Numerical Computation of the Radar Cross Section of a 120-mm Mortar

by Christopher S Kenyon and Traian Dogaru

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Numerical Computation of the Radar Cross Section of a 120-mm Mortar

by Christopher S Kenyon and Traian Dogaru

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This report investigates the modeling of radar scattering from a 120-mm mortar target in 4 radar frequency bands, L, S, C, and X, in a continuation of a previous report on radar cross-section (RCS) modeling of rockets and an artillery round. RCS calculations are performed by 2 different methods, implemented by the FEKO and AFDTD electromagnetic simulation software packages, over all the possible aspect angles. The solutions obtained by the 2 methods are compared for accuracy validation. The RCS analysis includes prediction of the variation with frequency and the azimuth angle, as well as a comparison among the 4 frequency bands of interest. The results indicated RCS returns slightly lower than the previously reported targets but still fairly close. No band stood out with stronger returns. The target signatures calculated in this study are an important tool for the radar engineers in system performance evaluation.
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1. Introduction

The US Army is interested in the radar detection and tracking of artillery rounds grouped under the generic category of rockets, artillery, and mortar (RAM). One important step in the radar system design consists of analyzing the radar cross section (RCS) of the targets of interest. The electromagnetic (EM) modeling team at the US Army Research Laboratory (ARL) has developed capabilities for modeling the radar signature of a wide variety of targets, using multiple numerical EM simulation methods. In this report, we apply 2 of these EM software packages, AFDTD\(^1\) and FEKO\(^2\), to the RCS calculation of a 120-mm mortar round in a continuation of the work reported in a previous ARL technical report.\(^3\) The reader is referred to this previous report for extended details about this current work.

The computer model of the mortar round was created from pictures and drawings available on public websites and does not contain all the small details of the mortar such as the propellant mounts. The analysis does contain all features relevant to our phenomenological study.

As stated in the preceding ARL technical report the goals are the following:

- Evaluate the RCS of the mortar round in the L, S, C, and X radar bands and compare their magnitudes across the bands. In all cases, the RCS is computed with respect to the aspect angle, with the target placed in a standard (upright) orientation.

- Assess the accuracy of the simulations by AFDTD and FEKO for this target, in the frequency bands of interest.

- Quantify the variation of the target RCS for small frequency deviations within the radar bands already mentioned. This analysis is useful for a radar system that uses frequency agility.

- Study the variation of the target RCS with the azimuth angle for targets that cannot be described as rotationally symmetric. This is the case of the mortar.

Both of the RCS calculation techniques, used by AFDTD and FEKO here, are advanced exact computational EM solvers as opposed to approximate solvers often used in the past. The validated AFDTD software was developed in-house at ARL and uses the finite-difference time-domain algorithm. We used a surface integral solver, Method of Moments, in the commercial FEKO software to assess the accuracy of the AFDTD results.

This report is broken into 5 more sections. In Section 2 we describe the mortar target. Section 3 compares the AFDTD and FEKO results. Section 4 shows the
variations of RCS among the 4 frequency bands of interest as well as variations of RCS within the bands. Section 5 looks at RCS variation with azimuth angle and Section 6 presents conclusions.

2. Description of the 120-mm Mortar Round

A computer model of our chosen 120-mm mortar round is shown in Fig. 1. The 120 mm is a common mortar bore diameter and there are many types of ammunition rounds for it from different countries and manufacturers. We have given the fins a thickness of 4 mm. Judging by surveying web images of mortar rounds, the one we have chosen is fairly typical, but the designs can vary in length and somewhat in shape. The body can have a fairly rounded shape or a more tubular shape. The nose can be longer and the fins are probably the most variable part. The fin number can be fewer than 10, but 10, as our mortar round has, is fairly common. The fin shapes can vary significantly, too. While the fin shape and dimensions may have an impact on the radar signature, we expect the mortar length and diameter to largely determine the target RCS.

![Fig. 1 FEKO computer model of 120-mm mortar round](image)

We have modeled the mortar as a perfect electric conductor (PEC) and oriented it vertically with tip up aligned with its axis on the Z-axis. In this way, using the spherical polar coordinate convention, the radar incidence angle is measured by the polar angle, \( \theta \), from the Z-axis. Azimuth variations were computed with the incidence varying in the \( \phi \) direction about the Z-axis measured from the X-axis.
The polar incidence angle, $\theta$, was varied $0^\circ$ to $90^\circ$. Since the 10 fins were $36^\circ$ apart we computed all $\theta$ incidences with $\phi$ varied from $0^\circ$, along a fin, to $18^\circ$, between the fins. By this means, with both vertical and horizontal polarization, we covered the possible combination of incident angles for the mortar geometry, excepting incidence from its rear hemisphere.

