SHIELD: A Comprehensive Earth Protection System, Updated

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1. INTRODUCTION

A complete planet impact hazard protection system must address the full range of problems including the detection of potentially threatening bodies, the assessment and characterization of those threats, and the protection of Earth from the threat by deflection or fragmentation. The basic concept of SHIELD was developed under a grant from the NASA Institute for Advanced Concepts in 1999. SHIELD is a four-fold defense system with: 1) Sentry, to accurately identify threatening bodies very early — years before impact; 2) Scout, to assess the threat and select an approach to protect the Earth; 3) Soldier to mitigate the threat if it can not be eliminated by improved knowledge of its orbit; and 4) The Earth Control Center to organize, coordinate, and operate the other three components The SHIELD report is still the only comprehensive analysis of an end-to-end Earth Protection system done to date. This study updates and refines the SHIELD concept, and incorporates knowledge gained since 1999.

2. SHIELD ARCHITECTURE

The SHIELD system of Sentries, Scouts, and Soldiers is grounded and guided by a crucial fourth component: Earth Control Center (ECC). Sentries will search and locate near-Earth objects (NEOs) of all types, including near-Earth asteroids (NEAs), short period comets (SPCs), and long period comets (LPCs). The Sentries are the least “futuristic” component of the SHIELD system. Capable Sentries could be launched today. The architectural characteristics of the Sentry design trade off the number, location, and search patterns of the Sentries against both the time to complete the catalog of NEAs and the warning time of LPCs. One ECC function is to coordinate this tradeoff and implement the resulting strategy. The ultimate goal of the Sentries is to provide the maximum lead-time for identifying a potential impact, which simplifies the tasks of the Scout and Soldier to characterize and deflect or disperse the object. Currently, set of three or four Sentries in heliocentric orbits at the radius of Venus orbit is the baseline SHIELD architecture.

The Scout component of SHIELD consists of spacecraft designed to characterize the threat of a potential impactor via flyby or rendezvous (and/or in situ) observations. Both flyby and rendezvous Scouts are currently technologically feasible, and the ECC would create, maintain, and operate orbital or earth-based Scout capability as part of its function.

The Soldier component of SHIELD consists of a series of spacecraft designed to mitigate the threat of an impact by deflecting or dispersing the potential impactor. The efficiency of the mitigation types is a function of the object size, velocity, physical properties, and warning time to impact. The ECC would be responsible for developing and maintaining Soldier capability, both for rapid response for imminent threats, and for mitigation of long lead-time threats.

The Earth-based component of SHIELD must receive the data from the Sentries, Scouts, and Soldiers, verify the calculations of impact potential, maintain the NEO database, communicate with the ground-based telescope surveys for prior and/or follow-up observations, commit Scouts to investigate potential threats, recommend to the global authority that a Soldier asset be committed to mitigate a potential threat and direct the Soldier activities. Portions of the Earth-based SHIELD component may be integrated with existing facilities such as the Minor Planet Center.

3. SENTRIES

Sentry is the detection component of the SHIELD system. A complete detection contingent will consist of multiple spacecraft, each with a visible imager specifically designed to detect Near Earth Objects. Each Sentry will have the processing power to register, background subtract, and difference several images of the same location spaced in time. When enough detections of a specific NEO are collected, the orbit of the object is calculated, and it is compared to the database to determine if it is a previously located object. If it is a new object, the potential for the object being an Earth crosser is evaluated, and, if the potential is high enough, the orbit is propagated forward in time onboard to provide a detailed determination of the chance of an impact. Finally, the object, its orbital parameters, and the impact risk are stored in the onboard database, and forwarded to the Earth Control Center and to the other Sentries. If the object is determined to have a probability of impact above a predetermined threshold, images containing the object will be forwarded to the Earth Control Center. Ideally, this operation is fully autonomous. A backup to onboard processing, within current capabilities, would be a regular downlink dump of summary data.

