Science & Global Security, 1993, Volume 4, pp. 1-63

Video Evidence on the Effectiveness of Patriot during the 1991 Gulf War

George N. Lewis[a] and Theodore A. Postol[b]

Many of the Patriot-Scud engagements during the 1991 Gulf War were recorded on video by news media camera crews. These videos are a unique and important source of information on Patriot's performance that has been completely ignored by the US Army in performing its assessments of Patriot's performance. The videos show many examples of Patriots missing their Scud targets, as well as a few examples of Patriots hitting Scuds but failing to destroy the Scud warhead. The videos also contain information about the nature of the Scud targets, and also about other important occurrences, such as Patriots diving into the ground. The videos we have been able to obtain contain no unambiguous evidence that Patriot destroyed even one Scud warhead. Rather, they contain substantial evidence that Patriot's success rate was very low, and provide a record of Patriot performance that clearly is inconsistent with the US Army's current claim that Patriot destroyed 52 percent of the Scud warheads that it engaged.

INTRODUCTION

During the 1991 Gulf War, approximately 80 modified Scud missiles launched by Iraq landed in or near Israel and Saudi Arabia. The Army initially claimed that there were 47 instances of Patriots engaging Scuds; however, Congressional experts report that the current Army figure is slightly lower. There were 16 to 17 engagements in Israel and 27 to 29 in Saudi Arabia.[1]

During the war, and in the weeks that followed, the US Army maintained that Patriot had successfully intercepted almost all of the Scuds (45 out of 47, or 96 percent). Since then, the Army has several times lowered its claims of

---

a. Defense and Arms Control Studies Program, Massachusetts Institute of Technology, Cambridge, Massachusetts.
b. Defense and Arms Control Studies Program and Program in Science, Technology, and Society, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Patriot effectiveness, most recently to just below 60 percent overall—over 40 percent in Israel and over 70 percent in Saudi Arabia. The Army also claims Patriot destroyed 52 percent of the Scud warheads it engaged, but only 40 percent of the claimed warhead kills[2] are in the "highest confidence" category.[3] Although the Army's data remain classified, they have been examined by several congressional agencies, which found the Army's data to be inadequate to support their claims of Patriot effectiveness.[4]

The Army's assessments completely neglect a crucial, and unclassified, source of information on Patriot performance: videos of Patriot-Scud engagements taken by news media camera crews. In this paper, we discuss what can be learned about Patriot performance from news media videos. We will proceed primarily by presenting a detailed analysis of videos showing the three engagements that occurred in Riyadh, Saudi Arabia on the nights of 25 and 26 January 1991. We will then present the overall results of our studies of the news media videos, which strongly suggest that the level of Patriot effectiveness during the Gulf War was very low.

NEWS MEDIA VIDEOS OF PATRIOT-SCUD ENCOUNTERS

The videos were taken by television camera crews located in the cities of Riyadh and Tel Aviv, and near the large airfield in Dhahran, Saudi Arabia.[6] The engagements were frequently filmed from the hotels in which the camera crews were staying.

Where possible, we have used videos which have not been edited for broadcast; such unedited videos have been provided to us by ABC News and by WETA-TV in Washington DC.[7] Other engagements were recorded directly off our televisions and have generally been edited for broadcast. In addition, as part of an analysis conducted at the request of Congress, we have also analyzed engagements contained in a collection of news broadcast videos that was provided to the Congress by the Raytheon Company.[8] In carrying out our analysis, we have correlated the video evidence with both broadcast and print media press reports and with official statements by the US, Israeli, and Saudi governments.

The videos we have examined contain data that bear on slightly more than half of the engagements. In some engagements, only part of the engagement has been captured. An entire engagement might not be recorded because the camera crew did not respond quickly enough to record the beginning of the engagement, or because the camera turned to another event before the engagement was completed, or because some of the engagement was obscured by clouds. Appendix A contains a brief summary of many of the significant events seen on the videos.

We have analyzed in detail 33 intercept attempts contained in 18 engagements. We define an intercept attempt as an attempt by one Patriot to destroy a Scud; an engagement is the set of all intercept attempts against one particular Scud. The engagements we have analyzed each contain between one and four intercept attempts. The 33 intercept attempts we have analyzed constitute a substantial fraction (about 38 percent) of all the intercept attempts during the Gulf War.[9]

The news media videos contain a great deal of important, useful, and unique information on the performance of Patriot in the Gulf War. The videos show many clear misses by Patriots as well as almost certain hits on Scuds (although without destroying the Scud warheads). They also contain many examples of Scud warheads surviving engagements and exploding on the ground, as well as Patriots diving into the ground and exploding. The videos also contain substantial information on the Scud targets, for example, on their breakups during re-entry and on the dynamics of their re-entry—for example, some of the Scuds appear to have followed helical trajectories.

Limitations of News Media Videos

The videos considered here were taken by news media cameras, not by high-resolution cameras on test ranges, and accordingly have a number of limitations. However, as we demonstrate below, the videos do provide information that is of critical importance to an assessment of Patriot's Gulf War performance.

One limitation of the press videos is that generally there is little detailed information about the conditions under which the videos were taken, such as the locations of the cameras, the directions they were pointing, or the focal lengths being used. In addition, the cameras were not fixed in known orientations, but were generally hand- or shoulder-carried and thus were continually in motion. Further, the videos also provide only a two-dimensional view of three-dimensional events.

The above limitations could be overcome to some extent in future studies by using the records of the television networks and major video repositories to identify the camera operators, who could then be interviewed to obtain additional data, such as camera locations. The data obtained from such interviews could be further enhanced by taking nighttime videos from the identified locations with cameras of the same type used to record engagements. Such additional videos could provide calibration information that could be helpful in interpreting the videos of Gulf War Patriot-Scud engagements. Coupled with information on Scud warhead impact locations—most of which remains classified—such information on camera locations could establish the viewing geometry of the intercept attempts seen on the videos.

Another limitation is the relatively low frame rate of the press videos. US televisions show only 30 frames per second, and as a result there is an uncertainty in the relative positions of the fireball produced by the detonation of the Patriot warhead and the Scud. The hot gases produced by the detonation of the high explosives in the Patriot warhead are rapidly (in at most a few milliseconds) stopped by air friction, traveling no more than roughly five meters.[12] The location of the center of the fireball therefore is uncertain by only about five meters in the first video frame in which it appears and the fireball is effectively stationary in subsequent frames. Thus the center of the fireball provides a fixed reference point for measurements. However, at a typical intercept altitude of roughly 10—12 kilometers, the Scud is moving at about 2.0-2.2 km sec , or about 70 meters per video frame.

The speed of the Scud produces an uncertainty in the location of the Scud at the time of the Patriot warhead detonation. This uncertainty arises because the shutter on the video camera is open only for a small fraction of each 0.033 second video frame. Since the Patriot fireball is stationary, it is seen at the same position no matter when during the frame time the detonation occurred. However, the moving Scud is seen at the location it occupied when the shutter was open. We refer to the resulting uncertainty as the "detonation location uncertainty"; it is simply equal to the distance the Scud moves between two successive video frames (roughly 70 meters). The camera, however, sees only the component of the Scud's motion that is in the plane perpendicular to the line of sight of the camera. This component is given by $(V/30) \cdot \sin \alpha = (70 \text{ meters}) \cdot \sin \alpha$, where V is the Scud's speed (in m sec^{-1}) and a is the angle between the camera's line of sight and the Scud's velocity vector.

We will refer to the two-dimensional detonation location uncertainty seen on the television screen as the apparent detonation location uncertainty, and the full three-dimensional distance as the actual detonation location uncertainty. We will use the same nomenclature to denote other distances, such as miss distances, where a two-dimensional projection is seen on the television screen.

A number of analysts have claimed that the limitations of the news media videos, the detonation location uncertainty in particular, prevent the videos from being a useful source of information on Patriot performance. In Box A on page 11 we refute the argument that the detonation location uncertainty prevents determination of hits or misses. Other criticisms, such as that the videos do not allow a precise measurement of miss distances or cannot determine where on a Scud's body a hit may have occurred,[13] are simply irrelevant to an overall assessment of Patriot's performance in the Gulf War. We will demonstrate that, despite their limitations, the news media videos *can* be used to determine whether a Patriot hit a Scud, or whether a Scud warhead survives an intercept attempt. The videos *can* show that some Patriot missiles were directed to the wrong points in space, and that other Patriots dove into the ground and exploded. Taken together, the videos are a unique and important source of data on Patriot's Gulf War performance, and they clearly and unambiguously indicate that the US Army's current claims of Patriot effectiveness are incorrect.

ANALYZING THE VIDEOS

To illustrate how the videos were analyzed and the types of information that can be extracted from them, we will consider three engagements in detail. These engagements occurred in Riyadh on the nights of 25 and 26 January 1991. These three engagements were selected because they contain examples of the three main types of Patriot-Scud encounters seen on the videotapes: "clear misses" and two types of "fireball overlaps" (intercept attempts that are too close to classify as misses based only on the apparent locations of the Scud and Patriot at the time the Patriot detonates). The first type of fireball overlap is one in which the Scud does not appear to be affected by the intercept attempt; the second is one in which the Patriot appears to hit and damage the Scud but does not detonate its warhead.

The images appearing in this article were produced by digitizing signals from a video cassette recorder.[14] The data were then transferred from the video capture electronics to the memory and display of a Super-VGA graphics adapter as 640 x 480 pixel and 256 color images. The images are constructed by interpolation of the 512 x 480 pixel, 24 bit per pixel captured raw video data from the digitizing input electronics. This choice of image-capture settings allows the images to be printed with a ratio of width to height of four to three, similar to that observed on a television screen, with pixels of equal width and height and with 256 colors or shades of gray. The images were then printed using a laser printer.

The images have been collected into sequences which we refer to as "Video Sequences"; these Video Sequences illustrate the nature of the information that can be obtained from the videos. Each image within the Video Sequences is referred to as a "frame" and is labeled by a number and a letter. Thus "frame 7c" means the third image in Video Sequence 7.

Some adjustments were made to the image brightness, contrast, hue, and saturation settings, which are standard controls on televisions, in order to make certain details of events visible. For example, in the second of the three engagements that are analyzed in this paper, four frames of the engagement (frames 5a, 5b, 5c, and 5d) are captured using extremely high-contrast and brightness settings relative to those used in later frames in that engagement (frames 6a through 60). Such variations in settings make it possible to show both the behavior of the faint arriving Scud target before it encounters the Patriot, and that of the much brighter exiting Scud target (and its subsequent breakup) after it is hit by the Patriot. However, (with a few noted exceptions), settings were not changed within sequences (except where they were adjusted to best show buildings on the ground), and there is no additional computer processing of the digitized video data other than the magnification of selected images in Video Sequence 7.[15]

Riyadh, 26 January 1991

The first engagement we consider occurred at about 10:50 PM (Saudi local time) on 26 January, when a single Scud was engaged by two Patriots. The engagement is shown on Video Sequences 1 through 4, which are taken from an uncut video clip extending from before the launch of the first Patriot until after the impact and explosion of the Scud warhead.[16]

First Patriot Miss

The video record of the engagement begins with the launch of a Patriot.[17] The standard operating procedure for a Patriot battery was to fire two Patriots, typically spaced about three seconds apart, at each Scud. Frame la shows the first Patriot, its bright booster flame easily visible, rising above the Riyadh city lights. The camera tracks the first Patriot and thus does not observe the launch or flight of the second Patriot. Twelve seconds after its launch, the rocket motor on the first Patriot burns out, and it disappears from view.

In engagements such as this one, where a complete flyout of a Patriot is seen (at least until its motor burns out), it is possible to combine the information from the video with simulations of Patriot interceptors and Scud targets to produce a rough timeline and range versus altitude plot of the engagement. Such a plot necessarily will be very approximate since only a two-dimensional view of the Patriot flyout is seen, but nonetheless can provide valuable insights into what occurred during an engagement. In this engagement, such

Frame 1a

Frame 1b t = - 0.033

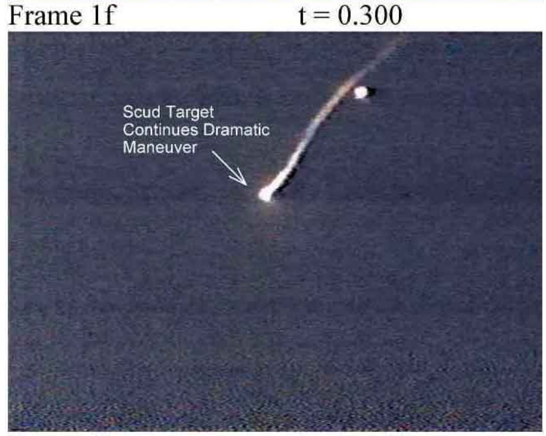
Frame 1c t = 0.000

Frame 1d t = 0.100

Frame 1e t = 0.200

Frame 1f t = 0.300

Frame 1g t = 0.400



Frame 1h t = 0.500

Video Sequence 1: Riyadh, 26 January 1991. The first of two Patriots misses the Scud. Time (in seconds) is referenced relative to the detonation time of the Patriot.

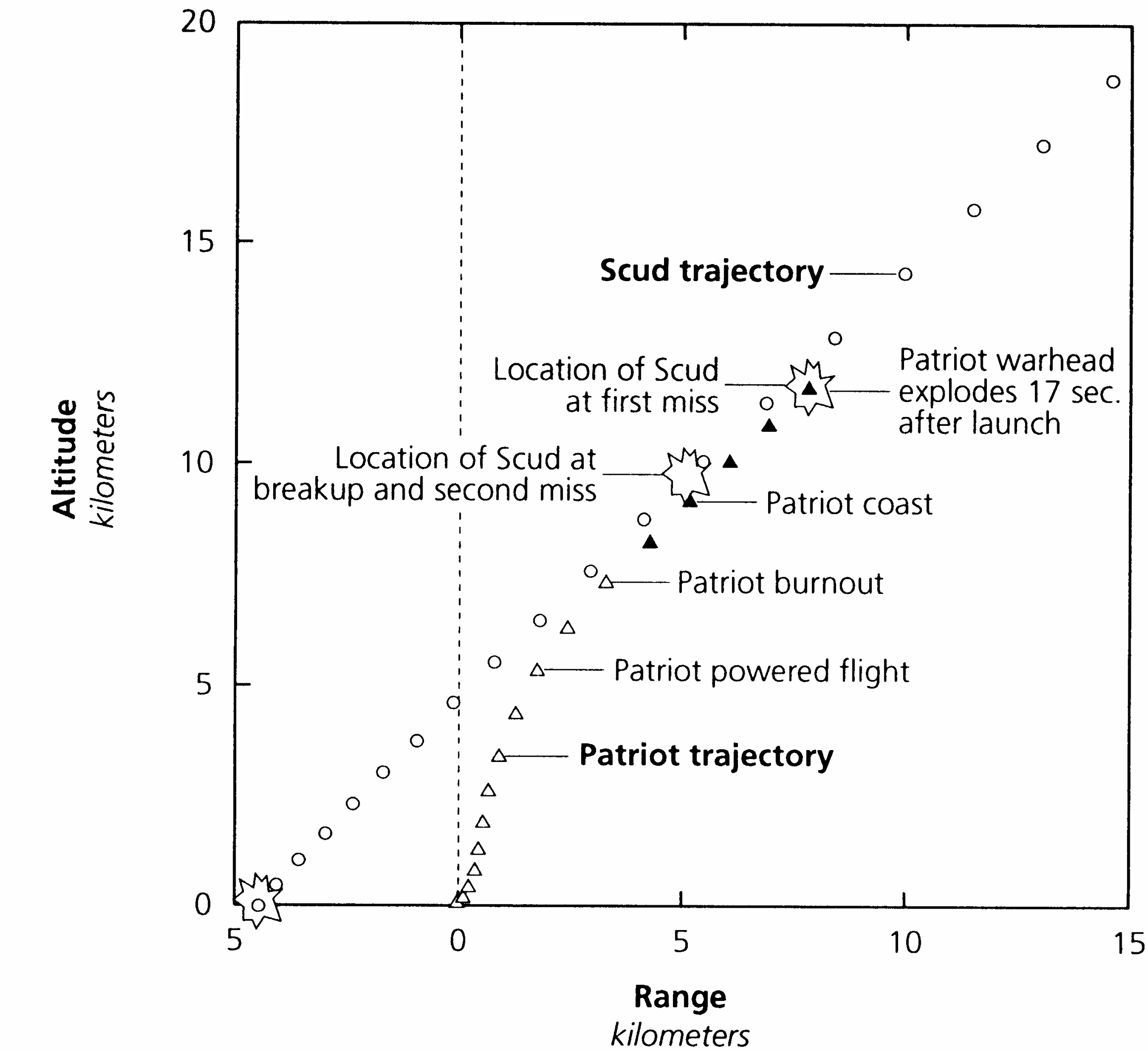


Figure 1: Estimated timeline and range versus altitude plot for the engagement at Riyadh on 26 January 1991. This plot is necessarily very approximate since only a two-dimensional view of the Patriot flyout is seen on the videos. This plot assumes that both Patriots flew the same trajectory. There is one second between each symbol.

an analysis suggests that the first Patriot intercept attempt could have taken place at an altitude of about 11.5 kilometers and the second one at about 9.5 kilometers. Figure 1 shows the estimated timeline and range versus altitude plot for this engagement.[18]

Two to three seconds after the Patriot burns out, the camera picks up the incoming Scud. At this point, the Scud is about 14 seconds from impact, and can be estimated to be at an altitude of roughly 13 kilometers and to be moving at roughly Mach 7 (about 2.0 to 2.2 km sec^{-1}). The drag due to air friction results in the dissipation of many tens of megawatts of power, ten percent of which is typically dissipated in the Scud's body, while the rest is carried off by the wake. This means that megawatts of power are being delivered to the surface of the Scud, resulting in skin temperatures that are high enough to make it easily seen by video cameras operating at visible wavelengths.

One and a half seconds after the camera acquires the Scud, the warhead on the first Patriot detonates. Frame 1b shows the falling Scud one video frame before the first Patriot warhead detonates.[19] Trailing behind the bright Scud body is a luminous wake, probably composed primarily of incandescent debris coming from the Scud missile body as it begins to break up due to aerodynamic re-entry forces. The shape of the luminous wake makes it clear that the Scud has undergone or is undergoing a dramatic maneuver.

Frame 1c is the next video frame, 0.033 seconds later, and it shows the fireball from the detonation of the Patriot warhead. The Patriot system attempts to detonate a Patriot warhead close enough to the target missile's warhead so that there is a high probability that the target warhead will be struck by one or more fragments from the Patriot warhead, causing the target warhead to detonate. The distance from the target warhead at which Patriot has a high probability of striking the target warhead with a fragment is often described in terms of an effective kill radius. According the General Accounting Office, in order to have a high probability of destroying a Scud's warhead, "the Patriot missile must detonate when it is within a few meters of the Scud." However, as we discuss in appendix C, the kill radius is strongly dependent on the intercept geometry. For example, since the Patriot warhead fragments are accelerated to at most 2.5 km sec^{-1}, which is less than the closing speed between the Scud and Patriot (typically 3.0 to 3.5 km sec^{-1}), an explosion behind the Scud warhead will not damage it.

The bright luminous fireball from the detonation of the Patriot warhead is clearly visible in frame 1c, and appears on the video to be well behind the Scud. It is important to note that the fireballs seen on the videos are not true fireballs—balls of hot radiating gas—but rather are complex mixtures of hot gas, smoke, and debris from the warhead and missile. As discussed in appendix B, the Patriot fireballs seen in the news media videos appear to be quite large, with diameters of order 100 meters. Thus the fireball radii seen on the videos are much larger than the Patriot's shrapnel kill radius, so that the details of the Patriot's shrapnel pattern are not important in analyzing intercept attempts in which the Patriot's fireball does not overlap the Scud's position.

The next five frames, 1d to 1h, show every third video frame, thus there is 0.1 seconds between these frames. These frames show the Scud falling away from the Patriot fireball, apparently unaffected by the intercept attempt.

The analysis of this intercept attempt begins with the Patriot's fireball, which, as discussed earlier, is very rapidly stopped by air friction. Using the center of the Patriot's fireball as a stationary reference point, we can then measure (on the television screen) the apparent miss distance (the distance between the Scud and the center of the Patriot fireball in the first video frame in which the fireball can be seen) as well as the distance that the Scud moves between successive video frames.[21] The distance the Scud moves between two successive frames is particularly significant, because, as discussed above, this distance is equal to the apparent detonation location uncertainty due to the frame time of the video.

Video Sequence 1 demonstrates, for the intercept attempt shown, that the detonation location uncertainty does not prevent us from determining that the Patriot missed the Scud. We find that the apparent miss distance is about nine times the apparent detonation location uncertainty. Therefore, the uncertainty in the Scud's apparent location due to the low frame rate of the video camera is at most a small fraction of the apparent miss distance. Thus the apparent miss shown in Video Sequence 1 is an actual miss. We therefore label this intercept attempt as a "clear miss." We encourage the reader to confirm this conclusion by making measurements on Video Sequence 1.[22]

In all the intercept attempts we label as clear misses, the apparent miss distance is at least roughly three times greater than the detonation location uncertainty, and in most cases is much larger (on average about ten times larger).

As discussed above, we cannot directly translate apparent miss distances on a television screen into actual miss distances because the Scud motion per frame corresponds not to the actual Scud velocity V, but to $V \cdot \sin \alpha$, and the angle a is not generally known. However, if, as Video Sequence 1 suggests, the Patriot detonated in or near the wake of the Scud (or where the Scud would have been if it had not been moving on a helical trajectory),[23] then the same sin α scaling factor would apply to both the detonation location uncertainty and the miss distance. In this case, assuming a Scud speed of 70 meters per frame (or about two km sec^{-1}) at the intercept attempt, the actual miss distance would be roughly $9 \cdot 70 = 630$ meters. Such a very large miss could well be the result of the self-destruction of the Patriot after failing to fuze on the target.[24]

If the assumption that the Patriot detonated in or near the wake of the Scud is not correct, then the miss distance must be scaled by the factor sin α. As discussed in appendix B, typical values for sin α are in the range 0.1-0.6 (camera angle of 6° to 37°). The resulting actual miss distance is still many times larger than the kill radius of the Patriot warhead, and is far too large for the Patriot to have had any effect on the Scud.

