# 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

(2003)

## 1 Introduction

Tests have been performed to assess the effects of emissions representative of radiolocation radars having a secondary allocation in the 2 900-3 100 MHz band on two representative maritime radionavigation radars having a primary allocation in that band. The maritime radionavigation radars used for these tests are identified as Radars A and B in this Report[1]. The tests were performed in two separate efforts. In the first effort, the radiolocation emissions were simulated by means of signal generators, using pulses with no intra-pulse modulation and were roughly representative of emissions from P0N type radiolocation radars described in Recommendation ITU-R M.1460 – Technical and operational characteristics and protection criteria of radiodetermination and meteorological radars in the 2 900-3 100 MHz band.

In the second effort, tests were performed with longer pulse width and higher duty cycle P0N type emissions, which are not typical of those radars identified in Recommendation ITU-R M.1460. Analog reconstructions of digitally recorded emissions from a stepped-frequency radiolocation radar that operates with the characteristics and parameters similar to that of Radar 2 in Recommendation ITU-R M.1460 were also used as unwanted stimuli to one of the maritime radars.

This Report describes the conduct of these two test efforts and their findings.

## 2 Objectives

The objectives of the testing were:

– to quantify the capability of representative maritime radionavigation radars interference-rejection processing to mitigate unwanted asynchronous P0N pulses due to emissions from radiolocation radars as a function of their duty cycle, pulse width, and power level;

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[1] These tests addressed pulsed maritime radionavigation radars having pulse widths, pulse repetition frequencies (PRFs), bandwidths, noise figures, and antenna beamwidths typical of those identified in Recommendation ITU-R M.1313. Those radars typically employ interference mitigation techniques/processing methods identified in Recommendation ITU-R M.1372 to allow them to operate in the presence of other radionavigation and radiolocation radars. Mitigation techniques of that kind are relatively inexpensive to provide now that powerful digital signal processing circuitry is available at low cost and is in wide use for other navigation radar functions. Older and less sophisticated maritime radionavigation radars may not have the same level of interference rejection capabilities as those typically provided in the International Maritime Organization (IMO)-category radars identified in Recommendation ITU-R M.1313 – Technical characteristics of maritime radionavigation radars.

– to quantify the capability of representative maritime radionavigation radars interference-rejection processing to mitigate an unwanted stepped frequency radiolocation waveform;

– to observe and quantify the effectiveness of representative maritime radionavigation radars interference rejection techniques to reduce the number of false targets, whether in the form of radial streaks (strobes), or point-like “speckle”;

– to observe and quantify the interference mitigating effects of applying antenna pattern modulations on the radiolocation radar emissions.

## 3 Radars under test

Radar A is an older system while Radar B was introduced recently (circa 2000). Nominal values for the principal parameters of the two radars were obtained from regulatory type-approval documents, sales brochures, and technical manuals. These are presented in Tables 1 and 2.

TABLE 1

**Radar A transmitter and receiver parameters**

| Parameter | Radar A (older radar) | | |
|---|---|---|---|
| Frequency (MHz) | 3 050 ± 30 | | |
| Pulse power (kW) | 60 | | |
| Range (nmi) | 0.25-3 | 6-12 | 24-64 |
| Pulse width (μs) | 0.06 | 0.50 | 1.0 |
| PRF (Hz) | 3 600 | 1 800 | 900 |
| IF bandwidth (MHz) | 22 | 4 | 4 |
| Spurious response rejection (dB) | 40 | | |
| System noise figure (dB) | 10 | | |
| RF bandwidth (MHz) | 100 | | |
| Antenna scan rate (rpm) | 33 | | |
| Antenna scan time (s) | 1.8 | | |
| Antenna horizontal beamwidth (degrees) | 1.25 | | |
| Polarization | Horizontal | | |

Additional quantities of interest are the antenna main-beam’s time-on-target and the associated numbers of pulses-on-target during the main-beam dwell. They are contained in Table 3. For each pulse repetition frequency, these quantities are derived from the parameters listed in Tables 1 and 2.

The radars were aligned by technicians prior to commencement of the testing to ensure their optimum performance.

TABLE 2

**Radar B transmitter and receiver parameters**

| Parameter | Radar B (newer radar) | | | |
|---|---|---|---|---|
| Frequency (MHz) | 3 050 ± 30 | | | |
| Pulse power | 30 | | | |
| Range (kw) | 0.375-1.5 | 3-6 | 12 | 24-96 |
| Pulse width (μs) | 0.08 | 0.30 | 0.60 | 1.2 |
| PRF (Hz) | 2 200 | | 1 028 | 600 |
| IF bandwidth (MHz) | 28 | 3 | 3 | 3 |
| Spurious response rejection (dB) | 60[(1)] | | | |
| System noise figure (dB) | 4 | | | |
| RF bandwidth (MHz) | Unknown | | | |
| Antenna scan rate (rpm) | 26 | | | |
| Antenna scan time (s) | 2.31 | | | |
| Antenna horizontal beamwidth (degrees) | 1.9 | | | |
| Polarization | Horizontal | | | |

(1) Measurement revealed a spurious response rejected by 44 dB.

TABLE 3

**Derived parameters of maritime radionavigation radars under test**

| Parameter | Radar A | Radar B |
|---|---|---|
| Time-on-target (ms) | 6.3 | 12 |
| Pulses-on-target | 23 11 6 | 23 13.4 7.3 |

## 3.1 Characteristics common to the radars

The two maritime radars are basically similar. Both have magnetron transmitters. Both can transmit pulses with pulse widths ranging from 0.06 (or 0.08) μs to 1.0 (or 1.2) μs. Both use a number of IF bandwidths, each geared to a different pulse width. Both radars can operate with range scales as short as a fraction of a nautical mile and as long as 64 to 96 nmi (approximately 118-178 km). Both operate nominally on 3 050 MHz. Both have an antenna scan time close to 2 s and a horizontal beamwidth between 1° and 2°. Neither radar performs moving-target-indication (MTI) or other Doppler-based signal processing. Both radars have a feature that rejects asynchronous pulsed interference.

Both radars use logarithmic IF amplifiers and use a.c. coupling in their video signal paths. This is almost universal in maritime navigation radars. These design choices are apparently based on a finding, made in 1956, that envelope-detected signal fluctuation due to clutter return having a Rayleigh distribution is essentially independent of the intensity of the clutter (or the effect of range) when the signal is processed in a logarithmic amplifier followed by a.c. coupling[2]. In practice, signal fluctuations of sea and rain clutter return depart somewhat from the Rayleigh model, with the result that the root-mean-square (r.m.s.) fluctuation does vary with clutter intensity and range, but less so than if a linear receiver or a logarithmic receiver with d.c. coupling were used.

Very significantly, both radars have processing to reject asynchronous pulsed interference. The form of the interference rejection (IR) process in Radar B differs somewhat from that in Radar A, but the process exploits the same principle in both radars. Radar A compares the contents of a given range cell on each pulse repetition interval (PRI) with the contents of that same cell on the previous PRI, and displays a spot (or blip) on the screen only if both cells contain detections. Radar B has a process that notes the signal levels in three consecutive sweeps instead of two. At any given range, if the signal pulse amplitude exceeds those on previous and following PRIs by an inordinate amount, it replaces that amplitude with a weighted average of the values on the preceding and following PRIs. In the Radar B variant tested in the first effort, the tolerable disparity between the signal amplitude in the current PRI and the amplitudes in the preceding and following PRIs was adjustable. In the second test effort, the software controlling the IR function had been revised; the operator could only disable it. The IR control enabled is the system's default setting.

Figure 1 illustrates typical occurrences of asynchronous pulses having the width (2 μs) used in the current tests as they appear within successive range sweeps of a radionavigation radar similar to Radar A or Radar B when operating on the range scale used in the current tests. The diagram also shows some of the pulses that would be returned from a real target at a range (2.37 nmi or 4.39 km) equivalent to a round-trip delay of 29.25 μs. (They are shown disproportionately long due to limitations of the software used to generate the diagram; they would actually be only one eighth as long as they appear.) Under the conditions that prevailed in the tests, a point target would give returns on 23 sweeps within the antenna's main beam, only 12 of which appear in the diagram. Since real-target return is synchronous, all returns fall into the same range cell.

Both radars have user-selectable sensitivity time control (STC), which attenuates heavy sea clutter return by desensitizing the receiver at short ranges but not at long ranges. Both radars also have a user-selectable fast time constant (FTC), which differentiates the video signal and is used to discriminate against rain clutter.

### 3.2 Characteristics that differ between Radars A and B

#### 3.2.1 Major differences

Radar B contains an RF preamplifier and has a nominal noise figure of 4 dB, while Radar A apparently has no RF preamplifier and has a noise figure between 9.3 dB and 11 dB. Radar B has more extensive signal processing and target tracking capabilities, including an adaptive local constant-false-alarm-rate (CFAR) feature and a scan-to-scan correlation feature, which Radar A does not have. The local CFAR (acting within a small fraction of one range sweep) is of a type

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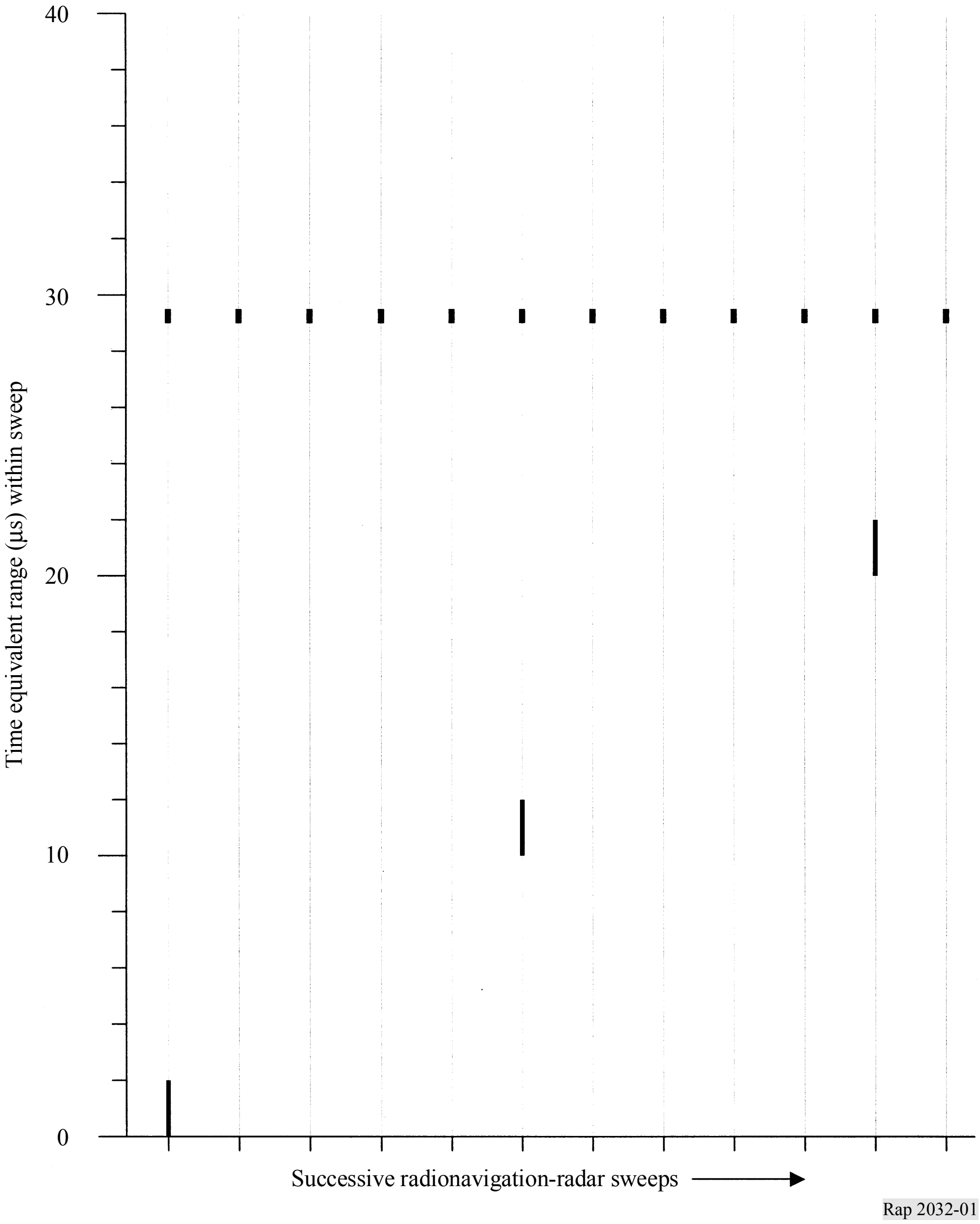
[2] CRONEY, J. [April 1956] Clutter on radar displays. *Wireless Eng.*, p. 83-96.