It should be noted that Sentries would in fact, also accomplish a significant amount of threat *mitigation* in concert with the ECC, in the form of characterizing and refining the orbits of potential threatening NEOs. Error ellipses of close passes that include the Earth may be shrunk significantly by re-imaging and intensive analysis of a potential threat's orbit. Better constraints on many objects' orbits will shrink the region of uncertainty sufficiently to discount the threat of impact.

3.1 Example Sentry Imager Design

The imager consists of a large aperture telescope with a large format, cooled CCD detector. The telescope parameters will be similar to existing ground-based telescopes. The telescope will require a 1-m-diameter aperture and will have a 1.6×1.6°FOV. If launched today the CCD would be 4096×4096, 15mm pixels with four-quadrant readout. The angular resolution of 1.4×1.4 arcsec would be sufficient considering the spacecraft pointing errors and jitter. A passively cooled, radiation-shielded, frame transfer CCD would be capable of discriminating against cosmic ray hits to the CCD. To maximize sensitivity, the CCD would be a high QE, back-thinned device with low-read noise. Imager sensitivity would need to be Vm = 22 with <100 s of integration time. The specific parameters of the imager would be optimized for the orbit and search pattern selected.

3.2 Example Sentry Spacecraft Design

The spacecraft subsystem designs are straightforward with attitude control and determination having the most stringent requirements. Attitude requirements include 3-axis control with arcsec pointing and knowledge over the maximum integration time of the CCD (~100 s), and sub-arcsec stability and jitter. Since the imager will nominally be pointed in solar opposition, the solar arrays are always in full sun providing a favorable power situation. One side of the spacecraft is therefore always looking away from the Sun, providing an ideal surface for passive cooling of the CCD.

For Sentries launched in the near term, telemetry will be downlinked once every day to two weeks to minimize the disruption of the scan sequence, allow for the high-gain antenna to be pointed toward Earth, and to minimize ground station costs. For Sentries launched further out in time, telemetry will be downlinked by Sentry request when a predetermined number of NEOs or downlink data size has been reached, a potential Earth impactor has been located or if certain autonomy rules have fired. Most required computations could be performed on the ground at the expense of higher mission operations costs. The image registration, background subtraction, differencing, and NEO detection should still be performed onboard to minimize the downlink data rate.

Communication between Sentries is required for autonomous operation of the SHIELD system and to provide a method for Sentries on the opposite side of the Sun to communicate with Earth. The Sentries would need to transmit and receive object orbital parameters, the object catalog, and the attitude and orbit data of the other SHIELD spacecraft. If a NEO is located that has a significant impact probability, each of the relevant images would be transmitted to the Earth Control Center for further analysis and impact assessment.

Table I shows essential "launch now" and optimal Sentry components, along with their Technology Readiness Levels (TRL) and Research and Development Degree of Difficulty (R&D^3).

3.3 Detection techniques, computational and storage requirements

NEO detection is accomplished by differencing multiple images of the same area of sky over time. Upon NEO detection, a Sentry will follow a series of steps in the and determination of the object's orbit [*Yeomans et al.*, 1994]. First the trajectory of the object is to be integrated forward, taking care of Earth and moon perturbations separately. General relativistic equations of motion and perturbations by all planets at each integration step are also included. For short and long period comets whose motions are affected by the rocket-like ice vaporization, a non-gravitational force model is used. If the numerical integration software senses a close approach to the Earth, an interpolation procedure is used to determine the time of the object's closet approach and the minimum separation distance at that time.

For those objects making an approach to Earth within specified distances, a full perturbation analysis is conducted on-board to determine whether or not the object's error ellipsoid at the time of closet approach includes the Earth's position. Upon determination that an impact cannot be ruled out the stored images, orbit determination, perturbation analysis results, and catalog information will be sent to the ground. This method for computing impact probabilities is only an approximation; however, it will significantly reduce mission operation costs. A more precise computation of impact probabilities can be obtained from a Monte Carlo approach, which requires a great deal more computation and is best performed at the Earth Control Center.

Image and object database memory requirements, assuming that the search patterns are repeated at a cadence of less than once per day and a catalog size of 10^8 objects, are 30 GB and 5 GB, respectively. The calculations of orbit determination, projection, and impact probability can be accomplished with the use of an equivalent modern day desktop processor.

