HQC Space Systems Design Docs

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1. Space Detection

I've been running some numbers on what sort of detection might be possible in Space using period technology. As is frequently the case, I was amazed at how old several sensors are – The Bolometer, Edison't Tasimeter, and Selenium-based Infrared detectors were invented/discovered in 1878. Lead sufilde detectors by 1904, and Thallium sulfide 1917. WW2 saw several other advances, some of which we might consider pulling in a bit sooner.

The IR detection problem for HQC is an interesting one. Chemical rockets and aerolyth rockets should be easy to detect from a substantial distance, though detectors are slow so they might slip by in the early days. E&S drives are a much trickier problem. A ship with and E&S drive doesn't leave a huge, hot plume like a rocket. It does produce a substantial amount of heat (on the order of a hundreds of kW), but this heat gets spread out with radiators, so the overall vehicle is not that warm (I assumed 30-50C).

Still, 'not that warm' is still 'really warm' compared to the coldness of space. The background radiation in the IR is not that high, so the biggest difficulty will be sensor noise. Some of the semiconductor based photodetectors might appear in niche applications (particularly military) but actually aren't super useful at detecting E&S ships. This is because an E&S ship's peak IR emission will be at about 9µm, and detectors like lead sulfide, many selenium detectors, or thallium detectors don't detect will after about 5-7µm. I think early detectors (pre 1900?) will use thermocouples or thermistors, but by 1900 cooled bolometers will come in and steadily improve. These technologies have relatively good response rates to the somewhat longer wavelengths of E&S ships.

Here are some numbers for various plausible sensor configurations and how they might detect medium-sized E&S ships:

[note: pixel sizes are the size at the maximum detection range given.]

- Early Long Range Sensor:
  - 50m aperture thermocouple, 3300m "pixel" size, 2160hr whole-sky scan time
  - 25% detection chance at 0.015AU (~2.2 million km) w/ skilled operator
  - I could see nations deploying these early on to track shipping and defend space stations. The sky-scanning time is high, but you can reduce that by using multiple sensors and/or not scanning the whole sky.
- Mid-term LR Sensor
  - 58.56m aperture bolometer @ 77K, 25800m "pixel", 1800h scan time
  - 25% detection chance at 0.172AU (about 25.7 million km)
  - A slightly larger aperture, and switching to a bolometer gives a 10x improvement in detection. A network of 10 or 11 of these could cover the solar system from the Sun to Earth along the ecliptic.

- Late term- Long Range Sensor
  - 74.96m bolometer-33K 77636 m pixel 2400h scan time
  - 25% detection chance at 0.53AU.
  - An improved bolometer and larger aperture gives another big detection range boost. 8 of these could cover the solar system from the Sun to Mars.
- Late ship-based sensor
  - 7.5m bolometer-33K 14000m "pixel" 8h scan time
  - 75% detection chance at 1 million km.
  - A smaller sensor, but still providing good detection out to a million km. It takes 8 hours to scan the whole sky, but if you are only looking along a portion of the 3D space, you can reduce that a lot.
- Missile sensor
  - 1m bolometer-77K 604m pixel
  - 99% detection at 8040m w/ machine detection
  - A small sensor that could fit in a guided missile. I assumed it scans a 45degree-by-45degree area in front of it and scans that patch 60 times an hour. If launched from that range (8000km), a ship's sensor could locate the target to within 100m, so the missile can start with pretty good pointing accuracy.
- Small craft sensor
  - 1m bolometer-77K 604m pixel

    - 99% detection at 14310km w/ skilled operator
    - The same sensor as above, but with a human operator.
- Small 'focus' sensor
    - 1.48m bolometer-77K
    - at 6000km this slightly larger sensor could provide a 66m pixel. At 2000km, 22m. This could be useful for fine targeting, or object identification, or to guide missiles to their target.

2. Space Defense

I've been looking into some space combat scenarios, particularly what might a ship-to-ship missile look like in HQC and how might it be defended against.

