COMMON INFRASTRUCTURE FOR NEO SCIENTIFIC AND PLANETARY DEFENSE MISSIONS

A Joint NASA MSFC – ATK White Paper

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EXECUTIVE SUMMARY

While defending the Earth against collisions with asteroids and comets has garnered increasing attention over the past few decades, our knowledge of the threats and methods of mitigation remain inadequate. There exists a considerable gap in knowledge regarding the size, composition, location, internal structure and formation of near earth asteroids and comets. Although estimates have been made, critical experiments have not yet been conducted on the effectiveness of various proposed mitigation techniques.

Closing this knowledge gap is of interest to both the planetary defense and planetary science communities. Increased scientific knowledge of asteroid and comet composition and structure can confirm or advance current theories about the formation of the solar system. This proposal suggests a joint effort between these two communities to provide an economical architecture that supports multiple launches of characterization and mitigation payloads with minimal response time. The science community can use this architecture for characterization missions of opportunity when multiple scientific targets or targets of uncommon scientific value present themselves, while the planetary defense community would be able to fire characterization or mitigation payloads at targets that present a threat to the Earth. Both communities would benefit from testing potential mitigation techniques, which would reveal information on the internal structure of asteroids and comets. In return, the Earth would have the beginnings of a viable response system should an impact threat prove real in the near future.

PROPOSED CONCEPT ARCHITECTURE

The catastrophic threat posed by a future collision of a Near Earth Object (NEO) with the Earth has gained worldwide attention in recent years. While ground based efforts continue to detect and catalog potential threats, there is at present no serious effort to field a system that can deflect an NEO when a collision threat is detected. In addition, ground based detection is generally not sufficient to characterize the potential threat. Measuring NEO orbital parameters is difficult from the ground, and details about the specific geometry of the NEO, its internal structure and composition, are nearly impossible to discern.

Our current understanding of the asteroid and comet population is similarly limited by what we can detect from ground installations. Although recent missions by the U.S.[1] and

Japan[2] visiting these planetary bodies have provided a wealth of new data, the gaps in our knowledge pertaining to asteroids and comets are substantial.

This proposal defines a common architecture for the scientific exploration and mitigation of the threat posed by asteroids and comets. We envision a set of vehicle components that are pre-constructed and warehoused near a launch site, ready for assembly and launch on short notice. The components include hardware options for either a set of scientific instruments to characterize the NEO, or for various mitigation options. The instrument package would be available for scientific missions of opportunity, or when a potential threat was detected the instrument package would be launched to characterize the threat. Should that threat prove to be real, then a mitigation option would be launched at the target using substantially the same architecture. Through the judicious use of existing spacecraft components, common architectures and synergy with planetary science goals, a credible planetary defense infrastructure can be mounted at moderate cost.

In the sections that follow we provide a high level overview for each key component of the common architecture. Some components have several potential options, which would have to be further evaluated to determine which set should be carried forward in a deployed architecture. Both near term and far term propulsion options are included. The near term options would allow system deployment relatively quickly, whereas the far term options will increase the capability of the evolving defense architecture as the underlying propulsion systems reach maturity.

CHARACTERIZATION OPTIONS

Observer operations, described in the section below, are designed to yield highly accurate information on the internal structure and possible composition of the NEO, as well as its geometry, rotation, orbital elements and the potential for orbiting dust, debris or small satellites. With this information, the probability of impact as well as the consequences of impact can be estimated to a much higher level of accuracy. If the results suggest further action is needed to protect the populace (based on guidelines ratified by the appropriate governing body) then the appropriate mitigation option will be assembled and launched.