3.4 Number and Location of Sentries

Sentries must have a heliocentric distance of <1 AU to efficiently locate Aten-type asteroids, which only cross earth's orbit near their aphelion. With a sensitivity of Vm = 22 located at the heliocentric distance of Venus (0.72 AU), Sentries can image 1-km-dia. NEAs located in the main asteroid belt, and 140 m diameter asteroids in the vicinity of

Earth's orbit. Multiple Sentries will result in completing the catalog 140 m and larger NEAs sooner. The baseline set of 3 Sentries can also enable detection of long period comets (LPCs) on the Earth's blind side, and provide full spherical sky coverage every 30 to 75 days.

A typical Sentry orbit, including the transfer from Earth, is shown in Fig. 1. The Sentry fields of regard, assuming a set of three Sentries, are shown in Fig. 2. The actual time that a Sentry takes to revisit a particular region in its coverage area depends upon the required exposure time and the search pattern. The Sentry fields of regard will rotate with the orbital motion of the Sentries.

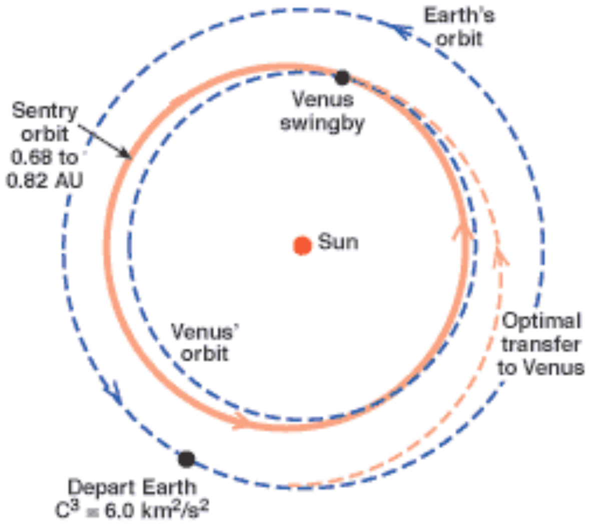

Figure 1. Typical Sentry orbit at a similar heliocentric distance as Venus including transfer trajectory from Earth.

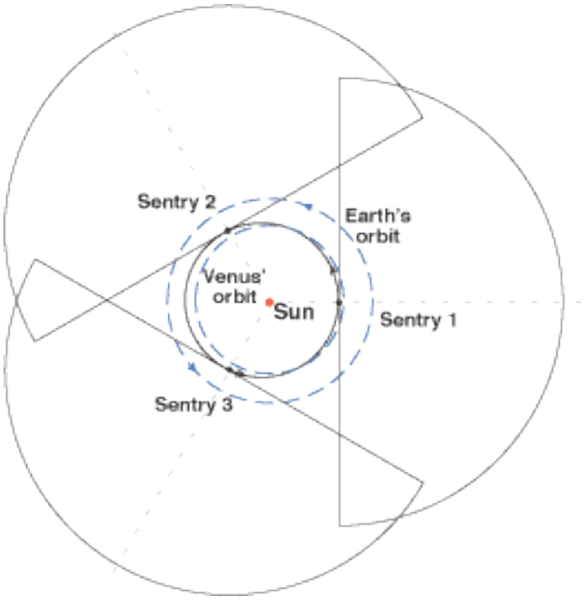

Figure 2. Sentry coverage with three Sentry spacecraft near the heliocentric distance of Venus observing 90° from the opposition direction.

4. SCOUTS

In the original SHIELD report, Scouts were considered as a subcategory of Soldier. The two missions have similarities in how they reach their targets, and how best to be distributed in the solar system for best effectiveness, but the Scout mission requires a different, generally simpler spacecraft to perform most of the critical characterization functions. Effective mitigation via Soldiers relies on knowledge of what techniques will be effective. Sending the incorrect Soldier to a target wastes time and resources, and may compound the threat. Scouts may also, in the same manner as Sentries, help mitigate potentially threatening bodies during the process of their characterization mission.