Box A: Criticism of the Use of Videos

A number of individuals and organizations have criticized the use of news media videotapes in assessing the performance of Patriot.[25] Their primary argument is that the detonation location uncertainty resulting from the low frame rate of news media video cameras makes it impossible to determine if a given Patriot actually hits or misses its Scud target. For example, the prime contractor for the Patriot program, the Raytheon Company, has stated: "No analysis performed by or for Raytheon failed to support the company's position that standard television video is an inadequate medium, because of its slow frame rate, to determine anything definitive or scientific concerning the success or failure of a Patriot-Scud intercept."[26]

Our argument is that, in all the cases we have labeled as clear misses, the apparent miss distance is so large that the detonation location uncertainty is irrelevant. However, with one notable exception, the critics simply assert that because the detonation location uncertainty exists, it is impossible to determine hits or misses; they do not attempt to relate the size of the uncertainty to the size of the misses seen on the videotapes. The one exception is Peter Zimmerman, who uses an assumed Patriot fireball diameter of eight meters to measure apparent miss distances on the videos. Zimmerman then compares the apparent miss distance with the detonation location uncertainty, which is about 70 meters. Zimmerman concludes:[27]

> *When the apparent miss distance as recorded on videotape is less than about five fireball diameters (about 40 meters), it is impossible to make any valid judgment about whether the intercept was successful or not, based only on the separation between the fireball center and the Scud warhead. The event could have been either a hit or miss, and the video record provides no evidence either way.*
>
> *As the apparent miss distance increases towards ten fireball diameters, the probability of Patriot's success slowly decreases. If the apparent miss distance exceeds ten fireball diameters, the probability of the intercept being within the lethal range of the warhead is sufficiently low that one may reasonably score the engagement as unsuccessful based only on the commercial videotape record.*

Since few of the intercept attempts appear to be off by more than ten fireball diameters, Zimmerman's criterion implies that the news media videos of intercept attempts are of little utility in determining hits and misses. However, there are two serious flaws in Zimmerman's argument. First, as is discussed in detail in appendix B, his assumed fireball diameter is far too small, probably by a factor of about 10. If he had used a more correct fireball size, Zimmerman's approach would lead to the conclusion that the videos show many clear misses.

Second, and even more important, Zimmerman compares the *apparent* miss distance (which will always be smaller than the actual miss distance) with the *maximum possible* detonation location uncertainty of about 70 meters. Although he uses his fireball diameter length scale to measure apparent miss distances, inexplicably, he does not use this length scale to measure the apparent detonation location uncertainty. The apparent detonation location uncertainty is smaller than the fireball diameter in all the engagements we have categorized as clear misses (see table B-2). Thus if Zimmerman had used his eight meter fireball diameter length scale to measure the apparent detonation location uncertainty, he would have found that the apparent detonation location uncertainty was always less than eight meters and typically was two or three meters. Thus even using Zimmerman's too-small eight meter fireball, the apparent misses seen on the videos are indeed actual misses.

Scud Breakup

Video Sequence 2 shows the subsequent motion of the Scud at 0.1 second intervals (except for 2h, which is only 0.067 seconds after 2g). The persistent and luminous Scud wake in the photographs strongly suggests that the Scud was following a helical trajectory, with a period of about one second, as it fell. If so, then the Scud was subject to very high lateral accelerations as it fell, which would have greatly increased the difficulty of intercepting it.

The Scud's maneuvers most likely are a result of instabilities introduced into the missiles when they were modified by the Iraqis to increase their range.[28] The aerodynamic forces associated with these maneuvers as well as the normal de-acceleration of the Scuds as they penetrate more deeply into the atmosphere, together with the poor quality of the Iraqi modifications, caused the Scuds to breakup during re-entry, typically at altitudes at or above roughly ten kilometers.

The Scud breakup illustrated in Video Sequences 1 through 3 is a typical one.[29] The first clear sign of the breakup is the increase in brightness of the Scud in frame 1g. Variations in brightness continue in Video Sequence 2 and the beginning of the formation of a luminous debris cloud associated with the breakup is seen in frame 2e. In frames 2f to 2h, two objects can be seen emerging from the front of the luminous cloud of Scud debris. As we shall see, the object on the left is the dense Scud warhead section, which continues to fall at a high speed, pulling away from the breakup debris cloud, which is rapidly stopped by the atmosphere. Frame 2h shows the situation one video frame before the detonation of the second Patriot warhead.

Second Patriot Miss

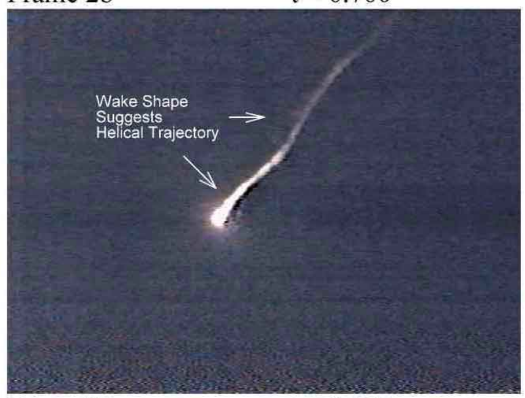
Video Sequence 3 shows the second Patriot intercept attempt, which occurred 1.3 seconds after the first intercept attempt. Frame 3a is a repeat of frame 2h, showing the situation one frame before the detonation, and the detonation of the second Patriot warhead is shown in frame 3b. The fireball from the Patriot warhead detonation overlaps both the objects that were seen emerging from the debris cloud. We refer to such an intercept attempt in which the Scud cannot be seen in the first frame following the Patriot detonation as a "fireball overlap."

The occurrence of a fireball overlap does not by itself establish whether a hit or miss occurred, because, as discussed in appendix B, the apparent size of the Patriot fireball is much larger than the kill radius of the Patriot warhead. Thus an overlapping fireball does not necessarily, or even probably, indicate that the Patriot has hit the Scud. Following a fireball overlap, the behavior of

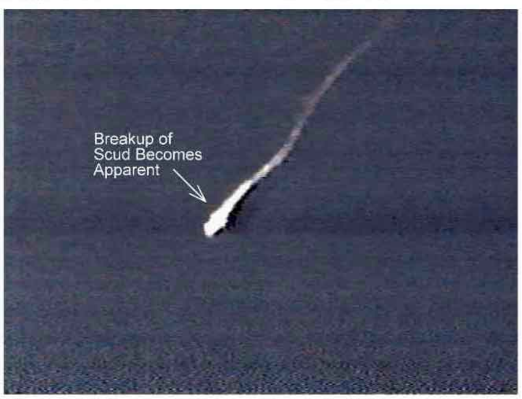
Frame 2a t = 0.600

Frame 2b t = 0.700

Frame 2c t = 0.800

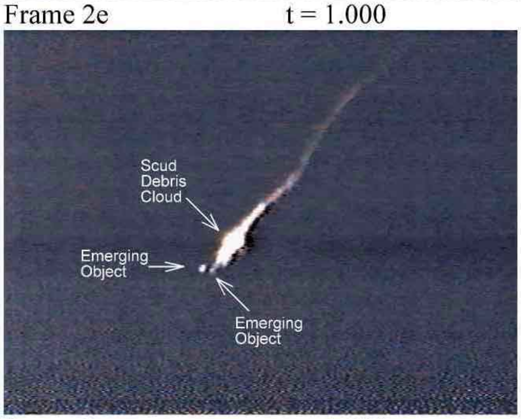


Frame 2d t = 0.900



Frame 2e t = 1.000

Frame 2f t = 1.100



Frame 2g t = 1.200

Frame 2h t = 1.267

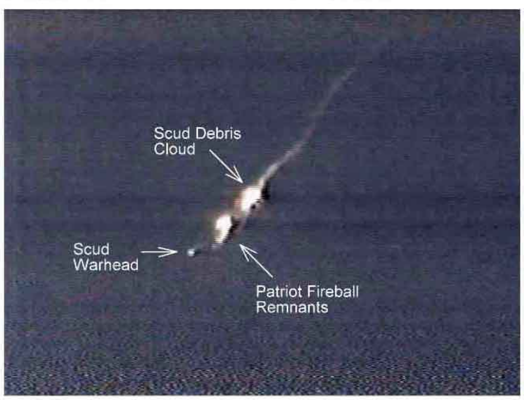
Video Sequence 2: Riyadh, 26 January 1991. The Scud breaks up due to aerodynamic forces and its warhead emerges from the breakup debris cloud.

Frame 3a t = 1.267

Frame 3b t = 1.300

Frame 3c t = 1.400

Frame 3d t = 1.500



Frame 3e t = 1.600

Frame 3f t = 1.700

Frame 3g t = 1.800

Frame 3h t = 1.900

Video Sequence 3: Riyadh, 26 January 1991. The warhead on the second Patriot detonates, and the fireball overlaps the apparent position of the Scud warhead. However, the Scud warhead continues onward.

the Scud target must be carefully observed for evidence of the effect of the intercept attempt.

Frames 3c to 3h show the events following the second Patriot warhead detonation at 0.1 second intervals. These frames show the leftmost of the two objects that emerged from the Scud breakup continuing to fall, apparently unaffected by the intercept attempt. Eleven seconds after the second Patriot detonation, this object—the Scud warhead—struck the ground, producing a bright flash and a large fireball.[30] The Scud warhead impact and explosion is shown in Video Sequence 4.

Frames 4a and 4b show the warhead falling to the ground. Frame 4c is taken one video frame before detonation; the warhead itself is lost among the lights on the ground. Light from the beginning of the Scud warhead explosion can be seen in frame 4d. One video frame later, a large fireball as well as an area of diffuse scattered light is apparent (frame 4e). By 0.5 seconds after the explosion (frame 4g), the amount of scattered light has decreased sufficiently to allow an apparently well defined "fireball" to become visible.[31] This fireball is approximately 35 meters high and 100 meters across.[32] The Scud fireball looks much larger on the video than the Patriot fireballs both because the Scud warhead contains several times more high explosive and because the Scud detonation is much closer to the camera than the two Patriot detonations. Even two seconds after the explosion (frame 4h), some glowing remnants of this fireball are still visible (frame 4h).

The warhead struck in an area described by a television reporter as a "wasteland," and no casualties or damage were reported.[33] The total time of the engagement, from the launch of the first Patriot until the impact and detonation of the Scud warhead, was about 31 seconds.

In summary, in this engagement two Patriots were fired at one Scud. The first Patriot missed by a large distance. The second Patriot appeared to explode relatively close to the Scud, and the apparent fireball from the detonation overlaps the Scud warhead position on the video. However, the Scud warhead was not destroyed and continued onwards, eventually exploding on the ground. The US Army apparently categorizes this engagement as a success.

Riyadh, 25 January 1991—First Engagement

The other two engagements we discuss in detail occurred about 10-15 seconds apart on the night of 25 January 1991 in Riyadh. All publicly available information indicates that two Scuds were fired at Riyadh that night and that both were engaged by Patriot.

Frame 4a t = - 0.433

Frame 4b t = - 0.233

Frame 4c t = - 0.033

Frame 4d t = 0.000

Frame 4e t = 0.033

Frame 4f t = 0.233

Frame 4g t = 0.500

Frame 4h t = 2.00

Video Sequence 4: Riyadh, 26 January 1991. The Scud warhead explodes on the ground. Time is referenced relative to the time of the Scud warhead explosion.

Camera Views

We have three different camera views of the first of these two engagements, in which a single Patriot attempts to intercept a Scud.[35] We will use two of the three different camera views in reconstructing the engagement.[36]

The first video is filmed from an unknown location and begins with the launch of a Patriot. The Patriot flies for about 9.3-9.4 seconds before it encounters a faint Scud target and detonates. The intercept attempt occurs at a relatively low altitude and the Patriot rocket motor is still burning when the Patriot warhead explodes.[37]

The second view of this intercept attempt was recorded by a camera located just outside of the Riyadh Marriott Hotel (and, unfortunately, views the intercept attempt over several street lamps). The video clip begins shortly before the detonation of the Patriot warhead, and thus does not include the launch and most of the flight of the Patriot.

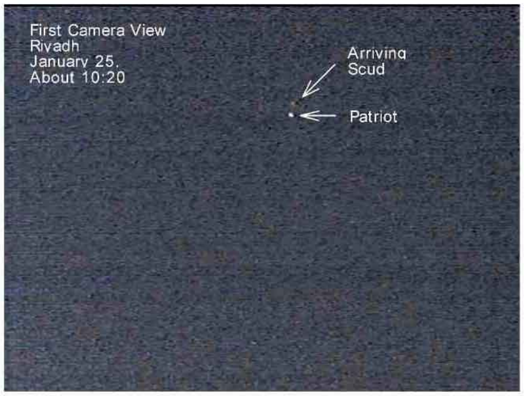
Patriot Detonation

Video Sequence 5 shows the Patriot detonation and the three video frames preceding it, as seen by both cameras. Frames 5a to 5d are from the camera at the unknown location, and frames 5e to 5h are from the camera at the Marriott. The Patriot appears to be moving nearly vertically towards the top of the television screen, and the Scud appears to be moving downwards.

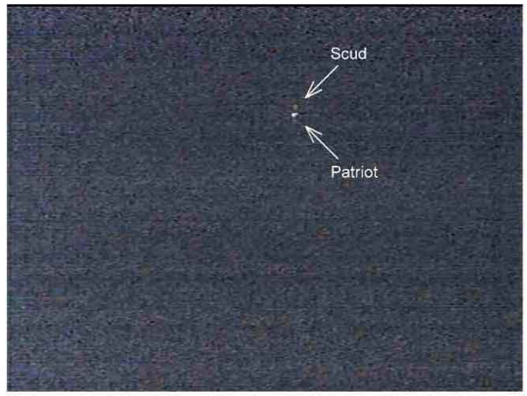
As seen by both cameras, the Patriot warhead appears to explode very close to the Scud's apparent position, and, as in the second intercept attempt on the 26 January Scud, the Patriot fireball overlaps the Scud's position (and so we label this intercept attempt as a "fireball overlap"). In this case, however, the behavior of the Scud target is dramatically and unambiguously altered by the intercept attempt.

Video Sequence 6 shows the sequence of events as the Scud target emerges from the Patriot fireball, as seen by the camera at the unknown location.[38] Frame 6a is the video frame before the Patriot warhead detonates, hov/ever, due to the brightness and contrast settings used in Video Sequence 6, neither the Patriot nor the Scud can be seen.[39] Frame 6b shows the Patriot warhead detonation—this is the same as frame 5d except for the different brightness and contrast settings. Frames 6c to Go then show the next 13 video frames, each separated by 0.033 seconds.

By frame 6d, the Scud begins to become visible as a separate bright spot below the center of the Patriot fireball, although it was still overlapped by the fireball (see Video Sequence 7 for a more detailed look at these events). The

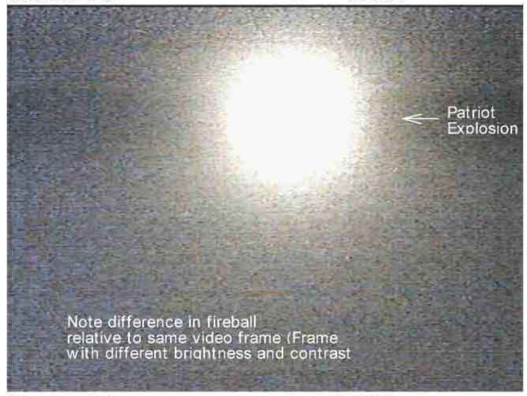


Frame 5a t = - 0.100



Frame 5b t = - 0.067

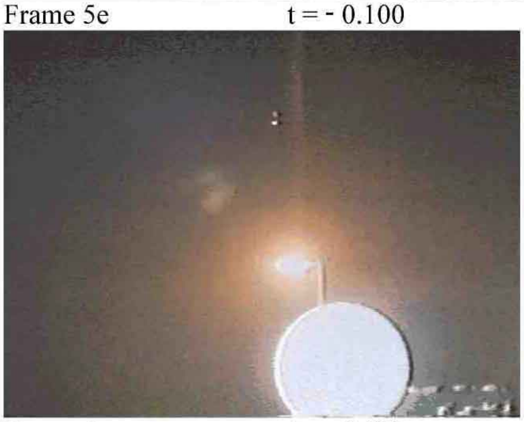
Frame 5c t = - 0.033



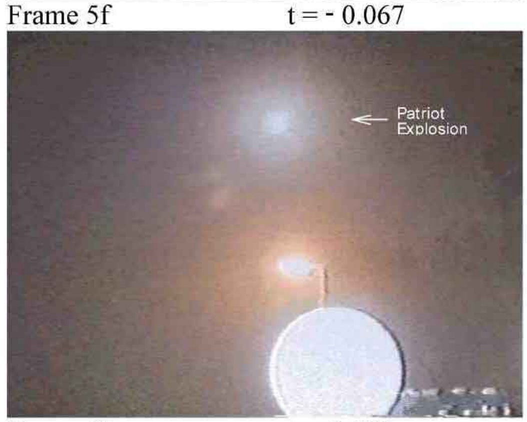
Frame 5d t = 0.000

Frame 5e t = - 0.100

Frame 5f t = - 0.067

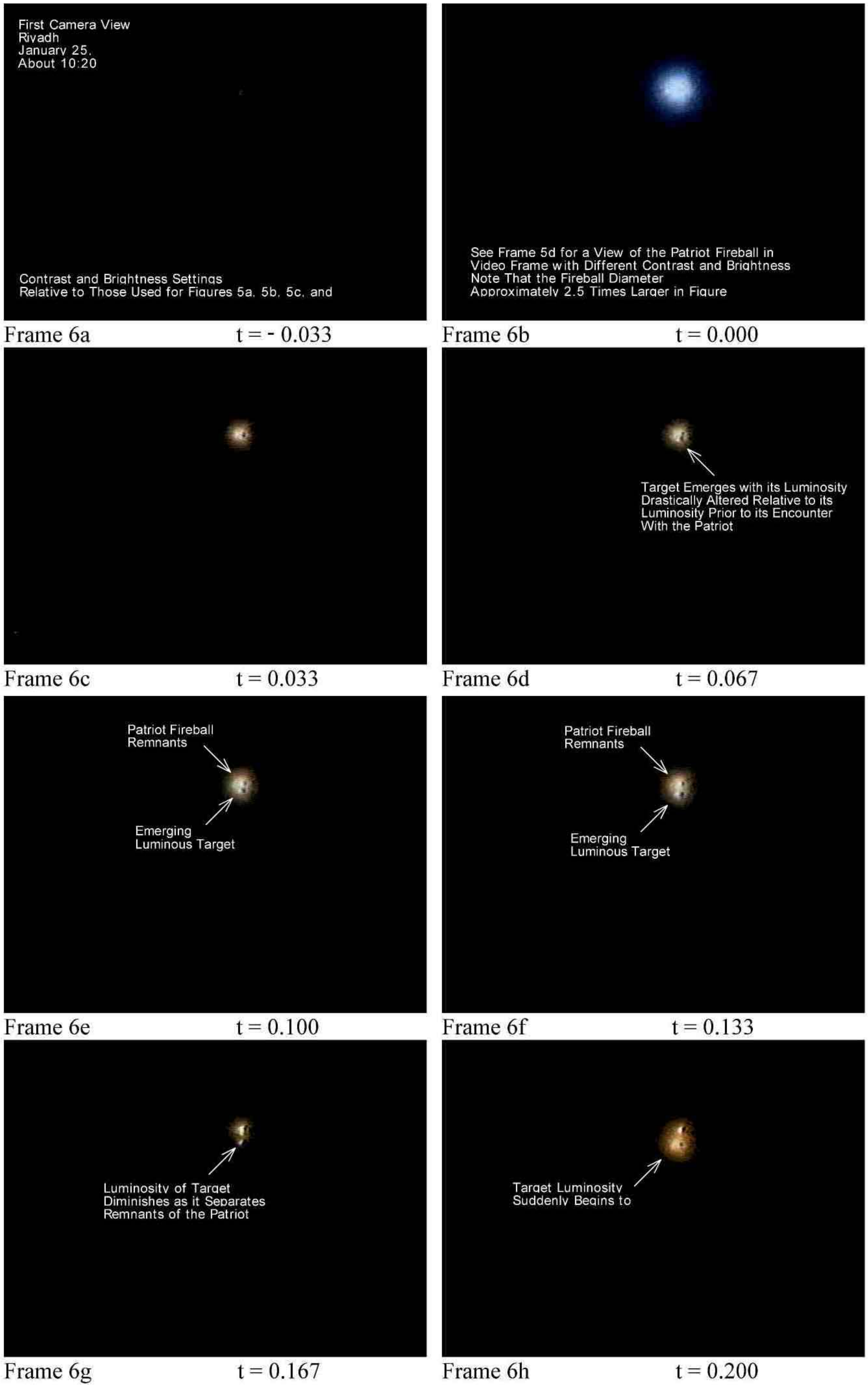


Frame 5g t = - 0.033

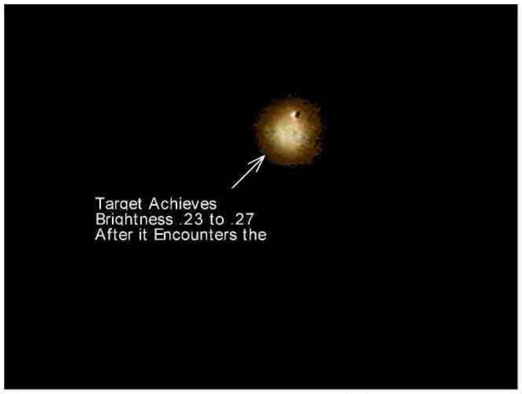


Frame 5h t = 0.000

Video Sequence 5: Riyadh, 25 January 1991, first Scud. Two different cameras record a Patriot intercept attempt in which the Patriot fireball overlaps the Scud position. Time is referenced to the time of the Patriot warhead explosion.

