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SHORT TERM THREAT RESPONSE REQUIRES LONG TERM PREPARATION

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ABSTRACT

Comets, such as the recent Comet C/2013 A1 (Siding Spring) can impact terrestrial planets with very short warning times: for Siding Spring the time from discovery to closest approach to Mars (135,000 km) was less than 22 months. Short warning times are also possible for certain asteroids approaching on unfavorable orbits. The time to design, build, test and launch a high-reliability Interceptor spacecraft is on the order of 5 years, a timescale incompatible with threat mitigation for such short warning times. A potential solution is to build the interceptor before the threat is detected and put it into storage until it is required. Launch of a stored spacecraft could be accomplished in less than a year after authorization based on experience with the DSCOVR program managed by NASA's Goddard Space Flight Center.

While asteroidal impacts are of order 100 times more likely than cometary impacts, comet impacts will carry more than 100 times the energy of a typical asteroid threat, making their destructive probability nearly equal. Cometary threats have been largely ignored to date, a situation that needs to change as our Planetary Defense efforts become more mature. An idealized threat response system will be described.

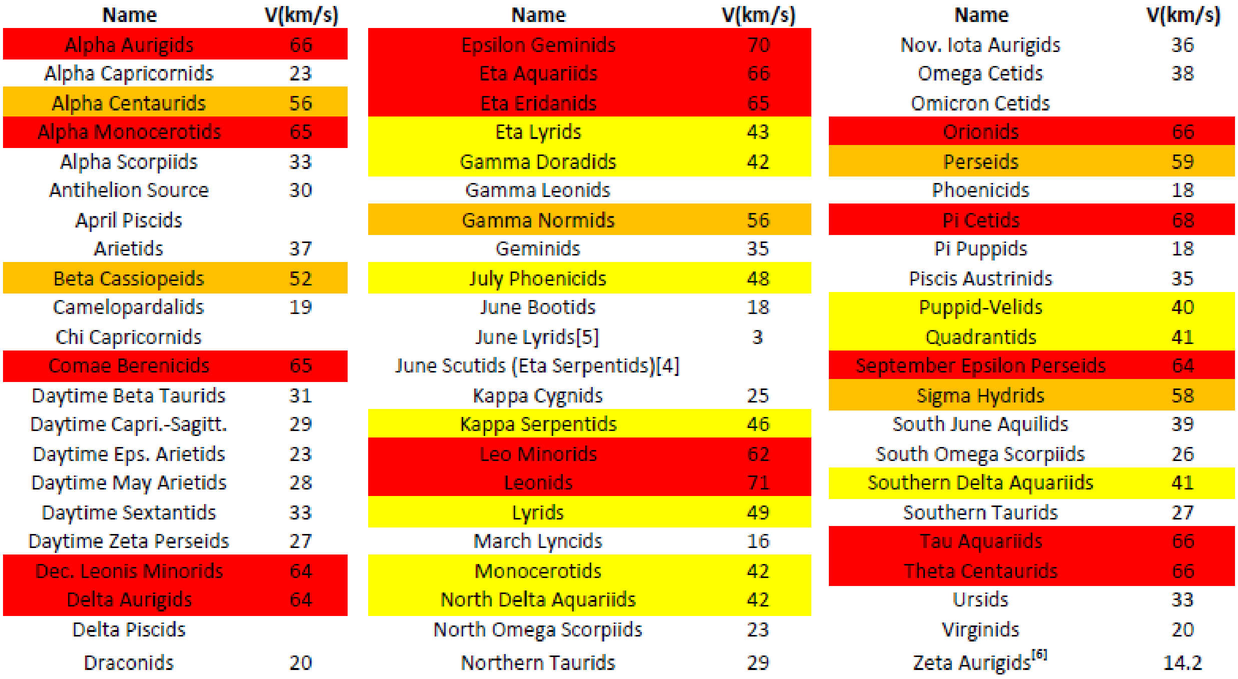
Introduction

Human civilization has come a long way since realizing that comets and asteroids posed a threat that has previously caused major extinction events on the Earth. The announcement that an asteroid impact was the probable cause for the extinction of the dinosaurs [1] was a shock to many earth scientists who firmly believed that forces outside the Earth had no virtually effect on terrestrial evolution. The impact of Comet Shoemaker-Levy IX was a graphic illustration of the power of small body impacts to change the atmospheric chemistry of even a giant planet such as Jupiter. Following these events the United States and other nations began work on the means to detect and monitor the asteroid population in order to fully evaluate any potential threat and to predict future impacts with the goal of either preventing the impact or mitigating its effect. Since initiating this program the number of known asteroids has increased from ~5000 to more than 700,000: these are tracked and their orbits are projected well into the future to search for potential threats.