OBSERVER OPERATIONS: THE MSFC 2007 STUDY

The observer satellite defined in the MSFC 2007 study[3] is loosely based on the Deep Impact spacecraft.[4] The observer satellite uses several of the same payload instruments, with additional instruments specifically designed to yield the maximum amount of information on the NEO. Whenever possible the payload package is selected to fly multiple instruments capable of measuring each aspect of the NEO. An initial list of instruments proposed for the NEO observer satellite, and the measurements and results expected from each instrument, are provided in Table 1 below. It is assumed that spacecraft power will be provided by extendable solar arrays or, for more demanding missions beyond Mars orbit, by the use of advanced radioisotope power systems. Additional analysis of power system options, including packaging and mass requirements, will be performed in conjunction with future mission trades studies.

Table 1. Preliminary instrument suite for NEO observer spacecraft

Category	***Instruments***	***Planned measurements***
Optical	Laser Ranger	Orbital elements
	Narrow Field CCD	surface mapping, geometry, dust environment
	Wide Field CCD	Dust environment, geometry, potential satellites
	Spectrometer	Composition, density
Radar	MARSIS radar sounder	Density, internal structure
	Dual mode radar/data link	Internal structure
Other	Gravity sensor	Mass, gravitational field

Instruments	***Planned measurements***
Chemical analysis package	Composition
Seismic sensor	Internal structure
Fly-by balls	Mass, Gravitational field

MITIGATION OPTIONS

Several options are outlined below for the mitigation of incoming asteroids and comets. These options are more fully explored in prior MSFC studies,[5] and are prevalent in the planetary defense literature. Other mitigation options could be implemented as part of the proposed common architecture. The specific options highlighted below include the Nuclear Interceptor, Kinetic Interceptor, Solar Collector and Laser Ablation.

NUCLEAR INTERCEPTOR

A nuclear release above the surface of an NEO will bombard it with hard x-rays, gamma rays, and neutrons. This pulse of energy is so fast that surface material does not have time to radiate or conduct away the heat. Hot, rapidly expanding plasma is created from the surface material and quickly escapes into space, transferring momentum to the NEO.

As shown in Figure 1, the nuclear interceptor is composed of the terminal intercept package, the nuclear warhead, and the main engine. The main engine is sized to provide 0.4 g's of thrust with a maximum ΔV of 0.55 km/s. The propellant load is sufficient to accelerate the first nuclear interceptor to a speed that allows it to strike the NEO target with a closure velocity of less than 10 km/sec. This speed is due to the limitations of the tracking hardware, currently used in several missile defense programs. Both the main engine and the

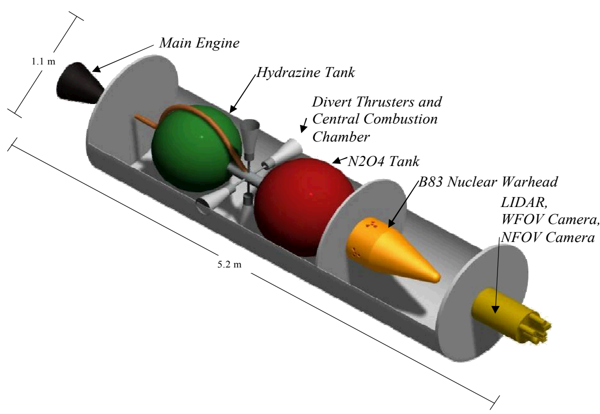

Figure 1 Nuclear interceptor design concept [5]

terminal intercept engines operate on hydrazine and N2O4, and both propulsion systems are fed from the same set of tanks.

KINETIC INTERCEPTOR

The kinetic interceptor employs a terminal intercept package similar to that of the nuclear interceptor, however in this case projectiles are fired into the NEO. The deflection efficiency of the interceptors increases with higher mass and higher relative velocity. Solar electric powered Hall thrusters maneuver the interceptor to strike the asteroid from the optimum direction while adjusting the closure velocity to the 10 km/sec tracking limit. The electric propulsion system also provides additional impact mass upon collision. A terminal intercept hydrazine/N2O4 propulsion system enables final guidance into the target. The kinetic interceptor concept is illustrated in Figure 2.

