DIRE - Dactyl-Ida Rendezvous Experiment

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ABSTRACT

The purpose of this paper is to discuss, at the system level, a theoretical spacecraft and mission named DIRE (**D**actyl-**I**da **R**endezvous **E**xperiment). The spacecraft will travel to the asteroid pair Dactyl and Ida, which is approximately 3 AU from the Sun, to achieve the following mission objectives:

- Measure the magnetic fields around the asteroid pair and each object individually.
- Take multispectral images at various altitudes to determine surface regolith composition and distribution.
- Using ground penetrating radar, attempt to discern the hidden structure of Ida and Dactyl and answer this question: are asteroids actually many rocks loosely coalesced into a single body and held together by gravity, rather than a huge monolith?
- Descend autonomously to each asteroid and retrieve samples of regolith, using micropropulsion systems. Analysis of regolith will then be performed with on board systems.
- Near the end of the mission launch a ground-penetrating explosive into Dactyl in an attempt to split into its subparts. The purpose here is to develop a technique for neutralizing a possible Earth damaging asteroid by separating it into smaller, less dangerous objects. DIRE will then make radar measurements of the ensuing asteroid breakup and determine if and how the asteroid re-coalesces.
- Get a first ever look at material from within an asteroid, after the explosive splits Dactyl.

This mission uses features of previous spacecraft missions and adds a never before attempted explosive penetrator to probe deeply and precisely into an asteroid. Thus, this mission will add to deep space object science and perhaps provide a way for mankind to defend itself against them.

1.0 Introduction

Asteroids and comets have been orbiting our Sun for billions of years. Incidental bombardment of Earth by comets and asteroids has been theorized to have contributed to Earth's formation. Much of our geology and atmosphere may indeed be the result of these objects adding their matter to Earth[i]. If this theory is true, then we owe a great debt to these snowballs and rocks from space.

Unlike comets that travel near the Sun, asteroids do not erode. However, small changes to the color of their regolith may occur as they age[ii]. Furthermore, except for impacts from other objects adding craters and material to their surfaces, asteroids have altered very little since the formation of our solar system. For this reason scientists have sought more information about these objects, as they hold clues to the beginning of our solar system.

Recently, though, the other side of the comet-asteroid coin has been theorized and studied. While the contribution of organic and inorganic matter to Earth's geology can be a benefit, the energy an incoming asteroid or comet can impart into Earth, and the effects on the biosphere, can be more detrimental than any hurricane, tsunami, earthquake, or for that matter, a nuclear war. A look through the telescope at the Moon's enormous Tycho crater will give evidence to the fact that objects from our own solar system can be immensely destructive. Moreover, if theories are true about the end of dinosaur age being the result of a cosmic collision, then it is reasonable that these objects can actually change the evolutionary path of Earth and all living things on it. It is not unreasonable to state that the influence of comet and asteroid impacts are second only to that of the Sun. Within recorded history, at least two encounters have been documented. First, on June 25, 1178 five British monks witnessed what was later determined to be an impact of the Moon by either an asteroid or a comet.[iii] The second event occurred on June 30, 1908 in the Tunguska area of Siberia, when an object later determined to be a possible cometary fragment, exploded at high altitude and flattened 2000 square kilometers of forest.[iv] Obviously, these events are not only isolated to the formation of the Earth many billions of years ago, but can occur within modern times as well.

Even though these bodies have enormous energy and size, there are theories based on measurements suggesting that they are not monoliths or solid blocks of ice but instead are collections of smaller objects very loosely held together by gravity[v]. If these theories are correct, then this fact can be thought of as an asteroid Achilles' Heel. Other studies of how to defend Earth have been to change an object's orbital elements by various inventive ways[vi] and thus making the object miss Earth. Others have proposed destroying the object with a nuclear device and obliterating it. What the authors of this paper suggest as a defense is neither to alter its path nor vaporize it. Instead, what we propose as the best solution is to use the low gravity of the object and its fractured structure to its disadvantage: split it into many smaller objects, each much less harmful and very possibly harmless and allow them to enter our atmosphere and burn up or, if any piece made it to the surface, cause much less damage than if a single rockpile rammed through the atmosphere and hit Earth.

This mission will attempt to develop this technique and add to the scientific knowledge of asteroids.

