Indicators of Iron Dome's Performance in Pillar of Defense

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This memo discusses some aspects of Iron Dome's performance in Operation Pillar of Defense that leads to the conclusion that Iron Dome intercepted a much lower percentage of target-rockets than the 84% intercept rate claimed by Israel Defense forces.

The materials presented herein are only a small piece of a much larger and more comprehensive body of analysis and data that indicates aspects of Iron Dome's performance. We expect substantial additional information to be made available shortly, that is complementary to what is presented here. This information will provide an additional very strong indicator that Iron Dome could not have performed at the very high level claimed by the Israeli government.

Serious questions about the high performance of Iron Dome are immediately apparent from videos of contrails and the location where Iron Dome warheads explode.

A very high percentage of the time, videos show that Iron Dome interceptors fly trajectories that would result in a near zero probability of destruction of the rocket-target's warhead. In numerous cases, two or more Iron Dome interceptors will fly in parallel trajectories each making the exact same maneuvers and then detonating at the same time. Such interceptor behavior should not be observed if the system is working as it was designed.

There is definite evidence in the video of Iron Dome intercept attempts that appear to have destroyed rocket warheads, but these events are extremely unusual relative to clear misses that can occasionally, but more often than hits, can be seen in both daylight and night videos. This data is very sparse, but it is absolutely consistent with the contrail data – which is an unambiguous indicator of performance problems with the Iron Dome system.

Further confirming the problems associated with Iron Dome interceptors crossing rocket trajectories at high angles and diving after rocket targets, there is significant photographic evidence of damage to rockets that are consistent with the failure of the fuse-warhead system to put warhead fragments on the rocket-target's warhead. In addition, the steep trajectories of the arriving rockets make it extremely unlikely that a hit that fails to destroy the warhead of an incoming rocket will result in a "safe divert" from valuable targets. All of these observations, which are totally consistent with each other, strongly indicate that Iron Dome performance had to be much lower than the 84% intercept rate being claimed by the IDF.

The photograph below (figure 1a) shows contrails for three Iron Dome interceptors that appear to be diving against what might have been an arriving rocket, or collection of rockets. Iron Dome interceptors on such trajectories have, for all practical purposes, no chance of destroying the warhead on the arriving rocket(s). This photograph is only one of many that indicate serious problems with the Iron Dome system's ground-based guidance command of interceptors.

The three Iron Dome interceptors can be seen flying first to a maximum altitude, and then diving in what appears to be attempts to intercept a rocket or collection of rockets. At the time these intercepts are being a tempted, the rocket-targets are falling at steep descent angles while Iron Dome is chasing them from behind.

By design, Iron Dome must fly a frontal trajectory for its fuse/warhead combination to have a significant probability of placing Iron Dome warhead fragments on a target-rocket's warhead. If the target-rocket's warhead is not destroyed, and goes on to the ground, it will almost certainly function properly and explode. Even though Iron Dome has a highly sophisticated electro-optical fuse (referred to in the literature as the electro-optical target detector, or EOTD), this fuse cannot possibly compensate for intercept geometries that are not frontal (what we mean by front told geometry will be explained below).

