A Preliminary Analysis of the Proposed USA-193 Shoot-down

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18 February 2008

(revised on 12 March 2008)

Background

The target Satellite, known to the public as USA 193, was launched on 13 December 2006 on a Delta II (7920-10). Based on images taken by an amateur satellite observer, John Locker, the satellite is about 4 to 5 meters long. (See Figure 1 for an image of the satellite Locker used to determine its length.) The satellite was originally put into a nearly circular orbit with an apogee of 376 km and a perigee of 354 km. At that altitude, the atmospheric drag would have still acted on the satellite and, if nothing was done—as in fact nothing was—it would decay in less than 620 days depending on solar activity. Other amateurs, who use their ham radio sets to follow satellites from their transmissions, report that USA-193 stopped transmitting about 1.7 days after reaching orbit. This is consistent with media reports that the satellite entered a "safe mode" but controllers were unable to reestablish communications with it.

Figure 1. John Locker took this image of USA 193 on 18 September 2007.[1]

There have been various reports about the amount of hydrazine onboard. Some have placed the amount at one ton, while others have placed it at 1000 lbs (i.e. half a ton). Depending on which is correct, the size of the hydrazine tank would be between 1 and 1.2 m in diameter (most of the volume of a sphere is at the outer radius). So the tank occupies between 20% and 30% of the length of the satellite.

USA 193 is now in a low Earth orbit with an inclination of 58.5^{o} and, currently, has an altitude (using the orbital parameters found by various amateur satellite observers) of 288 km (180 miles).[2] The inclination means that, when it reenters the Earth's atmosphere, it

[1] See John Locker's website at http://mysite.wanadoo-members.co.uk/satcom_transits/USA193Sepbw.jpg accessed on 16 February 2008.

[2] This is based on orbital parameters determined by amateur observers for 9 February 2008. The satellite is quickly decaying and is probably in a much lower orbit by now.

can only hit points on the Earth's surface with latitudes between $\pm 58.5^{o}$; roughly between the northern tip of Denmark and everywhere north of the Antarctic circle. Few people live in the regions that are safe, partly because they make up less than 10% of the Earth's surface and partly because they are so inhospitable.

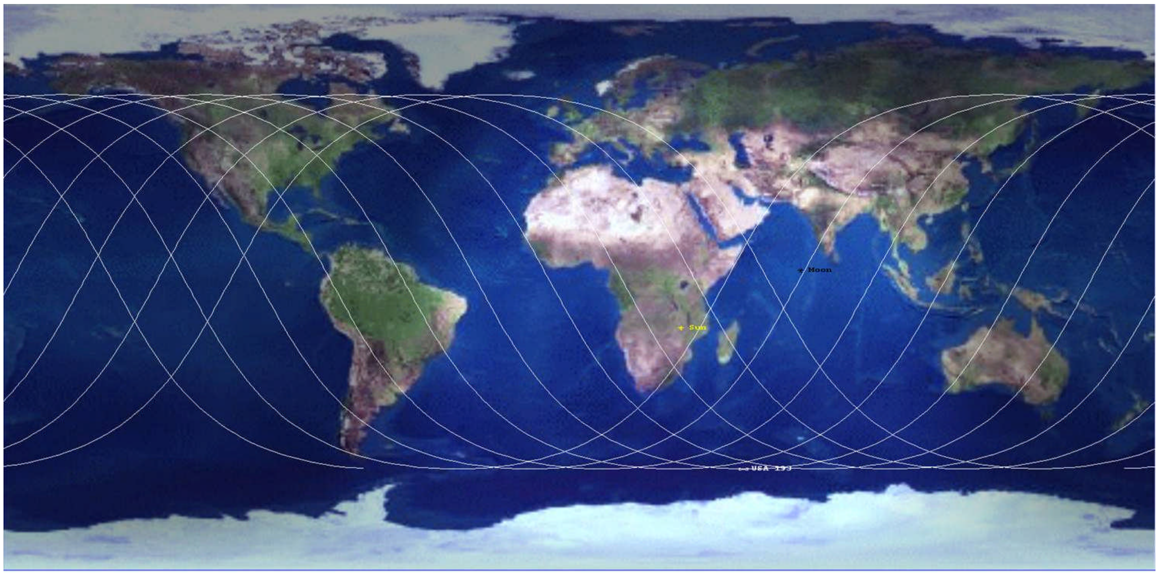

Figure 2. This figure shows the regions over which the satellite USA-193 passes. Regions above $\pm 58.5^{o}$ latitude are not in danger of being hit by the satellite even if it is not shot down. However, almost all of the world's population lives in the region between those latitudes.