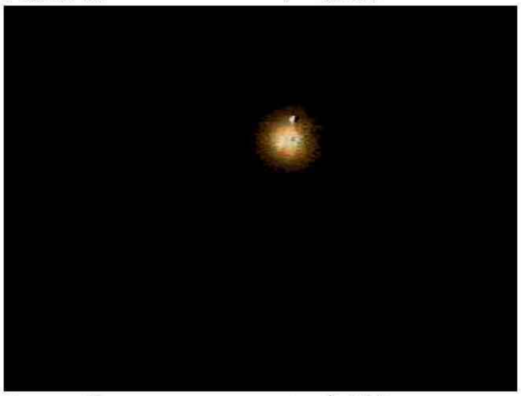


Video Sequence 6: Riyadh, 25 January 1991, first Scud. The Scud target emerges from the Patriot fireball with greatly increased brightness, then undergoes an abrupt increase in brightness, and then fades from view. Time is referenced to the time of Patriot warhead detonation.



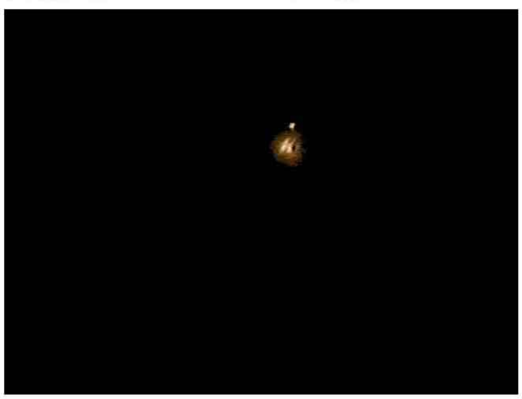
Frame 6i t = 0.233

Frame 6j t = 0.267

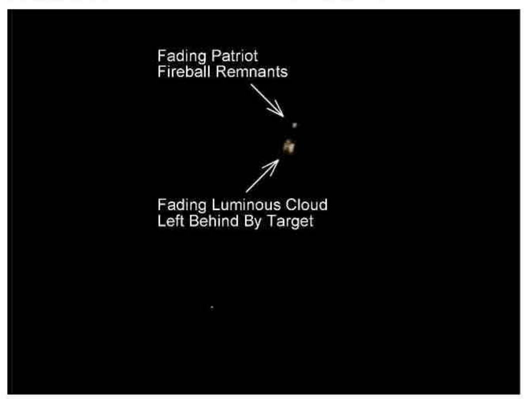


Frame 6k t = 0.300

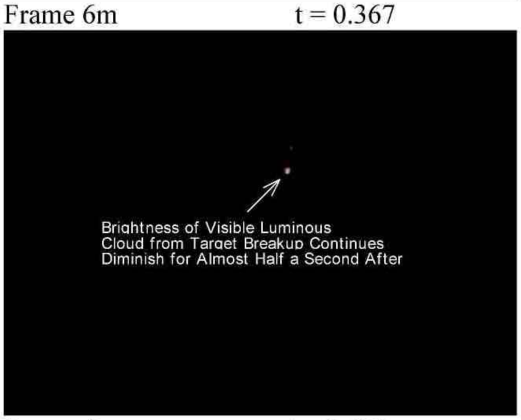
Frame 6l t = 0.333



Frame 6m t = 0.367



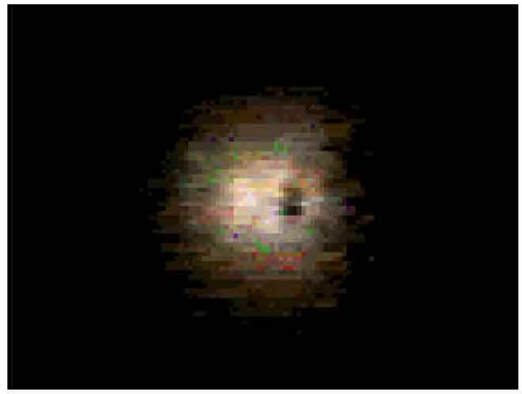
Frame 6n t = 0.400



Frame 6o t = 0.433

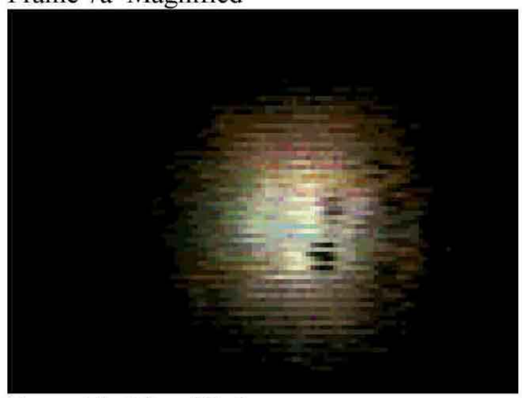
Video Sequence 6.

Frame 7a t = 0.033

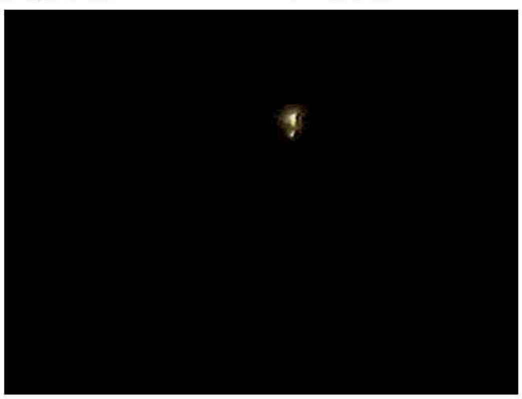


Frame 7a Magnified

Frame 7b t = 0.100

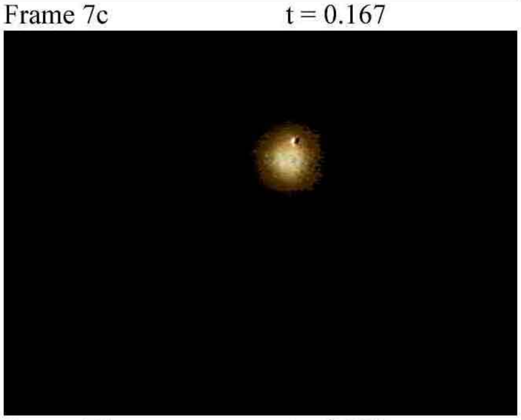


Frame 7b Magnified

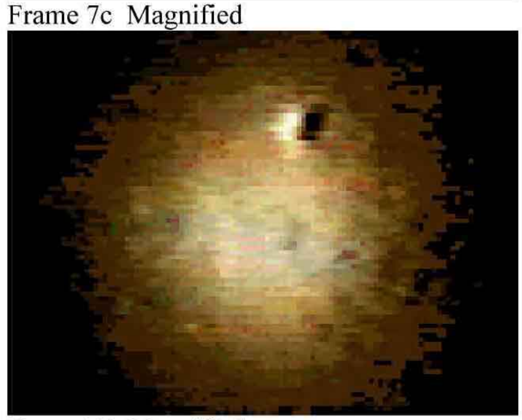


Frame 7c t = 0.167

Frame 7c Magnified



Frame 7d t = 0.233



Frame 7d Magnified

Video Sequence 7: Riyadh, 25 January 1991, first Scud. Selected images from Video Sequence 6 are magnified in order to more clearly show the Scud emerging from the Patriot fireball and then abruptly increasing in brightness.

separation between the Scud and the center of the Patriot fireball increases as the Scud continues onward, and by frame 6g the Scud is clearly visible as a separate bright spot just below the Patriot fireball. It is evident that the Scud emerges from the intercept attempt with a greatly increased brightness.

In frame 6h, about 0.2 seconds after the Patriot detonation, the Scud abruptly and dramatically increases in brightness and it continues to grow brighter in frame 6i. The Scud then fades in brightness until, about a half-second after the intercept attempt, it is no longer visible. Moreover, after the Scud flares up it also appears to stop moving relative to the Patriot fireball—the separation between the Scud and the Patriot fireball is essentially unchanged between frames 6h and 6n. This indicates that a Scud debris cloud formed and was rapidly stopped by air friction.

Video Sequence 7 shows magnified views of the Scud emerging from the Patriot fireball and flaring up. Frame 7a is the same as 6c—one frame after the Patriot detonation—and is shown magnified as frame 7a(M). Frames 7b(M), 7c(M), and 7d(M) are magnified versions of frames 6e, 6g, and 6i, respectively. The emergence of the Scud from the Patriot fireball and its subsequent flaring-up or explosion can be clearly seen in frames 7c(M) and 7d(M).

Interpretation of the Video

We believe that the sequence of events described above provides strong evidence that the Patriot hit the Scud, although as we shall see, it apparently did not destroy the Scud's warhead.

What would we expect to see if a Patriot hit a Scud and caused the Scud warhead to detonate? The detonation of the Scud warhead would break the warhead casing into many small fragments and would also heavily damage other parts of the Scud. Any remnants of the Scud's body would then break up due to the effects of aerodynamic forces. Such an event is unlikely to result in a single well-defined target emerging from the fireball, and an emerging object would never continue on a high-speed ballistic trajectory. In addition, the detonation of the warhead and the disintegration of the Scud body would result in the immediate development of a debris cloud. As with the Patriot fireball, this debris cloud would be rapidly stopped by atmospheric drag. If the Scud warhead detonated immediately, these events might be indistinguishable from the detonation of the Patriot warhead and the formation of its fireball.[40] Finally, there should be no ground explosion associated with the engagement.

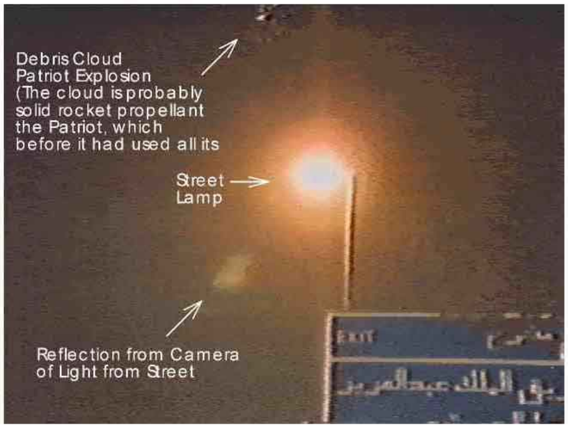
The intercept attempt shown in Video Sequence 6 has many of these characteristics, but is in other ways anomalous. Clearly the Scud warhead was not immediately detonated by the Patriot, because the Scud continues onwards for

0.2 seconds, although the Scud's increased brightness indicates that it had been hit and damaged. A delayed detonation of the Scud's warhead is unlikely, but is possible. The subsequent formation of the Scud fireball or debris cloud as seen on the video also differs from what would be expected due to the detonation of the Scud warhead, and in some ways more closely resembles a Scud breaking up. The Scud appears to increase in brightness over two or possibly three video frames, whereas a fireball from warhead detonation is typically brightest in its first frame. Nevertheless, it is possible for a warhead detonation to produce a pattern of brightness variation such as that demonstrated by the Scud in Video Sequence 6 if the timing of the camera shutter relative to the warhead detonation is just right.

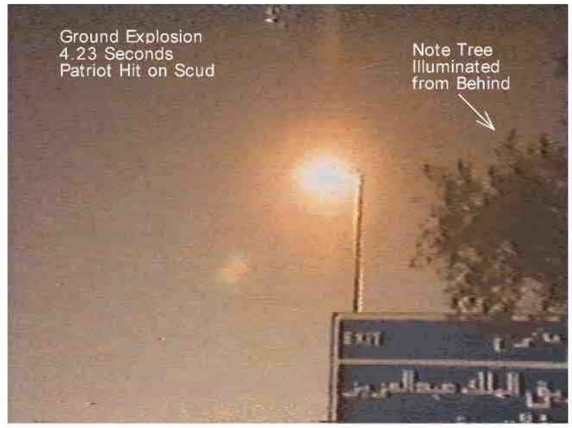
There is, however, at least one other explanation for the events seen in Video Sequence 6. An intercept attempt that does not damage a Scud's warhead could still lead to the Scud partially or completely breaking up. Any intercept attempt that does serious damage to a Scud would alter its aerodynamic characteristics, producing a change in its aerodynamic heating rate and thereby in its brightness. Thus a hit that does serious damage to a Scud should produce visible changes in the Scud's brightness and/or motion. As Video Sequences 1, 2, and 3 demonstrate, the breakup of Scuds due to re-entry stresses produces bright debris clouds[43] often comparable in brightness to the fireballs produced by Patriot warhead detonations. Such a bright debris cloud could occur if, for example, a Patriot detonated near a Scud, but its fragments struck behind the Scud warhead. In this case, the explosion of the Patriot warhead would tear the back part of the Scud body apart while leaving the warhead intact. In fact, the Patriot detonation shown in frame 3b was misidentified as part of the Scud breakup in a report issued by the US Army's White Sands Missile Test Range.[44] The breakup of a Scud caused by a Patriot explosion might produce even more spectacular visual results. Thus the events of Video Sequences 6 and 7 are consistent with the Scud being damaged by the Patriot explosion, leading to its breakup 0.2 seconds later.

The Iraqi Scuds re-enter at higher speeds than the missiles Patriot was designed to intercept. As we discuss in appendix C, there have been reports that Patriot was not fuzing properly against the Scuds. Appendix C also shows that based on the publicly available data on Patriot's warhead and fuzing system, it is plausible that Patriot's fuze could have been detonating the Patriot warhead too late to damage the Scud's warhead. If true, this would be consistent with the second interpretation of this intercept attempt: the Patriot fuzed on the Scud but the warhead detonated too late and Patriot warhead fragments struck the Scud body, but hit behind the Scud warhead.

The anomaly associated with this explanation is that the warhead is not



Frame 8a t = 4.20 seconds



Frame 8b t = 4.23 seconds

Frame 8c t = 4.33 seconds

Video Sequence 8: Riyadh, 25 January 199], first Scud. The Scud warhead explodes on the ground, 4.23 seconds after the Patriot intercept attempt.

seen continuing onward. However, there are several other instances on the videos where warheads were not visible after normally occurring Scud break-ups or where warheads were not visible during Patriot intercept attempts.[45]

In the absence of further information, it might be difficult to choose between these two explanations of the events following the intercept attempt. As we shall see, however, the video record provides strong evidence that the Scud's warhead survived the intercept attempt and detonated on the ground.

Frames 8a to 8c are a sequence of three video frames, respectively 4.20, 4.23, and 4.33 seconds after the Patriot detonation. These frames are from the camera at the Marriott.[46] Despite the bright street lights and the camera being pointed above the horizon, a bright flash from a ground explosion is clearly seen in frame 8b—note the silhouette of the tree above the street sign and the illumination of one side of the street lamp pole. All three cameras show the ground flash occurring 127 video frames, or 4.23 seconds, after the Patriot warhead detonation.

Since, viewed from this location, the Scud appeared to have been falling nearly vertically, this explosion appears to have occurred at the approximate

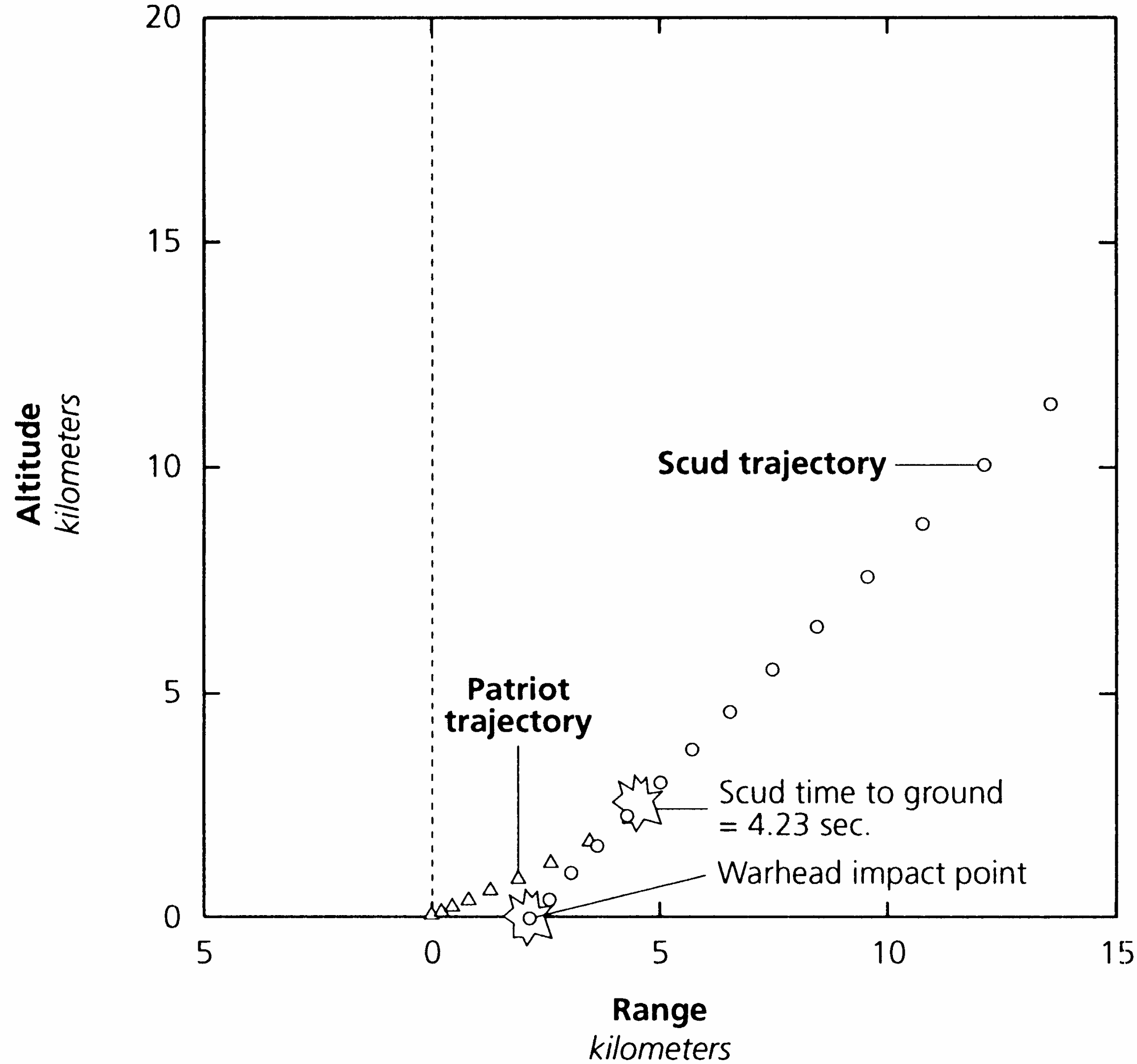


Figure 2: Estimated timeline and range versus altitude plot for the first engagement at Riyadh on 25 January 1991. This plot is necessarily very approximate since only a two-dimensional view of the Patriot flyout is seen on the videos. This plot indicates that a ground explosion 4.23 seconds after the intercept attempt is consistent with the intercept attempt occurring about 9.3-9.4 seconds after the Patriot launch.

azimuth where the Scud warhead would have impacted. The object in the sky at the top of frames 8a to 8c provides a reference point—it is a debris pattern produced by the Patriot's unburned solid rocket fuel.[47]

Moreover, the timing of the ground flash is also consistent with a detonation of the Scud's warhead. Figure 2 shows an estimated timeline and range versus altitude plot for this engagement. Assuming that the ground explosion was due to the Scud, and that the Scud was on a trajectory such as that described in appendix B, then the intercept attempt would have occurred at an altitude of about 2.5 kilometers. The Patriot flew for about 9.3-9.4 seconds before its warhead detonated; because the Patriot launch site, the direction of Scud approach, and the first camera location (the camera that observed the entire flight of the Patriot) lie nearly in a line, it is not possible to determine the angle of the Patriot's trajectory. However, as figure 2 shows, a flight time of about 9.3 seconds is entirely consistent with a Scud warhead explosion 4.23 seconds after the intercept attempt. Thus it is highly likely that the observed ground flash is due to the detonation of the impacting Scud's warhead. As with most of the Scud warheads, the impact point of the warhead is not publicly known and there were no reports of damage or casualties.[48]

In summary, in this engagement one Scud was engaged by one Patriot. The Patriot appears to detonate close to the Scud, and we label the intercept attempt as a "fireball overlap." The behavior of the Scud after the intercept attempt strongly suggests that the Patriot hit the Scud. However, the Scud warhead reached the ground and exploded.

Other Video Evidence of Patriots Hitting Scuds

There is only one other intercept attempt (out of the 33 intercept attempts we analyze) that shows the type of behavior seen in this instance—a Patriot fireball overlapping the Scud position, followed by a dramatic change in the Scud luminosity and with no target observed continuing on a high-speed ballistic trajectory. This other intercept attempt occurred at Riyadh on 11 February, when a single Scud was engaged by two Patriots. The first intercept attempt was a fireball overlap, but there was no apparent effect on the Scud, which continued onwards and then underwent an apparently normal breakup. The second intercept attempt, however, produced a sequence of events very similar to those in Video Sequence 6, in that the Scud flared in brightness and then began to fade. We have only a broadcast video clip of this engagement, and the clip was cut shortly after the second intercept attempt so that we cannot be certain whether or not the Scud warhead continued onwards. However, the continuation of the broadcast news story then cuts to an explosion on the ground.

There is no doubt that the warhead of this Scud hit the ground and exploded. There was only one Scud fired at Riyadh on 11 February (and there were none for several days before and after the llth). The Scud warhead hit near a school or university, producing a crater roughly three feet deep and 10-15 feet across and causing extensive damage to a nearby building, although only two night watchmen suffered minor injuries.[49] The video recorded at the impact site includes scenes of the shattered concrete exterior walls of a steel reinforced building, clearly indicating an intense pressure wave due to an explosion.

In addition, two other intercept attempts captured on video may show a Patriot hitting a Scud: the second intercept attempt on the infrared video (date and place unknown) and the second intercept attempt at Tel Aviv on 19 February. However, in both these cases the Scud warhead was seen to continue onwards.

In the video recorded with an infrared camera, the Scud emerges from the fireball with a greatly changed appearance. It appears smaller, dimmer, and with a much less pronounced wake. The emergence of the Scud from the fireball looks in some ways similar to what is seen at visual wavelengths when a Scud warhead emerges from a normal Scud breakup. This suggests that the Patriot hit the Scud, although without destroying its warhead. However, the video clip ends shortly after the intercept attempt, so that the Scud warhead is not tracked to the ground.