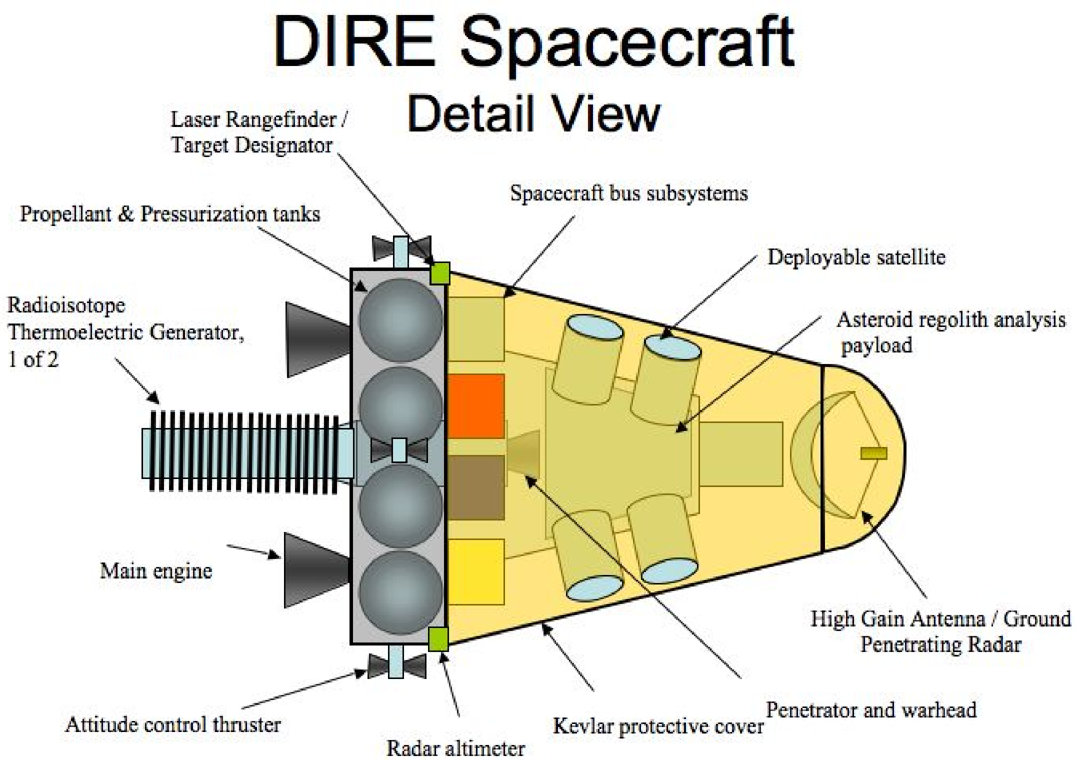

Figure 1

2.0 Mission and Spacecraft Description

The Dactyl-Ida Rendezvous Experiment (DIRE) mission has dual purposes: the first, a scientific mission to determine the composition, structure and dynamics of each asteroid; the second, to launch a small penetrator with a conventional warhead at the smaller asteroid Dactyl in an attempt to split the asteroid into multiple parts, while using radar to determine the effects of the munition on Dactyl.

After launch, DIRE will travel to the asteroid pair, located about 3AU via a Holmann transfer or a flyby of Mars. The spacecraft has an estimated launch weight of 2023 kilograms and will require an insertion burn at Dactyl-Ida of approximately 7.1 km/sec. A mass breakdown of the spacecraft, after separation from an upper stage, is shown below in Table 1. Mass allocations are based on the CONTOUR and NEAR spacecraft.

Table 1. DIRE Spacecraft Mass Breakdown

System	***Mass, kg***
Spacecraft Bus	400
RTGs (2 each)	112
Extra hydrazine for maneuvering	100
R4-D bi-propellant engines (2 each)	7.5
Propellant tankage/plumbing	80
Bi-propellant for R4-D engines	960
DIRE penetrator	363
Total Mass =	2023

Upon arriving and establishing an orbit about the Dactyl-Ida common center of mass, magnetometry measurements will be taken, to see if these two bodies have formed a magnetic field and what effects the two asteroids have on it. The NEAR mission carried a magnetometer and discovered that the asteroid Eros did not have a magnetic field. Like this mission, DIRE will also fly a magnetometer to determine if Dactyl-Ida has one, its strength, and map the contours of it.

While in orbit, visual, infrared, near infrared, gamma and X-ray photography will be taken. This photography will be used to map the two objects and determine the most interesting sites to retrieve regolith from each. Geological composition of the regolith can be used to study the nature of surface materials. Also, ground-penetrating radar will be used to attempt to see into the subsurface structure of the asteroids. Ground observers can use this data to find the most likely places to send the penetrator, during the last stage of the mission.

After a high-altitude survey of Ida is completed, the spacecraft will be de-orbited to make a low approach to hover over areas where regolith can be recovered, and brought on board. The spacecraft will then reestablish an orbit and analysis will be made of the retrieved samples.

Two techniques for retrieving soil have been studied. One is to use a small tethered flyer, deployed from the spacecraft. It will use integral micropropulsion system to maneuver down to the surface and collect material. Once this has been achieved, the spacecraft will reel in the device and bring the sample on board for processing. This miniature satellite can be used as many times as desired. Given that the gravity of Ida and Dactyl is minimal, very little propellant and thrust is necessary providing for frequent use. Both asteroids can be analyzed in this fashion. Another technique studied was to use shoot a small projectile, at a low angle, towards an area under investigation. The spacecraft would then fly a deployable boom into the resulting dust cloud. At the end of the boom, an aerogel collector would absorb material as the encounter is made. The boom and aerogel assembly would then be retracted into the spacecraft and the sample analyzed.

