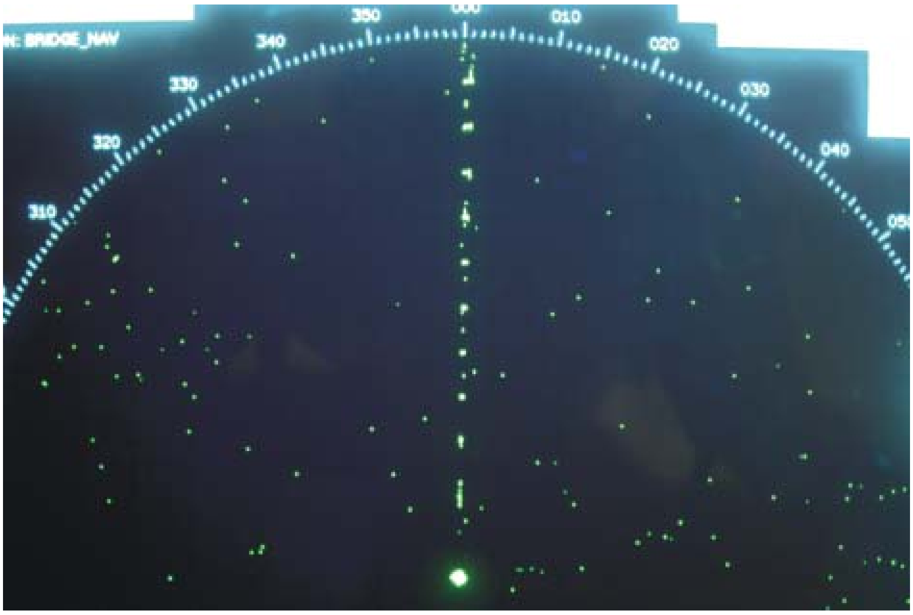
9.1 Marine radionavigation radar

The test results for the marine radionavigation radar are contained in Table 9. The table shows that the marine radar did not suffer any degradation to its performance with any of the chirped, phase-coded, or EESS waveforms at an *I*/*N* of +40 dB. For the unmodulated pulses the radar did not suffer any degradation at a duty cycle of 5% and an *I*/*N* of +40 dB. At the higher duty cycles for the unmodulated radiolocation waveform, the radar produced a strobe on the ppi at the same azimuth of the targets when the *I*/*N* was above +20 dB. At lower *I*/*N* ratios the strobe on the PPI was reduced to an increase in the amount of false targets or speckle. These effects are shown in photographs of the radar's PPI in Figs. 3 and 4. Note that these photographs are representative of the condition and there was a variation from scan-to-scan in the amount of false targets.

When looking at these photographs, it should be noted that since the PPI observer knows in advance where on the targets will be displayed it is "easier" for them to discern the targets from the background speckle. Radar operators viewing targets on a PPI in an operational environment may not have that that condition available to them, which could make the targets harder to detect from an increase in background speckle. In an operational scenario, the targets can also be distributed at any azimuth on the PPI.

FIGURE 3

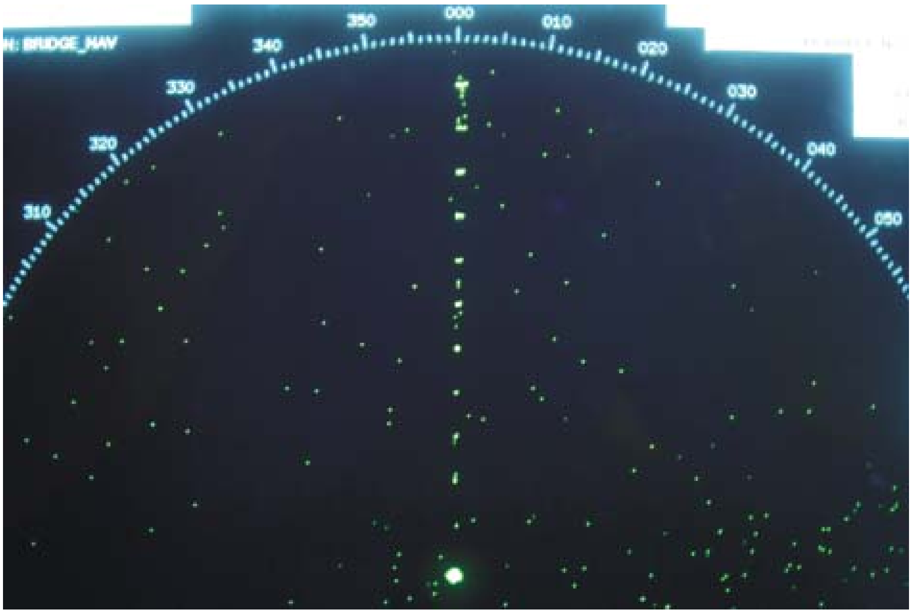
1 μs pulsed interference at 7.5% DC and +40 *I*/*N*



Rap 2081-03

FIGURE 4

1 μs pulsed interference at 7.5% DC and +12 *I*/*N*



Rap 2081-04

TABLE 9

Results of tests on marine radionavigation radar

Radiolocation waveform	Effect at *I/N* ratio (dB)									
	–9	–6	–3	0	+3	+6	+9	+12	+20	+40
Chirp1	None	None	None	None	None	None	None	None	None	None
Chirp2	None	None	None	None	None	None	None	None	None	None
Chirp3	None	None	None	None	None	None	None	None	None	None
Phase1	None	None	None	None	None	None	None	None	None	None
Phase2	None	None	None	None	None	None	None	None	None	None
Unmod1	None	None	None	None	None	None	None	None	None	None
Unmod2	None	None	None	None	None	None	None	None	None	None
Unmod3	None	None	None	None	None	None	None	None	None	None
Unmod4	None	None	None	None	None	None	None	None	None	None
Unmod5	None	None	None	None	None	None	None	False targets	Strobe	Strobe
Unmod6	None	None	None	None	None	None	None	False targets	Strobe	Strobe
Unmod7	None	None	None	None	None	None	False targets	False targets	Strobe	Strobe
EESS1	None	None	None	None	None	None	None	None	None	None
EESS2	None	None	None	None	None	None	None	None	None	None
EESS3	None	None	None	None	None	None	None	None	None	None
EESS4	None	None	None	None	None	None	None	None	None	None

When no effect is indicated the radar P_d as within ±3% of the baseline P_d, and the number of false targets or "speckle" was at the baseline state as well.

9.2 Airborne weather radar

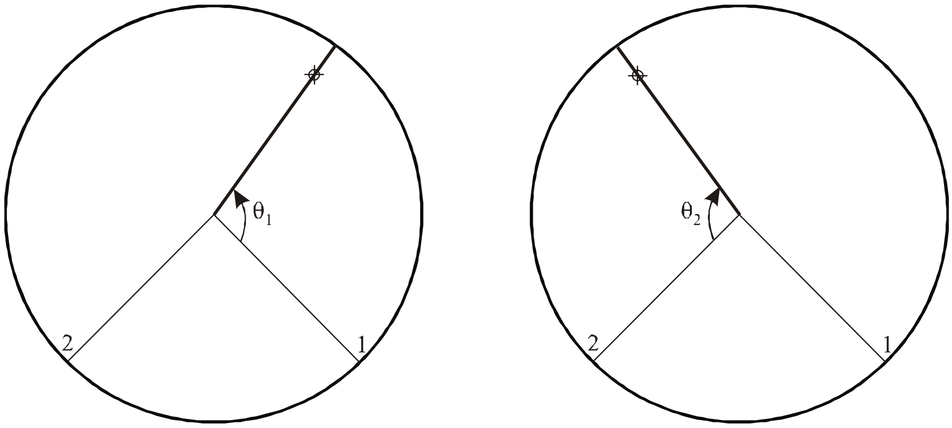
9.2.1 Description of interference coupling

The interference was injected into the radar at the RF level via cable to a port between the receive antenna and receiver front end. To simulate the de-coupling affect of scanning, the interference was gated on for a brief period of time corresponding to the antenna dwell time scanning across a stationary object, which was 0.045 s. In order to help distinguish this interference from occasional ambient sources, the frequency of these impact times, ψ, was approximately matched to the scan rate (twice for every back and forth scan). Because the radar is a sector scan device, each scan consists of two sweeps, one from right to left, clockwise (CW), and one from left to right, counter clockwise (CCW).