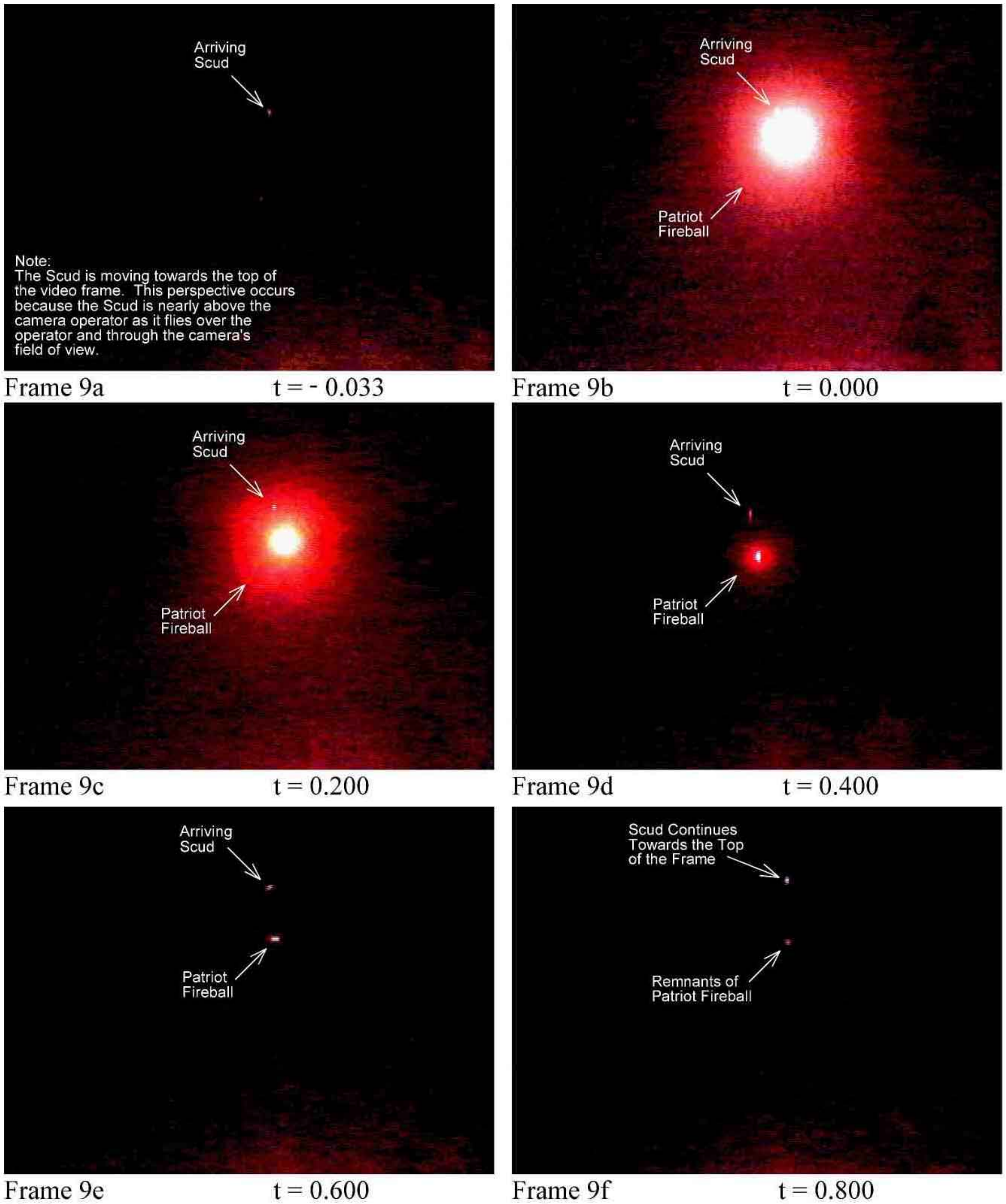
In the 19 February engagement, the Scud appears unaffected as it emerges from the fireball. However, about 0.6 seconds after the intercept attempt, the Scud breaks up, leaving a debris cloud, and the warhead continues onward. This would be unremarkable, except that the video shows that the Scud had already broken up, raising the possibility that the Patriot was responsible for this unusual second breakup. None of the three videos recording this engagement show a ground explosion. According to Israeli military sources, the Scud warhead did not explode, and there was no evidence of damage to the warhead due to Patriot fragments. Defective fuzes were believed to be the most likely cause of the failure to explode.[50]

The US Army claims that Patriot caused three Scud warheads to fail to explode.[51] However, despite recovering the warheads, the Army could not produce for Congressional investigators any chemical or metallurgical evidence that Patriot was responsible for preventing the warheads from exploding, and in no case was a Patriot warhead fragment recovered from a dud Scud warhead.[52] In addition, it is known that at least one Scud warhead that was not engaged by Patriot did not explode.[53]

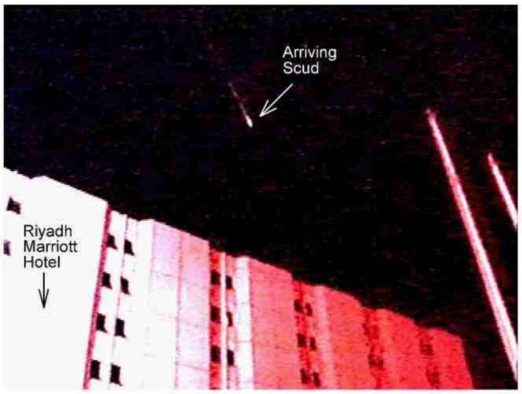
Riyadh, 25 January—Second Engagement

The second engagement at Riyadh on the evening of 25 January occurred about ten seconds after the first and is illustrated in Video Sequences 9, 10 and 11.

Shortly after the ground flash from the detonation of the first Scud, the camera at the Marriott suddenly swings upwards and to the left, where it acquires a second Scud about seven seconds after the intercept attempt on the first Scud. The camera tracks the Scud and, within a few tenths of seconds, a Patriot is seen to detonate, apparently behind the Scud. Frame 9a shows the Scud one frame before the Patriot warhead detonation and frame 9b shows the

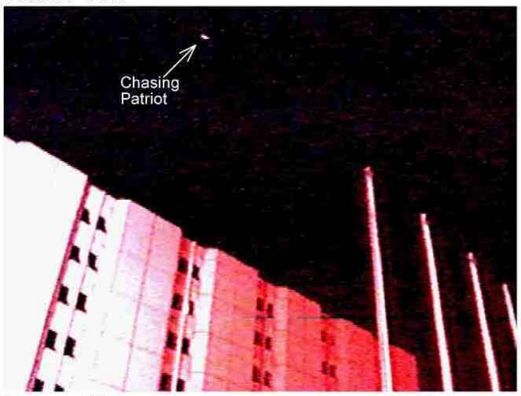


Video Sequence 9: Riyadh, 25 January 1991, second Scud. The first of two Patriots misses the Scud.

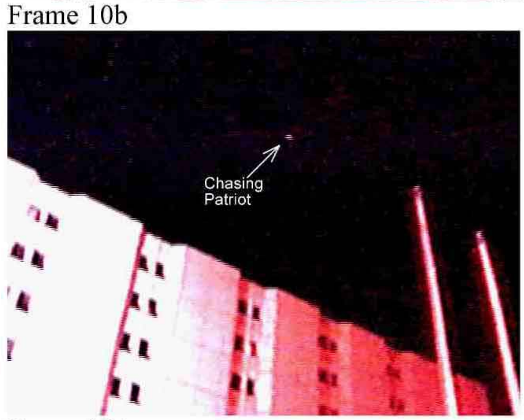


Frame 10a

Frame 10b

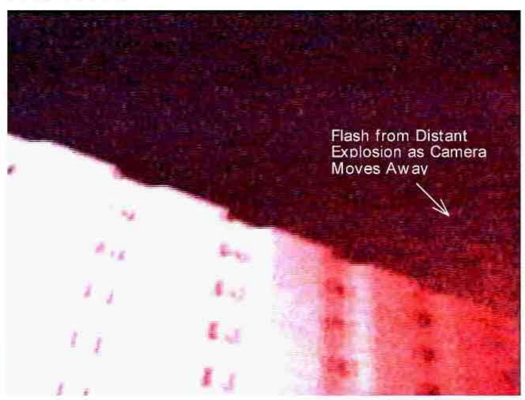


Frame 10c

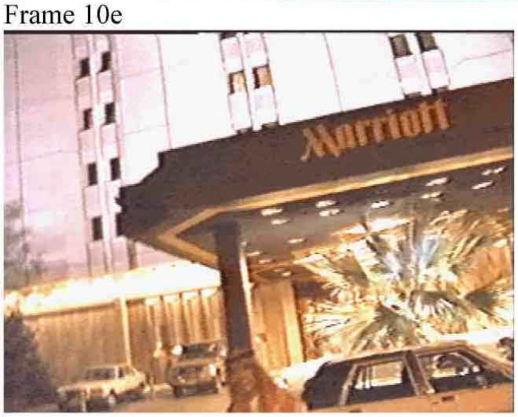


Frame 10d

Frame 10e

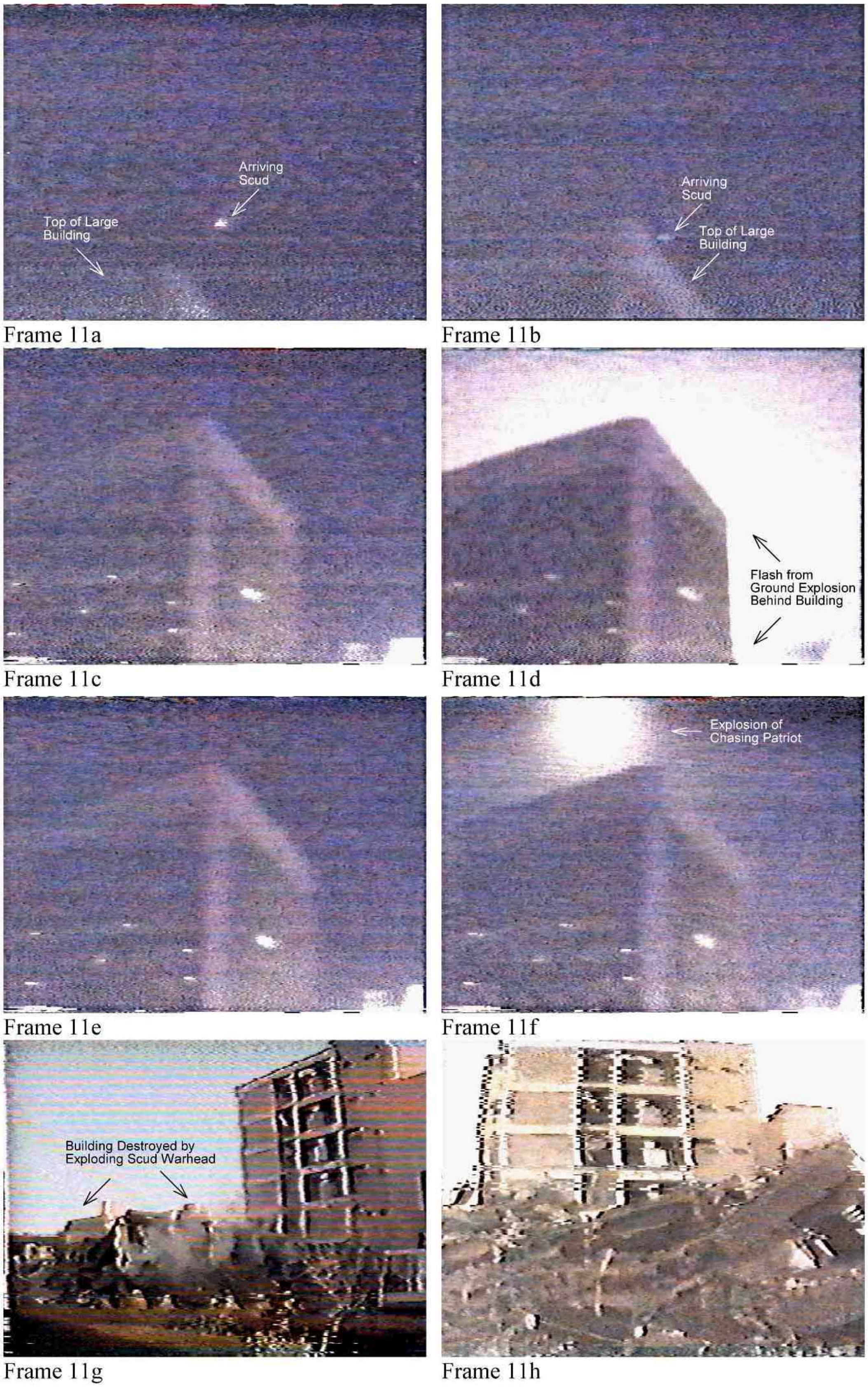


Frame 10f



Frame 10g

Video Sequence 10: Riyadh, 25 January 1991, second Scud. The Scud is seen falling over the Riyadh Marriott hotel, chased by a Patriot, and a flash from an explosion is seen as the camera turns away.



Video Sequence 11: Riyadh, 25 January 1991, second Scud. The Scud is seen falling over a building, followed by a flash from a ground explosion. The explosion of the warhead of the chasing Patriot is seen 1.1 seconds after the ground explosion.

Patriot warhead detonation. The Scud is just visible in 9b at the edge of the Patriot fireball. This Patriot fireball appears unusually large and bright and some of the apparent diameter of the fireball in 9b appears to be due to scattered light. By turning down the television brightness control, the size of the Patriot fireball can be reduced by a factor of about two relative to that shown in 9b, with the Scud still visible, now clearly separated from the fireball.[54]

Note that in this sequence the Scud is moving towards the top of the television screen. This occurs because, as we shall see, the Scud flew nearly directly over the camera. Frames 9c through 9f were taken 6, 12, 18, and 24 video frames, respectively, after the Patriot detonation and show the Scud continuing onwards in apparently normal fashion. In the first 24 frames after the detonation, the total distance the Scud moves relative to the center of the fireball is only about half of the apparent fireball diameter in frame 9b (since the Scud is on the edge of the fireball in 9b, half the apparent fireball diameter is also equal to the apparent miss distance). As with the first intercept attempt analyzed in this paper, this establishes that the apparent detonation location uncertainty is only a very small fraction of the apparent miss distance. Accordingly, it is clear that this apparent miss is an actual miss and so we label this intercept attempt as a clear miss.[55]

Following the intercept attempt, the camera follows the Scud for about two and a half seconds before the video clip abruptly ends. A second video clip apparently begins shortly after the end of the previous clip. As we shall see, this Scud passed almost directly over the camera, and we believe that the second clip is a continuation of the first clip after the camera operator has turned to reacquire the Scud as it passes overhead.[56]

Video Sequence 10 is taken from the second video clip. Frames lOa and l0b show the Scud flying over the Riyadh Marriott and disappearing behind the building. Roughly one-half second after the Scud disappears behind the building, the camera acquires a second object which appears to be following the Scud along the same general trajectory (frames lOc and lOd). As it moves, it does not slow up but becomes dim, following a brightness profile similar to that of Patriots as their motors burn out. As the camera is turning away, 1.3 seconds after the Scud disappears behind the Marriott, the video reveals a flash behind the Marriott (frame l0f).

Frame lOg shows how the location of the camera is known. After the events described above, the camera pans around, revealing the entrance to the Marriott hotel.

Another video clip,[57] filmed from a different location, shows the same Scud flying over and falling behind a large building (not the Marriott). This is shown in frames lla and l1b. About 1.4 seconds after the Scud vanishes behind the building, a bright flash from a ground explosion can be seen behind the building (frame lid). A Patriot detonates in the sky above the building (frame llf) 1.1 seconds after this ground flash.

The Scud hit a six-story building in downtown Riyadh.[58] The building, which belonged to the Saudi Interior Ministry, was demolished (frames llg and llh). Despite the building reportedly being unoccupied (the attack occurred at about 10:20 PM on a Friday night), one person was killed and about 30 injured. The building was about 2.25 kilometers south of the Marriott hotel. Since the Scuds were coming from the north, the Scud must have passed almost directly over the camera crew at the Marriott at an altitude of over two kilometers. The events associated with this Scud attack were described by BBC reporter Barnaby Mason as follows, "Then another, apparently a Scud, came shooting right over our heads across the city and, in pursuit of it, another missile—what appeared to be a Patriot—racing after it. The Patriot apparently failed to catch up with the Scud which came down to the ground with an enormous explosion."

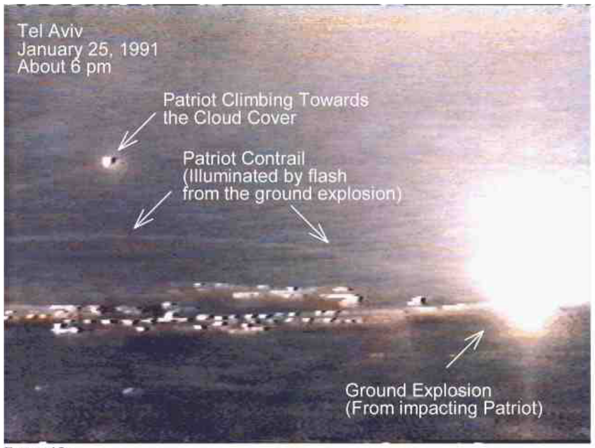
In summary, the second of the two Scuds that arrived in Riyadh was engaged by at least two Patriots. The first Patriot missed the Scud by a large distance, and the second Patriot detonated in the air after the Scud had already hit the ground.

OTHER INFORMATION CONTAINED ON THE VIDEOS

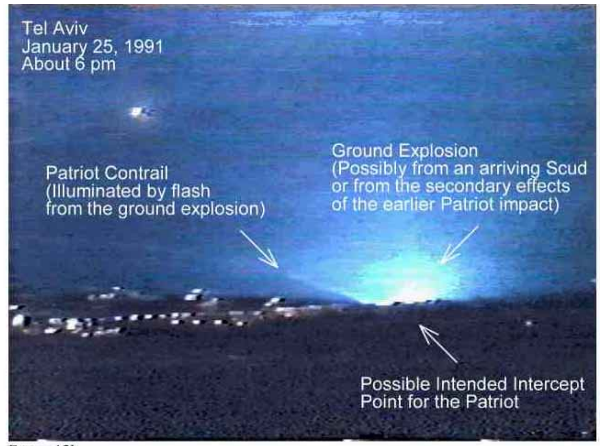
The videos contain significant information on events other than Patriot hits or misses. For example, as the 26 January engagement in Riyadh (in which the Scud is seen falling with a helical motion) illustrates, the videos contain potentially very useful and important information on the Scud targets. Many of the Scud breakups are recorded on the videos, and following some of the breakups, showers of debris can be seen falling away from the breakup debris cloud. These breakups caused serious problems for Patriot by creating many potential debris targets—yet it appears that this problem was not identified and corrected until after the attacks of 25 January, by which time more than half of the engagements had already taken place.[60]

One particularly important class of events captured on the video is Patriots diving into the ground and exploding. The videos we have been able to obtain show at least five Patriots diving into the ground[61] (see appendix A) although we believe the total number of Patriots that dove into the ground is likely to be considerably higher.[CO]

Video Sequence 12 shows the first and second of a group of three Patriots



Frame 12a



Frame 12b

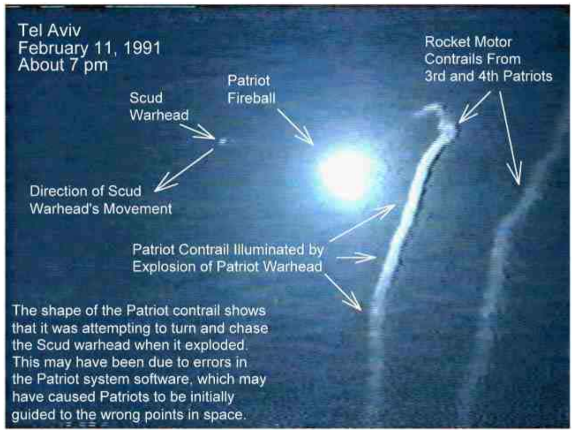
Video Sequence 12: Tel Aviv, 25 January 1991. A Patriot dives into the ground and explodes in or near Tel Aviv. The Patriot explosion was followed by two additional explosions, the first of which is shown here. The additional explosions may be secondary explosions caused by the Patriot explosion and/or Scuds exploding on the ground.

that was launched from the Patriot battery located at Tel Aviv's Dov Airport (just north of downtown Tel Aviv) at about 6 PM on 25 January 1991. (The third Patriot detonated prematurely a few seconds into flight.)

Frame 12a shows the bright explosion produced by the impact of first Patriot on the ground. This Patriot flew a low arcing trajectory, striking the ground about nine seconds after launch. The Patriot's contrail is illuminated by the flash from the explosion, so that the Patriot's trajectory can be easily seen. It seems likely that the trajectory that this Patriot planned to fly was too low and intersected the ground.[63] After 25 January, the Patriot software was changed to raise the minimum intercept altitude, and there are no reports of Patriots diving into the ground after this date.

Immediately following the Patriot impact and explosion, two additional bright explosions are seen. Frame 12b shows the first of these explosions, which occurred one second after the Patriot impact. These two explosions may be secondary explosions produced by the Patriot impact or one of the explosions may be from the Scud that the Patriot was trying to intercept (and the other could be from a more distant Scud impact).

Video Sequence 13 (which is only one image) shows another example of the type of information that can be obtained from the videos. Video Sequence 13 shows the fourth clear miss on a Scud fired at Tel Aviv at about 7 PM on 11 February 1991.[64] The Patriot warhead detonation illuminates the Patriot's contrail, which shows that the Patriot was attempting to turn and chase the Scud warhead. This indicates that the Patriot system had initially sent the Patriot interceptor to the wrong point in space—strongly suggesting that serious systematic problems remained with Patriot even quite late in the war. (Eighty-five percent of all the engagements had taken place by 11 February.)



Video Sequence 13: Tel Aviv, 11 February 1991. The fourth of four clear misses on a Scud is shown. The detonation of the Patriot warhead illuminates its contrail (as well as that of the third Patriot), showing that the Patriot had attempted to turn and chase the Scud.

CONCLUSIONS

We have described three engagements in detail and briefly discussed several additional occurrences in order to illustrate the type of information that can be obtained from a careful analysis of news media video tapes of Patriot-Scud engagements.

