APPENDIX A: EXAMPLE INTERFERENCE REJECTION (IR) RESPONSES OF A MARITIME RADIONAVIGATION RADAR

The IR feature of radars is discussed at length in Section 1. IR is fundamentally a correlator function that operates on either a pulse-to-pulse basis (on either the repetition interval or the pulse width) or else on a scan-to-scan basis. For pulse correlation techniques, repetition intervals and pulse widths of return echoes that match the transmitter's nominal characteristics are allowed to pass through the correlator and are displayed, whereas other received pulses are rejected. IR only works against pulsed, asynchronous interference. It is not effective against high duty cycle interference, such as communication signals.

This appendix shows examples of the interference rejection performance in the presence of various types of pulsed interference inputs for maritime radionavigation Radar A. The radar characteristics are described in detail in Section 6.

In these tests, the interference was always pulsed, with a pulse width of 10 µs. But the duty cycle of the interference varied from one test to the next. The results shown here were obtained with duty cycles of 0.1%, 1%, and 5%, corresponding to prfs of 100 Hz, 1 kHz, and 5 kHz. For each duty cycle, the amplitude of the interference was gradually increased and the performance of the radar receiver was assessed by examining the PPI display with the IR function turned on versus turned off. "Gated" refers to the case where the interference is created on the azimuth of the targets, for the duration required for a radar mainbeam to sweep across stationary targets. "Ungated" means that the interference is generated for the duration of an entire 360-degree sweep of the radar beam.

IR was found to be an effective method for mitigating the effects of pulsed interference up to a duty cycle as high as 1-3%. The effectiveness of IR decreased for higher duty cycles. IR was found to be totally ineffective against high duty cycle interference such as communication signals.

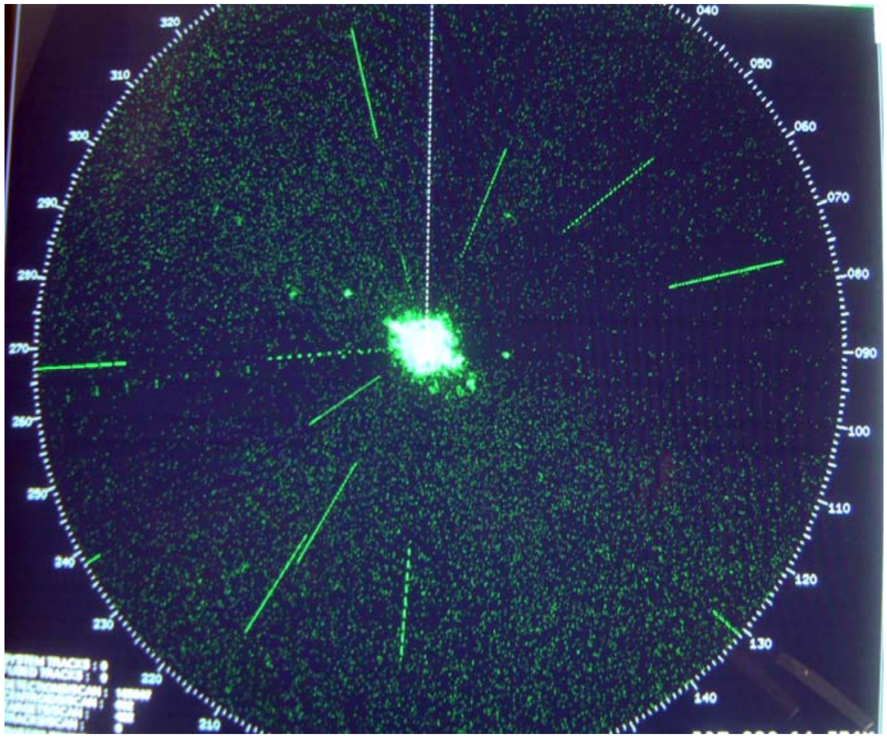

Figure A-1. +50 dB *I/N*, ungated,10 μs pw, 0.1% duty cycle, IR off.

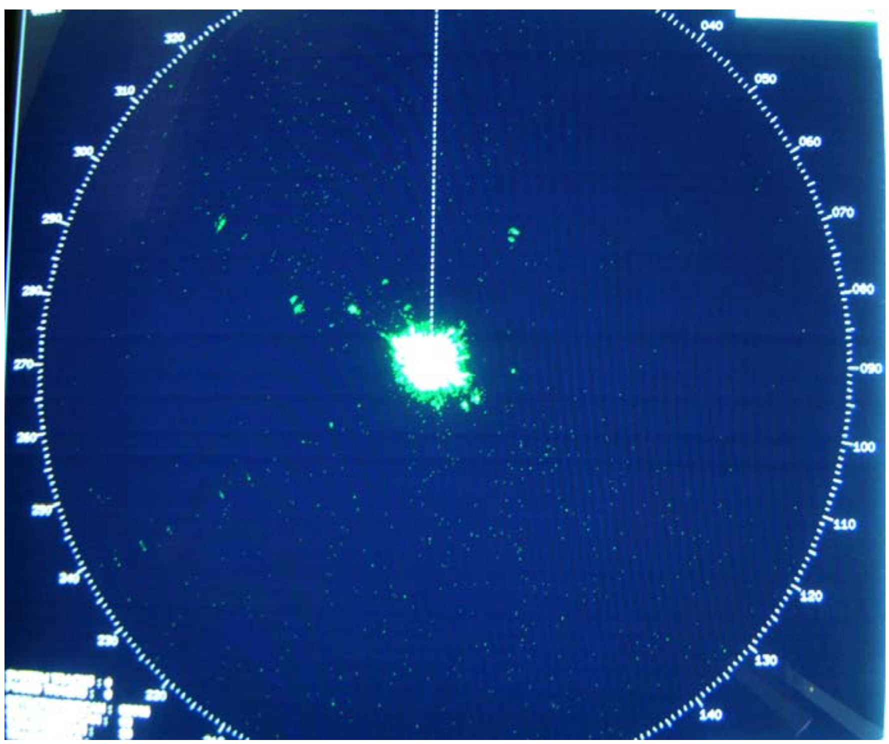

Figure A-2. +50 dB *I/N*, ungated, 10 μs pw, 0.1% duty cycle, IR on.

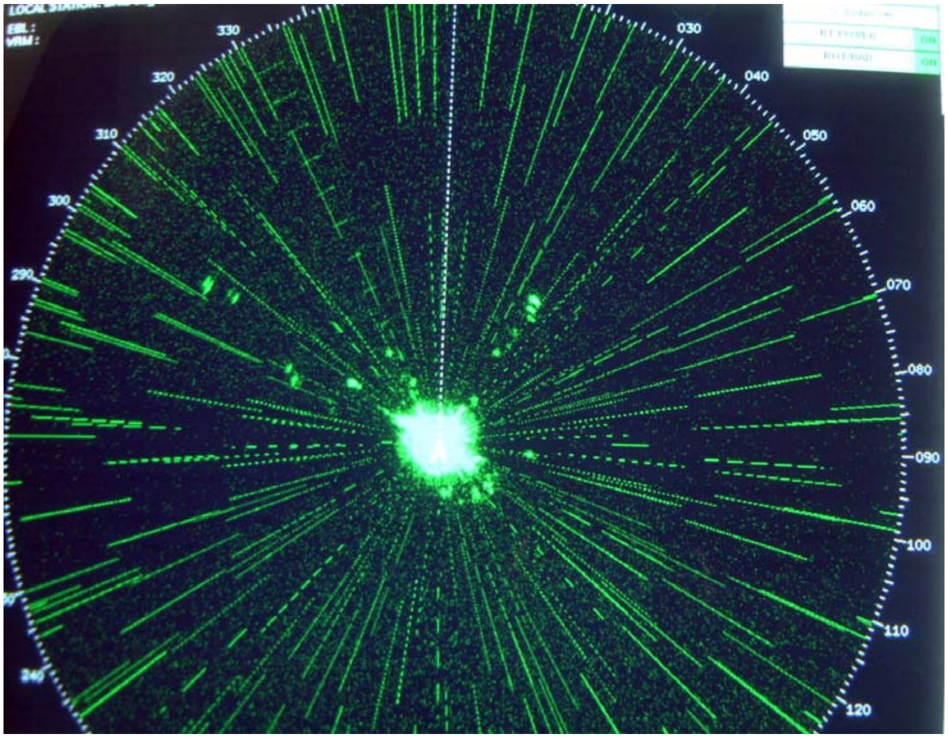

Figure A-3. +50 dB *I/N*, ungated, 10 µs pw, 1% duty cycle, IR off.

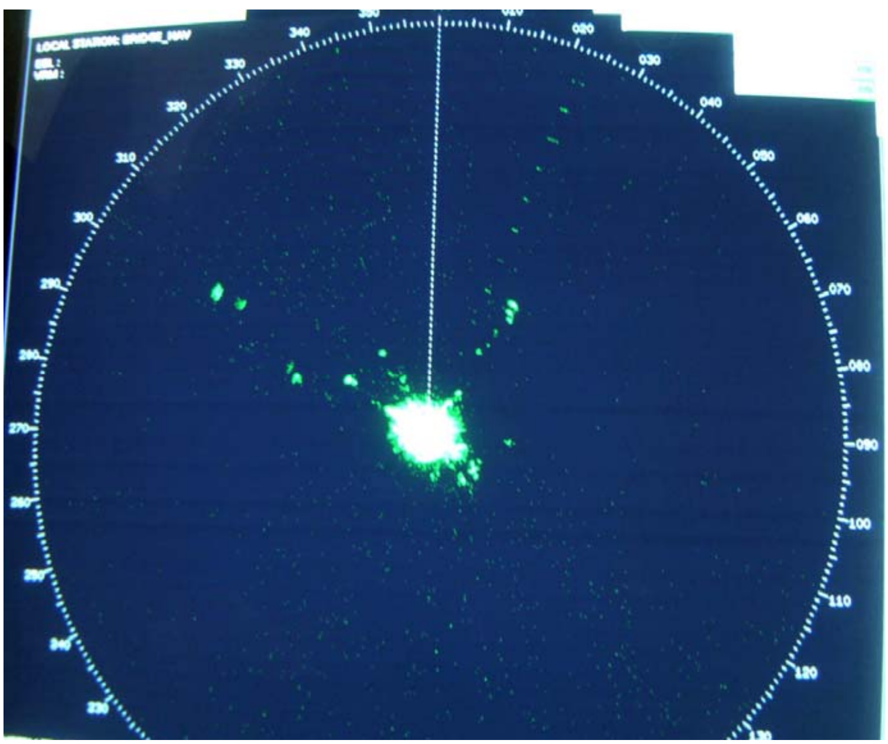

Figure A-4. +50 dB *I/N*, ungated, 10 µs pw, 1% duty cycle, IR on.

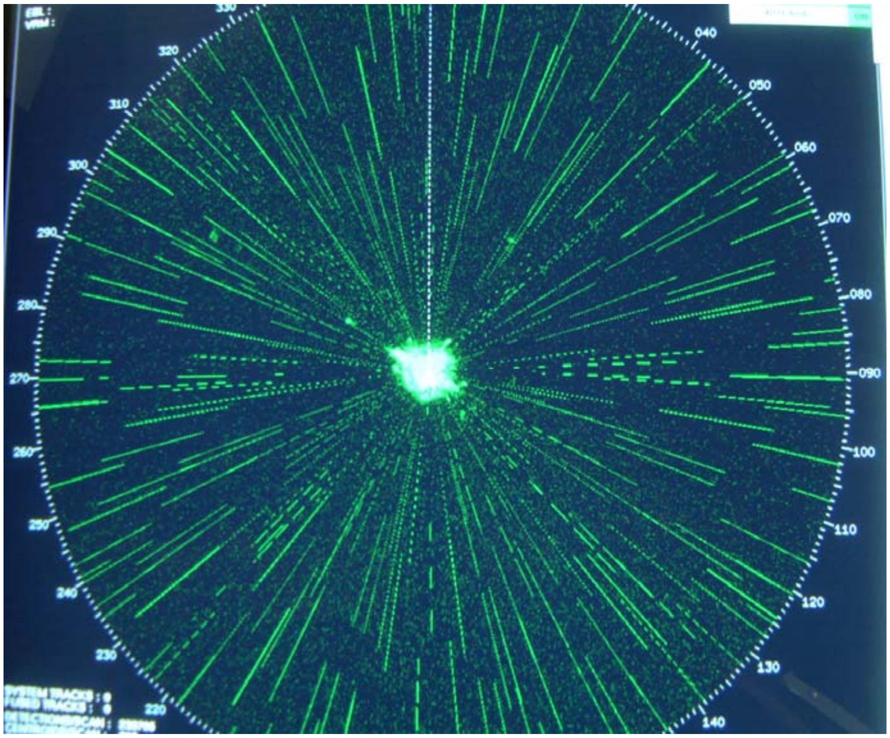

Figure A-5. +80 dB *I/N*, ungated, 10 µs pw, 1% duty cycle, IR off.