The triangle mesh surface model of the mortar shown in Fig. 1 was created in the CADFEKO frontend of FEKO from web drawings. FEKO computed the RCS using this surface mesh. The triangle meshes for the model were then exported as STL files and imported into the ARL software, AFDTDGRID, to create a volumetric grid of small cubic cells for use with the AFDTD computations.

For this model we used FEKO’s “standard” meshing on a PC for each frequency so that the FEKO mesh triangles averaged $\lambda/12$ on a side, where $\lambda$ is the radar radiation wavelength. The AFDTD grid cell size was set at 1 mm to minimize any effects from stair stepping over the surface of the model. The previous report had confirmed that a 1-mm AFDTD grid size gave better results than a 2-mm grid. The AFDTD computation was done on ARL’s Excalibur high-performance computing (HPC) system using 32 cores for each incidence angle. With both the FEKO and AFDTD, computations produced both vertical-vertical (V-V) and horizontal-horizontal (H-H) polarized RCS that we analyze in this study. We focused on results for 4 specific frequencies, 1.3, 2.4, 5.6, and 9.5 GHz, to characterize the L-, S-, C-, and X-bands, respectively. Additionally, in some of the analysis we included frequencies $\pm 100$ MHz, at 50-MHz intervals about these frequencies, to cover the possibility of frequency hopping radar.

3. Comparison of FEKO and AFDTD RCS Predictions

In this section, we show the computed AFDTD and FEKO RCS results for the 120-mm mortar. Figure 2 shows both the RCS at both V-V and H-H polarizations for the L, S, C, and X frequency bands versus incidence angle $\theta$ for the 2 azimuth angles, $0^\circ$ and $8^\circ$. The latter angle was chosen as a sample of a radar return for a geometry not symmetrical about the incidence plane for our model with fins separated by $36^\circ$ in azimuth.

The results shown in Fig. 2 show a high level of agreement between the AFDTD and FEKO results, consistent with the earlier report that included a 107-mm rocket with fins had shown. Again, over most of the ranges agreement held to within 2 dB with a few nulls being some exceptions. Since the 3-dimensional (3D) cubic geometry of AFDTD and the triangular surface geometry for the FEKO model are slightly different representations of the mortar round, one would not necessarily expect nulls, whose position and depth would be highly sensitive to geometry and
therefore slightly different, to be exactly the same in the results. Mismatch in the higher frequency results shown in the C- and X-bands would again be more likely to occur as both methods lose some accuracy at those higher frequencies.

The RCS for this round shows little tendency to increase as the incidence angle goes from nose-on to broadside incidence, unlike the simulations for the artillery round and 107-mm rocket showed. This is likely due to the very limited cylindrical character of the mortar round body. Viewed from the side, it is bowed out in the middle and has only a short prolonged surface parallel to its axis in contrast to the earlier 155-mm artillery round and 107-mm rocket. For near broadside incidence, a V-V polarized radar beam would not have a long tube to excite in phase. The variable circumference length that an H-H polarized radar would excite would possibly induce returns not in phase, so that their received sum, or equivalently the H-H polarized RCS, would be diminished.

The VV radar return is 10 dB or more higher than the H-H return between 10° and 30° incidence from the nose. Possibly, this could be due to a surface wave being generated on parts of its surface along its length. Notice that the first RCS peak gets closer to 0° as the frequency increases, which is consistent with surface wave behavior. As we noted in the earlier report, we saw evidence of a surface wave return in the simulated time signature of the radar return for the 107-mm rocket and expect the same phenomenon to occur with the mortar round.
Fig. 2  RCS of the 120-mm mortar round vs. elevation angles, computed by AFDTD and FEKO software in 4 frequency bands: a) L-band, $\varphi=0^\circ$; b) L-band, $\varphi=8^\circ$; c) S-band, $\varphi=0^\circ$; d) S-band, $\varphi=8^\circ$; e) C-band, $\varphi=0^\circ$; f) C-band, $\varphi=8^\circ$; g) X-band, $\varphi=0^\circ$; and h) X-band, $\varphi=8^\circ$.
4. Variation of RCS with Frequency

In this part of our analysis, we look at the RCS variation with frequency for our chosen mortar round target. Specifically, we examine the variation the RCS within a 200-MHz band about the central frequency of our chosen bands. We computed RCS between 1.2 and 1.4 GHz for the L-band, between 2.3 and 2.5 GHz for the S-band, between 5.5 and 5.7 GHz for the C-band, and between 9.4 and 9.6 GHz for the X-band. Within these bands, we computed RCS at 50-MHz intervals.