After orbiting and sampling the two asteroids the final phase of the mission would start. Based on ground-penetrating radar data, a location on Dactyl providing the best possible path for the penetrator-warhead would be determined. DIRE would orbit and locate itself in alignment with the intended flight path of the penetrator. DIRE would release the penetrator, which using divert thruster rockets, would stabilize and guide itself while the solid rocket motor accelerates it to 500 m/s. After penetrating the asteroid surface a fuze set before launch would detonate the warhead. The DIRE spacecraft would, from a standoff distance, map the asteroid using ground-penetrating radar before, during and after the explosion. Data would be downlinked as the fragmentation progresses.

2.1 Description of Ida and Dactyl

Asteroid 243 Ida is a Koronis asteroid orbiting the Sun at an average distance of 428 million km and was discovered in the 19th century by the Austrian astronomer Johann. It has dimensions of 56 x 24 x 21 kilometers with a density between 2.2 and 2.9 grams/cc. Its period of rotation is 4 hours and 38 minutes[vii]

Dactyl, discovered by the Galileo spacecraft in 1993, orbits Ida with a period of 1.54 days with approximate dimensions of 1.6 x 1.4 x 1.2 km. Together, Dactyl and Ida have a total estimated mass of $4.2 \pm 0.6 \times 10^{16}$kg.[viii] Both asteroids are pictured together in Figure 2.

Why choose this asteroid pair for study? First, paired asteroids are rare. Most asteroids photographed from Earth or by flybys are not indeed multiple objects. Additionally, the difference in size between the two might yield some intriguing data when their compositions are compared. Furthermore, the smaller asteroid Dactyl is about the size of what might be achievable if the technique of splitting an asteroid is to be studied.

Figure 2 Ida and Dactyl as photographed by the Galileo spacecraft. Credit: Galileo Project, JPL, NASA.

3.0 Spacecraft Architecture

3.1 Power

DIRE spacecraft system architecture is shown in Figure 3. This spacecraft is based on CONTOUR and NEAR spacecraft. For power, it will use two Radio Isotope Thermoelectric Generators (RTG) as sunlight power at 3 AU is too weak to power most spacecraft without incorporating huge solar arrays. Additionally, it would become critical in the final phase of the mission to reduce the vehicle cross section to the possible debris cloud generated by the penetrating explosive device, further precluding the use of large solar arrays.