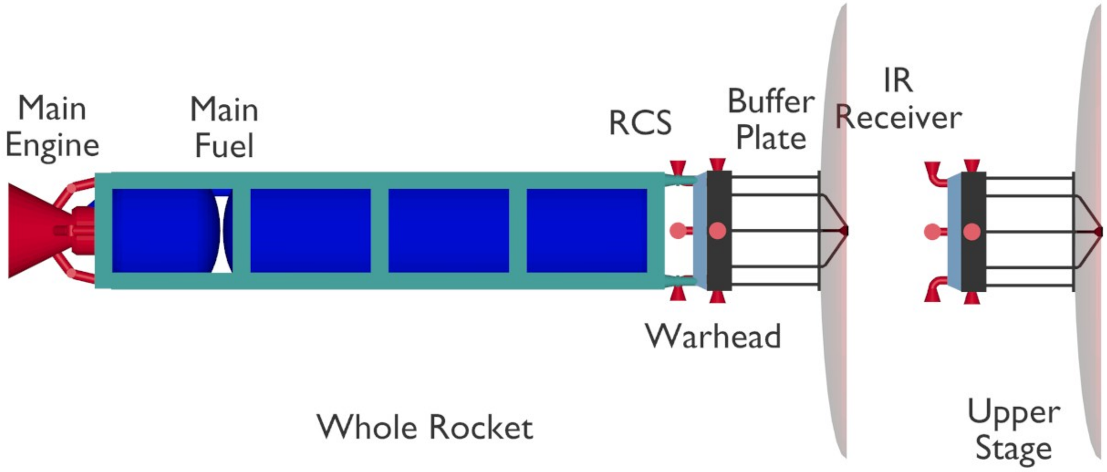
In general, I'm looking at if a missile is fired at a target ship what might the target ship do to avoid being hit. In this case, I'm looking at if the target ship responds with an anti-missile missile (AMM) which attempts to close with the incoming anti-ship missile (ASM) and disable or destroy it. I assume that, rather than attempt a head-on collision, the AMM tries to disable its target with a burst of shrapnel impacting at hypervelocity (in this case, about 7km/s).

This breaks down into 2 main questions:

- What does it take to disable / destroy a missile?
- How likely is it that the anti-missile will hit the missile?

2.1. What does it take to disable / destroy a missile?

First, I assume an ASM that looks roughly like this:



It consists of a 1st stage that is liquid fueled and provides a delta-V of about 5km/s. The total rocket masses about 700kg, so the upper stage is about 200kg. The upper stage contains the "warhead" (a 140kg block of steel, about 13cm thick), fuel, guidance systems, an IR detector, a 1.5m receiver for the detector, a reaction control system, and a 7mm thick buffer plate. The buffer plate is a "Whipple shield" which tries to break up and disperse any objects which impact the missile before they hit the main body. The body is about 37cm by 37cm.

I look at four main mechanisms to destroy or disable the missile:

- Sensor destruction: Anything that hits the IR sensor will render the rocket unable to find it's target and most likely disable it
- Penetration: a projectile that pierces the buffer plate and the warhead will probably spray enough debris into the delicate guidance and RCS system to disable the missile
- Spallation: an impact which penetrates the buffer plate but does not penetrate the warhead might still cause the rear of the warhead to spall – that is, the shockwave created by the impact could still cause enough local pressure on the rear of the warhead plate to cause pieces to break off and damage the more delicate internals
- Deflection: a projectile striking off-center will cause a torque force on the missile, causing it to turn. The guidance and RCS system can detect this sudden angular acceleration and adjust, but if the upper stage turns too much, it will lose track of the target and be disabled. (note: it might be able to reacquire, but I don't look at that). For this analysis, if the upper stage turns more than 45 degrees before it is corrected, I consider it disabled.

I used the Cour-Palais equation to determine penetration depth and assumed that spallation occurs when the target is less than 2.3 times the penetration depth (Based on 'HYPERVELOCITY IMPACT IN METALS, GLASS AND COMPOSITES' by Burton G. Cour-Palais).

For deflection, I modeled impacts at a number of positions on the front of the missile. I used an equation from Stephen Karl Remillard's dissertation 'Debris Production in Hypervelocity Impact ASAT Engagements' to estimate the dispersion of the post-buffer plate debris cloud. The equation seems to match similar results from 'Optimum structure of Whipple shield against hypervelocity impact' by M.Lee. I considered the momentum transfer of that portion of the debris cloud that strikes the body and assume that it takes 1/10 of a second for the RCS system to begin to respond.

