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Simulation of W-band Frequency-Modulated Continuous-Wave (FMCW) Radar Signal Processing

by Jose Avila

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CCDC Data & Analysis Center

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14. ABSTRACT Frequency-modulated continuous-wave radars operate by sweeping the signal frequency and calculating distance from the echo of a target. Two situations are explored in this report: 1) the maximum distance the operating radar can be picked up by a receiver and 2) what jamming power is needed for the signal processing to not have detections. The distance is calculated analytically, while the jamming power is done through simulation by incorporating jammer noise to the radar signal processing.			
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1. Introduction

1.1 Background

1.1.1 Frequency-Modulated Continuous-Wave Radar (FMCW)

FMCW radars operate by sending out a continuous-wave signal while modulating the frequency, usually a linear frequency modulation. During operation, the emitted wave first strikes the target then rebounds back to the radar, where it is processed. These radars use two antennas, one to transmit the continuous wave and one that receives the echo return from the target. The FMCW radar has a sweep time and specific bandwidth from which it modulates. The radar begins operating at a start frequency and ramps up to a specific stop frequency in a certain period of time. This waveform is capable of repeating in either up-chirp pattern, down-chirp pattern, or up-down-chirp.

1.1.2 Radar Signal Processing

The echo received from a wave bouncing off a target will be a time-delayed replica of the transmitted signal. After receiving the echo from the target, the radar will process it to acquire information about the target. The processing is typically done in two stages. The first will frequency shift the signal to the baseband and identify the difference in frequency between the original signal and the echo. In the second stage the information from the first stage is used to calculate the range of the target. FMCW radars mix the incoming signal with the original signal to de-chirp it, then apply a Fourier transform to get the beat frequency. The beat frequency, f_b, is the difference in frequency between the transmitted and received signals. The range of the target is proportional to the beat frequency. Figure 1 shows the spectrogram of the FMCW waveform and its echo; the echo is delayed by Δt and the difference in frequency is the f_b.

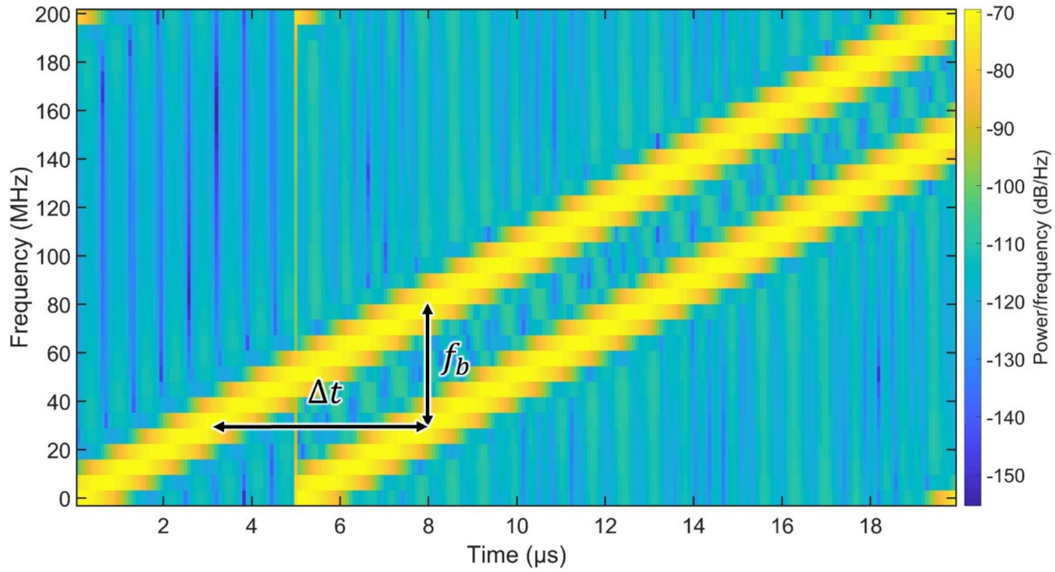

Fig. 1 Linear chirp and the echo

1.1.3 Jamming

Jamming can be accomplished by introducing noise into the incoming echo return received by the radar. This noise will introduce errors to the signal processing of the radar. With enough noise the signal from the target will become indistinguishable from the background noise. The ratio of the original signal to the noise introduced is simply known as signal-to-noise (SNR) ratio and is typically presented in decibels (dB).