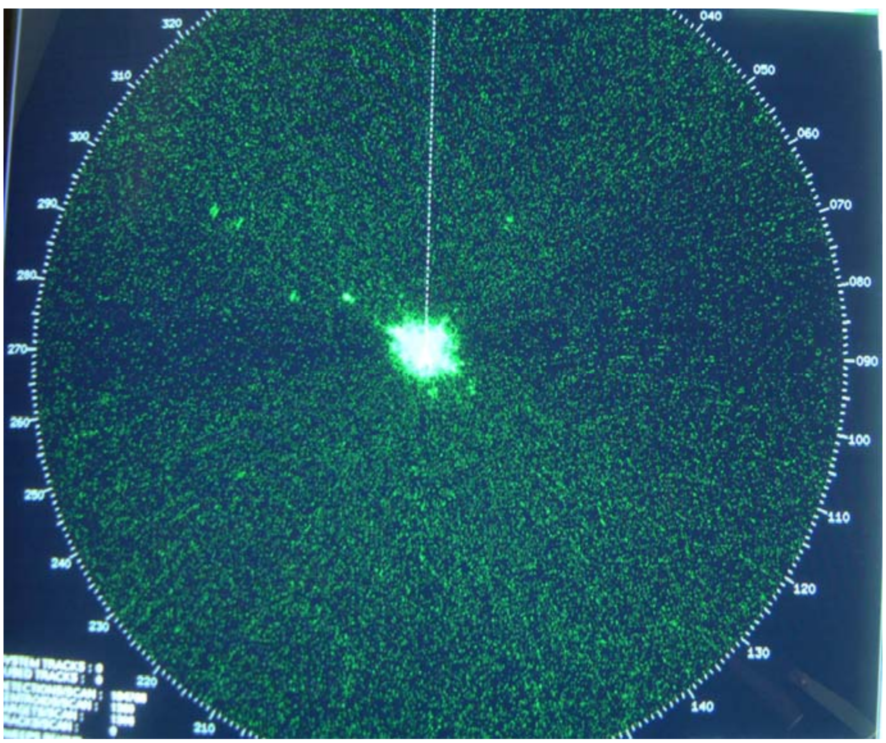

Figure A-6. +80 dB *I/N*, ungated, 10 µs pw, 1% duty cycle, IR on.

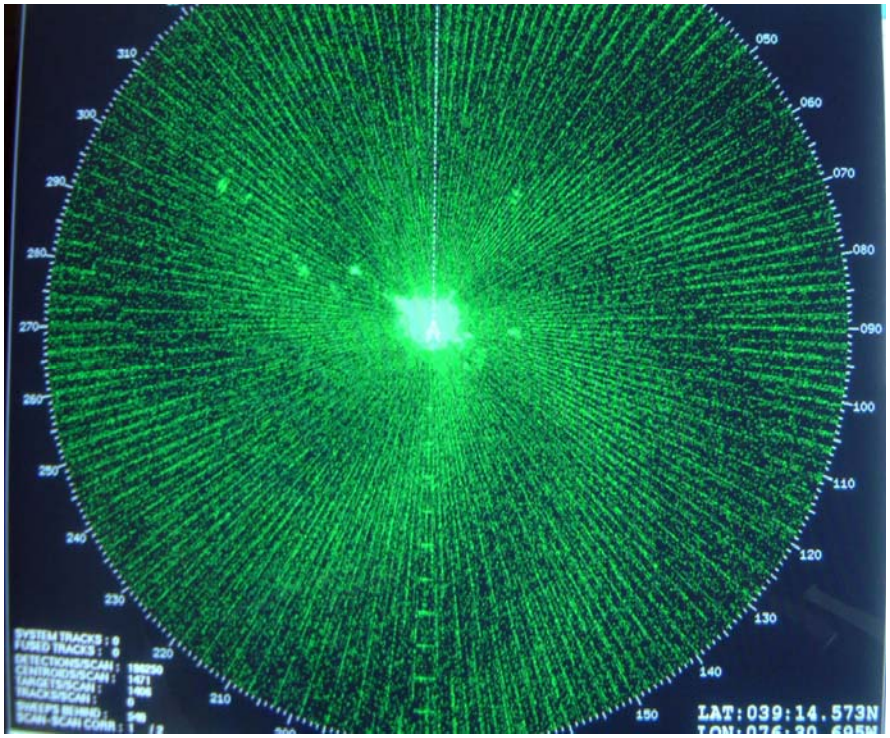

Figure A-7. +10 dB *I/N*, ungated, 10 μs pw, 5% duty cycle, IR off.

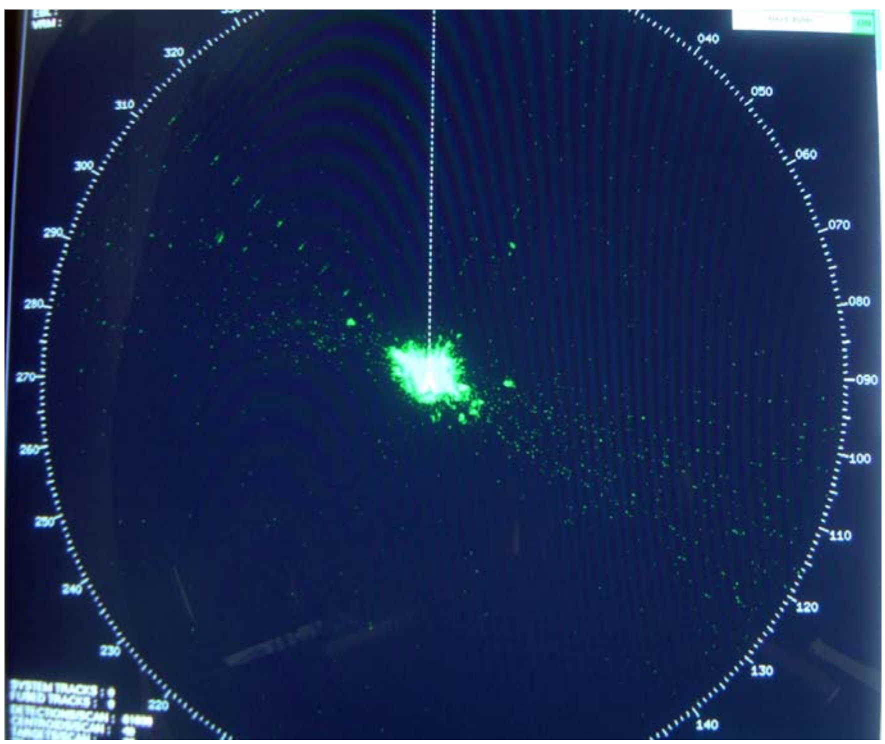

Figure A-8. +10 dB *I/N*, ungated, 10 μs pw, 5% duty cycle, IR on.

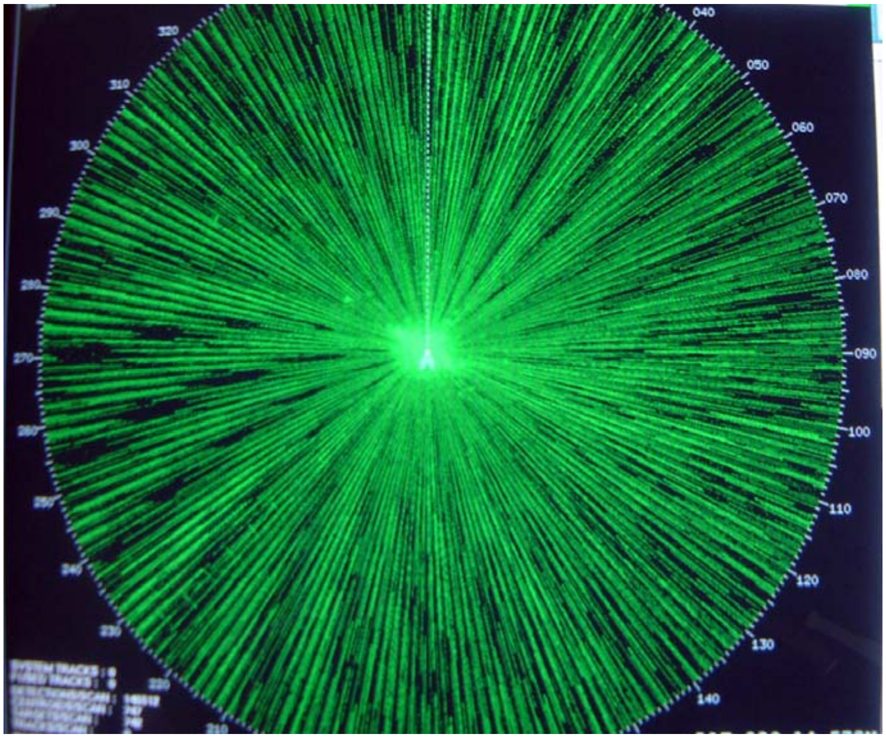

Figure A-9. +15 dB *I/N*, ungated, 10 μs pw, 5% duty cycle, IR off.

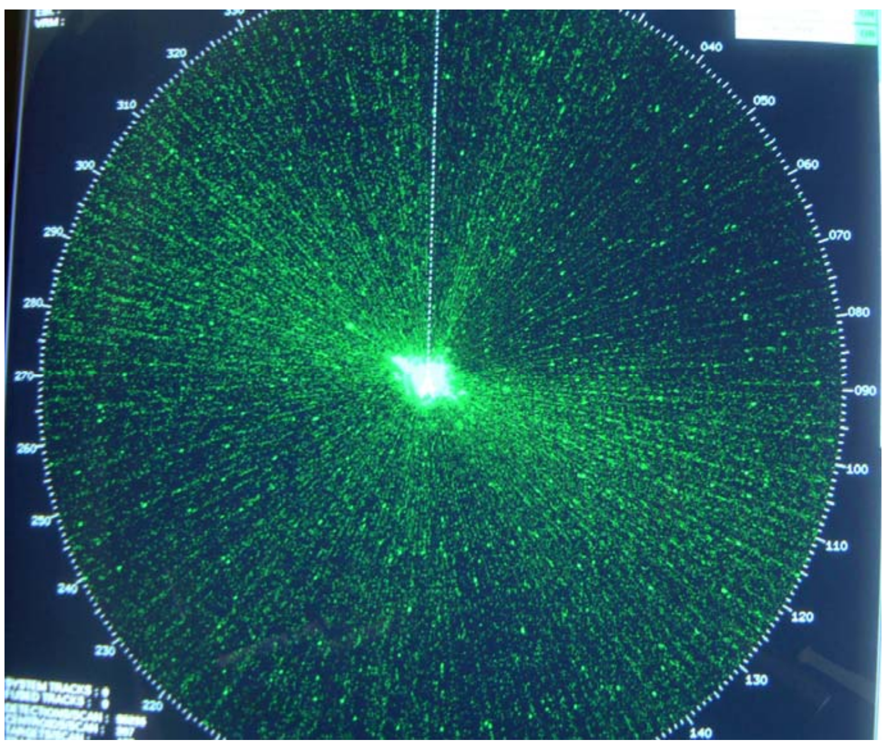

Figure A-10. +15 dB *I/N*, ungated, 10 μs pw, 5% duty cycle, IR on.