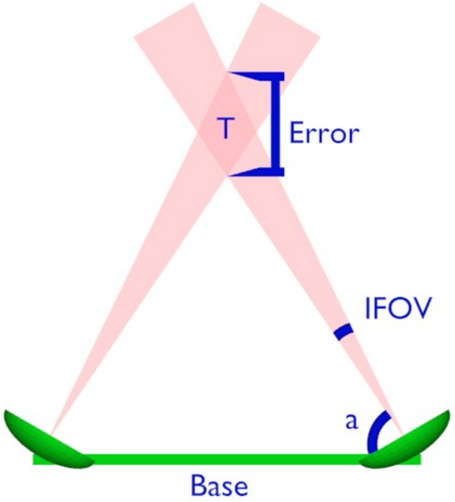
Somewhat surprisingly, deflection was the most likely cause of disabling the missile. An 80g projectile has a 73% chance of disabling the missile and a 120g projectile has a 90% chance.

2.2. How likely is it that the anti-missile will hit the missile?

The interception problem is an interesting one because of the limitations of HQC technology. Specifically, IR sensors (which, unlike radar can't determine range easily), and the primitive state of computing (which makes signal processing more difficult).

For the anti-ship missile, the ability to determine range is less important, since it is attempting a direct impact or explosion near a slowly accelerating target. But, for the AMM, determining range is important so it can set off its fragmentation burst. Setting it off too soon results in the shrapnel cloud being too dispersed, too late and it won't hit anything.

Determining range requires two sensors to triangulate the target – somewhat like a coincidence range finder. In addition to measurement error, two sensors are inherently limited in their accuracy because of diffraction – particularly at the long wavelengths that the IR detectors have to be tuned to. Each sensor can only locate the target within a certain angle (called the IFOV or Instantaneous Field of View). The target can only be narrowed down within a region where the area traced by the IFOV's overlap – see the next figure.



The figure also defines angle a, which is the angle from the sensor's direction and the baseline connecting both sensors. The distance to the target can only be determined within the the error bar, where the distance is equal to tan(a+IFOV)*Base/2. As you can imagine, unless the base is huge, if the angle a is very high the error can be huge. For a large ship sensor with an IFOV of 3.5 micro-radians and a 100m base, the error for a target 950km distant is 32km. A smaller sensor on an anti-missile missile might have an IFOV of 150 micro-radians and a base of only 10m, so it has a much larger error – at 33km, it has an error of 32km.

To estimate the accuracy of the AMM, I simulated the two rockets closing on each other. The ASM maneuvers randomly, changing its acceleration every second. Whenever it leaves the IFOV ahead of the AMM, it's movement can be detected and the AMM maneuvers to match. Every 1/10th of a second, the AMM checks the range. When the AMM determines (accounting for error) that it is close enough to the ASM, it detonates. Given those assumptions, the chance of the anti-missle's shrapnel cloud overlapping the trajectory of the anti-ship missile, depending on distance when it was launched, is:

dist (km)	Shrapnel cloud intercept
950	70%
500	82%
250	78%
125	100%

Assuming the anti-missile missile produces 140kg of shrapnel and it is evenly distributed, and given what we know of the missile size and probability of being disabled, the probability of a 'kill' (P_k), depending on the shrapnel size, is:

Distance	P_k,80g	P_k,110g
950	4.6%	4.2%
500	6.6%	6.0%
250	15.4%	13.4%
125	72.8%	89.0%

A short distance shot gives a very high probability of a kill, but 125km may be too close. If the anti-missile is fired when the ASM is 125km away it will intercept only a few kilometers away from the target ship – at that distance a piece of shrapnel might disable the ASM, but not knock it off course enough to avoid it hitting the target.

2.3. Summary

AMMs have a good chance of hitting incoming missiles – if they can be detected and tracked and if the AMMs can be launched in a relatively narrow window – close enough that they hit, but far out enough that hitting will make a difference. Although detecting a missile is quite possible at ranges of several thousand km, it takes time for a sensor to sweep the sky and more time to estimate range. One or more missiles could slip by while the target is searching.