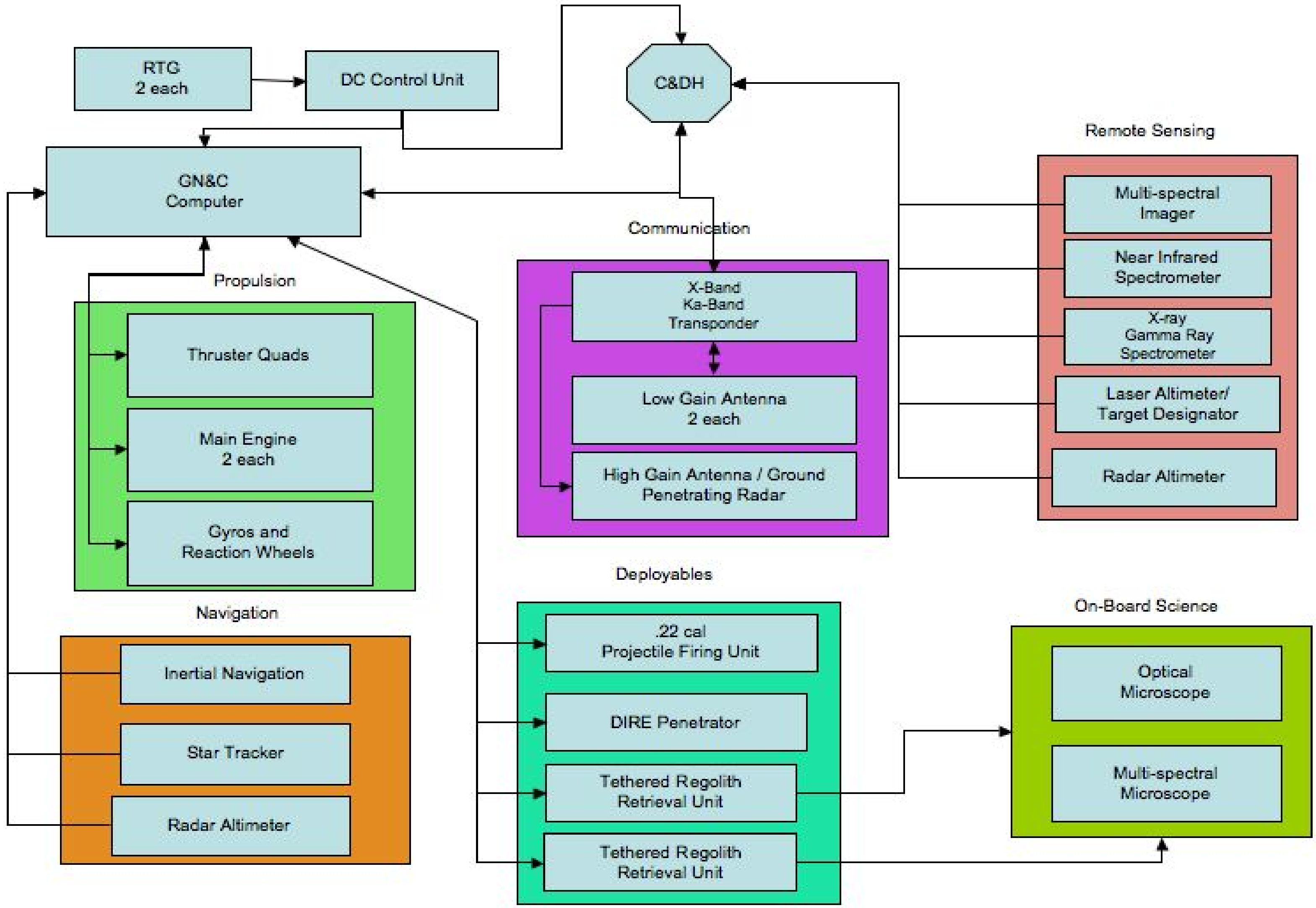

Figure 3. DIRE System Architecture

3.2 Guidance Navigation and Control (GN&C)

The spacecraft will require 3-axis attitude control due to the pointing requirements of the imaging and radar systems.

Attitude detection and control requirements for this mission will be quite severe since fine pointing will be required when the projectile is fired as well as for imaging and radar measurements.

Due to the distance from Earth, autonomous operation of the spacecraft will be required. This will allow a more flexible mission with higher scientific payoff than simply running preprogrammed sequences. GN&C of a two-body object like this has not been attempted before. Yet with modern processing power this is achievable, even autonomously.

The first spacecraft autonomy experiments were conducted by Clementine. Spacecraft Command Language Scripts were used to plan orbital mapping operations at the moon. Clementine demonstrated algorithms for autonomous operation based on position, orbit and attitude data from on-board sensors.

Star trackers provide autonomous position and orientation data to the on-board attitude determination computer subsystem running a Kalman filter for current attitude state information. Pointing of the spacecraft is done with reaction wheels with thrusters used for momentum dumping. Large slew maneuvers will be conducted with the on-board thrusters. With the aid of radar altimeter data, the autonomous system will 'fly' the spacecraft very close to the asteroid. An inertial navigation system (INS) is anticipated to be required as well, as a backup to the star tracker system. The reason is that after the explosion of the munition and asteroid, there will be many objects in the sky that will fool a star tracker. During this period, another way to establish attitude is necessary and an INS is ideal for this purpose.

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3.3 Remote Sensing – Radar

Up until now, most radar-based asteroid science has been conducted from Earth-based radio telescopes such as Arecibo, Puerto Rico. Asteroids appear to have a porous structure which can affect their internal structure and fragmentation behavior. Radar observations can penetrate into the interior of an asteroid and make more detailed observations of the porosity and overall internal structure of Ida and Dactyl.

Normally ground penetrating radar studies from space are conducted in the frequency range from 100 to 300 MHz, which requires large boom antennas. However, since we anticipate the asteroid regolith to be extremely dry and we know that DIRE can pass very close to an asteroid surface, the high gain antenna operating at a frequency of 300 MHz (1 meter) will be used for ground penetration.

The radar can be used to observe both objects before the fracture of Dactyl. After the explosive event, debris can be observed to characterize the shape, texture, and structure of the material. Anticipated range to target for the radar system is from 1 kilometer down to several meters.

Radar altimetry observations will be performed. This will be used for close-in navigation near the asteroid while the regolith sampling part of the mission is conducted. This radar can be used to observe the debris cloud and surface features of the asteroid.

3.4 Remote Sensing – Optical, IR, Gamma and X-ray

The NEAR (Near Earth Asteroid Rendezvous) sensor suite is the departure point for DIRE. These sensors will need to discriminate surface materials to discover their constituents. Multi-spectral, near IR sensors and a gamma ray/ x-ray spectrometer will detect mineral types and distribution using different wave length bands and techniques.

3.5 Deployables

DIRE will have three deployables. First are .22 caliber projectiles, which shall be fired at a low angle to an asteroid, to disturb asteroid surface regolith. The spacecraft can then fly through the dust and retrieve the dust for analysis.