There are approximately 6.7 billion people living on the Earth for an average population density of 45 people per square kilometer of land surface area (which makes up about 30% of the Earth's surface or approximately 33% of the surface area between $\pm 58.5^{o}$ latitude). The Pentagon has reported that they expect the area contaminated by a fully loaded hydrazine tank, if it reached the Earth's surface intact, to be 30 yards (27 meters) in radius. Taking into account the probability of crashing on land and the average density of people, we can expect 3% chance of killing or injuring a single individual (average casualty would be 0.03 people) somewhere on the Earth assuming that the tank lands intact—and that is an important if. (After a year and half in space without power or thermal control, the hydrazine is almost certainly frozen solid and, protected as it is inside the body of the satellite; many aeronautical engineers feel that there is certainly a good chance that it will.) This is, of course, based on an average population density and an urban area can have considerably higher densities. For instance New Delhi has 7,758 people in a square kilometer. If the satellite crashed down there, an average causality count would be 37 people. Of course, urban areas make up only a very small fraction of the Earth so the chances of hitting an urban center are very small. For instance, there is only a 1 in ten million chance that it will hit New Delhi.

While this paper has used a methodology also found in articles for peer-reviewed journals,[3] other analysts[4] have attempted a more sophisticated analysis using world

[3] See, for example, WH Ailor and R P Patera, Spacecraft re-entry strategies: meeting debris mitigation and ground safety requirements, Proc. IMechE Vol. 221 Part G: J. Aerospace Engineering, pp. 947-953

population densities as given by LandScan 2005 (developed by Oak Ridge National Labs). That more sophisticated analysis, which only included those regions of the Earth that had population densities greater than or equal to 4 people per hectare (they estimate that the hydrazine contaminated error—if the same assumptions made in this paper are correct—would equal about a quarter hectare) calculated a probability of killing or injuring one or more persons as 0.5%. This range can perhaps be taken as an estimate of the systematic error of the calculation presented here. However, the assumptions in that analysis include that if you live in a region with a population density less than 4 people per hectare (such as one with 3 people per hectare), you are safe. This assumption could account for the differences between the two analyses.

NASA has a requirement on its controlled reentries that there be a 1 in 10,000 chance of killing somebody on the Earth. If the chances of the hydrazine tank surviving the reentry are greater than roughly 1 in 1,000 than then this uncontrolled decent does not satisfy NASA's requirements and it can be argued that other measures should be taken. On the other hand, there are certainly political considerations that would argue against that. It could be argued, for instance, that it increases the legitimacy of China's ASAT test on 11 January 2007. Legitimating any kinetic kill anti-satellite weapon increases the chances that a space war might actually be fought; creating tremendous swarms of debris that could, as some experts on space debris argue, cause a catastrophic chain reaction that would put so much junk in space that it would be impossible to orbit a satellite for thousands of years. That would be a humanitarian disaster considering the benefits humanity derives from space such as warning of ruinous floods and aiding in the relief of tsunami victims.

The Interceptor

The Pentagon has announced that it will use its Standard Missile III (SM-3, see Figure 3) to shoot down the satellite when its orbit has decayed to an altitude of 130 miles (roughly 240 km, at which point it would have between one and six days life left before it reenters the atmosphere). Latest reports indicate that this engagement might happen as early as Thursday, 21 February 2008. The Pentagon also reports that the collision will take place with a closing speed of 22,000 mph (9.83 km/s). Since the satellite will have picked up speed as its orbit decays, it will have an orbital speed of 7.517 km/s, relative to the Earth's surface, at the time of the collision.

Using the parameters for the SM-3 missile that have been culled[5] from various government sources, the trajectory of the interceptor can be calculated. One of the important results of these calculations is that the SM-3 will not be using its "third stage" onboard the LEAP interceptor. Using the third stage would drive the closing speed much higher than the planned 9.8 km/s. These parameters, for use in simulating the SM-3 missile[6], are given in Table 1.

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[4] See the post to the space_sanctuary email list by Nancy Gallagher entitled: "VERY SMALL Risk from Hydrazine onboard USA 193", 18 February 2008.

