REPORT ITU-R M.2128*

Test results and simulations illustrating the effective duty cycle of frequency modulated pulsed radiolocation and EESS system waveforms in marine radionavigation receivers

(2008)

1 Introduction

This Report was developed based on measurements that were performed with marine radionavigation radars operating at 9 410 MHz and 3 050 MHz. Typical waveforms of chirped radiolocation and earth exploration satellite service (EESS active) systems were simulated using test equipment and injected into the 9 410 MHz radar receiver to investigate how the signal's duty cycle and pulse width are altered from the transmitted RF pulse, to the one that is presented to the radar's detector/processor. For the 3 050 MHz radars, mathematic simulations were performed to determine the response of the radars to the EESS and radiolocation systems.

2 Background

This Report was prepared to provide information on test results for possible consideration of World Radiocommunication Conference 2007 Agenda item 1.3.

3 Test signals

Table 1 shows the parameters of the radiolocation waveforms. They were developed based on the characteristics of Radars A7 and A3 from Recommendation ITU-R M.1796 – Characteristics of and protection criteria for terrestrial radars operating in the radiodetermination service in the frequency band 8 500-10 500 MHz. As a baseline signal, unmodulated pulses with a width of 1µs were also generated.

TABLE 1

Radiolocation system waveforms

System waveform No.	Pulse width (µs)	Pulse repetition frequency (Prf) (Hz)	Pulse repetition interval (Pri) (ms)	Duty cycle (%)	Chirp (MHz)	Chirp rate (MHz/µs)
Radiolocation 1	10	750	1.3	0.8	10	1
Radiolocation 2	10	750	1.3	0.8	50	5
Radiolocation 3	13.6/1.65	5 000	0.20	0.8	660/80	48.5

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 passband. This rate, called chirp rate, R_c, is given by:

* This Report should be brought to the attention of Radiocommunication Study Group 7.

$$R_c = (B_c / t)$$

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 passband 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 Recommendation ITU-R M.1796. 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 1, 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 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 passband of the victim is equal to or less than 50 MHz wide.

The EESS system waveform characteristics are shown below in Table 2. As in the case of the chirped waveforms from Table 1, the values are scaled to the maximum 80 MHz chirp bandwidth of the test equipment. The duty cycles are calculated using the scaled pulse widths.

TABLE 2

EESS system waveform characteristics

System waveform No.	Pulse width (µs)	Scaled width (µs)	Prf (Hz)	Pri (ms)	Duty cycle (%)	Chirp (MHz)	Chirp rate (MHz/µs)
EESS 1	10	2	2000	0.5	0.4	400/80	40
EESS 2	80	16	4500	0.22	7.2	400/80	5
EESS 3	10	17.7	515	1.94	0.91	460/80	4.6
EESS 4	10	1.7	5150	1.94	0.88	460/80	46

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 passbands 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 and measuring the effective duty cycle.

4 Measurement technique

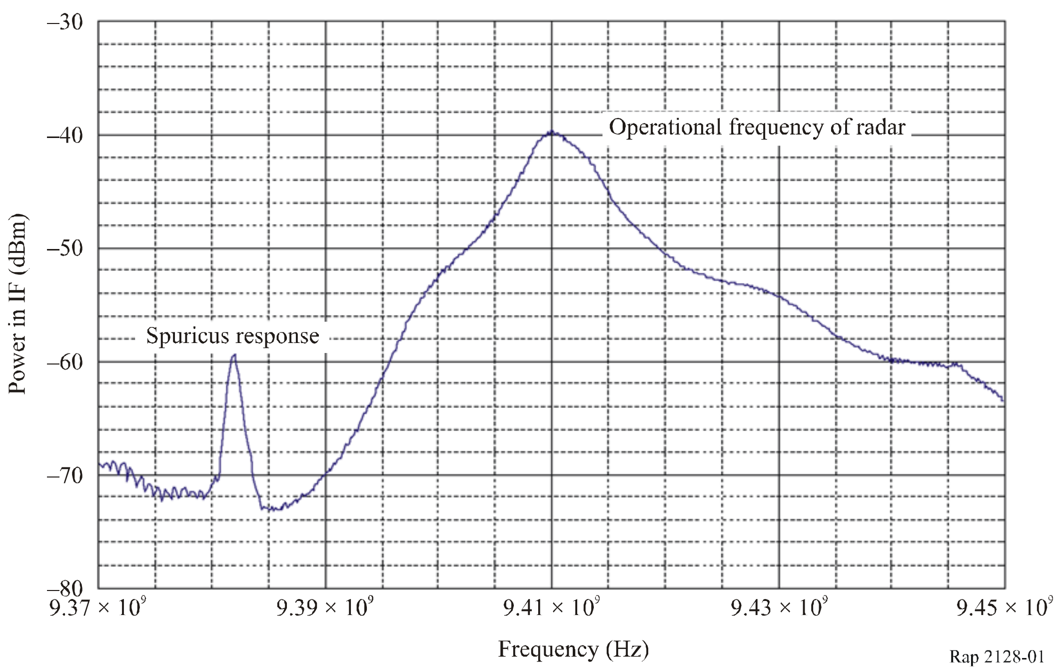
The pulses were injected into the radar at the nominal frequency of 9 410 MHz at the low noise amplifier (LNA) input of the radar receiver. The radar was not connected to its antenna, so no other signals were able to get into the receiver. A test point was located on the IF circuit card and a spectrum analyser was set to zero-span mode with a resolution bandwidth consummate with the radar receiver and connected to that point to measure the response of the radar to the radiolocation and EESS systems. The radar was placed on stand-by mode so that the receiver was activated, but its transmitter was not generating pulses. The analyser was used to collect data that was plotted to show the power of the pulses versus time at the fundamental frequency.

The radar uses a summing multistage logarithmic amplifier. A test point was provided that is located at the output of the third amplifier. A CW signal was swept in frequency from 9 370 to 9 450 MHz to determine the response of the receiver and measure the IF bandwidth. The result is shown below 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 3 NM, was measured to be about 6 MHz. Note that there is a spurious response in the receiver at 9 381 MHz 20 dB down from the peak response at 9 410 MHz.

Note that these measurements were not done in a manner to verify frequency dependent rejection (FDR) values. The radiolocation and EESS system input powers and corresponding output powers at the radar's IF were not calibrated to perform that measurement. These measurements were only done in a manner to show how the pulse width was reduced due to the signal chirping through the radar receiver, *not* the peak power. The effective pulse width is defined in this Report as the width of the EESS and radiolocation chirped pulse that is presented to the radar's target detector/processor *after* it has passed through the radar's LNA and been convolved with the IF filter. For example, if the width of the transmitted EESS and radiolocation pulse is 10 μs, but at the radar's IF output it is 2 μs, then the effective pulse width is 2 μs.

FIGURE 1

Frequency response of marine radar to CW input signal



5 Results

The results of the measurements are shown in Figs. 2 through 9. The figures are annotated and show the width of the pulse after it has passed through the receiver's LNA and IF circuitry as it is presented to the receiver's processor and detector. Note that the figures show power versus time, so for these measurements the –6 dB points are used to determine the pulse width. Fig. 2 shows that the unmodulated pulse (the baseline signal) was 1 µs wide in the radar's IF bandwidth, which is the same value as the transmitted pulse. However, for the chirped radiolocation and EESS systems, the width of pulses as seen in the IF passband of the receiver are shorter than the ones that were transmitted at the RF level. Since the pulse repetition interval (pri) has not changed, the effective duty cycle has been lowered as well.

Figures 2 through 9 show the results using radiolocation and EESS systems that are chirped as described in § 3 of this Report. Table 3 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 percentage difference was calculated by dividing the received pulse width by the transmitted pulse width and then multiplying by 100.