Figure 5 shows a representation of the display for a CCW sweep and a CW sweep. The time to sweep CCW from antenna stop 1 to stop 2 is t_{12}. The scan rate is constant throughout except for direction changes every time the mainbeam axis hits 1 or 2. If the centre of the simulated target is represented by ⌖, then the gating occurs at an arbitrary time t_1 from 1, after the antenna has swept through an angle θ_1. Because ψ, the time between interference bursts, was constant throughout CCW and CW sweeps, and set nearly equal to t_{12}, but was not synchronized to the radar sweep, it caused the angle swept from antenna stop 2, θ_2, to equal θ_1. Thus the gated target appeared to jump back and forth between CCW and CW sweeps, mirrored about a vertical diameter. Because it was difficult to set ψ precisely equal to t_{12} it caused the magnitude of θ_1 and θ_2 to drift over time. Nevertheless, because the target appeared to be mirrored with each CCW and CW sweep it provided a positive way to distinguish the simulated interference from other sources that occasionally coupled through the antenna at random azimuths.

FIGURE 5

Representations of CCW and CW sweeps for airborne weather radar



9.2.2 Test results for airborne weather radar

Results for the airborne weather radar are summarized in Table 10. The results show that the chirped waveforms, Phase Coded waveform 1, EESS1, EESS3, and EESS 4 did not cause any visible strobes on the radar's display at *I*/*N* ratios from +43 to +63 dB. EESS2 caused an effect for *I*/*N* greater than +30 dB. The unmodulated waveforms (1 and 2) caused an effect when the *I*/*N* was greater than 18-19 dB. The unmodulated waveform 3 caused an effect when the *I*/*N* was greater than +25 dB. Note that in Table 8, the maximum (*I*+*N*)/*N* was due to the limitations of the Agilent vector signal generator (VSG). Each waveform produced by the VSG was limited to some maximum power output which was determined by the characteristics of the waveform itself. Waveforms with longer duty cycles had less available power output on the VSG front panel, and conversely the maximum interference, I, was limited to that value in the receiver's bandwidth.

TABLE 10

Results of tests with airborne weather radar and radiolocation and EESS waveforms

Signal	Peak-to-RMS (*I*+*N*)/*N* (dB)	Peak-to-RMS *I*/*N* (dB)	Effect on radar
Chirped 1	+63 (maximum)	+63	No visible effect on display
Chirped 2	+52 (maximum)	+52	No visible effect on display
Chirped 3	+43 (maximum)	+43	No visible effect on display
Phase Coded 1	+47 (maximum)	+47	No visible effect on display
Phase Coded 2	+60 (maximum)	+60	Visible strobes
	+36	+36	Visible strobes
	+30	+30	Barely visible strobes
	+28	+28	Almost gone
	+25	+25	Nothing visible on display

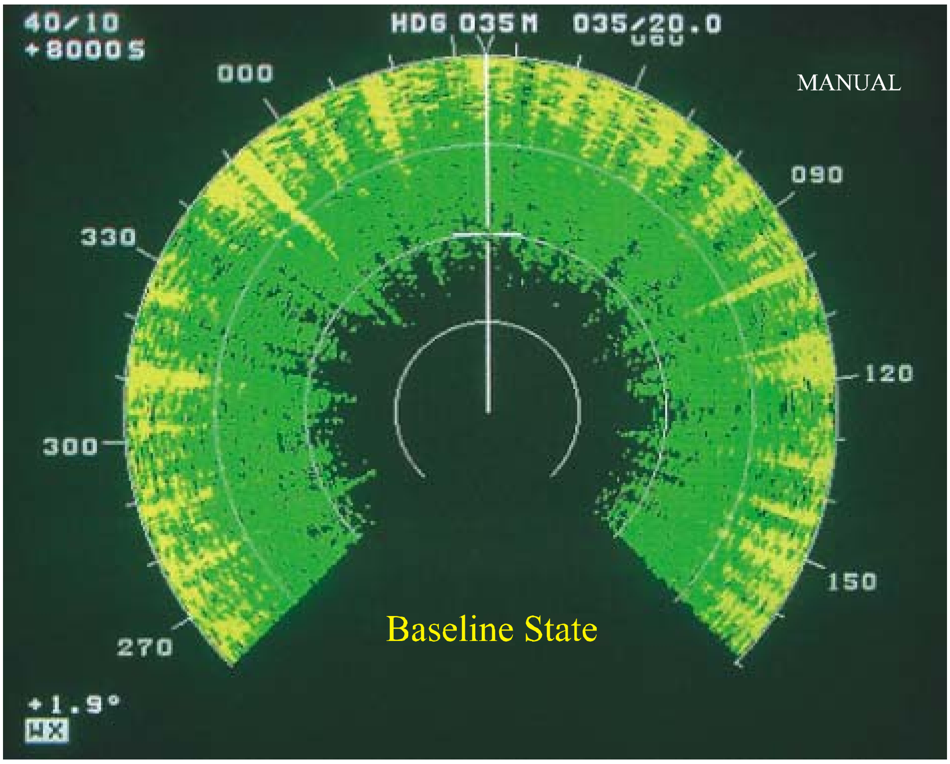
TABLE 10 (*end*)

Signal	Peak-to-RMS (I+N)/N (dB)	Peak-to-RMS I/N (dB)	Effect on radar
Unmodulated 1	+57 (maximum)	+57	Visible strobes
	+22	+22	Marginally visible strobes
	+19	+19	No visible effect on display
Unmodulated 2	+57 (maximum)	+57	Visible strobes
	+21	+21	Marginally visible strobes
	+18	+18	No visible effect on display
Unmodulated 3	+32	+32	Visible strobes
	+29	+29	Marginally Visible
	+25	+25	No visible effect on display
EESS1	+44 (maximum)	+44	No visible effect on display
EESS2	+52 (maximum)	+52	Visible strobes
	+32	+32	Marginally visible strobes
	+30	+30	No visible effect on display
EESS3	+54 (maximum)	+54	No visible effect on display
EESS4	+43 (maximum)	+43	No visible effect on display

Figures 6 through 8 show examples of the three states of the radar display: no visible effects of the interference/baseline state, visible strobes, and marginally visible strobes. In Fig. 6, the test's baseline state, the radar transmitter is turned off, and the receiver is operating normally (in single frequency mode). The green and yellow on the display is background noise, and had no effect on the interference testing. The strong strobe case is shown in Fig. 7. The interference can clearly be seen at an azimuth of 110°. This strobe indicates that the interference caused the radar signal processor to interpret it as a wedge of excessive rain (magenta colour) extending from before the 10 NM (18.5 km) circle (inner circle on display) to the 40 NM (74 km) circle (outermost circle on display), with the flashing white indicating areas of strong wind shear and turbulence. To the radar operator, this wedge is an unrealistic weather target because it does not display the random shape and movement characteristics of a rain or thunderstorm event (which it would have to be to realistically produce these effects on the radar display). Figure 8 shows a marginally visible strobe. The interference has caused the radar signal processor to interpret it as a heavy rain (red colour) wedge/patch at 80° azimuth. This wedge begins at the 10 NM (18.5 km) circle, but is hard to distinguish from the background noise until the red patch.