Various physical and chemical properties of an asteroid must be known to effectively implement any deflection technology. The most important physical properties and the instrumentation needed to measure them are the primary drivers for the Scout. A suite of slightly less critical but still significant physical and chemical properties of an asteroid must be known to best achieve the goal of deflection.

4.1 Critical Asteroid Properties and Instrument Payload

The most important characteristics of the asteroid required for deflection include its mass, density, rotation rate and pole, and whether the body is competent (a "shard") or not (a "rubble pile"). The asteroid mass determines the minimum mass and velocity of a kinetic energy impactor, the minimum fuel required by chemical thrusters, the minimum size of the nuclear device, etc., required for deflection. The density of the asteroids provides a first order view of the internal structure of the asteroid, helping to define whether or not the asteroid is either a porous or volatile-rich rock, or a solid rock. This density is important for implementing the most effective deflection strategy. For example, if the asteroid possesses a low density and many large craters whose diameters approach that of the asteroid (e.g., 244 Mathilde [see *Veverka, et al.,* 1997; *Yeomans et al.,*1997]), this asteroid is probably quite porous and/or volatile rich. As with 244 Mathilde, such an asteroid probably has a better ability to withstand fragmentation during either an impact or a nuclear event. A large impactor or nuclear device could, therefore, be used to deflect this body with lower fragmentation risk. Knowledge of the rotation rate is equally important in implementing any of the deflection techniques. For example, landing a thruster on the surface of a very rapidly rotating asteroid will be significantly more challenging than on a slow rotating body. Knowledge of the interior structure of an asteroid also constrains possible mitigation techniques. Monolithic or fractured but competent bodies like 433 Eros [*Wilkison et al.*, 2002] may be less likely to break apart by ΔV imparted by engines than loose "rubble pile" asteroids like 25143 Itokawa [*Fujiwara et al.*, 2006].

The mass and density of an asteroid can be obtained by a simple flyby using a visual imager and some tracking technique (e.g., Doppler tracking) of the spacecraft. Such tracking provides a measurement of the mass of the asteroid while the imager determines its size and shape. Combining this information allows one to compute the asteroid's density. NEAR Shoemaker used such a technique to determine the density of 244 Mathilde [*Yeomans et al.,*1997] and 443 Eros.

The rotation rate of the asteroid can be determined from the space-based Sentries by observing the periodic variation of the area and/or average albedo of the visible surface [e.g., *Harris and Lupishko*, 1989]. This technique is already extensively used from Earth-based observations of asteroids [e.g., *Binzel et al.* 1989]. Understanding of the competency or interior structure of an asteroid is critical to determining the best method of mitigation. It may be very difficult to alter the orbit of loose agglomerations of rock. Alternate methods of disruption and dissipation may be required for rubble piles, requiring different base mitigation mechanisms, and thus different Soldier types.

4.2 Second Order Physical Parameters and Instrument Payload

Although such cursory information provides a good first order understanding of the physical properties of an asteroid, a more complete picture of the physical characteristics of the asteroids is required by all the deflection techniques discussed. A thorough understanding of the physical nature of the asteroids is required at two scales: (1) the upper tens of meters, and (2) the deep internal structure. In the upper tens of meters, the presence or lack of a soil or regolith layer that covers the asteroid must be determined. In the eventuality that such a layer is present, the physical characteristic of this layer must be known, including its dominant grain size, porosity, cohesiveness, and depth. The deep internal structure is most critical if the asteroid a rubble pile, in which case it is important to determine from the deflection view-point what holds the various rubble pieces together. Some chemical information on the threatening asteroid must also be known. For any of the shock-based techniques (kinetic impact and nuclear), the presence of volatile-rich materials can significantly influence the production of vapor. Although the exact consequence of vaporization are not known, several studies indicate for impacts and certainly also for nuclear devices, that significant vaporization alters cratering efficiency, ejecta production, and ejecta velocity [*Vickery*, 1986]. The impulse generated by these deflection techniques would be, therefore, influenced by the volatile content of the asteroid threat.