FIGURE 2

1 µs unmodulated pulse in radar receiver

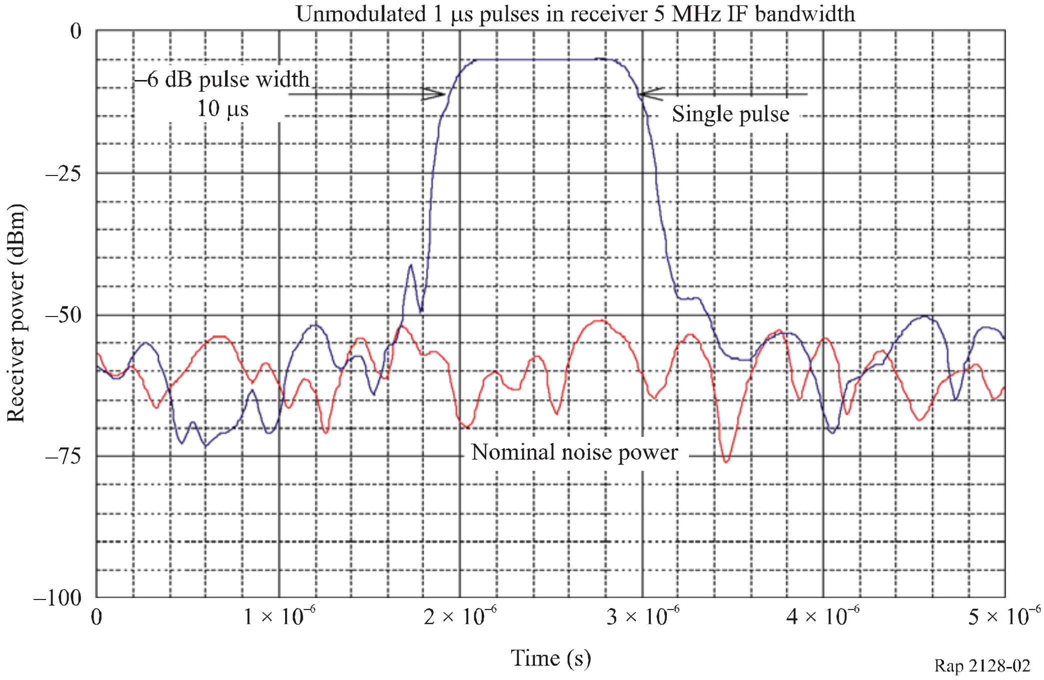


FIGURE 3

Radiolocation system waveform 1 in radar receiver

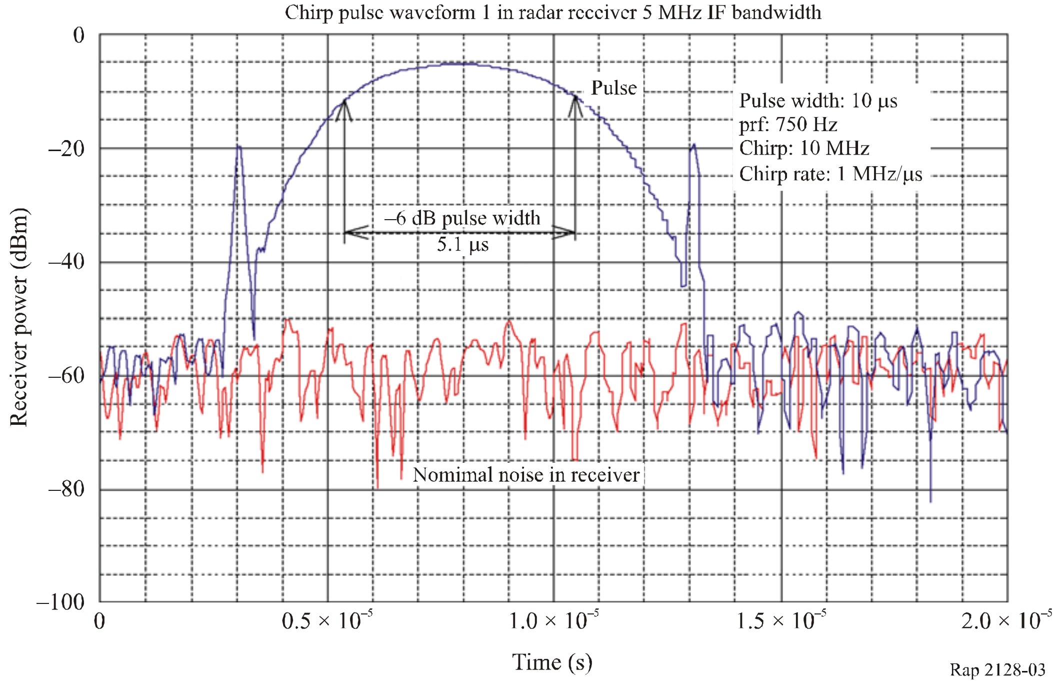


FIGURE 4

Radiolocation system waveform 2 in radar receiver

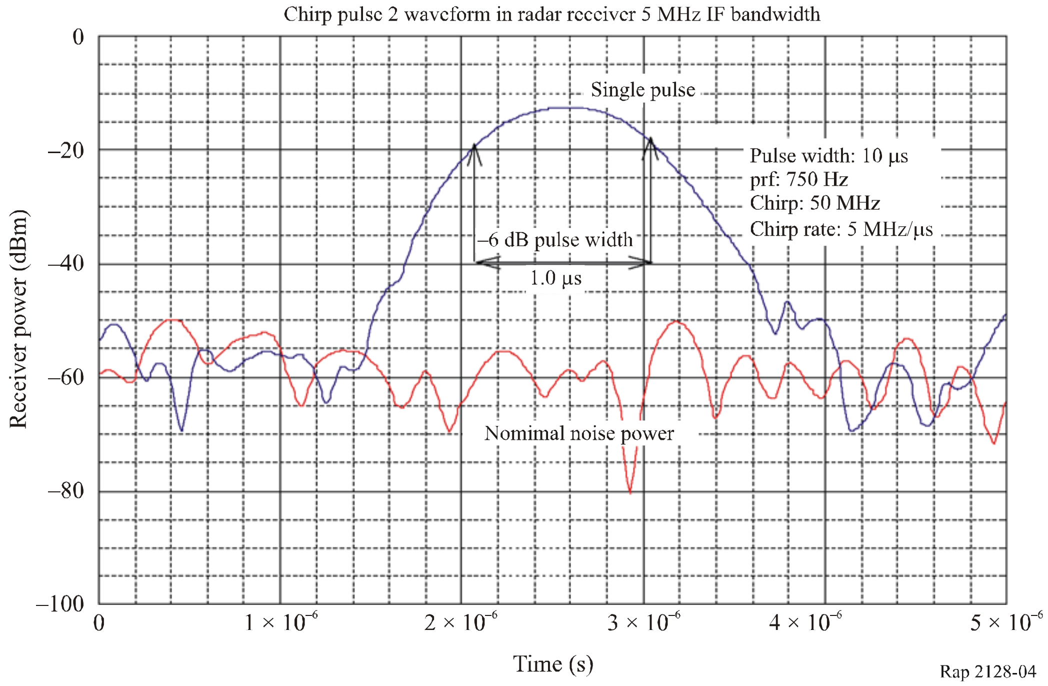


FIGURE 5

Radiolocation system waveform 3 in radar receiver

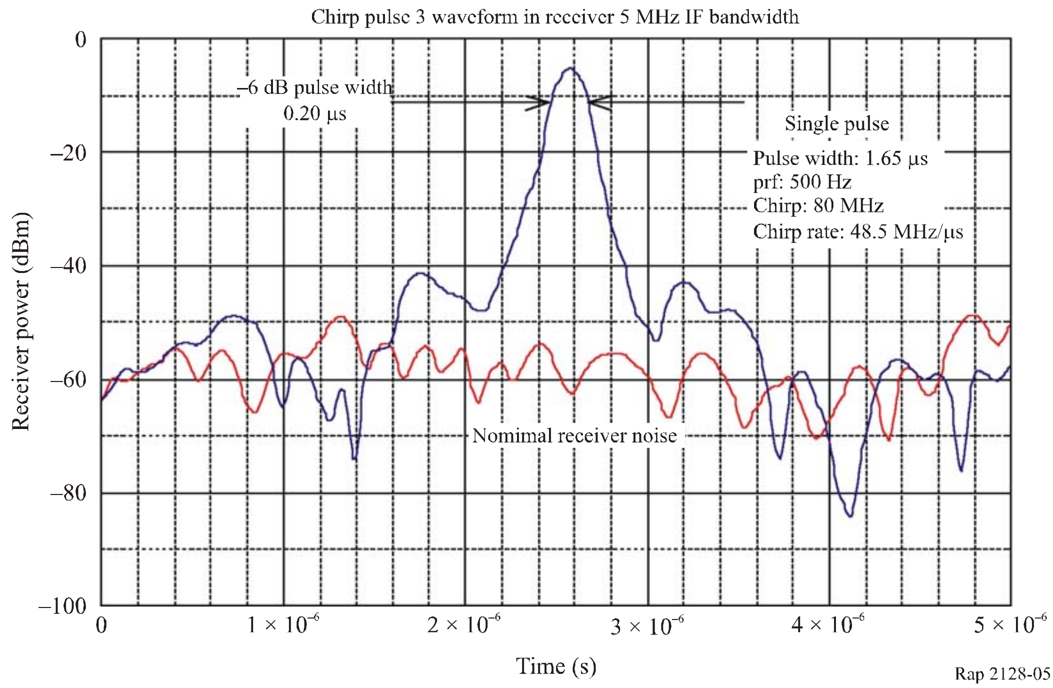


FIGURE 6

EESS system waveform 1 in radar receiver

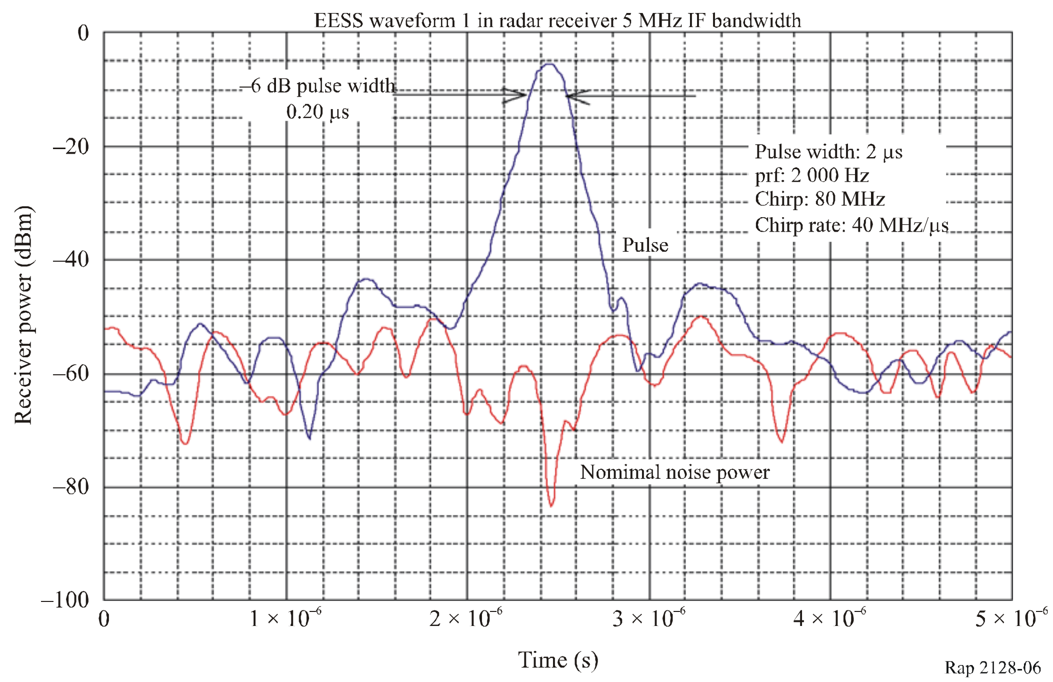


FIGURE 7
EESS system waveform 2 in radar receiver

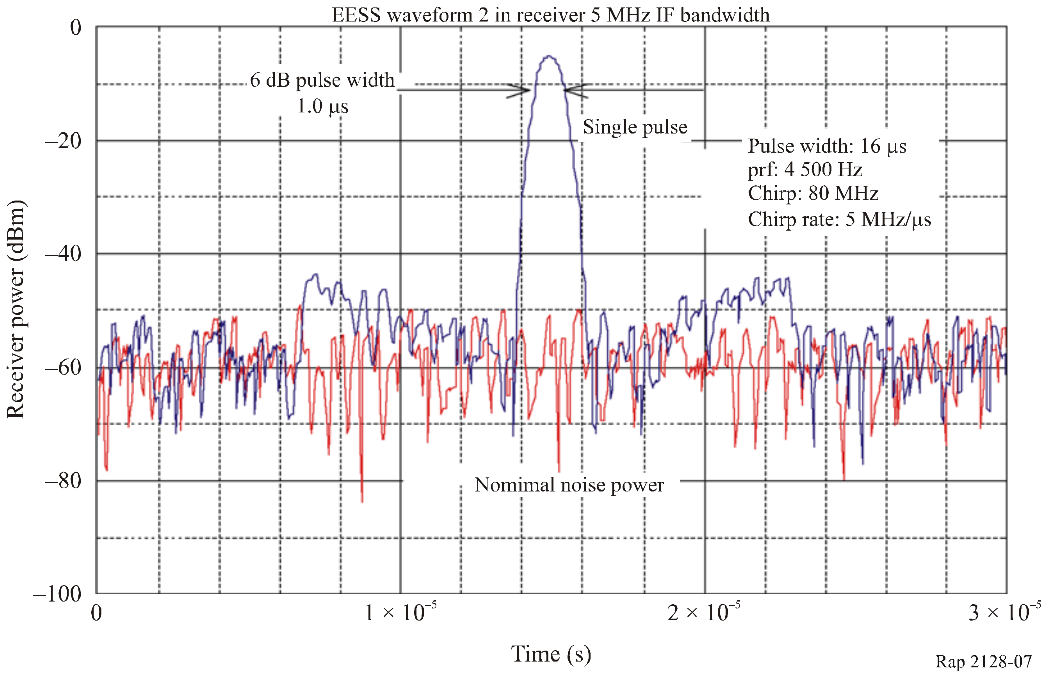


FIGURE 8
EESS system waveform 3 in radar receiver

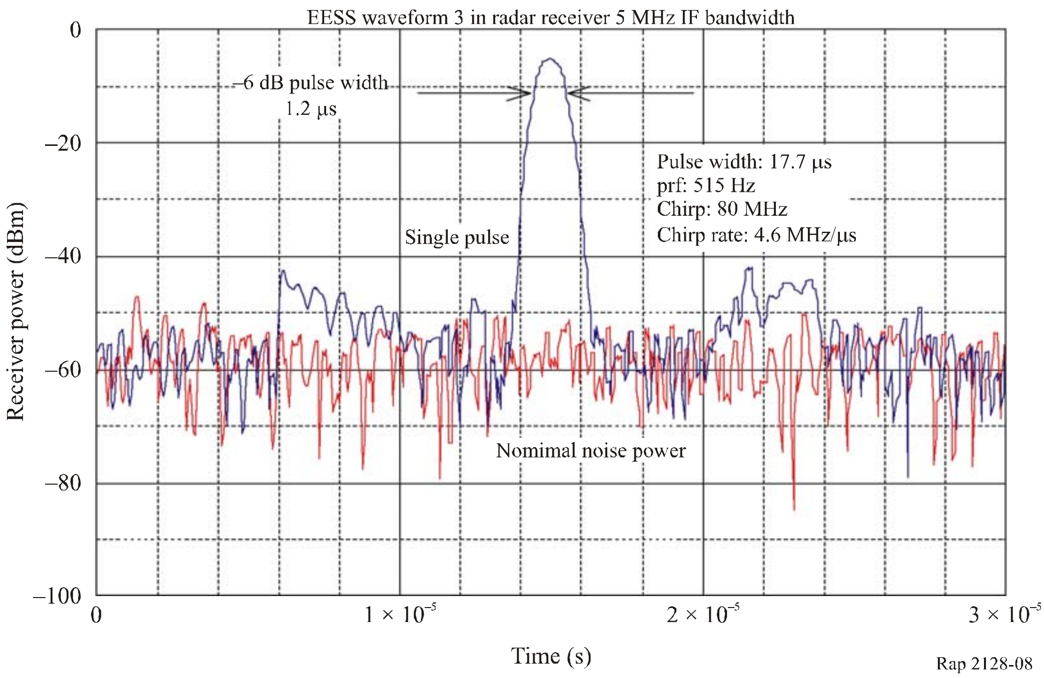


FIGURE 9
EESS system waveform 4 in radar receiver

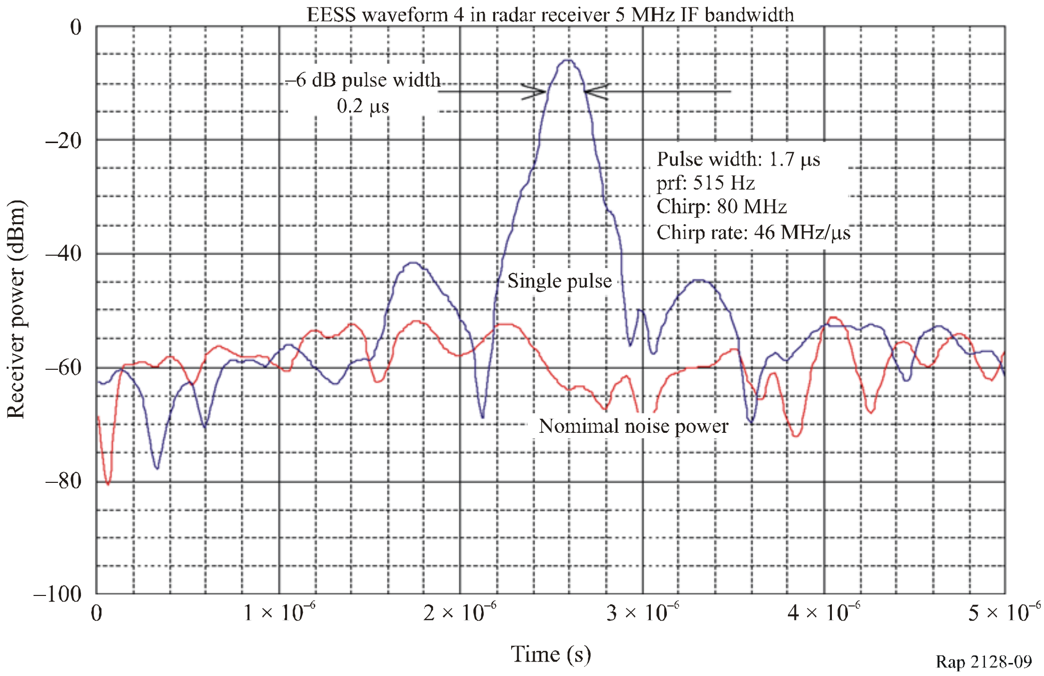


TABLE 3

System waveform	Transmitted pulse width (µs)	Pulse width (µs) at detector/processor	Percentage difference
Radiolocation 1	10	5.1	51
Radiolocation 2	10	1.0	10
Radiolocation 3	1.65	0.20	12
EESS 1	2	0.20	10
EESS 2	16	1.0	6.3
EESS 3	17.7	1.2	6.8
EESS 4	1.7	0.20	11.8

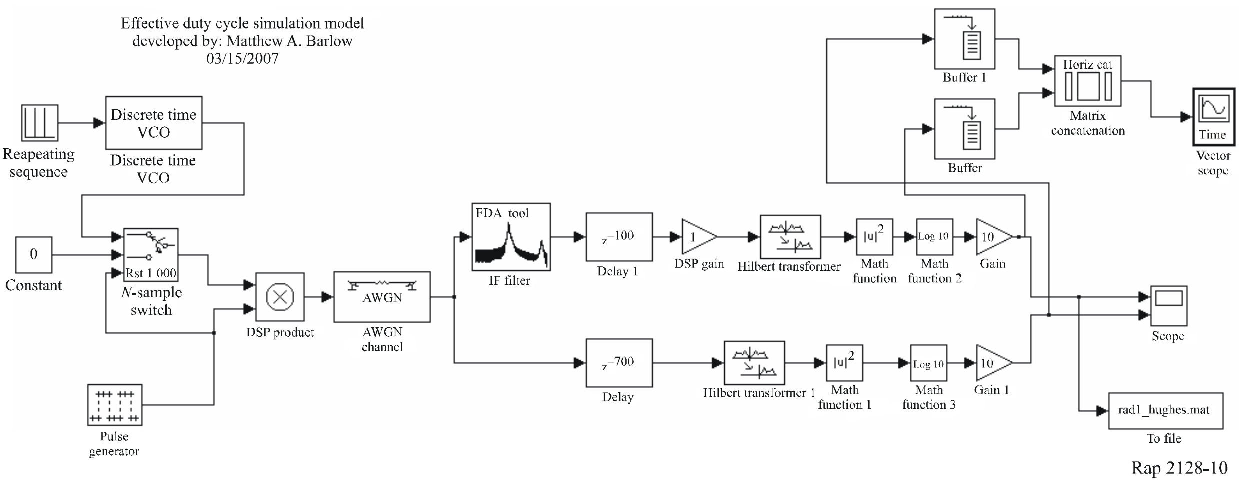
6 Simulations

The simulations were performed in Simulink™, a model-based design package available as a toolbox in MATLAB™. A picture of the model is shown in Fig. 10. The left portion of the model creates the chirped signals. A repeating sequence and discrete-time voltage controlled oscillator (VCO) are used