1.2 Purpose and Payoff

The purpose of this report is to assess the front end of a W-band FMCW radar through simulation. The simulations will include a study of jamming levels through varying the SNR. Specifically, the jamming introduced in simulation for this report is additive white Gaussian noise. The simulation will only consider the signal-processing portion of the FMCW radar. The transmitter amplifier and the receiver low-noise amplifier are not included in the results of the simulation runs.

2. Methodology

2.1 Block Diagram

Figure 2 shows a block diagram of the flow for simulation of the radar signal processing.

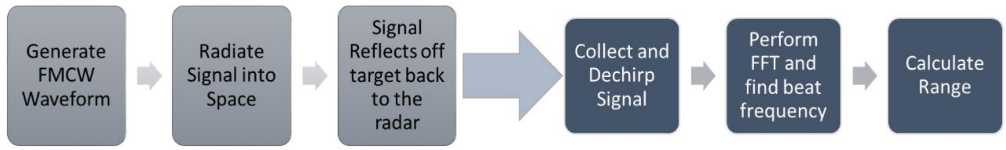

Fig. 2 Block diagram of simulation

The simulation was performed in MATLAB using the Phased Array System Toolbox. First the FMCW signal is created, and then the signal is propagated through space, strikes the target, and is reflected back. A target model that takes into consideration the radar cross section (RCS), distance, and velocity of a target is used to compute the reflected signal. The radar's transmitter and receiver consist of a typical dish antenna. The received signal is de-chirped and saved into a buffer. Once a predetermined number of sweeps fill the buffer (64 sweeps were used for the simulations in this report) a Fourier transform is performed to find the beat frequency. From the beat frequency the range of the target is then derived.

2.2 W-band Radar

The operating frequency for the radar in simulation was $f_c = 94$ GHz, the sweep time used was $t_m = 20$ µs, and a sweep bandwidth of 200 MHz was used. This simulation assumed both transmit and receive antennas were identical dish antennas with 11-inch diameters. Line of sight (LOS) was assumed for all presented results. Two different transmit power levels were used, 24 and 26 dBm. A linear FMCW radar with maximum modulation frequency of 200 MHz was used for the simulations presented in this report. Figure 3 shows the FMCW waveform, in this case a linear chirp, and Fig. 4 shows the spectrogram of the waveform, which has a clearer picture of the linear frequency modulation.