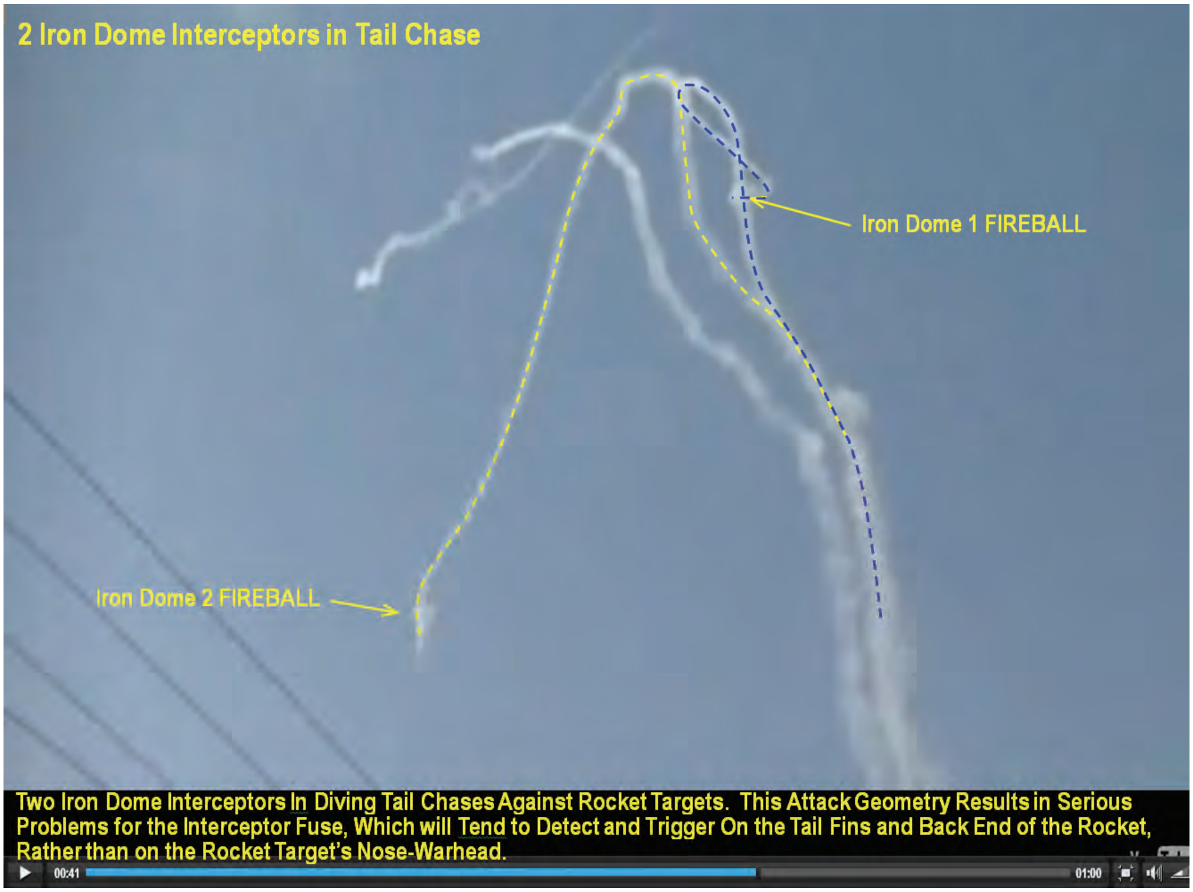


Figure 1a Iron Dome Diving On Rocket Makes For Difficult Endgame Geomerty

For a tail-chase geometry, it is not possible for the fuse to reliably initiate the Iron Dome's fragment spraying warhead so that fragments will impact a target-rocket's warhead. When an Iron Dome interceptor engages a rocket-target from its tail or side, the projected area of the rocket's warhead relative to the rod spray pattern varies between zero and 100%. This means that if random attack angles are the norm, the projected area of the rocket warhead, will vary roughly as the cosine of the engagement angle, and will therefore present a projected area that is quite small relative to the much higher efficiency front-on attack geometry.

Figure 1B shows how rods from the Iron Dome interceptor warhead travel relative to the rocket-target for a tail-chase engagement geometry. As can be seen by inspection of the diagram, the fuse will detect the rocket's tail first. Detailed analysis of the rod spray pattern and fuse combination, which includes consideration of the fuse lean angle, shows that the probability of placing fragments on the warhead will be very low, except in the situation where the Iron Dome interceptor flies an inverse trajectory (see inset A in figure 1B). Only the inverse trajectory makes it possible for the warhead fuse combination to engage the rocket in a geometry that allows for a proper rocket nose detection and warhead detonation time. The front on engagement geometry is essentially the only case where it could be reasonable to expect that Iron Dome would be able to reliably place a high density of rods on the rocket-target's warhead.

Many engagements observed in the videos show Iron Dome interceptors attempting to intercept rocket-targets from the side. In this geometry there is at best a 50% chance Iron Dome can put rods on the rocket warhead? If Iron Dome arrives earlier than the optimal time, there is little to no chance of putting rods on the rocket warhead.

If Iron Dome instead arrives later than the optimal time, there is a chance that rods can be placed on the rocket warhead, as long as the fuse time delay equation properly accounts for the geometry of the engagement and the rocket-target. However, the rocket is falling at a steep angle, and if the fuze detects the side of the rocket instead of the nose, then it will not be able to determine where the warhead is relative to the region on the rocket body that is detected. Since the fuse cannot obtain this critical information, there is no way to correct the warhead detonation time-delay to increase the chances that rods will hit the target-rocket's warhead. In addition, there is a huge reduction in the lethality of a hit on the warhead if the fragments hit the warhead at oblique angles. This large reduction in lethality is due to the obliqueness of a hit, which results in a significant reduction in the chances that hits on the target-rocket warhead will actually detonate the target-rocket's warhead. Unless the Iron Dome "kills" the warhead on the rocket-target by causing it to detonate in a high or low order explosion, the intercept attempt will not reduce the potential for damage when the warhead hits the ground.