The second deployable is a tethered mini-satellite (Figure 4) with its own micropropulsion system. On board Reaction Control System jets will also be used to maneuver a microspacecraft regolith collector that is tethered by a power and data cable to the main spacecraft. The

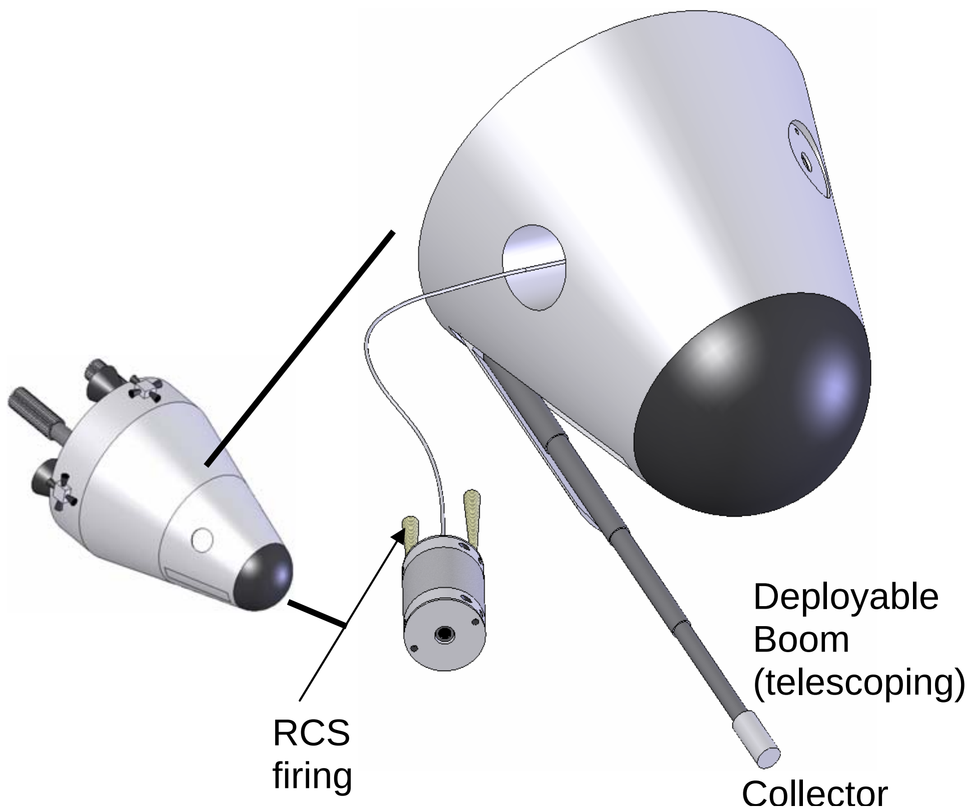

Figure 4. DIRE Deployables - Boom and Tethered Mini-satellite

microthrusters (Figure 5) will provide 50 milli-newtons of thrust to finely point the collection vehicle. These small thrusters have demonstrated pulse mode operation with over 1 million 1 to 5 milli-second pulses. This mini-satellite will allow data to be collected and then sampled on-board the main spacecraft.

A MEMS (Micro Electro-Mechanical Systems)-based miniature inertial measurement unit (Figure 6) will be used in the collector for attitude reference with updates through the camera system back to the main spacecraft. The MEMS IMU is low power (<0.6 watts) and low mass (<100 grams).

The third deployable is a telescoping boom. This device is mounted in the forward portion of the DIRE spacecraft and is covered with aerogel. This aerogel would be used to collect regolith. The boom would be used twice during the mission: the first use would be when collecting regolith scattered by the .22 caliber projectiles during low approaches to Ida and Dactyl; the second use would be to capture debris in the cloud formed by the penetrator detonation. After each use of the boom, it would be retracted and material collected by the aerogel would be analyzed.

Figure 5. 50 millinewton thruster on stand

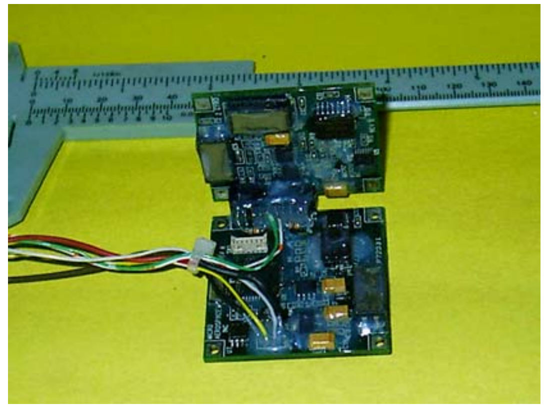

Figure 6. MEMS-based Miniature Inertial Measurement Unit

3.6 On-board Science

DIRE will retrieve regolith for analysis. Two instruments will perform the regolith analysis inside the spacecraft. One instrument will be a small optical microscope, the other a spectrographic instrument. The objective here is to perform up-close analysis of the regolith to determine composition and structure. This approach would preclude the need for sample-return science, reducing overall mission complexity.

3.7 Structure

The DIRE spacecraft bus structure will be either aluminum or composite. What will be unique is most of the subsystems and high gain antenna/radar will be protected by a Kevlar (or other suitable material) cover. Objects from the explosion of the penetrator are likely to strike the spacecraft and some form of protection must be provided.