known as an ordered-statistic CFAR, which is a type that permits the desensitizing effect of interfering pulses to be lessened or avoided. In this type of CFAR, a selectable number of background signal samples (range-bin contents) can be discarded, so that only the remaining ones (and particularly the strongest remaining one) can be used to establish the detection threshold. The process discards the samples having the greatest amplitude, so that as more samples that are discarded, the less influence the high amplitude pulses are likely to have on the sensitivity of valid target detection.

FIGURE 1

**Occurrences of asynchronous 2 μs pulses in radar sweeps and range cells**



Radar B can also perform a scan-to-scan correlation process that provides an additional means for discriminating between signals that are present consistently, such as a valid target, and signals that appear at random times, such as asynchronous pulsed interference.

The more sophisticated signal processing capabilities of Radar B are attributable to the advances in digital microcircuits, including cost reductions, that have been made in the years since Radar A was designed. Implementation of this local CFAR process requires substantial amount of digital memory, which was not available when Radar A was developed. It is expected that future designs of maritime radionavigation radars will improve these features as well.

### 3.2.2 Minor differences

There are also some more subtle differences between the two radars. While both radars have logarithmic IF amplifiers, Radar A uses diode networks to perform log shaping within the IF amplifier, while Radar B uses a logarithmic amplifier/detector implementation; i.e. it makes use of several log IF gain stages each with an associated envelope detector. The outputs of the IF amplifiers/detectors are summed to provide a video signal with a logarithmic characteristic.

Table 4 summarizes the similarities and differences between the maritime radionavigation Radars A and B.

TABLE 4

**Similarities and differences between maritime navigation Radars A and B**

| Feature | Radar A | Radar B |
|---|---|---|
| Location of transmitter and receiver circuitry | Below deck | Antenna pedestal |
| IF amplifier type | Log amplifier | Log amplifier/detector |
| Video coupling | a.c. | a.c. |
| STC | Yes (operator adjustable) | Yes (operator adjustable) |
| FTC | Yes (operator adjustable) | Yes (operator adjustable) |
| Asynchronous pulse rejection (interference rejection) | 2 pulse comparison | 3-pulse comparison with substitution (see text) |
| Automatic gain control (AGC) | Yes (selectable) | Yes (selectable) |
| Autotuning | No | Yes |
| RF preamplifier | No | Yes |
| False-alarm-rate control | Manual | Adaptive local CFAR (synthetic targets only) |
| Scan-to-scan correlation | No | Active on synthetic target symbols |
| Display intensity | 2 non-zero levels | Up to 15 non-zero levels |
| Display type | Real-time radial scan | Raster scan |
| Persistance | Fixed by cathodic ray tube (CRT) phosphor | Variable |

### 3.3 Radar A and B receiver IF bandwidth and noise figure measurements

The noise floor of the radar receiver was computed as *k T B* plus the noise figure, where *B* represents the radar 3 dB IF bandwidth.

#### 3.3.1 Radar A

The measured 3 dB IF bandwidth was 21.3 MHz when the radar was set for short-range operation (0.25 to 3 nmi range, or approximately 0.46-5.56 km). This closely corresponds to the specifications contained at one point in the radar technical manuals.

For Radar A, the measured receiver noise figure was 11 dB, which is 1 dB higher than the specification in one technical manual (10 dB) and 1.7 dB higher than the specification in another technical manual (9.3 dB). The noise floor of Radar A was calculated to be –90 dBm.

#### 3.3.2 Radar B

Additional measurements were performed on Radar B to better characterize its IF response. These measurements included determining its input-output response, measuring the IF selectivity (for a 3 nmi range), and noise figure.

As stated previously, the radar uses a multistage logarithmic IF amplifier/detector. The tests showed that the radar has up to 70 dB of rejection at off-tuned frequencies within the 2 900-3 100 MHz band and has a high dynamic range as well. The dynamic range of the radar is shown in Fig. 2 and the response of the IF circuitry at a video output test point with the radar set to a 3 nmi (5.56 km) range is shown in Fig. 3.

FIGURE 2

**Radar B dynamic range**

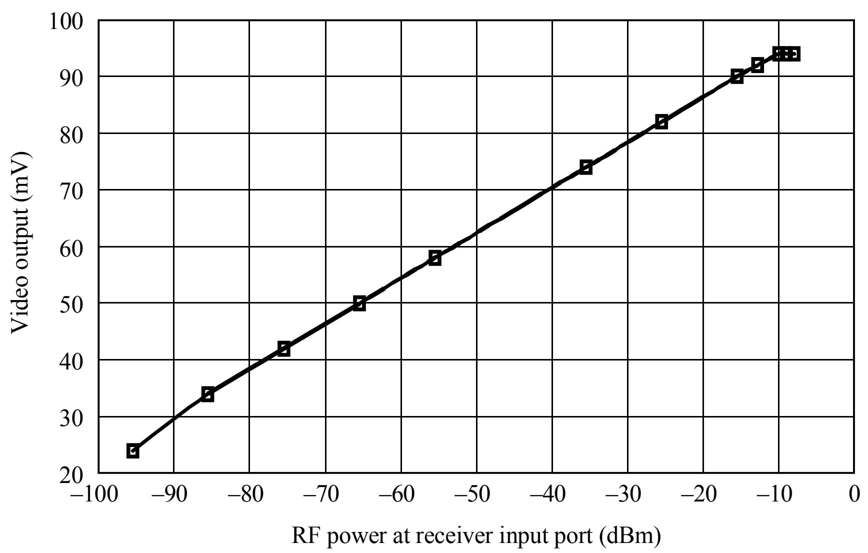



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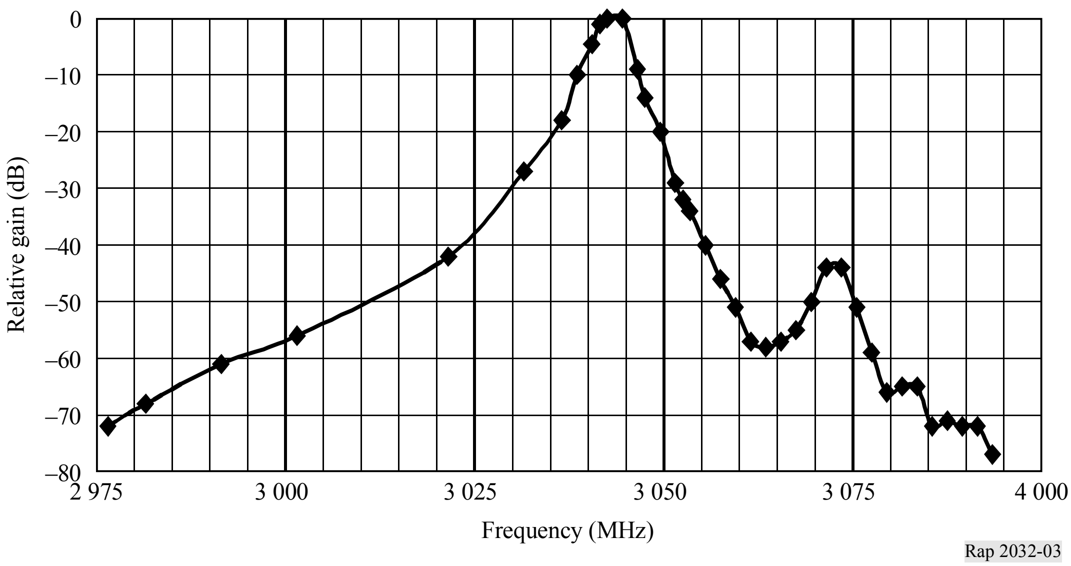
FIGURE 3

**Radar B IF selectivity**




Measurements at a video level slightly above the mid-pulse minimum visible signal level revealed a spurious response, visible in Fig. 3, that was suppressed by 44 dB approximately 30 MHz above the tuned frequency. There is no reason to expect that this spurious response had any effect on the findings of these tests. However, radionavigation radars with spurious responses may be responsive to off-tuned continuous waveforms.

The noise figure of Radar B was measured and was found to be 5.3 dB, which was consistent with the nominal value of 4 dB. The noise floor of Radar B was calculated to be –104 dBm.

## 3.4 Radars A and B video and target displays

Radar A has two non-zero levels of intensity for display of detections, while Radar B has either 3 or 15 such levels, depending on the operator's choice. Radar A uses a radially-swept plan-position indicator (PPI) and displays targets as amorphous raw-video "blips" (known as the image display). That is, it displays the radar image in real time; new sweeps are added while previously-written sweeps remain displayed except for decay of intensity. The persistence of the older radar's display is fixed by the characteristics of its CRT phosphor (except to the extent that adjustment of brightness might modify the persistence experienced visually). Radar A does not display synthetic video symbols, but it does stretch the return pulses in the outer portion of the displayed range to enhance their visibility.

In contrast, Radar B has a raster display: digitized radar returns are processed and the results stored in memory; the content of the synthetic raster display is assembled based on the stored results; the raster display is updated only after many sweeps have elapsed since the radar return was received. Instead of advancing gradually around the screen, sweep by sweep, radar B's display advances by sectors on the order of 15° at a time. The display's persistence is operator adjustable.