[5] Theodore Postol, personal communication.

[6] For instance, these can be directly used in GUI_missileFlyout, by Geoffrey Forden, and is available for free download at http://mit.edu/stgs/downloads.html

Table 1. Parameters used for simulating the SM-3 ASAT weapon.

	Stage 1	Stage 2a[7]	Stage 2b[7]
Burn time (sec)	6	6	36
Stage mass, empty (kg)	195	0	150.5
Stage mass, full (kg)	780.13	160	350
Specific Impulse (s)	260	270	270
Stage diameter (m)	0.34	0.34	0.34

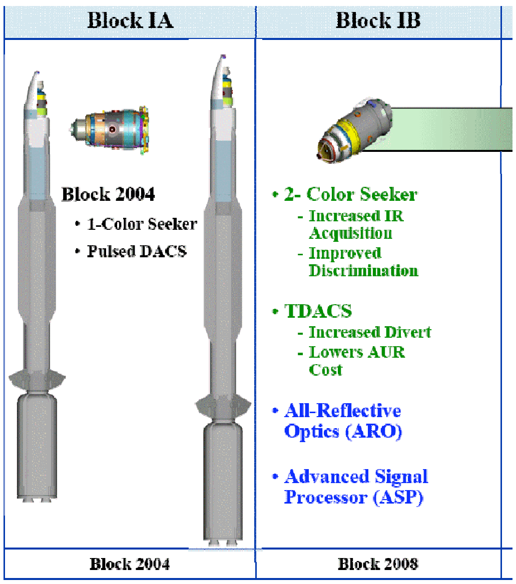

Figure 3. Overview of the Standard Missile 3, Block 1. Source: U.S. Missile Defense Agency, 13 September 2006.

The LEAP interceptor has been used in thirteen attempted interceptions with eleven of them successful. However, all of these have been against targets with much lower relative speeds (an educated guess would place the closing speeds for all the interceptions below 6 km/s and perhaps considerably lower for most of them.) Higher closing speeds imply that both the accelerations required to intercept the target and the changes in velocity are greater than they would be for lower closing speeds. It also implies that the required corrections have to be more accurately made than would be required for a lower closing speed interception. All these considerations make the satellite interception much more stressing than the previous tests that have been done with the SM-3.

The Interception

Current reports indicate that the first interception attempt will take place somewhere in the Pacific, perhaps on Thursday, 21 February 2008. When it does, the United States will station an Aegis cruiser somewhere along the ground track of the satellite, which it will

7 I have broken the second stage down into two segments, one (listed here as 2a) is a very high thrust booster section while the other section of stage 2 is a lower thrust sustainer section.

know by extrapolating the orbit from previous observations. It will, of course, be making measurements on the satellite's position with various radars and optical tracking devices both on the surface of the Earth and in space. (The US currently has a single satellite, the MSX, with an optical detector—known as the SBV or Space-Based Visible—for tracking satellites though there have been proposals for increasing the number.) Shortly before Chinese ASAT test on January 11, 2007, the US made at least six observations of its target satellite's position.

The satellite track and the simulated trajectory of the interceptor are shown in Figure 4. A detailed view of the interceptor's track is shown in Figure 6. Twenty second intervals for the trajectory are shown as circles along the trajectory to indicate its flight. The entire interceptor flight last just over five minutes and is still rising as it reaches the target satellite at 249 km altitude. The engagement has been chosen so that at the collision the interceptor is on the downward portion of its trajectory. As a consequence, it occurs about 519 km (ground range) from the launch point and at an altitude of 249 km. The closing speed—which is combination of the interceptor speed and the satellite's orbital velocity—for the collision is 9.4 km/s, which is slightly lower than the announced intended closing speed of 9.83 km/s.