Potential target ships will have to have a lot of sensors sweeping space to avoid being caught by surprise.

2.3.1. Other anti-missile defenses

The target ship can also use decoys, flares, maneuvers, and probably a slew of other tactics and mechanisms to avoid the ASM as well.

2.3.2. Anti-anti-Missiles

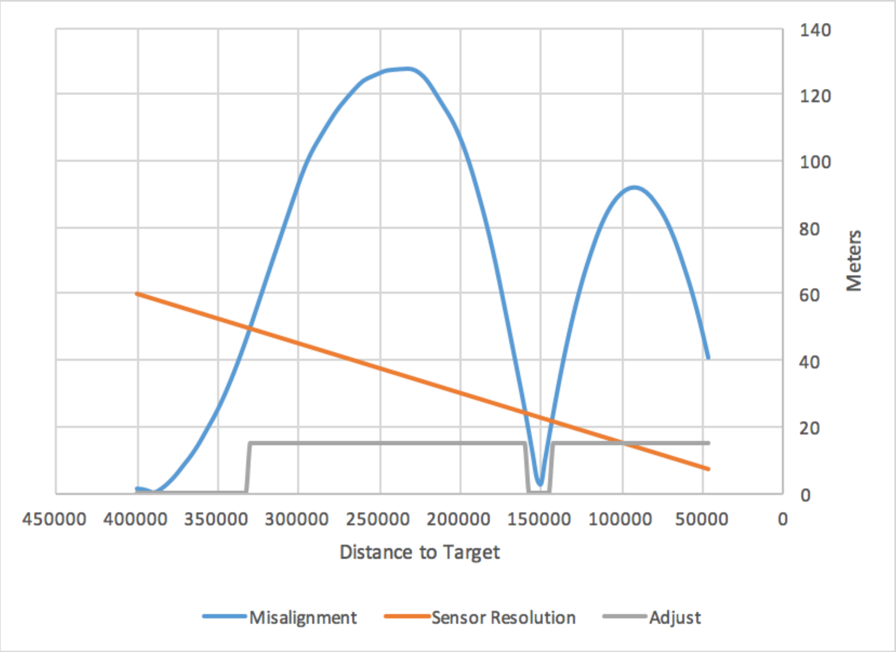
Anti-ship missiles can also contain counter-measures of their own:

- Flares: Since the anti-missiles don't have a human operating them, they will be susceptible to flares
- Cold-gas thrusters: During the main engine boost phase, missiles will be very visible, but at that range (2000-10000 km), it will be hard to determine a precise trajectory or location. If the anti-ship missile also contains a cold-gas thruster it could give a substantial 'lateral' velocity so it is coming in at an unexpected angle
- Decoys: Anti-ship missiles could deploy a number of decoys to saturate defenses. Due to the low resolution of the IR sensors at these ranges, they may be easy to fool - particularly if they are not operated by a human
- Multiple Independent warheads: Instead of a single 140kg warhead, a single missile could carry several smaller warheads, each independently maneuvering, making interception more difficult
- Cooled IR receiver: The IR receiver could act like a thermal shield, making detection harder

    - Angled bumper: It may be possible to angle or shape the bumper shield to reduce the torque an impact imparts on to the vehicle. Since deflection is the easiest way to disable a missile, reducing its effectiveness could be very beneficial.
- Reacquisition: If deflected, the ASM could – with a more complex guidance system – attempt to reacquire it's target. This would make ASMs much harder to stop. A penetration-based kill could require as much as a 450g fragment.
- Radio control: If the firing vehicle is not aerolyth based (e.g. a space station or a subsidiary vehicle from the aerolyth craft) it could use a radio to impart simple messages to its missiles. For example, missiles could "run cold" – not maneuvering and hiding behind their cooled receivers – until the launch craft detects that the target has fired anti-missile missiles. At that point a radio signal could tell the anti-ship missiles to begin maneuvering, launch decoys, etc...