3.8 DIRE Penetrator Vehicle

An overview of the DIRE penetrator vehicle assembly is presented in Figure 7. Major components include: penetrator body, guidance navigation, and control (GN&C) package, reaction control system (RCS), and a single solid rocket motor (SRM). The penetrator body is filled with a conventional high explosive formulated and optimized for ground penetrator performance. Fuzing is contained within the aft section of the penetrator body to minimize impact loading on the associated electronics and to place electrical connections in close proximity

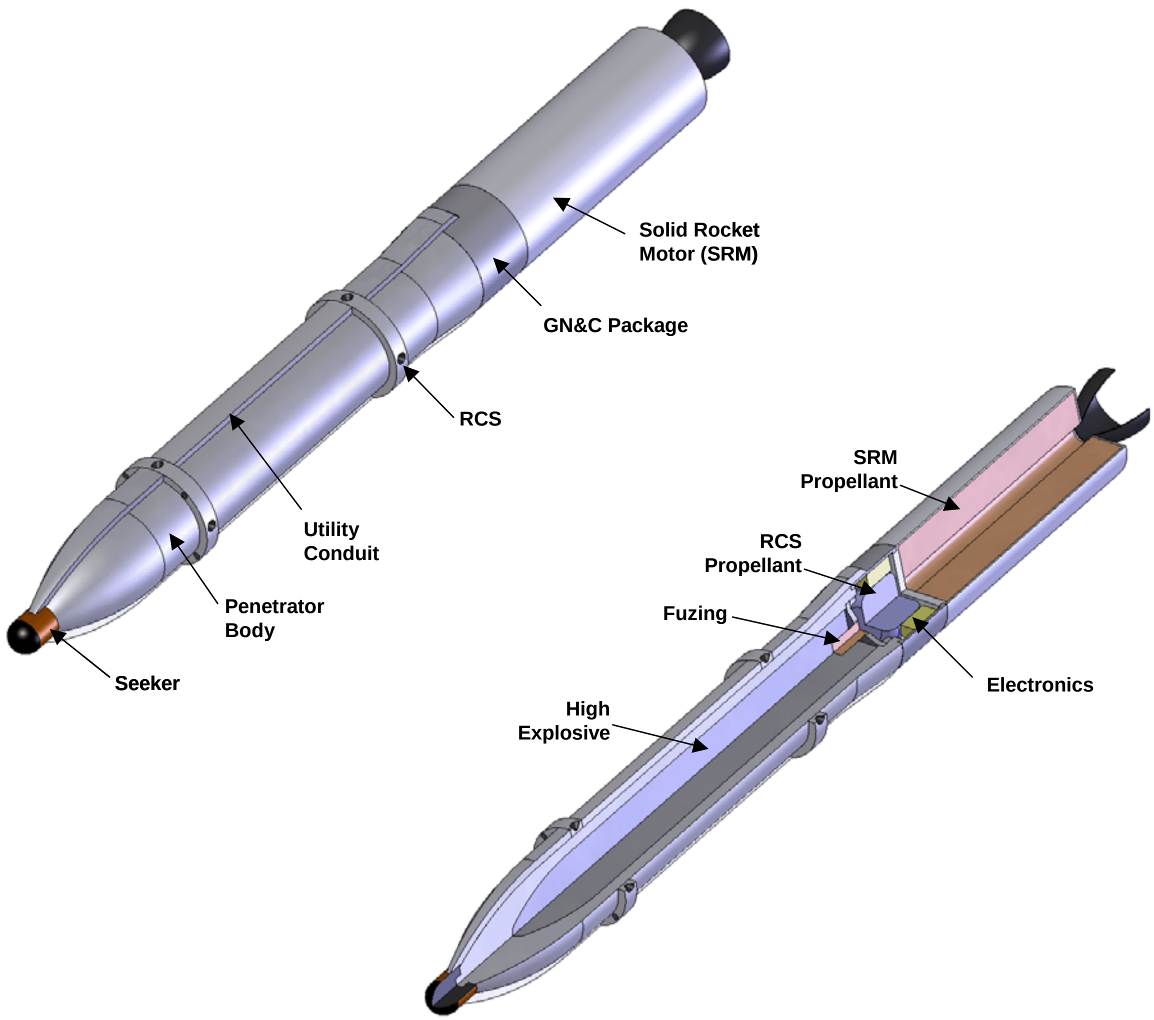

Figure 7. Overview of DIRE Penetrator Assembly

to the GN&C hardware. The GN&C section contains all electronic assemblies required to control the SRM and RCS systems, fuze arming, and target acquisition through a seeker located at the front of the vehicle. The RCS assembly is attached to the penetrator body and is used to maintain course towards the acquired target. The SRM provides the necessary boost to terminal impact conditions, following a 'dry launch' from the onboard deployment system. An integrated utility conduit systems provides for protected raceways to connect the forward mounted seeker to the GN&C package, as well as fluid interconnects for the RCS system thruster array.