Radar B has the ability to display various types of targets in different combinations. The radar is able to display the amorphous blips, synthetic targets that appear as an "o", and/or tracked targets that appear as an "x". 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 compared to the raw-video targets to obtain the same probability of detection (Pd) when operating at minimum detectable signal (MDS) level but do not change their brightness in correspondence to the reflected signal strength.

## 4 Performance measurements

### 4.1 Overview of unwanted emissions testing

These tests were mainly concerned with the capacity of asynchronous pulsed signals from radiolocation radars to influence the occurrence of false alarms, the probability of detection of valid targets, and the visibility of detected valid targets amidst false alarms. Valid targets were simulated as described in § 4.2. The RF power output of the simulated-target generator was initially adjusted to produce stationary target detections consistent with a fixed probability of detection. Asynchronous pulse waveforms were then injected into the radar along with the simulated targets and the effects those asynchronous pulses had on the visibility of the displayed targets was observed and photographed with a digital camera. The simulated targets and the unwanted radiolocation signals were injected directly into the maritime navigation receiver, not coupled via the latter's antenna.

The test results are expressed in terms of ratios of unwanted-waveform power to system noise power, referred to as *I*/*N* ratios. Observations were made for numerous *I*/*N* ratios for the unwanted P0N emissions and the stepped frequency waveform. For the P0N emissions, observations were made for various duty cycles.

### 4.2 Target generation

Targets were simulated by means of the instrumentation shown in Fig. 4. The output of the simulated-target generator is illustrated in Fig. 5.

FIGURE 4

**Test equipment setup used to simulate target returns and inject unwanted signals**

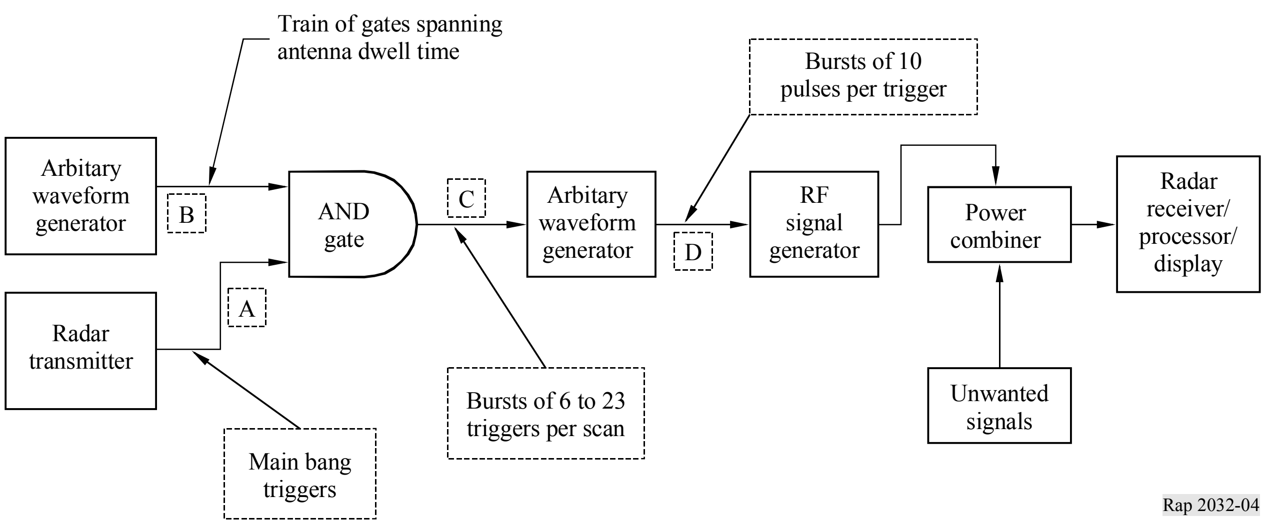
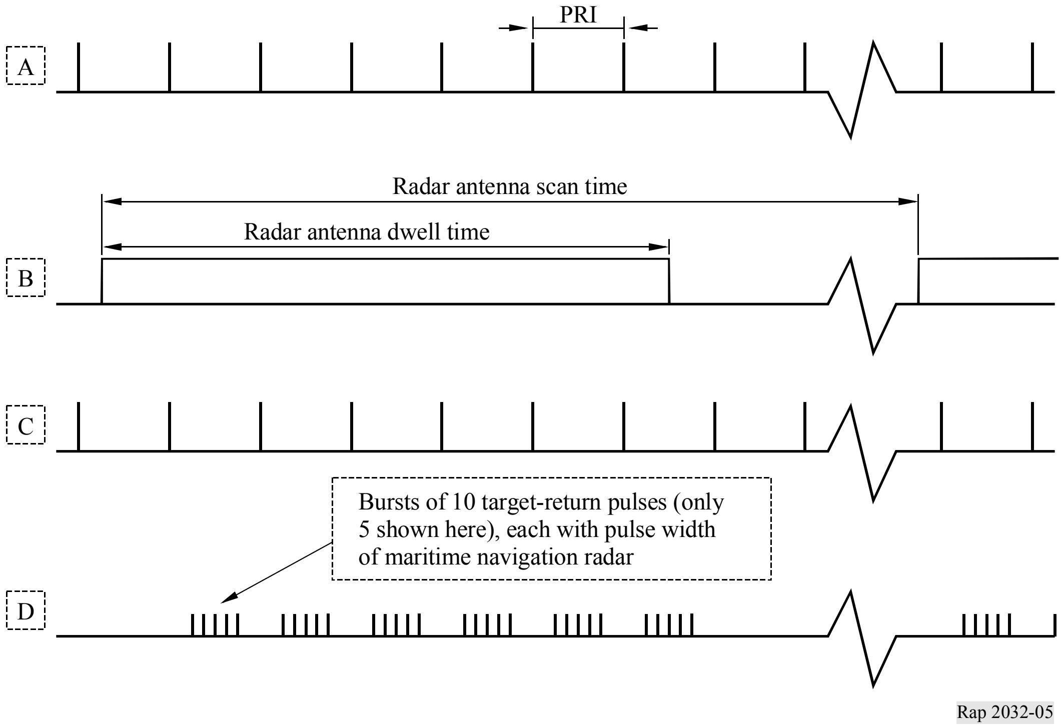


FIGURE 5

**Typical waveforms at nodes A, B, C, and D in Fig. 2**




The train of transmitter trigger pulses (A) was used to trigger the simulated-target generator. A free-running pulse generator was used to produce gate pulses (B) representing the amplitude modulating effect on target return due to the antenna beam. Those pulses gated the train of transmitter triggers in an AND gate circuit, producing bursts (C) of trigger pulses containing from 6 to 23 pulses each. Each trigger pulse was applied to an arbitrary waveform generator, which delayed the trigger appropriately and generated a burst of nine or ten pulses (D), each having the width of one of the radar's short or long pulses (usually 0.06 or 1.0 μs for Radar A and 0.08 or 1.2 μs for Radar B). Only nine pulses were generated in some of the stepped-frequency tests, but otherwise ten were generated; the discussion refers to "ten pulses" or "ten targets" with that understanding. All ten of these occurred within one sweep of the radar; i.e. within the displayed fraction of one PRI. Each of those pulses, in turn, modulated an RF signal generator set to a frequency near 3 050 MHz to produce a simulated-target-return pulse train. The specific RF signal generator frequency was adjusted to maximize the radar's response, thereby simulating return pulses from actual targets when the receiver's local oscillator is properly tuned.

The ten target pulses triggered by each radar trigger all occur within the return time of one of the radar's range scale. Therefore, the pulses simulate ten targets along a radial; i.e. a single bearing.

The ten simulated equally-spaced targets (nine during some of the stepped-frequency tests) were generated along a radial with the radar operating at a 3 nmi (5.56 km) range. At this range, Radar A automatically sets the pulse width to 0.06 μs with a PRF of 3 600 pps and Radar B automatically sets the pulse width to 0.30 μs with a PRF of 2 200 pps. At this range Radar A employs a bandwidth of 22 MHz and Radar B employs an IF bandwidth of about 3 MHz. Some additional tests were also done on Radar B by manually selecting a pulse width of 80 ns, which results in the radar selecting a wider IF bandwidth.

The RF power of the target (i.e. the signal level of the simulated target returns) was adjusted so that, without any unwanted signal, all ten targets were marginally detectable as evenly spaced blips on the radar PPI display with the radar's video controls set to positions representative of normal operation. On about twenty consecutive scans, approximately nine of the ten targets on average were visible along the radial. The targets are visible in the photographs of the radar's PPI as blips, which are included as figures in § 4.3 and 5 of this Report. The pulse repetition rate of the target generator was adjusted so the targets would appear at the same azimuth on consecutive scans of the PPI. In some tests for Radar B, the targets were also generated as un-gated ring targets.

## 4.3 Unwanted signals

Two types of radiolocation signals were used as unwanted waveforms for these tests, a generic on-tune P0N emission type and a stepped frequency waveform. The P0N unwanted signal was tested with both Radars A and B. The stepped frequency waveform was only used as stimuli to Radar B.

The on-tuned P0N type emission used pulses with widths of 2 µs and 10 µs with duty cycles of 0.1, 1, 5 and 10%. The pulses were asynchronous with respect to the target pulses being generated. The P0N pulses were injected using two methods. In the first method, they were applied as a continuous train of pulses that simulated the unwanted signal occurring at all azimuths at all times. This represents a severe environment. In the second method, the P0N signal was gated so that the pulses would only occur within the maritime radar's horizontal beamwidth at the azimuth of the target generation. The gated P0N signals represent a more realistic case that simulates the maritime radar "looking" at another radiolocation radar through its mainbeam.

The second radiolocation signal consisted of an analog reconstruction from digital recordings of waveforms from a radar transmitting 27 µs stepped frequency pulses that operates with the characteristics and parameters similar to those of Radar 2 in Recommendation ITU-R M.1460. It will be referred to as radiolocation Radar 2 in this Report. A diagram that shows the relationship of the pulse timing, power, and frequency and elevation-angle relationships for RL Radar 2 is shown in Fig. 6. Note that there are frequency steps within each pulse (shown for simplicity in Fig. 6 as if they were continuous bands) as well as from pulse to pulse.

Two radiolocation Radar 2 horizontal-plane antenna patterns were also measured at the time its emissions were recorded. One pattern was measured at 3 050 MHz, which is the nominal frequency of S-band maritime navigation radars. At this frequency the main beam of the radar is elevated, so the horizontal pattern is a cut through the side-lobe, the strongest of which is approximately at the azimuth of the elevated main beam. The other was measured at 2 957 MHz, which is the frequency at which radiolocation Radar 2's main beam is on the horizon.

The horizontal plane antenna pattern of Radar B was measured during previous tests. Mutual gain antenna patterns at 2 957 MHz and 3 050 MHz were developed from the patterns of radiolocation Radar 2 and Radar B that show the strength of antenna coupling between the two radars. These patterns are shown in Figs. 7 and 8 for 2 957 MHz and 3 050 MHz, respectively.