FIGURE 6

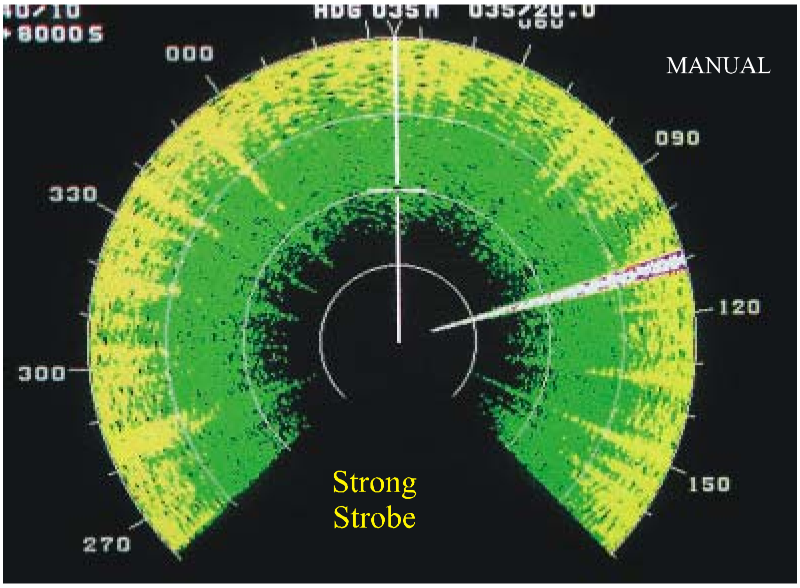
Airborne weather radar colour display, baseline state



Rap 2081-06

FIGURE 7

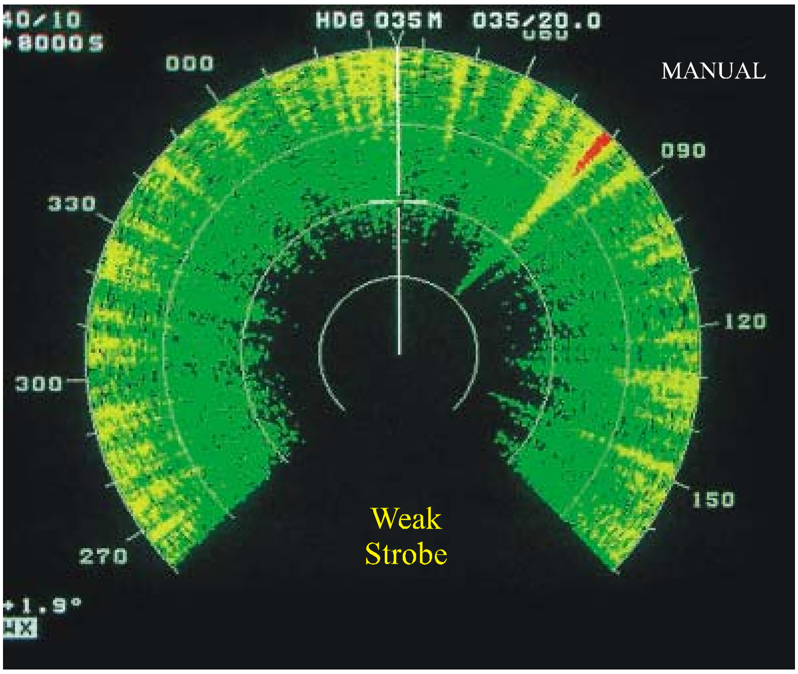
Airborne weather radar colour display, interfering signal causes magenta (excessive rain) wedge and flashing white indicates turbulence on display at 110°



Rap 2081-07

FIGURE 8

Airborne weather radar colour display, weak interfering signal causes small red (heavy rain) wedge/patch to appear on display at 80°



Rap 2081-08

All of the waveforms caused similar appearing strobes on the radar's display, if one was manifested. When the radar operated in the frequency hopping mode, all of the interference was mitigated. When interference appears in a channel the receiver is designed to stop hopping to that frequency. This is what was seen during the tests. In frequency hopping mode with interference on one frequency, the effect would appear on the CRT as it did for the radar operating on a single frequency, but as soon as one full scan was made, the receiver would stop hopping the frequency (or frequencies) of the interference, and the display would appear to be in the baseline state.

9.3 Airport surface detection equipment (ASDE-X) radar

9.3.1 Description of interference coupling

Results for the ASDE-X radar are summarized in Table 11. The results show that waveforms Chirped 2, Phase Coded 1, and EESS4 did not cause any visible strobes, lost or false targets on the radar's display at an *I*/*N* ratio of +60 dB. Waveforms Chirped 1, Chirped 3, and EESS1 began to show a slight strobe effect at the *I*/*N* level of +60 dB. Waveforms EESS 2 and 3 began to show display strobing at an *I*/*N* of +50 dB and introduced false targets at an *I*/*N* level of +60 dB. Waveform Phase Coded 2 and Unmodulated 3 began to display strobing at an *I*/*N* level of +40 dB. The Phase Coded 2 waveform also caused loss of targets at an *I*/*N* of +60 however, at an *I*/*N* level of +60 Unmodulated 3 did not cause lost targets. Waveforms Phased Coded 2 and Unmodulated 1 caused strobing at *I*/*N* levels of +30 and +20 dB respectively and a further 10 dB increase in interference levels caused strobing and false targets. Waveforms Unmodulated 6 and 7 caused strobing at *I*/*N* levels of +20 and +10 dB respectively and also caused false and lost targets with a further 10 dB increase in interference signal levels. For baseline comparison purposes a CW signal was injected at an *I*/*N* of –9 dB which caused no effect, but when increased to level of –8 dB *I*/*N* caused loss of targets, When the CW signal was injected at an *I*/*N* level of –3 dB, all targets were lost. Figure 9 depicts the display showing the injected targets. Figure 10 shows the effects of false targets and strobe. Due to time constraints, waveforms Unmodulated 4 and Unmodulated 5 were not tested.

TABLE 11

Results of tests with ASDE-X surface movement radar and radiolocation and EESS waveforms

Signal	**Peak-to-RMS, *I*/*N* (dB)**	**Effect on radar**
Chirped 1	+60	No targets lost; occasional strobes
Chirped 2	+60	No targets lost; no strobes
Chirped 3	+60	No targets lost; very occasional strobes
Phase Coded 1	+60	No targets lost; no strobes
Phase Coded 2	+60	Few lost targets; occasional strobe
	+40	No lost targets; occasional strobe
Unmodulated 1	+60	A few false targets; occasional strobes
	+40	Occasional false targets; occasional strobes
Unmodulated 2	+40	Many strobes; occasional false targets
	+30	Many strobes; occasional false targets
	+20	Many strobes (50% of scope)
Unmodulated 3	+60	No lost or false targets; occasional strobes
	+50	No lost or false targets; small No. of strobes
	+40	No lost or false targets; small No. of strobes
Unmodulated 6	+30	False and lost targets; many strobes
	+20	No false or lost targets; some strobes
Unmodulated 7	+20	False and lost targets
	+10	No False or lost targets; strobes 50%
EESS1	+60	No False or lost targets; few strobes
EESS2	+60	Few False and no lost targets; some strobes
	+50	No lost or false targets; occasional strobes
EESS3	+60	Occasional false targets and strobes
	+50	No lost or false targets; occasional strobes
EESS4	+60	No lost or false targets; few strobes