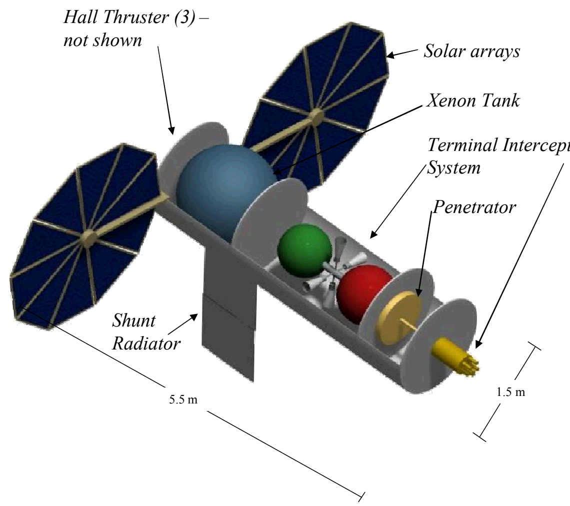

Figure 2 Kinetic interceptor design concept [5]

SOLAR COLLECTOR

Unlike the interceptor options, the solar collector maintains station near the NEO. The concept consists of a 100-m diameter parabolic collector that faces the Sun and focuses sunlight onto a smaller reflector (Figure 3). The reflector directs the collected solar beam upon the NEO, and has a fixed orientation relative to the Sun. As the NEO rotates beneath the solar collector, a swath of NEO material is continuously energized by the collected beam. Some of the energized NEO material evaporates into a jet, producing thrust and deflecting the NEO.

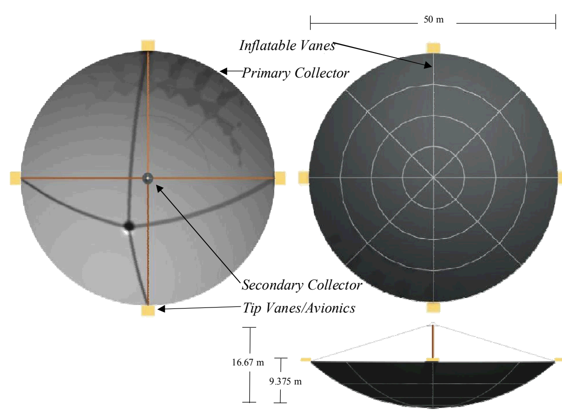

Figure 3 Solar Concentrator design concept [5]

Once released, the solar collector fully inflates to a predetermined shape. Vanes running along seams in the primary collector fill with nitrogen, unfolding the primary collector. The primary collector membrane is made from materials similar to that used in solar sails. Guide wires from the primary collector hold the secondary collector in place.

The primary collector is a thin-film membrane with very little thermal mass. Because the concave face of the primary collector must always point toward the sun, the convex face always points towards deep space. As a result, the primary collector thermally stabilizes to an acceptable temperature. However, the secondary collector experiences a high luminous intensity that complicates the thermal design. To deal with high luminous intensity, the secondary collector is designed to be a beryllium panel electrochemically plated with gold. Heat pipes and vanes on the backside of the collector dump residual energy from space as quickly as possible, and a sun shade is also mounted on the secondary collector.