FIGURE 6

**Radiolocation Radar 2 timing diagram**

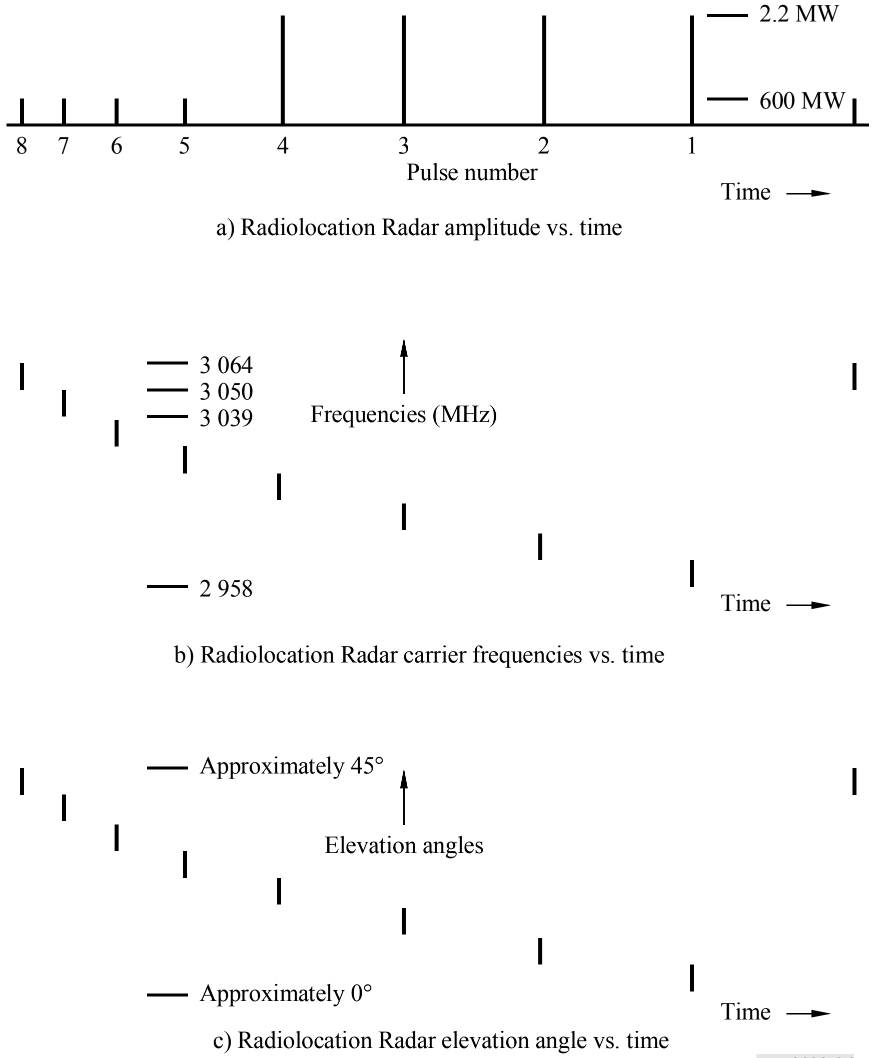



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FIGURE 7

**Mutual gain antenna pattern at 2 957 MHz**

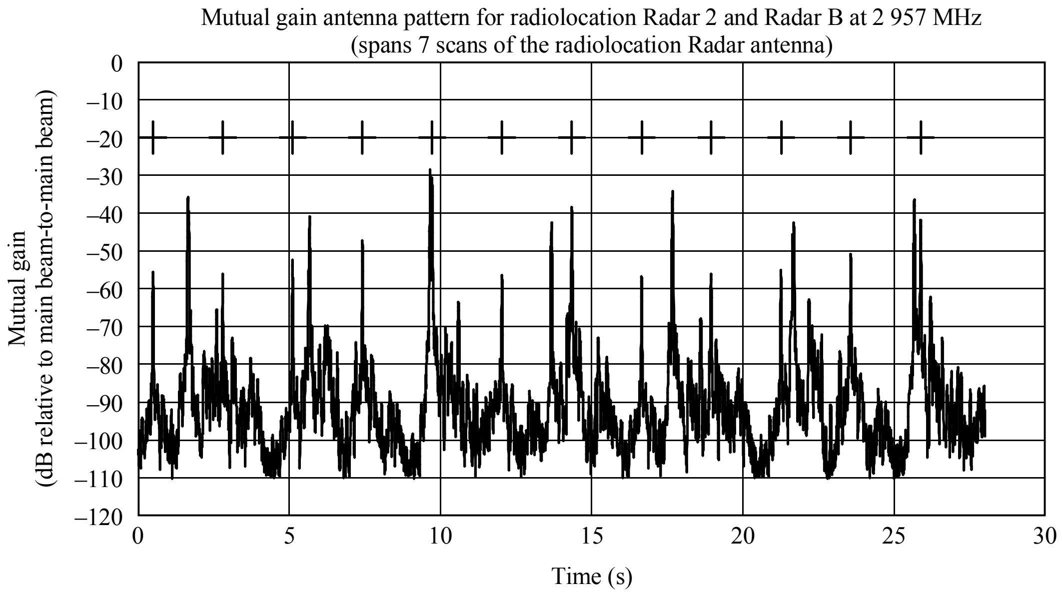


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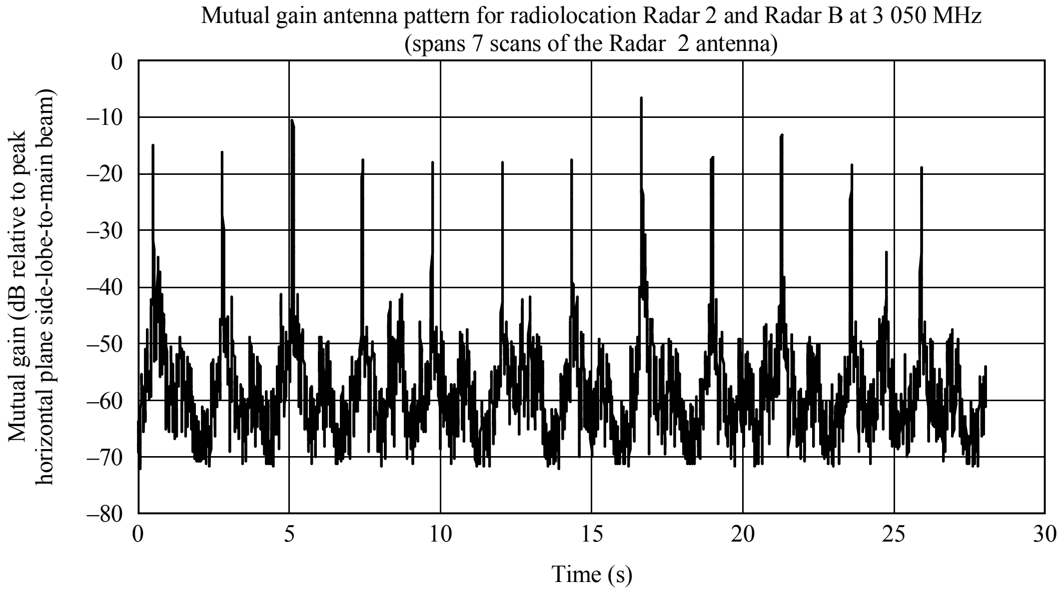
FIGURE 8

**Mutual gain pattern at 3 050 MHz**

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In Fig. 7, the plus signs mark the peaks of the radiolocation Radar 2 main beam; careful observation reveals that none of those peaks coincide with the other peaks, which are due to the main beam of maritime Radar B. Thus, main beam-to-main beam coupling rarely occurs. This pattern and its counterpart for 3 050 MHz (see Fig. 8) were used to modulate the trains of unwanted stepped-frequency pulses in some of the testing.

Note that the 0 dB reference levels in Figs. 7 and 8 represent the maximum possible mutual gains that can occur at the respective frequencies. At 2 957 MHz (Fig. 7), 0 dB represents the product of the main beam gain of both radars, since both have main beams at the horizon at that frequency. But at 3 050 MHz, 0 dB represents the product of the highest horizon plane side-lobe times the main beam gain of the maritime navigation radar. Either type of conjunction would be an exceedingly rare event, as Figs. 7 and 8 suggest.

## 4.4 Summary of test conditions

The tests were performed with the following parameters set on the maritime radionavigation radars as shown in Table 5.

TABLE 5

**Radar A and B control settings**

| Parameter | Setting |
|---|---|
| Pulse width (ns) | Radar A: 60, Radar B: 300 |
| STC | Disabled |
| FTC | Disabled (default) |
| IR | On (default) and off |
| AGC | On (default) |
| Image selected | Raw video ("image") and/or synthetic targets[(1)] |
| Range scale | 3 nmi (5.56 km) |

(1) Synthetic targets were only available for Radar B.

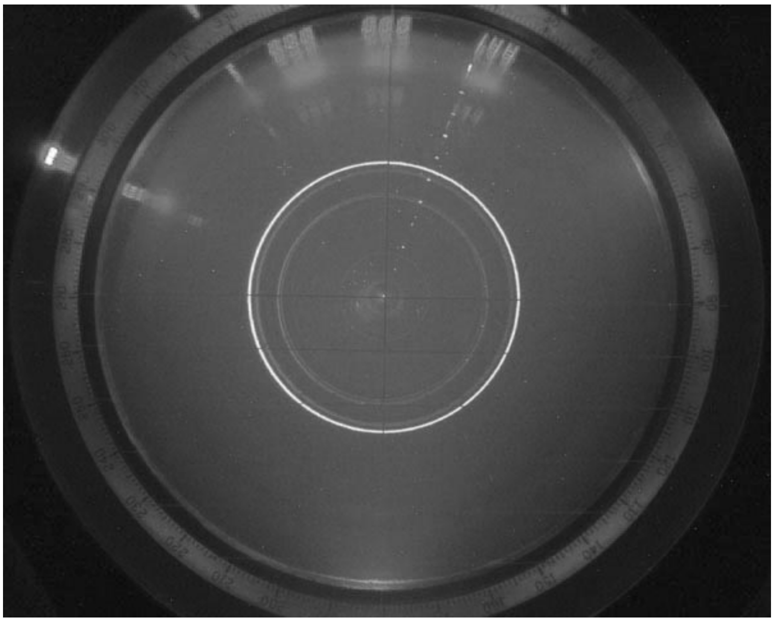
Since the IR function is enabled by default in both radars, most tests were run under that condition. However, some tests were performed with it disabled to better gauge its effectiveness. The 3 nmi (5.56 km) range scale was selected because this is a range that would typically be used for collision-avoidance purposes in harbours and for inland waterway navigation.

## 4.5 Test procedures

The RF power output of the target generator system was adjusted so that the target Pd was about 90% without radiolocation signals being present. For Radar A this value was approximately −81 dBm at the circulator's receiver port. For Radar B this value was approximately −90 dBm at the waveguide input of the receiver after the antenna but before the RF and mixer circuitry. Figures 9 and 10 show digital photographs of the Radars A and B PPI baseline operating states (no radiolocation signal injected), respectively. Note that the raw-video targets appear along a radial at about 20° for Radar A and 320° for Radar B. Local clutter returns from buildings and slight speckling are also visible on the radar display for Radar B.

