# Tackling Complex Problems: Analysis of the AN/TPQ-53 Counterfire Radar

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## THE PROBLEM

The performance of combat systems can be affected by a wide variety of operating conditions, threat types, system operating modes, and other physical factors. The character of the resulting multivariate test data can preclude simple or standard analysis methodologies. IDA's analysis methods rely on a variety of advanced statistical techniques to provide a better characterization of system capabilities than the techniques historically used to evaluate test results of combat systems.

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## BACKGROUND

Mortar, rocket, and artillery fire posed a significant threat to U.S. forces in Afghanistan and Iraq and will likely continue to pose a significant threat to ground troops in future conflicts. The AN/TPQ-53 Counterfire Radar (see Figure 1) is a ground-based radar designed to detect incoming mortar, artillery, and rocket projectiles; predict impact locations; and locate the threat geographically. Threat location information allows U.S. forces to return fire on the enemy location, and impact location information can be used to provide warnings to U.S. troops. The Q-53 is the next generation of counterfire radar, replacing the currently fielded AN/TPQ-36 and AN/TPQ-37 Firefinder. The Army conducted the Initial Operational Test and Evaluation (IOT&E) for the Q-53 in 2014, and the Army has

Note: The command and control vehicle is not shown.

**Figure 1.** Soldiers Emplacing the Q-53 Radar during the IOT&E

since made changes to the software and hardware designed to address discovered issues. The system had another IOT&E in June 2015. Because of urgent wartime requirements, the Army fielded 32 systems of an earlier version of the Q-53 radar. The Army plans to purchase an additional 136 Q-53s to allow every Army combat Brigade, Fires Brigade, and Divisional Artillery to have two Q-53 radars.

The Q-53 has a variety of operating modes designed to help optimize its search. The 360-degree mode searches for projectiles in all directions around the radar, while 90-degree search modes can be used to search for threats at longer ranges in a specific sector. In addition, the 90-degree mode has two sub-modes. In the 90-degree normal mode, the radar searches a 90-degree sector out to 60 kilometers. In the 90-degree Short Range Optimized Mode (SROM) mode, the radar focuses on short range threats, sacrificing some performance at longer ranges.

In addition to the various operating modes, the Q-53 radar's performance can vary depending on characteristics of incoming projectiles' trajectories and geometry relative to the radar's position. Determining how much the radar's performance varies across all these factors is essential to inform users of the capabilities and limitations of this system as well as to identify deficiencies in need of correction. Figure 2 outlines a standard fire mission for the Q-53. During a threat fire mission, the threat will fire projectiles at a target inside the search area of the Q-53. (Figure 2 shows a Q-53 operating