Several different instruments can determine the physical characteristic of the upper tens of meters of the asteroid. From orbit, a ground penetrating sounder will provide the necessary information. Such an instrument was flown on Apollo and similar concepts are being utilized on the European Space Agency's Mars Express (MARSIS, *Picardi, et al.*, 2000) and NASA's Mars Reconnaissance Orbiter (SHARAD, *Seu et al.*, 2004). Using a range of radar bands, the physical properties of the surface layers can be determined from appropriate models for the dielectric constants. The rock or boulder coverage can also be estimated. The sounder results can be complemented with a thermal infrared instrument (such as TES on Mars Global Surveyor) that allows determining the porosity at the surface of the regolith, as well as the mean or dominant grain size present. These and other possible components of Scout missions are shown in Table II.

4.3 Number and Location of Scouts

Current technology is capable of developing a variety of scout missions, and several Scouts should be kept "at ready" either on-ground or in Earth or Venus Orbit.

For quick response threats, at least one Scout spacecraft should to be ready for near-immediate launch from Earth, preferably within a very few weeks of threat confirmation, capable of flying by a potential threat and gathering as much critical data as possible. Longer timescale threats require either a near-ready earth-launched rendezvous Scout (or multiple scouts), or a deployment of a Scout on station in high-energy Earth-return or Venus-return orbit.

The CONTOUR mission plan [*Farquhar et al.,* 1997] was to use a high-energy orbit with multiple Earth swingbys to intercept multiple comets. The Earth swingbys were to allow flexibility in the mission, permitting a change of targets after launch, with a high probability that even a LPC could be reached. Figure 3 shows CONTOUR's nominal trajectory projected in the ecliptic plane in a rotating reference plane, with fixed Sun-Earth line. Scouts in similar orbits around Earth would need to wait until the they returned to the planet to be redirected, and thus might be slower in reaching a new object than one that could be launched soon after discovery. However, Scouts in orbits like this about other planets could reach many approaching objects much more quickly than those ready for launch from the Earth, and the possibilities for rendezvous with threatening objects also increases. The best planet for Scouts would be Venus, since it (and the Scouts accompanying it) has a shorter period of revolution (225 days) than the Earth, yet has nearly as much mass and similar size, allowing large bend angles at the Venus swingby to reach objects approaching from many different directions.

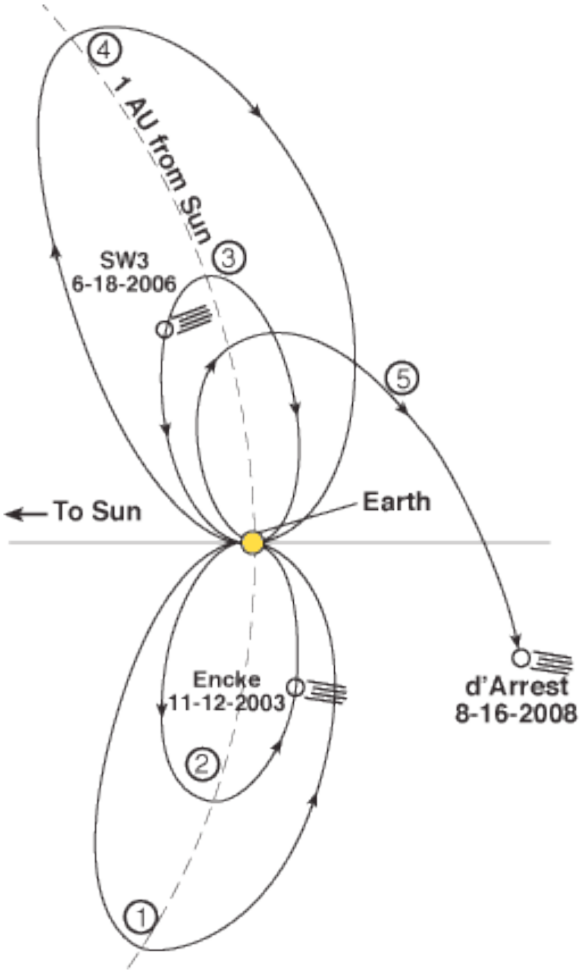

Figure 3. CONTOUR's nominal trajectory projected in the ecliptic plane in a rotating reference plane, with fixed Earth-Sun line.