Studies are in progress to increase the efficiency of the search program by placing a near infrared detection system into space. Such a system is essential if NASA is to meet a U.S. Congressional mandate to detect 90% of all asteroids larger than 140 m within a reasonable timeframe. However, while we have made excellent progress in finding and tracking asteroids to date, we have ignored a major component of the small body population: comets. In addition, we have done little to ensure that we could deflect or disrupt a small body threat that we might detect within a few years of impact. It is these aspects of Planetary Defense that we believe deserve additional attention.

Comets as Impact Threats

It is commonly assumed that since comets are about 100 times less likely to impact the earth compared to asteroids that they are only a minor threat. Unfortunately, we do not believe that this analysis is complete. The average comet is much larger than the typical asteroid by a factor of at least three or more [2]. Since the mass of an object scales as the cube of the diameter (for constant density) the average comet could easily be a factor of ten times more massive than a typical asteroid even though its average density could be as little as 0.6 g/cc. The second important factor in the destruction potential of an impact is velocity. Typical asteroid impacts will have velocities on the order of 20 km/s. Comet impacts could potentially occur over a much wider – and generally higher - range in velocity.



Name	V(km/s)	Name	V(km/s)	Name	V(km/s)
Alpha Aurigids	66	Epsilon Geminids	70	Nov. Iota Aurigids	36
Alpha Capricornids	23	Eta Aquariids	66	Omega Cetids	38
Alpha Centaurids	56	Eta Eridanids	65	Omicron Cetids	
Alpha Monocerotids	65	Eta Lyrids	43	Orionids	66
Alpha Scorpiids	33	Gamma Doradids	42	Perseids	59
Antihelion Source	30	Gamma Leonids		Phoenicids	18
April Piscids		Gamma Normids	56	Pi Cetids	68
Arietids	37	Geminids	35	Pi Puppids	18
Beta Cassiopeids	52	July Phoenicids	48	Piscis Austrinids	35
Camelopardalids	19	June Bootids	18	Puppid-Velids	40
Chi Capricornids		June Lyrids[5]	3	Quadrantids	41
Comae Berenicids	65	June Scutids (Eta Serpentids)[4]		September Epsilon Perseids	64
Daytime Beta Taurids	31	Kappa Cygnids	25	Sigma Hydrids	58
Daytime Capri.-Sagitt.	29	Kappa Serpentids	46	South June Aquilids	39
Daytime Eps. Arietids	23	Leo Minorids	62	South Omega Scorpiids	26
Daytime May Arietids	28	Leonids	71	Southern Delta Aquariids	41
Daytime Sextantids	33	Lyrids	49	Southern Taurids	27
Daytime Zeta Perseids	27	March Lyncids	16	Tau Aquariids	66
Dec. Leonis Minorids	64	Monocerotids	42	Theta Centaurids	66
Delta Aurigids	64	North Delta Aquariids	42	Ursids	33
Delta Piscids		North Omega Scorpiids	23	Virginids	20
Draconids	20	Northern Taurids	29	Zeta Aurigids[6]	14.2

Table 1. These meteor streams represent potential comet impacts that never happened because the comet did not cross the earth's orbit at the "correct" moment. For ease in understanding the velocity distributions the streams have the following color code: Velocity > 60 km/s (red); Velocity > 50 km/s (orange); Velocity > 40 km/s (yellow); Velocity <40 km/s (no highlight).

Meteor streams are the result of the earth passing through the debris clouds shed by comets along their orbits through the inner solar system [3]. In essence, these streams represent comets that might have impacted the earth had it been in a different spot along its orbit. If we take the velocities of meteors in meteor streams as proxies for the potential collision velocities of these comets we find that they range from a low near 3 km/s to a high of 71 km/s (see Table 1), with the median at 39.5 m/s and the mean at 41.5 m/s. Therefore the typical comet will impact at about twice the velocity of a typical asteroid.