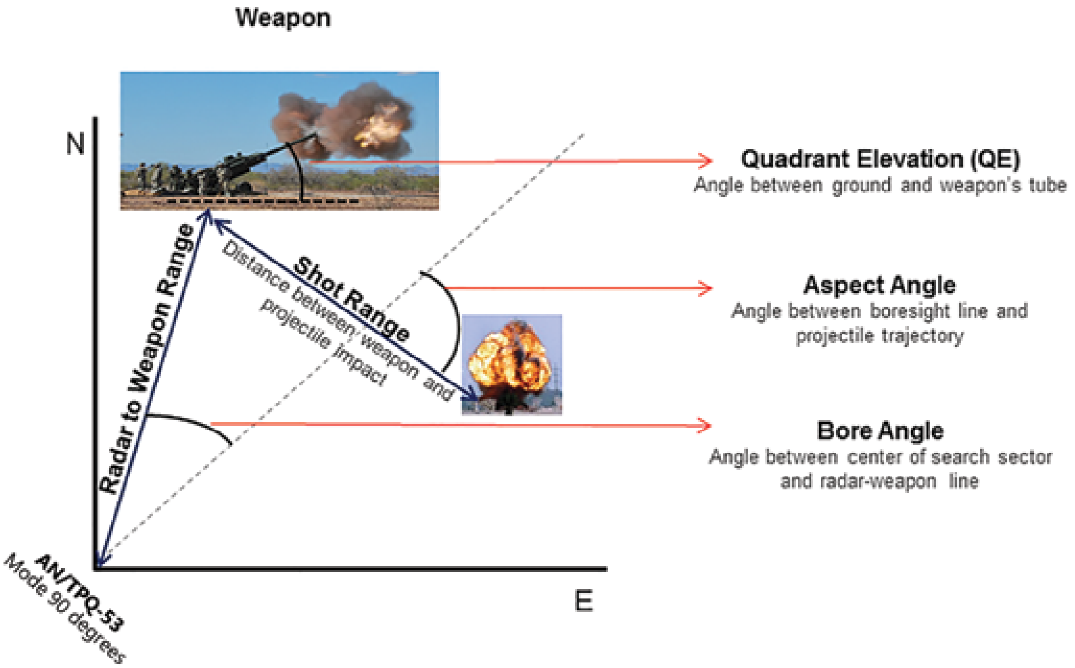


**Figure 2.** Example of a Fire Mission Including Relevant Geometric Factors Impacting Q-53 System Performance

in a 90-degree mode, so its search sector is limited to the area within the black bars.) The Q-53 must detect the projectile's trajectory and then estimate the position of the threat's weapon so U.S. forces can counter-attack. The specific geometry of the scenario will impact the Q-53's ability to track the projectile. Relevant factors include radar weapon range (the distance between the Q-53 and the weapon firing the projectile), quadrant elevation (the angle of the projectile's trajectory relative to the horizon), and shot range (the distance between the weapon and its target). When operating in 90-degree modes, the angle between the center of the radar's sector and the projectile's trajectory (bore angle) may also impact performance.

The key questions about system performance are: (1) Can the Q-53 detect shots with high probability? (2) Can the Q-53 locate a shot's origin with sufficient accuracy to provide an actionable counterfire grid location?

## Q-53 OPERATIONAL TESTS

The June 2014 Q-53 IOT&E replicated typical Q-53 combat missions as much as possible given test constraints. Four radars (two Battalions) observed shots fired from a variety of weapons. Each Battalion decided how to employ the radar, within given test parameters, based on intelligence reports provided by the test team. Test personnel fired U.S. and threat weapons throughout four 72-hour test phases. During a single threat fire mission, test personnel fired projectiles (between 1 and 20, typically 10) from a single location using the same gun parameters, simulating a typical engagement that a Q-53 Battalion might encounter in a combat scenario. During a volley fire mission, test personnel fired projectiles from three weapons at the same time. Volley fire is a common technique used to increase the number of rounds hitting the target in a fire mission. Since the radar did not move during these missions, all of the factors in Figure 2 were held constant during each threat fire mission. Many missions were observed by two radars, enabling a single threat fire mission to be detected by two radars. Testers fired 2,873 projectiles, which resulted in 323 usable fire missions.

Figure 3 shows the raw probability of detection data. Each point represents a fire mission, with the size of the point determined by the number of shots taken in the fire mission, ranging from a single shot to as many as 20 projectiles. The percentage of those shots detected by the Q-53 counterfire radar is shown on the y-axis. The colors of the points show the munition, and different operating modes and fire rates are separated across the x-axis.

As Figure 3 shows, there is substantial variability in probability of detection across different combinations of operating mode, munition, and rate of fire. There are geometric differences between operating modes, complicating the definition of a shot's geometry. For example, in 360-degree mode, there is no angular center and therefore no bore angle. As a result, the 90-degree modes must be analyzed separately from the 360-degree modes to ensure that bore angle is properly taken into account. Additionally, the data are heavily imbalanced. The