A baseline four Scouts would permit pairs of spacecraft to return to Venus every 112 days, and in each pair, one would approach from the north, facilitating southern departure asymptotes, while the other would approach from the south, facilitating northern departure asymptotes. Half the time, Venus is on the opposite side of the Sun as the Earth, giving good coverage of that region, which is much less accessible from the Earth. Soldiers in Mars and/or Mercury return orbits could help fill the gaps when Venus is on the same side of the Sun and relatively close to the Earth, but those planets have weaker gravity, restricting the achievable departure asymptote directions. If there is time, Earth-based Scouts, or inner Solar System Scouts in high-energy orbits, could be sent to Jupiter and even put into retrograde heliocentric orbits that, in conjunction with a good low-thrust propulsion system (solar-electric, nuclear-electric), would allow rendezvous with most threatening objects.

Development and coordination of an optimum multiple Soldier architecture to minimize intercept and/or rendezvous times is a primary early function of Earth Control Center.

5. SOLDIERS

The main function of the Soldier spacecraft is the alteration of the target's orbit away from Earth intercept. A soldier will carry varying equipment depending on the diversion strategy to be used. After Scout data evaluation at the Earth Control Center, the Soldier, depending on its mode of operation, will dock, grapple, or intercept the target and impart a ΔV to it to divert it from a collision trajectory with Earth.

5.1 Soldier Design

Soldier design will rely on the method chosen for diverting the target, but will generally fall into one of two broad categories: rendezvous and intercept. In the case of a rendezvous-type diversion, the Soldier arrives in the vicinity of the target, matches orbital velocities, lands on or docks with it, and executes its diversion function. The prime example of a rendezvous diversion is a chemical rocket used to push the target. In the intercept case, the Soldier arrives at high velocity, spending little time in the vicinity of the body before executing its diversion action. The main examples of intercepts are impacts and nuclear devices. Best coverage of the variety of asteroid and comet threats may require a mix of both Soldier types. Soldier equipment by function is summarized in Tables III and IV.

5.2 Rendezvous Diversion

The rendezvous diversion could be performed either by a pair of spacecraft with separate Scout and Soldier functions, much like the intercept diversion or by a single Soldier craft that integrates both functions. The single-craft rendezvous Soldier carries both the survey package and diversion package together in an all-in-one design to the target. The survey mission profile and goals are the same for the independent Scout, except that the site selection is dependent on the diversion method being carried. In the case of a chemical rocket "pusher," the search is for a Soldier landing/docking site on the target.

Once the survey is complete, the Soldier maneuvers close to the asteroid for landing/ docking at the selected site. The Soldier will use anchors or grapples to secure itself to the target surface. Anchor design must be flexible enough to allow for secure placement on surfaces ranging from metallic to rock to ice to deep regolith. Anchoring is essential for stability of a thruster-type design, especially if the applied thrust axis is to be off the spacecraft axis. The anchor must hold the Soldier so that the thrust is applied in the correct direction.

Direction of thrust will be controlled both by synchronized application of ΔV (e.g., thruster firing timed as required by the rotation of the target), and if necessary, by rotating the thrusters or the entire soldier by a set of gimbals.

5.3 Intercept Diversion

The crucial Scout-derived information for an intercept soldier is intercept target or warhead detonation site. Intercept Soldiers would be composed of an inert mass (in the impact case) or a nuclear warhead (or number of warheads) with steering, targeting, and guidance and control systems. The Soldier would be launched independent of the Scout on a trajectory that would intercept the target at a desired time, place, and relative velocity to maximize the diverting effect. Depending on the situation, the Soldier could be launched at the same time or after the Scout is dispatched, or after it has completed its assessment of the target.

The most essential components of an intercept Soldier are highly accurate targeting and guidance systems. They have to ensure delivery of the payload to the proper place at relative velocities of up to several tens of kilometers per second.