The news media videos are a substantial, and in many ways unique, source of hard physical data on Patriot performance in the Gulf War. Although much of the video data is fragmented, in many cases the videos provide a fairly complete picture of individual engagements. They not only provide substantial detail about the outcome of many engagements, but they also contain detailed information on the breakup and aerodynamic behavior of the Scuds as well as information on related occurrences such as premature Patriot detonations and Patriots diving into the ground. We believe that a comprehensive search through the press video, particularly looking for unedited video, would uncover a great deal more data.

With the videos we have been able to obtain, we have been able to classify 33 individual intercepts as either "clear misses" or "fireball overlaps."[65] Twenty-five of the thirty-three intercept attempts were clear misses.

The other eight intercept attempts were "fireball overlaps." (Two of the fireball overlaps occurred on the same engagement.) In all of the fireball overlaps, either the Scud warhead is seen to continue onwards (four cases), or a ground explosion is seen (two cases), or both (two cases). Thus, in all eight of the fireball overlaps, it is clear that the Scud warhead was not detonated in flight.

These 33 intercept attempts were drawn from 18 different engagements.

The videos show at least five other Scuds that were engaged hitting the ground and exploding (see appendix A), and the videos show at least part of the flight of several other Scuds that were likely to have been engaged. In addition, the videos also show at least five Patriots diving into the ground and exploding.

Overall, the videos we have analyzed contain significant information on at least half of the Patriot-Scud engagements. (The exact number of engagements remains classified, but is no more than 46.) In all of this video, there is no unambiguous evidence of a Scud warhead being destroyed in the air. About the best claim that can be made for Patriot is that, in a few cases, the video data cannot prove that Patriot did not cause the Scud warhead to become a dud. However, no mechanism has been advanced that could produce such an occurrence except as a relatively low probability event (particularly in cases where the Scud does not appear to have been damaged by the intercept attempt).[66]

Thus the videos contain no unambiguous evidence indicating that Patriot destroyed even one Scud. The videos instead contain substantial evidence that Patriot's success rate was very low, possibly even zero. Although the videos cannot establish what Patriot's actual success rate was (if for no other reason than that they provide information on only about half the engagements), they do provide a record of Patriot performance that is inconsistent with the US Army's current claim that Patriot destroyed 52 percent of the Scud warheads that were engaged.

The information contained on the videos is of particular importance given that the Army's claims rely almost entirely on data that remains classified, and that the Army's data has been criticized by Congressional investigators as being incapable of supporting the Army's claims.[67]

One lesson relevant to assessing the future performance of Patriot has apparently been learned: Patriots recently deployed to Kuwait reportedly are equipped with digital data recorders.[£Q] The deployment of video cameras to routinely record all future Patriot engagements should also be considered; such video cameras could very effectively complement the use of digital data recorders in assessing the combat effectiveness of any future use of Patriot (at least for those intercept attempts occurring at night). Had such video information been available and used during the Gulf War, some of the problems Patriot had during the Gulf War might well have been identified earlier than they were.

The development and deployment of defenses against tactical and theater ballistic missiles seems certain to be a major element of defense policy in the United States and other countries in the near future. Tens of billions of dollars may be spent in this area in the next decade. It is essential that in the development of these anti-missile systems, the lessons of the only operational experience with missile defense, the use of Patriot in the Gulf War, be fully understood and exploited. By continuing to deny the utility of the news media videos, the US Army is denying itself the benefits of a unique and important source of information on the performance of missile defenses and, even worse, may be proceeding with the development of future defenses based on a flawed assessment of Patriot's performance.

We believe that a thorough, independent review of Patriot's performance in the Gulf War is essential. This review should make use of *all* the available information, both classified and unclassified, and should be conducted by a reputable, *independent* organization, such as the National Academy of Sciences or the American Physical Society. Given the inadequate data collected by the US Army, even such a review may be unable to yield a completely definitive verdict on Patriot's performance. But it will certainly provide a much clearer picture of Patriot's performance in the Gulf War and the implications of this performance for future efforts to defend against ballistic missiles.

ACKNOWLEDGEMENTS

We would like to thank the Ploughshares Foundation for very rapidly providing us with funds for our research on Patriot at two critical points in our work. Ploughshares' contributions were absolutely critical to the success of our research program. We would also like to thank the John D. and Catherine T. MacArthur Foundation, the John Merck Fund, and the W. Alton Jones Foundation for funding various parts of the work which led to this paper. During part of the period during which this work was performed, one of us (Lewis) was supported by a Research and Writing Grant from the MacArthur Foundation's Program on Peace and International Cooperation. Dr. Richard L. Garwin's continual support, encouragement, and critical review of our work has been invaluable throughout the process of our research. Drs. Dan Fenstermacher, Lisbeth Gronlund, and David C. Wright provided us with numerous valuable technical and editorial comments. Finally, we would like to thank Dr. Harvey Sapolsky, Director of the M.I.T. Defense and Arms Control Studies Program, for his unwavering support, encouragement, and constant good humor throughout what was often a very trying process.

NOTES AND REFERENCES

1. See John Conyers, Jr., "The Patriot Myth: Caveat Emptor," *Arms Control Today,* November 1992, pp. 3—10, note 3 and Eric Schmidt, "Israel Plays Down Effectiveness of Patriot Missile," *New York Times (International Edition),* 19 October 1992, p. A8;

Ethan Bronner and John Aloysius Farrell, "US, Israeli Experts Dispute Patriot *Claims," Boston Globe,* 19 March 1992, p. 1.

2. If we assume a total of 46 engagements, then the Army's claimed success rates lead to the following:

Israel	17 engagements • 40% ≈	7 successful engagements
Saudi Arabia	29 engagements • 70% ≈	20 successful engagements
total	≈	27 successful engagements

Since the Army claims that 52% of the engagements were warhead kills:

46 engagements • 52% ≈ 24 warhead kills The above calculations lead to the conclusion that in three engagements claimed as successes, Patriots diverted Scuds off their trajectory and out of the defended area without destroying the Scud warheads or caused the Scud warhead to detonate with less than full yield (such a result was termed a "mission kill").

3. However, the Army's classification of an engagement as a high confidence war head kill is misleading. The assignment of a high confidence warhead kill to a particu lar engagement only means that the Army has higher confidence of a warhead kill relative to other engagements in which the Army believes there is some evidence of success. The GAO review of the Army's claims reports that, "According to the Deputy Project Manager, the assignment of a high confidence level to an engagement's outcome did not mean that the Army was absolutely confident that the assessed outcome was correct. Rather, given the limited data available for assessment purposes, the Army scorers had higher confidence in the assessed outcome of these engagements than in others." US General Accounting Office, *Operation Desert* Storm: *Data Does Not Exist to Conclusively Say How Well Patriot Performed,* GAO/NSIAD-92-340, September 1992, p. 3.

4. US General Accounting Office, *Operation Desert Storm: Project Manager's Assess ment of Patriot Missile's Overall Performance is Not Supported,* GAO/T-NSIAD-92-27, 7 April 1992; Steven A. Hildreth (Congressional Research Service), *Evaluation of US Army Assessment of Patriot Antitactical Missile Effectiveness in the War Against Iraq,* Testimony prepared for the House Government Operations Subcommittee on Legisla tion and National Security, 7 April 1992; and US General Accounting Office, *Operation Desert Storm: Data Does Not Exist.* All of the above reports are reprinted in Hearing before the Legislation and National Security Subcommittee of the House Government Operations Committee, *Performance of the Patriot Missile in the Gulf War* (Washington D.C.: US Government Printing Office, 1993). See also Conyers, "The Patriot Myth."

5. A US Army report concluded that the news media videos were not useful in deter mining whether a Patriot hit or missed a Scud. Army Material Test and Evaluation Directorate, White Sands Missile Range, *Analysis of Video Tapes to Assess Patriot Effectiveness (Rev 1),* 31 March 1992.

6. There are also a small number of videos from Haifa, Israel. However, we have seen no videos from the other major Scud target, the large military complex at King Khalid Military City in Saudi Arabia.

7. An entire engagement, from the launch of the first Patriot interceptor to the impact of the Scud warhead on the ground, typically lasts about 25 seconds. Broadcast video is generally cut to show only what the news media judges to be the most interest ing parts of the engagement, such as Patriot launches, the detonation of Patriot war heads, or Scud explosions on the ground. Unedited video typically allows a much more complete reconstruction of events. The videotapes provided to us by ABC and WETA-TV contained both edited and unedited footage.

8. George N. Lewis and Theodore A. Postol, *An Evaluation of the Army Report "Anal ysis of Video Tapes to Assess Patriot Effectiveness," Dated 31 March 1992: A Study Per formed in Response to a Request by Congressman John Conyers, Jr., Chairman of the House Government Operations Committee,* (Cambridge, Massachusetts: M.I.T. Defense and Arms Control Studies Program, September 1992).

9. Although 158 Patriots were fired during the Gulf War, approximately 24 were launched accidentally ("were launched at empty airspace") while about another 47 were fired at Scud debris. Thus only about 87 Patriots were actually fired at Scud tar gets. Joseph Lovece, "Electronic Noise From US Gear Prompted Errant Patriots," *Defense Week,* 28 September 1992, p. 1.

10. The US Army did not use video cameras to record any of the Patriot engagements. Further, digital data recorders were used in only three of the roughly 47 engagements. The Israelis did, however, set up high-resolution test-range video cameras near Tel Aviv and recorded a number of engagements there (although many of the engagements near Tel Aviv took place in cloudy conditions).

11. One of the videos (containing two intercept attempts on one Scud) is almost cer tainly not from the news media: it appears to have been taken with an infrared cam era. At present we do not know the source of this video, although it is known that the Israelis did record some engagements using infrared cameras. The infrared video was broadcast on the program "Admiral William J. Crowe: The Lessons of Modern War," broadcast on the Boston PBS station WGBX at 11 PM on 10 January 1993.

12. Lewis and Postol, "An Evaluation of the Army Report," pp. 63-65.

13. For example, such arguments against the use of the news media video tapes have been made by analysts at the White Sands Missile Range (where miss distances can be determined to within 0.3 meters). Army Material Test and Evaluation Directorate, "Analysis of Video Tapes."

14. Each video frame is captured as a digital picture that is 512 pixels wide and 480 pixels high. The color information associated with each digitized pixel is stored as a 24 bit number, which can potentially represent 16.7 million colors or shades of gray. Although only eight bit (256 color) data was used for the pictures in this article, the full 24 bit raw data from the video board is readily captured and stored as digitized images with our current system.

15. Thus frames lOg, llg, and llh use different settings than the other frames of the Video Sequences in which they are contained. In addition, frames 5a through 5d use different settings than 5e through 5h (which were taken by a different camera).

16. This video clip was provided to us by WETA-TV in Washington DC.

17. For background information on the Patriot system and the Scud targets, see The odore A. Postol, "Lessons of the Gulf War Experience with Patriot," *International Secu rity* 16 3 (Winter 1991/92), pp. 119-171.

18. The assumptions used in calculating the Scud trajectories used in this paper are described in appendix B. The Patriot trajectory shown in figure 1 is calculated by assuming that the Patriot first flies up nearly vertically and then attempts to fly up the Scud's expected trajectory.

19. It appears that the Patriot detonation actually began just as the video camera's shutter was closing for this frame. This is indicated by a diffuse patch of light along side the Scud's wake; this patch is in the same location as the Patriot fireball in the

next frame.

20. US General Accounting Office, *Operation Desert Storm: Data Does Not Exist,* p. 6. The GAO also reported (p. 7) that, "[The Patriot Project Office] Chief Engineer said that Patriot's fuze can sense its target and detonate at up to six times the required miss distance, resulting in an extremely low or no probability of kill. However, the sys tem would still record a kill."

21. Because the available data does not allow a precise determination of the fireball diameter (and because it is also likely that the observed fireball diameters may vary depending on factors such as intercept altitude and camera settings), we do not use the fireball diameter as a length scale in determining hits and misses or in measuring miss distances. In addition, in some of the brighter Patriot fireballs observed in the videos, where there is a considerable amount of light scattering around the fireball, the appar ent size of the fireballs are strongly dependent on the brightness and contrast settings of the television (especially in the first few frames after the warhead detonation). See frames 5d and 6b of this paper, which show the same video frame with different bright ness and contrast settings, and between which there is a factor of two or more differ ence in the fireball diameters. (However, the Patriot fireballs in the engagement we are now discussing do not appear unusually bright and their size is not dependent on the television settings.)

22. A simple way to roughly analyze this engagement is to assume that the Scud's tra jectory is a straight line passing through the center of the fireball (this assumption will lead to only a small error in this case). For example, first measure the apparent miss distance (the distance between the center of the fireball and the Scud) on frame Ic—about 6 millimeters. Then measure this same distance in frame If (nine frames later)—about 12 millimeters. Thus the Scud moved about 6 millimeters in nine frames. Thus the video uncertainty is about 0.7 millimeters and the miss distance is about $6/0.7 \approx 9$ times the video uncertainty.

23. In cases where we observe clear misses, it is apparent, given the large size of miss distances, that the Patriots could not have fuzed on the actual Scud targets. Indeed, it seems likely that many of the clear misses we see involve the Patriot self-destructing after failing to fuze on the Scud target. Since the Patriot generally attempts to inter cept the Scud head-on (that is, the Patriot is flying the Scud's trajectory in reverse), this self-destruct would be expected to occur in or near the Scud's wake. Alternatively, some of the clear misses might involve the interception of debris trailing behind the Scud, in which case the Patriot detonation would also be expected to occur in or near the Scud's wake.

24. When an engagement failed, the Patriot missile was commanded to self-destruct after a pre-set time delay. US General Accounting Office, *Operation Desert Storm: Data Does Not Exist,* p. 6.

25. Army Material Test and Evaluation Directorate, *Analysis of Video Tapes;* Peter D. Zimmerman, *Report for the House Government Operations Legislation and National Security Subcommittee on "Patriot Effectiveness (Rev 1)" and Other Related Subjects Concerning Patriot ATBM Performance During Operation Desert Storm,* 14 September 1992. See also affidavits by Lawrence S. Silverman and Kerns H. Powers, which are reprinted in House Government Operations Committee, *Performance of the Patriot Missile,* pp. 328-341.

26. Letter from James W. Carter (Vice President, Raytheon Company) to US Repre sentative John Conyers, Jr., Chairman of the House Committee on Government Opera-

tions, 14 August 1992, p. 11. This letter is reprinted in House Government Operations Committee, *Performance of the Patriot Missile,* pp. 309-327.

27. Peter Zimmerman, *Report for the House,* p. 13.

28. Postol, "Lessons of the Gulf," pp. 126-130.

29. As far as can be determined from publicly available information, most or all of the Scuds fired by Iraq during the Gulf War, whether engaged by Patriot or not, broke up on re-entry. The persistent and incandescent wake trailing behind many of the Scuds strongly suggests that debris was coming off the Scuds throughout much of the time they were in the atmosphere. Thus it may be more accurate to think of the Scuds as undergoing a series of breakups, with the breakup such as the one illustrated in Video Sequence 2 being the "main" breakup (the one in which the warhead section separates from the Scud missile body).

30. The ground explosion and fireball were also observed by another camera at a dif ferent location. However, cases such as this where the camera is relatively close to the impact point and has a clear line of sight to the impact point are relatively rare. The only other such case we have seen is the Scud that landed on or near the airbase at Dhahran on 23 January (there are also two additional video clips in which the Dhahran 23 January explosion is seen as a flash occurring behind nearby buildings). In most cases, the explosion of the Scud warhead is seen only as a flash on or over the horizon.

31. Although it may appear that a well-defined fireball is visible in frames 4e and 4f, when the video is viewed on a color television, it is apparent that much of the apparent fireball diameter in these frames is actually due to scattered light.

As we will see below, this fireball is far too large to be a true fireball (a ball of hot radiating gas). The exact nature of what is seen here (and when a Patriot warhead detonates) is unclear, but undoubtedly involves complex physical phenomena.

32. These dimensions can be established by noting that the width of the fireball in 4g is somewhat greater than the distance the Scud moves in the six video frames between 4a and 4b (this must be measured with respect to stationary ground features, because the camera is moving). The speed of the Scud at impact is not known precisely, but a figure of 700 m see" is reasonable (this is the impact speed for the trajectory shown on figure 1 and discussed in appendix B—an intact Scud would hit the ground at about 1.5 km sec"^{1}). The warhead will hit the ground at an angle from the vertical of about 48°, so sin α is at least 0.74. Thus the camera sees the Scud moving at 0.70 • 0.74 = 0.52 km sec"^{1} = 17 meters per frame, for a total of roughly 100 meters between 4a and 4b.

33. Due primarily to the inaccuracy of the Scuds, only a relatively small fraction of the Scuds (less than one in four) are reported to have caused casualties or significant ground damage. Despite this, the video record contains a number of cases where a flash from a ground explosion is seen and for which it is known that the Scud that pro duced this flash caused casualties or significant damage. In Tel Aviv, such cases are two Scuds on 25 January, a Scud on 9 February, and a Scud on 12 February. In Riyadh, these cases include the second Scud on 25 January, and single Scuds on 3 and 11 Feb ruary. In Dhahran, the explosion of the Scud that destroyed the US military barracks on 25 February is also on the videos. These cases provide clear examples of what dis tant Scud warhead explosions look like.

34. Former US Representative Frank Horton (who was the ranking minority member on the House Government Operations Committee during that Committee's investiga tion into the performance of Patriot) recently stated, apparently based on the classified

US Army assessment, that this engagement was successful. Frank Horton, "The Patriot Debate: Part 2," Arms *Control Today,* January/February 1993, pp. 26-29.

35. All three of the camera views of this intercept attempt are from the tape provided to us by ABC.

36. The third view of this intercept attempt is very similar to the second view described below, and possibly was filmed from the same location.

37. The Patriot's rocket motor burns for about 12 seconds. The only other intercept attempt we have seen where the Patriot's motor was still burning (or had just burnt out) when the Patriot warhead exploded was the fourth intercept attempt on the Scud at Tel Aviv on 11 February (see Video Sequence 13).

38. Both of the other cameras show an identical sequence of events.

39. Frame 6a is the same as frame 5c, but with different brightness and contrast set tings.

40. It might be expected that the fireball produced by the detonation of a Scud war head would be considerably larger than that produced by a Patriot warhead detona tion, since the Scud warhead contains several times more high explosive (roughly 200 kilograms) than does the Patriot (roughly 40 kilograms). However, given the wide variation in apparent Patriot fireball diameters seen on the videos, it is not clear that this difference would be discernible.

41. The argument has also been raised that a Scud could be hit by one or a few Patriot warhead fragments that do not detonate the Scud's warhead but result in the Scud's warhead not detonating when it strikes the ground. However, to our knowledge, no one has proposed a mechanism which could produce such a result except as a relatively low probability and thus infrequent event.

42. However, in such cases there is normally a very small bright core to the fireball in the first frame that is surrounded by an area of scattered light. The flaring of the Scud here does not have that appearance.

43. Such debris clouds are readily visible in the press videos. They are typically pro duced during a time interval of tenths of seconds as a Scud breaks up, and once created they remain visible in the press videos for seconds.

44. This engagement is catalogued as tape VMS-8 at 33:14 in Army Material Test and Evaluation Directorate, Analysts *of Video* Tapes, Appendix A.

45. In addition, this intercept attempt occurs at a low altitude (less than fuve kilome ters). Thus the main Scud breakup, which typically occurs at or above an altitude of ten kilometers, should have already occurred. However, little is known about what happens in such breakups and it is possible that there is enough of the Scud remaining with the warhead section to produce a second large breakup debris cloud.

46. The shoulder-carried camera has been moving towards the street light seen in Video Sequence 8 (the same one seen in frames 5e to 5h), and the large round light seen at the bottom of frames 5e to 5h is now just behind the camera.

47. Such a long-lasting debris pattern is not seen following Patriot detonations that occur after the Patriot's solid rocket motor has burned out (which is what normally occurs). However, the debris pattern is similar in appearance to that seen when Patri ots detonate prematurely after only a few seconds of flight.

48. The videos we have analyzed show eight ground explosions in or near Riyadh—

seven due to Scuds and one due to a Patriot that dove into the ground. Three of the seven observed Scud detonations produced reports of casualties and damage to buildings, three did not, and one probably did not. The only other reported instance of casualties and damage in Riyadh probably resulted from a Patriot that dove into the ground.

49. This description is based on reporting from the impact scene and video of the impact scene and damaged building that was broadcast on CNN and ABC.

50. Private communication from Reuven Pedatzur.

51. Letter from Major General Jay M. Garner, US Army, to Representative John Conyers, Jr., Chairman of the House Government Operations Committee, p. 10. This letter is reprinted in Government Operations Committee, *Performance of the Patriot Missile,* pp. 277-308.

52. According to the Chairman of the House Government Operations Committee, "In the Army assessment, a dud Scud scored as a warhead kill if a Patriot had attempted an intercept. However, many of the Scuds were duds to begin with. Scuds were found with concrete warheads, or little explosive, or broken wires in the fuzing section. Sev eral of these were scored as kills, even without corroborating evidence such as radar data. The duds were often burned and broken from impact, but this was hardly "clear physical evidence of Patriot intercept damage," although in one case an Army officer thought a Patriot fragment caused a hole. This opinion was not supported by any chemical or metallurgical analysis or recovery of a fragment. Duds not engaged by Patriot showed similar damage." John Conyers, Jr., "The Patriot Debate: Part 2," *Arms Control Today,* January/February 1993, pp. 27, 29.

53. On 19 January, before Patriot was operational in Israel, a Scud warhead struck a multi-story building in downtown Tel Aviv. The warhead was recovered intact from a ground floor jewelry store. See George N. Lewis, Steve Fetter, and Lisbeth Gronlund, *Casualties and Damage from Scud Attacks in the 1991 Gulf War,* Working Paper 93-2, Defense and Arms Control Studies Program, M.I.T., March 1993, p. 29.

54. It is unclear why some fireballs appear to be unusually large and bright on the videos. Brighter fireballs might be due to detonations that occurred relatively close to the camera or to variations in video camera settings.

55. There are at least two reasons for the very large ratio of fireball diameter to apparent Scud motion per frame in this intercept attempt. First, as discussed above, the apparent fireball diameter as seen on the video may be larger (by a factor of about two) than the "true" fireball because, in the frames shortly after the detonation, there is a great deal of light scattering in the air around the fireball which makes the actual extent of the fireball difficult to measure. Second, this Scud landed relatively close to the camera—about 2.25 kilometers away. Thus when the Scud is first acquired by the camera, its angular position will change relatively slowly.