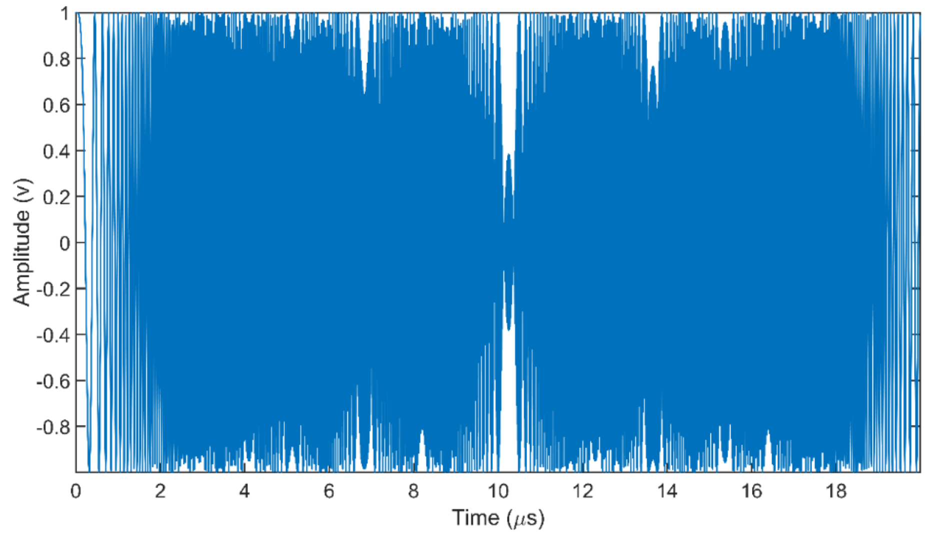

Fig. 3 FMCW waveform

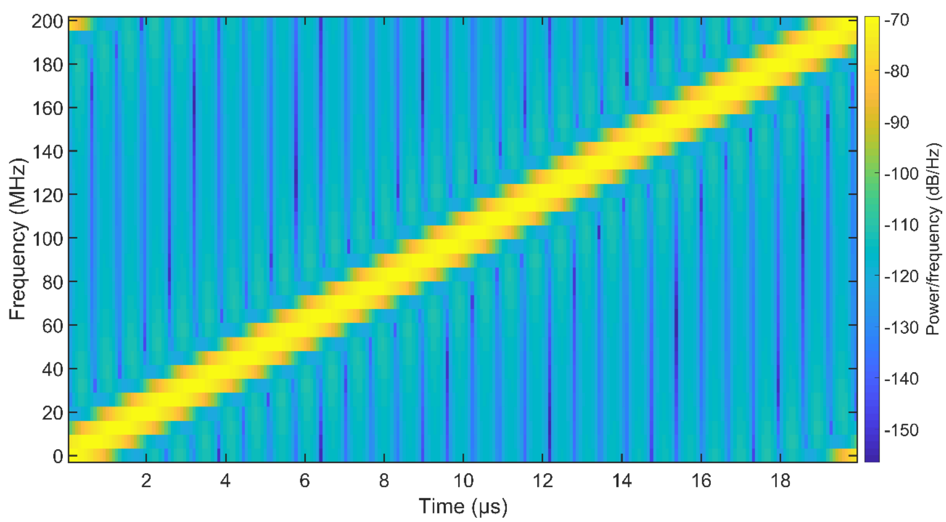

Fig. 4 Spectrogram of FMCW waveform

3. Results

3.1 Range for Detecting the Radar

When transmitted, the waveform travels through a medium, in this case air, and has a specific range limit from which the signal is able to be detected via open air frequency monitoring. As the signal travels, it attenuates, and this is known as the free space path loss (FSPL). In a controlled test environment, such as an anechoic chamber, the detection distance can be found using a receiver in combination with an attenuator to simulate the path loss versus distance. The link budget is an accounting for gains and losses from the transmitter to the receiver through the media. A simple link budget equation is as follows:

$$Received\ Power(dB) = Transmitted\ Power(dB) + Gains(dB) - Losses(dB). \quad (1)$$

The calculations performed here will be the distance for a receiver with a sensitivity or power received of $P_r = -90$ dBm. The transmitter antenna gain was calculated from the following equation for a dish antenna:

$$G_T = A_E \left(\frac{d\pi}{\lambda}\right)^2, \quad (2)$$

where A_E is the antenna efficiency, with a standard value usually ranging from 0.5 to 0.6, and d is the diameter of the dish and chosen to be 8 inches. The calculated gain with an antenna efficiency of 0.55 is $G_T = 43$ dB. The dimensions were picked from a search for dish antennas at a frequency of 94 GHz, found from mWAVE Industries, but the gain was calculated using those dimensions and a generic gain calculator. To calculate the maximum range at which a receiver can detect the transmitter, in this case the W-band radar, with LOS conditions, first the FSPL must be found from Eq. 1:

$$P_r = P_T + G_T - FSPL. \quad (3)$$

Solving for FSPL yields

$$FSPL = P_T + G_T - P_r. \quad (4)$$

Figure 5 shows the conditions for this calculation in LOS: a receiver antenna monitoring.