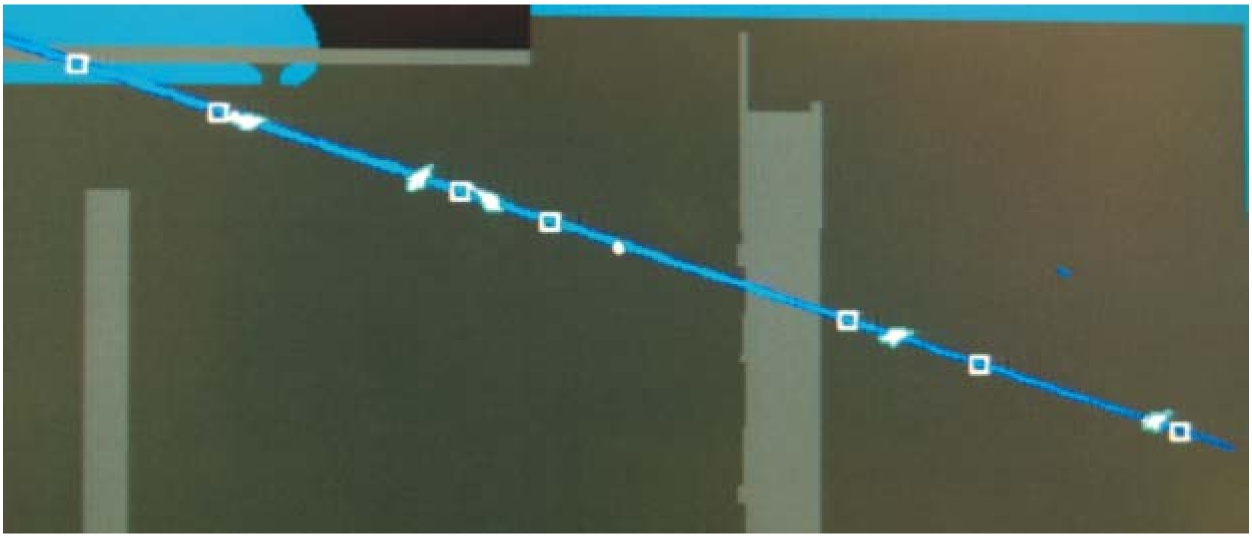
FIGURE 9

Baseline state for ASDE-X display

Rap 2081-09

FIGURE 10

Strobe and false targets on ASDE-X display



Rap 2081-10

9.4 PAR test results

The results of the PAR tests are shown in Table 12. The results show that in most cases the radar was able to withstand *I*/*N* values of +30 dB or greater from the test waveforms. For many cases the value was +40 dB. The results show that the Phase Coded 1 waveform did not have any effect on the radar's display at an *I*/*N* ratio of +60 dB. The Phase Coded 2 waveform did not have any effect on the radar's display until the *I*/*N* ratio exceeded +40 dB. Increasing the *I*/*N* ratio above +40 dB produced blocks of speckling that covered many ranges at one elevation and azimuth, and increased proportionately in intensity with increasing *I*/*N* across the range of the display.

Waveforms Chirped 1 and Chirped 3 had no effect on the display until the *I*/*N* exceeded +30 dB and Chirped 2 had no effect until the *I*/*N* exceeded +40 dB. Further increasing the *I*/*N* produced a varied speckling across the range of the display, the intensity of which increased with increasing *I*/*N*. The unmodulated waveforms produced no effect until the *I*/*N* exceeded +30 dB. Higher *I*/*N*s had the effect of producing blocks of speckles across many range cells at one elevation and azimuth. The higher duty cycle waveforms had the effect of producing thicker blocks, and these blocks approached a bar covering almost all range cells at one elevation and azimuth. Increasing the *I*/*N* of the waveforms increased the intensity of the pattern of the bars. Waveforms EESS 1 and EESS 2 began to cause a very light speckling with an *I*/*N* of +25 while EESS 3 and EESS 4 produced a similar effect when the *I*/*N* reached +30 dB. Although the amount of speckling increased as the *I*/*N* was increased to +60 dB, in all of the EESS waveforms, the speckling was minimal and less frequent that the other test cases.

Figure 11 shows the radar in the baseline state. The radar targets are shown as blocks at one range (~10 NM (18.5 km)) and all elevations and azimuths, as this was how the test target generator operated. The display was set by the radar operator to approximate that state that would be seen in the field. Figure 12 shows the radar with light interference. Figure 13 shows the radar with moderate interference, shown as blocks of speckle. Figure 14 shows the PAR display with severe interference. The display shows blocks of speckle at many ranges, in both the elevation and azimuth portions of the display.

TABLE 12

Test results for the precision approach radar for radiolocation and EESS signals

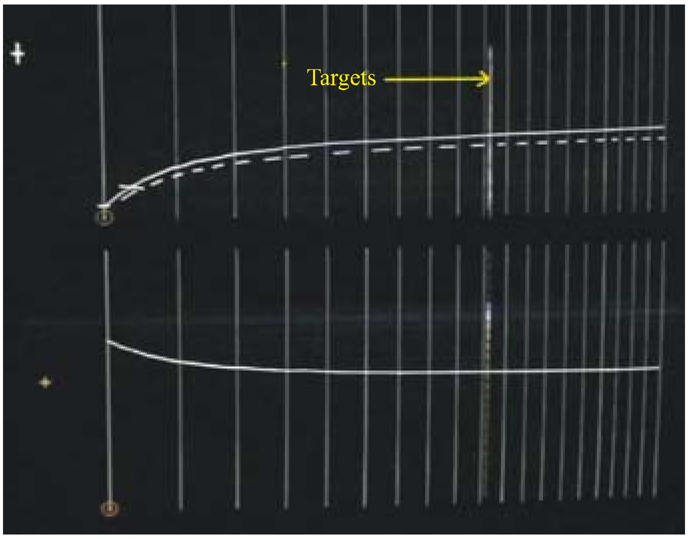
Signal	Peak-to-RMS *I*/*N* (dB)	Effect on radar
Chirped 1	+60	Distinct speckling
	+50	Less intense speckling
	+40	Faint speckling
	+30	No effect
Chirped 2	+60	Speckling (smaller in width than Chirped 1)
	+50	Speckling (smaller in width than Chirped 1)
	+40	No effect
Chirped 3	+60	Speckling (quicker and fainter than Chirp 1 and Chirp 2)
	+50	Speckling (quicker and fainter than Chirp 1 and Chirp 2)
	+40	Weak speckling (quicker and fainter than Chirp 1 and Chirp 2)
	+30	No effect
Phase Coded 1	+20 to +60	No effect
Phase Coded 2	+60	Blocks of speckles across range swath
	+50	Blocks of speckles across range swath
	+40	Weak blocks of speckles across range swath
	+30	No effect
Unmodulated 1	+60	Blocks of speckles across range
	+50	Blocks of speckles across range
	+40	Weaker blocks of speckles across range
	+30	No effect
Unmodulated 2	+60	Blocks of speckles across most ranges in groups of 1, 2 or 3 blocks
	+50	Blocks of speckles across most ranges in groups of 1, 2 or 3 blocks
	+40	Weak blocks of speckles across most ranges in groups of 1, 2 or 3 blocks
	+30	No effect
Unmodulated 3	+60	Complex speckling pattern in groups of 1, 2 or 3 blocks
	+50	Complex speckling pattern in groups of 1, 2 or 3 blocks
	+40	Weak complex speckling pattern in groups of 1, 2 or 3 blocks
	+30	No effect
	+60	Blocks of speckles across range, some blocks thick

TABLE 12 (*end*)

Signal	Peak-to-RMS *I*/*N* (dB)	Effect on radar
Unmodulated 4	+50	Blocks of speckles across range, some blocks thick
	+40	Weak blocks of speckles across range, some blocks thick
	+30	No effect
	+60	Thick blocks of speckles across range
Unmodulated 5	+50	Thick blocks of speckles across range
	+40	Weak thick blocks of speckles across range
	+30	No effect
	+60	Thick blocks of speckles across range
Unmodulated 6	+50	Thick blocks of speckles across range
	+40	Weak thick blocks of speckles across range
	+30	No effect
	+60	Thick blocks of speckles, almost bar-like across range
Unmodulated 7	+50	Thick blocks of speckles, almost bar-like across range
	+40	Weak, thick blocks of speckles, almost bar-like across range
	+30	No effect
EESS1	+60	Slight speckling
	+50	Slight speckling
	+40	Weak speckling
	+30	Very faint speckling
	+25	Few speckles
	+20	No effect
EESS2	+60	Widely spread speckles
	+50	Widely spread speckles
	+40	Weak widely spread speckles
	+30	Weak widely spread speckles
	+25	Faint widely spread speckles
	+20	No effect
EESS3	+60	Slowly timed speckling
	+50	Infrequent speckling (less frequent than EESS2)
	+40	Infrequent speckling (less frequent than EESS2)
	+30	Faint infrequent speckling (less frequent than EESS2)
	+25	No effect
EESS4	+60	Occasional speckles
	+50	Weak occasional speckling
	+40	Infrequent weak speckling
	+30	Very infrequent faint speckling
	+25	No effect