5.4 Design Diversity

Multiple Soldier designs are likely to be necessary. Assuming the Sentry surveys and its predecessors do not encounter imminent threats in their early years, the three main threat reservoirs will be long lead-time asteroids, short lead-time comets and imminent unexpected threats. The latter two threats are not a primary subject of this study, but would fall under the umbrella of a long term, truly comprehensive Earth protection system. The first category will be amenable to mitigation by either rendezvous or intercept diversion methods. The long warning will likely allow a choice of methods and timing. The second category is unlikely to provide enough warning to perform a full rendezvous mission. An intercept diversion can potentially take less time to execute, especially if essential survey functions can be accomplished by a flyby Scout rather than rendezvous. The final category will use whatever method is most expedient with whatever information can be obtained quickly.

The different threats suggest that both intercept and rendezvous Soldier designs (also including integrated Soldier/Scout) be utilized and kept on station. This will also help to enable functional redundancy of either the scouting or diversion missions.

5.5 Engineering Issues

A large number of engineering issues that need to be addressed are recognized for Soldier development. Some of these are summarized in Tables III and IV. Both rendezvous and intercept Soldier missions are currently likely to fall into a New Frontiers to Flagship mission cost profile, but validation of components and proof of concepts may be achievable in Discovery class missions (the Deep Impact mission [*A'Hearn et al.,* 2005] is a good example of a mission with important conceptual groundwork for intercept Soldiers).

5.6 Number and Location of Soldiers

Soldier numbers and locations follow a very similar rationale to Scouts. Fast-response and on-station capabilities are both required. For imminent threats, at least one intercept Soldier spacecraft need to be ready for almost immediate launch from Earth. A rendezvous-capable Soldier should also be available on short notice, for threats that are time critical, but not immediate. Other rendezvous and intercept Soldiers can be kept in Earth and Venus return orbits the same way as Scouts.

As with Scouts, four Soldiers in Venus return orbit would provide good coverage of NEO threats – though given the possible variety of threats, more on-orbit and/or Earth-launched Soldiers of different types would be optimal. Development and coordination of an optimum multiple Soldier architecture to minimize intercept and/or rendezvous times is a primary early function of Earth Control Center. For a discussion of Soldier capabilities see Rogers and Izenberg, 2006 (white paper, this volume).

Table 1. Sentry Components

Equipment	Purpose	Engineering	TRL	R&D[3]
1-Meter telescope*	Detect NEOs down to 140 meters in diameter	Optimization for survey characterization	6	I
Communications system	Downlink to Earth*/ share information with other Sentries	**	9/4	I/II
Power/computer system*	Power/control instruments	Optimization	9	I
Data storage system	On-board analysis and/or storage for relay to ECC or other Sentries	~30 GB for 1000 images, ~5 GB for Object Catalog		
Autonomous analysis system	Perform on-board analysis of NEO detection and threat level		4	III

*These constitute the bare minimum for fulfillment of survey duties.

** Advance systems such as optical communication would enable greater autonomy of Sentries.

Table II. Scout Components

Equipment	Purpose	Engineering	TRL	R&D[3]
Imager / spectrometer*	Composition, regolith properties, structure, rotation	Optimization for survey characterization	9	I
Radio science*	Gravity field, interior structure	Optimization	9	I
Power Computer System*	Power/control instruments	Optimization	9	I
Lidar	Shape	Optimization	9	I
GPR radar	Interior Structure, regolith	Optimization	6	II
Seismic network	Interior structure, composition	Design of deliverable seismic network and signal source	5	II

*Minimum components for rendezvous characterization of an asteroid for potential mitigation.