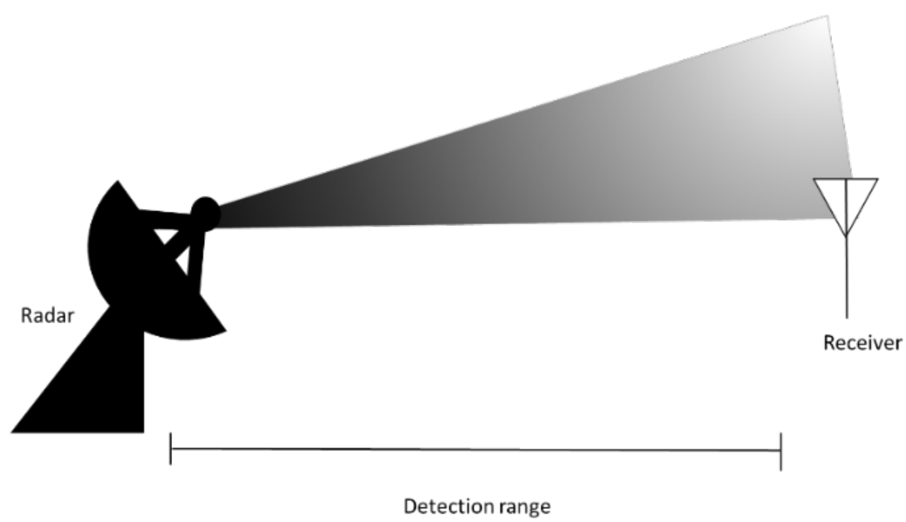

Fig. 5 Radar and listening receiver

The distance can be calculated from the FSPL with the following equation:

$$FSPL = 20\log(R) + 20\log(f_c) + 20\log\left(\frac{4\pi}{c}\right), \qquad (5)$$

where R is the distance, $f_c = 94$ GHz is the center frequency, and c is the speed of light. Solving Eq. 5 for distance gives

$$R = 10\hat{}\left(\left(FSPL - 20\log(f_c) - 20\log(\frac{4\pi}{c})\right)/20\right). \qquad (6)$$

Two different transmitted power levels were used: $P_T = 24$ dBm and $P_T = 26$ dBm. Three transmitter gains were explored: $G_T = 37$ dB, $G_T = 0$ dB, and $G_T = 43$ dB. Plugging these values into Eqs. 4 and 6 yields the values shown in Table 1 for the maximum detection range for a receiver to pick up the radar transmission for LOS conditions.

Table 1 Maximum detection range with LOS conditions

Transmitted power (dBm)	Transmitter gain (dB)	FSPL (dB)	Maximum detection range (km)
24	37	151	9
26	37	153	11.3
24	40	154	12.7
26	40	156	16
24	43	157	18
26	43	159	22.6

3.2 Jamming Simulation

The W-band radar signal processing was simulated, and jamming was introduced to the simulation via additive white Gaussian noise. The simulation was performed using MATLAB with the Phased Array System Toolbox. The simulation was performed for two different power levels, 24 and 26 dBm. The target RCS was also varied from –30 to +20 dBsm, and the range varied from 10 to 300 m. Figure 6 shows the process for the simulation, similar to Fig 2.