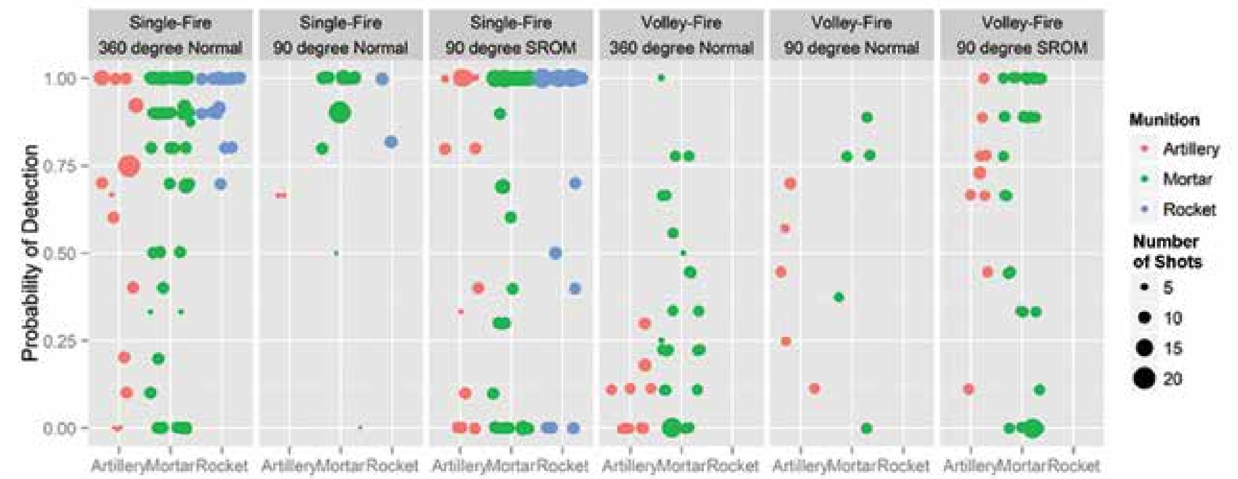


**Figure 3.** Detection Probabilities for 323 Fire Missions Conducted During the Q-53 IOT&E

choice of the 90-degree operating mode was left to the Brigades. They quickly learned that most of the threat missions were within SROM capabilities, so 90-degree Normal was used substantially less than 90-degree SROM. There are substantially fewer volley fire shots than single fire shots. (No volley fire rocket missions were undertaken because of test limitations.) Furthermore, many of the geometric factors described in Figure 2 were confounded with each other because of limited available firing points on the test range. As often happens in operational testing, the Q-53 test conditions resulted in imbalanced correlated data. The challenges in analyzing these types of data are best addressed with advanced analytical techniques.

## LOGISTIC REGRESSION

When characterizing system performance, it is important to account for all factors that impact system performance. While Figure 3 shows some of the major factors that impact Q-53's ability to detect projectiles, the geometry of the shot (as shown in Figure 2) is not taken into account. Therefore, IDA employed a logistic regression analysis, a natural choice considering the complex nature of the problem. It allowed us to identify which factors were driving performance and to generate estimates of probability of detection for all combinations of factors. Most importantly, this approach allowed us to look at the impact of each factor, after accounting for the others, to determine which factors have the largest impact on performance. The general logistic regression equation is

$$log\left(\frac{p}{1-p}\right)=\beta_0+\beta_1 x_1+\cdots+\beta_N x_N.$$

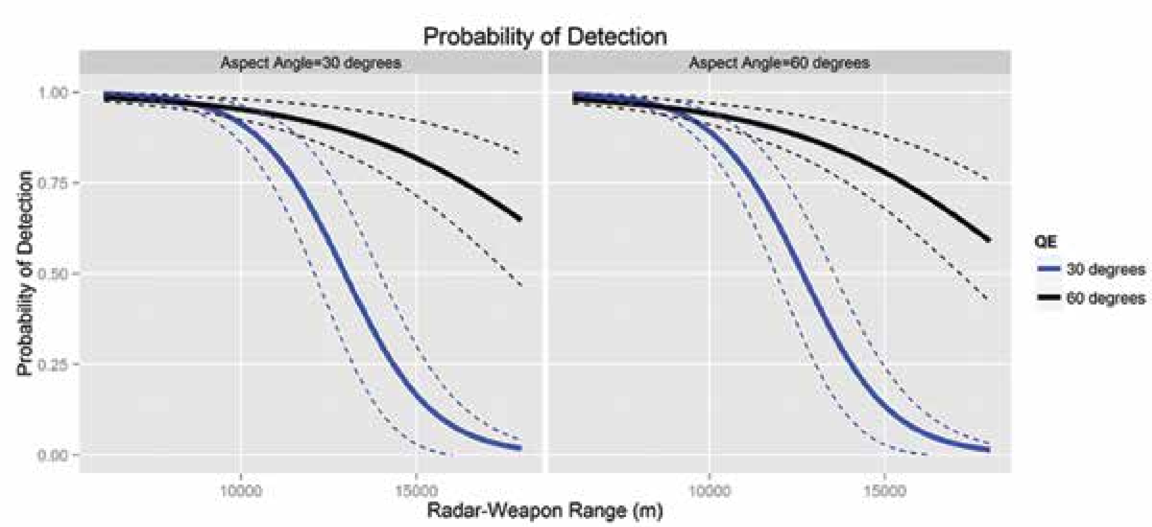
In our case, $p$ is the probability of detection, and the $x_i$ and $\beta_i$ represent the factors and coefficients, respectively. This approach relates the log of the odds ratio of probability of detection to the various factors that impact the probability of detection. Unlike a more traditional approach that looks at factors one at a time, this method allows us to attribute changes in probability of detection to specific factors.