FIGURE 11

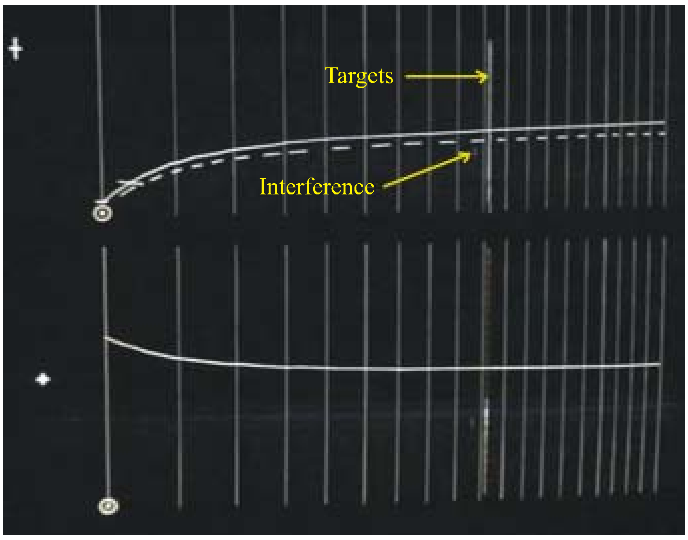
PAR display in the baseline state



Rap 2081-11

FIGURE 12

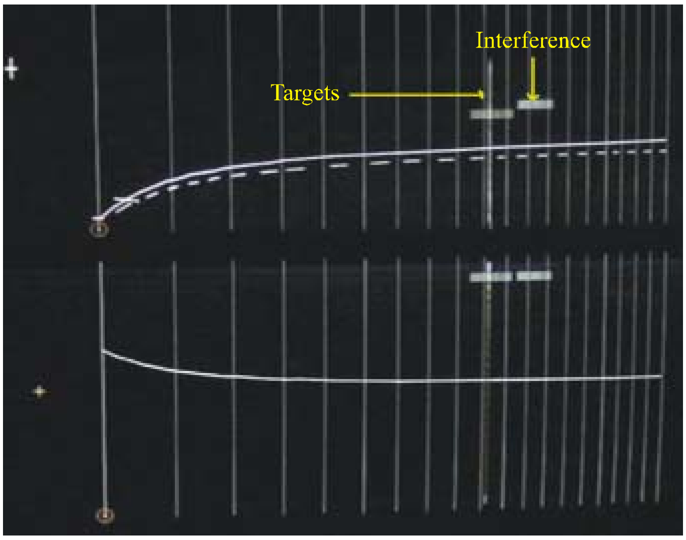
Light interference on the PAR display



Rap 2081-12

FIGURE 13

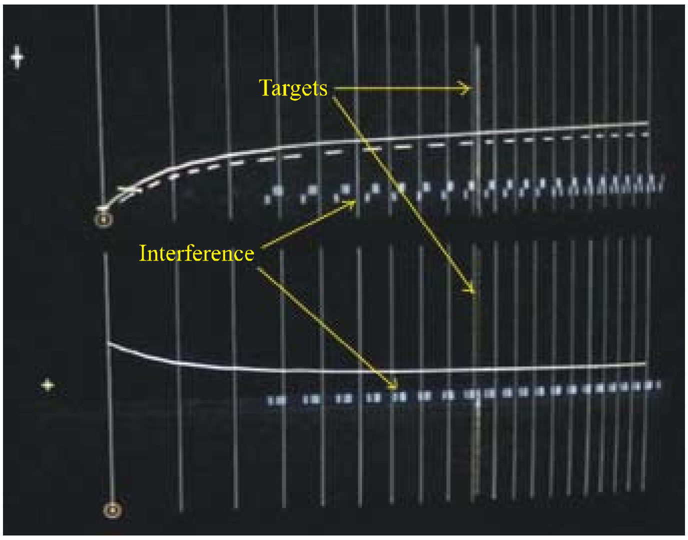
Moderate interference on the PAR display



Rap 2081-13

FIGURE 14

Severe interference on the PAR display



Rap 2081-14

10 Conclusions

The results with the marine radionavigation radar show that it was compatible with the EESS and radiolocation systems that were represented by the test waveforms at peak I/N levels of +40 dB. As most marine radionavigation radars of this type are similar to the one that was tested also employ interference mitigation techniques to prevent/reduce interference among *themselves*, it can be expected that they would also be compatible with the EESS and radiolocation systems represented by the test waveforms.

The results of the tests with the airborne weather radar show that it is compatible with the radiolocation and EESS waveforms as they did not cause any effect on the radar's display at I/N ratios up to +18 dB. In addition, the scanning effect of the radar's antenna along with the scanning/motion of the platform housing the system that generates the radiolocation and EESS waveforms, would make main beam coupling between the airborne weather radar and these systems not likely to occur. Most commercial weather radars are fixed tuned, which is how this radar was tested. Therefore, the radiolocation and EESS waveforms should be compatible with other airborne weather radars systems as well.

The results of the test of the ASDE-X surface movement radar (SMR) show that it is compatible with all of the radiolocation and EESS waveforms at *I*/*N* levels up to +20 dB, as they did not cause any effect on the radar's display at this high *I*/*N* ratios. Under normal operations the ASDE-X uses four channels (other models use as many as 16) and frequency hops from pulse-to-pulse to reduce the effects of fading and target fluctuation. The frequency hopping would make it more robust at mitigating any interference due to the radiolocation and EESS waveforms, as the chances of the interference occurring on *all* hopping channels at *all* times is unlikely.

The results of the test of the PAR show that it is compatible with all of the radiolocation and EESS waveforms at *I*/*N* levels of up to +30 dB, as they did not cause any effect on the radar's display at this high *I*/*N* ratios. Under normal operations the PAR uses multiple channels and MTI processing to reduce the effects of fading and target fluctuation. These factors would make it even more robust at mitigating any interference due to the radiolocation and EESS waveforms, as the chances of the interference occurring on *all* channels at *all* times is unlikely.

Annex 1

Maritime radar test procedures

1 Overview

The United States Administration has previously tested the S-band (23 GHz) version of this radar for gathering information on its ability to suppress low duty-cycle pulsed interference and its reaction to continuous types of communication signals. That data was used to support the upgrade of the radiolocation service to primary status in the 2.9-3.1 GHz band and to establish radar protection criteria at WRC-03. The data was published in Report ITU-R M.2032.

As in the previous tests, the targets were generated at the RF level and injected into the radar at known levels to generate a target probability of detection, P_d, of about 90%. Once this level was determined, the interfering signal was also injected into the radar at calibrated levels and the resulting effects on the radar's PPI display was observed and recorded with a digital camera.

For these new tests, an extra housing was purchased and bulkhead connectors were installed on it that were used to send/receiver signals to-from the radar. This sealed the radar receiver from the elements and provided RFI protection.

2 Target generation

Ten simulated equally spaced targets were generated on a single bearing using a combination of test equipment and software for the radar operating at a 3 NM (5.6 km) range. At this range, the radar automatically sets the pulse width to 200 ns with a prf of 2 200 pulses-per-second (pps) and employs an IF bandwidth of about 4.5 MHz.

Trigger and timing signals were used by the target generator for it to accurately generate radar targets at the same azimuth for each scan.

3 Test conditions

The tests were performed with the following parameters set on the maritime radionavigation radar as shown in Table13.

TABLE 13

Marine radar control settings

Parameter	Setting
Sensitivity time control (STC)	Disabled
Fast time constant (FTC)	Disabled (default)
Interference rejection (IR)	On (default) and off
Automatic gain control (AGC)	On (default)
Image selected	Raw video (“image”) and/or synthetic targets
Range	3 NM (5.6 km)

4 Test procedures

The RF power output of the target generator system was adjusted so that the target probability of detection, P_d, was about 90% without undesired waveforms being present (video targets). This value was recorded at the waveguide input of the receiver. Synthetic targets were experimented with.

After the radar was set to its baseline condition, the undesired waveforms were injected into the radar receiver. The power level of the radiolocation, EESS, and OFDM signal was varied while the power level of the targets was fixed. As the undesired signal power level was set to levels to produce specific I/N values, the display of the radar was to be observed for a decrease in the target P_d, an increase in the number of false targets, radial streaks (“strobes”), and an increase in background “speckle” or noise.

Each data point consisted of 20 rotations. Each point represents a specific I/N level for each radiolocation and EESS, and waveform. The radiolocation and EESS, waveforms were injected into the radar and 2-3 rotations were allowed to occur before the data is collected for that data point. This allows the radar to achieve a steady state operation. Between each data point the undesired waveforms were be turned off for 5 rotations and the radar was allowed to recover to its baseline state. Baseline P_d counts and photographs were taken at various times to ensure the radar had not permanently changed state.