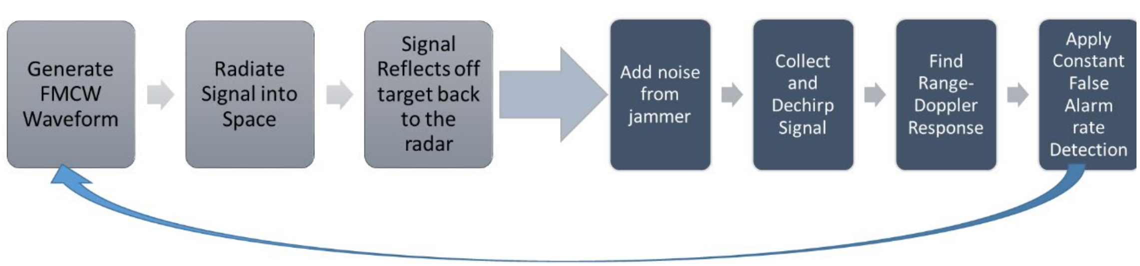

Fig. 6 Block diagram of signal processing simulation

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First, the waveform is generated, propagated through space, and reflected off a target. Next, jamming is added by adding white Gaussian noise to the signal, and the signal is de-chirped. Then the Range-Doppler response is calculated. If there is no jamming, the response will look similar to Fig. 7, which shows the Range-Doppler response for a target 40 m away, with a velocity of 20 m/s and an RCS of 10 dBsm. The Doppler frequency is the frequency shift of the signal caused by the target. The radar simulated in Fig. 7, as well as subsequent data, used a transmitted power of 26 dBm, antenna gain of 43 dB, and operating frequency of 94 GHz, as mentioned previously. The target can be visualized in the response as a bright yellow spot that corresponds to 40 m.

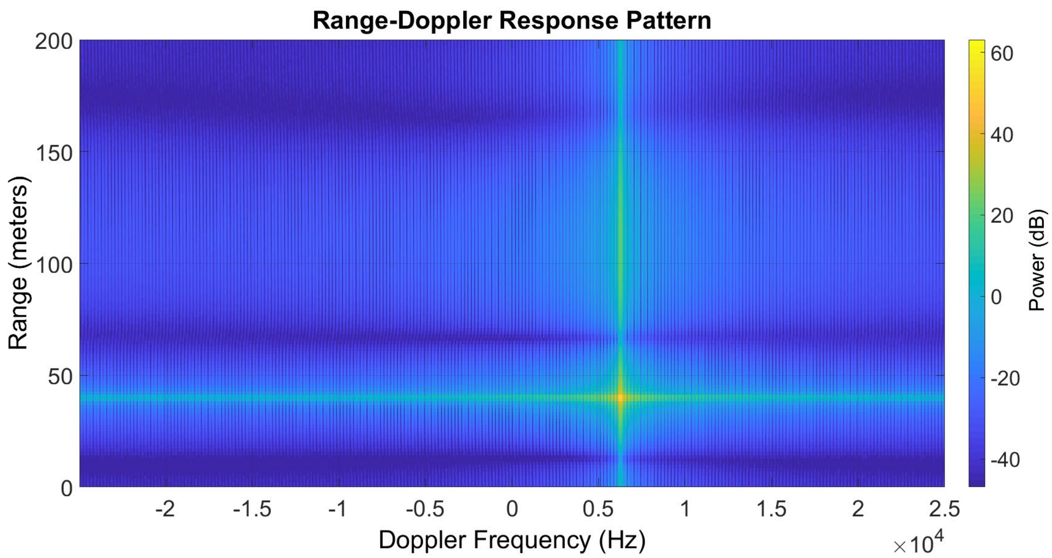

Fig. 7 Range-Doppler response with no jammer present

Introducing jamming will bring up the background noise, which is shown in Fig. 8. The SNR at the radar in Fig. 8 is 0 dB, which means that at the radar the signal power from the wave reflecting from the target and the jammer power are equal. The radar is still able to discern the target, and thus more power from the jammer will be needed to drown the signal and make it indistinguishable.