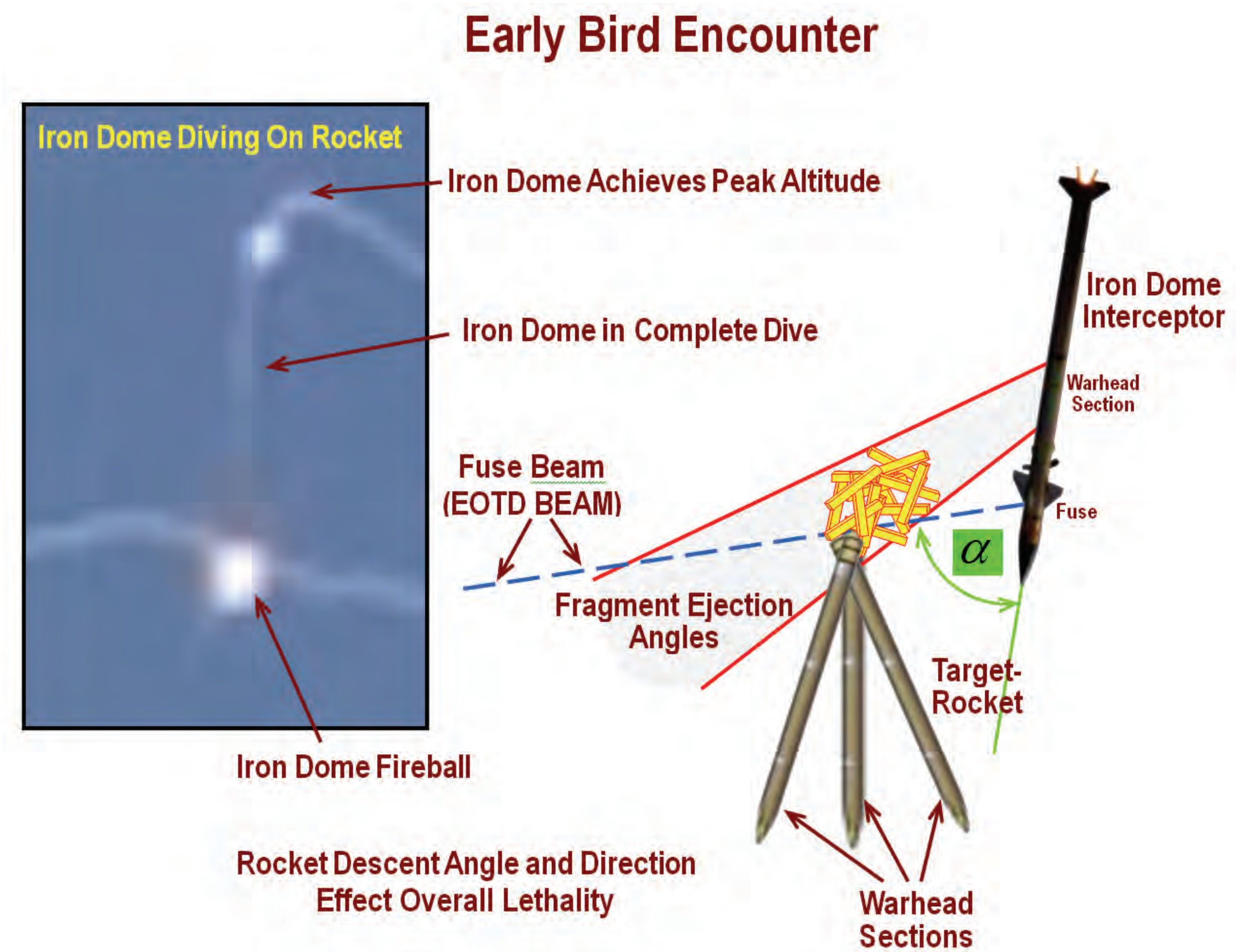


Figure 1b Endgame Engagement Showing EOTD/RODS Relative To Rocket

The Iron Dome has a laser fuse that detects the presence of an approaching target-rocket. As the rocket and the Iron Dome pass each other the laser fuse senses the rocket nearby and after a short delay detonates the Iron Dome warhead. The fragments from the Iron Dome warhead are carried forward by the motion of the Iron Dome and if the timing of the warhead detonation is correct, the fragments would hit the warhead. If the fragments hit the warhead with enough force, the warhead will be detonated harmlessly before the rocket reaches the ground.

It is worthy of note, that the Qassam rocket warhead is made from a mixture of TNT and ball bearings. The combination of an insensitive high explosive and the ball bearings requires a highly energetic impact of Iron Dome fragments in order to detonate the warhead. This is because of two effects, the TNT is insensitive to detonation, and more importantly, the ball bearings spread the impact pressure from the fragment impacts, which then results in a significant reduction of the probability that the target warhead will detonate. Some Grad rockets also contain short L/D rods that are packaged in the warhead which makes their warheads much harder to detonate.

In figure 1 inset B, the Iron Dome is depicted as chasing the rocket, as it would when it dives to make an intercept. In this geometry, the laser fuse on the Iron Dome detects the tail and the rear body of the rocket and detonates at the backend, leaving the warhead to go on to the ground and do damage.

In insets C and D, Iron Dome's are depicted as approaching the rocket-targets from a side-on geometry. Intercept attempts using this geometry are extremely sensitive to the arrival time of the Iron Dome interceptor. Inset C shows one possible outcome of such an intercept attempt and inset D shows the outcome if the Iron Dome interceptor arrives three thousandths of a second later. Because of the high crossing speeds, it is extremely unlikely that the fuse will detonate the interceptor's warhead at a time that will cause fragments to hit the target-rocket's warhead.

Making destruction of the warhead yet more improbable, is the small radius of the Iron Dome warhead, which results in fragments that are not big enough, numerous enough, and moving fast enough to reliably detonate the warhead. We estimate that the number of fragments in the warhead is roughly 270 to 280 fragments. This could result in a one-sigma lethal range of perhaps 3 to 5 feet, but probably lower. These basic facts about the Iron Dome design, and the numerous videos where Iron Dome interceptors are on trajectories where there is almost no chance of destroying the warheads on the rocket-targets, are strong evidence that Iron Dome could not possibly have had a high intercept rate.

Why Most Iron Dome Attack Trajectories
Will Not Destroy Warheads on Enemy Rockets