5 Data collection

The targets missed per each rotation per I/N point were counted for the 20 rotations and representative photographs were taken of the PPI. The target P_d was determined by dividing the number of targets seen by the radar operator by the total number of targets generated (200). Curves of I/N vs. target P_d will be generated and/or photographs of the PPI were taken for each radiolocation and EESS, waveform. The PPI was also observed for an increase in the number false targets and/or strobes. This information was noted in the test logbook with a photograph.

Annex 2

PAR radar test procedures

The PAR includes a mode called special test, and this is the mode the radar was set in during the test. This mode allows the receivers to be operational while giving more control to the users for testing purposes. This mode also allows for the frequency diversity to be controlled. The radar can be set to operate in (A1, A2), (B1, B2), or any one of the individual frequencies desired. The radar can also be set for linear normal mode for receiver operation. This would turn off the coherent MTI and non-coherent MTI processing. Also disabled are the CFAR, FTC, and 2nd return rejection processing. Many of these features are accessed on the radar's front panel as toggle switches. The STC was unable to be turned off, and was present during the testing. Another feature of the radar front panel is the availability of the scan prf trigger. This will allow the target generator to lock on to the radar's staggered prfs (to be described in detail below).

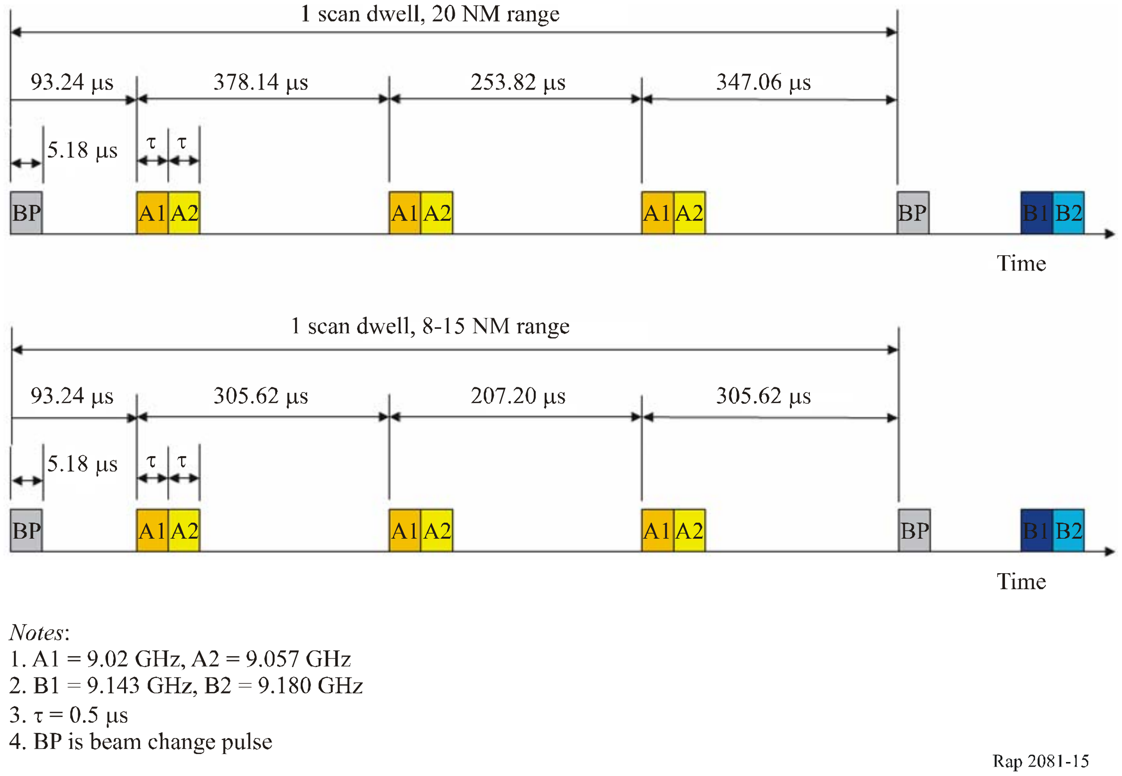
The track mode of this radar was also unable to be turned off. This did not affect the results of the tests, as *I*/*N* levels were calculated during scan mode (it was easy to distinguish scan and track modes in spectrum analyser at IF). Since the tracking of this radar is manual and not automatic, tracking symbols did not appear on the display during the test, and therefore did not hinder the ability to recognize the effects of interference.

For this test, the radar antenna was disconnected from the receiver front end, and the interference and targets were injected into the front-end waveguide. With the antenna disconnected, there was no effect from outside interferers. The radar high-power transmitter was used in conjunction with the radar's test set to produce the targets. There was a built-in test feature that allowed the transmitter's RF output to bypass the antenna and be directly combined with the interference and input into the receiver front-end. The *I*/*N* level was monitored using a spectrum analyzer (set to zero-span, at 74 MHz, with 2 MHz bandwidth) connected to a test port in the IF.

The PAR utilizes four frequencies in scan mode for frequency diversity. Each 1 μs pulse is made of two sequential 0.5 μs pulses, first at A1 (9.02 GHz) followed by one at A2 (9.057 GHz). This repeats for one scan dwell (a scan dwell is 3 pulses), as shown in Fig. 15. After this, the beam position is updated, and the frequency of each pulse is changed. Now transmitted is 0.5 μs at B1 (9.143 GHz) followed by 0.5 μs at B2 (9.180 GHz). This repeats for one scan dwell, and then the radar returns to the (A1,A2) frequency set. Each 0.5 μs sub-pulse is down-converted and processed separately (separate IF scan receivers), leading to dual channels of scan data. This data is integrated before being sent to the display. For the interference testing the radar will be set in one frequency mode. This will allow for on-tune injection of interference. The frequency was set to A1 (9.02 GHz) for these tests.

FIGURE 15

Timing diagram for precision approach radar



The PAR is a MTI radar, and is designed to remove stationary targets and clutter. One side-effect of MTI is that it also removes targets at all multiples of the prf. The speeds associated with these Doppler frequencies are called blind speeds. When using MTI, the radar has blind speeds v_n that are defined as:

$$v_n = \frac{n * \lambda * f_p}{2}$$

where

n = 1,2 ... ∞

λ: transmitted wavelength (m)

f_p: pulse repetition frequency (Hz).

One way to combat this blind speed is to use multiple prfs. That is what the PAR does, and all of its prfs are multiples of a 193 kHz clock (5.18 µs period). As shown in Fig. 15, for the 20 NM range scan dwell, the time between the first pulse and second pulse is 378.14 µs, which corresponds to a prf of 2.644 kHz. The time between the second and third pulse (253.8 µs) corresponds to a prf of 3.94 kHz. The third prf is 2.88 kHz, corresponding to the 347.06 µs between the third pulse and the start of the beam change pulse. The 93.24 µs that occurs after the rising edge of the beam change pulse is used to change the position of the scan dwell. The prfs associated with the shorter range are 3.27 kHz and 4.83 kHz. The prf trigger that is sent to the radar's front panel is an active high signal with a 5.18 µs duration. The prf trigger does not trigger the beam change pulse, so it becomes active only when a pulse is transmitted. This signal was used to trigger the target generator. The radar gave no way to set the interference to occur at the same elevation and azimuth for every complete volume scan. Therefore the testing had to be done with the interference gated in such a way that it changed to a different beam position on every complete volume scan (although it was only gated for one beam position per volume scan).

Target generation will be accomplished with the radar's test set and the radar transmitter. The test set is capable of creating targets out to a distance of approximately 20 NM (36 km), with range rates of ±2 000 knots. It has a pulsed feature, with RF from 8.4 GHz to 10 GHz, with peak pulsed power up to +50 dBm, and pulse widths ranging from 0.12 μs to 5 μs. The target was generated at 9.02 GHz (frequency A1 of the radar), at a range of approximately 10 NM (18 km), with the power set to assure detection near the minimum discernable signal level. The targets appeared on the display at every elevation and azimuth (at one range) instead of one elevation and one azimuth as a real target would appear. This is why there is a bar-like appearance for the targets in Figs 11-14. The radar display parameters were set by an experienced radar operator. He set the brightness, contrast, and target signal power to approximate what would be seen in the field. All tests were conducted with his settings on the display.