56. The two video clips follow immediately one after the other on the videotape pro vided to us by ABC. However, it is also possible that the second clip was taken by the third camera. Following the intercept attempt on the first Scud, the clip from the third camera is cut. It is immediately followed by two short video clips, the first one showing a Scud rapidly streaking across the sky, and the second one is a repeat of the video clip from which Video Sequence 10 was taken. In either case, as we will see, the camera was at the Marriott.

57. This clip was broadcast on NBC Nightly News, 25 January 1991.

58. Malcolm W. Browne, "2 Office Buildings Leveled in Riyadh; Body Recovered," *New York Times (International Edition),* 26 January, p. 16; Richard Owen and Christopher Walker, "Two Killed and 70 Hurt in New Scud Onslaught," *London Times,* 26 January 1991, p. le. (One of the deaths and many of the injuries cited in the title of the *London Times* article occurred in attacks on Israel on the same night.)

59. Owen and Walker, "Two Killed and 70 Hurt."

60. The commander of the US Patriot forces in Israel testified that: "We deployed with software version 33, which we had confidence in, but a lot of unknowns about because it was brand new to us.

"Now, within three days [the first Patriot engagement in Israel was on 22 January —three days later is 25 January] we found out it was flawed. It was flawed not simply because it wasn't engineered well. It was engineered against a different kind of threat. And if I can put it into context, in the United States, we were trained and the system was designed against a system that pitched a fast ball. What we got was a system that threw a knuckle ball. It was not a simple process to understand exactly what was happening.

"But we within a few days—the soldiers who represented the United States of America and Israel made changes to that system based on their own ingenuity that caused us to stop the problems we experienced on 25 January." Testimony of Colonel David Heebner, House Government Operations Committee, *Performance of the Patriot Missile,* p. 234.

Starting on 26 January, the Patriot batteries in Israel switched from operating in automatic mode to operating in semiautomatic mode. This change allowed Patriot to attempt to intercept only the fastest falling object to emerge from the Scud breakup—the Scud warhead section.

61. Two Patriots are seen on the videos diving into the ground in Saudi Arabia and three in Israel. There are several other instances on the videos of Patriots diving into the ground, however, we believe that these are likely to be different camera views of the five Patriots cited above.

62. Representative John Conyers, Jr., Chairman of the House Government Opera tions Committee, submitted the following written question to the US Army: "There are reports of eight PATRIOTS hitting the ground in Israel alone, are these reports cor rect?" The Army's response is classified. (House Government Operations Committee, *Performance of the Patriot Missile,* p. 279) In private communications with three Israe lis, we have been given the figures of 8, 9, and 11 for the number of Patriots that dove into the ground in Israel.

63. The Patriot that dove into the ground in Haifa followed a similar, although per haps somewhat higher, trajectory. However the other three Patriots seen diving into the ground followed significantly different trajectories. Each of these three Patriots was heading upwards until it abruptly made a sharp turn and dove into the ground. This behavior may reflect some other problem with the Patriot system.

64. All four intercept attempts on this Scud were clear misses. It is not known why four Patriots, all from the same battery, were fired at this Scud.

65. We believe that all of the 33 intercept attempts are unique events, but we cannot absolutely rule out that two of them (one clear miss and one fireball overlap), contained in two engagements, could be different views of other intercept attempts already eval uated. (In appendix A, these two engagements are listed as the third Scud at Dhahran on 20/21 January and the first "date-and-place-unknown" event).

66. There were three engagements containing fireball overlaps in which no ground explosion was seen on the videos. In one of these cases (in appendix A, this is listed as the third Scud at Riyadh on 21 January), the Scud did not appear to be affected by the intercept attempt, but the camera did not track the Scud to the ground. In another case, (the third Scud at Dhahran, 20/21 January) the Scud again did not appear to be affected by the explosion, but was tracked most or all of the way to the ground and no explosion was seen. However, this Scud appeared to have landed at a large distance from the camera, and it is possible the flash of a ground explosion was not seen for this reason. (Another Scud that appeared to land quite far from the camera (Tel Aviv, 12 January) had a ground flash that was only faintly visible). Moreover, some Scuds that were not engaged by Patriot are also known to be duds. The third Scud was the one to Tel Aviv on 19 February; it is discussed in the text. See also the discussion in note 52.

67. See the sources cited in note 4.

68. "Raytheon Wins Kuwaiti Contract," *Aviation Week and Space Technology,* 18 January 1993, p. 21.

Appendix A: Video Tape Summary

This appendix summarizes many of the significant events seen on the videos we have analyzed. Of these, 33 intercept attempts that were categorized either as "clear misses" (25) or "fireball overlaps" (8) are listed as such.

Tel Aviv

25 January	At least 2 Scuds are seen hitting the ground and exploding. In addition, 2 Patriots are seen hitting the ground in Tel Aviv (and also 1 in Haifa).
26 January	2 Patriots fly up into the clouds, then 1 Scud comes down out of the clouds and explodes on the ground.
9 February	3 clear misses, and the Scud warhead explodes on the ground.
11 February	4 clear misses, but the camera does not track the Scud to the ground.
12 February	1 clear miss, and the Scud warhead explodes on the ground.
19 February	1 clear miss and 1 fireball overlap, with the second Patriot possibly hitting the Scud. The Scud continues onward, and the camera appears to track it to the ground, but no ground explosion is seen.

Riyadh

21 January	*First Scud*	Only the end of the Scud's flight is seen, and its warhead explodes on the ground.
	Second Scud	1 Patriot explodes behind clouds, the other Patriot dives into the ground and explodes, and the Scud warhead falls and explodes on the ground.
	Third Scud	1 fireball overlap and 1 clear miss. The Scud continues

onward but the camera does not track it to the ground

22 January Four Patriots and probably two Scuds seen. It is difficult to interpret what is occurring; the Patriots do not seem to be engaging the Scuds that are seen.

25 January *First Scud* 1 fireball overlap. The Scud was almost certainly hit, but the Scud warhead explodes on the ground.

Second Scud 2 clear misses, and the Scud warhead explodes on the ground.

26 January 1 clear miss and 1 fireball overlap. The Scud warhead continues onward and explodes on the ground.

3 February 2 clear misses, the Scud warhead continues onward and explodes on the ground.

8 February 2 clear misses but the camera does not follow the Scud to ground.

11 February 2 fireball overlaps, and the second Patriot almost certainly hits the Scud, but the Scud warhead explodes on the ground.

24 February *First Scud* 2 Patriot detonations, but the Scud is not visible until well after the intercept attempts.

Second Scud 1 premature Patriot detonation (a few seconds into flight) and 1 clear miss, but the camera does not follow the Scud to the ground.

Dhahran

20/21 January (it is not known if the "third" Scud occurred before or after the other two):

First Scud Is only seen briefly towards end of its flight but is not followed to the ground.

Second Scud 1 clear miss, camera does not follow the Scud to ground.

Third Scud (this may be a view of one of the other two Scuds from a much more distant camera, but this seems unlikely)—1 fireball overlap. The Scud continues onwards, and the camera tracks it most or all of the way to the ground, but no ground explosion is seen.

A Patriot is also seen diving into the ground and exploding.

23 January 1 premature Patriot detonation, 1 clear miss, and 1 Patriot detonation behind clouds. The Scud warhead falls to the ground and explodes.

26 January 3 clear misses, and the Scud warhead explodes on the ground.

25 February An unengaged Scud explodes on the ground. This is the Scud that hit the US barracks in Dhahran.

Date and Place Unknown: 1 clear miss, then the Scud disappears (possibly behind a cloud), followed by a Patriot detonation when Scud is not visible. The clip ends immediately after the second Patriot detonation.

Date and Place Unknown: 1 clear miss and 1 fireball overlap. The Scud warhead continues onward, but clip ends soon after second intercept attempt. This is infrared video and its source is not known. The second Patriot may have hit the Scud without detonating the Scud's warhead.

Appendix B: Intercept Geometry and Fireball Size

In this appendix, we discuss what we can learn about the apparent size of Patriot fireballs from careful measurements and analyses of the news media videos. The Patriot fireball diameter is of interest for two reasons. First, the erroneous claim that the Patriot fireball is as small as eight meters has played a central role in the arguments made by critics of using the news media videos as a source of data about Patriot's performance. Second, a relatively large fireball size would indicate that the shrapnel pattern of the Patriot warhead should not play a central role in analyzing the videos. However, we stress that we do not, and never have, used the fireball diameter as a distance scale for determining hits and misses.

As noted in the main text, the fireballs seen on the videos are not simply balls of hot gas, but rather are complex mixtures of combustion products, smoke, and warhead and missile debris. Test-range videos of Patriot intercept tests, taken with precision cameras during daytime lighting conditions, typically show Patriot fireballs with diameters of about 20-30 meters. Figure B-l is a photograph of such a test-range intercept,[1] showing a fireball with a 25-30 meter diameter.[2] However, the available evidence indicates that the nighttime fireballs recorded by the news media cameras in Israel and Saudi Arabia appear to be at least several times larger than the daytime test-range fireballs.

As discussed in the main text, the video cameras see only a component of the Scud's velocity, given by $V \cdot \sin \alpha$, where V is the Scud's speed and a is the angle between the Scud's velocity vector and the line of sight of the camera. If we knew both V and a, then we would have a length scale with which to measure the fireball diameter, since the motion of the Scud between two consecutive video frames would correspond to a distance of $(V \cdot \sin \alpha)/30$.

The velocity of a Scud can be at least roughly estimated by modeling its trajectory. Given such a model of the Scud's flight path, the angle a could then be estimated if we know the location of the camera, the Scud's impact point, and the time between the intercept attempt and the Scud's impact on the ground.

Many of the Scud impact points are known in Israel; however, most of the intercept attempts caught on video occurred in Saudi Arabia, where very few impact points are known. However, there are a few cases where enough information is available to allow some conclusions to be drawn regarding the size of the Patriot fireballs.

Figure B-l: A Patriot intercept attempt on a Lance missile at the White Sands Missile Range. The Patriot has damaged the control surfaces of the Lance (which will later cause it to tumble), but otherwise the Lance is intact. A measurement of the length to diameter ratio of the Lance (a Lance is about 6.14 meters long and 0.56 meters in diameter) indicates that the Lance is not significantly foreshortened by viewing angle effects (alternatively, the fireball diameter can just be measured with respect to the Lance diameter). The fireball diameter is four to five times the Lance length, or about 25-30 meters.

12 February, Tel Aviv

We first consider the Patriot-Scud engagement at Tel Aviv on the morning of 12 February. In this engagement, a single Patriot appears to miss a Scud by a large distance, with the Scud continuing onward and exploding on the ground. The location of the Scud impact is approximately known.[3] It fell between two houses in a neighborhood of individual homes in or near the town of Savyon. It leveled both houses and irreparably damaged a number of other homes.

The location of the video camera is not precisely known, but it was certainly on an upper floor of a tall building in downtown Tel Aviv, most likely at the Hilton hotel. Savyon is about ten kilometers from downtown Tel Aviv, about 20° south of due east from the major hotels located along the Mediterranean shore. The Scuds approached from about 10° north of due east. For simplicity, we will assume that the Scud trajectory (and thus the intercept point), the impact point, and the camera location all lie in

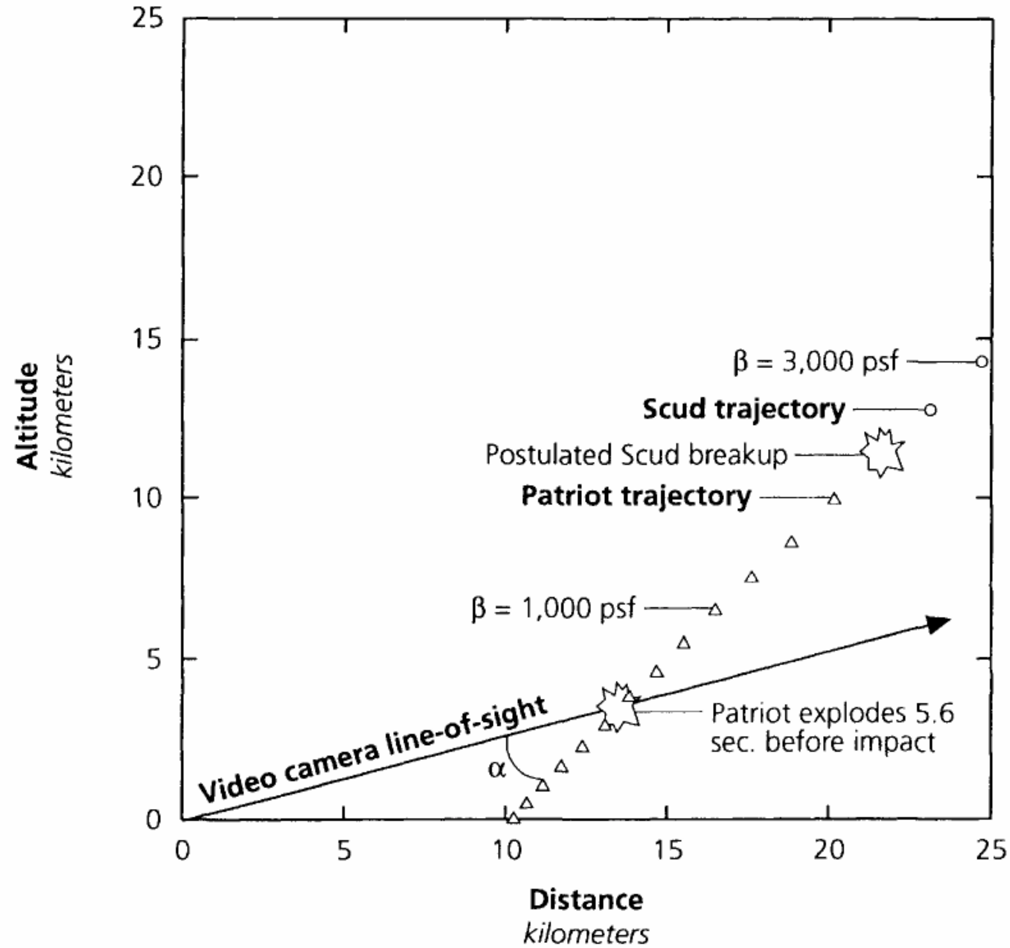


Figure B-2: Estimated video camera viewing geometry for the engagement at Tel Aviv, 12 February 1991. This figure assumes that the Scud's direction of approach, the intercept point, and the camera location all lie in a single plane. The figure also assumes that the Scud breaks up at an altitude of 11.4 kilometers, reducing its ballistic coefficient p from 3,000 to 1,000 pounds per square foot. The camera sees a component of the Scud's velocity Vat the time of the intercept which is given by $V \cdot \sin \alpha$.

a single plane. This assumption reduces the intercept geometry to a two dimensional problem, and will lead to a slight underestimate of the fireball diameter.

The geometry of this intercept attempt is shown in figure B-2. The choice of the Scud trajectory is important, because the fireball diameter will depend on the intercept altitude and on the Scud's speed at the time of the intercept attempt. The Scud trajectory shown on figure B-2 assumes that an intact Scud, with a ballistic coefficient of 3,000 PSF (pounds per square foot), breaks up at an altitude of about 11.4 kilometers. The warhead section is then assumed to continue onwards, but with its ballistic coefficient reduced to 1,000 PSF. The resulting trajectory is in good agreement with what is known about the time it took for Scud warheads to reach the ground following intercept attempts.[4] Table B-l provides relevant numerical data for this Scud trajectory.

In the 12 February engagement, the Scud is intercepted at an unusually low altitude, and the Scud warhead strikes the ground only 5.6 seconds after the intercept

Table B-I: This table lists the characteristics of the Scud trajectory used in this paper. The Scud is assumed to have a ballistic coefficient of 3,000 PSF (pounds per square foot) until it descends to an altitude of about 11.4 kilometers. At this point, the Scud is assumed to break up, reducing its ballistic coefficient to 1,000 PSF.

Time to impact *km sec*$^{'1}$	Altitude *kilometers*	Downrange distance *kilometers*	Re-entry angle *degrees*	Speed *km sec*$^{'1}$
13.0	11.38	11.36	43.6	2.04
12.0	10.02	9.94	43.8	1.90
11.0	8.76	8.62	44.0	1.75
10.0	7.59	7.42	44.3	1.61
9.0	6.51	6.32	44.5	1.48
8.0	5.52	5.31	44.8	1.35
7.0	4.61	4.40	45.1	1.24
6.0	3.77	3.57	45.5	1.13
5.0	2.99	2.81	45.8	1.03
4.0	2.28	2.12	46.2	0.95
3.0	1.62	1.50	46.6	0.87
2.0	1.01	0.93	47.1	0.80
1.0	0.45	0.41	47.6	0.74
0.0	0.00	0.00	48.0	0.69

attempt. For the Scud trajectory shown in figure B-2, the intercept attempt would occur at an altitude of about 3.5 kilometers and at a ground range from the camera of about 13.3 kilometers. Thus the angle between the line of sight from the camera to the Scud and the horizon is about 14.7°. At the intercept attempt, the Scud's velocity vector is oriented about 45.6° above the horizon, so a is about 30.9°. The Scud's speed is about 1.09 km sec"^{1}, so the apparent distance the Scud moves per frame is about (1,090/30) • sin (30.9°) = 18.7 meters. In this case, the fireball diameter is about six times the Scud motion per frame (see table B-2). We thus get a fireball diameter of about 110 meters.[5]

In this engagement, the apparent miss distance is roughly 19 times the distance the Scud moves per frame, so that the minimum possible miss distance is about 350 meters. It is possible that the actual miss distance is much larger, since we see only a two dimensional projection.

25 January, Riyadh

Next consider the last of the three engagements discussed in detail in the main text—

Table B-2: The ratio of the Patriot fireball diameter to the apparent distance the Scud moves between two consecutive video frames.[0] The intercept attempts shown here are all of the ones we label as "clear misses" (except for the one recorded by the infrared camera) where this ratio could be directly measured.

Date	Place	Intercept attempt	Ratio
9 February	Tel Aviv	1	3.4
		2	1.9
		3	3.1
1 1 February	Tel Aviv	1	2.4
		2	1.5
		4	1.5
12 February	Tel Aviv		5.9
19 February	Tel Aviv		11.5+
21 January	Riyadh, Scud #3		6.9
25 January	Riyadh, Scud #2	1	15.4
26 January	Riyadh		3.2
3 February	Riyadh	1	5.4
		2	3.1
8 February	Riyadh	1	2.4
		2	1.2
24 February	Riyadh		4.2
20/21 January			1.4
26 January	Dhahran	1	5.0
		2	3.3
		3	1.6
unknown	unknown	1	17.9
Average			4.8
Average ratio if the three intercept atte jmpts with ratios greater than 10 are dropped			3.2

i. In order to be conservative in our analysis, we have used (with one exception) the smallest fireball size seen on the first five video frames after the Patriot warhead detonation (this is why, for example, the ratio for the second Scud to Riyadh on 25 January is only about 15, instead of the value of 24 cited in the main text—which was obtained using the Patriot fireball diameter in the first frame after the detonation). Since the fireballs are generally somewhat asymmetric, the diameters given here are the average of the fireball's "length" and "width." The exception noted above is one case where the camera just catches the beginning of the warhead detonation, which is visible as a small bright point. For this case, the smallest fireball diameter on frames 2 through 5 after the detonation is used.

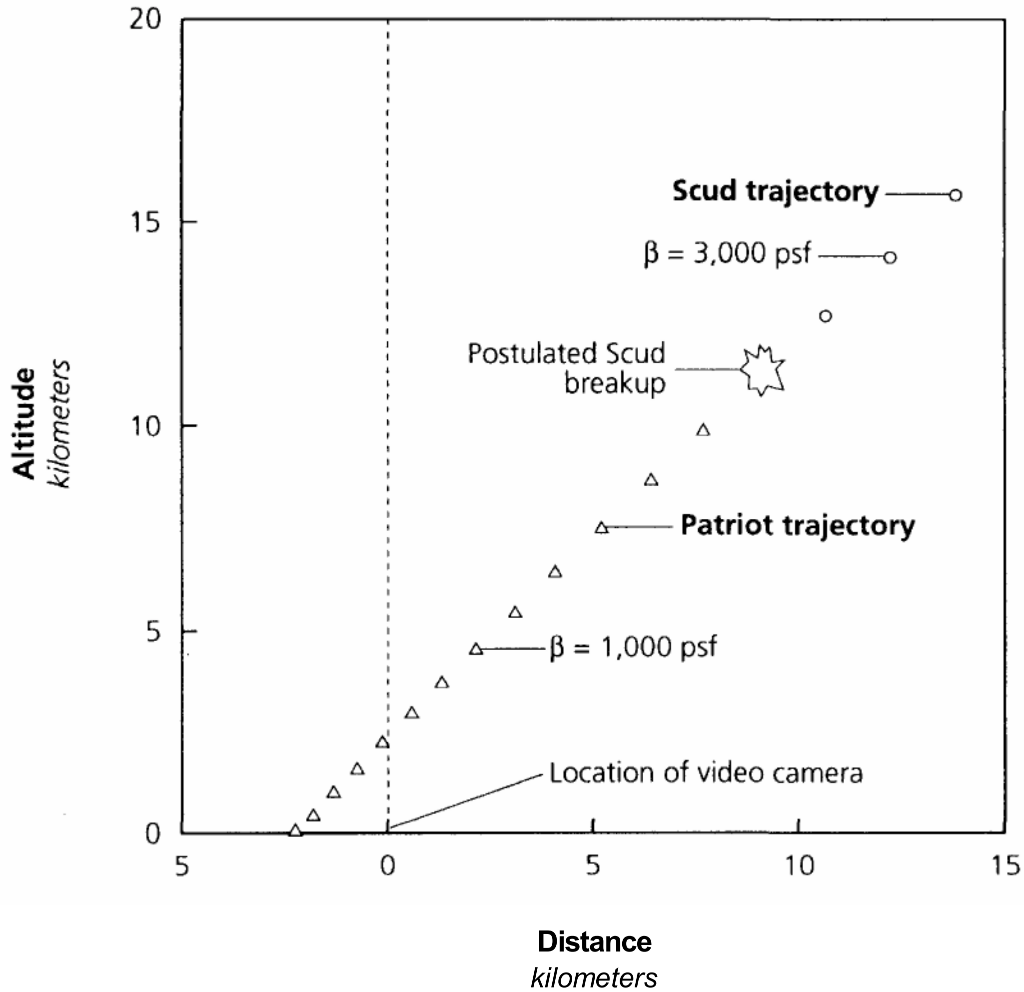


Figure B-3: Video camera viewing geometry for the second engagement in Riyadh on 25 January. The figure assumes that the Scud impact point, the intercept point, and the video camera location all lie in single plane. No intercept point is shown because the intercept altitude is not known.

the second Scud at Riyadh on 25 January 1991. The camera viewing the first intercept attempt on this Scud (shown on Video Sequences 9, 10, and 11) was located just outside the Riyadh Marriott Hotel. The Scud struck a Saudi Ministry of Interior building located about 2.25 kilometers south of the Marriott. Since the Scuds were coming from the north, this Scud must have passed nearly directly over the camera at an altitude of about two kilometers.