LASER BASED DEFLECTION

Focused laser energy may also be used to ablate surface material from the NEO. Deflection concepts have been suggested for ground based laser systems, space based laser systems in near proximity to the Earth, and space based laser systems sent to rendezvous with the target object.[6] Although ground based laser systems have access to abundant power, the significant propagation distance to the target causes unacceptable beam spreading and loss of intensity for aperture diameters less than several kilometers. Phased array techniques could potentially be used to shape and combine the output of several smaller beams into a far field diffraction pattern whose central spot retains a useful fraction of the total beam energy. Such optical arrays are of current military interest both for beamed weapon and communication applications, and it is anticipated that progress will continue to be made in these areas. Locating the laser system in near Earth orbit mitigates issues with atmospheric distortion, but problems are introduced in launching or constructing sufficiently large space optics. A sparse phased array of formation flying laser stations could provide an attractive alternative, but this concept has yet to be investigated in detail. Laser system sent to rendezvous with the target NEO would provide much closer proximity to the target and alleviates large laser aperture requirements; it also mitigates issues with atmospheric beam distortion encountered in ground based systems. While the required power on target is still significant, the laser station can remain in close proximity to the NEO to provide smaller incremental deflections over an extended period of time. The electrical power required by a repetitively pulsed, high power laser also fits well with mission architectures using high power electric propulsion; once a rendezvous is performed, most of the electrical power can be transferred to the laser system. While significant technical advances are required, space based laser deflection concepts remain a potentially viable alternative for NEO defense.

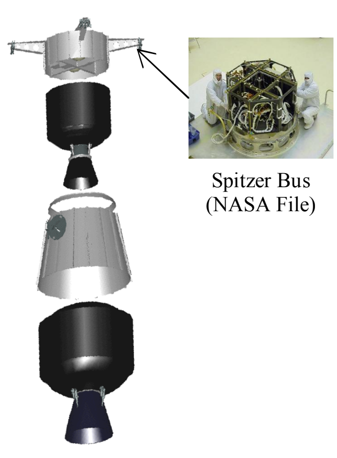

Figure 4 NEO spacecraft configuration showing payload, bus, adaptor, and propulsion systems

VEHICLE DESIGN

The selection of a spacecraft for a common architecture must address compliance to mission requirements as well as potential hardware commonality. Spacecraft used for NEO science, characterization, or mitigation missions will have unique requirements that could make it difficult to use a single common Bus design. Instead, the proposed approach is to identify common spacecraft requirements and then select common features that when incorporated will maximize the commonality of processes and parts. The extent of any such commonality will have a direct impact on operational time, reliability and program cost. Even with the maximum use of possible common elements of the Bus, the potentially broad differences in the size of the various mission payloads will likely require different size structures for both interfaces and loading. This disparity can be mitigated through the use of various common adapters (interstages) to adapt common hardware (i.e. propulsion elements) in the proposed architecture.

Characterization and mitigation spacecraft for NEO missions have similar requirements. Both the characterization and mitigation operations will require observation, propulsion, command, control, guidance, navigation, data handling and communication capabilities. Common requirements and mission specific technologies must be evaluated to develop spacecraft designs that will minimize processing differences. The goal of a more detailed architecture study will be to develop as much commonality as possible in spacecraft hardware and software for both characterization and mitigation missions.

PROPULSION SYSTEM

The propulsion system needed to put the observation or mitigation payload on an intercept or rendezvous trajectory with the proper NEO orbit will vary depending on the intercept location and the NEO velocity. A few preliminary scenarios were examined as part of this proposal for the three classes of near Earth asteroids (NEAs); the required ΔV's are shown in Table 2. To estimate the ΔV required to reach each asteroid, solutions to Lambert's problem were calculated for all combinations of Earth departure and NEA arrival true anomaly, in 30° increments, searching for the minimum ΔV required to achieve the transfer with time-of-flight as an independent variable. Departure ΔV is that required to depart from a low earth orbit, assumed to be coplanar with the hyperbolic excess velocity vector, in order to achieve the heliocentric velocity required by the minimum ΔV Lambert solution. In Table 2, the departure ΔV can also be thought of as the intercept ΔV for mitigation scenarios where rendezvous is not required.