APPENDIX B: SELECTED INTERFERENCE EMISSION SPECTRA

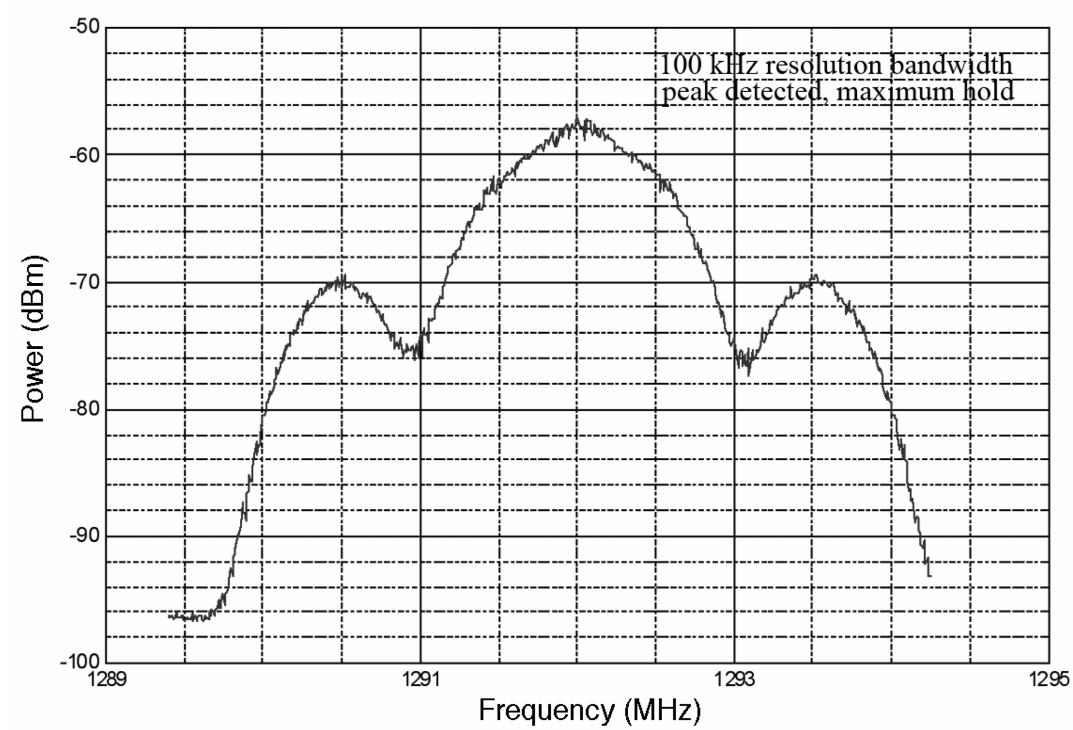

Figure B-1. 1.023 MBit/s BPSK interference signal spectrum.

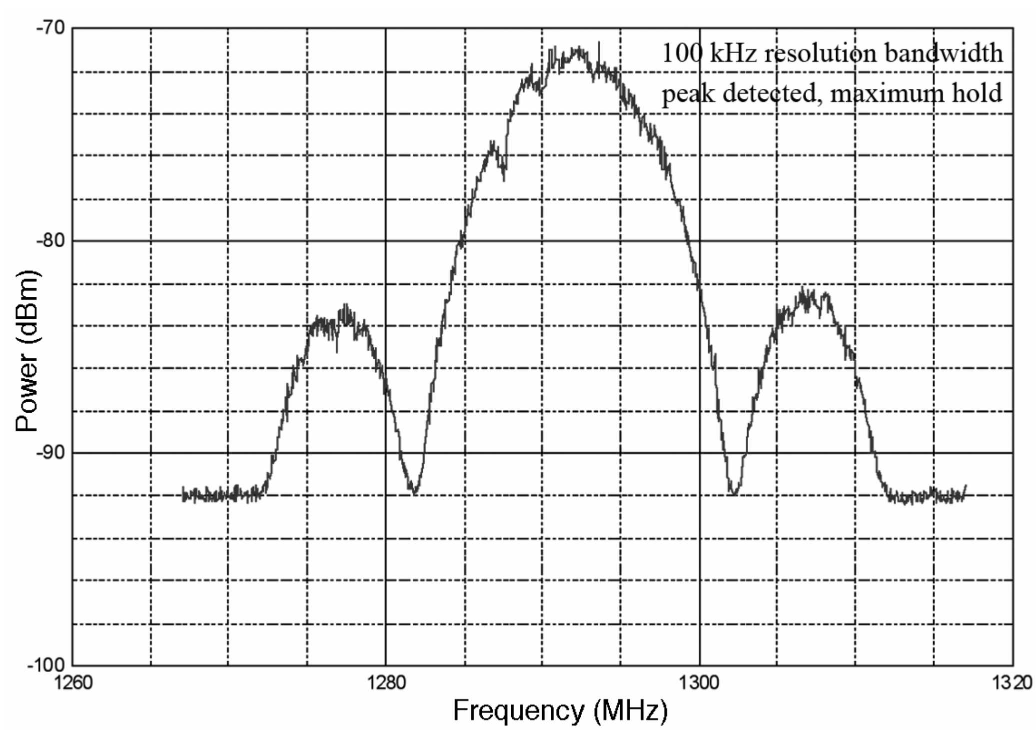

Figure B-2. 10 MBit/s BPSK interference signal spectrum.

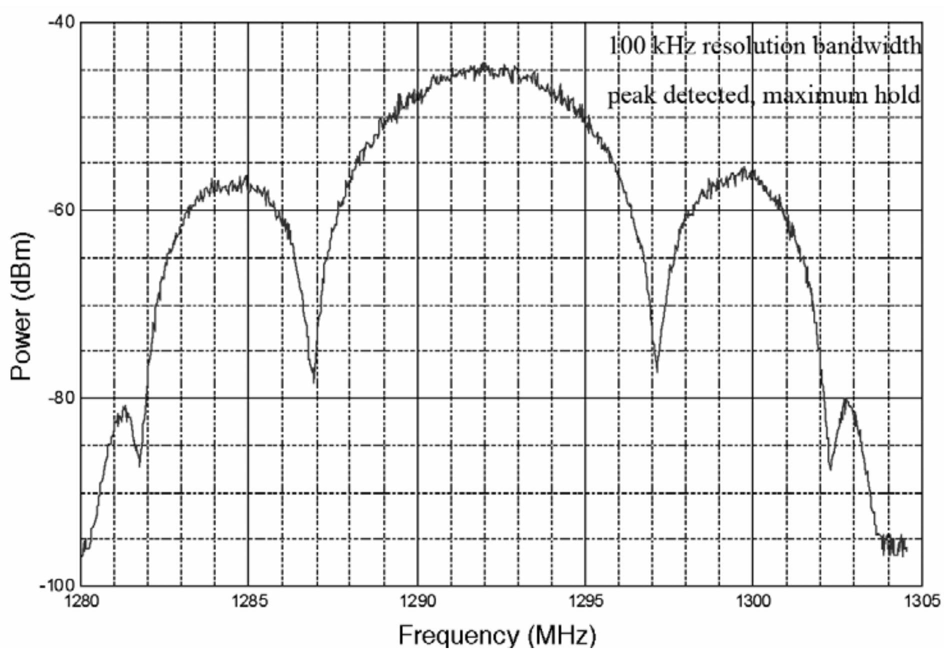

Figure B-3. 5 MBit/s BPSK interference signal spectrum.

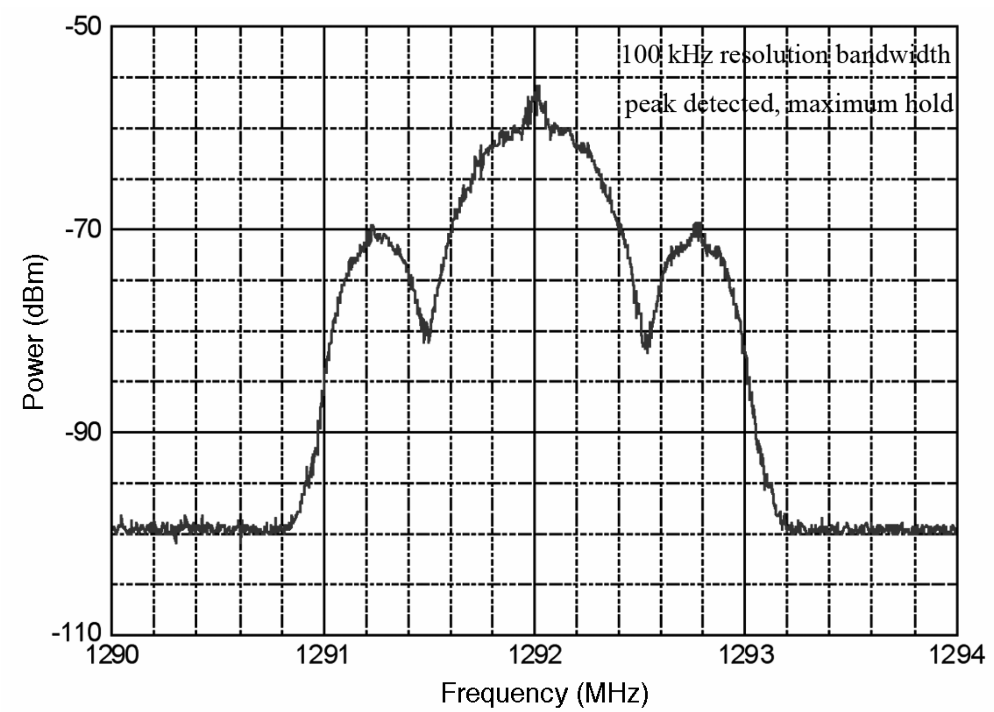

Figure B-4. 0.5 MBit/s BPSK interference signal spectrum.

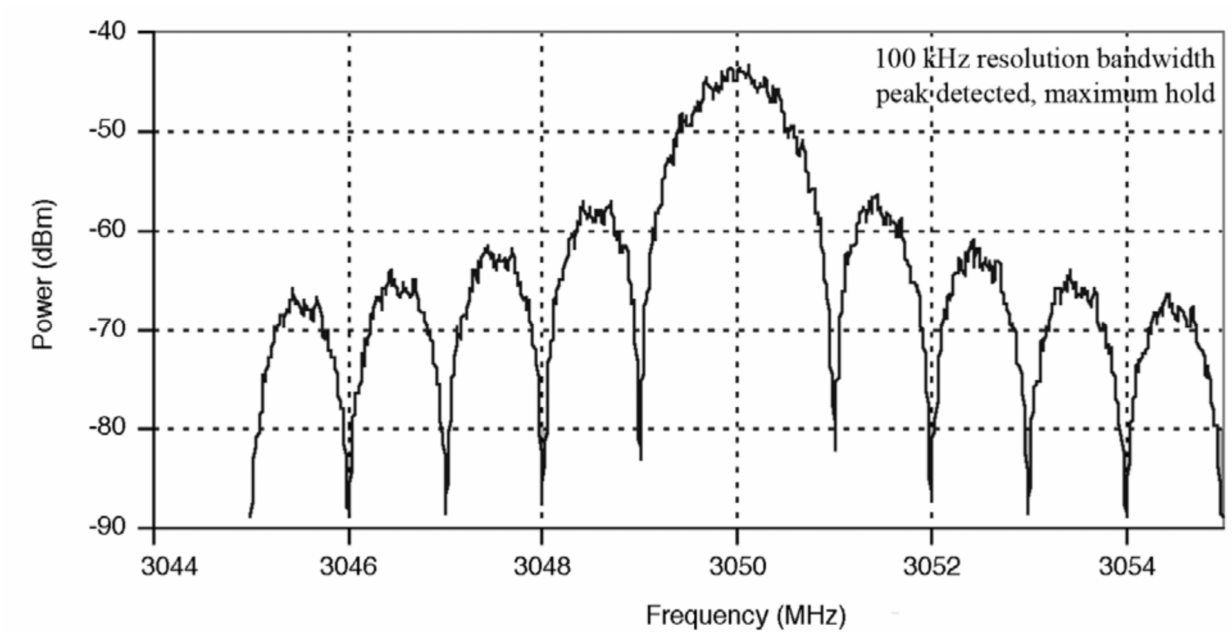

Figure B-5. 2 MBit/s QPSK interference signal spectrum.