Figure B-3 shows the geometry of the intercept attempt, assuming the same Scud trajectory used in figure B-2. The only problem here is that we cannot directly estimate the intercept altitude, since there is a cut in the tape between the intercept attempt and the ground explosion.

Nevertheless, we can proceed by calculating the angle a and the fireball diameter as a function of intercept altitude. Proceeding in the same way as in the previous example, we get the plot of fireball diameter versus altitude shown on figure B-4. This shows a minimum fireball diameter of roughly 200 meters, assuming a relatively high intercept altitude of about 12 kilometers.

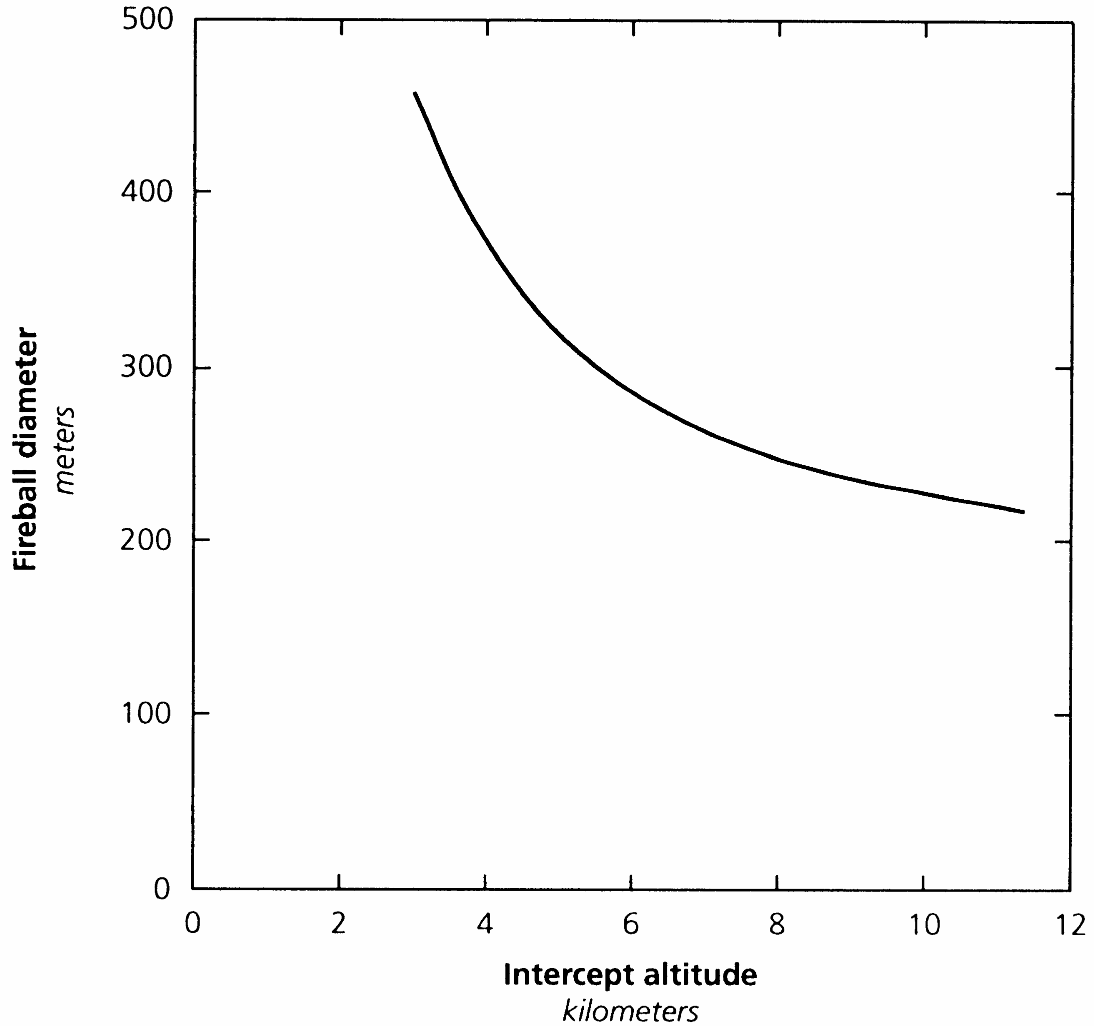


Figure B-4: Estimated Patriot fireball diameter as a function of the altitude of the intercept attempt for the first intercept attempt on the second Scud at Riyadh on 25 January 1991. The fireball diameter is calculated using the geometry shown in figure B-3 and is calculated as a function of intercept altitude since the intercept altitude is not known.

The analysis leading to figure B-4 also indicates that the minimum possible miss distance is about 200 meters. But the minimum possible miss distance is so large in this case that the Patriot could not possibly have fuzed on the Scud. This strongly suggests that the Patriot explosion we see was due to the Patriot self-destructing after having failed to acquire its target (or possibly due to the Patriot intercepting debris from the Scud's breakup), which indicates that the Patriot detonation probably occurred in or near the Scud's wake. In this case, most or all of the sin α factor would be cancelled out, leading to an actual miss distance many times greater than 200 meters.

The two cases analyzed here can provide only very rough estimates of Patriot fireball diameters, in part due to the erratic trajectories followed by some of the Scuds captured on video. Nevertheless, the cases analyzed here clearly indicate that the observed nighttime Patriot fireball diameters are at least several times larger than the roughly 25 meter diameter Patriot fireballs observed in daylight conditions.

It is also informative to consider what a review of the broader body of data on

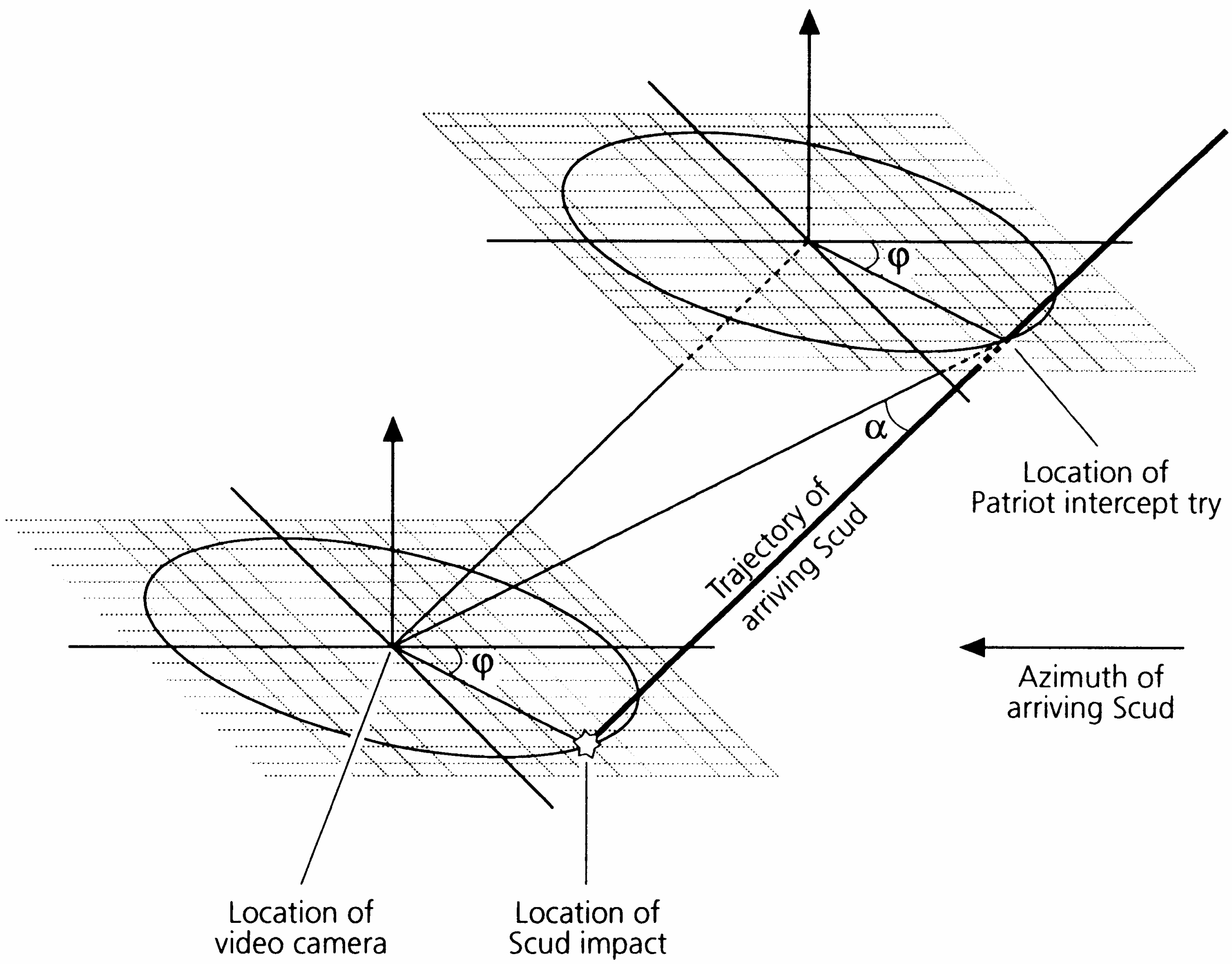


Figure B-5: Geometry used in estimating the value of a (the angle between the Scud's velocity vector and the line of sight from the camera to the Scud) as a function of the position of the Scud's impact point relative to the camera. The model assumes that intercepts occur at an altitude of ten kilometers and that the Scud falls at a constant angle of 45°. It is then straightforward to calculate a as a function of the distance of the Scud impact point from the camera and the angle *ty* between the azimuth of the direction of approach of the Scud and a line from the camera location to the Scud impact point.

intercept attempts indicates about the Patriot fireball diameter. Table B-2 shows the ratio of the Patriot fireball diameter to the Scud motion per frame for 21 intercept attempts. The intercept attempts in table B-2 are all of the ones that we label as clear misses where this ratio could be directly measured.[6] Table B-2 shows that in every case, the Patriot fireball diameter is larger than the distance the Scud moves per frame. Given that these intercept attempts are from 14 different engagements, with a variety of different viewing geometries, this strongly suggests that typical Patriot fireball diameter is comparable to or somewhat larger than the distance a Scud moves in one video frame time (or about 70 meters at a typical intercept altitude of ten kilometers).

Table B-2 shows that the ratio of the Patriot fireball diameter to the apparent Scud motion per frame ranges from 1.2 to about 18. On average, the Patriot fireball is about 4.9 times larger than the apparent distance the Scud moves per frame. If we exclude the three intercept attempts where the ratio of fireball diameter to Scud motion per frame is very large (greater than 10) the average value of this ratio is about 3.2.

In order to interpret these ratios, we need to know the range of typical values for the angle *a*. This can be estimated by constructing a simple geometrical model. This model relies on two assumptions:

- The Scud falls from the intercept point to the ground at a constant angle of 45°. As the Scud trajectory on figures B-2 and B-3 suggest, this assumption is likely to be reasonable for many of the engagements that are on the video tapes.
- The intercept attempt takes place at an altitude of ten kilometers. This altitude is a reasonable choice for a typical intercept attempt, although it is likely that some intercept attempts are a few kilometers higher, and it is known that some were lower.

The geometry used in our model is shown in figure B-5. The video camera is located at the origin of an x, y, z coordinate system (the z axis is vertical). The Scud is assumed to be approaching in an x-z plane (that is, its ground track is parallel to the y axis). The Scud's impact point is defined in spherical coordinates by its distance *R* (in kilometers) from the camera and by an angle ϕ measured from the x-axis. Thus $\phi = 0$ corresponds to a Scud that is directly on line with the camera but falls short, whereas $\phi = 180°$ corresponds to a Scud that flies directly over the camera.

The coordinates of the impact point (in kilometers) are then given by $x = R \cdot \cos\phi$, $y = R \cdot \sin\phi$, $z = 0$ and the intercept point is simply at 45° up from the impact point: $x = R \cdot \cos\phi + 10$, $y = R \cdot \sin\phi$, $z = 10$. Since the Scud's velocity vector is assumed to be 45° from the horizontal, it is then a simple matter to compute the angle α. Figure B-6 shows the result: it plots the value of $\sin\alpha$ as a function of the angle ϕ to the impact point for several different values *of R* (the distance of the Scud impact point from the camera).[7]

How far from the camera did Scuds typically land? Consider the case of Tel Aviv. The exact or approximate impact locations are known for 16 Scuds that landed in the general vicinity of Tel Aviv.[8] Most of camera crews were apparently filming from the hotel they were staying at, and for the purpose of discussion here, we will assume that the camera was located at the Tel Aviv Hilton. The points corresponding to 14 of these Scuds are plotted on figure B-6.[9] As can be seen on figure B-6, the values of $\sin\alpha$ range from about 0.14 to 0.57, with an average of about 0.30.[10]

The product of the average ratio of fireball diameter to Scud motion per frame and the average value of $\sin\alpha$ can be thought of as giving an "average" fireball diameter in terms of the distance the Scud moves in one video frame time (roughly 70 meters at a typical intercept altitude often kilometers). This product is (3.2 to 4.9) • 0.30 = 0.96 to 1.47, indicating a fireball diameter of order (0.96 to 1.44) • 70 = 67 to 103 meters.

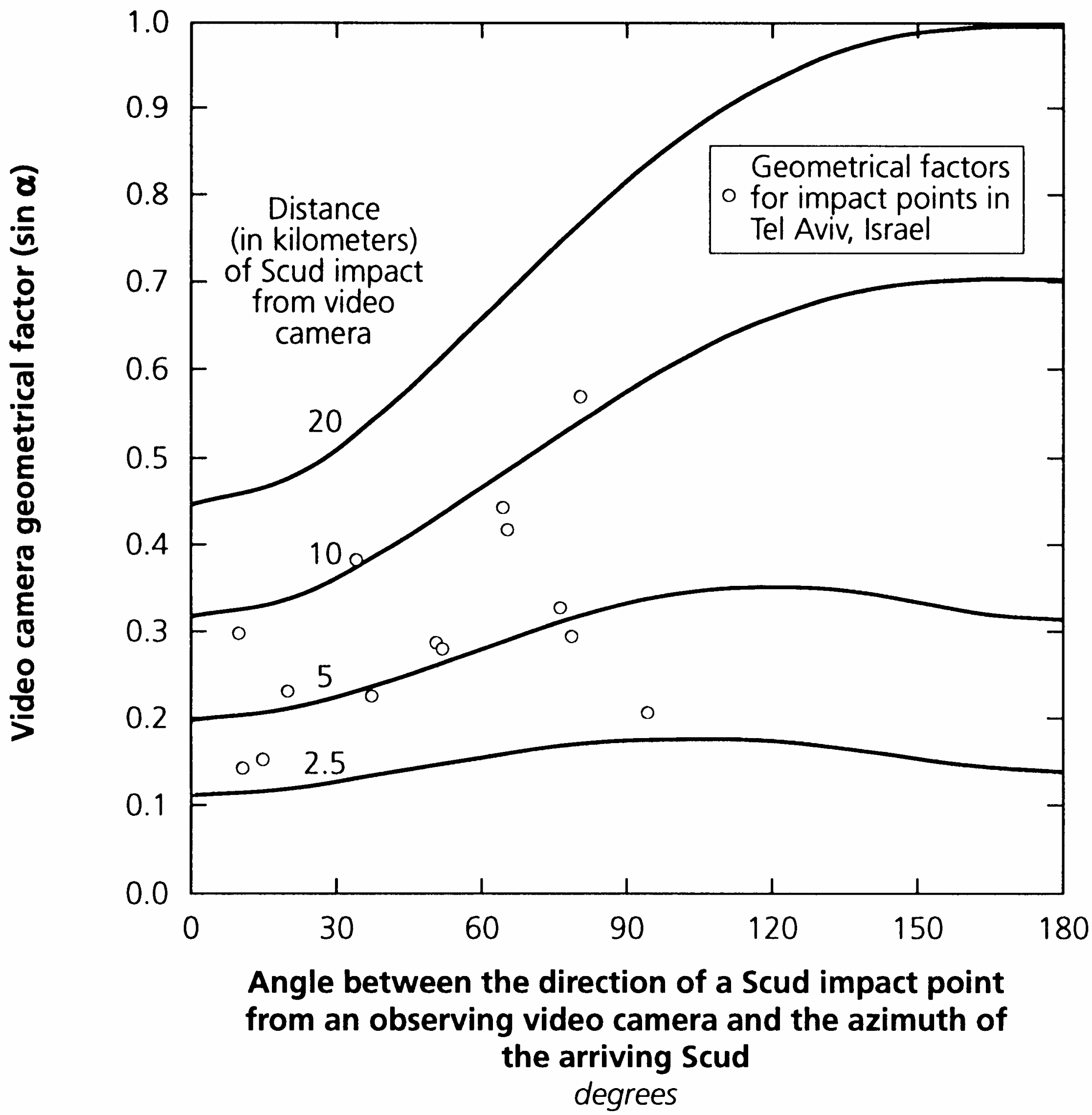


Figure B-6: The value of the geometrical factor sin a as a function of the distance of the Scud impact point from the video camera and the angle ϕ between lines drawn from the camera to the Scud impact point and the Scud's azimuth of approach. The geometry used to calculate a is shown in figure B-5. The four solid lines are for Scuds assumed to land respectively 2.5, 5, 10, and 20 kilometers from the camera. Only positive values of ϕ are shown, since sin α is symmetrical about ϕ = 0. The circles show the values of ϕ, sin α, and the distance of the impact point from the camera for 14 Scud impact points in or near Tel Aviv, assuming that the camera is located at the Tel Aviv Hilton.

NOTES AND REFERENCES

1. This photograph is identified as: "Patriot Intercepts Lance Missile," 11 September 1986. US Army Photo by: Optics Land/Air, WSMR, NM, photo # 6." This is thus a PAC-1 warhead intended for use against airplanes; however, we are aware of no reason why the PAC-2 warhead used against the Scuds should produce a significantly different size fireball.

2. In figure B-l, the fireball is four to five times the length of the Lance (which is 6.14 meters long—indicating a fireball with a diameter of 25-30 meters. The length to diameter ratio of the Lance in figure B-l establishes that the Lance is nearly intact and is viewed from near side-on.

We have obtained test-range video showing eight Patriot intercepts of missiles (including, it appears, the one shown in figure B-l). These videos are not as clear as the original of the photograph reproduced in figure B-l, but rough measurements of fireball diameters are possible. In two cases, the fireball diameter-missile length ratio was about four, in four cases it was about five, in one case about 10, and in the other case more than 20 (the reason for this very large fireball is not known—it may be due to unburned fuel in one of the missiles or to some similar cause). No corrections have been made for angular factors—the videos generally appear to be side-on views—and in at least some cases, the relevant missile length is that of a Patriot (5.3 meters) rather than that of a Lance, and it cannot be conclusively ruled out that one or two of the videos are different camera views of the same intercept attempt.

The test-range intercept attempts are from the following three videotapes: "Patriot ATM Capability Deployed for Multi Threat Capability," Missile Systems Division, Raytheon Company, Bedford, Massachusetts; "After Desert Storm," Independent Communication Associates, Ltd., London; and "The Patriot Missile: Hero or Hoax," an episode of the Arts and Entertainment Network's "Investigative Reports" series.

3. Lewis, Fetter, and Gronlund, *Casualties and Damage.*

4. Typical intercept altitudes were apparently about ten kilometers. The average time to ground for Scuds following an intercept attempt was about 11.8 seconds. The trajectory assumed here has a time to ground of 12 seconds from a ten kilometer alti tude.

The average time to ground for Scuds following an intercept attempt was determined by averaging over 12 of the 14 intercept attempts for which this time could be measured. Two intercept attempts that clearly took place at unusually low altitudes were excluded from this average. These are the first intercept attempt in Riyadh on 25 January, and the intercept attempt at Tel Aviv on 12 February—the one we are discussing here. The twelve times to ground used were (in seconds):

Riyadh	26 January	12.4,11.1
Dhahran	26 January	13.3, 11.4,9.3
Tel Aviv	9 February	15.5,12.3,12.0
Riyadh	3 February	12.8, 11.5
Dhahran	23 January	11.1,8.9

5. If we had assumed that the Scud behaved like an intact Scud (with a ballistic coef ficient of 3,000 PSF), then the intercept altitude would have been 6.7 kilometers, the Scud speed at the intercept attempt would have been 1,890 m sec""^{1}, and a would have been 22.4°, giving a fireball diameter of about 140 meters.

6. In a few of the clear misses, the Patriot fireball and the Scud cannot both be seen on the television screen at the same time. In addition, the clear miss on the infrared

video is not included, because the appearance of the fireball is significantly different from that of the fireballs recorded by cameras operating at visual wavelengths.

7. Since sin α is symmetric for positive and negative values of ϕ, we plot sin α only for the positive values of ϕ.

8. A map showing the impact locations plotted in figure B-6 is in Lewis, Fetter, and Gronlund, *Casualties and Damage,* p. 23.

9. Two Scuds that landed at larger distances (15 and 16 kilometers) from the Hilton are not plotted because it is not clear if Patriot would have attempted to engage them. Note that not all of the Scuds plotted on figure B-6 were engaged: some of them fell before Patriot was operational.