Since the impact energy scales with the square of the impact velocity and linearly with mass, the typical comet impacts with about 50 - 100 times the energy of a typical asteroid; e.g., ~27 times the mass and ~twice the impact velocity or ~108 times the impact energy. Viewed from the perspective of destructive potential, even though a comet is much less likely to strike the earth than an asteroid, when one does strike, it does so at much higher energy. We, therefore, contend that comets represent about half of the threat of small bodies to human civilization. Unfortunately, comets have been largely ignored by the Planetary Defense community (though not necessarily by Hollywood).

The Real Problem with Comets

While the probability of a comet impact is low, the warning time for such an impact is also likely to be exceedingly short compared to an asteroid impact. Search programs are most likely to find asteroids orbiting near the ecliptic plane in reasonably circular and predictable orbits. It has often been stated that large threatening asteroids can be found 20 to 200 years before impact (in the ideal case) and that civilization will have plenty of time to deal with such threats using kinetic impactors, gravity tractors, ion beams or other means that can slowly alter the orbit of the offending body onto a more acceptable course. This assumption may even be correct for Jupiter Family comets that have been captured into well-behaved, ~6 year period orbits and that constitute the majority of known comets. Unfortunately, these do not constitute the majority of comets in the solar system.

The recent apparition of Comet Siding Spring illustrates the ultimate problem with comets: ***short reaction time***. Comet Siding Spring was discovered on 3 January 2013 by Robert H. McNaught at the Siding Spring Observatory. Over the next few weeks it was determined that the comet would come close to (and possibly collide with) Mars. Continued observations were required to refine our estimates of the comet's orbit over the next year in order to position orbiting satellites away from potential harm on the other side of Mars as Comet Siding Spring passed within 135,000 km of the planet on 22 October 2014. This close passage was just 22 months after discovery and even less time after a well-characterized orbit was obtained. While Comet Siding Spring did come into the inner solar system from the ecliptic pole, larger telescopes would not have revealed its presence much earlier as it was detected relatively soon after it began to exhibit a coma. The problem was that the comet was on a very eccentric orbit with a high velocity and a short travel time to Mars as it fell into the inner solar system. A slightly different orbit as it fell from the outer solar system could just as easily have sent it towards the Earth.

Planetary Missions Require Time

While Hollywood screenwriters can imagine launching missions to intercept and destroy threatening comets or asteroids on very short timescales, the reality is quite different. Typical high-reliability NASA missions require on the order of at least 48 to 60 months between the budgetary “authorization to proceed” and launch, distributed over several distinct phases as illustrated in Figure 1. Of course in most instances such missions have also been the subject of one or more preliminary studies that eventually led to this approval so that the actual time from mission conception to launch is much longer than shown in Figure 1. There is no doubt that such a schedule can be compressed – and, in a true emergency, compressed significantly. However, the steps and timescales below have evolved over time as an efficient compromise between building and launching a spacecraft quickly and cheaply, and building a spacecraft that is reliable and accomplishes its mission. In an emergency situation, do we really want to quickly throw together a spacecraft to save the planet and simply hope that it functions long enough to do the job?