The radar was calibrated by first determining the underlying system RMS noise level in the scan mode using the spectrum analyser in zero-span mode (the track mode had a different noise level). After making this determination, a CW signal was injected into the radar, and the power level (dBm) that was required to have an I+N/N of 3 dB was recorded (corresponding to an I/N of 0 dB). This was repeated for each interfering signal, and these numbers were used to create a table of power levels for each signal for the vector signal generator (VSG). These power levels corresponded to I/N levels of –12 dB to +60 dB.

After calibration, a target was generated and sent into the front end of the radar, and it was displayed at the range set in the test set (~10 NM in the 20 NM range setting). This was the baseline for operation. The interfering signal was injected and the display was monitored for false targets or a drop in the generated target. Movement of the generated target (in range) was also noted. The I/N level was varied over a set range (starting at +60 dB and decreasing until no effects were seen on the display), and all effects were noted in the logbook. This was repeated for each interfering signal. Screens were captured to show representations of differing levels of interference.

Note that for this system, there was no need to generate ten targets along a radial as that is not a practical application of the radar as it assists aircraft landing.

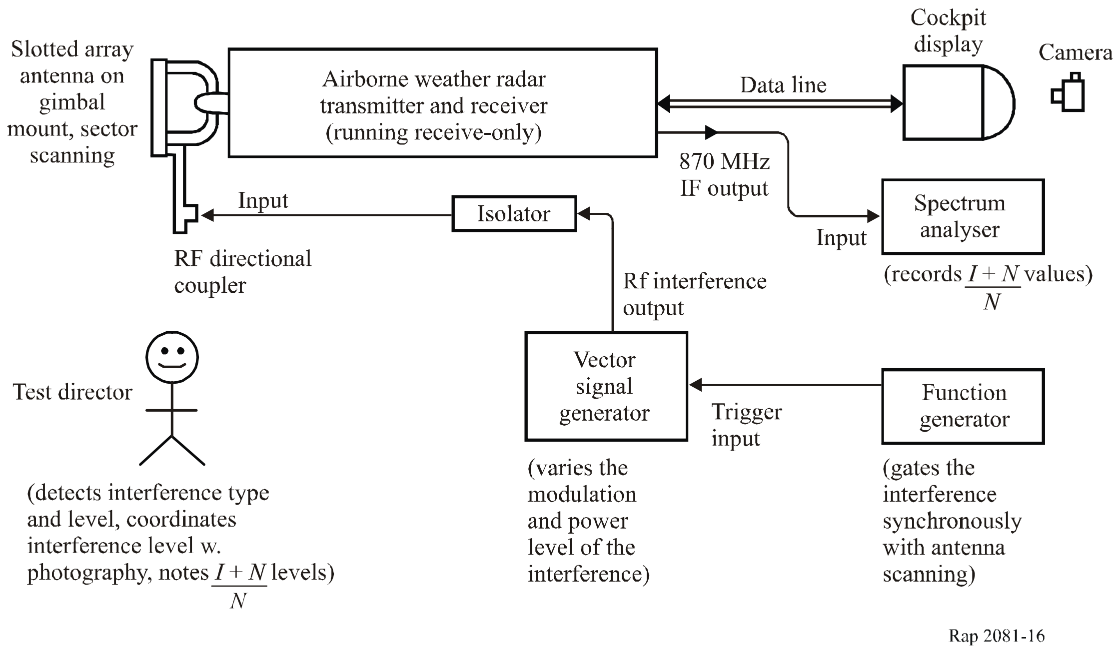
Annex 3

Airborne weather radar test procedures

1 Test methodology

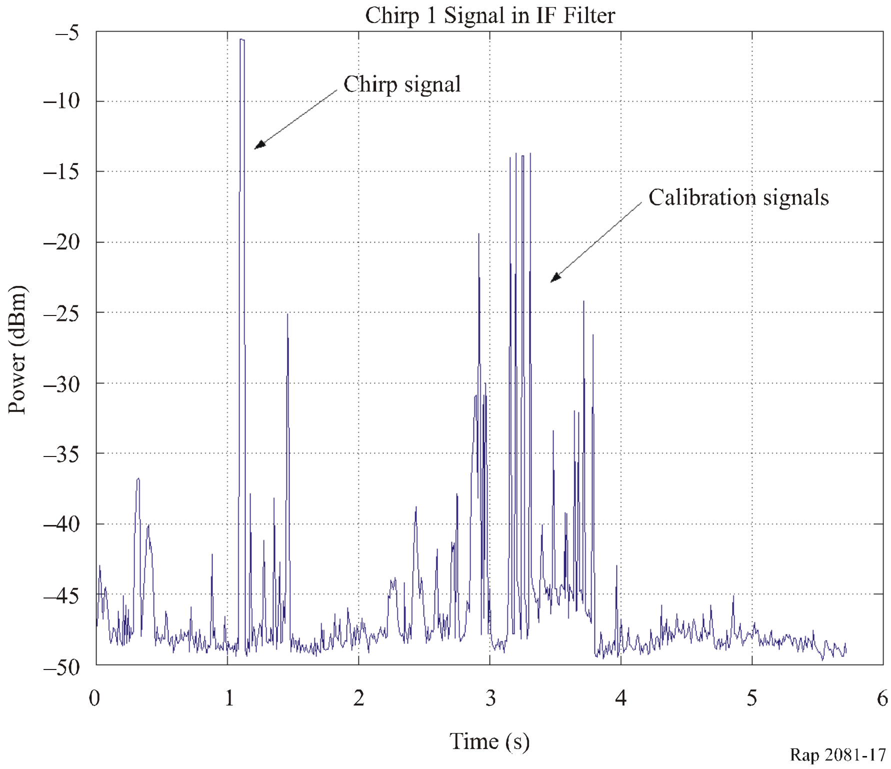
The radar was tested by injecting the radiolocation and EESS signals into a coupled port between the antenna and the front-end of the receiver (see Fig. 16). The IF of the radar was monitored by setting the spectrum analyser to zero-span in a 6 MHz bandwidth. The (I+N)/N values are corrected to be in the bandwidth of the receiver. The radar transmitter was disabled for the tests but the antenna was still connected to the system. The radar was set to the 40 NM range setting, with a +1.9° tilt angle, and scanned ±135° from the defined boresight. The receiver was fixed to 9 335 MHz. On occasion interference from other high power radars located near the test range was visible on the radar's display. The external interference did not affect the test's results, as the interference from the radiolocation and EESS waveforms was easily identifiable on the radar's display as two wedges that were symmetrical about the centre azimuth. The waveforms were gated to last the duration of the antenna sweeping across a stationary target. The duration was 45 ms.

FIGURE 16



In past testing, the interfering signal I/N levels were calibrated and adjusted individually by changing the power of the VSG that produced the radiolocation and EESS signals using a front panel control. For this radar, that was not possible because it would change its gain after about two sweeps and the I/N would change level automatically. This effect was used as an advantage in that the peak value of the I/N occurred after two calibration routines were completed every 12 sweeps or so (as sweep is one complete right-left movement of the antenna). The radiolocation and EESS signals were visible in the IF output that was monitored using the spectrum analyser, and the I/N values were determined in that manner. The radar slowly changed its gain as it swept and correspondingly every two sweeps the I/N would decrease with the gain.

FIGURE 17



The (*I*+*N*)/*N* values were read off the analyser display in the form of a peak-to-RMS function and noted in a logbook. The radar display was visually monitored at each level for any type of visible effect. The (*I*+*N*)/*N* values were allowed to "walk" down automatically by the radar itself once the maximum *I*/*N* was initially set using the controls of the VSG. The maximum *I*/*N* value was dependent of the signal structure as a function of the VSG's operational parameters. For example, the maximum power available from the VSG produced an (*I*+*N*)/*N* of 50 dB or better for the pulsed waveforms. As the antenna swept, the radar receiver decreased its gain and therefore the *I*/*N* value also decreased till the calibration routine occurred. Once calibration occurred, the gain would be reset to its maximum value and the cycle repeated. If, at the end of a cycle, the effect was still visible on the radar display then the power of the VSG was adjusted so that the initial maximum *I*/*N* value would stat at a lower level then the initial test run.

It should be noted that in testing ground based meteorological radars in the past, the results showed that the weather data was corrupted by interference sources *before* an effect was visible on the radar's display. This may also be true with this airborne radar, but system level diagnostics were not available for review. The ARINC performance metric is only for visible effects.