10. The points plotted in figure B-6 are primarily at angles between 0 and 90°. Larger angles are uncommon because the camera location is near the coast; most Scuds with higher angles would have fallen into the Mediterranean. Since higher angles tend to give higher values of sin α, it seems likely that a somewhat higher average value of sin a would be obtained if it were possible to include Scuds that fell into the Mediterra nean.

Appendix C: Patriot Warhead Kill Radius and the Patriot Fuze

This appendix discusses some of the fuzing-related factors that determine whether it is possible for a Patriot to successfully destroy the warhead of an incoming Scud missile. Since the end of the Gulf War, there have been credible and persistent reports that Patriot was not fuzing properly against Scud targets during the Gulf War.[1] In this appendix, we will show that publicly reported technical details about the properties of the Patriot's fuze and its warhead indicate that it is entirely plausible that these reports are correct and that the Patriot fuze may have been detonating the Patriot warheads too late to destroy the Scud warheads.

The Patriot PAC-2 warhead and fuze were developed for use against missiles with ranges comparable to that of the Scud-B, which has a range of about 300 kilometers, and they were tested against such targets. However, during the Gulf War, Patriot was attempting to engage 600 kilometer range modified Iraqi Scuds, which re-enter at a speed that is approximately 40 percent higher than the shorter-range Scud-B. As a result, the closing speeds between the Patriots and the Iraqi Scuds were higher than the speed for which the Patriot fuzing system had been designed. Because of this high closing speed, it is possible that the Patriot fuze may have been detonating the Patriot warhead too late to destroy the Scud warhead.

The Patriot system is designed to destroy its target by detonating a fragmentation warhead close to the target. When a Patriot warhead detonates at the proper time, steel fragments from the Patriot warhead are sprayed out towards the target causing it to be damaged or destroyed. As we will show below, the fragments from a Patriot war-head travel at a speed that is lower than the closing speed between the Scud and Patriot. As a result, unless the Patriot warhead is detonated with near perfect timing, the front end of the Scud (which contains the warhead) will be missed by the Patriot fragments and the Scud warhead will be undamaged. We will show below that the Patriot PAC-2 fuze cannot sense an arriving Scud until it is nearly at the last possible point where a Patriot warhead detonation can damage the Scud warhead, raising the possibility that the Patriot's fuze will sense the Scud too late to have any chance of hitting the Scud warhead.

Patriot missiles attempt to intercept missiles such as Scuds by flying the Scud's trajectory in reverse, so that the two missiles approach each other head-on, and this is the intercept geometry we will discuss here. The large closing speed between the two missiles (typically about 3.0-3.5 km sec"[1])[2] will result in the Patriot's fragment pattern being peaked forward into a conical volume in the Scud's rest frame. Figure C-l illustrates the intercept geometry.

The cone angle shown in figure C-l depends on the speed of the Patriot's warhead fragments relative to the closing speed between the two missiles. The high-explosive in the Patriot warhead is Octol, and the ratio of the warhead's high explosive charge mass (C) to its fragment mass (M) is about *C/M* = l.l.[3] The fragment speed can then be estimated from the following equation:[4]

$$V = G\left(\frac{\frac{C}{M}}{1+0.5\frac{C}{M}}\right)^{\frac{1}{2}} \qquad \text{(C-l)}$$

where *G* is the Gurney constant, which is 2,965 m sec [1] for Octol.[5] The resulting fragment speed is 2.5 km sec"[1]. Since the form of the equation used here is for an infinitely long cylinder, the actual fragment speed will be somewhat lower when end effects are taken into account. The half-angle of the conical volume into which the fragments are confined (in the Scud's rest frame) is then given by $\alpha = \sin^{-1}$ (fragment speed/closing speed) = $\sin^{-1}$ (2.5/3.5) = 46°.[6] Thus in order for an intercept attempt to succeed in destroying a Scud's warhead, for the conditions assumed here, the Patriot warhead must detonate in a conical volume with a half-angle of 46° ahead of the Scud warhead.

The PAC-2 Patriot missile used during the Gulf War has one or more fixed strip-line fuzes along the side of the missile.[7] This pulse-doppler fuze produces two beams: a broad side-looking beam for use in aircraft intercepts, and a narrower forward-looking beam for use in missile intercepts.[8] The narrower anti-missile beam is oriented about 40-55° off the nose of the Patriot.[9] If the Patriot is close enough to the target missile, the fuze will detect the target as it sweeps through the narrow beam, and the Patriot warhead will then be detonated. The Patriot fuzing geometry is illustrated in figure C-2.

Figure C-2 shows that a comparison of the cone angle into which fragments from the Patriot warhead will be sprayed and the cone angle formed by the radar beam of the Patriot fuze indicates that only near perfect and instantaneous operation of the Patriot fuze will result in any chance that fragments from the Patriot warhead will hit even the back of the Scud warhead. For example, if the missiles are on antiparallel trajectories but their centerlines are offset from each other by five meters, the nosetip of the Scud will first intersect the leading edge of the fuze beam when the Scud is 4.2 meters ahead of the Patriot.[10] (This calculation assumes that the leading edge of the fuze beam is 40° off the Patriot's nose and the fuze is located at the Patriot warhead location, 1.8 meters behind the nosetip of the Patriot.) Approximately one millisecond later, with the Scud now 0.5 meters ahead of the Patriot, the Patriot warhead passes

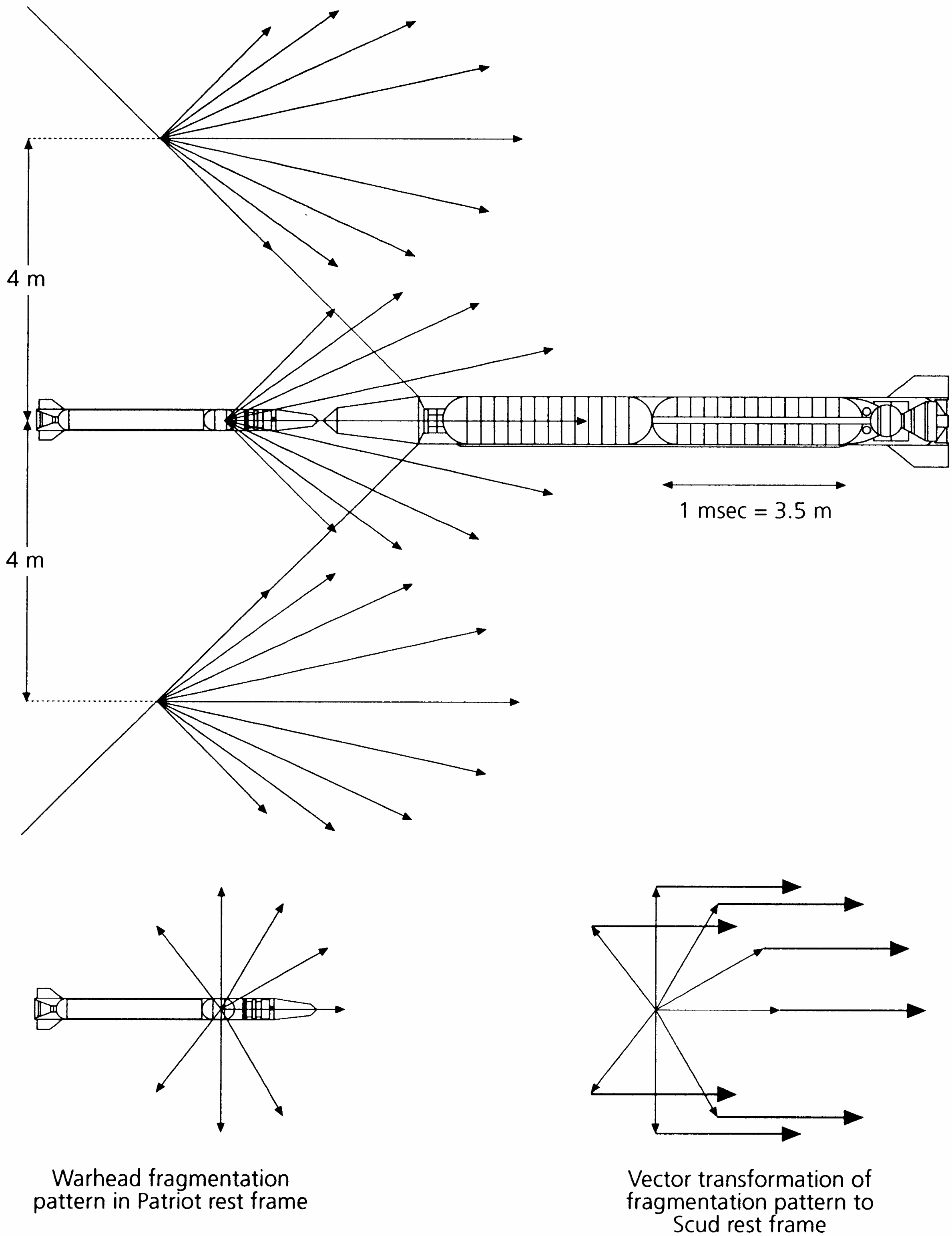


Figure C-I: The geometry and timing of a head-on intercept attempt. This figure assumes a Patriot warhead fragment speed of 2.5 km sec"^{1} and a Patriot-Scud closing speed of 3.5 km sec"^{1}. In the Scud's rest frame, the large closing velocity between the two missiles causes the fragment distribution to be peaked forward into a cone with a half angle of about 46°. Thus if a fragment is to strike the Scud warhead, the Patriot warhead must detonate in a conical volume ahead of the Scud warhead.

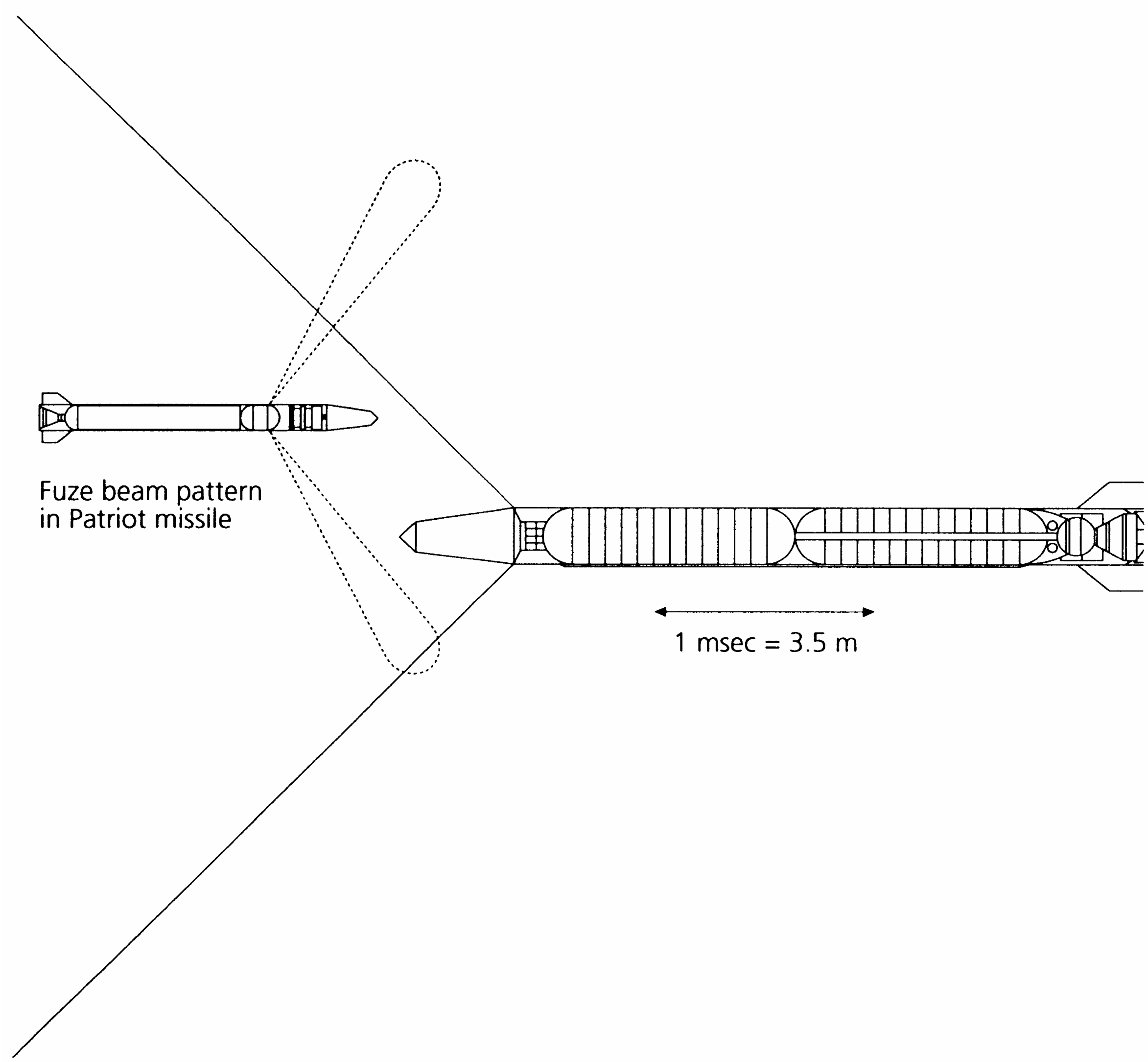


Figure C-2: Fuzing geometry for an intercept attempt on a Scud. The closing speed is assumed to be 3.5 km sec"[1]; the 3.5 meter distance the missiles move relative to each other in one millisecond is shown by the arrow beneath the Scud. In order for a Patriot warhead fragment to hit the Scud warhead, the Patriot warhead must explode within the conical volume defined by the solid lines. The fuze beam, oriented 40-55° off the nose of the Patriot, is shown by the dashed lines. (The fuze is assumed to be located at the same position as the Patriot warhead.) The Patriot fuze pattern will begin to intersect the nose of the Scud only very shortly before the last opportunity to destroy the Scud's warhead.

out of the conical volume in which it is possible for a Patriot fragment to strike the Scud warhead. If the Scud warhead is to be destroyed the Patriot must be detonated within this 3.7 meter interval, which corresponds to about one millisecond of time. If the offset distance between the missiles' centerlines is 20 meters instead of five, then the Scud nosetip first intersects the fuze beam when the Scud is 22 meters ahead of the Patriot. About two milliseconds later, with the Scud now 15 meters ahead of the Patriot, the Patriot warhead passes out of the conical volume in which a warhead kill is possible.

Thus if Patriot is to kill a Scud warhead, the Patriot warhead must *not* explode at the point of closest approach to the Scud warhead; it must explode ahead of the Scud. The distance ahead it must explode will be different for each different centerline offset distance. Moreover, a detonation behind the Scud warhead will never damage it.

The analysis here indicates that, with the assumptions used here, it is possible for the Patriot's fuze to detonate the Patriot warhead so that fragments will strike the Scud warhead. However, the margin of error is extremely slim—roughly 3.5 meters or one millisecond for a five meter offset.

However, small departures from the near-ideal parameter values assumed in our model can result in conditions where the fuze cannot act quickly enough to destroy the Scud warhead before it has passed by the Patriot. Two such possible non-ideal engineering limits on the fuze are:

* As discussed above, our estimate of the Patriot fragment velocity is probably too high. If the actual velocity is ten percent lower (2.25 km sec^{-1}), then the half-angle of the conical volume in which a warhead kill is possible falls to 40°—the same as the fuze beam leading edge—and the margin of error is cut to about 0.6 milliseconds (independent of the offset distance).

» The pointed nose of the Scud should result in only a very small initial reflected signal for the Patriot radar fuze to detect. As a result, it is unlikely that the Patriot fuze would detect the leading edge of the Scud missile. If the fuze triggers the warhead detonation when the Scud's nosetip reaches the middle of the fuze beam (here assumed to be at 47.5°) instead of the leading edge, the margin of error will be only about 0.5 milliseconds for a five meter offset. Combined with the effect of ten percent slower fragments, it would not be possible to hit the Scud warhead if the offset distance was eight meters or larger. If the fuze triggers only when the full body diameter of the Scud first reaches the center of the beam pattern, it will be too late for any fragments to strike the Scud warhead at any offset distance.

The analysis presented here, based on the best publicly available data, cannot firmly establish over what range of closing speeds and angles Patriot would have been able to fuze in time to have a chance of destroying a Scud's warhead. Such an analysis would require much detailed information about the Patriot system that is not publicly available, including data on the fragmentation pattern of the Patriot warhead, the precise speed of fragments produced by the detonating warhead, and details of the beam geometry of the Patriot fuzing system. In addition, the closing speed between the Scud and the Patriot, and the geometry of the Patriot-Scud encounter, will vary with each intercept attempt, and these factors will strongly affect the possible outcomes of an intercept attempt.

Nevertheless, the analysis presented here gives a good qualitative picture of what the Patriot fuze had to accomplish to achieve warhead kills against Gulf War Scuds. It also clearly indicates that accounts, such as those cited at the beginning of this appendix, that indicate that there was a Patriot fuze problem are entirely plausible. The source of such a fuzing problem would be the inability of the Patriot's fuze to sense the front end of an Iraqi Scud before it has passed beyond the point where the Patriot's fragmentation warhead can destroy it. The Gulf War video data we have studied, which show that in at least two engagements Patriot apparently hit a Scud without destroying the Scud's warhead, is completely consistent with the possibility that the Patriot's fuze was incapable of performing adequately against the Iraqi Scud missile.

An understanding of Patriot's fuzing performance is central to operating the Patriot system in the most effective way. For example, if Patriot's fuze actually was incapable of detonating the Patriot warheads in time at closing speeds of 3.5 km sec^{-1}, it might have been more effective to try to make intercepts at lower altitudes, where closing speeds would be smaller. Given that the performance of the Patriot fuze was recognized to be a potentially serious problem, one would expect it to be the subject of detailed analyses by the US Army both during and after the Gulf War. Instead, however, according to the GAO, the Army has not used *any* of the (albeit limited) Gulf War data to analyze how Patriot's fuzing system performed:

> Computer-generated data also do not provide information on whether the Patriot's fuze reacted quickly enough to destroy the Scud. A Project Office engineer told us the closing velocity, or the speed at which the Patriot and Scud approach one another, helps determine whether the Patriot's fuze had time to arm and detonate before the Scud passed the intercept point. He said this information could be determined from recorded data. However, the project officials did not develop the information because they did not believe it would benefit the assessment process. The additional data would not have shown that the Patriot detonated sufficiently close to the Scud to have a high probability of killing it.[11]

NOTES AND REFERENCES

1. *Defense News* reported that according to an Israeli source, "...the Patriot fuze was often found to be ineffective against tactical ballistic missiles whose closing speeds were more than 2,700 meters per second. According to the Israeli source, closing speeds in the Persian Gulf War were typically 3,600 meters per second." This reported problem with the Patriot fuze was also discussed in sworn testimony before the House Government Operations Committee on 7 April 1992 by Reuven Pedatzur who stated that: "Further analysis [by a team of Israeli Air Force analysts] turned up a problem related to the Patriot's fuze. It was found to be unsuited to the high closing speeds which developed between the al-Hussein [Scud] and the Patriot."

More recently, shortcomings in Patriot's fuzing performance during the Gulf War were strongly implied in statements reported in *Defense News* about one of the most important and publicized aspects of the proposed Patriot PAC-3 upgrade, which is the use of a new multimode seeker as the Patriot warhead fuze: "[Alan] Sherer [acting director for theater missile defense programs at the US Army Missile Defense Command] added that improvements to the Patriot's ability to aim and fuze its warhead will provide a measure of effectiveness lacking during the gulf war. 'We want the missile to be able to hit what we call the sweet spot, and that spot will be located in different places in different missiles. So knowing when to ignite the blast will be key to improved lethality,' Sherer said."

See Barbara Opall, "Patriot Debate Resumes: Israeli Study Revives Clash on Missile Performance," *Defense News,* 18 November 1991, pp. 3, 37. House Government Operations Committee, *Performance of the Patriot Missile,* p. 129, and George Leopold and Barbara Opall, "US Army Starts Tests on Upgraded Patriot," *Defense News,* 8-14 February 1993, pp. 4, 52.

2. At the 7 April 1992 Congressional Hearing on the Patriot, Major General Jay M. Garner stated that: "We have a closing velocity somewhere around 9,000 miles per hour [4.0 km sec^{-1}]." US House Government Operations Committee, *Performance of*

the Patriot Missile, p. 218.

3. The mass ratio is estimated from a drawing of the PAC-2 warhead in an advertis ing brochure produced by the warhead's manufacturer. ("Patriot Antitactical Missile Warhead," Chamberlain Manufacturing Corporation, Waterloo, Iowa.) Estimates made from the drawing indicate that the volume ratio of high-explosives to fragments is about 4.7. Since the fragments are made of steel, which has a density of about 7.8 gm cm^{-3}, and the Octol high-explosive has a density of about 1.81 gm cm^{3}, the volume ratio indicates that the Patriot warhead explosive to fragments mass ratio is about 1.1.

4. Gilbert F. Kinney and Kenneth J. Graham, *Explosive Shocks in Air, 2nd ed.* (New York: Springer-Verlag, 1985), p. 27; Gordon E. Jones, James E. Kennedy, and Larry D. Bertholf, "Ballistic Calculations of R.W. Gurney," *American Journal of Physics,* April, 1980, pp. 264-269.

5. Kinney and Graham, *Explosive Shocks in Air,* p. 237.

6. For the geometry analyzed here, and assuming that fragments are sprayed with equal velocities in all directions, the largest half angle is given by fragments that are thrown back (in the Patriot's rest frame) at an angle of 135° from the direction of the Patriot's motion. It is unclear if the Patriot warhead is designed to throw fragments back at such large angles; if it is not, then the half angle will be smaller.

7. David Hughes, "Successful Test of Advanced Patriot Confirms Value of Multi-Mode Seeker," *Aviation Week & Space Technology,* 27 April 1992, pp. 22-23.

8. Mark Hewish, "War-Winning Technologies: Patriot Shows its Mettle," *Interna tional Defense Review,* May 1991, p. 457.

9. Hughes, "Successful Test," p. 23.

10. That is, the component of the distance between the two missiles' nosetips that is parallel to the missiles'motion is equal to 4.2 meters.

11. US General Accounting Office, "Data Does Not Exist," p. 7.