FIGURE 9

**Radar A baseline state with video targets at 20°**



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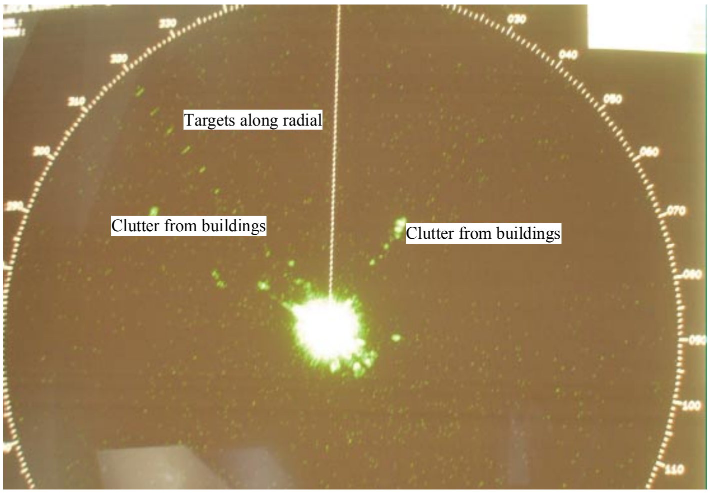
After the radars were set to their baseline conditions, the unwanted radiolocation emissions were injected into the radar receivers. The power level of the unwanted radiolocation signal was varied while the power level of the targets was fixed. As the radiolocation power level was varied, the display of the radar was observed for a decrease in the target Pd, and an increase in the number of false targets. These appear as radial streaks (strobes) in some cases, and as an increase in distributed point-like blips or speckle in other instances.

FIGURE 10

**Radar B baseline state with video targets at 320°**

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## 5 Test results

### 5.1 Radar A with unwanted P0N radiolocation signal

Observations of video image targets on the Radar A display were made while on-tuned 2 μs P0N emissions were applied to its receiver with duty ratios of 0.1% and 1% for *I*/*N* ratios of 20 dB to above 80 dB. The pulses were injected asynchronously as a continuous train of pulses. The IR function was enabled and disabled. The *I*/*N* ratios were determined by subtracting the noise floor values stated in § 3.3 from the applied radiolocation signal levels.

Despite the marginal target-return power, the probability of target detection was essentially unaffected by the asynchronous pulsed signal, even at high ratios of unwanted pulse power to system noise power. This was found regardless of whether the IR feature was on or off. However, the target detections could become masked (i.e. obscured) by false alarms when the IR function was forced to the off position (default setting is IR enabled).

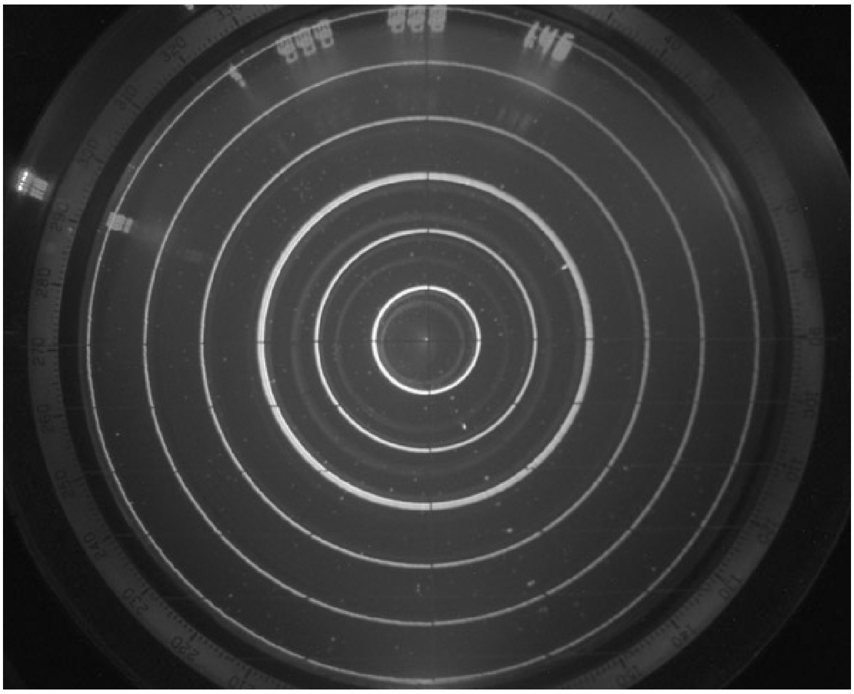
The results of these tests show that the IR control had a great effect on the radar's ability to operate in the presence of pulsed interference. With the IR feature enabled, the display contained very few isolated randomly located background detections, referred to as speckle. In contrast, when the IR control was deliberately disabled, background speckle was appreciable even when unwanted pulse signals were not injected. More importantly, as long as the IR feature was activated, unwanted pulses were not detected, even when injected at very high *I*/*N* ratios.

#### 5.1.1 Radar A: 2 μs P0N pulses with 0.1% duty cycle (DC)

The case in which the pulse-train DC was 0.1% with the IR enabled is illustrated by Fig. 11, where the *I*/*N* was 80 dB. There the targets on the PPI display are clearly visible with only a few random specks also present. With the IR disabled, in contrast, the unwanted P0N pulses were detected and displayed at about 160° relative when injected at *I*/*N* ratios assessed at much lower values, such as 26 dB. This is illustrated in Fig. 12, where the relatively long (2 µs) pulses appear as long spoke-like dashes and the targets (at about 165° relative) are barely discernable amid the interference.

FIGURE 11

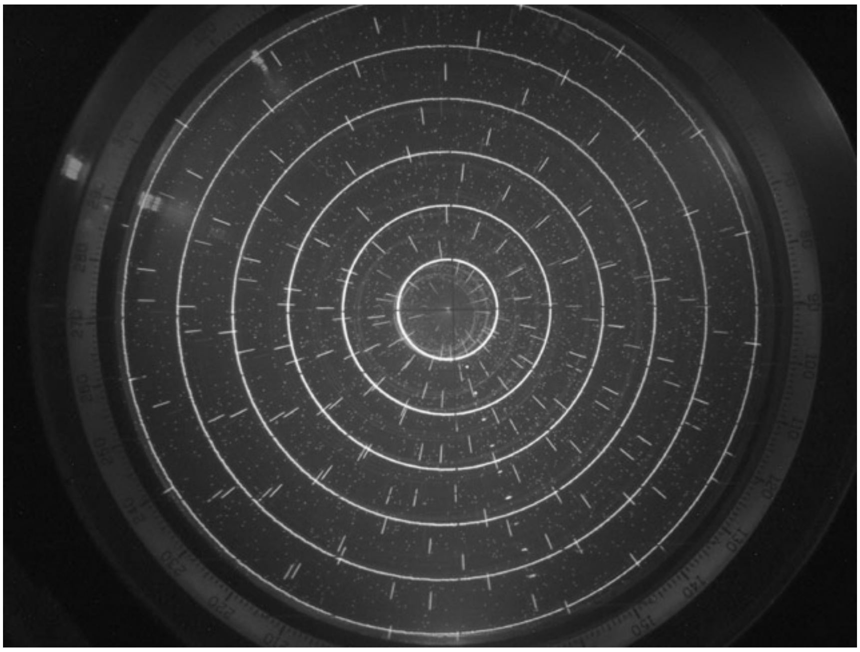
**Radar A: 2 µs unwanted pulses with 0.1% DC, IR on (*I*/*N* = 80 dB)**



Rap 2032-11

FIGURE 12

**Radar A: 2 µs unwanted pulses with 0.1% DC, IR off (*I*/*N* = 26 dB)**



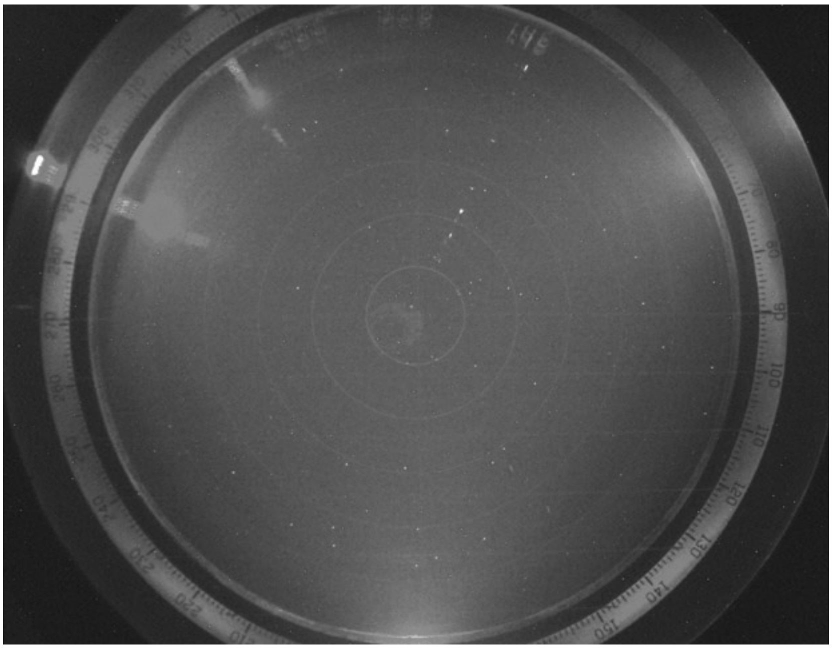
Rap 2032-12

### 5.1.2 Radar A: 2 µs P0N pulses with 1% DC

For the case in which the pulse-train DC was 1% with the IR enabled, the absence of background speckle and absence of "false alarms" (detected unwanted pulses) is illustrated by Fig. 13. The *I*/*N* was 62 dB but the targets were readily visible at about 20° relative. But with the IR off, unwanted pulses were again detected and displayed when injected at much weaker *I*/*N* ratios, as occurred with a 0.1% DC. For example, an *I*/*N* of 23 dB with the IR disabled produced the congested image shown in Fig. 14. The targets were at roughly 120° relative.