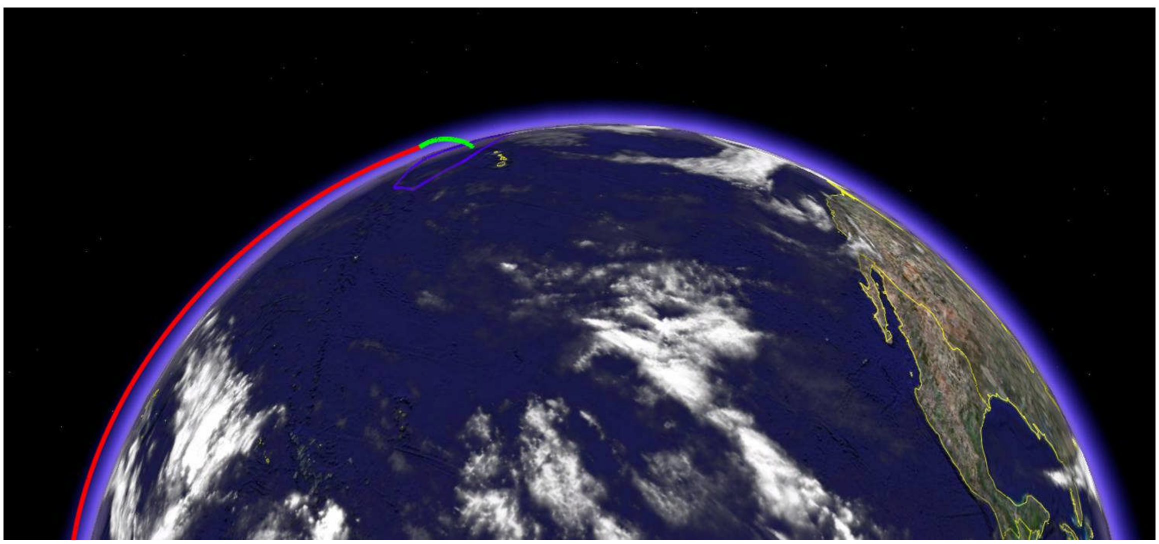

Figure 4. A simulation of the engagement between the spy satellite (whose orbit before the interception is shown in red) and the SM-3 interceptor (whose trajectory is shown in green). The stay-clear zone announced by the U.S. Government is shown in bright blue.

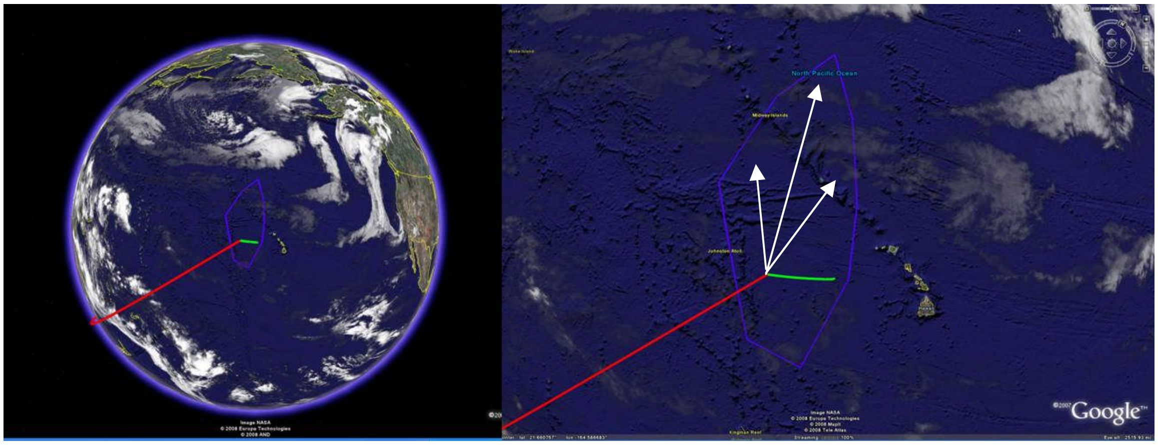

Figure 5. The orbit of the satellite, USA-193, is shown in red, the stay-clear zone declared by the U.S. Government is shown in bright blue, and the simulated trajectory of the SM-3 ASAT is shown in green. The announced stay clear zone is shown in bright blue. Note that the stay-clear zone is elongated towards the North and off the axis of both the satellite and the interceptor. This zone is likely to be shaped like this so that debris from the interceptor, after acquiring some velocity from its collision with the satellite, to fall to Earth without endangering passing aircraft (or ships?). The white arrows in the figure on the right are conjectured interceptor debris directions.