Table 2 Delta V Requirements for NEO Rendezvous

Delta V Required to Rendezvous with Asteroid				
Asteroid Class	PHO Asteroid From Class	Departure Delta V (m/s)	Arrival Delta V (m/s)	Total Delta V (m/s)
Apollo	1862 Apollo	4,089	302	4,392
Aten	99942 Apophis	4,346	283	4,628
Amor	3122 Florence	6,414	3,321	9,735

This preliminary study assumed an observation payload with an attitude control system (ACS) for fine maneuvering around the asteroid. Based on a prior MSFC study,[5] the combined payload and bi-propellant ACS thruster weight is assumed to be 1,500 kg for an observation or single mitigation mission, and 11,000 kg for a full mitigation mission with cradle and 6 bullets. Two current and four near term primary in-space propulsion options are listed in Table 3. Available options include solid propellant and LOX/ LH_2 propulsion systems. Near term in-space options include gridded ion thrusters, such as

Table 3 Typical propulsion system parameters

Propulsion Type	Representative Vacuum Isp (sec)	Propulsion Mass Fraction
Solid rocket	295	0.90
LOX/LH2 engine	450	0.88
BPT-4000 Hall Effect Thruster	1500	TBD
NEXT Ion Thruster	4000	TBD
VASIMR Thruster	5000	TBD
Lithium MPD Thruster	6200	TBD

those used on the NASA Deep Space - 1[7] and Dawn missions;[8] commercial Hall thrusters such as the Aerojet BPT-4000;[9] the experimental VASIMR thruster, which offers variable specific impulse at high power;[10] and the experimental MPD thruster, which has demonstrated efficient laboratory performance using lithium propellant.[11] While insufficient time was available in the current white paper study to evaluate the electric propulsion options, it is recognized that the higher specific impulse offered by these systems may provide significant benefits for NEO class missions, and they will be explored in a future study.

For each ΔV shown in Table 2, an appropriate solid or LOX/LH_2 propulsion stage was sized for LEO departure and NEO arrival burns. The results are shown graphically in Figure 5 for an observation mission to the Amor class asteroid 3122 Florence. The chart can be read by selecting the departure propulsion system along the front axis, and the arrival propulsion system along the right axis. Total propulsion weight is on the vertical axis. The payload and ACS weight of 1,500 kg should be added to this total. The results show that higher specific impulse (Isp) systems reduce the overall propulsion weight.

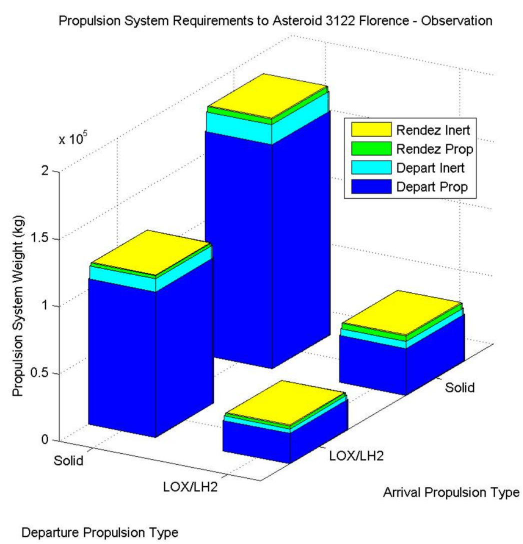

Figure 5 Example propulsion system requirements for asteroid mitigation mission

For some mitigation missions only an intercept is required. In this case both the required ΔV and the propulsion system masses are reduced. For the intercept mission with an 11,000 kg payload, the propulsion masses are shown in Figure 6.