Importantly, this also allows us to identify which of our considered factors are not driving performance. Such factors can be eliminated from the statistical model, simplifying the final expression without surrendering its explanatory power.

## ESTIMATING Q-53 DETECTION PERFORMANCE

The logistic regression model, once determined from the data, showed that – in addition to projectile type, operating mode, and rate of fire – radar weapon range, quadrant elevation (QE), aspect angle, and shot range had an impact on system performance. Figure 4 shows how the probability of detection changes as the distance between the weapon and the Q-53 counterfire radar increases when the system is in the 360-degree operating mode observing single-fire artillery engagements. The data also revealed that radar-weapon range and quadrant elevation affected Q-53's ability to detect incoming projectiles. These factors are linked to the time the projectile travels through the radar search sector. High arcing shots (larger values for quadrant elevation) are easier to see than shots with shallower trajectories that stay closer to the ground (low quadrant elevation) and are more likely to be masked by terrain. Longer shots (higher shot ranges) and shots with trajectories exposing larger cross-sections of the projectile to the radar (smaller aspect angles) were also easier for the Q-53 to detect, although the data showed these factors to be less important than radar-weapon range and quadrant elevation.

The logistic regression approach we employed also allows us to analyze the impacts of these factors simultaneously and observe how they interact. In Figure 4, as the radar-weapon range increases, the probability of detection drops sharply around 12,000 meters for shots with



**QE – Quadrant Elevation**

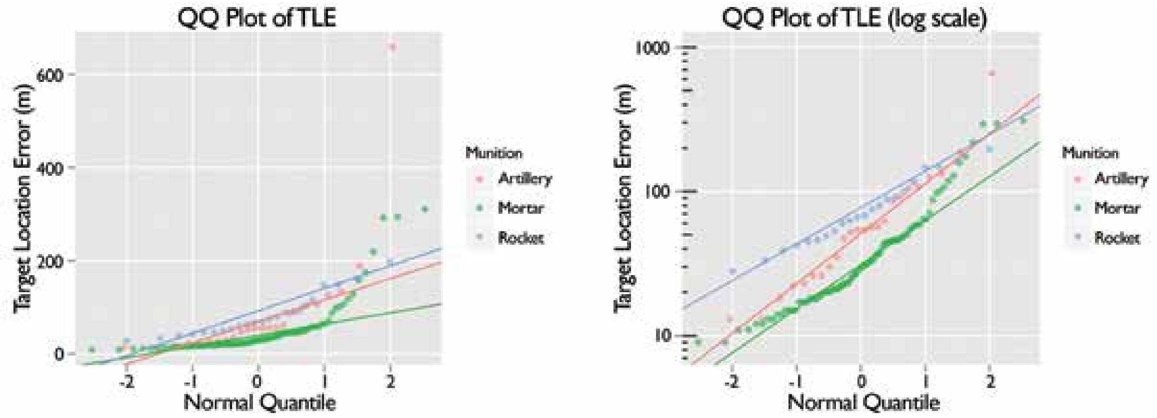
**Figure 4.** Probability of Detection for the Q-53 Counterfire Radar Using the 360-Degree Operating Mode Against Single-Fired Artillery

shallow shot trajectories (QE=30 degrees, shown with the blue lines). For the shots with more arc (QE=60 degrees, shown with black lines), the Q-53 is still able to detect with high probability at much longer ranges. While these factors have significant effects, other factors such as aspect angle have relatively minor effects on the probability of detection. Comparing the left and right panels of Figure 4, we can see that a 30-degree change in aspect angle results in a change in the probability of detection no greater than 7 percent. This logistic regression analysis allowed IDA to determine the relative impact of each factor on the probability of detection. While Figure 4 shows results for only a single combination of operating mode, munition, and projectile, IDA estimated the probability of detection across all factor levels. The Army could use this analysis to inform tactics for employing the system effectively in combat as well as identifying areas for future improvement of the system.