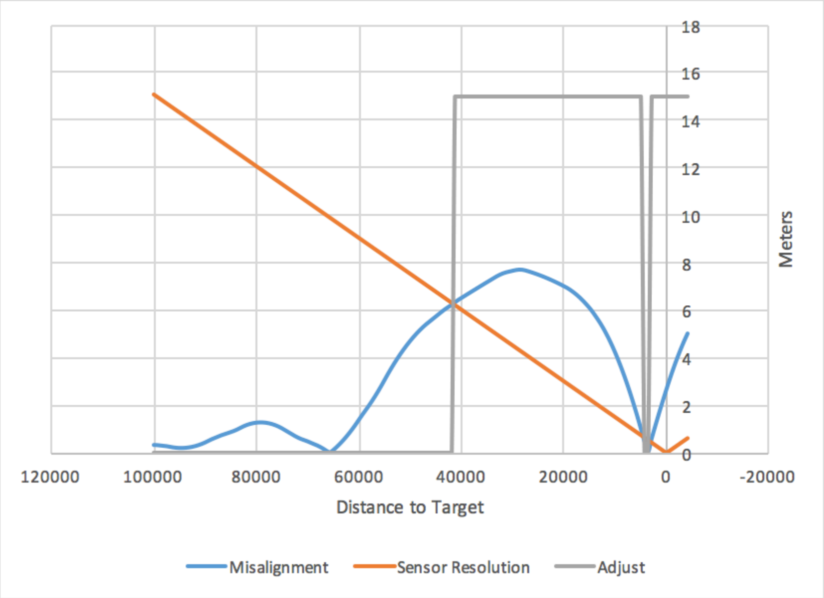
2.4. Visualization

The first graph shows characteristics of an AMM fired at a target 400km away. The red line is the sensor resolution – the closer the sensor gets the better the resolution. Think of it as the size of a pixel in a display. The blue line is the absolute misalignment (in the plane parallel to the missile's motion) between the AMM and the target. Remember, the target is randomly maneuvering. The grey line shows when the AMM is maneuvering to match the target. Remember, it can only do this when it is able to detect the target has moved at least one 'pixel' off center.



So, in this example when the AMM fires it is pointed at the ASM target pretty closely, but it doesn't know (and can't yet detect) that the ASM is changing direction. A little later, when the distance to target has closed to about 325km, the ASM is not about 50m off-center from the AMM's direction. It has moved a "pixel's-worth" of distance away from its expected location, so the AMM knows it needs to change its course to compensate. It does so, and by 160km away the ASM is back on center. The ASM stops adjusting. But, perhaps it has over-adjusted or perhaps the ASM has performed some more maneuvers. By 150km, the misalignment is increasing. Again, the AMM doesn't notice this until the ASM is misaligned by a pixel's worth - about 22m in this case. So, by 140km or so the AMM realizes it is off target again and starts correcting. By 80km it is catching up to the ASM's course change, but it is sill not quite able to compensate for the error, and ends up missing by 10m or so (or maybe it explodes on time and hits the ASM with some shrapnel, either way there is a sizeable error).

The second graph:



Shows a similar missile fired at a target 100km away. Again, the ASM is maneuvering and this isn't detected immediately, but because the resolution at these ranges is smaller / better the misalignment is detected more rapidly and the AMM can adjust more quickly. The ASM never gets more than 8 meters out of misalignment and is only 2-3 meters off center of the path of the AMM when they pass.

You can improve the AMM's performance if it was guided by the launching ship (or a friendly picket) using either radio or optical communication, but there still will be a range dependence.

3. Space Pickets

I've been thinking more about what space combat might look like in HQC. Specifically, the possibilities for "Space Pickets." They are a staple of sci-fi, but are often impractical in a 'hard' sci-fi setting. However, I think there is a good argument thatSpace Fighters (in some form) might make sense in HQC.

3.1. Summary

Because of the characteristics of HQC technology (most notably, E&S drives and IR detectors), space 'fighters' or pickets may have a role in combat. This is because of their better ability to maneuver, estimate range to targets, and resolve targets.

3.2. Background

First, the term 'Space Picket' is not well defined. For this post, let me define it as "A space vehicle, carried by another larger vehicle and deployed for short-duration combat." For HQC, I would say that they don't carry E&S drives and probably not aerolyth rockets. You might call what I'm proposing a "bomber", "fighter-bomber", "torpedo boat", "lancer" or any of a dozen terms just as well.