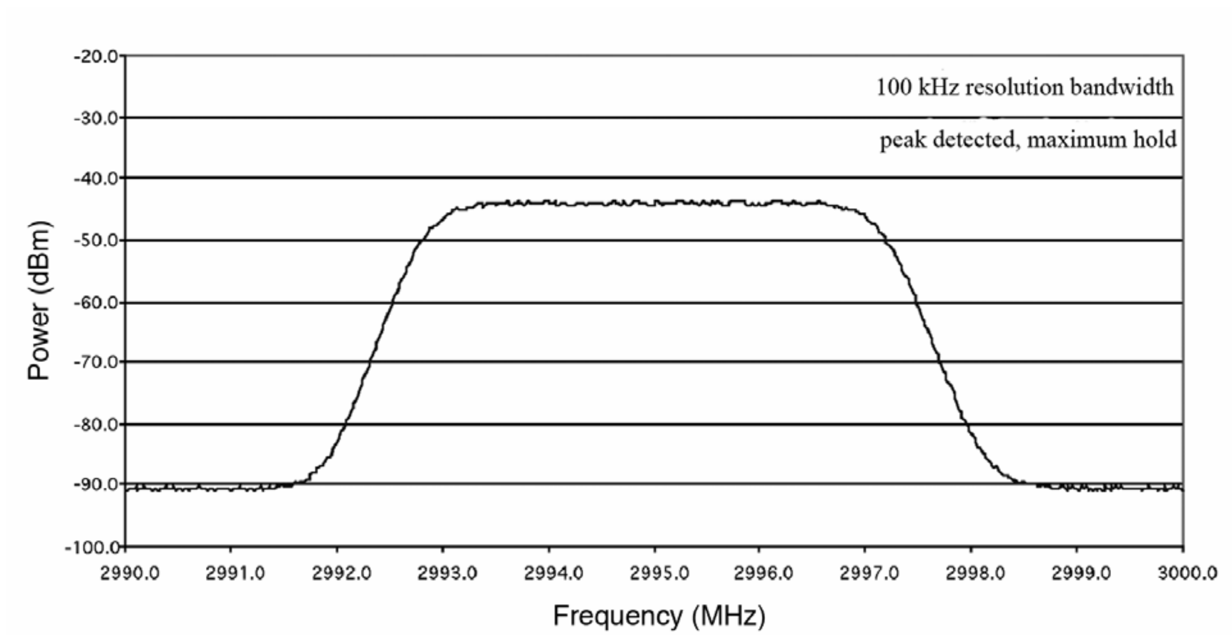

Figure B-6. W-CDMA interference signal spectrum.

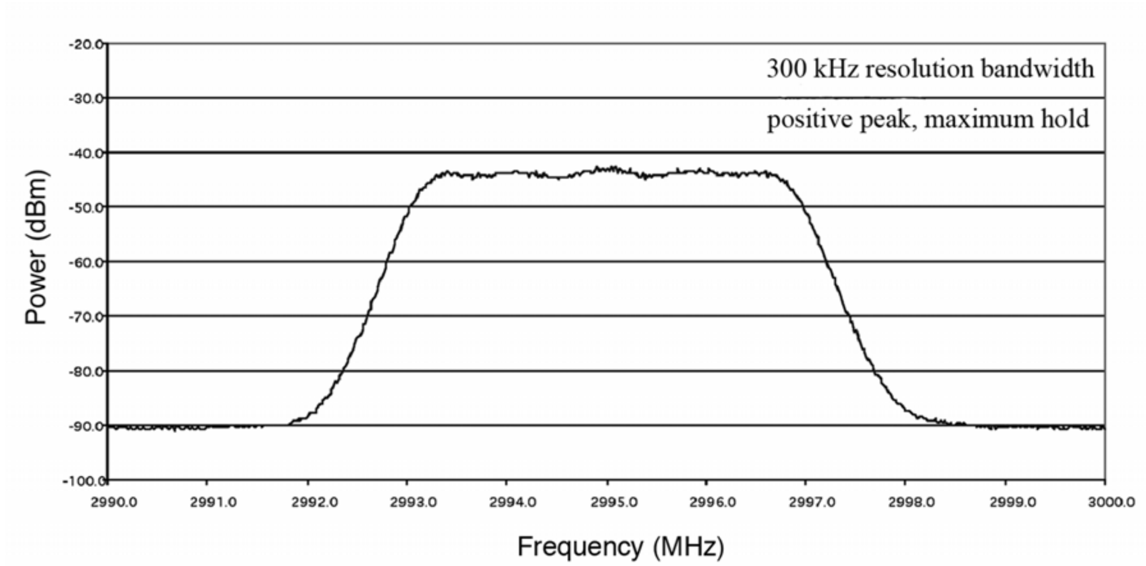

Figure B-7. CDMA-3X interference signal spectrum.

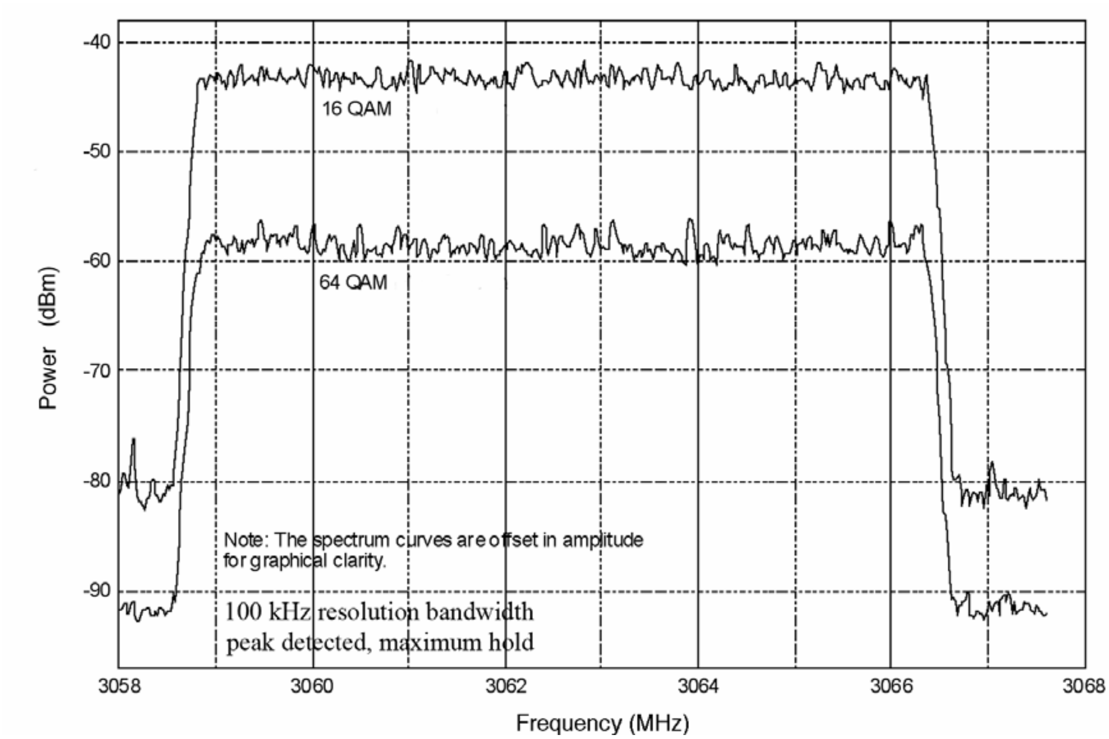

Figure B-8. QAM interference signal spectra for maritime radar tests.

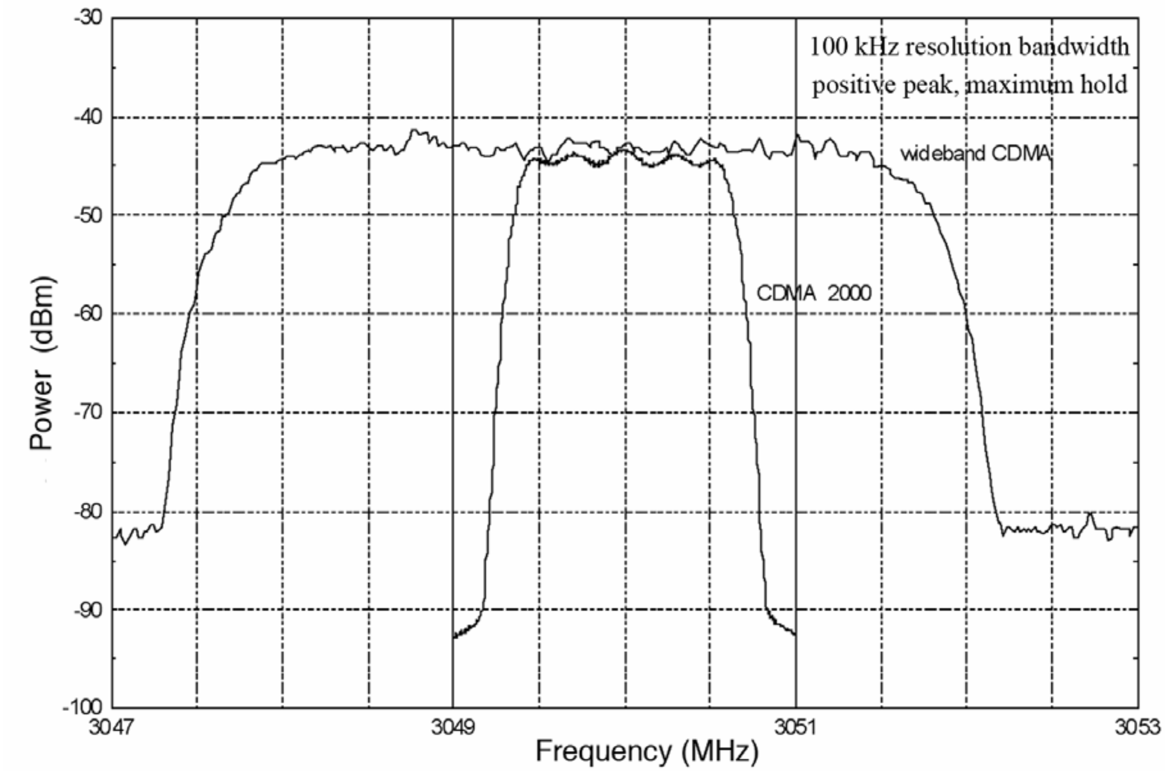

Figure B-9. CDMA interference spectra for maritime radar tests.

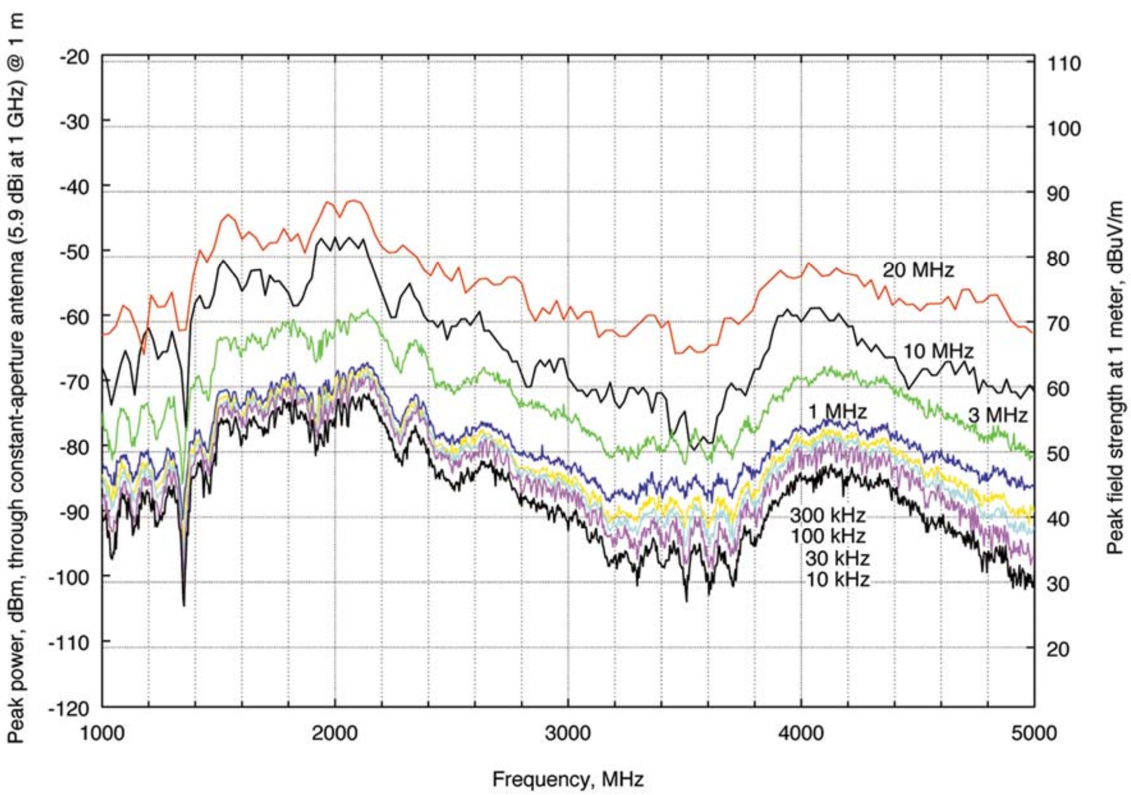

Figure B-10. UWB interference spectra as a function of receiver bandwidth.