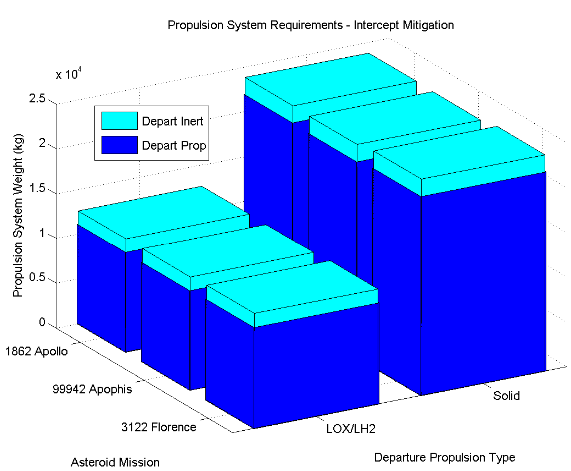

Figure 6 Propulsion system requirements for intercept mission

Solid propulsion is well understood and has been used successfully on many space missions. Solid rocket motors currently in production span the range from a few kilograms to over 50,000 kg total mass that would be appropriate for NEO class missions. The ATK STAR, Orion, and Castor motors are examples of these propulsion systems.

Upper stage LOX/LH_2 bipropellant propulsion has historically been provided by the Centaur RL-10 engine. The current version of this stage, used on the Atlas V, is 22,700 kg total mass and 22,300 lb thrust for the single engine configuration. This stage is large for the observation mission example but entirely appropriate for a larger mitigation mission payload requiring a rendezvous. Use of this stage with an appropriately sized solid STAR motor would provide a high performance, off-the-shelf option for a NEO mitigation mission.

LAUNCH VEHICLE SELECTION

The results from the three preliminary asteroid trade studies can be used to size potential launch vehicles. The Apollo and Aten asteroid mission examples have similar ΔV requirements and can be launched on an Athena III or Atlas V launch vehicle for observation missions, or on a Delta IV Heavy or Ares I for rendezvous mitigation missions. The rendezvous missions require a Centaur type departure stage and a solid propulsion arrival stage. The Amor asteroid example requires much more ΔV to rendezvous. For this mission a larger propulsion system and launch vehicle is required. A Delta IV or Ares I launch vehicle with a LOX/LH2 departure and solid propulsion arrival stage can meet either the observation or mitigation intercept mission. The mitigation rendezvous mission would need a propulsion system in the 100,000 to 140,000 kg mass class and would require an Ares V launch vehicle. In the future, an advanced high power electric propulsion system may be used for the departure/arrival stage, allowing the use of a smaller launch vehicle. The following table is an example of a common hardware/launch vehicle selection matrix for missions to various asteroid classes. There are asteroids in each class that may require larger propulsion systems to perform either observation or mitigation missions. For example, the Apollo class asteroid 1981 Midas requires 16,680 m/s to rendezvous, four times the ΔV of the asteroid 1862 Apollo.

Table 4 Launch vehicle selection for various NEO mission architectures

		Asteroid Classes					
		Apollo		Aten		Amor	
		Characterization	Mitigation	Characterization	Mitigation	Characterization	Mitigation
Payloads (kg)	Science	1500	-	1500	-	1500	-
	Characterization	1500	-	1500	-	1500	-
	Mitigation (single)	-	1500	-	1500	-	1500
	Mitigation (6+Cradle)	-	11000	-	11000	-	11000
Propulsion Elements: Departure	Solid	-	-	-	-	-	-
	LOX/LH2	Centaur	Centaur	Centaur	Centaur	Centaur	-
	Hall Thruster	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	May be required
	VASIMR	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	May be required
	Li-MPD Thruster	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	May be required
Propulsion Elements: Arrival	Solid	Star 27	Star 37	Star 27	Star 27	Star 63	-
	LOX/LH2	-	-	-	-	-	-
	Hall Thruster	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	May be required
	VASIMR	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	May be required
	Li-MPD Thruster	Not evaluated	Not evaluated	Not evaluated	Not evaluated	Not evaluated	May be required
Bus Stage	Common	-	-	-	-	-	-
	ACS	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant	Bi-propellant
Inter-stage	A	Required	-	Required	-	-	-
	B	-	Required	-	Required	Required	-
	C	-	-	-	-	-	Required
Launch Vehicles (kg)	Athena III	7450	-	7450	-	-	-
	Atlas V	20500	-	20500	-	-	-
	Delta IV Heavy	-	24000	-	24000	24000	-
	Ares I	-	26000	-	26000	26000	-
	Ares V	-	-	-	-	-	162000