The penetrator vehicle interfaces to the orbiter through a deployment assembly. An overview of the deployment assembly is shown in Figure 8. The deployment assembly serves multiple purposes: protect the assembly during transit from space environmental effects, provide the structural interface between the penetrator vehicle and the DIRE orbiter, and to deploy the penetrator vehicle towards the acquired target. Thermal control system (TCS) heaters and multilayer insulation (MLI) are mounted to the exterior of the deployment tube, insuring minimum thermal conditions are maintained for nominal electronics operation and on-board explosive/propellant integrity. A 'dry launch' type deployment mechanism expels the penetrator vehicle through a high-pressure gaseous system, which provides safe separation prior to SRM ignition. Additionally, the RCS would be used as required to assist successful deployment and safe separation. The penetrator vehicle is supported within the deployment assembly using forward and aft structural supports as indicated in Figure 8. To provide egress of the penetrator, both forward and aft structural supports are broken from the vehicle and deployment tube just prior to launch through a pyrotechnically driven system.

Notional system architecture for the penetrator vehicle and deployment assembly is shown in Figure 9. Interoperability of the penetrator vehicle and orbiter GN&C is maintained through to impact event, primarily through a one-way datalink from penetrator to orbiter. Power and control of the deployment mechanism and TCS is provided by orbiter systems, with charged batteries providing power to those penetrator vehicle systems that would ultimately operate autonomously. These systems include propulsion, fuze arming/command, and vehicle targeting.

Reconnaissance of the asteroid surface and substructure would be performed prior to launch of the penetrator vehicle, to determine the most suitable location for targeting. As part of this activity, ground-penetrating radar would be used to characterize the uppermost few meters of asteroid geology, complemented by visual observations utilizing on-board cameras. Target areas

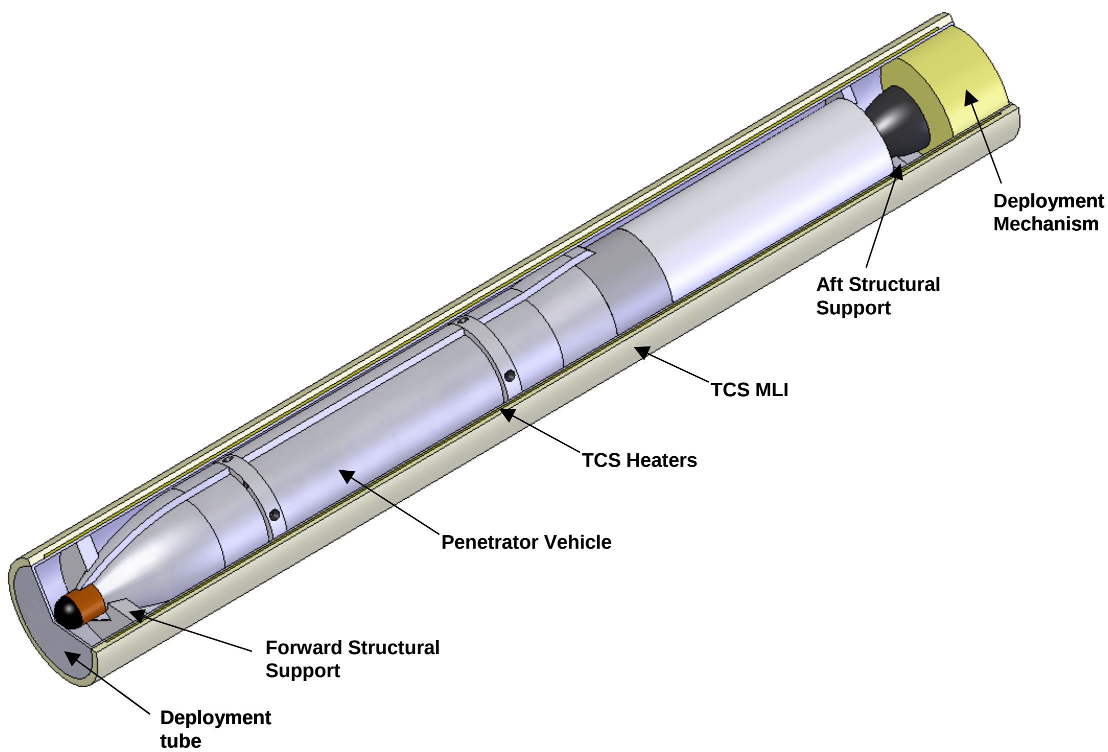

Figure 8. Overview of penetrator vehicle deployment/carriage assembly (shown in section for clarity)

would be evaluated and cataloged based upon those deemed most appropriate to maximize penetration depth and blast performance. Attention would be placed upon homogeneity of the sub-surface structure, as well as potential weak areas or fissures in the underlying rock structure, where the penetrator vehicle impact would be focused. Once the target area is selected and the orbiter parked in its launch station, additional measurements would be made using the laser range finder to determine distance-time criteria used for explosive fuzing.