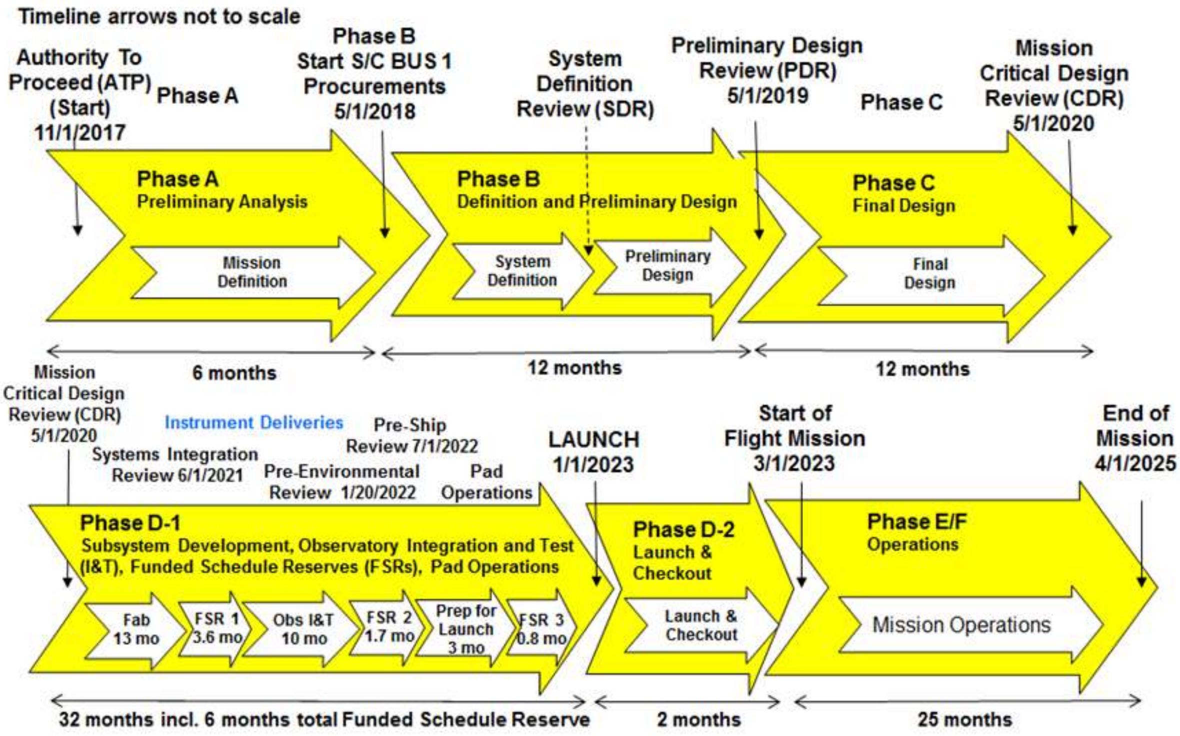


Figure 1. This schedule illustrates a typical design, review, construction, testing and integration schedule preceding launch, spacecraft in-flight checkout and operations.

We argue that when millions or billions of lives, associated property and even geopolitical stability are at stake it is even more important that the spacecraft used to deflect or destroy the threat is carefully designed and that the design is thoroughly reviewed. The spacecraft should then be built and tested to the highest possible standards. Instrumentation required for such a mission should be built and tested to at least the same exacting standards as for more routine missions. But how can such deliberate, careful work be done under such intense time constraints?

Recommendation Number One

The simple solution to elimination of the time pressure to design, build and test a spacecraft to intercept a potential impactor is not to wait until the threat is discovered but instead, to build and test the spacecraft before it is needed. We can then put it into storage until its use is required. If a threat is detected we then have the option to tailor the intercept mission around the capabilities of this spacecraft or (if time permits) to modify the spacecraft to more efficiently divert or destroy the threat. This approach is much the same as we use in our building codes where fire suppression systems are installed in public buildings with the hope that such systems will never be activated, yet, if needed, will work exactly as designed to put out a fire. Thus, there are ample precedents for our suggested approach to planetary defense preparation.

In October, 1998 the Triana Mission was selected for implementation by NASA [4]. Named for the sailor on Columbus' voyage who first saw the New World, Triana was a satellite mission to L1 that would have had a continuous, full disk, sunlit view of the Earth and that would have provided this view of the Earth for distribution over the Internet. Triana would have carried two main instruments: the Earth Polychromatic Imaging Camera (EPIC), and an advanced radiometer (NISTAR). Triana also would have included a small, next-generation space weather monitoring instrument to contribute to understanding how solar events affect Earth-orbiting spacecraft such as communications satellites.

Unfortunately, Triana was a highly politicized space mission with strong ties to Vice-President Al Gore, and this association resulted in a storm of opposition to the mission. Although the spacecraft was completed in late 2000 and was scheduled for launch on the Space Shuttle Columbia in February 2003, the Bush administration dropped the launch from the Shuttle manifest, instead prioritizing construction payloads to the International Space Station, microgravity experiments, and a reboost for the Hubble Space Telescope at a time when, in any given year, only six Shuttle flights were scheduled. Launching Triana on an expendable rocket would have doubled the cost of the mission: the spacecraft was put into storage in 2001.