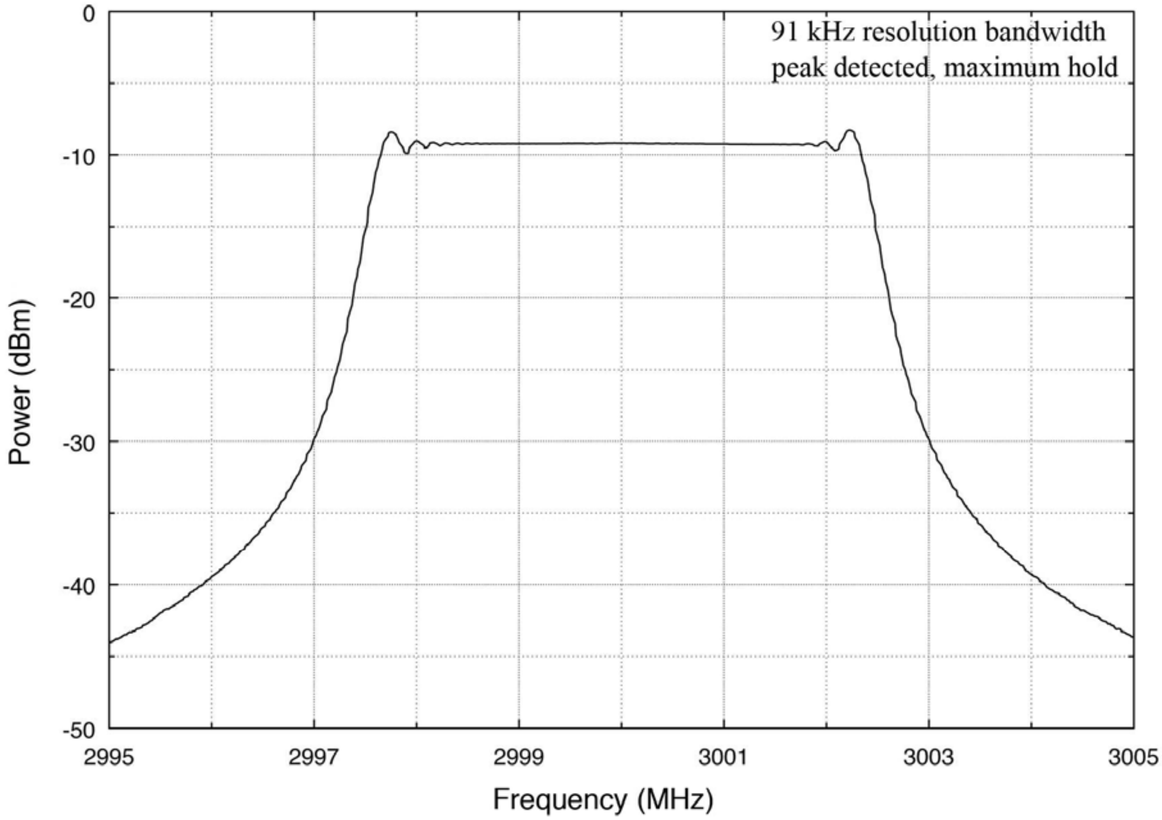

Figure B-11. Chirped-pulse interference spectrum. Chirp width was equal to about 5 MHz.

APPENDIX C: CALIBRATION OF UNDESIRED SIGNALS AND EXAMPLES OF RADAR IF SELECTIVITY CURVES

CW and interference signal calibrations on radars were performed as follows. An Agilent E-4440A spectrum analyzer, set in zero span mode and with the RMS detection selected, was connected to a radar channel IF output. A CW signal tuned to the radar operating frequency was then injected into the radar RF port and a level was found that produced an [$(I+N)/N$)] of 3 dB; equivalent to an I/N ratio of 0 dB. The undesired signal level was recorded, and identified to be equivalent to an I/N ratio of 0 dB. The process was repeated for channel B (if such a channel was present), and for each type of interference signal. Using the calibrated I/N ratio of 0 dB, the other I/N values were determined.

In addition, a CW signal was swept in frequency and the response of the IF circuitry of the radar receivers was measured for each channel and recorded with a spectrum analyzer. The 3-dB IF bandwidth of the radar receiver was determined in this way. Selected measurements of radar IF bandwidths are shown in the figures below, with names of the radars referring to the titles of the main text sections. The actual frequency of the IF outputs is usually around 32 MHz. However, in some cases (Figures C-1 and C-2) the frequency axes have been changed to show the corresponding RF frequencies of the radars.

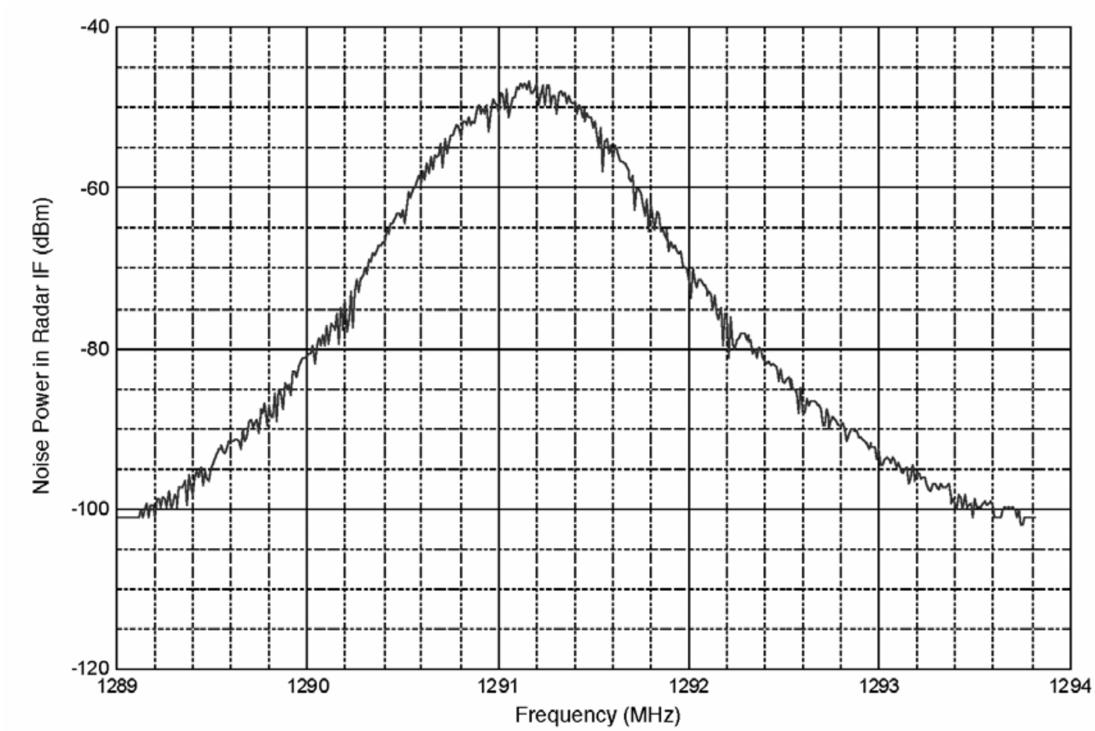

Figure C-1. Channel A IF response of Long Range L-Band Radar 1, referred back to RF frequencies. 100 kHz resolution bandwidth, peak detected, maximum-hold.

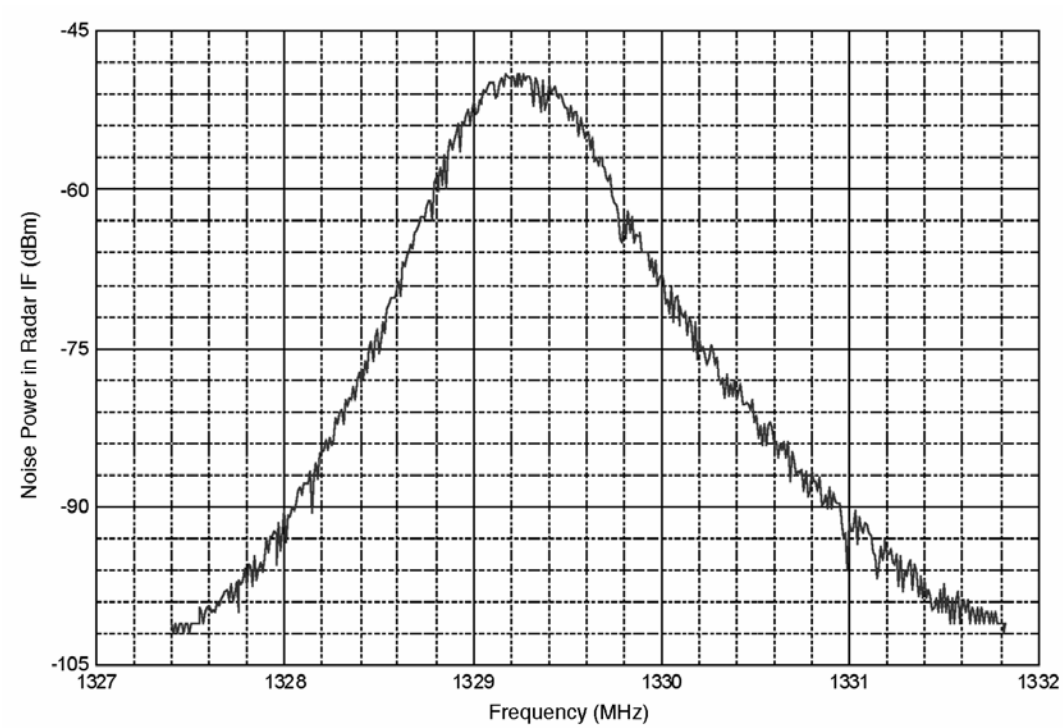

Figure C-2. Channel B IF response of Long Range L-Band Radar 1, referred back to RF frequencies. 100 kHz resolution bandwidth, peak detected, maximum-hold.