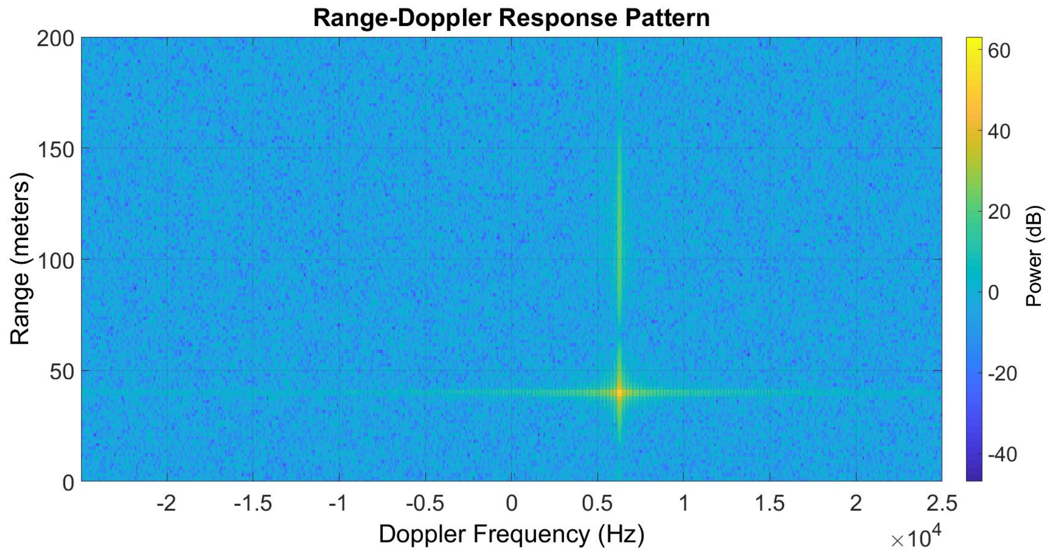

Fig. 8 Range-Doppler response with jamming, SNR = 0 dB

In Fig. 9 the jamming power is turned up so the SNR has degraded to –50 dB. Now the target is indistinguishable from the noise. Constant false alarm rate (CFAR) detection was used to process the Range-Doppler response and find if targets were detected. CFAR performs cell averaging on the response to find targets. A probability of false alarm from the example of 10^{-5} was used with CFAR detection. The SNR was degraded by increasing the jamming power until CFAR would not have any detections in order to find the threshold for how much jamming power was required. Once this threshold was found, the RCS was changed and the process repeated. These simulations were repeated 100 times and the result averaged. The findings were that the threshold when transmitting with 24 dBm was an SNR of –43 dB at the radar. For 26 dB, the threshold was –44 dB, so any SNR less than –44 dB would make the signal from the target indistinguishable from noise. Tables 2–13 show the jamming power needed at different distances and for different targets to achieve the threshold SNR. The signal power is the echo from the target.

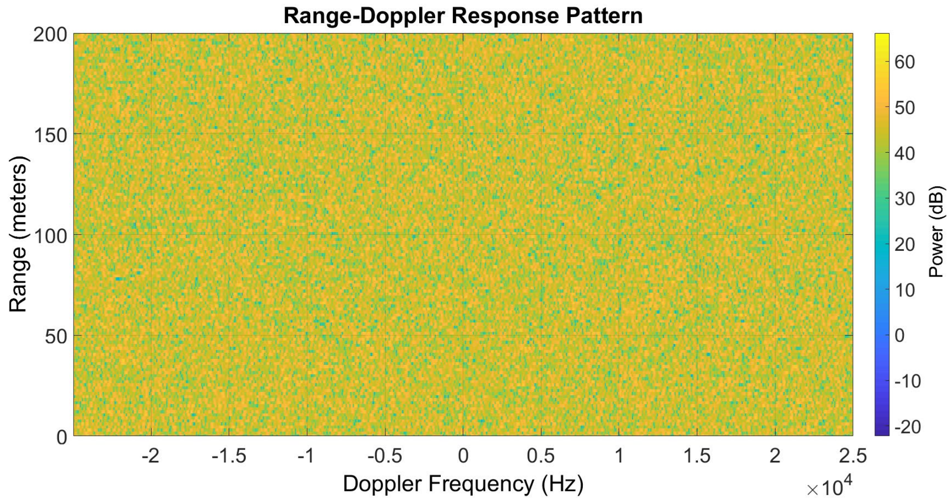

Fig. 9 Range-Doppler response with jamming, SNR = –50 dB

Table 2 Simulation with transmitted power (Tx) = 24 dBm, target RCS = 20 dBsm, and SNR = –43 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–53.7	–10.7
40	–65.4	–22.4
60	–70.5	–27.5
80	–78.0	–35.0
100	–80.9	–37.9
120	–83.1	–40.0
140	–87.8	–44.8
160	–88.6	–45.6
180	–90.6	–47.6
200	–94.1	–51.1
220	–93.7	–50.7
240	–96.0	–53.0
260	–98.5	–55.5
280	–97.3	–54.3
300	–100.3	–57.3