The purpose of this particular effort was to cover a radar designed to operate at slightly different frequencies within a band at another time, in a manner termed “frequency hopping.” With these simulations, we can see how much the RCS could vary within a given band.

Figure 3 shows graphs of the variation of RCS within each band as error bar plots. The green bars show the maximum and minimum RCS over each 200-MHz band for each incidence angle. The blue line shows the mean RCS for the band, while the red line shows the RCS for the center frequency of the band as in Fig. 2. Just as in the case for the 155-mm artillery round and the 107-mm rocket, the RCS variation within a frequency band is smaller at higher baseline RCS values, especially when approaching –10 dBsm. Again, this is consistent with the fact the RCS is represented as logarithms or ratios of the strength.

Also, the variation is larger where the baseline is varying more with the incidence angle. Where the baseline RCS changes more rapidly with changes in incidence angle, the different frequencies within a band will respond at incident angles somewhat offset from where the baseline did. For a slightly higher frequency, the RCS pattern will respond much as though the target cross section presented to them were slightly larger. This procedure may also reveal somewhat different nulls in the RCS curves, which are sampled in a discrete manner in both polar angle or frequency.

At incidence angles near nose-on, the effective size of the target is increasing more rapidly than when the incidence approaches broadside. If the RCS is changing rapidly with incidence angle along parts of the graph, then small frequency variations will cause an effective broadening in the characterization of the RCS over those angles. For example, in Fig. 4, we compare the RCS at 2.40 and 2.45 MHz (within the S-band). It is apparent in this figure that the shift in the RCS peaks and nulls corresponding to frequency increases is equivalent to increasing the target size while keeping the frequency constant. When considering bands with multiple, closely spaced frequencies, this phenomenon is a source of effective broadening of the RCS response.
Fig. 3  Mean, mid-band, and upper-lower limits of the 120-mm mortar computed by AFDTD over a 200-MHz bandwidth in all 4 bands: a) L-band, V-V; b) L-band, H-H; c) S-band, V-V; d) S-band, H-H; e) C-band, V-V; f) C-band, H-H; g) X-band, V-V; and h) X-band, H-H
Fig. 4 Comparison of 120-mm mortar RCS at 2.4 and at 2.45 GHz for a) V-V polarization and b) H-H polarization

In Fig. 5 we compare the RCS versus incidence angle for all 4 frequency bands averaging over the 5 frequencies in each 200-MHz band and over 10 azimuth angles from 0° to 18° (from along a fin to the middle between fins). The curves in the graphs tend to follow each other within a 10-dB band, with the exception of the L-band RCS, which runs about 10 dB higher roughly between 20° and 40° incidence. Table 1 condenses the comparison even further by taking the average over all the incidence angles and comparing the average RCS in each band for the mortar round with the 155-mm artillery round and the 2 versions of the 107-mm rocket. Although most of the mortar’s RCS values shown in the table are within 3 or 4 dB of the other targets, they are mostly somewhat lower, which is consistent with its smaller size and more curved surfaces.
Fig. 5  Average RCS of the 120-mm mortar round computed by AFDTD in all 4 radar frequency bands for a) V-V polarization and b) H-H polarization

Table 1  Mean RCS of the 120-mm mortar round compared with the mean RCS of 3 targets considered in the previous study, computed over all possible aspect angles and a 200-MHz bandwidth within each of the 4 frequency bands

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<th>Target</th>
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<th>107-mm Rocket(no fins)</th>
<th>107-mm Rocket(with fins)</th>
<th>120-mm Mortar Round</th>
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5. Variation of RCS with Azimuth Angle

In this part of the study, we examine the effect of variation in azimuth angle for the 120-mm mortar round. This round has 10 fins, each separated by 36° in azimuth from its neighbors. With this geometry, we can fully capture the effect of differences in the azimuth by computing RCS over any 18° azimuth span. We computed RCS for the middle value of each frequency band over the usual range of θ from 0° to 90°, while choosing azimuth, or φ, to vary from 0° to 18° in 2° intervals, where 0° was aligned with a fin. The graphs in Fig. 6 show the mean RCS over the azimuth range as well as the maximum and minimum RCS over the φ range for each θ angle, depicted by the error bars.