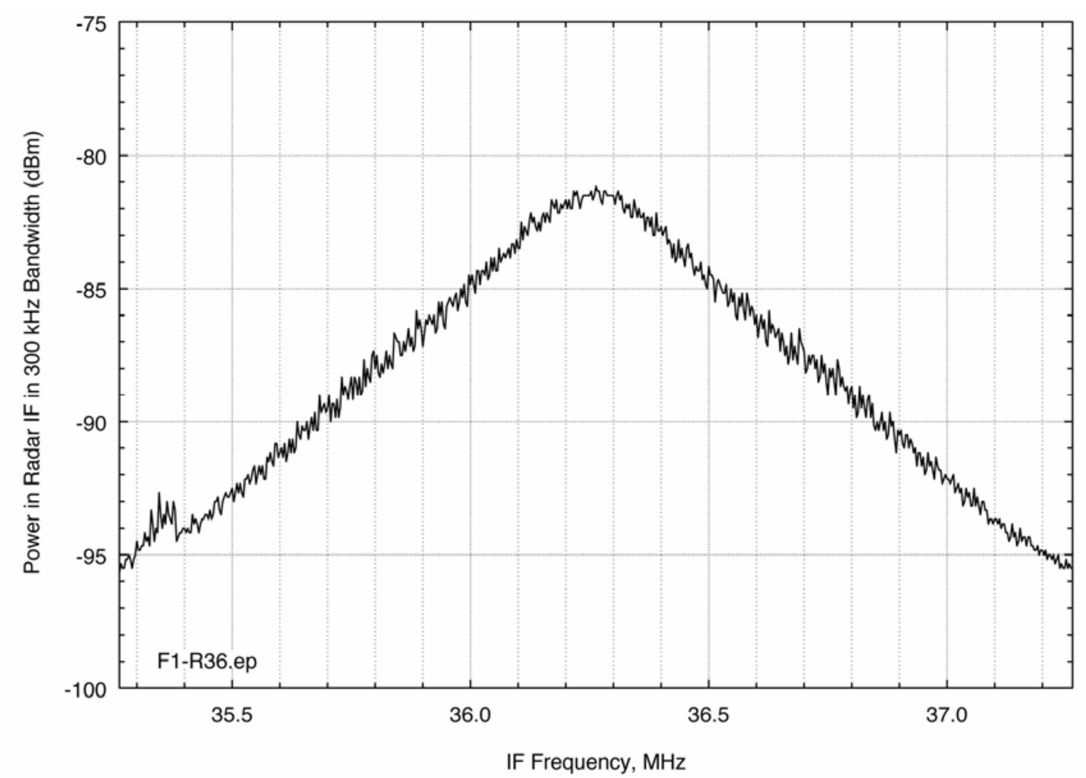

Figure C-3. IF response of one channel of Long Range Radar 2, centered at 36.25 MHz. 300 kHz resolution bandwidth, peak detected, maximum-hold.

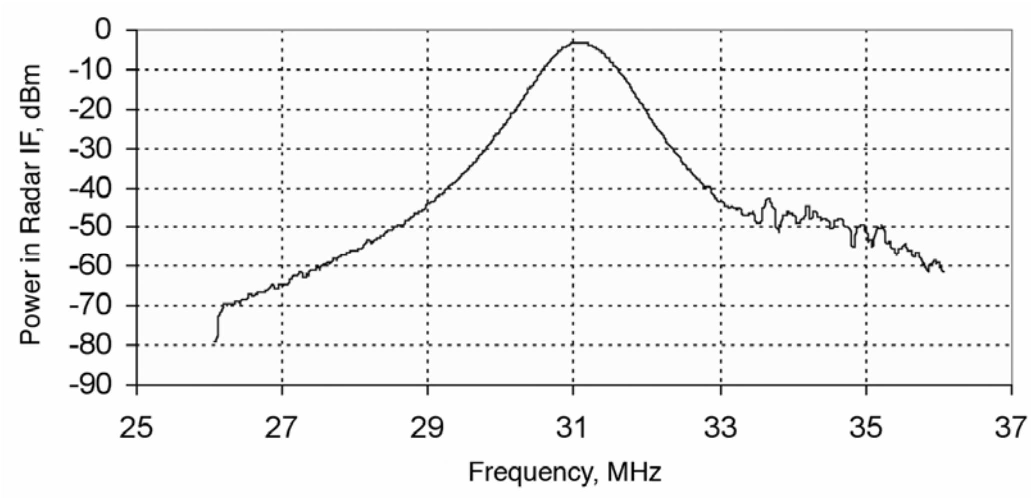

Figure C-4. IF response curve of the short-range air search radar, centered near 31 MHz. 100 kHz resolution bandwidth, peak detected, maximum-hold.

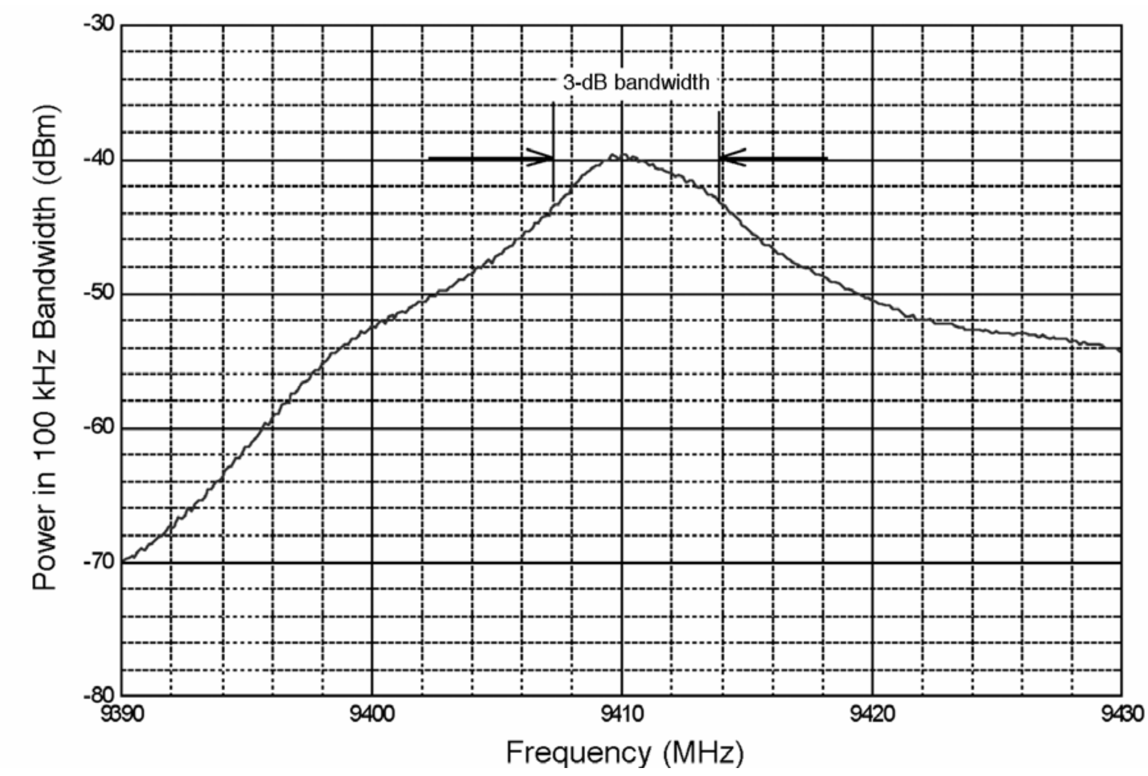

Figure C-5. IF response curve of a typical maritime radionavigation radar (Radar F). The IF frequencies are mapped to their RF equivalents. 100 kHz resolution bandwidth, peak detected, maximum-hold.

APPENDIX D: TEST RESULTS ILLUSTRATING THE EFFECTIVE DUTY CYCLE OF FM-PULSED WAVEFORMS IN A MARINE RADAR RECEIVER

The measurements in this appendix were performed with marine radionavigation Radar F described in the main body of the report. The chirped waveforms identified in Tables 18 and 21 were injected into the radar receiver to investigate how the signal's duty cycle and pulse width are altered through the receiver, changing from the RF pulse waveform that was originally transmitted to the form that is manifested in the radar's detector/processor.

Testing has shown that the effective duty cycle of the interfering waveform is a key element in the ability of a radar receiver to suppress interference effects from unwanted pulsed signals. The results of these tests show that the effective duty cycle of chirped pulsed interference is reduced inside the receiver as compared to the duty cycle that occurs at the radar receiver RF front end.

D.1 Background

The victim receiver's 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: $R_c = (B_c/\tau)$, where R_c is the sweep rate (in megahertz per microsecond), B_c is the chirp frequency range (in megahertz) and τ is the pulse duration (in microseconds). Victim radar receivers should not respond to interference on frequencies outside the -20 dB 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.

D.2 Measurement Technique

The pulses were injected into the radar receiver at the nominal RF frequency of 9410 MHz at the LNA input. The receiver was not connected to its antenna, to ensure that no other signals could couple into the receiver during testing. A measurement point was identified on the IF circuit card, a spectrum analyzer was set to zero-span mode with a resolution bandwidth commensurate with the radar receiver, and then the analyzer was connected to the measurement point to monitor the response of the radar to the injected waveforms[30]. The radar was placed in stand-by mode so that the receiver was activated, but its transmitter was not generating pulses.

The radar receiver used a summing multistage logarithmic amplifier (Figure 3 in the main report). The IF test point that was used is located at the output of the third amplifier. A CW signal was swept in frequency from 9370 to 9450 MHz to determine the response of the receiver and to measure the receiver's IF bandwidth. The result is shown in Figure D-1. The 3-dB IF bandwidth of the radar was set to short pulse mode 1. This mode, which used a pulse width of 200 ns for a maximum range of 3 nautical miles, was measured at 6 MHz. A spurious receiver response was noted at 9381 MHz, 20 dB below the peak response at 9410 MHz.

[30] The spectrum analyzer was also used to measure and record the time waveform envelopes of the pulses at the fundamental RF frequency, prior to injection into the radar receiver.

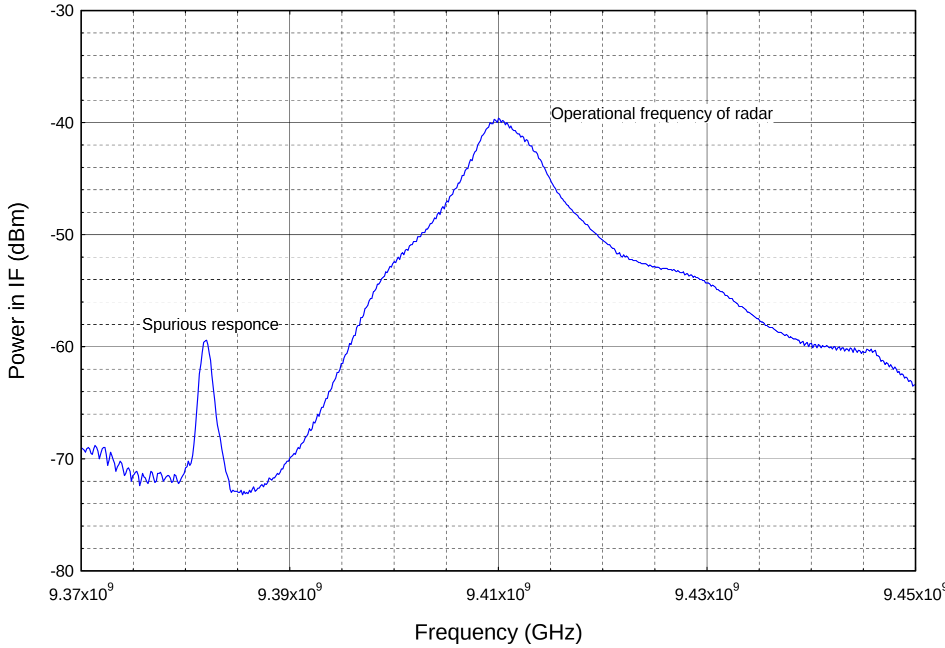

Figure D-1. Frequency response of the IF stage of marine Radar F to a CW input signal when the radar was in its short-pulse mode, shown as a function of the RF frequency of the CW input.

D.3 Results

The results of the measurements are shown in Figures D-2 through D-9. The figures show time waveforms of the pulses after they have passed through the receiver's LNA and IF circuitry. These are the waveforms that are sent into the receiver's processor and detector. For these measurements the -6 dB points are used to specify pulse widths. Figure D-2 shows that unmodulated 1-µs RF pulses (the baseline signal) were still 1-µs wide in the radar's IF bandwidth. However for the chirped pulsed signals, the widths of these pulses in the IF passband of the receiver were shorter than the ones that were transmitted at the RF level. Since the pulse repetition interval (pri) did not change, the effective duty cycle was consequently reduced.

Table D-1 summarizes the results of the differences in pulse width between the RF transmitted pulses and the pulses that are presented to the detector/processor of the radar receiver. The percent difference was calculated by dividing the received pulse width by the transmitted pulse width and then multiplying by 100.