Second, many of the reasons pickets might be plausible in HQC stems from the sensor technology, specifically, Infrared (IR) detectors. Unlike radar (where you send out a signal and then can time how long the return 'echo' takes to get back to you), an IR sensor is a passive sensor. If you get a signal, you know roughly what direction that signal is coming from, but you don't know how far away it is. Using multiple sensors separated by a baseline you can triangulate the distance, but there is still quite a bit of error in this because the resolution of the sensor is limited (see attached image for an visual explanation).

Essentially, to get a good range with an IR sensor you need a very large separation between your sensors or a very good resolution. Because of the distances in space, the sensors are diffraction limited, so improving resolution requires a larger reciever, which can get prohibitive.

The other relevant aspect of IR detectors is their resolution. At the sizes and ranges we're looking at (combat ranges of a several hundred to a few thousand km), the resolution is several meters across. So when you detect an object you might get a signal that is only a few 'pixels' across – it will be hard to get much information from that.

Third, there are three major propulsion sources in HQC space: chemical rockets, E&S drive, and aerolyth rockets. Chemical rockets allow fast acceleration, but require a lot of fuel. The E&S drive allows reactionless travel (i.e. no 'fuel') but only allow very small acceleration (cm/s^2 or mm/s^2). Aerolyth rockets allow even faster acceleration than chemical rockets, but are more difficult to restart without massive capacitors and (most importantly) aerolyth-aerolyth interactions mean you can't use an aerolyth rocket on an E&S ship.

With those factors in mind, let me make a case for where pickets could find a role.

3.3. Defense

In a previous post, I estimated that anti-missile missiles (AMMs) can be a good defense against attacking anti-ship missiles (ASMs), but they have to detect the incoming missile quickly, and fire within a fairly narrow window – too far out and they will probably miss, too close and they might hit, but not do enough damage to deflect the missile:

https://groups.yahoo.com/neo/groups/Hivequeen/conversations/messages/52321

Having space fighters might improve the defensive odds for four reasons: Defense in depth, improved resolution, improved ranging, and anti-stealth capabilities.

3.3.1. Defense in Depth

Having a fighter deployed with AMMs could improve your odds of hitting an incoming ASM by providing multiple 'layers' of defense. Put another way, you can get more shots off at an incoming attack. Suppose an AMM has roughly a 25% chance of 'killing' an incoming ASM if launched when the ASM is 250km away. So, the defending ship needs to launch a salvo of 11 AMMs for every incoming ASM, to have a ~95% chance of intercepting. At 11:1, it would be easy to swamp the defending ship. But, if the defender has a fighter deployed a few hundred km forward, this fighter can take a 'first pass' at the incoming ASMs, allowing the defending ship to only have to engage the surviving ASMs. If the fighter fires just 4 AMMs per ASM, it would intercept about 68% of the incoming salvo. If the defending ship then fires 11 AMMs at each remaining ASM, the total AMM:ASM ratios is about 7:1. With multiple layers of fighters, the ratio is even smaller.

Additionally, the effect is even greater. A single ship defending itself needs to launch AMMs in a narrow window (too far and you'll probably miss, too close and you might hit, but not knock the missile off trajectory enough to avoid getting hit). However, a forward deployed fighter has a much larger window. It can engage a missile 125km from the fighter and have a 70% chance of throwing it off course sufficiently. With two layers of fighters, the AMM:ASM ratio drops to 2.3:1. With theadditional advantages below, the ratio should drop even more.

3.3.2. Resolution

At closer ranges, a picket can get better resolution on the incoming object. This is particularly important fordetecting the direction of incoming missiles. With 20m resolution, you may not be able to determine much about an ASM other than that it was launched. But with 2m resolution, you might be able to detect the direction and intensity of the thrust, giving a much better chance of intercept.

3.3.3. Ranging

The ranging error for a pair of detectors on a ship separated by tens of meters can be very high - particularly when trying to estimate the range to a small target like an ASM which is hundreds of km away. Deploying a fighter with a detector even a few dozen km away from the ship's sensor could provide enough distance to reduce the error by two orders of magnitude. Even if that 'fighter' is just a forward observer, it could provide much more accurate ranging and speed estimates.