What is interesting here is the lack of variation from the mean RCS in the L-band and S-band cases, but with a strong presence of the variations in the C- and X-band cases, at least beyond 30° from nose-on. The variations that occur in the C- and X-band are strong even at higher RCS magnitudes. The 0° to 30° incidence in θ is not expected to show much azimuthal variance since it is at, or near, nose-on. However, for L- and S-band, both the high density of fins and their smaller size relative to these wavelengths have eliminated variations that otherwise do appear in the C- and X-bands. The fins are about 56 mm high and 40 mm long (from the main body), and their tips are separated by only 33 mm. This compares with the S-band wavelength of 125 mm and the C-band wavelength of 54 mm. In the case of S-band, the fins are less than ½ wavelength and the fins appear not to have been completely resolved. Consequently, there is no difference in response when the azimuthal aspect changes. This lack of resolution is even more evident for the L-band. However, for C- and X-band, the fins are close to or larger than a wavelength, and so differences do appear with different azimuthal incidences when the polar angle θ is larger than 30°. The graph in Fig. 7 also illustrates this issue, by halving the θ angular sampling interval to 0.25° and looking at 3 separate azimuthal incidence angles, 0°, 8°, and 18°. The curves are virtually unseparated until the radar frequency reaches into the C- and X-bands.

This lack of resolution of the separate fins for the mortar round is in contrast to the 107-mm rocket with 4 fins, where the variance of the RCS curve over various azimuth aspects is fairly large over most of the θ angular incidence and all 4 frequency bands. In the case of the finned 107-mm rocket, the fins are roughly twice as large and larger than or comparable to the radar wavelengths. The lower fin density also means the geometrical or optical broadside cross section will clearly change with azimuth angle. Also, in the 107-mm finned rocket, the wider fin spacing may allow more effective corner-type scattering at broadside.
Fig. 6  Mean and upper-lower limit RCS of the 120-mm mortar round computed by AFDTD over a 180° azimuth angular range, in all 4 radar frequency bands: a) L-band, V-V; b) L-band, H-H; c) S-band, V-V; d) S-band, H-H; e) C-band, V-V; f) C-band, H-H; g) X-band, V-V; and h) X-band, H-H

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Fig. 7  RCS of the 120-mm mortar round at 3 azimuth angles in all 4 radar frequency bands: a) L-band, V-V; b) L-band, H-H; c) S-band, V-V; d) S-band, H-H; e) C-band, V-V; f) C-band, H-H; g) X-band, V-V; and h) X-band, H-H
6. Conclusions

We have extended our *Numerical Computation of the Radar Cross Section of Rockets and Artillery Rounds* report\(^3\) by modeling a fairly close representation of an actual 120-mm mortar. Again the AFDTD and FEKO results were in excellent agreement for the frequencies and incidence angles of our study, even though the modeling techniques of the 2 software were different.

Also, we found that the RCS of the mortar round was not greatly different from that of the previous 3 models in the earlier report, namely, the artillery round and the two 107-mm rocket models when we considered ±100-MHz deviation from the central frequency of the L-, S-, C-, and X-bands. The RCS at broadside incidence was slightly lower for our mortar round and the overall RCS was slightly lower, consistent with a slightly smaller and more rounded target. We found significant variations in the RCS with azimuth aspect angle in the C- and X-bands. However, these variations disappeared with the lower frequency, L- and S-bands. This suppression of the azimuthal RCS variation was consistent with the smaller fin size relative to wavelength as compared to the 107-mm rocket. The density of the fins in our 10-fin mortar round as compared to the 4-fin, 107-mm rocket also played a major role in the different effect of the azimuth angle on RCS between the 2 targets. This could suggest that the radar return for this mortar would be more predictable at the lower frequencies than at the higher frequencies, especially since the azimuth incidence angle of the radar beam on a finned target would be uncertain.

Overall, however, no radar band return stood out as consistently stronger than the others. Higher frequencies might be more sensitive to details in the target, but for azimuthally non-symmetric targets, such as finned mortars and rockets, their spin could result in a higher variance of the radar signature.
7. References


6. The website for the ARL DSRC Excalibur HPC can be found at http://www.arl.hpc.mil/hardware/index.html#excalibur.

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