D.4 Summary

Due to the chirping characteristics of the waveforms and the response of the radar receiver, the effective duty cycles and pulse widths of the waveforms at the radar's detector/processor input are *smaller* than those of the *transmitted* waveforms. The interference susceptibility tests have shown that a radar's robustness against the effects of pulsed interference is closely related to the duty cycle and pulse width of the interfering waveforms. As the effective duty cycles and pulse widths are lowered, radar receivers are able to better mitigate the effects of pulsed interference, as the CFAR circuitry and other mitigation techniques outlined in ITU-R Recommendation M.1372 become more effective. Therefore, when assessing the compatibility of radionavigation radars and chirped pulsed waveforms, tests and measurements along with analyses should take such effects into account. As the data in this appendix demonstrate, the *effective* duty cycle and pulse width in radar receivers should be considered along with the *I/N* ratio when assessing the impact of chirped waveforms on radar receivers.

Table D-1. Characteristics of Chirp-Pulse Waveforms Injected into Marine Radar F

Waveform	**Transmitted Pulse width (μs)**	**Pulse width (μs) at detector-processor**	**Detector-processor pulse width divided by full pulse width**
Chirp 1	10	5.1	0.51
Chirp 2	10	1.0	0.10
Chirp 3	1.65	0.20	0.12
Chirp 4	2	0.20	0.10
Chirp 5	16	1.0	0.063
Chirp 6	17.7	1.2	0.068
Chirp 7	1.7	0.20	0.118

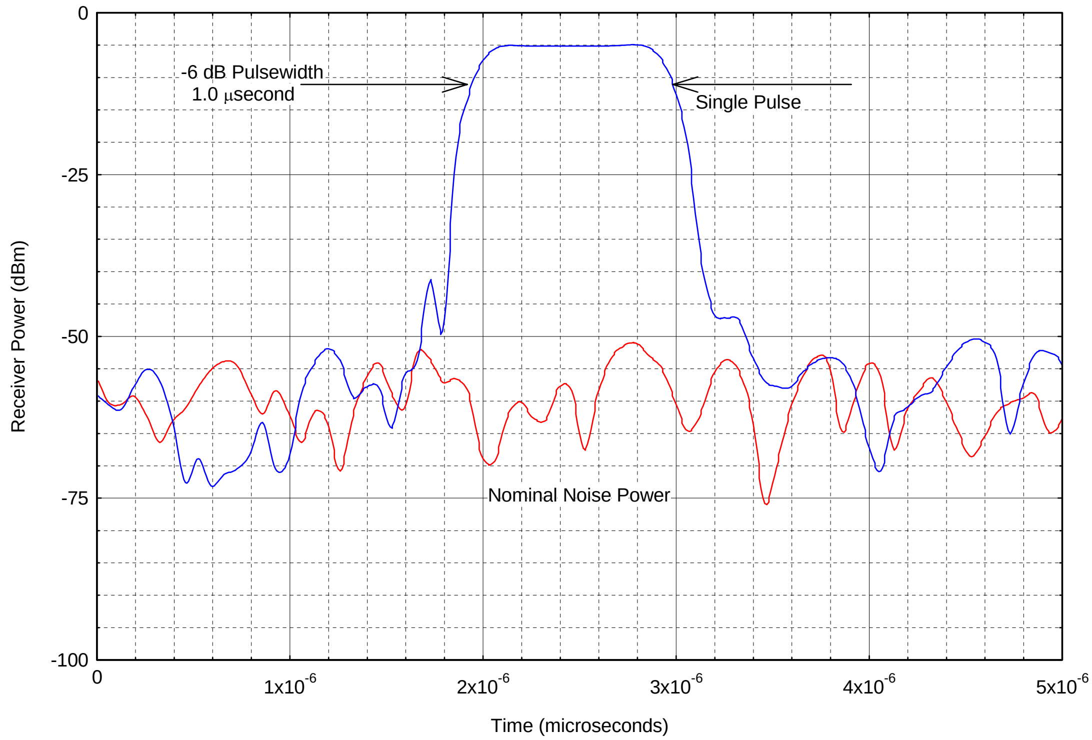

Figure D-2. 1-µs unmodulated pulse in marine Radar F receiver. Because the radar IF bandwidth is greater than 1 MHz, the pulse appears well-formed in the time domain.

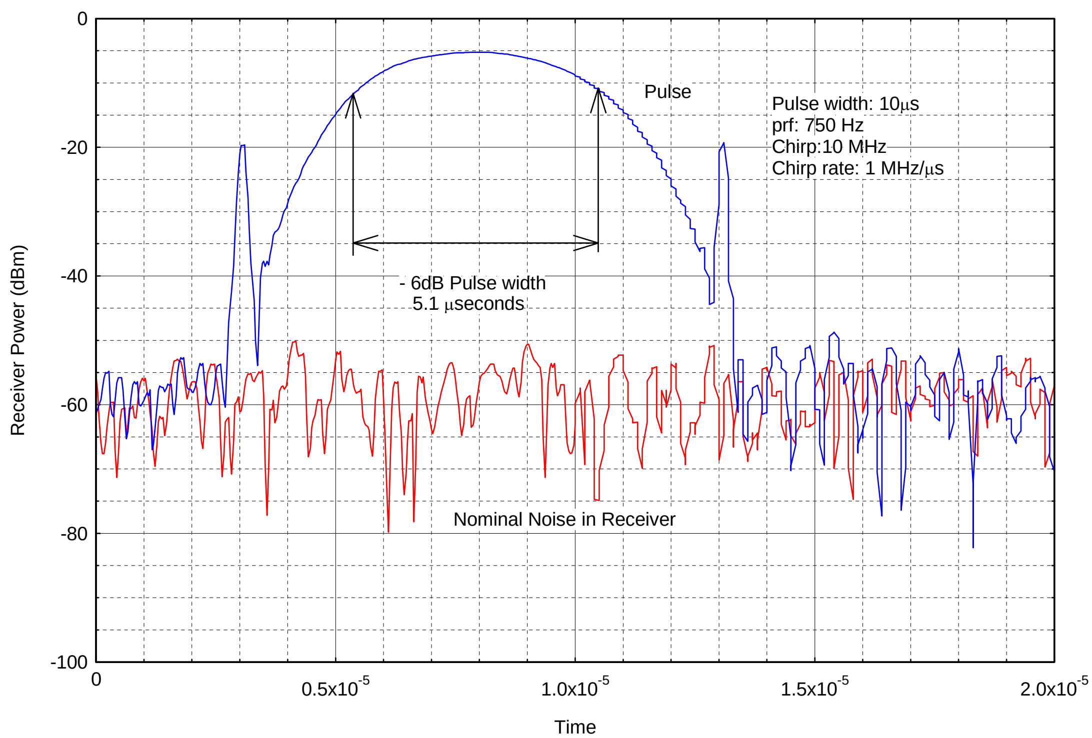

Figure D-3. Chirped waveform 1 in marine Radar F receiver. The time waveform is a result of the Radar IF bandwidth being less than the chirp bandwidth.

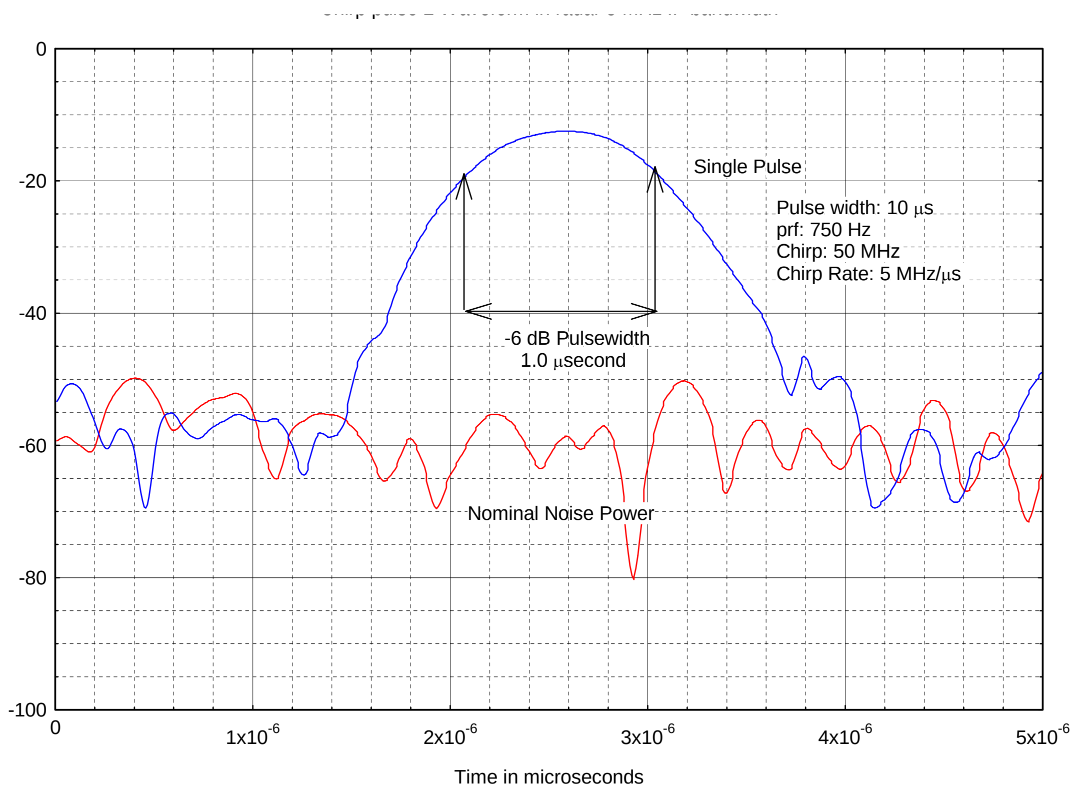

Figure D-4. Chirped waveform 2 in marine Radar F receiver.

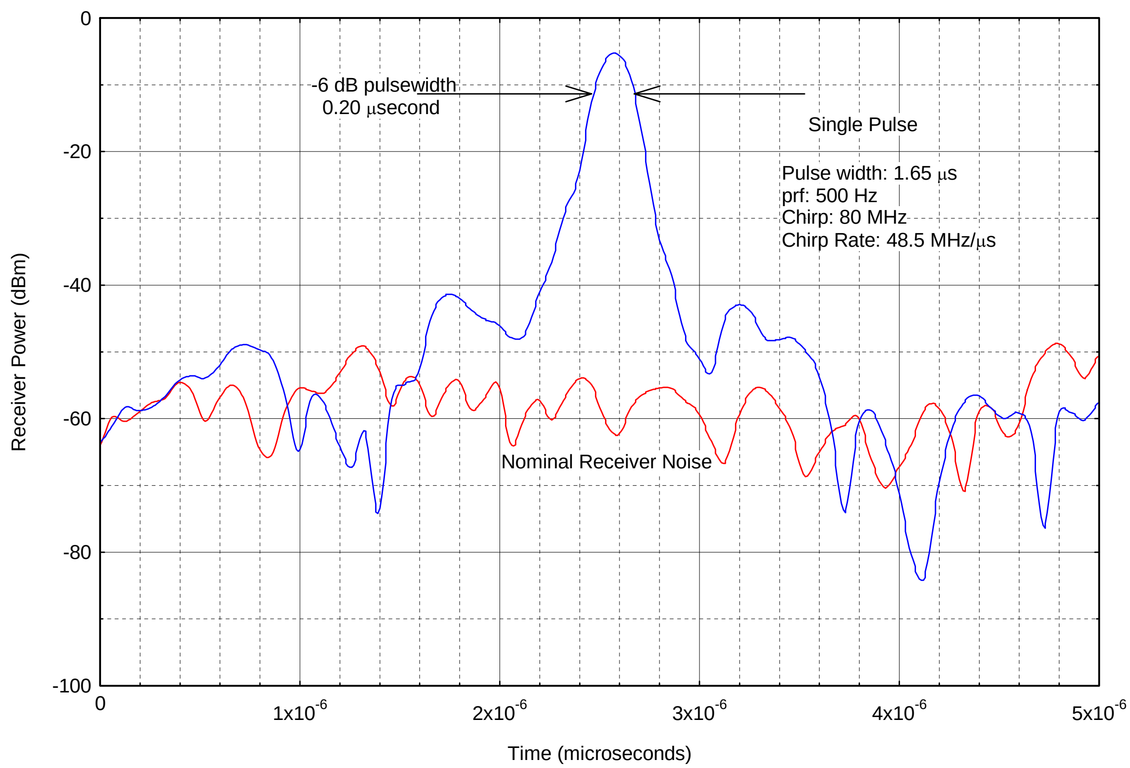

Figure D-5. Chirped waveform 3 in marine Radar F receiver.