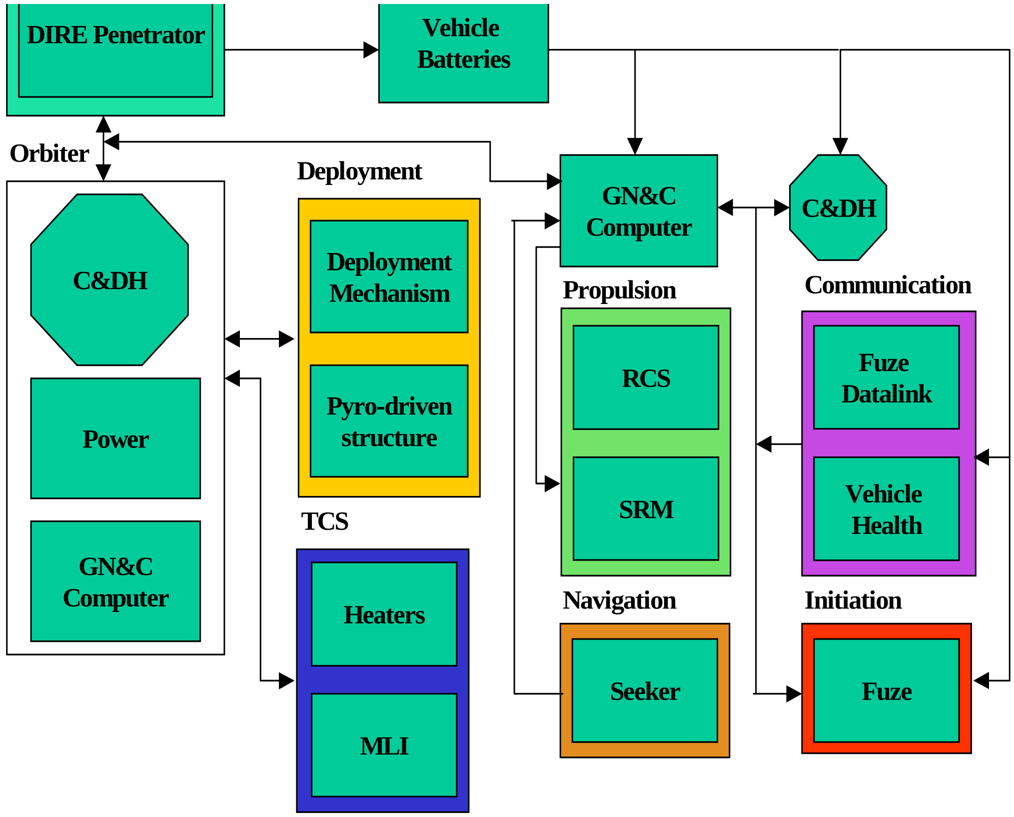

Figure 9. DIRE Penetrator vehicle and deployment assembly system architecture

Following surface/sub-surface reconnaissance, calculated targeting information is downloaded from the orbiter into the onboard penetrator vehicle GN&C prior to launch. This is achieved via electrical interconnect umbilical or inductive pick-up. Reconciliation of the downloaded data is made between GN&C systems, and then the penetrator vehicle is prepared for deployment.

As the penetrator vehicle is deployed and proceeds to the predetermined target, the main SRM motor fires to achieve terminal intercept velocity with course corrections provided by the RCS as required to insure intercept. Upon target approach, the forward mounted seeker integrated into the payload vehicle receives and detects the reflected energy from the orbiter laser illuminator and directs the vehicle towards the specific location. To minimize vehicle systems, it is proposed to utilize the orbiter's laser range finder to act as target illuminator.

Prior to penetrator vehicle impact, the fuzing train is armed and one-way communication established with the orbiter. Upon initial impact, and through the penetration event to detonation, deceleration measurements are transmitted and stored on the orbiter for later transmission back to mission control. As a sufficient deceleration environment is sensed, fuzing is energized causing detonation of the payload. To insure that the detonation event is contained within the asteroid target, distance-timing information previously downloaded from the orbiter is used as back up triggering of the explosive payload.

The acquired deceleration data, along with additional remote sensing observations, will prove valuable in determining more specific material composition of the asteroid target. As such, analytical simulations of the impact and subsequent penetration event can be improved to optimize penetrator body geometry, body material composition, and explosive fill formulation.

4.0 Conclusion

Science will be performed using heritage instruments as well as new micropropulsion devices to study the surface constituents of two asteroids. Using ground-penetrating radar, the sub-surface structure of Ida and Dactyl will be explored to determine if asteroids may indeed be rockpiles rather than monoliths. Retrieval and analysis of regolith material will be performed, during low altitude reconnaissance. After a thorough study of both Ida and Dactyl has been completed, a penetrator munition will be launched in an unprecedented attempt to split the smaller asteroid Dactyl into multiple parts. As the asteroid fragments, knowledge of the deep sub-surface materials will be gained.

The outcome of the DIRE mission would be to further expand the database of scientific knowledge relevant to these mysterious heavenly bodies, and to exercise our ability to intercept and interact with these objects. The mission would also aid in the development of techniques in defense of Earth, hence human civilization, from these massive objects.

5.0 Acknowledgement

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