PRELIMINARY COST ESTIMATES

As a preliminary costing exercise, the proposed architecture is assumed to include a trans-asteroid insertion (TAI) kick stage plus a rendezvous kick stage topped with either a characterization probe or mitigation interceptor. Each of these stacks can be launched by a number of vehicles currently available or under development. Table 5 lists the estimated development, design, test and evaluation (DDT&E) cost, plus a per-unit cost, associated with the payload components of the stack. All costs are in 2007 dollars, and were generated by the MSFC Engineering Cost Office using the NAFCOM prediction program.[12] Costs include 30% contingency, but do not include standard launch vehicle, operations, or propellant costs. The nuclear device for the nuclear interceptor is also not priced as it is expected to be government furnished equipment. All values should be considered rough order of magnitude (ROM) costs.

Table 5 Estimated costs for example payload technologies

Component	DDT&E ($M)	Per Unit ($M)
Characterization Probe	987.3	354.1
Nuclear Interceptor	81.2	28.1
Kinetic Interceptor	354.2	137.8
Solar Collector	675.5	168.3

The proposed architecture uses currently available stages (Centaur, Star-37, or Star-63 motors) for the TAI and rendezvous stage, which provides significant cost savings by eliminating DDT&E costs for those stages. Estimated costs for these stages are 3%-10% of the launch vehicle cost. It is anticipated that all of these components would be stored in a building near the launch range for quick response launches. The storage and assembly building is not priced in this proposal, and organizational responsibility for the administration and security of this building remains to be determined. The potential need for nuclear devices, plus the need for an integrated detection and response capability, strongly suggests the involvement of the Department of Defense. While there is a link between the planetary science and defense communities, NASA's anticipated science budget will unlikely be able to fund the major cost of this endeavor. Ideally this would become a joint project between several agencies (NASA, DoD, Homeland Security, DoE), with well defined roles and responsibilities, and dedicated funding.

SUMMARY

The proposed architecture yields a number of potential mission opportunities for the scientific community and initiates the near-term beginning of a defensive architecture against NEO collisions with Earth. This powerful synergy can accomplish several goals at reduced cost, while retaining the paramount capability of defending Earth against a looming and catastrophic global threat. Identifying the common interests and needs of the scientific and planetary defense communities regarding near Earth objects allows the economic pooling of resources to develop common mission architectures.

Developing a constrained set of options to package and launch characterization or mitigation payloads minimizes DDT&E costs, and the use of existing stages provides additional cost savings and earlier implementation of the architecture. The use of advanced electric propulsion technologies later in the program yields a path to improved performance and greater defensive capability.

The proposed system is scalable, meaning that multiple characterization and/or mitigation vehicles can be launched to meet a more difficult threat; these multiple mitigation technologies provide options when dealing with different threat modes. As new mitigation technologies are proposed and developed by the community, they can be integrated into the given architecture.

Several questions remain to be answered as this architecture is developed. Certainly more detailed development of the characterization and mitigation options are needed, both to confirm that no insurmountable technical obstacles exist and to refine the ROM cost estimates presented here. High level agreements with DoD and other government agencies will be required to determine the administration of a facility dedicated to the storage and assembly of the payloads and spacecraft components. Security issues related to nuclear devices must be resolved, and multiple international legal issues must be considered. The science community must remain a key partner in developing efficient plans for acquiring the needed scientific knowledge.

In conclusion, the proposed architecture allows for the early adoption of a defensive architecture against asteroids and comets. It acknowledges common needs between the scientific and defense communities, and proposes the pooling of resources to meet those needs. The architecture offers maximum use of available and near-term components to reduce DDT&E costs, while mapping out an evolutionary plan for future architecture enhancements.

REFERENCES

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