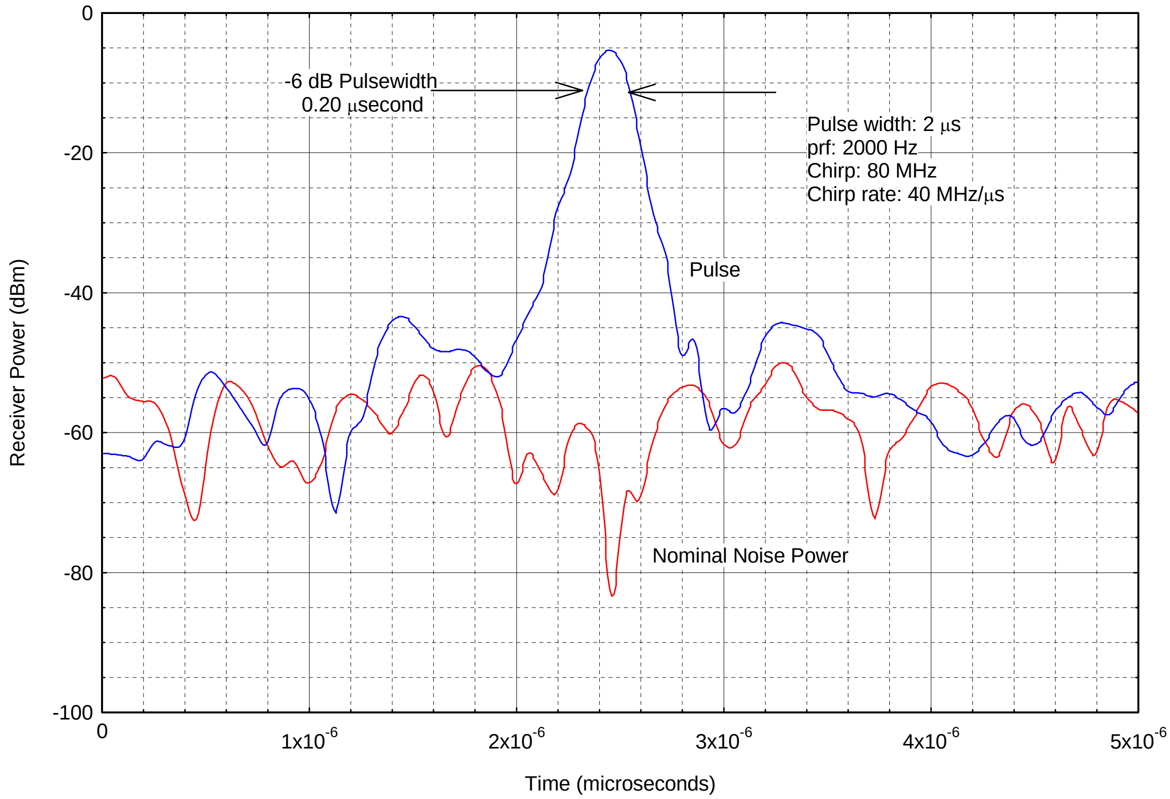

Figure D-6. Chirped waveform 4 in marine Radar F receiver.

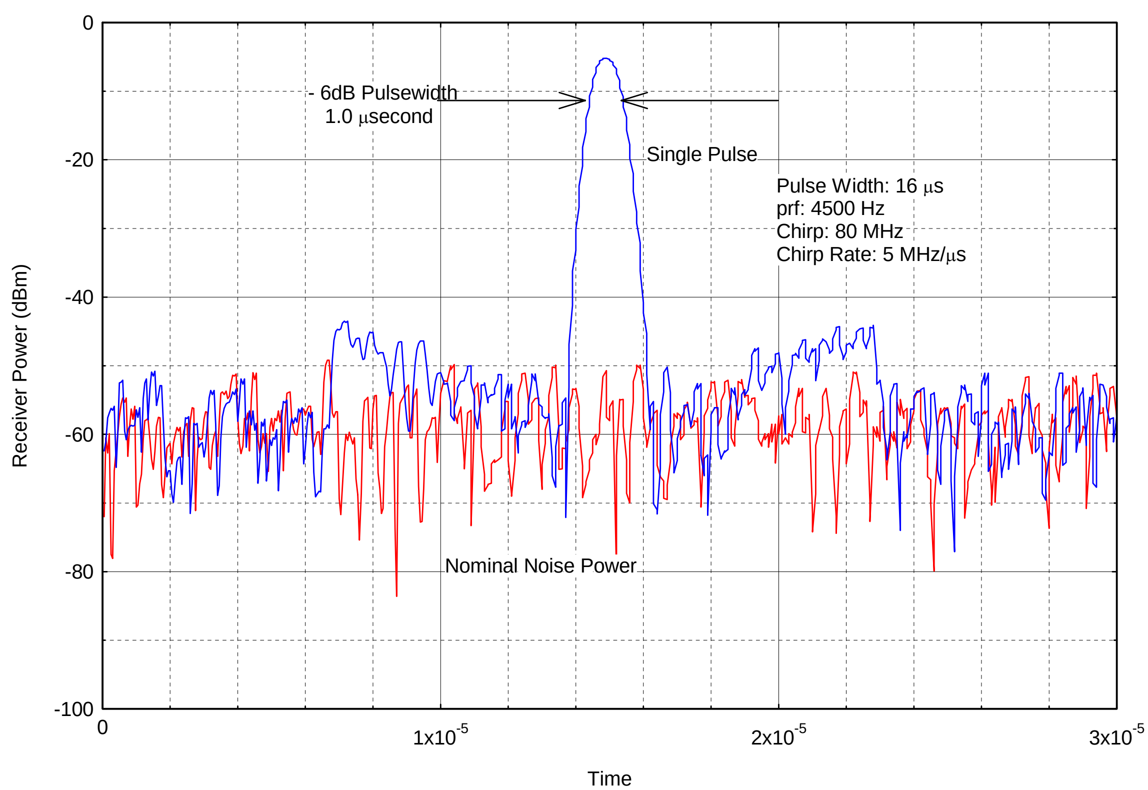

Figure D-7. Chirped waveform 5 in marine Radar F receiver.

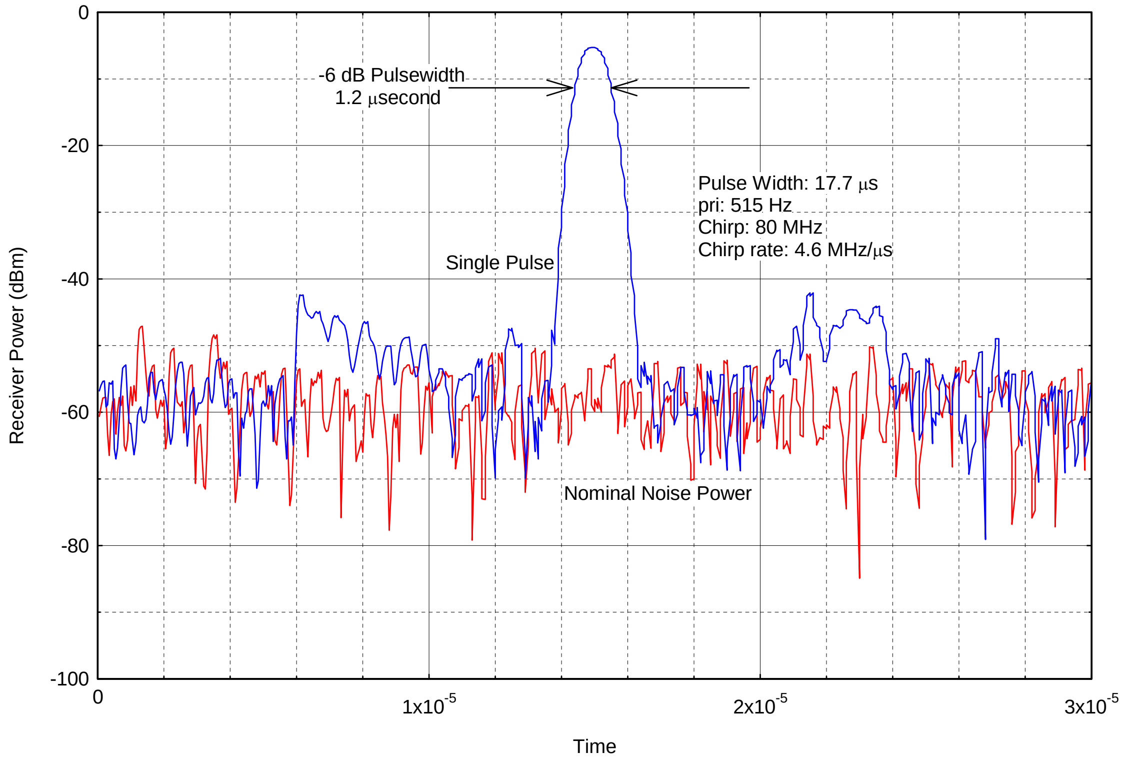

Figure D-8. Chirped waveform 6 in marine Radar F receiver.

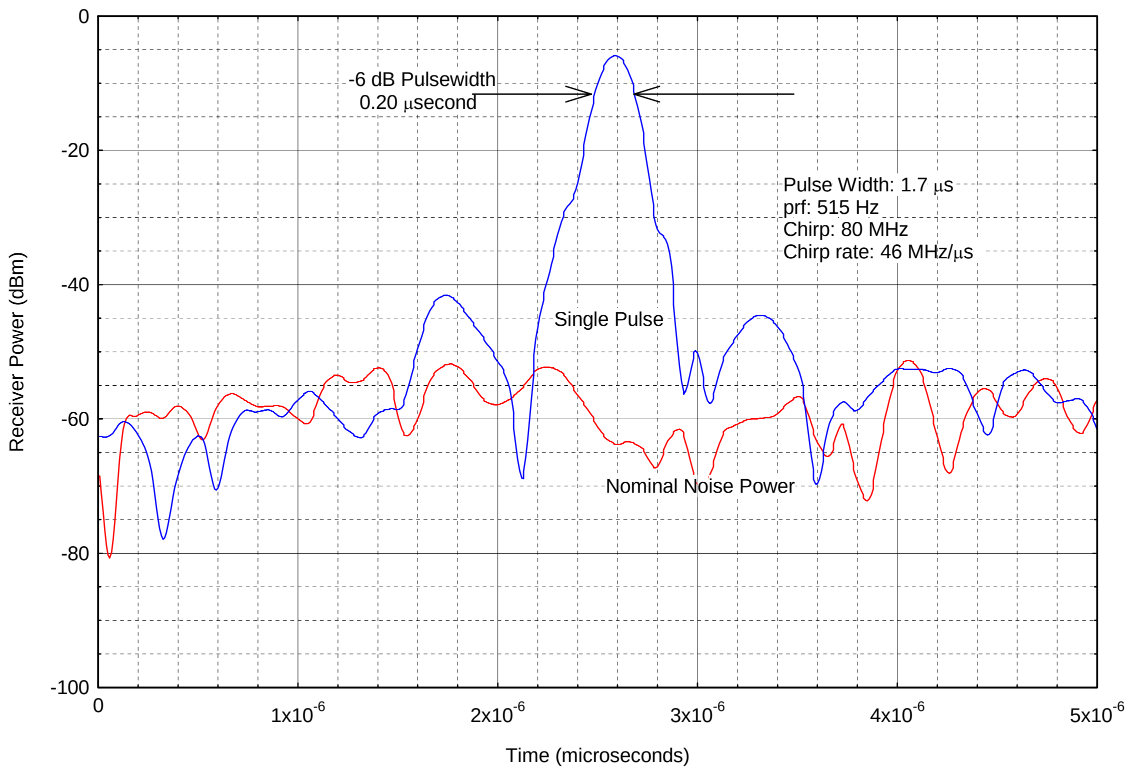

Figure D-9. Chirped waveform 7 in marine Radar F receiver.