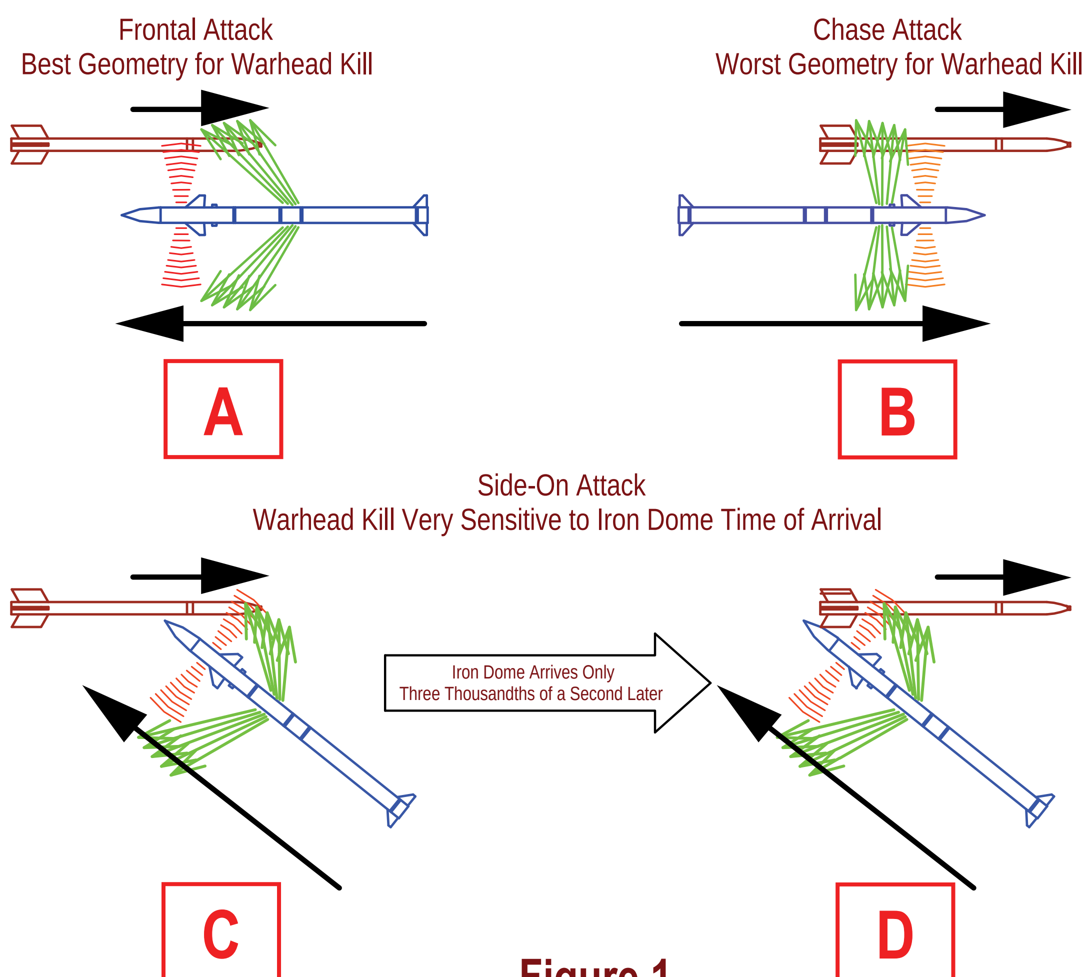


Figure 1

The photo below shows an example of a rocket carcass that was hit by a fragment near the top of the rocket motor casing. This indicates that there was a fusing error that led to a failure to place fragments on the rocket's warhead

The next photograph shows another example of a rocket casing that has been bent by glancing blows from Iron Dome warhead fragments. Oblique impacts at such low angles relative to the axis of symmetry of the rocket would be extremely unlikely to detonate the warhead, unless the interceptor happened to place fragments directly through the nose of the rocket. One can see on the front end of the rocket, bent back sheets of rocket motor casing indicating that the warhead exploded.

Still another photograph below shows damage from the antipersonnel ball bearings in the Qassam rocket's warhead. The process of actually constructing the warhead can be found in videos published on the web. As already noted, an unintended consequence of the use of these ball bearings results in the Qassam rocket warhead being much harder to detonate during intercept attempts.

The altitude distance shape of target-rocket *trajectories* also presents a significant challenge for Iron Dome. The photograph below shows a farm of rocket stands used for launching variants of the Qassam rocket. Although the rockets can be launched at a 45° inclination, there is hardly a loss of range by launching them at higher inclinations. This is simply because the trajectories of these rockets are substantially modified by aerodynamic drag.

Rockets launched on more lofted trajectories (see Figure 2) rise to higher altitudes where the density of air is lower and thereby can reach the same ranges as rockets fired at loft angles closer to that of minimum energy trajectories, which is only a valid concept when there is no air drag to modify the trajectory of the rocket.

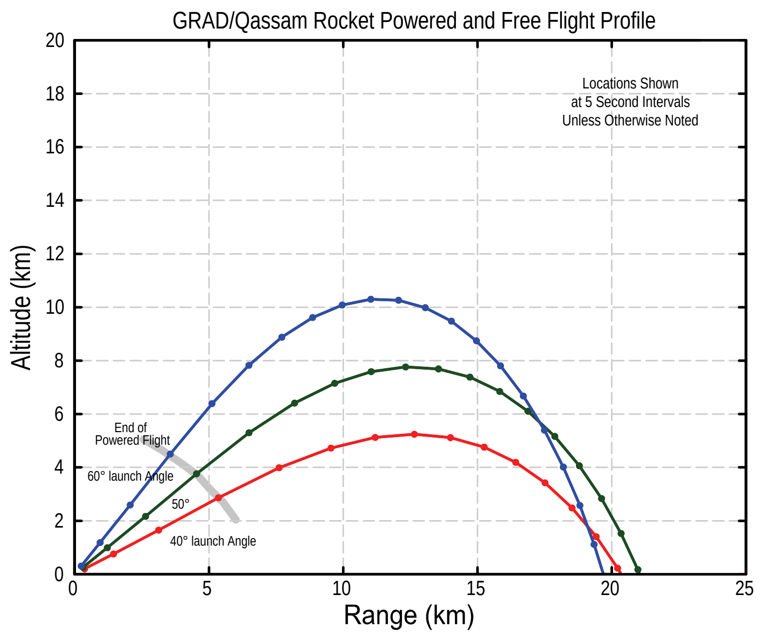


Figure 2

As can be seen from the geometry of the trajectories shown in figure 3, the very steep reentry angles lead to an effect similar to that observed during the Gulf War of 1991. In 1991, the Al Hussein SCUDs broke up due to aerodynamic deceleration in an altitude range between 10 and 12 km. When the breakup occurred, even though the ballistic coefficient of the warhead became drastically smaller relative to the ballistic coefficient of the fully intact SCUD, the warhead still had a high enough ballistic coefficient to essentially follow the trajectory that would have otherwise occurred. The result was an impact at slower speed but only at a slightly different location.