FIGURE 13

**Radar A: 2 µs unwanted pulses with 1% DC, IR on (*I*/*N* = 62 dB)**



Rap 2032-13

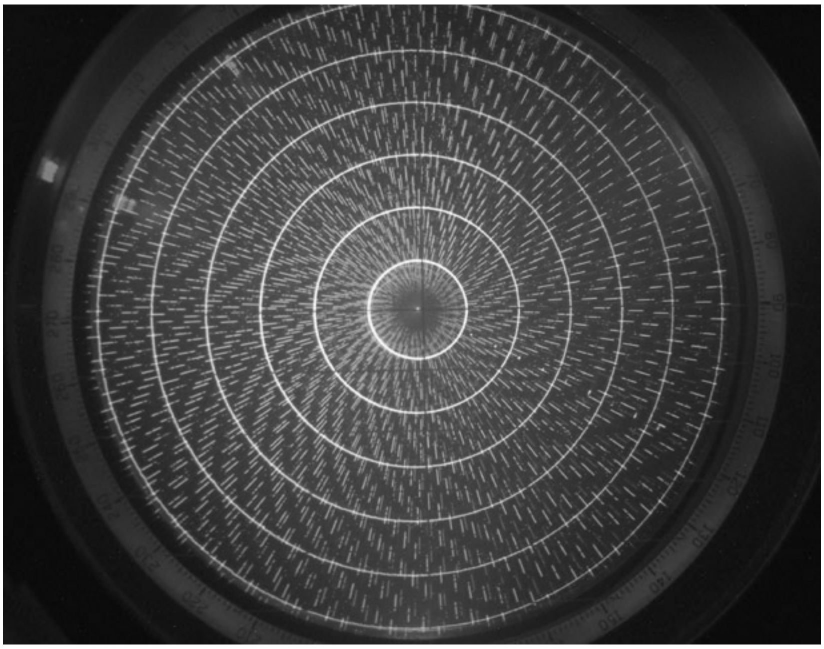
## 5.2 Radar B with unwanted P0N radiolocation signal

Observations of video image targets on the Radar B display were made while on-tuned 2 µs and 10 µs P0N emissions were applied to its receiver with DC ratios of 0.1, 1, 5 and 10%. The pulses were injected asynchronously. In some tests, they were gated to bracket the target azimuth (see Fig. 4) and in other tests they were injected ungated. The IR function was enabled in some tests and disabled in others.

As in the case for Radar A, the test results for Radar B show that despite the marginal target-return power, the probability of target detection was essentially unaffected by the asynchronous pulsed signal, even at high ratios of unwanted pulse power to system noise power. This was found regardless of whether the IR feature was on or off. However, the target detections could become masked by false alarms when the IR function was forced to the off position (default setting is IR enabled).

FIGURE 14

**Radar A: 2 μs unwanted pulses with 1% DC, IR off (*I*/*N* = 23 dB)**



Rap 2032-14

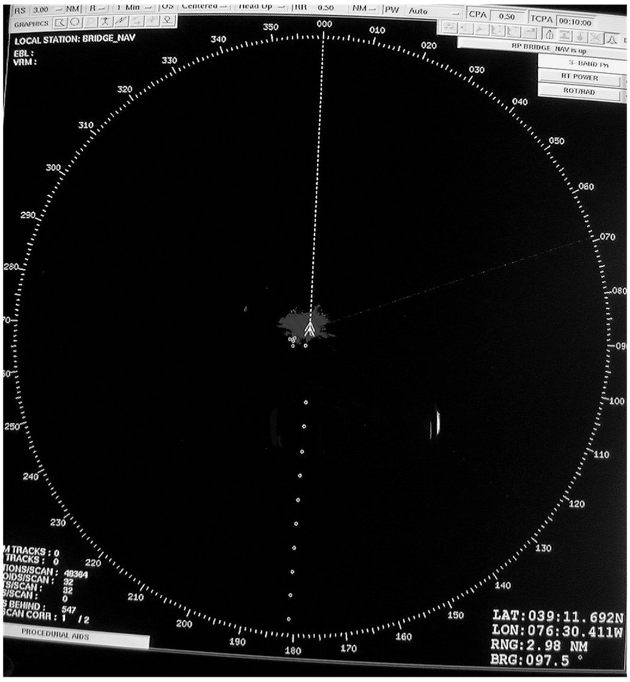
### 5.2.1 Radar B: 2 μs P0N pulses with 1% DC

The 2 μs P0N pulses with a DC of 1% were injected into the marine radar at power levels to produce *I*/*N* values of 80 dB with the IR fully enabled and 57 dB with the IR disabled. Note that for these tests the software controlling the IR function was adjustable. Figure 15 shows Radar B with the *I*/*N* of 80 dB (IR enabled) and Fig. 16 shows an *I*/*N* of 57 dB. The Figures show that with the IR enabled (set to 100%), the radar was able to compensate for the unwanted P0N pulses. For this condition, the unwanted P0N signal was not gated.

In Figure 16, the IR control was disabled (set to 0%). That Figure shows that unwanted pulses appear as many unprocessed detections, much as they did with 1% duty cycle on Radar A. Even so, the unwanted pulses did not evoke any processed detections (synthetic target) symbols except possibly in the vicinity of a valid simulated target. This may be due to the fact that Radar B implements adaptive local CFAR processing when generating synthetic target symbols and performing target tracking. The 2 μs pulses used here are much wider than radar B's own pulses, spanning 33 of radar B's range cells when that radar operates on its 3 nmi (5.56 km) scale. Because of that, the unwanted pulses can raise the detection threshold through local CFAR action and prevent themselves from being detected. The local CFAR processing is thus providing a form of pulse width discrimination that depends on CFAR settings selected at the factory and typically not available to the console operator.

FIGURE 15

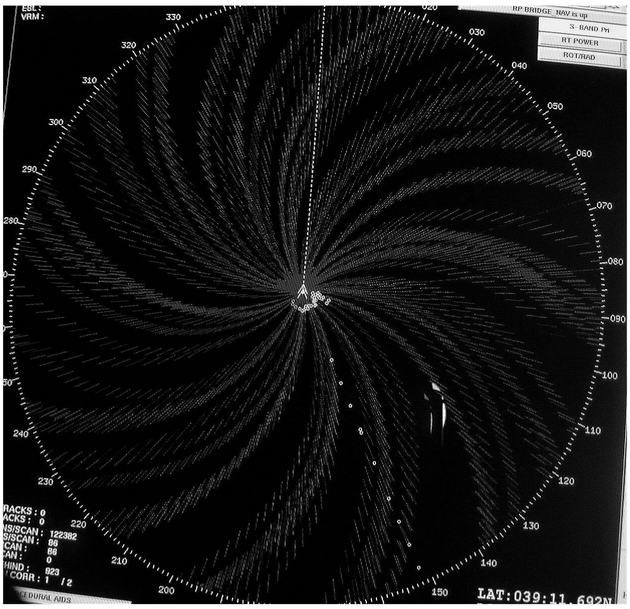
**Radar B: 2 µs unwanted pulses with 1% DC, IR on ($I/N$ = 80 dB)**




Rap 2032-15

FIGURE 16

**Radar B: 2 µs unwanted pulses with 1% DC, IR off ($I/N$ = 57 dB)**




Rap 2032-16

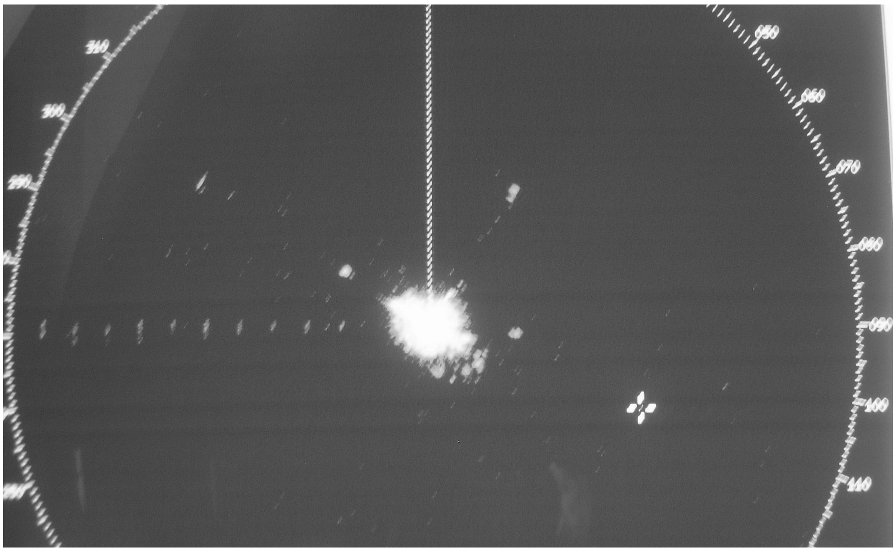
### 5.2.2 Radar B: 2 µs P0N pulses with 5% and 10% DCs

The 2 µs P0N pulses with duty cycles of 5% and 10% were injected into the marine radar with DCs of 5% and 10% at power levels to produce *I*/*N* values of 0, 5, 10, 15, 20, 30, 50, 60, and 80 dB.

The marine radar display did not show any effects from gated 2 µs pulses with a 5% DC up to and including an *I*/*N* of 60 dB when the IR function was enabled. This is shown below in Fig. 17 where the targets are at 270° relative.

FIGURE 17

**Gated 2 µs pulse with 5% DC, IR on (*I*/*N* = 60 dB)**



Rap 2032-17

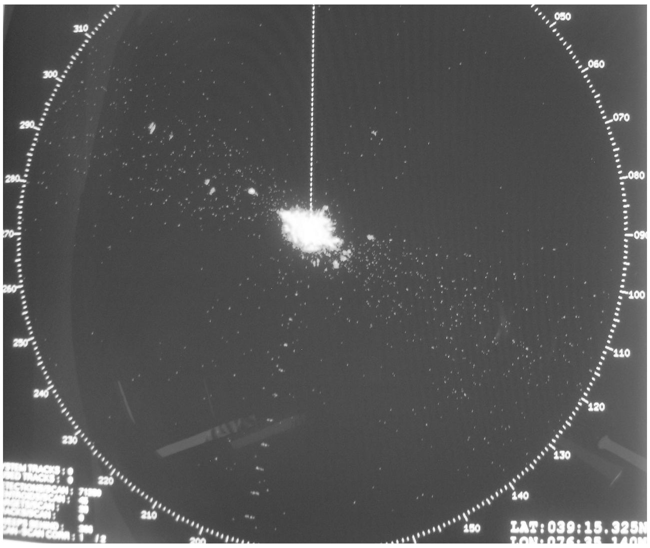
For an un-gated 2 µs pulse waveform with a 5% DC and an *I*/*N* of 60 dB, the IR function was again able to process out the interference. This is shown in Fig. 18. The targets are clearly visible along the radial at 190° with a slight increase in the background speckle.

The marine radar display started to show effects from gated 2 µs pulses with a 10% DC at an *I*/*N* ratio of 15 dB with the IR function enabled. This is shown in Fig. 19. Targets are at 190° relative, but are largely obscured.

This result may seem inconsistent with other test results with P0N interference. It is a unique case that, due to the radiolocation pulse width and PRF, Radar B's interference circuitry/signal processing seems to be unable to compensate. However it should be noted that, no S-Band radiolocation radar with a 2 µs pulse and with a 10% DC has been identified at this time. In addition, high DC radiolocation radars identified at this time are likely to be frequency-agile and/or have wide chirps that distribute their energy over a wider band than the passbands of navigation radars. S-Band radars almost always have substantially lower PRFs than the value (50 kHz) corresponding to this case.