1.1 Effects of waveforms on radar display

The radar uses colours to display various weather phenomena as a function of range on the display. The radar's display is a small cathode ray tube (CRT) and is representative of what the aircraft pilot or navigator would view during flight operations. Rain, windshear, and other weather phenomena vary the colours of the display as a function of their intensity. A description of colour scheme, from the radar user manual, is shown in Table 14. The radiolocation and EESS waveforms, produced, in some cases, "wedges" on the CRT that were clearly visible with their intensity a function of the (*I*+*N*)/*N* ratio. As the (*I*+*N*)/*N* ratio decreased, the wedge became less intense until it would finally look no different from the background colours.

TABLE 14

Colour display attributes

Rain rate	Description	Reflectivity	Colour
1 to 4 mm/hr	Light	23 to 30 dBz	Green
4 to 12 mm/hr	Moderate	30 to 40 dBz	Yellow
12 to 50 mm/hr	Heavy	40 to 50 dBz	Red
>50 mm/hr	Excessive	>50 dBz	Magenta
N.A.	Turbulence	N.A.	Flashing white
N.A.	Masked region	N.A.	Blue

N.A.: Not applicable.

Annex 4

ASDE-X radar test procedures

1 Test methodology

Under normal operation, the ASDE-X hops between four channels from pulse to pulse. In order to facilitate the generation of the radiolocation and EESS signals to be injected into the ASDE-X receiver, the unit under test was programmed to use the same channel for all desired signals and the various modulation injected into the system. The sensitivity time control (STC) used on the short pulse was turned off. The tests were performed with the transmitter turned off while the receiver was operated in a normal operational mode and signals were synced with the North pulse from the antenna. Both the desired and interfering signals were combined and then, before the receiver blanking switch, injected into the port on the wave guide coupler. The receiver was monitored with a spectrum analyser connected to a directional coupler after the signal was downconverted to 150 MHz.

Two vector signal generators (VSGs) were used to create the desired signal and the interfering levels was –91 dBm. A signal level of –91 dBm gave instable targets. Once a stable target level was established a CW source was used to get a baseline to determine the effects of interference on the receiver. A CW signal was injected at an *I*/*N* level of –12 dB and increased in 1 dB increments to determine the effect on the receiver. An *I*/*N* level of –9 dB had no effects on the target display however, at an *I*/*N* level of –8 dB, some targets were lost. At an *I*/*N* level of –3 dB all targets were lost from the display.

1.1 Effects of waveforms on radar display

Once the baseline was established the various waveforms were injected into the receiver at a relatively low level and incrementally increased until either, an effect, consisting of strobing, false targets, or lost targets were observed, or the interfering signal reached a maximum *I*/*N* level of +60 dB was reached.

Annex 5

The difference between 10 log((*I*+*N*)/*N*) and 10 log(*I*/*N*)

Spectrum analysers measure the total power in a bandwidth. That power includes both the input signal and the power in the analyser's internal noise. If the input signal is designated as interference, I, and the analyser's noise is designated as N, then the analyser measures the decibel power, P_{meas}:

$$P_{meas} = 10 \log(I+N)$$

Often it is necessary to compare the value of P_{meas} to the value of N itself. This circumstance arises especially in cases in which N is the noise produced by the IF stage of a receiver, and P_{meas} is the measured value of the interference signal. In that case, the decibel value of the interference ratio, X, that is measured is:

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

But whereas the quantity $(I+N)/N$ is what is observed with a spectrum analyser, theoretical electromagnetic compatibility studies normally reference a different quantity, the exact ratio between the strength of the interference signal and the noise level of a receiver, I/N.

A connection needs to be established between the measured interference ratio, $(I+N)/N$, and the theoretically useful quantity I/N.

Algebra yields the connection. If the mathematics are performed in decibel units, then:

$$X = 10 \log((I/N)+1)$$

Which can be rearranged as:

$$((I/N)+1) = 10^{(X/10)}$$

or

$$I/N = 10^{(X/10)} - 1$$

Therefore,

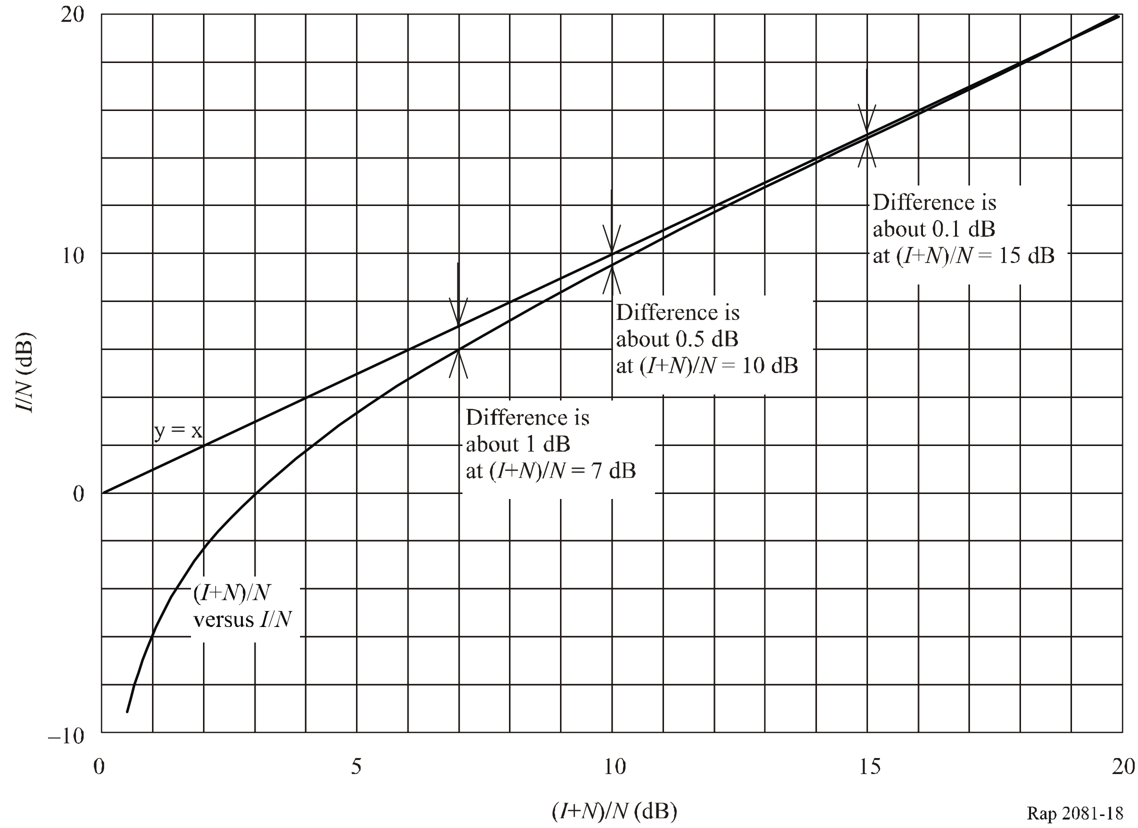
$$10 \log(I/N) = 10 \log(10^{(X/10)} - 1)$$

This relationship is shown in the graph of Fig. 18.

FIGURE 18

Graph of *I*/*N* as a function of (*I*+*N*)/*N*

The straight, log-log line y = x is provided to show the convergence between the two quantities when *I*/*N* is sufficiently large



There are several useful points on this graph. First, *I*=*N* when the interference level is observed 3-dB above the noise level. This point is useful for calibrating interference-to-noise ratios during interference testing. Additional points of interest are noted in Table 15.

TABLE 15

Points of practical interest when measuring (*I*+*N*)/*N*

(*I*+*N*)/*N* (dB)	*I*/*N* (dB)	Difference (dB)
3	0	3
7	6	1
10	9.5	0.5
15	14.9	0.1

The practical upshot of the mathematical relationship between these quantities means that, if the uncertainty in the power measured by a spectrum analyser is even as small as 0.1 dB, then when the interference signal is observed 15 dB or more above the noise level, the actual *I*/*N* level can be taken to be the same value. For many situations, this point of practical equivalence can be pushed even lower, to 10 dB.