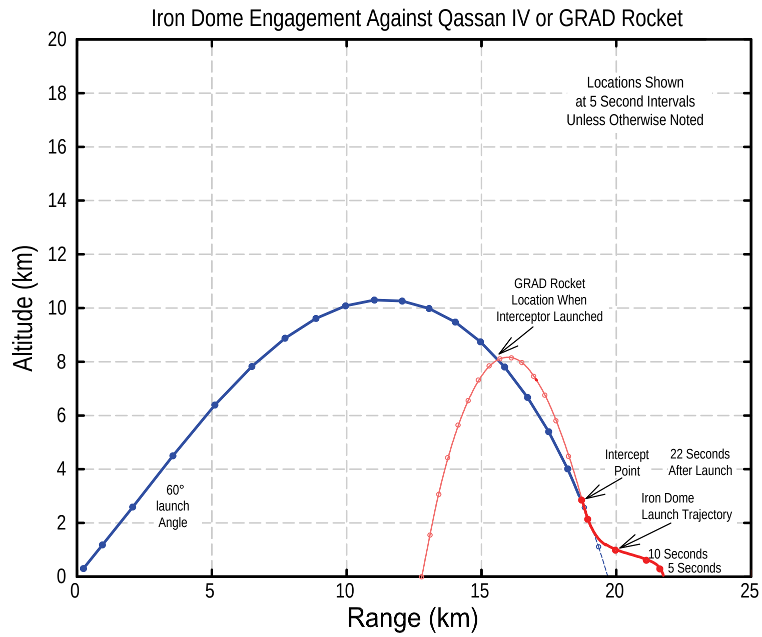
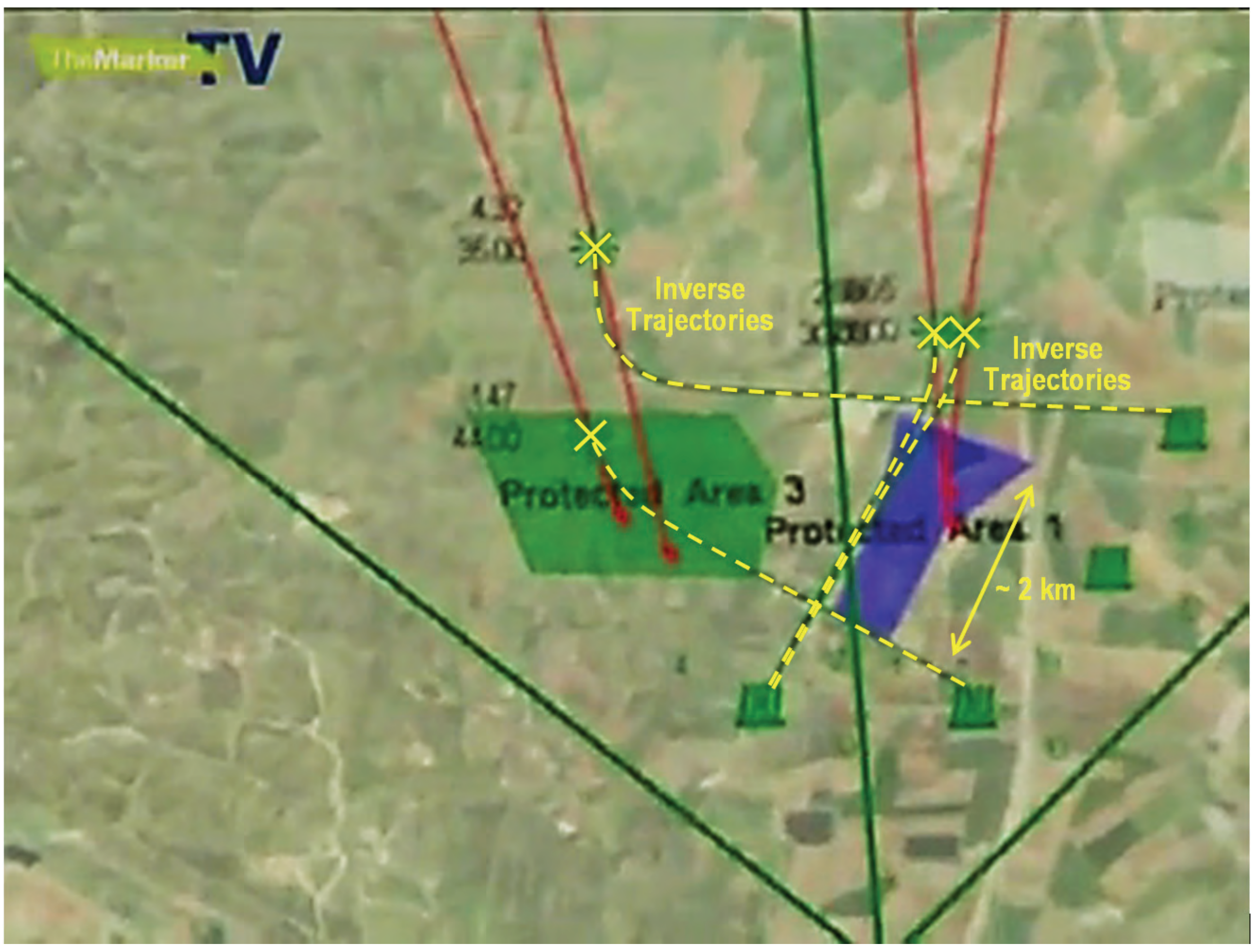
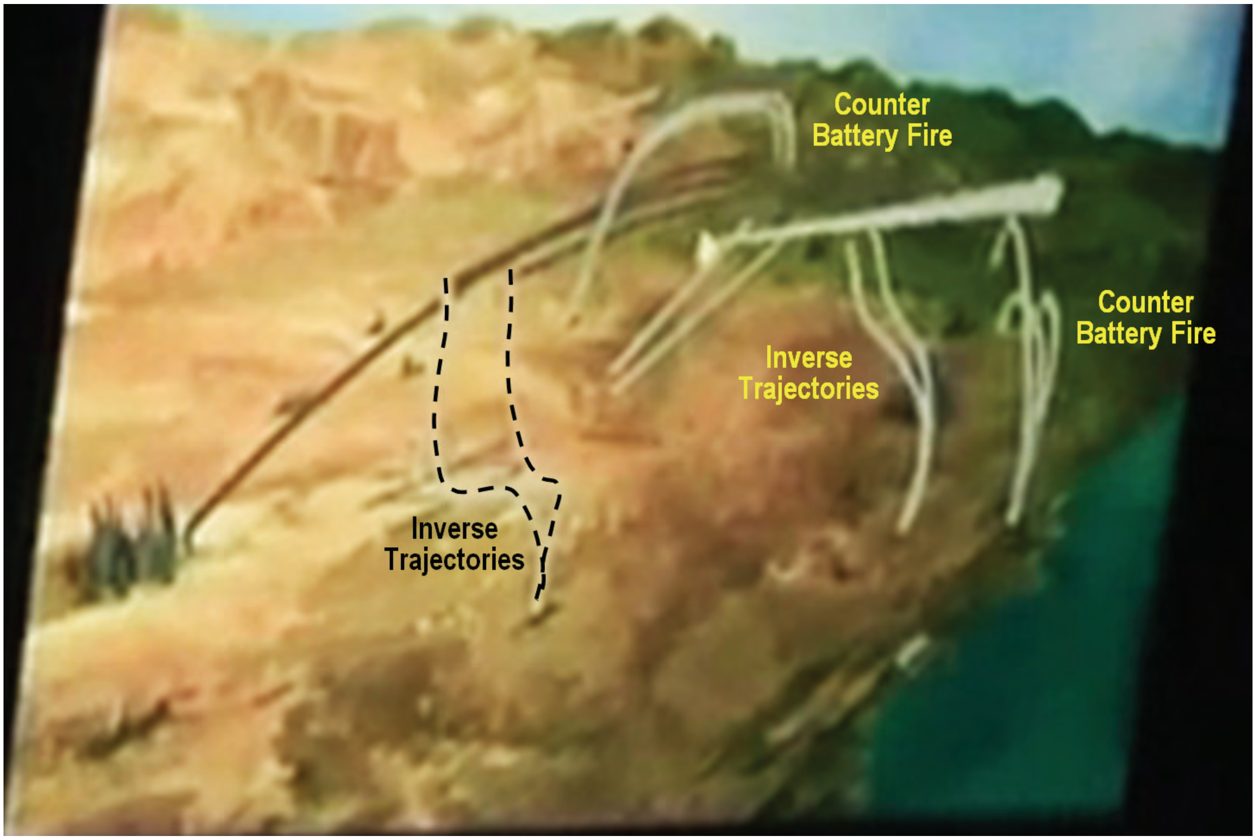