to assure coherence from pulse to pulse. The centre frequency changed for each filter, but the structure of the signal, bandwidth, and pulse width remained as described in the tables. The waveforms for each filter are otherwise identical to the ones described in Tables 1 and 2. The FDA tool block is the IF filter for a given radar, and can be easily changed to simulate different systems. The filters used in this simulation were created from actual spectrum analyser data. The first filter tested was based on that shown in Fig. 1 (although shifted down in frequency to 60 MHz to speed up processing), to compare theoretical results with measured results. The measured IF filters from three other radars were also used in the simulation. The right-hand portion of the model is used for plotting the data on screen (in power versus time format) and saving it to a MATLAB™ file for later processing. The power versus time format was used since this is the format of the data collected from the spectrum analyser.

It must be noted that by using the discrete-time VCO, the high frequency edge of each pulse was sometimes rounded off due to lack of frequency resolution. This only caused minor errors in the results. The simulation included 4 pulses of each waveform, and the second pulse was used for comparison. This allowed the simulation to not have any zeros once noise was added (at the start or end of the simulation) and prevented large negative values once power was calculated.

FIGURE 10

MATLAB™ Simulink™ model used for the effective duty cycle simulation



The simulated responses of IF filter 1 to the EESS and radiolocation systems are shown in Table 4. It must be noted that the filter was shifted down to a 60 MHz centre frequency for this simulation. Table 4 shows that the simulated –6 dB pulse width has a difference of less than 0.85 µs for each waveform, and that the simulation overestimates the measured pulse width in each case. Plots for the time domain pulses are shown in Figs. 11 through 17, with power versus time. The simulated results show more detail in the time domain than the actual measurements, which are taken as zero-span spectrum analyser data in a measurement bandwidth. For example, in Fig. 15 (simulated filtered pulse), the spurious signal indicated in Fig. 1 (IF filter shape) is clearly visible, as is the overall IF filter shape. However, in the actual measurement, shown in Fig. 7, this spurious signal is not present. These results show that the simulation leads to a slightly pessimistic prediction (larger pulse width than actually measured) of how the actual IF filter would operate with the test waveforms. Therefore the simulation tool can predict a good worst-case estimate of the EESS and radiolocation system pulse width when no actual measurements are taken.