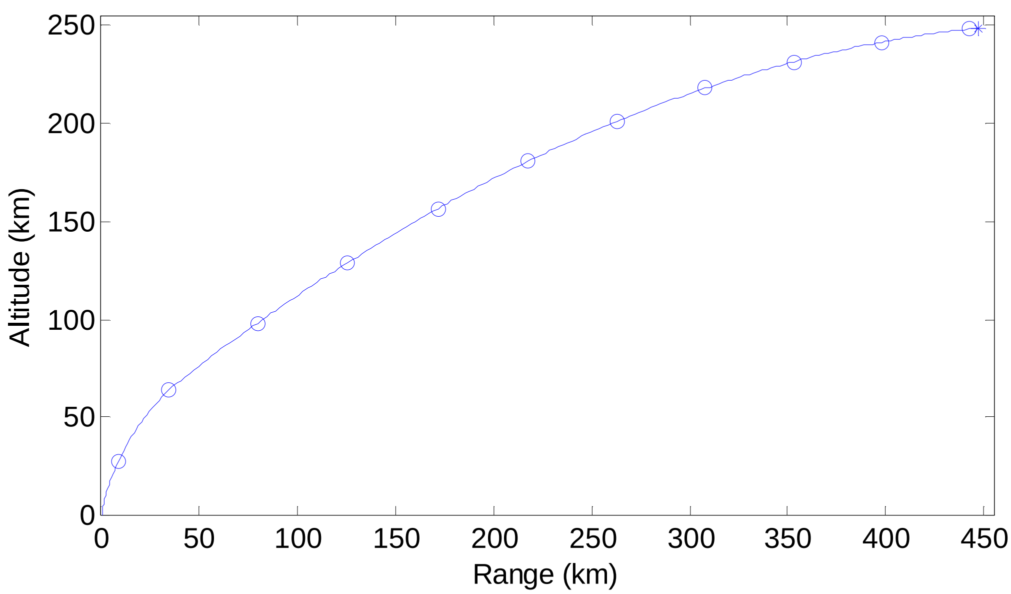

Figure 6. The trajectory of the SM-3 interceptor is shown in here. Time intervals of 20 seconds are shown (o) along the trajectory are shown to give an indication of the flight of the interceptor. The interception point is shown as a *.

Since the interception occurs just five minutes after the interceptor is launched, the target satellite is below the horizon when the launch occurs. The interception occurs 519 km away (slant range)[8] from the ship launching the missile and an altitude of roughly 249 km. If the interceptor misses on the first attempt, the next time the satellite comes around

[8] This is the slant range, the length of a line drawn from the ship to the satellite. Slant range is important for the Aegis radar to observe the target, which it can do since the radar does not have to search for the satellite. (Searching effectively reduces the range of the radar.)

the Earth will have rotated more than 2000 km, taking the ship with it. (See Figure 7.) So, instead of firing at the satellite during its next orbit, the ship will have to wait approximately 13 hours for the next opportunity to attack. That is how long it will have to wait for the next time the satellite comes within range of the interceptor.