Figure 3

So in cases where Iron Dome cuts a rocket into pieces, the section containing the warhead will tend to travel the same line of motion as it would if it were still attached to the full rocket body. The only way this would not be the case, is if the interaction with the Iron Dome interceptor resulted in an intact rocket-target tumbling, which would very sharply increase the total drag on the rocket. However, this outcome will almost never, if ever, be the result of an intercept attempt.

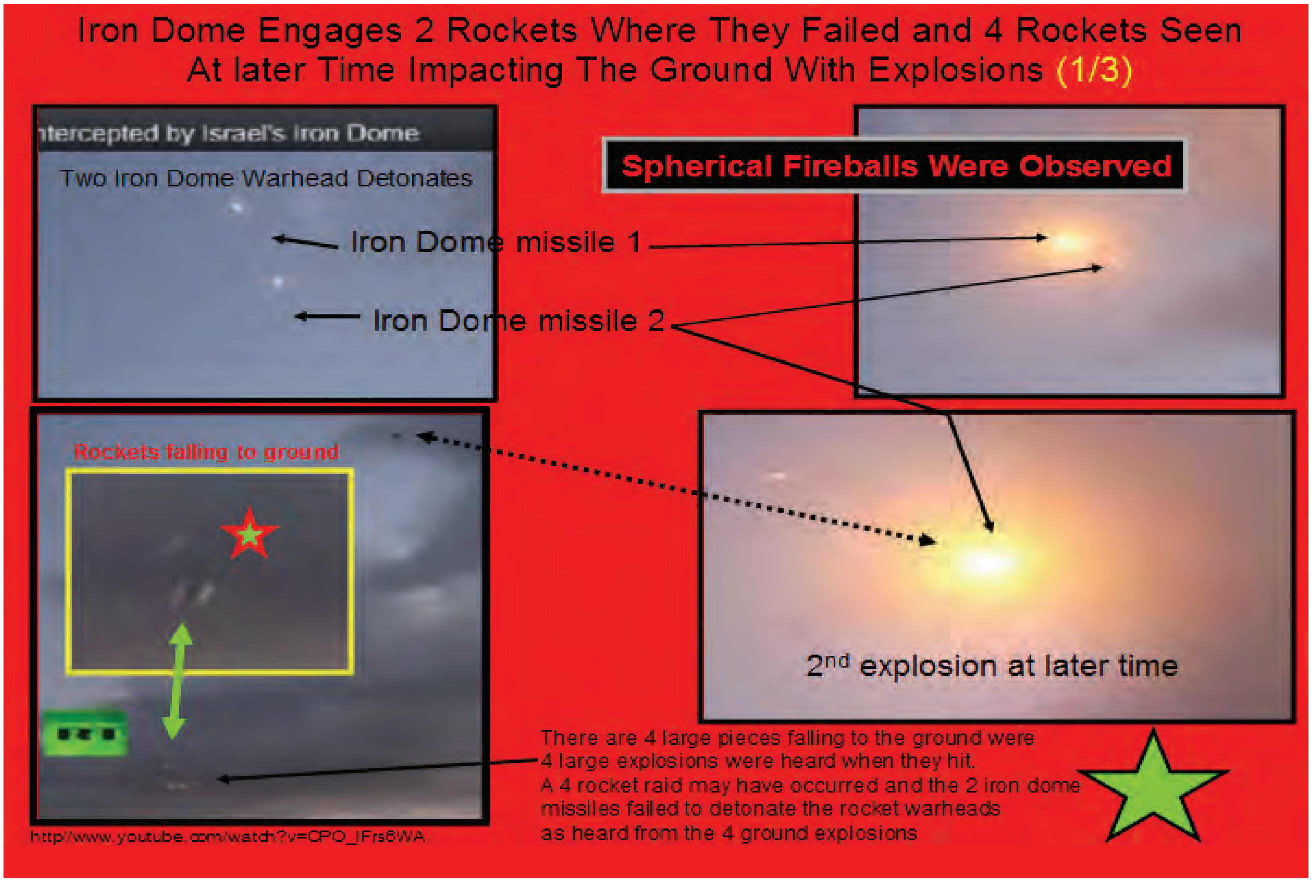
The two pictures below are from a video showing simulated battle management screens that the IDF allowed to be filmed. Both of the pictures depict Iron Dome interceptor trajectories that first fly to an expected point along the trajectory of an arriving target-rocket, and then fly up an "inverse trajectory" to engage the target head-on. The choice of this trajectory is dictated by the fuse warhead combination. The only way an interceptor could in principle have a relatively higher chance of hitting the warhead from non-nose on trajectories would be if it had a forward-looking fuse – similar to the more than $3 million per interceptor Patriot PAC-3. Such an interceptor may in principle be possible, but it would also require a much shorter maneuver reaction time to assure that the target-rocket's warhead will be hit. In the case of the PAC-3, the maneuver reaction time is shortened by use of a collar with 180 small rocket motors along the forward section of the interceptor's body. Hence, instead of using a $50,000 to $70,000 interceptor to intercept a $500 rocket, a much more expensive interceptor would instead be required.