TABLE 4

Measured versus simulated –6 dB pulse widths for IF filter 1 (Fig. 1)

System waveform	Measured pulse width (µs) at detector/processor	Simulated pulse width (µs) at detector/processor	Difference (µs)
Radiolocation 1	5.1	5.95	0.85
Radiolocation 2	1.0	1.24	0.24
Radiolocation 3	0.20	0.22	0.02
EESS 1	0.20	0.24	0.04
EESS 2	1.0	1.24	0.24
EESS 3	1.2	1.37	0.17
EESS 4	0.20	0.22	0.02

FIGURE 11

Radiolocation system waveform 1 in IF filter 1 (Fig. 1)

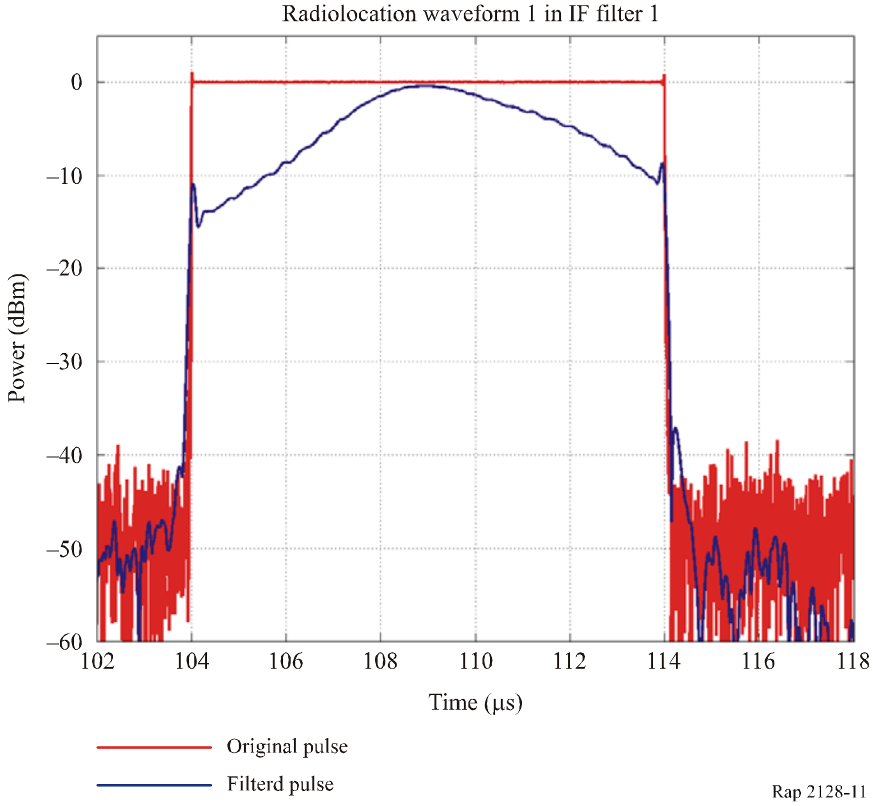


FIGURE 12
Radiolocation system waveform 2 in IF filter 1 (Fig. 1)

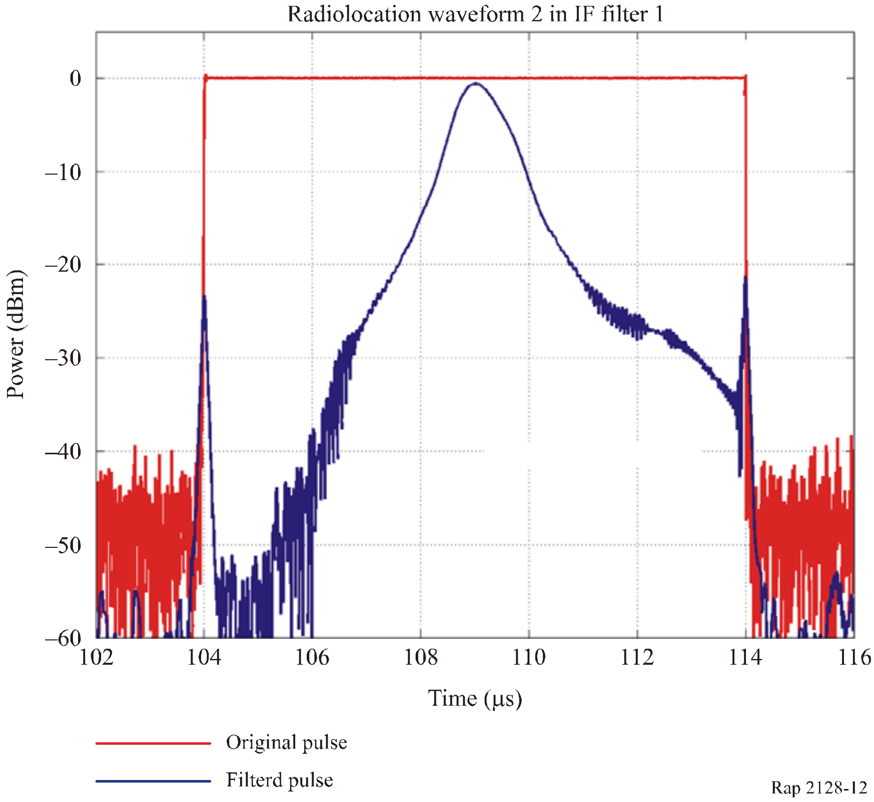


FIGURE 13
Radiolocation system waveform 3 in IF filter 1 (Fig. 1)

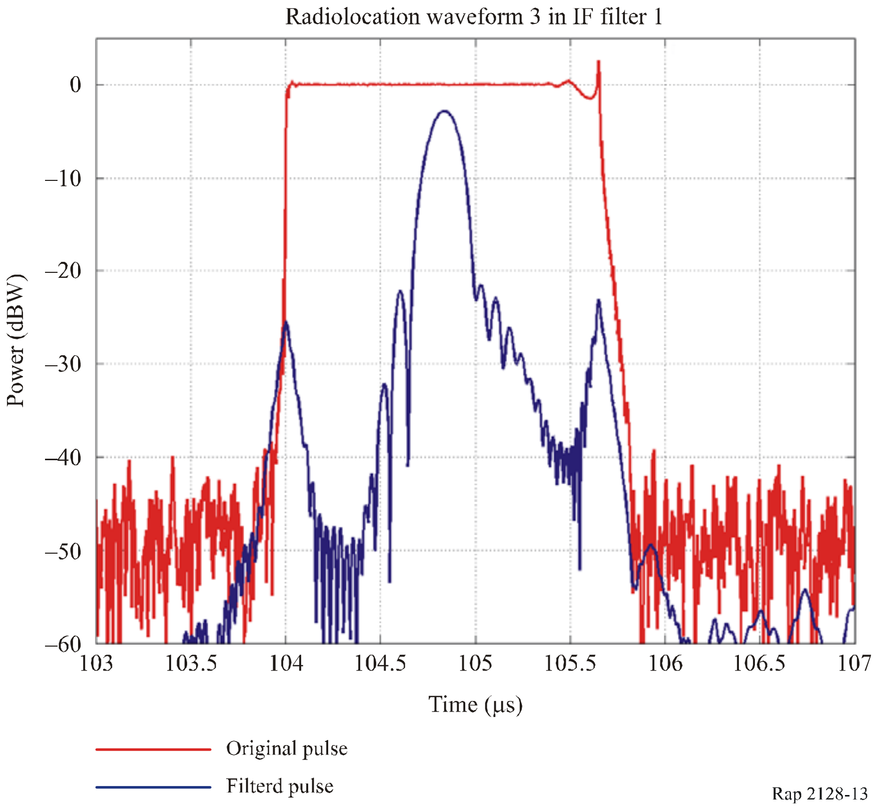


FIGURE 14

EESS system waveform 1 in IF filter 1 (Fig. 1)