Table 3 Simulation with Tx = 24 dBm, target RCS = 10 dBsm, and SNR = –43 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–63.7	–20.7
40	–75.4	–32.4
60	–80.5	–37.5
80	–88.0	–45.0
100	–90.9	–47.9
120	–93.1	–50.1
140	–97.8	–54.8
160	–98.6	–55.6
180	–100.6	–57.6
200	–104.1	–61.1
220	–103.7	–60.7
240	–106.0	–63.0
260	–108.5	–65.5
280	–107.4	–64.4
300	–110.3	–67.3

Table 4 Simulation with Tx = 24 dBm, target RCS = 0 dBsm, and SNR = –43 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–73.7	–30.7
40	–85.4	–42.4
60	–90.5	–47.5
80	–98.0	–55.0
100	–100.9	–57.9
120	–103.1	–60.1
140	–107.1	–64.1
160	–108.6	–65.6
180	–110.6	–67.6
200	–114.1	–71.1
220	–113.7	–70.7

Table 4 Simulation with Tx = 24 dBm, target RCS = 0 dBsm, and SNR = –43 dB at receiver (continued)

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
240	–116.0	–73.0
260	–118.5	–75.5
280	–117.4	–74.4
300	–120.3	–77.3

Table 5 Simulation with Tx = 24 dBm, target RCS = –10 dBsm, and SNR = –43 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–83.7	–40.7
40	–95.4	–52.4
60	–100.5	–57.5
80	–108.0	–65.0
100	–110.9	–67.9
120	–113.1	–70.1
140	–117.8	–74.8
160	–118.6	–75.6
180	–120.6	–77.6
200	–124.1	–81.1
220	–123.7	–80.7
240	–126.0	–83.0
260	–128.5	–85.5
280	–127.4	–84.4
300	–130.3	–87.3

Table 6 Simulation with Tx = 24 dBm, target RCS = –20 dBsm, and SNR = –43 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–93.7	–50.7
40	–105.4	–62.4
60	–110.5	–67.5
80	–118.0	–75.0
100	–120.9	–77.9
120	–123.1	–80.1
140	–127.8	–84.8
160	–128.6	–85.6
180	–130.6	–87.6
200	–134.1	–91.1
220	–133.7	–90.7
240	–136.4	–93.4
260	–138.5	–95.5
280	–137.4	–94.4
300	–140.3	–97.3

Table 7 Simulation with Tx = 24 dBm, target RCS = –30 dBsm, and SNR = –43 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–103.7	–60.7
40	–115.4	–72.4
60	–120.5	–77.5
80	–128.0	–85.0
100	–130.9	–87.9
120	–133.1	–90.1
140	–137.8	–94.8
160	–138.6	–95.6
180	–140.6	–97.6
200	–144.1	–101.1
220	–143.7	–100.7
240	–146.0	–103.0
260	–148.5	–105.5
280	–147.4	–104.4
300	–150.3	–107.3

Table 8 Simulation with Tx = 26 dBm, target RCS = 20 dBsm, and SNR = –44 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–51.7	–7.7
40	–63.4	–19.4
60	–68.5	–24.5
80	–76.0	–32.0
100	–78.9	–34.9
120	–81.1	–37.1
140	–85.8	–41.8
160	–86.6	–42.6
180	–88.6	–44.6
200	–92.1	–48.1
220	–91.7	–47.7
240	–94.0	–50.0
260	–96.5	–52.5
280	–95.4	–51.4
300	–98.3	–54.3