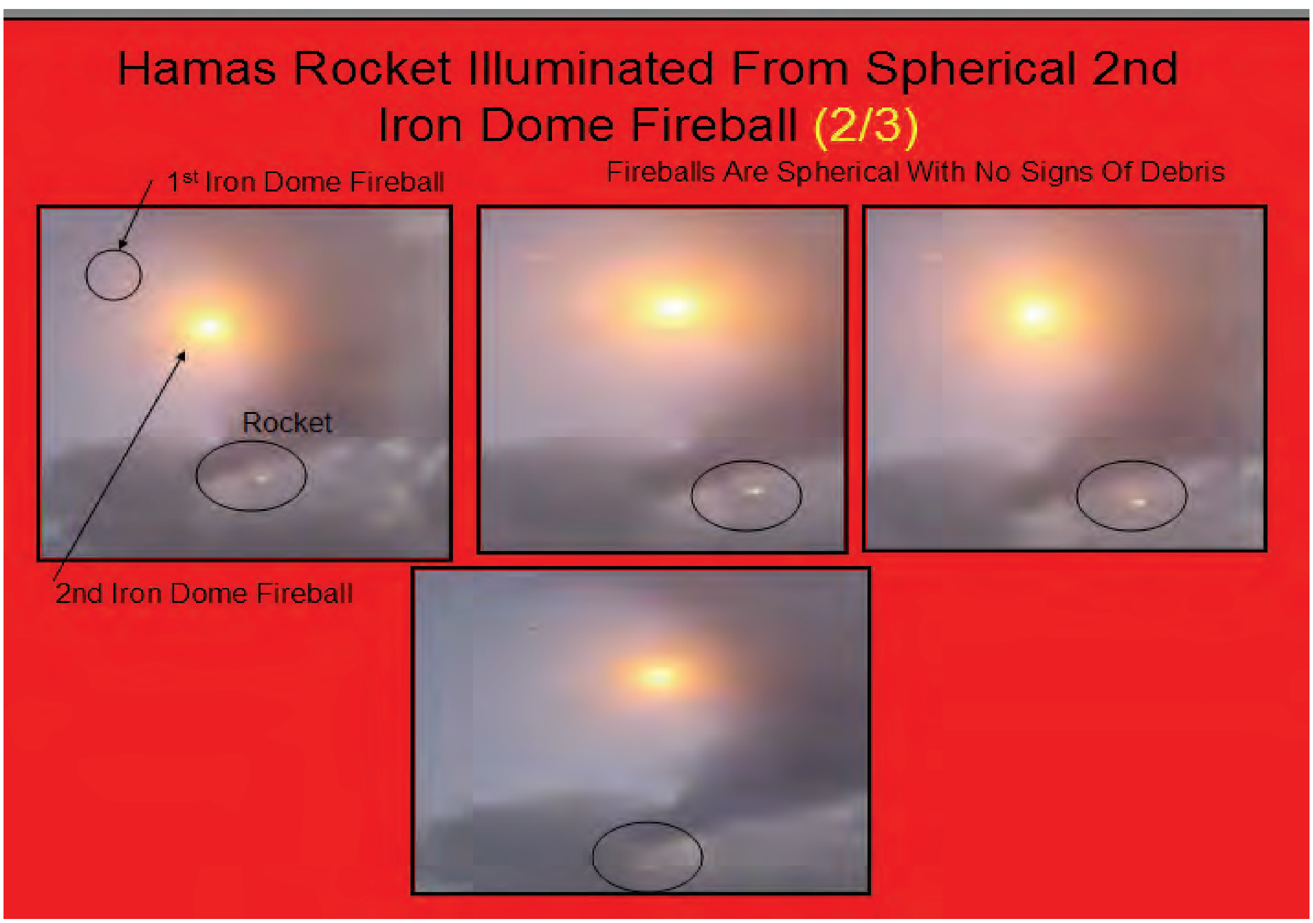




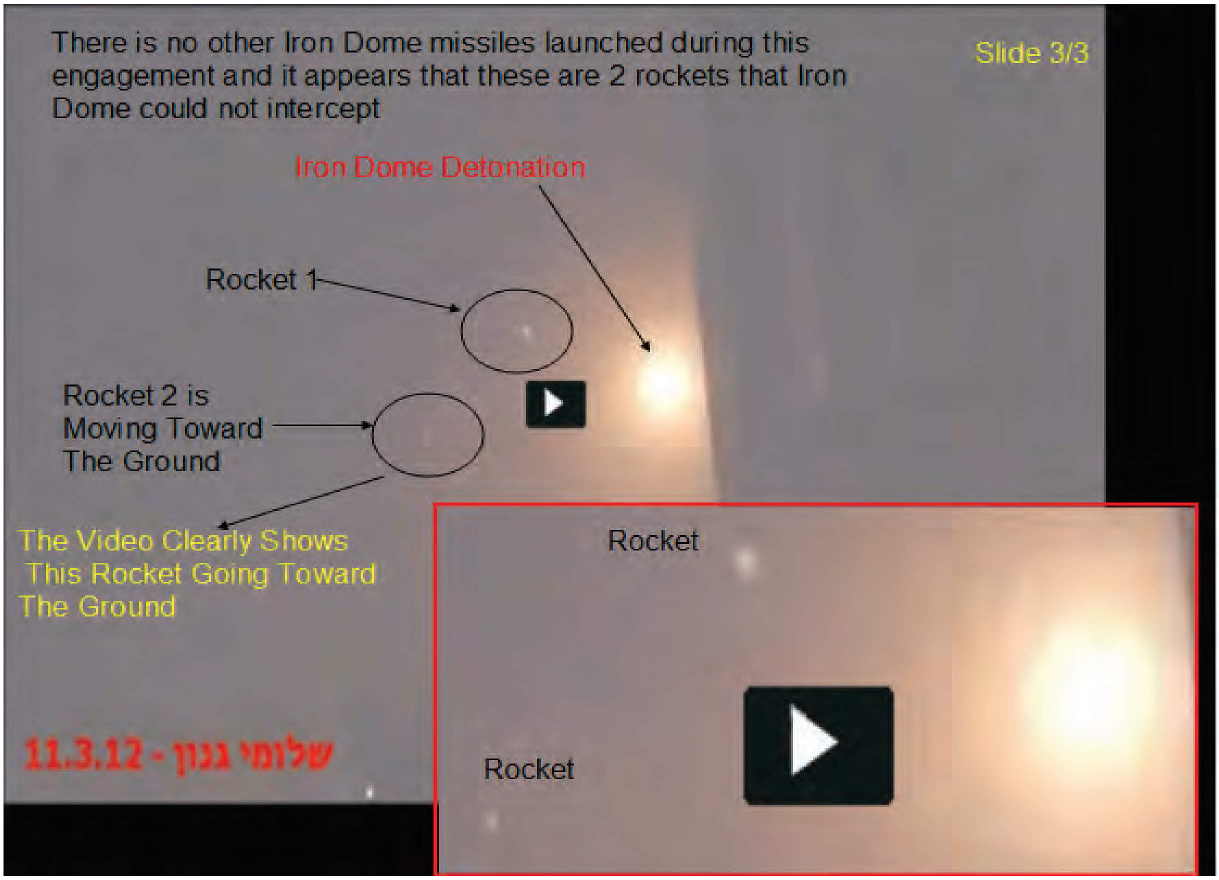
There are also many videos where the detonation of an Iron Dome warhead acts as a "flashbulb" that illuminated live target-rockets that were missed. The Iron Dome warhead generates about 120 Mwatts and it lights up the sky illuminating all objects around the fireball for 0.2-0.35 seconds. This is plenty of time for street cameras to see falling objects that the Iron Dome missed.

We have analyzed many of these videos to ensure that these falling objects are not Iron Dome missiles but rockets. In many engagements we can hear the explosions of the rockets on the ground. We also found 6 videos of rockets hitting buildings because the person with the camera is filming the sky showing the intercept and then the rocket hits very close to where they are standing. The last picture in the sequence of pictures below shows an example of such an event.





Iron Dome missed 4 rockets where they are observed hitting the ground with 4 explosions



Iron Dome illuminates 2 rockets that it missed where no other iron dome is near to engage

Observer filming the sky of Iron Dome where it missed and rocket explodes in front of him

Rafael has made public 2 Iron Dome Warhead Arena tests and descriptions of the explosive weight and rocket types to be killed. This information reveals how the Iron Dome warhead was designed. There are also very useful photographs of the laser fuse, which is called the EOTD (Electro-Optical Target Designator). We know that the warhead has rods or p-charges, we know the Iron Dome interceptor's diameter, and we know the weight of the warhead.

From these data we can calculate the thickness of the warhead's casing. It turns out that the casing is quite thin, and compact cubic fragments cannot be accelerated to high enough speeds to detonate thick rocket explosives with such a warhead. The Iron Dome warhead must be either P-charges or medium sized rods. Since the thickness of the warhead case is the same as many rod warheads that are open to the world, we can do very detailed analysis on the warhead/fuse sub-system. Such analyses lead to the conclusion that the type of warhead being used will have limited effectiveness detonating target-rocket warheads. The low lethality of Iron Dome warhead fragments is further exacerbated at high obliquity angles even though the fragment speeds are high.