Table III. Soldier Rendezvous Diversion* Components

Equipment	Purpose	Engineering	TRL	R&D^3
Anchors	Secure Soldier to target surface	Materials, mechanics, strength, ability to anchor on various potential targets	3	III
Gimbals	Reposition soldier to align thrust direction for maximum effect	Mechanism, control, strength	3	II
Thrusters	Provide ΔV for diversion	Chemical, ion, other propellants; radio-nuclear. Thruster design, restartability, sector firing.	9-3	I-IV
Power System	Power in-situ equipment	Type (solar, RTG, other), required power	9-3	I-III
Controller Electronics	Enable synchronized or sector firing of thrusters	Synchronization of thruster and other functions, docking capabilities	4	II
Communications		Autonomy issues	9	I
Structure		Must withstand docking and diversion activities	7	II

*For baseline thruster ΔV Soldiers. Other, diversion types, such as thermal emission "engines", mass drivers or standoff methods require different components currently at lower TRL and higher R&D^3

Table IV. Soldier Intercept Diversion Components

Equipment	Purpose	Engineering	TRL	R&D^3
Inert mass/warhead	Provide ΔV for diversion	Materials, mechanics, strength, ability to anchor on various potential targets	9/3	I/IV
Targeting system	Deliver interceptor to correct location on target	Provide rapid response information for high velocity approach to target	9	II
Guidance and control thrusters	Course corrections during high velocity approach	Chemical, ion, other propellants; radio-nuclear. Thruster design.	9	II

REFERENCES

A'Hearn, M.F., M.J.S. Belton, A. Delamere, W.H. Blume, Deep Impact: A Large-Scale Active Experiment on a Cometary Nucleus, *Space Sci. Rev.* 117, p. 1-21, 2005.

Binzel, R. P., P. Farinella, V. Zappala, and A. Cellino, Asteroid Rotation Rates: Distributions and statistics, in *Asteroids II*, edited by R. P. Binzel, T. Gehrels, and M. S. Matthews, p. 416–441, University of Arizona Press, 1989.

Farquhar, R. W., D. W. Dunham, and S. Jen, "CONTOUR Mission Overview and Trajectory Design," *Advances in the Astronautical Sciences,* 95, p. 921–934 Univelt, San Diego, 1997.

Fujiwara et al. (21 others), The Rubble-Pile Asteroid Itokawa as Observed by Hayabusa, *Science*, 312, p. 1330-1334, 2006

Harris, A. W. and D. F. Lupishko, Photometric Lightcurve observations and reduction techniques, in *Asteroids II*, edited by R. P. Binzel, T. Gehrels, and M. S. Matthews, University of Arizona Press, p. 39–53, 1989.

Picardi, G. S. Sorge, R. Seu, R. Orosei, C. Zelli, E. Zampolini, The subsurface investigation by Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), *Proc. IGARSS 2000. IEEE 2000 Int'l*, 4, p. 1730-1732, 2000.

Seu, R., D. Biccari, R. Orosei, L.V. Lorenzoni, R.J. Phillips, L. Maringaneli, G. Picardi, A. Masdea, E. Zampolini, SHARAD: the MRO 2005 shallow radar, *Planet. and Space Sci*, 52, p. 157-166, 2004

Veverka, J., P. Thomas, A. Harch, B. Clark, J. Bell, B. Carcich, J. Joseph, C. Chapman, W. Merline, M. Robinson, M. Malin, L. A.

McFadden, S. Murchie, R. Farquhar, N.Izenberg, and A. Cheng. NEAR's Flyby of Mathilde–The First Look at a C-type Asteroid, *Science,* 278, p. 2109–2114*,* 1997.

Wilkison S.L., M.S. Robinson, P.C. Thomas, J. Veverka, T.J. McCoy, S.L. Murchie, L.M. Prockter, D.K. Yeomans, An Estimate of Eros's Porosity and Implications for Internal Structure. *Icarus* 155, p. 94-103, 2002

Yeomans, D. K., and P. W. Chodas, "Predicting Close Approached of Asteroids and Comets to Earth," in *Hazards Due to Comets and Asteroids*, edited by T. Gehrels, The University of Arizona Press, Tucson, 1994.

Yeomans, D. K., J.P. Barriot, D. W. Dunham, R. W. Farquhar, J. D. Giorgini, C. E. Helfrich, A. S. Konopliv, J. V. McAdams, J.K.Miller, W.M. Owen Jr., D.J. Scheeres, S. P. Synnott and B. G. Williams. Estimating the mass of asteroid 253 Mathilde from tracking data during the NEAR flyby, *Science* 278, p. 2106–2109, 1997.

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