3.3.4. Anti-'stealth'

In the previous post on space defenses I threw out some 'stealth' mechanisms that an ASM could use to reduce its detectability. Having a fighter forward deployed could help defeat such measures. For example, the shorter distance (better sensitivity, better resolution) might allow a fighter to detect cold-gas thrusters, or discern decoys from real targets. Having a different angle of view might also defeat things like a cooled IR receiver or shroud.

3.4. Offense

Similarly, pickets offer advantages on the offensive.

3.4.1. Resolution

Higher resolution on the detectors of a forward-deployed fighter also provide advantages when attacking. It may be able to get a more precise target bearing, discern decoys, and providing better ranging. This could make a fighter a better launch platform than the 'parent' ship.

3.4.2. Direction

Another possibility would be if the fighter could direct a swarm of ASMs launched from itself or from the parent ship. Using radio or light communication, it could provide updates to the ASMs, adjusting their course, ordering them to deploy flares, or commanding them to ignore target decoys. If the ASMs use flak warheads, the fighter could provide ranging information so they know when to explode. This might also mean that the 'fighter' is just a very small observer – basically a sensor platform with communications and enough life support for a small crew. It might only carry a few AMMs or even be unarmed.

3.5. Overhead

The disadvantage of a fighter is that it takes up mass. Carrying 10 ASMs in a ship will take less mass than carrying 10 similar ASMs in a fighter in a ship. The questions are: how much does carrying the fighter add? and do the advantages outweigh the costs?

First, an estimate for a fighter-less ship. This is based on the interplanetary cargo ship design we used for estimating interplanetary cargo costs, but with a longer endurance, bigger crew, sensors, etc... Power, thermal, life support, etc... are all scaled up.

Mass breakdown (all masses in metric tons):

- Structure 50t
- Armor 150t
- E&S Engines 90t
- Secondary 10t
- Misc 3t
- Computing 120t
- Crew Support 92t (100@120days)
- Crew Accommodation 50t
- Weapons 350t (500 700kg missiles 5km/s dV)
- Sensors 20t
- Power 12t
- Thermal 34t
- Total: 881t

Using the 11:1 AMM:ASM ratio and assuming it wants to defend against as many ASM as it can carry, we would have: 458 AMMs 42 ASMs

Next, estimates for a space fighter (masses in tons):

- Struct 6 (inc 2.2t which is ejected after the 1st tage)
- Armor 1t
- Engine 0.5t
- Misc 1t

- Computing 5t
- Crew 2t (8 crew @250kg each (90kg of person, 160 of life support + accommodation))
- Sensors 7t
- Power 1t
- Thermal 3t
- Weapons 50t (80 600kg missiles 4.4km/s dV)
- Fuel 53.5t
- Total: 130t

This design has a dela-V of 3km/s. The rough mission envelope is to expend ~1km/s deploying, ~1km/s coming to a stop, and then ~200m/s returning after the battle. This leaves about 600m/s for extra maneuvering. The fuel is split up assuming 1640m/s dV in the first "stage" then 1360 in the second.

I assume the fighter's missiles can be a little smaller, since it is already traveling at some speed so they don't need as much delta-V.

Adapting the earlier E&S ship to carry a fighter would yield:

- Structure 50
- Armor 150
- E&S Engines 90
- Secondary 10
- Misc 3
- Computing 120
- Crew Support 101 110@120days (assume 10 crew for fighter)
- Crew Accommodation 55
- Fighter 130t
- Fighter support 6t
- Weapons 100 (142 700kg missiles 5km/s dV)
- Sensors 20
- Power 12
- Thermal 34
- Total: 881t

This gives us 222 missiles. So, less than half as many missiles in the same mass.

But, since the AMMs are much more effective (say, 2.5:1 instead of 11:1) than the fighter-less design, we can get the same defensibility with far fewer AMMs. So, maybe the breakdown is 105 AMM and 117 ASM.

This would mean you can get the same defensive strength and 2.8x as much attack in the same mass.

This is somewhat conservative as well – we may be able to reduce the dV of the fighter's AMM/ASMs even more. Another possibility is a "forward observer" fighter that has even fewer missiles and more sensors.