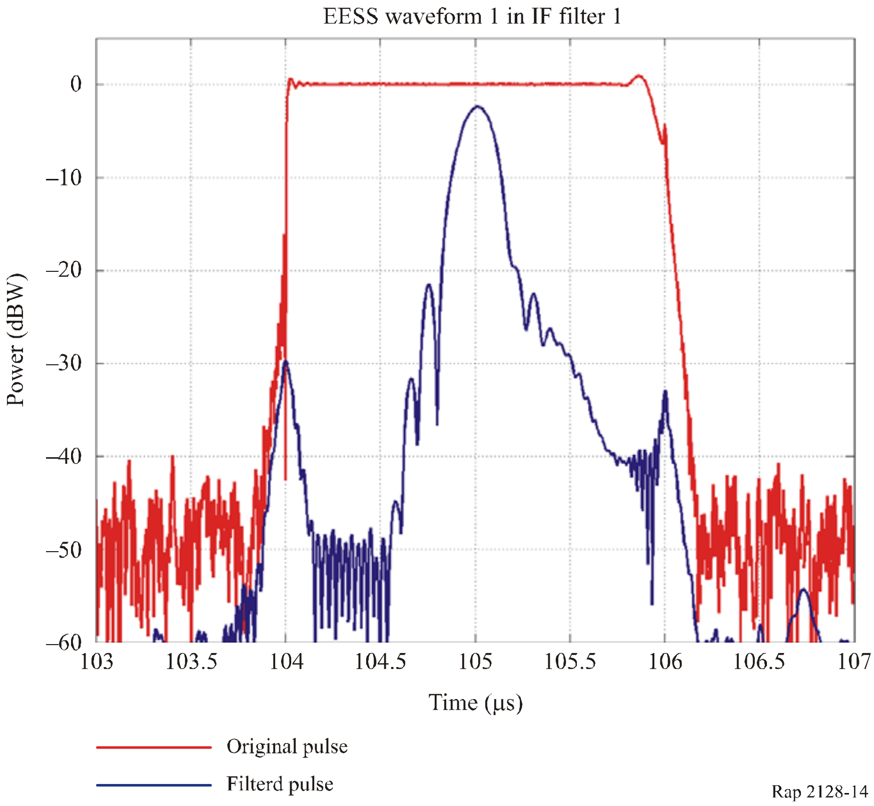


FIGURE 15

EESS system waveform 2 in IF filter 1 (Fig. 1)

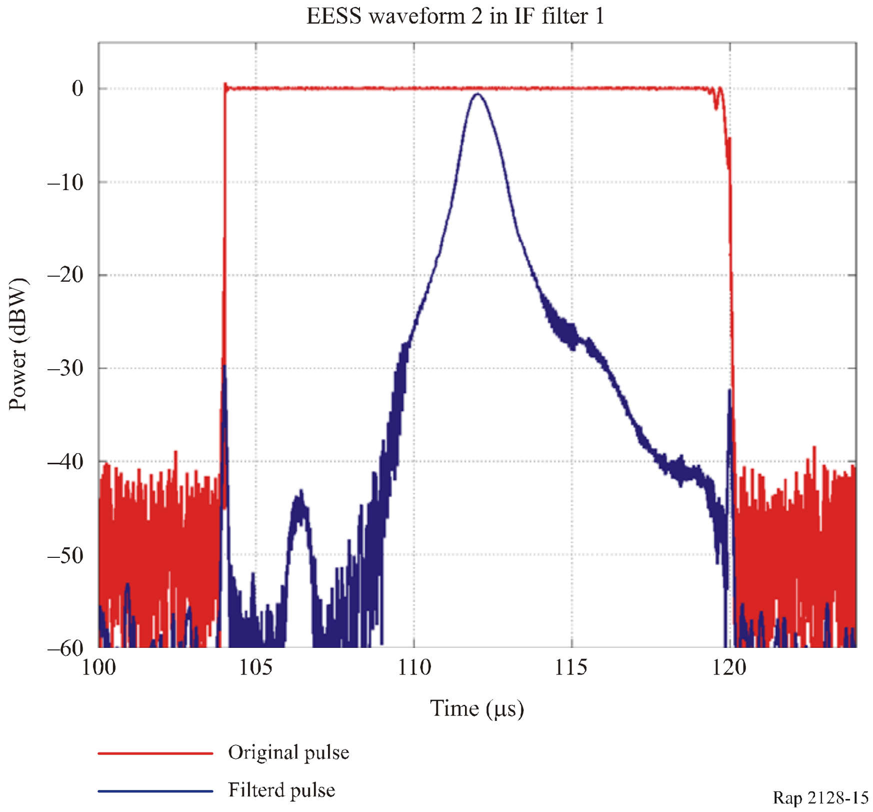
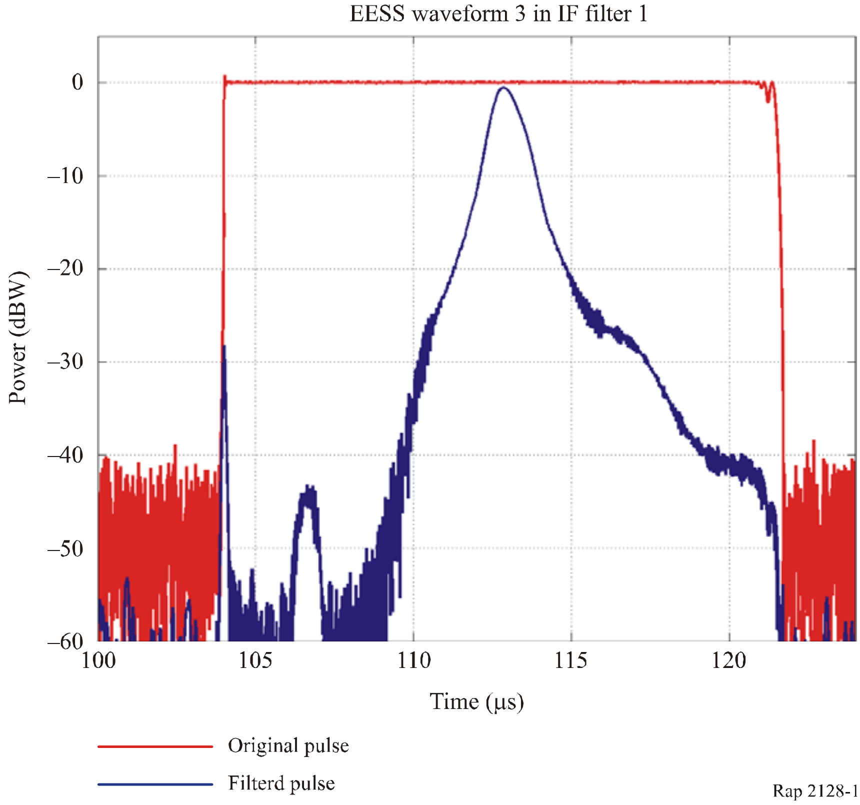


FIGURE 16

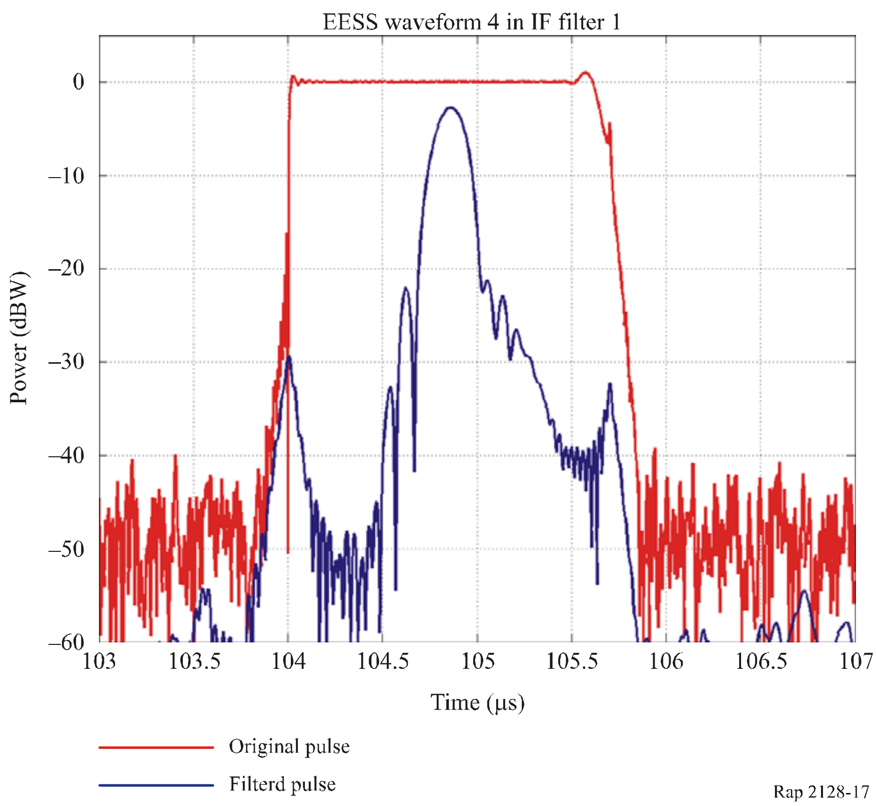
EESS system waveform 3 in IF filter 1 (Fig. 1)



Rap 2128-16

FIGURE 17

EESS system waveform 4 in IF filter 1 (Fig. 1)



Rap 2128-17

For simulation only with the EESS and radiolocation systems, measured IF filter responses for three other radars were available. These IF filters, shown in Figs. 18 though 20 represent two marine radionavigation radars operating in the band 2 900-3 100 MHz one operating in the 10 GHz band, respectively. The centre frequency of each filter has been shifted down to accommodate the simulation. The results of the simulation for each IF filter with the EESS and radiolocation systems are summarized in Table 5, and one sample plot for each filter's response is shown in Figs. 21 through 23.