In summary, we surely cannot say what the performance of Iron Dome was in Operation Pillar of Defense, but we can say surely that all the available evidence unambiguously indicates a drastically lower level of performance than the 84% claimed by the IDF.

My guess, and it is only a guess, is that the intercept rate was probably no better than 5 or 10%. This is only a guess based on relatively limited data – but I do think it is likely correct.

If the IDF wants to make a public claim of a much higher intercept rate then it can and should provide the data to prove its claims. This discussion is very reminiscent of the discussion over Patriot. The advocates make extraordinarily implausible claims but provide no data, and those of us who can make informed observations from the outside find only evidence to the contrary.

It is troubling that a country like Israel, who has such a strong tradition in accurately and relentlessly assessing the performance of its weapon systems, could get involved in this kind of extended deception.

I believe it was a reasonable strategy for Israel to claim that Iron Dome was working as an excuse to not invade Gaza at an enormous cost to both sides. I also believed that lying about Patriot's performance during the Gulf War of 1991 was a useful deception to reduce any political leverage that the Iraqis might have obtained during the period of combat.

However, continuing such a deception can only result in the misappropriation of limited defense assets. In turn, this can actually weaken the situation of the country.

In addition, as an American supporter of Israel's right to self-defense, I do not feel comfortable seeing the US spend money on a weapon system that hardly works and that can be used for political purposes to promote other bad ideas with regard to defense and defensive tactics.

Sincerely,

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Professor of Science, Technology, and National Security Policy
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