FIGURE 18

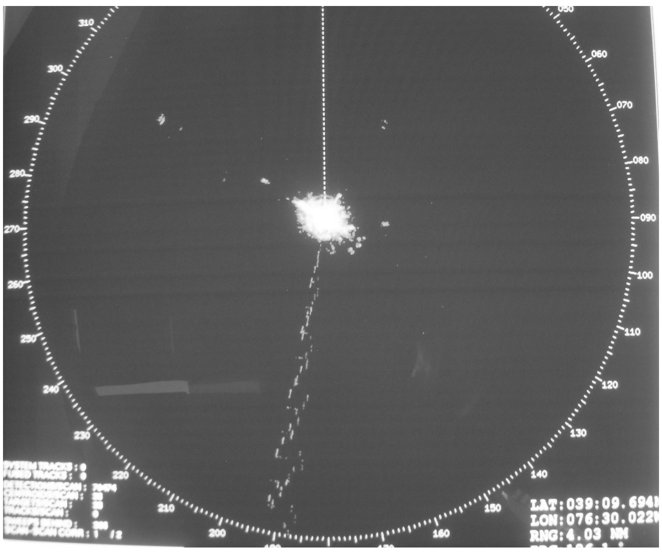
**Un-gated 2 µs pulse with 5% DC, IR on ($I/N$ = 60 dB)**




Rap 2032-18

FIGURE 19

**Gated 2 µs pulse with 10% DC, IR on ($I/N$ = 15 dB)**




Rap 2032-19

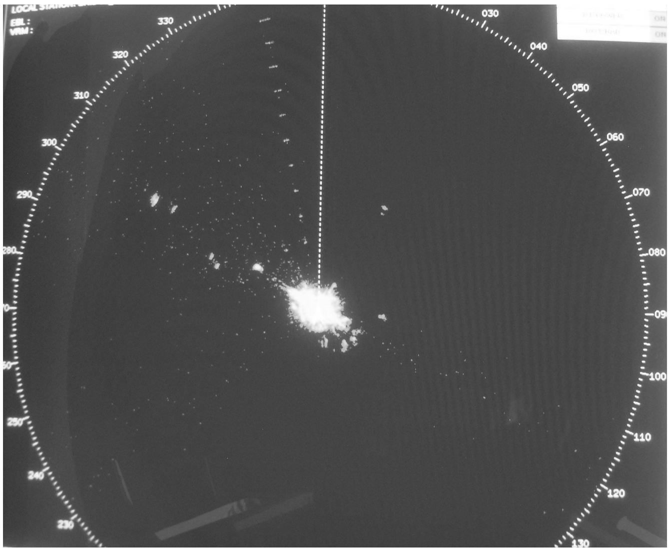
### 5.2.3 Radar B: 10 µs P0N pulses

The 10 µs P0N pulses were injected into the marine radar with DCs of 0.1%, 1%, 5%, and 10%, at power levels to produce *I*/*N* values of 0, 5, 10, 15, 20, 30, 50, 60, and 80 dB.

The results show that the marine radar interference rejection circuitry/software was able to process out the effects from gated 10 µs P0N pulses at DCs up to 10% with an *I*/*N* of 60 dB. Figure 20 shows the case for the *I*/*N* ratio equal to 60 dB and the interference gated with the simulated targets and the IR function enabled. The targets are still clearly visible at 350° along with the normal background clutter. The background speckle is about at baseline level.

FIGURE 20

**Gated 10 µs pulse with 10% DC, IR on (*I*/*N* = 60 dB)**



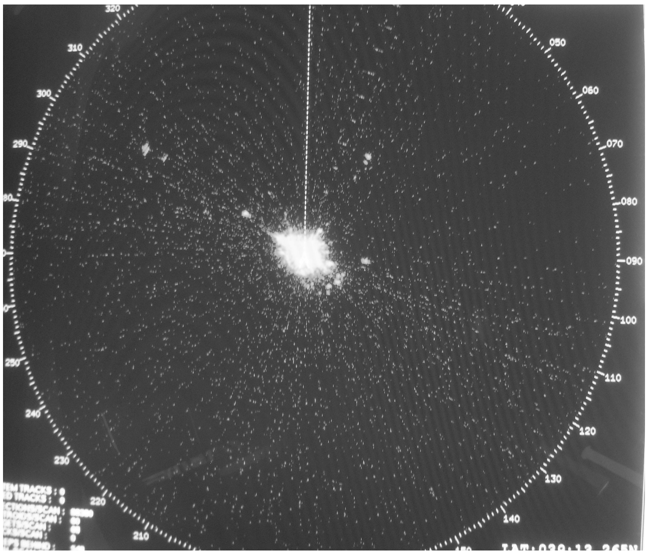
Rap 2032-20

Figure 21 shows the case of the un-gated P0N interference with the IR function enabled for a duty cycle of 10% and an *I*/*N* of 60 dB. In this case the targets are still visible at about 30° but the background is showing lines of radial speckling.

The differences in the amount of background speckle and false targets between Figs. 20 and 21 show that for the gated interference case, the marine radar IR circuitry/processing enabled a vast improvement on the radar display for an *I*/*N* of 60 dB. When the *I*/*N* was set to 80 dB, the display bloomed and the targets were obscured.

FIGURE 21

**Un-gated 10 µs pulse with 10% DC, IR on ($I/N$ = 60 dB)**



Rap 2032-21

### 5.2.4 Stepped frequency radiolocation signal (Radar B only)

Observations of raw-video targets on Radar B's display were made while on-tuned and off-tuned (with respect to Radar B) pulses of radiolocation Radar 2 were applied to its receiver. The on-tuned emissions consisted of periodic trains of two stepped-frequency pulses in which the sub-pulse carrier frequencies ranged from about 3 038 MHz to 3 064 MHz. Those frequencies span the passband of Radar B when it operates on a 3 nmi range scale, using its default pulse width and IF bandwidth. When transmitting on those frequencies, the main beam of the radiolocation radar's antenna is elevated, so that only side-lobes of its antenna couple to Radar B.

The off-tuned parts consisted of periodic trains of two long stepped-frequency pulses in which the sub-pulse carrier frequencies ranged from 2 957 MHz to 2 970 MHz. When transmitting on those frequencies, the main beam of the radiolocation Radar 2's antenna is at or close to the horizon. This provides maximum directivity towards surface-based systems in the environment, including maritime navigation radars.

Both the on-tuned and the off-tuned emissions contained two pulses per period, with each pulse being 27 µs long and containing 9 sub-pulses separated from each other in carrier frequency by 1.5 MHz. The carrier frequencies in each pulse thus spanned 12 MHz, and the carrier frequencies in the on-tuned and off-tuned waveforms each spanned about 25.5 MHz. The period of the composite waveform was 97 pps, which is the period of the radiolocation radar's emission for the mode that encompasses pulses on-tuned to maritime navigation radars. The pulse timing, powers, frequencies, and elevation angles are shown qualitatively in Fig. 3.

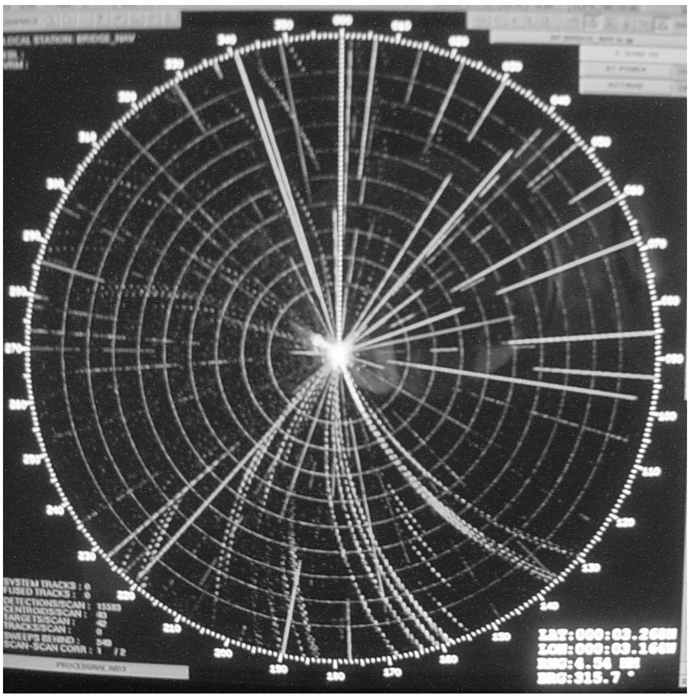
#### 5.2.4.1 On-tuned unwanted signal

When the on-tuned pulses of radiolocation Radar 2 were applied without simulating the antenna-pattern modulation (i.e. at full amplitude throughout the radionavigation radar's scan period) and with the interference-rejection feature deselected, they produced image display interference in the form of densely-spaced radial streaks or strobes throughout the full 360° of the PPI.

At other times, a pattern of the mutual antenna gain, determined at 3 050 MHz, was impressed onto the on-tuned pulse train. During some observations, that pattern repeated every 4.9 s, in which case its highest peak represented a mutual gain 15 dB lower than the highest possible mutual gain that can occur at that frequency (the product of the strongest horizon-plane side lobe of radiolocation Radar 2 and the main-beam gain of the maritime radionavigation radar). During other observations, that pattern repeated every 15 s, in which case its highest peak represented a mutual gain 10.3 dB lower than the highest possible mutual gain. Whenever either pattern was used, the highest peak unwanted signal power applied to Radar B was the same; only the interpretations of results in terms of required propagation loss will differ. When the antenna pattern modulations were impressed on the unwanted-signal waveform but the IR function was still disabled, the streaks were sparser and spanned less than 360° of the PPI except when the peaks of the unwanted signal were raised to $I/N$ ratios exceeding 60 dB. This is shown in Fig. 22.

FIGURE 22

**Radar B with on-tuned stepped-frequency waveform and radionavigation radar emission, IR disabled**



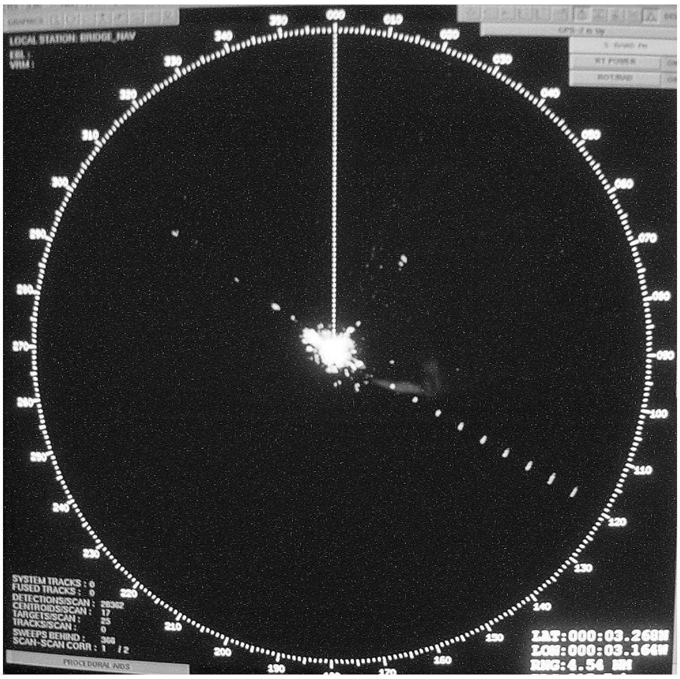
Rap 2032-22

The straight radial lines or strobes are due to the stepped frequency radiolocation emissions from radiolocation Radar 2. The dotted spiral lines are due to the emissions (even though the antenna was disconnected from the receiver) from a radionavigation radar, which was operating nearby. In this case, the targets were un-gated, appearing as 360° rings.