FIGURE 18
IF filter 2, S-band radar

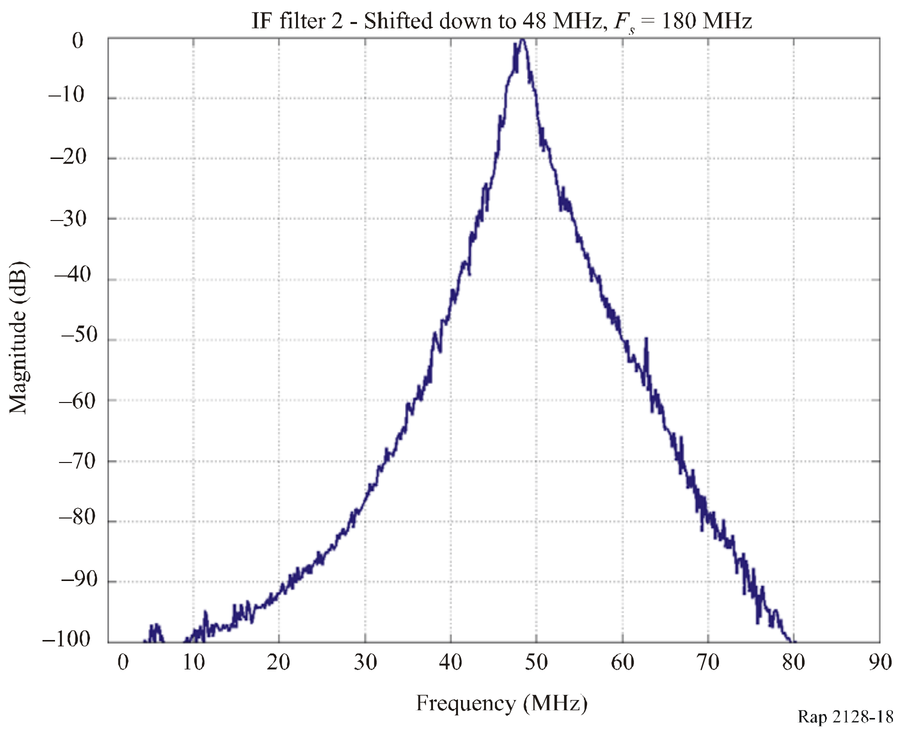


FIGURE 19
IF filter 3, S-band radar

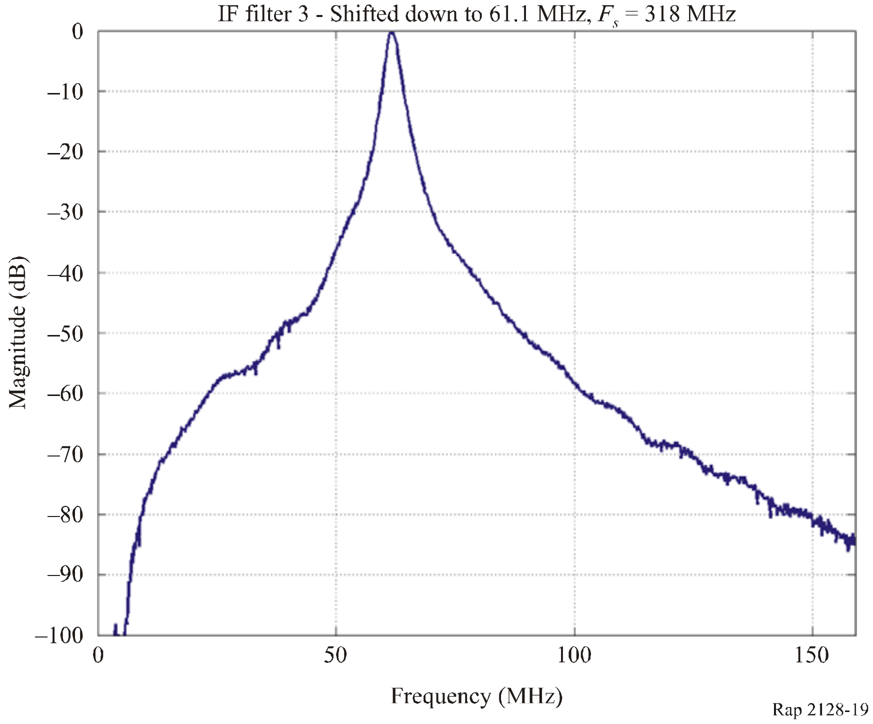


FIGURE 20
IF filter 4, X-band radar

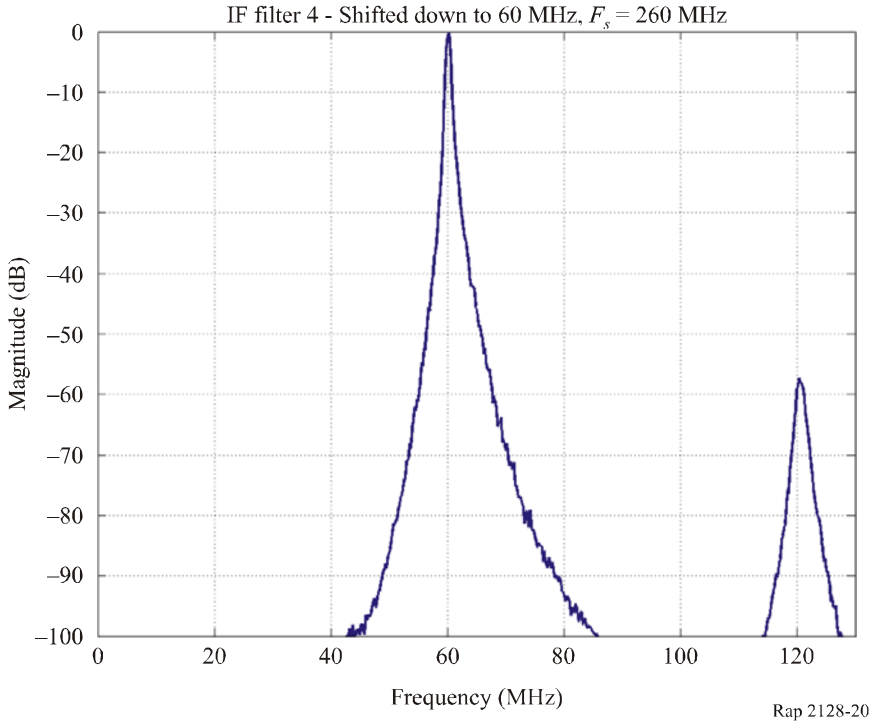


TABLE 5

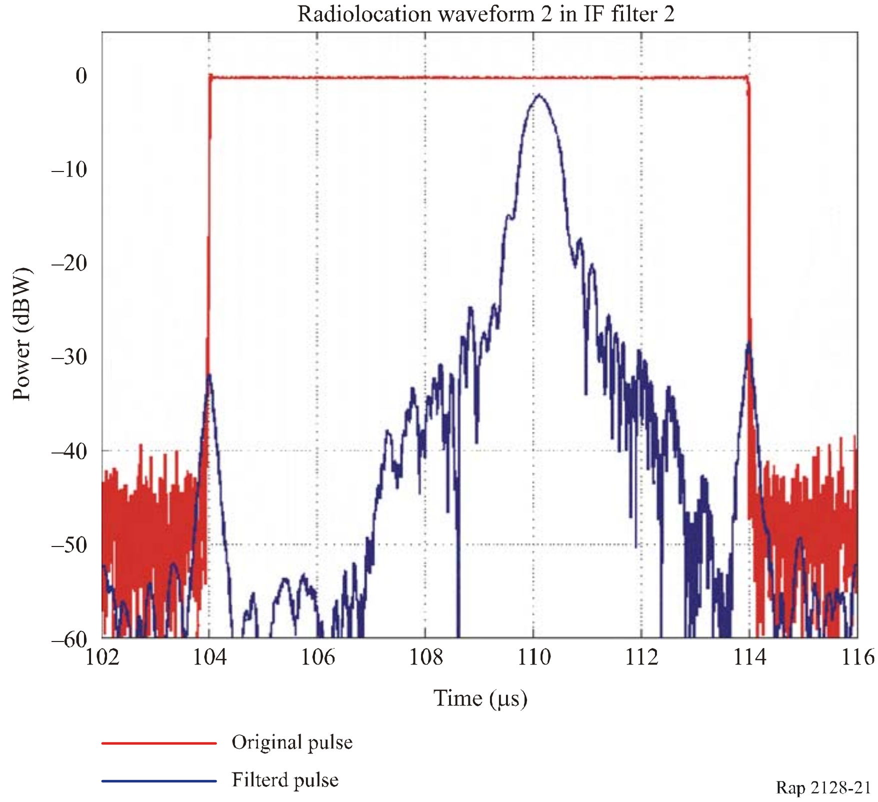
Simulated –6 dB pulse widths for IF filters 2 through 4

System waveform	IF filter 2 Simulated pulse width at detector/processor (µs)	IF filter 3 Simulated pulse width at detector/processor (µs)	IF filter 4 Simulated pulse width at detector/processor (µs)
Radiolocation 1	1.24	NA(1)	NA(1)
Radiolocation 2	0.73	0.62	0.88
Radiolocation 3	0.26	0.29	0.81
EESS 1	0.27	0.30	0.78
EESS 2	0.73	0.68	0.88
EESS 3	0.78	0.72	0.90
EESS 4	0.26	0.29	0.82

(1) This filter reduced the waveform amplitude to the noise level, and showed no pulse shape except at the beginning and end of the pulse. Therefore, no estimate of pulse width was available.

In all cases, the simulated pulse width at the radar detector/processor is less than the width of the transmitted pulse. As in the case of IF filter 1, this reduces the effective duty cycle of the EESS and radiolocation systems, which allows their interference reduction circuitry/processing to better mitigate their effects.