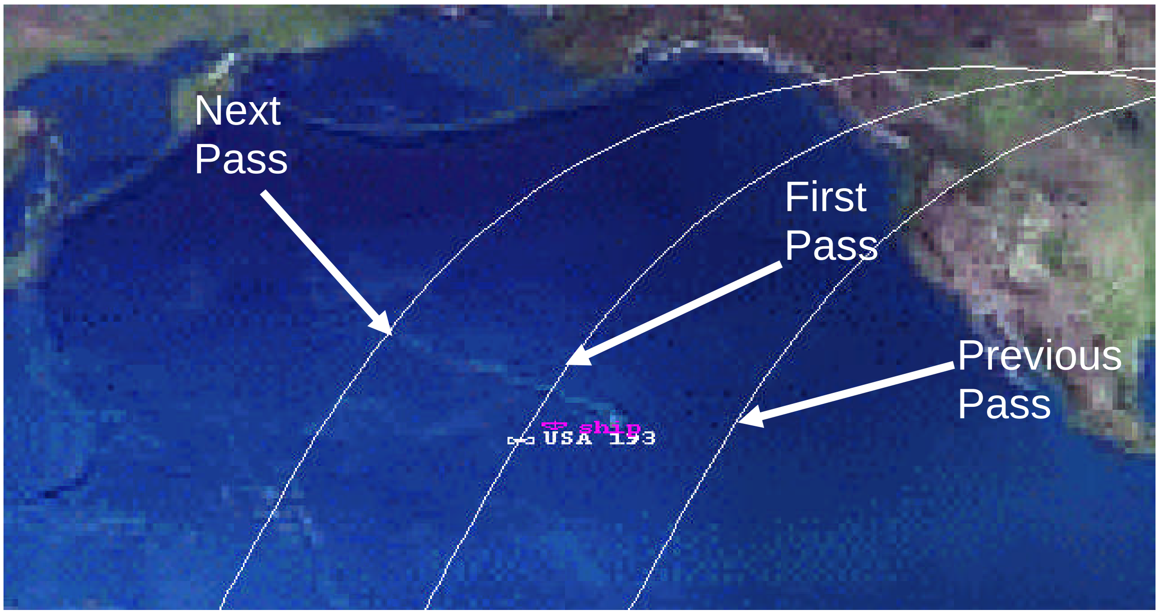

Figure 7. The distance between passes of the USA 193 are too large for the Aegis cruiser to shoot at the satellite on the next pass (or the previous one for that matter). The position of the engagement illustrated in this image was arbitrarily selected since the Pentagon had not yet announced from where the interceptor will be launched.

The most difficult technical hurdle the US has to overcome in the proposed engagement is the very large closing speed (9.4 km/s, or approximately 21,100 mph[9]) between the interceptor and its target. As mentioned above, this is considerably greater than previous closing speeds the LEAP interceptor had to deal with in missile defense tests. However, a successful interception—while very impressive—will not imply that the LEAP interceptor will be an effective missile defense interceptor. The most importantly reason is that the satellite will not have the most stressing parts of an actual missile defense engagement: countermeasures. In fact, there have been troubling statements by government officials that indicate countermeasures might be even more stressing for the missile defense system than previously thought. For instance, some of the comments Gen. Cartwright made at his 14 February 2008 news conference can be interpreted as indicating that the interceptor is particularly sensitive to the appearance of the target. During that conference, the General stated that the interceptor software would have to be changed so that the interceptor would look for something like the satellite.[10]

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[9] The Pentagon announced that the interception would have a closing speed of 22,000 mph, or 9.83 km/s, which is slightly more than the closing speed calculated by the simulation here. Of course, this could be simply the natural rounding associated with press releases or the interceptors trajectory could be slightly different.

[10] Presumably in terms of infrared intensity.

Space Debris

It is difficult to estimate the amount of space debris that will be created by the collision. The 1985 US ASAT test caused 280 pieces of debris large enough to be cataloged by telescopes and radars on Earth. There is some evidence, however, that this test hit the solar panel and might not be expected to cause too many pieces of debris.[11] The Chinese test in 2007, by contrast, created over 2600 pieces of debris. This is considerably higher (perhaps a factor of two or more) than NASA models predict the amount of debris created. One possible explanation for this underestimation might be the fact that it is two extended spacecraft hitting each other rather than a small rock hitting a satellite.

If the debris pattern created by the Chinese test is used to model the USA 193 test, it is possible to say a great deal about the lifetime and orbital parameters of the debris created this engagement. An important question is the lifetime of the debris created. At 200 km altitude, reducing an orbiting object's speed by 45 m/s (out of the 7,784 m/s for a stable orbit at that altitude) will cause it to reenter that orbit. Figure 8 shows an estimate for the distribution of debris speeds relative to the satellite's original orbital velocity taken directly from measurements of the debris from the Chinese test. The debris shown in red are the pieces that would immediately reenter the atmosphere; they amount to roughly 12% of the total amount produced.[12] Those pieces of debris created with speeds less than the original satellite's orbital speed plus 100 m/s will decay within a month, depending on their exact speeds and the solar activity. This amounts to 82% of the debris large enough to be tracked from Earth. The remaining 6% have relatively high orbital speeds and could last in orbit considerably longer. In fact, the highest changes in orbital speeds could result in debris with apogees 2700 km in altitude. And it should also be remembered that the most likely mechanism for getting pieces with speeds significantly greater than the original satellite all have these debris coming from the interceptor. In this case, the interceptor is considerably smaller and less massive than the Chinese ASAT so the numbers of high apogee pieces will be significantly less.

Regardless of how many there are, all of those pieces of debris with larger speeds than the original satellite will have their perigees at the altitude of the original satellite, i.e. 210 km, and will decay within the next year. These differences in lifetimes between the debris from the three collisions discussed, the 1985 US test (which took place at an altitude of 650 km), the 2007 Chinese test (which took place at 850 km), and the engagement discussed here (which is reported to be planned when the satellite has an altitude of 210 km), are all caused by the differences in orbital altitudes. (See Figure 9 for a plot of the lifetimes of the debris created by the 1985 US ASAT test Figure 10 for the 2007 Chinese test debris lifetimes.)