When the antenna-pattern modulation was impressed onto the on-tuned unwanted signal and the interference-reject function was enabled, the streaks essentially disappeared and so did the spirals caused by the other maritime navigation radar. Apart from some residual clutter caused by return from nearby structures, only the simulated targets appeared on the PPI even when the peaks reached by the unwanted signal pulses during the strongest mutual-gain-pattern lobes used in the test reached about 90 dB above the receiver's noise floor. When the statistics of the mutual gain patterns are considered, the median *I*/*N* prevailing during the pulses in these observations was approximately 49 dB when the 4.9 s mutual-gain pattern was used and approximately 44 dB when the 15 s mutual-gain pattern was used. This condition is shown in Fig. 23, which was photographed when a mutual-gain pattern of 4.9 s period was used.

FIGURE 23

**Radar B with stepped frequency on-tune waveform, IR enabled**




Rap 2032-23

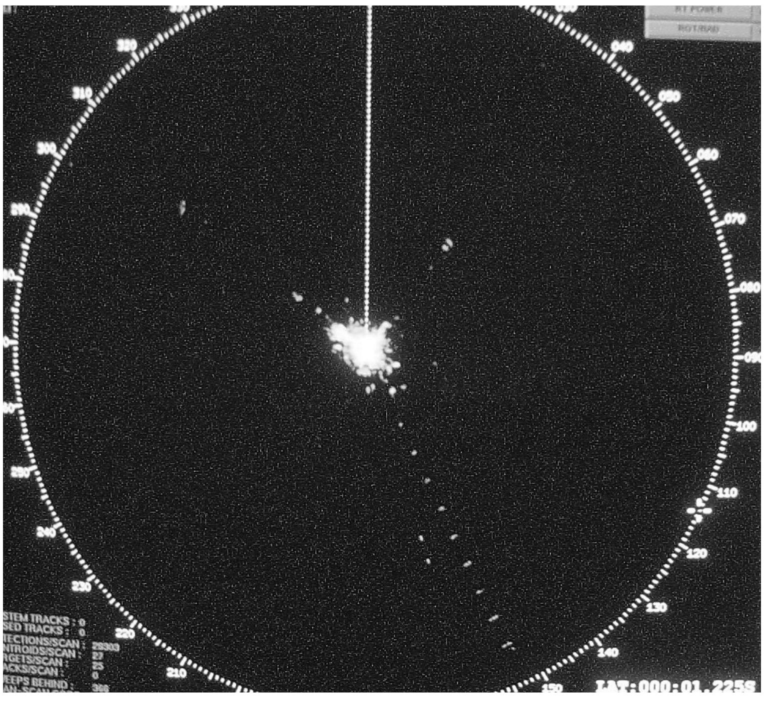
The sensitivity of the maritime navigation radar's image display was essentially unaffected by the unwanted signal, with a high probability of detection (nearly 100%) and adequately visible target blips achieved at an *S*/*N* of about 15 dB. Faintness was a bigger limitation than probability of detection. It is noteworthy that the IR function did not affect the sensitivity to the desired signal.

### 5.2.4.2 Off-tuned unwanted signal

When off-tuned pulses of radiolocation Radar 2 were applied to Radar B, the findings were very similar to those made when the on-tuned unwanted signal was applied. Observations were made only with a mutual-gain antenna pattern impressed onto the unwanted-signal pulse train, which is more realistic than applying them at full strength at all times. That pattern, determined at 2 957 MHz, was impressed onto the 2 957 MHz portion of the pulse train transmitted by radiolocation Radar 2. It consisted of the first 4.9 s of the pattern shown in Fig. 7, repeated periodically. Its highest peak therefore represented a mutual gain fully 35.8 dB weaker than the product of the main-beam gains of radiolocation Radar 2 and Radar B (0 dB in Fig. 7). When that antenna pattern modulation was impressed on the unwanted-signal waveform but the IR function was disabled, radial streaks appeared throughout 360° of the PPI image display when the unwanted signal peaks were about 90 dB above the receiver noise floor. (Observations were not made using weaker unwanted-signals.) When the antenna-pattern modulation was impressed and the IR function was enabled, the image display contained only target blips and clutter return, with essentially no unwanted signal streaks or spirals, when the unwanted signal was at that level. This is illustrated in Fig. 24. From Fig. 7, it can be seen that the median mutual gain used during the test was approximately 50 dB weaker than the highest peak reached, so the median $I/N$ was approximately $90 - 50 = 40$ dB during the pulses.

FIGURE 24

**Radar B with stepped frequency off-tuned waveform, IR disabled**



Rap 2032-24

### 5.2.5 Unwanted maritime navigation radar signals

During the tests, interference effects were produced in Radar B inadvertently by several maritime navigation radars, one of which was known to have been operating at a location about 1/3 nmi (620 m) from the test site. This is shown in Fig. 22. The known interfering radar had a transmitter power of about 20 to 30 kW. With the image display in use, the IR function suppressed that interference as well as suppressing the interference effects of the radiolocation-radar waveforms[3].

## 6 Discussions

### 6.1 Target display factors

It should be noted that since the simulated targets were evenly spaced on a radial they were more visible than real targets would have been, since they could be located anywhere on the PPI display in real world radar operations. Therefore, caution should be used in referencing these test results to real world radar operations because the *I*/*N* values where the simulated targets were discernable on the PPI in the presence of pulsed interference are higher than for real world randomly distributed targets. On the other hand, the photographs shown herein do not show the enhancement of visibility that accrues from observation of multiple scans, during which the positions of false alarms shift randomly while the positions of valid target detections remain fixed. Actual detected pulses from other radars would be concentrated in one or a few azimuth sectors and the densest sector of such false alarms would fluctuate in intensity and rotate in azimuth, providing additional opportunities for discriminating between the valid target detections and the false alarms.

It should also be noted that maritime radionavigation radar operators typically discern valid target detections in the presence of sea clutter false alarms at the short ranges studied in the tests described herein.

### 6.2 Unwanted P0N radiolocation pulses in Radars A and B

The results found with the P0N radiolocation radar emissions as an unwanted signal in Radar A show that it was able to withstand *I*/*N* ratios up to 80 dB without suffering performance degradation when its interference rejection/signal processing circuitry was enabled. For Radar A tests with P0N emissions the unwanted signal was a continuous stream of pulses occurring at all azimuths, which is an unrealistic case because Radar A would have to be surrounded by other radars for this to occur. Had an antenna pattern been applied to the P0N waveform or had it been gated (as in the tests of Radar B) the tests would have been more realistic and shown even better results.

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[3] The radiolocation radars with the longer pulses (the 10 µs P0N pulses and the 27 µs pulses recorded from radiolocation Radar 2) caused radial streaks because each radiolocation-radar pulse spans much of the 37 µs duration of the 3 nmi (5.56 km) sweep. The maritime navigation radar caused spirals because each of its pulses occupies a small fraction of that sweep time and each spiral spoke is composed of numerous pulses occurring asynchronously during different sweeps of the radar under test.

The results found with the P0N radiolocation radar emissions as an unwanted signal in Radar B show that it was able to withstand *I*/*N* ratios slightly above 60 dB without suffering performance degradation when the radiolocation emissions were gated and its IR/signal processing circuitry was enabled. This is attributable to the gating limiting the number of radiolocation pulses that are being seen by the radar receiver as it scans and the algorithm of its IR programming (see § 4). In addition, the gated unwanted radiolocation emissions represent a worse-than-worst case antenna coupling situation because in reality both radars are rotating, which would further lessen the interference effects.

### 6.3 Stepped frequency waveforms

The results found with the recorded emissions of radiolocation Radar 2 as an unwanted signal show that Radar B was able to withstand *I*/*N* ratios well above 60 dB without suffering performance degradation when the mutual gain pattern was applied and its IR/signal processing circuitry was enabled. This is attributable in part to the fact that the DCs of those signals were low. The radiolocation radar from which waveforms were recorded and played back during these tests is representative of many radiolocation radars at these frequencies in that its effective DC, insofar as its potential for interfering with navigation radars is concerned, is substantially lower than its overall DC.

In addition, the modulation of the unwanted signal by the mutual antenna-gain patterns contributed substantially to dilution of the interference effects on the PPI. It is reasonable to expect that this latter factor would have improved the results obtained previously for testing Radar A with unwanted pulse trains applied at a constant pulse power level, if this more realistic factor had been implemented. The actual mutual-gain patterns (for example, the one shown in Fig. 7) show that the lobe amplitudes fluctuate and rarely reach the gain of the highest lobes. Thus, the *I*/*N* ratios reported herein for the stepped-frequency waveforms represent values reached more seldom, during the tests and during actual operation, than those reported herein for the P0N pulses.

### 6.4 Antenna coupling factor

It is significant that main beam-to-main beam coupling seldom occurs between two radars. Figure 7 shows that, for a random sample spanning seven scans of the slower-scanning radar, the mutual gain at 2 957 MHz is always at least 28 dB weaker than the main beam-to-main beam value and is usually more than 80 dB weaker than that value. The mutual-gain pattern at 3 050 MHz is not as far reduced below its highest value. However, at that frequency the highest value of mutual gain is far lower than it is at the frequency (2 957 MHz) to which Fig. 7 pertains. The test results with antenna pattern modulation applied to the radiolocation radar need to be understood in that context. In the tests of radiolocation Radar 2 in the vicinity of 3 050 MHz, mutual-gain samples were used in which the highest peaks represented mutual gains 10 dB and 15 dB below the product of peak radiolocation Radar 2 side-lobe gain times the main-beam gain of radionavigation Radar B. This is illustrated in the first 5 s and 15 s portions in Fig. 5.

## 7 Conclusions

The test results contained within this Report do much to explain the long history of successful sharing in the band 2 900-3 100 MHz between radiolocation and radionavigation radars.

The maritime radionavigation radars withstood *I*/*N* ratios of 60-90 dB from unwanted radiolocation emissions due to the low DCs, asynchronous nature of the interference, low probability of main beam coupling, and their robust IR circuitry/signal processing capabilities.

The maritime radionavigation radars that were tested are representative of those that operate in the band 2 900-3 100 MHz and one would expect similar results with other maritime radionavigation radars. Therefore, the data herein are found to support the radiolocation service upgrade to co-primary status in the band 2 900-3 100 MHz with the radionavigation service.

## Terminology

| | |
|---|---|
| CFAR | Constant false alarm rate |
| DC | Duty cycle |
| FTC | Fast time constant |
| IF | Intermediate frequency |
| *I*/*N* | Interference-to-noise ratio |
| IR | Interference rejection |
| MDS | Minimum detectable signal |
| MTI | Moving target indicator |
| Pd | Probability of detection |
| P0N | Emission designator for unmodulated pulses (RR) |
| pps | Pulses per second |
| PRF | Pulse repetition frequency |
| PRI | Pulse repetition interval |
| STC | Sensitivity time control. |