In 2009 under the Obama administration, NOAA saw an opportunity to replace the aging ACE Mission to monitor solar activity at only a fraction of the cost of a new spacecraft [4]. By investing about $32 million over 2011 and 2012, the Triana spacecraft was revived as DSCOVR (Deep Space Climate Observatory) and made ready for launch. The small, next-generation space weather monitor was now the mission's primary payload with the EPIC and NISTAR instruments at much lower priority. The longest delay in getting the mission to L1 was in the procurement of a launch vehicle. DSCOVR launched on February 11, 2015 and is operational today.

The takeaway message from this story is that spacecraft can be successfully stored for at least a decade before launch preparations begin. [Note that for DSCOVR, the spacecraft was originally designed for launch on the Space Shuttle, and some of the required refurbishment was to allow launch on a Falcon 9.] Much of the delay in the actual launch after the mission was approved in 2011 was due to the procurement of that expendable launch vehicle and getting the launch into the queue.

A spacecraft originally designed to ride a variety of expendable launch vehicles could be ready for launch on a much faster timescale than was DSCOVR. In addition a mission to stop a small body from impacting Earth would have a much higher priority for launch than did the DSCOVR mission. Overall, we estimate that a purpose built interceptor could be removed from storage and launched within a year of receiving authorization. This would allow a well-designed, carefully built and thoroughly tested mission to be launched in time to intercept most short-warning time threats.

Recommendation Number Two

There are many factors that should be understood prior to conducting an attempt to deflect or disrupt a small body. Among these are the shape, spin axis, rotation rate, internal strength, mass, and composition of the target. These factors differ in their relative importance depending on the deflection method that one intends to employ. For short warning time events we assume that only a stand-off nuclear blast has the energy density to achieve deflection or disruption when launched within a year of a projected impact. For deflection, all of the above factors are significant, whereas for disruption the spin axis and rotation rate become less important. Unfortunately for a short warning time threat, none of these factors will be sufficiently bounded prior to the launch of the interceptor spacecraft. Even for reasonably well observed small bodies remote sensing observations are not very reliable for determination of the shape, spin axis or rotation rate and are even less able to determine mass and composition; *e.g.,* see Figure 2.

Figure 2. Above, left is an artist's impression based on remote sensing observations of the nucleus of Comet 67P/Churyumov-Gerasimenko, portrayed far from the Sun with little to no activity (Image via ESA – C. Carreau [5]). Above, right is an Image of Comet 67P obtained by Rosetta after arrival in August, 2014.

While Comet 67P/Churyumov-Gerasimenko may be an extreme example of an irregularly shaped small body, radar observations of asteroids [6] have shown that many small bodies are far from spherical. Deflecting a non-spherical body no longer depends upon simply hitting near the center-of-mass, but now depends as well on timing the impact (or blast) to occur along a particular axis of a rotating body where the axis of rotation may not be either in the plane of the impact or orthogonal to it, but could be at some intermediate angle. However, it is highly unlikely that precise information on the spin axis, shape or rotation rate will be available for short warning hazards based on remote sensing observations alone. We therefore recommend that a second spacecraft be built and put into storage for launch on warning of a threat.

The second spacecraft would be a simple observer, optimized to carry a minimal payload for assessment of the shape, spin axis and rotation rate of the threat. A simple set of cameras would suffice to accomplish this task: a narrow field of view, long ranged system for estimation of the rotation rate and spin axis and a wider field of view, mapping camera to obtain a shape model. The addition of a long-range lidar system together with Radio Science could be used to estimate the mass of the target during a close fly by, while use of an infrared spectrometer could yield an estimate of composition.

In principle the observer spacecraft would be launched upon suspicion that a newly discovered small body constitutes an impact threat such that the vital information required to plan a deflection or disruption mission is obtained as far in advance as possible prior to the launch of the interceptor. It is even possible that the observer spacecraft will enable estimation of a more precise solution for the object’s orbit than was previously possible via remote sensing instruments alone and that these measurements will show that the potential impactor is, in fact, not a threat. This could preclude the need to launch the interceptor at all and thereby avoid all of the problems associated with the launch of a nuclear device into space.

Of course there are many ways to parse the functions of observer and interceptor spacecraft. The simplest and most versatile is simply to divide the functions between two separate vehicles. However, if there is sufficient time and capability that it is possible to rendezvous with the target well before the detonation of a nuclear device is required to ensure the deflection (or more likely the destruction) of the threat, then such a solution might provide a less expensive alternative compared to a solution that requires two separate launches. While such a solution might be possible for a typical asteroid impactor, it is highly unlikely to be suitable for a cometary threat with an approach similar to that of Comet Siding Spring.