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[11] It is also possible that the US ability to track and catalog pieces of debris has improved so much since then that it might be hard to compare the numbers produced.

[12] Using the Chinese ASAT test to estimate the percentage of debris that decays immediately underestimates this fraction because those pieces of debris that immediately in the Chinese test do not show up in this plot. In fact, any debris produced with a change of velocity more negative than 0.22 km/s in the Chinese test would have decayed immediately. This is strikingly close to the cutoff in the low delta V tail in Figure 8. On the other hand, this is clearly in the tails of the distribution.

Finally, it is interesting to note that the danger of the debris resulting from the Chinese ASAT test is important only in the long run. For instance, while that debris did double the chance of any satellite being hit (it went from 12% chance that some satellite would be hit per year by a piece of debris big enough to be cataloged to 18% that some satellite would be hit if no evasive action was taken) the chances are still relatively small. As will be shown below, the chances that some satellite will be hit by the debris created in this engagement are much, much smaller and last for a much, much shorter time.

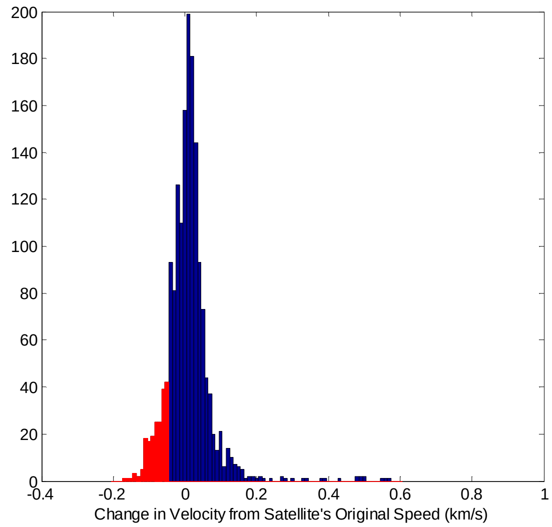

Figure 8. Using the Chinese ASAT test as a model, this graph shows the distribution of debris speeds, relative to the satellite's orbital speed. Those in red will decay within one orbit (88 minutes) of the interception. See the text for a discussion of the lifetimes of the other pieces.

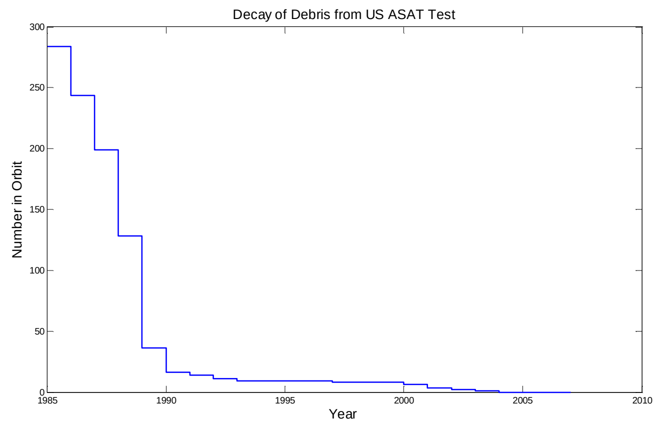

Figure 9. Lifetime of debris created by the US ASAT test in 1985. All the cataloged debris had reentered the Earth's atmosphere by 2005. While there was a lower number of cataloged debris created by the 1985 test than the 2007 Chinese test, it is possible that this is an experimental bias since the discovery and tracking technology used might well have been less efficient than is used today.