## ESTIMATING THE THREAT'S LOCATION

In addition to detecting incoming projectiles, the Q-53 counterfire radar also estimates the location from which the detected projectiles were fired. The radar tracks the projectile through most of its flight and then backtracks the trajectory to estimate the threat's location (the point of origin of the trajectory). The distance between this point of origin and the location estimated by the Q-53 is referred to as target location error (TLE). The estimated location needs to be as accurate as possible, since it can become a target for counter-attack by U.S. forces. For this analysis, a single target location estimate was calculated for each fire mission, since all projectiles from a fire mission originated from the same location. As a result, there are fewer data for the TLE problem than the probability of detection problem. TLEs present an additional challenge, because these measurements are not normally distributed, which means standard analysis approaches will produce biased results. Figure 5 shows quantile plots of TLEs for the 360-degree operating mode, broken down by munition type. These quantile plots are arranged so data originating from a normal distribution will fall along the straight lines shown in the plot. The further away the data points fall from the straight line, the more the actual data distribution differs from a normal distribution. The chart on the left plots the raw data and reveals that they fall far from the straight lines. The plot on the right shows the same data on a log scale; the data fall much closer to the straight lines, which indicates that a lognormal distribution better represents the actual data distribution.

As a result, IDA analyzed the TLE data using a lognormal regression. This approach allows us to take the skewness of the data into account so that the fit has the same characteristics as the data. Figure 6 shows the results, with the figure on the left showing TLE for mortars and the figure on the right showing TLE for artillery and rockets. The green lines show the system's requirements, and the black lines show the estimated median TLE along with 80 percent confidence intervals. While TLE for mortars showed substantial variability,



If the data are normally distributed, the points should conform closely to the line. The plot for TLE shows that the largest observed TLEs far exceed the values expected from normally distributed data. By using the natural logarithm of the data (right plot), the data conform more closely to the normal distribution.

**Figure 5.** Quantile-quantile (QQ) Plots Used to Visually Assess Normality

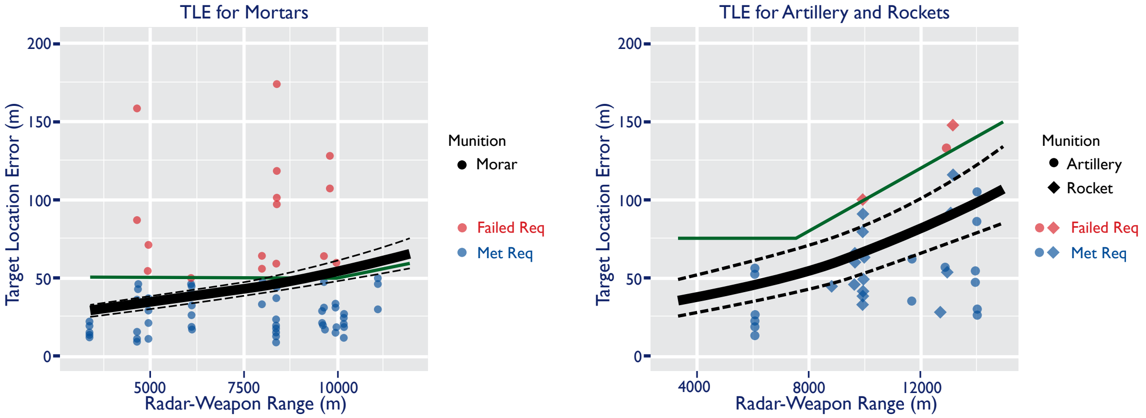


**Figure 6.** Q-53 Target Location Error for Estimated Weapon Locations

the large number of mortar fire missions allows us to make precise estimates of median TLE. The analysis revealed that the estimated median TLE tends to increase (get worse) as radar-weapon range increases. While the Q-53 is more accurate at estimating a mortar's location than the location of artillery and rocket weapons, the requirements for artillery and rockets were less stringent. As with probability of detection, IDA's regression approach accounts for the variety of factors impacting system performance, resulting in rigorous system evaluation.

## SUMMARY

IDA's analysis of the Q-53 Counterfire Radar illustrates the benefits of using more advanced data analysis techniques. Many factors, including physical factors related to the shot's geometry as well as threat and operating mode, affect Q-53 performance. Understanding the effects of these factors helps commanders in the field choose the best operating mode for the system, allowing them the best chance of detecting incoming projectiles and locating their origins accurately for a counterfire response. IDA's application of modern statistical techniques identified those factors that affected system performance and quantified their impact and practical significance for soldiers employing this system. These methods also enable testers to identify potential ways to improve system performance. Despite the challenges presented by complex data forms (e.g., right-skewed data, binary response data), the use of advanced statistical tools supports rigorous, defensible analyses.

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