Table 9 Simulation with Tx = 26 dBm, target RCS = 10 dBsm, and SNR = –44 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–61.7	–17.7
40	–73.4	–29.4
60	–78.5	–34.5
80	–86.0	–42.0
100	–88.9	–44.9
120	–91.1	–47.1
140	–95.8	–51.8
160	–96.7	–52.7
180	–98.6	–54.6
200	–102.1	–58.1
220	–101.7	–57.7
240	–104.0	–60.0
260	–106.5	–62.5
280	–105.4	–61.4
300	–108.3	–64.3

Table 10 Simulation with Tx = 26 dBm, target RCS = 0 dBsm, and SNR = –44 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–71.7	–27.7
40	–83.4	–39.4
60	–88.5	–44.5
80	–96.0	–52.0
100	–98.9	–54.9
120	–101.1	–57.1
140	–105.8	–61.8
160	–106.6	–62.6
180	–108.6	–64.6
200	–112.1	–68.1
220	–111.7	–67.7
240	–114.0	–70,0
260	–116.5	–72.5
280	–115.4	–71.4
300	–118.3	–74.3

Table 11 Simulation with Tx = 26 dBm, target RCS = –10 dBsm, and SNR = –44 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–81.7	–37.7
40	–93.4	–49.4
60	–98.5	–54.5
80	–106.0	–62.0
100	–108.9	–64.9
120	–111.1	–67.1
140	–115.8	–71.8
160	–116.6	–72.6
180	–118.6	–74.6
200	–122.1	–78.1
220	–121.7	–77.7
240	–124.0	–80.0
260	–126.5	–82.5
280	–125.4	–81.4
300	–128.3	–84.3

Table 12 Simulation with Tx = 26 dBm, target RCS –20 dBsm, and SNR = –44 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–91.7	–47.7
40	–103.4	–59.4
60	–108.5	–64.5
80	–116.0	–72.0
100	–118.9	–74.9
120	–121.1	–77.1
140	–125.8	–81.8
160	–126.6	–82.6
180	–128.6	–84.6
200	–132.1	–88.1
220	–131.7	–87.7

Table 12 Simulation with Tx = 26 dBm, target RCS = –20 dBsm, and SNR = –44 dB at receiver (continued)

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
240	–134.0	–90.0
260	–136.5	–92.5
280	–135.4	–91.4
300	–138.3	–94.3

Table 13 Simulation with Tx = 26 dBm, target RCS = –30 dBsm, and SNR = –44 dB at receiver

Distance (m)	Signal power at radar (dBm)	Jammer power at radar (dBm)
20	–101.7	–57.7
40	–113.4	–69.4
60	–118.5	–74.5
80	–126.0	–82.0
100	–128.9	–84.9
120	–131.1	–87.1
140	–135.8	–91.8
160	–136.6	–92.6
180	–138.6	–94.6
200	–142.1	–98.1
220	–141.7	–97.7
240	–144.0	–100.0
260	–146.5	–102.5
280	–145.4	–101.4
300	–148.3	–104.3

4. Conclusions

Simulations of a W-band FMCW radar's signal processing were performed in MATLAB to find the effect and threshold for noise jamming. The maximum detection distance for being able to monitor the signal from the radar was found analytically. The signal processing for the W-band radar simulated was found to be jammed with a threshold SNR less than –44 dB. These simulations omit any pre-amplifier or low-noise amplifier as well as countermeasures to the jamming; for example, antenna-based interference such as sidelobe blanking, adaptive beamforming, or signal-processing-based interference estimation and suppression.

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List of Symbols, Abbreviations, and Acronyms

CFAR	constant false alarm rate
dB	decibel
FMCW	frequency-modulated continuous-wave
FSPL	free space path loss
LOS	line of sight
RCS	radar cross section
SNR	signal-to-noise ratio
Tx	transmitted power

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