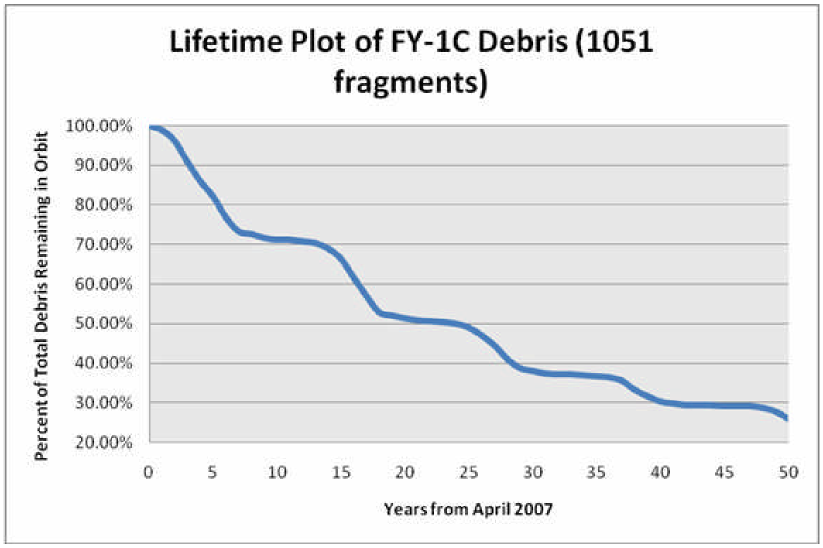

Figure 10. The lifetimes of the debris created during the 2007 Chinese test. This calculation, which is done by another analyst who does not want to be identified, uses the actual experimentally determined drag coefficients for each piece to determine their lifetime. By comparison, the cataloged debris from the US test all decayed within 21 years.

Striking the Hydrazine Tank

The most desirable outcome of the interception is that the hydrazine tank is hit by the interceptor or by debris created by the interception as it passes through the satellite. However, this is difficult to guarantee even if the interceptor hits the satellite. For one thing, it is quite possible that the satellite will be tumbling (amateur satellite observers have reported seeing it "flare" or have a sudden change in brightness that indicates it is tumbling). This will make it nearly impossible to determine before hand where to hit the satellite to ensure that the hydrazine tank is hit.

However, a study of the debris pattern from the Chinese ASAT test indicates that the debris comes off in a cone aligned with the direction of the interceptor and with an opening angle of 100 degrees.[13] That implies that most, but not all, debris created come in this cone. This is illustrated in Figure 11. Clearly, it would be desirable for this cone to intersect the hydrazine tank.

[13] Geoffrey Forden, "China's Anti-satellite Weapon: its Capabilities, Utilization in a Space War, and Possible US Responses" to be submitted to Science and Global Security. This opening angle corresponds to a half opening angle of 55 degrees.

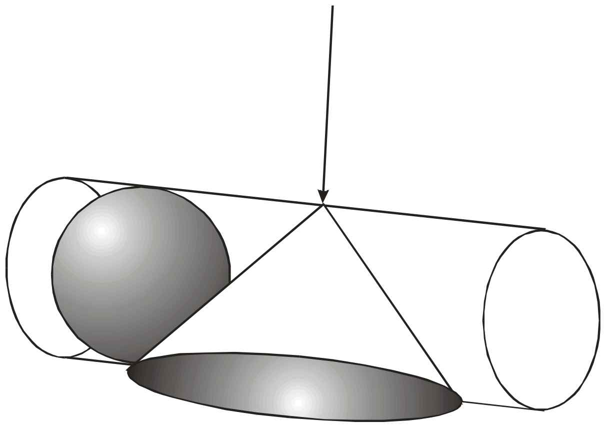

Figure 11. The analysis approximated the USA 193 satellite as a cylinder 4 to 5 meters in length and one meter in diameter with the hydrazine tank shown as a spherical container located at one end of the cylinder. In this diagram, the interceptor (whose trajectory is represented by an arrow at the top of the diagram) strikes the satellite on its side at a point so that the debris cone just grazes the hydrazine tank.

Under the assumptions that the satellite can be represented by a cylinder four to five meters long and one meter in diameter (which is consistent with the observations of the amateur satellite observers) and that the tank is to one side and that the interceptor strikes the satellite perpendicular to its long side, then the chances of the debris cone intersecting the tank are between 28% and 35%. (Incident angles different from perpendicular give rise to geometries that are too difficult to calculate on the time scale in which this study is being done.) Of course these assumptions could be wrong. For instance, if the satellite designers had placed the hydrazine tank in the middle of the satellite than the chances of hitting it might be more than doubled. Of course, these details are known to the government. It is also possible that even if the cone of debris misses the tank, the collision could still have generated enough pieces outside of the cone to puncture it or that the structural damage done to the satellite by the collision will be enough to cause the tank to be destroyed during its decent or perhaps even cracked open before reentry. These issues, the large closing speeds and the uncertainty of puncturing the hydrazine tank, raise substantial questions as to the effectiveness of the intercept attempt.