Recommendation Number Three

Modern launch vehicles are highly reliable, yet this reliability has not yet reached perfection. In a very small number of launches something goes wrong resulting in the loss of the spacecraft or the injection of the payload onto an unacceptable trajectory. What level of reliability is required or acceptable for a system designed as a last minute response to an impact threat? We suggest that the ability to launch a single interceptor spacecraft within a year of detection of an impact threat is an excellent step up from our present situation. However, the addition of a backup interceptor, able to launch after the initial intercept attempt has been completed or that could react in flight to lessons learned from that initial intercept attempt, would represent an important and possibly essential increase in system reliability.

In the ideal situation we would have available both primary and backup observer spacecraft as well as primary and backup interceptors that could be launched in short order in response to a potential threat. However, these spacecraft do not need to be built all at once and do not even need to be of the same design. A reasonable approach would be to design and build the first interceptor spacecraft over the next decade. With this completed we could then review the previous design, incorporate any improvements and innovations into the newer interceptor and build the next generation spacecraft which would become the new primary interceptor. Once the interceptors are in storage the program could design and build the first observer spacecraft, followed in similar fashion by a second – possibly improved – version.

We recommend that NASA establish a new line item under the Planetary Defense Coordination Office (PDCO) to create a fast response capability for the deflection or disruption of short-response asteroid or cometary threats. The full capability described above could be built out over the next several decades. However, once the initial complement of interceptors and observers are in place, the program should continue at a lower level so as to continuously upgrade these spacecraft with more modern technology. This could entail replacement of obsolete components or simply building and testing an entirely new design. The older spacecraft could then be released to other NASA programs to carry out appropriate science or technology missions. This would be a cost-effective program to ensure that humanity always has available the means to defend the Earth from an impact threat.

Summary

In the relatively short time that we have been aware that small celestial bodies could constitute a major threat to human civilization, we have made remarkable progress in detecting and cataloging the asteroid population and in predicting the probability of impact threats from this source. While comets are much less likely to impact Earth compared to asteroids, because the typical comet is larger than a typical asteroid and will intercept the earth at significantly higher velocity, the destructive potential of a cometary impact will be much larger than that of a typical asteroid. Therefore the destructive potential of these two sources is approximately equal. The addition of space-based platforms could significantly increase the detection efficiency of asteroid threats. Unfortunately, such systems would be only minimally effective in finding the much less common danger from comets. While asteroid impact threats may be detectable many decades in advance, yielding plenty of time to mitigate these hazards, comets are more likely to be discovered only shortly before impact, yielding very little time to deflect or disrupt such bodies.

We recommend that, at a minimum, an interceptor spacecraft be constructed in advance of the detection of any threat to ensure that a solution is available for the deflection or disruption of a small body on a short time scale. The interceptor would be designed to carry a nuclear device, though the device need not be integrated into the spacecraft until just before launch and would always remain the responsibility and in the custody of the NNSA. Following the construction and thorough testing of the interceptor, the spacecraft would be placed into storage until needed. To increase the probability of success and to eliminate the potential that a faulty launch could result in a failed attempt to mitigate an impact threat, we also recommend that at least two interceptor spacecraft be constructed and kept in storage at all times. These would be launched in sequence if necessary so that the second spacecraft could take advantage of any lessons learned from the first mission, in addition to serving as a backup against any initial launch anomaly.

Because the success of a potential deflection or disruption mission depends critically on understanding the nature of the target we also recommend that an observer spacecraft be built, tested and placed into storage. This vehicle would be launched on warning to provide information essential in planning and executing an intercept mission. In an ideal program a backup observer spacecraft would also be in storage just in case of a launch anomaly in the primary mission. We therefore recommend that PDCO oversee a program to establish the full capability described above over the next several decades, including the availability of at least two interceptors and two observer spacecraft. As the interceptors would of necessity be designed to carry nuclear devices, the program would demand close coordination with the NNSA. We recommend that PDCO begin a design study to determine the capabilities of the spacecraft required in such a fleet as soon as possible and thereafter review these options on a regular cadence as new technology becomes available. PDCO would then continue to upgrade this fleet based on the results of these reviews so that the world would always have the option to rapidly counter short-response-time threats using the best available technology.

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