FIGURE 21
Radiolocation system waveform 2 in IF filter 2



Rap 2128-21

FIGURE 22
EESS system waveform 2 in IF filter 3

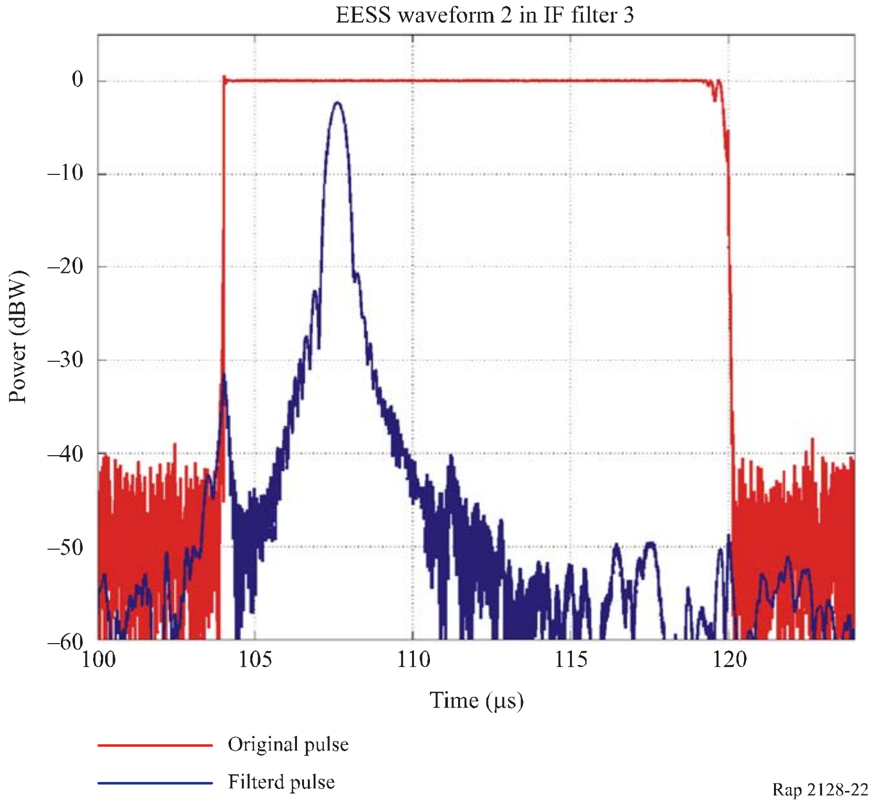
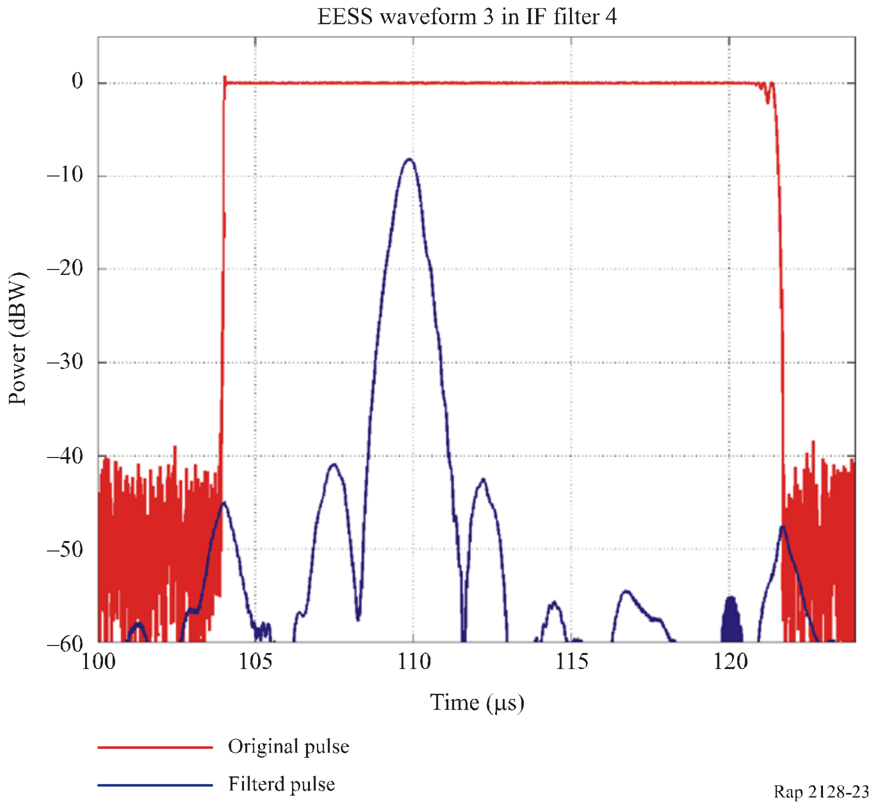


FIGURE 23
EESS system waveform 3 in IF filter 4



7 Conclusions

The measured results show that due to the chirping of the radiolocation and EESS systems and the response of the radar receiver, the effective duty cycles and pulse width of the waveforms at the radar's detector/processor input have been reduced to a value much lower than the *transmitted* waveforms. The simulated results show that the MATLAB™ based simulation shows good agreement with the measured results of effective pulse width. For EMC analyses, this allows the effective pulse width of a chirped signal in a radar receiver's IF circuitry to be accurately predicted. The model allows for actual IF data or user-designed filters, to be used as inputs so that radar designers can evaluate the performance of their interference rejection capabilities in the presence of these types of waveforms.